WATER QUALITY GUIDELINE SERIES

Nutrients and Algae Water Quality Guidelines (Reformatted Guidelines from 1985)

Ministry of Environment and Climate Change Strategy
Water Protection & Sustainability Branch

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The Water Quality Guideline Series is a collection of British Columbia (B.C.) Ministry of Environment and Climate Change Strategy water quality guidelines. Water quality guidelines are developed to protect a variety of water values and uses: aquatic life, drinking water sources, recreation, livestock watering, irrigation, and wildlife. The Water Quality Guideline Series focuses on publishing water quality guideline technical reports and guideline summaries using the best available science to aid in the management of B.C.'s water resources. For additional information on B.C.'s approved water quality parameter specific guidelines, visit:

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PREFACE

The Ministry of Environment is developing province-wide water quality criteria for variables that are important in the surface waters of British Columbia. This work has the following goals:

(i) to provide criteria for the evaluation of data on water, sediment and biota for water quality assessments.
(ii) to provide criteria for the establishment of site-specific water quality objectives.

The water quality objectives for specific waterbodies will be based on the criteria as well as on present and future water uses, waste discharges, flow patterns and water quality. The process for establishing water quality objectives is more fully outlined in "Principles for Preparing Water Quality Objectives in British Columbia", copies of which are available from the Water Management Branch.

The definition adopted for criterion is:

"A maximum and/or a minimum value for a physical, chemical or biological characteristic of water, sediment or biota, which must not be exceeded to prevent specified detrimental effects from occurring to a water use under specified environmental conditions".

The criteria are province-wide in application but use specific, and are being developed for the following water uses:

- Drinking (includes food processing)
- Aquatic life
- Wildlife
- Agriculture (livestock watering and irrigation)
- Recreation and aesthetics
- Industrial (other than food processing)

Criteria from the literature and other jurisdictions are evaluated, and criteria are adopted or developed from this evaluation. Recognizing that criteria from the literature do not necessarily reflect adequately the effects of contaminants in all waterbodies, the criteria in this document should be interpreted as guidelines. Site-specific criteria may be developed in special cases where the province-wide criteria are judged to be inadequate.

If a waterbody has several water uses, then the criteria for the most sensitive water use will be considered for developing water quality objectives. For specific waterbodies, particular circumstances could lead to objectives which are either more or less stringent than the criteria.

The criteria will be subject to review and revision as new knowledge becomes available, or as other circumstances dictate.

SUMMARY

Criteria are proposed to protect water resources in British Columbia from degradation by excessive amounts of algae. Criteria are proposed for three groups of beneficial uses: water based recreation and aesthetic values; drinking water supplies; and protection of aquatic life. Criteria are specified in terms of phosphorus concentration or algal biomass.

Eutrophication is the process by which lakes and streams become biologically more productive due to increased supply of nutrients (phosphorus and/or nitrogen). If sufficiently large amounts of nutrients enter lakes and streams, man’s use of waters can be impaired by the algal biomass present. A number of negative consequences may result from the presence of excessive amounts of algae.

Algae in drinking water can impart unpleasant tastes and odours and cause additional costs for water utilities, which must have increasingly expensive treatment (filtration, settling) to remove algal particles. Algae and algal metabolites in water can form carcinogenic compounds when chlorine is added to water as the standard disinfection procedure. There have been many reports of persons exhibiting allergic reactions to ingestion of water containing algae or to having algae in contact with skin when swimming.

Eutrophication in some cases may benefit sport fisheries, however in most cases there are negative consequences. An increase in nutrients generally brings about changes in fish food organism communities (plankton or benthos) and usually changes habitat conditions (decreased dissolved oxygen or feeding visibility). A shift in fish species often results. Generally this is a reduction in a desirable (sports) species. Fish from lakes which have large amounts of algae can acquire an unpleasant taste to their flesh.

An increased amount of algae in lakes where recreation is important is invariably viewed as an undesirable change since it decreases water clarity. Water clarity is generally determined by the amount of algae in suspension, and the recreational and aesthetic attractiveness of a lake is primarily a water clarity perception.

A key consideration in specifying criteria is the quantification of both algae and nutrients. A variety of methods of measuring algae are possible and these methods can be divided into two groups: measurement of the rate of growth of algae (production), or measurement of the amount of algae present (biomass). For the purposes of specifying criteria, biomass is the more appropriate measurement, and of the techniques for measuring biomass, chlorophyll *a* is recommended because of its relative simplicity and general usage.

For measuring nutrients, the most important consideration is to deter- mine the fraction of phosphorus or nitrogen which is available to algae. In the overwhelming majority of cases, phosphorus is the limiting nutrient and nearly all scientific investigations regarding bioavailability have been directed toward defining bioavailable phosphorus. The nitrogen concentration is only rarely of concern since it does not limit algal growth except in very unusual circumstances. However, if a nitrogen-limited lake is identified and a criterion is needed, a method for deriving nitrogen criterion values is discussed.

Because of fundamental differences between streams and lakes, particularly in terms of water residence times, bioavailable phosphorus must be defined differently for moving water (rivers and streams) and lakes. In streams algae can only make use of phosphorus that is dissolved and directly available for uptake. The best analytical measurement presently available which approximates this is orthophosphorus (or soluble reactive phosphorus which is functionally equivalent). For lakes, other forms of phosphorus are also available due to the relatively rapid cycling of phosphorus from particulate to dissolved and the much longer water residence time compared to streams, Mineralization of dead algae and other biota makes much of what is in the water column available to algae. Thus the analytical fraction which is recommended

as an estimate of bioavailable phosphorus is total phosphorus. This fraction generally overestimates the bioavailable fraction but appears to be the best estimator at present, This guideline only applies to lakes where insignificant amounts of suspended inorganic sediment is present. Estimation of bioavailable phosphorus in lakes with significant suspended sediments and in inflow streams to lakes is an area of active present research.

Criteria are specified separately for streams and lakes. For streams there is a possibility of suggesting criteria in terms of nutrients (phosphorus) or biomass. Biomass (chlorophyll) was chosen for the following reasons. In streams there are several necessary conditions which must be satisfied before phosphorus becomes a factor causing nuisance levels of al gal growth. These conditions are suitable water velocity, substrate, light, temperature and grazing pressure. Only when all of these conditions are within favourable ranges does phosphorus hold the potential of being the limiting factor. It should be noted that very low concentrations of phosphorus (< 3 µg/L) can cause heavy stream algal biomass accumulations. Since phosphorus concentration in the stream is such a relatively poor indicator of algal biomass, and biomass itself is likely to be the focus of concern, algal biomass was chosen as the measure of the criterion.

To define what levels of algal biomass in a stream represented an impairment of use, the scientific literature and the experience of environ- mental biologists working in B.C. were surveyed. From these sources, ranges of algal biomass were identified which could be associated with loss of use. A value of less than 50 mg/ m^2 chlorophyll is suggested for protection of uses related to recreation and aesthetics in streams. A value of less than 100 mg/m^2 chlorophyll a is suggested to protect against undesirable changes in aquatic life. No criterion value could be suggested for drinking water supply since any impairment of water use would only occur from sloughing of algae, No relationship between the amount of periphytic algae present and problems with algae drawn into water intakes appears to exist.

For lakes a well defined relationship exists between phosphorus, generally measured at spring overturn, and the amount of algal biomass in a lake during the growing season. Since phosphorus is much less difficult to measure than algal biomass, and can be easily related to other important lake characteristics such as water clarity and hypolimnetic dissolved oxygen, the lake criteria are specified as total phosphorus.

In examining what levels of phosphorus could be suggested for protecting particular water uses, data from the scientific literature and from lake studies conducted in British Columbia were examined. For water-based recreation and aesthetics, a major consideration is water clarity. As such, there is a distinct preference for oligotrophic lakes which are generally defined as having less than 10 µg/L phosphorus. This value, or a value close to this, has also been used by other jurisdictions as a water quality standard and suggested by other authors as being a value which ensures lakes are acceptable for recreation. The criterion which is suggested for this water use is a total phosphorus concentration at spring overturn of 10 µg/L. Some qualification is required since spring overturn phosphorus is only a valid estimator of summer algal biomass, water clarity, and oxygen deficit, if the lake’s summer epilimnetic water exchange rate is less than six months. For lakes with more rapid flow-through characteristics, a mean summer phosphorus concentration should be used. This requirement applies to the criteria suggested below as well.

For drinking water, the major considerations for using a lake as a water supply are the amount of algae in surface water, which can cause increased cost in water treatment and taste and odour problems; and avoidance of drawing low-oxygen water from partially or wholly deoxygenated hypolimnia. The criterion chosen for drinking water supply is 10 µg/L phosphorus since problems with algae are unlikely to occur below this concentration, ensuring water withdrawn from surface water is of high quality. At concentrations greater than 10 µg/L, the risk increases of hypolimnetic oxygen depletion, with hydrogen sulphide, soluble iron or manganese and increased amounts of organic compounds being included in water withdrawn from deep (and cool) water. Many water utilities prefer to draw from deeper waters because of the cooler temperature.

The criterion chosen for protection of aquatic life is specified as a range: 5-15 µg/L phosphorus because individual lakes can have a wide range of characteristics which must be taken into account. The criterion *is* based primarily on fisheries, and on salmonids in particular. Fish represent the largest economic consideration in freshwater lakes and most management emphasis in B.C. lakes is directed toward salmonid species.

A major point is whether an increase in nutrients causes a significant change in the aquatic community in a lake. For instance, if dominant species of phytoplankton change then herbivorous grazers may be adversely affected. If zoo plankton or benthos species or numbers change appreciably then feeding efficiency for some fish species could be affected and a change in numbers of fish or the species present may occur. Some limited eutrophication of lakes may be beneficial to fish production, particularly where very low amounts of nutrients occur naturally such as in coastal lakes, and artificial enrichment of sockeye salmon lakes is presently being carried out as part of the Salmonid Enhancement Program.

It would appear that, in general, a higher concentration of phosphorus is required to optimize fish production than is desirable for recreation and drinking water supply (10 µg/L). This is particularly important for non salmonid (warm water) species which may require much higher phosphorus concentrations for optimum fish production. Some lakes would be best maintained at a low phosphorus concentration (5-10 µg/L) if an increase could cause a change in the food chain. If the lake is sensitive to oxygen depletion because of morphometric characteristics, it might consequently exhibit hypo- limnetic oxygen depletion at low phosphorus concentrations (<10 µg/L). Generally, symptoms of hypolimnetic oxygen depletion begin to occur at 10 µg/L and this is sometimes a major constraint to lake enrichment. How- ever, many lakes, if they are highly flushed or have very large hypolimnion to epilimnion ratios, may be able to have high phosphorus concentrations (10-15 µg/L or higher) and a consequent high fish production with no adverse oxygen depletion. This situation assumes that the principal use of the lake is for fish production and that recreation or drinking water supply are mi nor or unimportant, si nee a phosphorus concentration of 10-15 µg/L or higher would likely interfere with these uses.

The criterion range given (5-15 µg/L) is a basis for setting lake specific concentrations in lakes where salmonids are the most important species. The procedure requires detailed knowledge of the chemical, physical and biological processes of that particular lake.

In summary, the criteria which are proposed here are designed to protect particular water uses. Few previous attempts have been made by other government agencies to specify standards for nutrients or algae on such a detailed basis. The criteria are intended to serve as the basis for more specific water quality objectives which will require a detailed evaluation of individual streams or lakes (or parts thereof). The criteria values a:re conservative and therefore favour protection. These criteria will be subject to periodic review and to modification as understanding of the subject area increases. The criteria are summarized below.

Table
Recommended Criteria

	USES	**CRITERIA**
STREAMS	Drinking water	no recommendation made
	Recreation	< 50m g/ m2 chlorophyll *a* *
	Aquatic life	<100m g/ m2 chlorophyll *a* *

	USES	CRITERIA
LAKES	Drinking water	<10 µg/L total phosphorus **
	Recreation	<10 µg/L total phosphorus **
	Aquatic life (lakes with salmonids as predominant fish species)	>5 and <15 µg/L total phosphorus **

*standing crop from natural substrate

**spring overturn concentration (lake epilimnetic residence time> 6 months) or mean epilimnetic growing season concentration (epilimnetic residence time <6 months)

No criteria for protection of estuarine or marine waters from eutrophication are proposed due to the lack of information available on levels of nutrients or algal biomass which would be desirable in B.C. coastal waters.

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1. INTRODUCTION

In many parts of the world, there has been deterioration of water quality caused by excessive amounts of algae. The general cause and effect relationship between nutrients and algal growth is now well accepted. Nutrient input to lakes and rivers can originate from a number of sources: sewage, agricultural runoff, land disturbance, industrial effluents, storm runoff and a variety of other sources including natural sources. Some of the consequences of eutrophication of water bodies are discussed in section 2.

The intention of this report is to review the relationship between nutrients and algae in lakes and streams and to provide the basic background information so that concentrations of phosphorus or algae might be specified which would protect different water uses. Considered here are drinking water supply, recreation and aesthetics, and aquatic life. Impairment by algal growth of water for industrial use or irrigation appears to be uncommon although reports of irrigation users whose pumps clog with algae is not uncommon. Industry and irrigation are uses for which nutrient and/or algae criteria are difficult to set, so no attempt is made in this report to address these two water uses. The water uses which are considered have generally much more stringent requirements for algal concentrations in water than industrial use or irrigation; therefore, algal concentrations which meet the requirements for water supply, recreation, and fisheries would, for all but extraordinary circumstances, satisfy the requirements for irrigation or industrial use.

British Columbia is in an unusual position with regard to nutrient problems. In some areas of the province, for example the Okanagan Valley, very large expenditures of government revenues are being made to remove nutrients from discharges to prevent deterioration of water quality. In other areas, large expenditures are being made to add nutrients to lakes and rivers to increase the algal production to benefit fish production.

Cases in B.C. where nutrients and/or algae have caused problems provide useful data for determining acceptable levels of phosphorus and algae and the responses to reduction in phosphorus loading which have been accomplish- ed. Examples include the Thompson River near Kamloops (Anonymous 1973; Olan 1974; Langer and Nassichuk 1975; Kussat and Olan 1975; St. John et al. 1976; Kamloops Waste Management Task Force 1981; Bothwell and Daley 1981), Kootenay Lake (Northcote 1972, 1973; Daley et al. 1980), Skaha Lake (Nordin 1983; Truscott and Kelso 1979), Okanagan Lake (Truscott and Kelso 1979) and the Nicola River (Langer and Nassichuk 1976). All of these examples provide information which will be discussed in detail in sections 4.3 and 5.3.

The British Columbia experience with algal problems, particularly in streams, is included for two reasons. First, few criteria presently exist for algal growth and nutrients. Second, the intention was to take into account the local perceptions of algal related problems and local conditions to provide a scale which would be applicable to B.C. rather than adopting inappropriate criteria from other jurisdictions.

This report is by necessity, very restrictive. There is no intention to deal with any other biological water quality problems associated with lakes or streams other than algal growth related to nutrient oversupply (i.e. autotrophic responses). Two other categories of problems which can be encountered are bacterial or fungal growth due to input of organic or inorganics (heterotrophic or lithotrophic systems) (Wuhrmann 1974; McKinley and Wetzel 1979). Systematic classifications of heterotrophic stream systems have been developed for a number of years - the sabrobic system (Kolkwitz and Marsson 1908, 1909), but no equivalent classification exists for systems where al gal growth (phototrophy) is the predominant process. No attempt is made to discuss nitrogen or phosphorus outside of the context of algal nutrients. Elemental phosphorus, un-ionized ammonia, nitrate and nitrite can be toxicants. These aspects are not included in this report.

The report’s intended audience is not the research scientist, but the field biologist and manager who require the justification for the proposed criteria, and who require basic information on which to assess problems of algal growth caused by nutrients. Because of the technical nature of the material, some terms may be unfamiliar. A glossary is included at the back of the report (Section 7).

The criteria for nutrients which are proposed here are considered in the context of British Columbia only. They would not be appropriate or even acceptable in many other geographical areas of the world. They reflect relatively stringent levels which are representative of the present water quality of the Province. In British Columbia, there appears to be an expectation for much “cleaner” water than might be expected in other areas of the world, where perhaps degradation of water has been on-going for a very long period of time, or where concentrations of nutrients are naturally very high because of geology, topography or land use. Vollenweider (1968) lists phosphorus concentrations from a variety of flowing waters which demonstrate the relatively high concentrations found in many rivers in Europe, as well as North America - especially in agricultural or urban areas. These concentrations of phosphorus (and the consequential algal growth) would likely be unacceptable in British Columbia. A point of contrast to this general intent of maintaining low nutrients and algal growth in surface water is exemplified by the situation in China. In China, most of the streams, rivers, ponds and lakes are biologically extremely productive, since nutrient loading to Chinese surface waters is generally encouraged. The difference between an area of North America like British Columbia and China is that freshwater in B.C is used as a supply for drinking, agriculture, industry, fish production and for aesthetic and recreational purposes. For these multiple uses, it is advantageous to have the surface waters relatively pure with low nutrient content. In China, the fresh water is primarily used to produce food i.e. fish, so high aquatic productivity is a priority (Francko and Wetzel 1983).

2. EUTROPHICATION - IMPAIRMENT OF WATER USE

The occurrence of heavy growths of algae in lakes and rivers has been noted as a problem and commented on for hundreds of years. The process of eutrophication became a serious one in the 1950’s and 1960’s, partially as a consequence of widespread use of phosphorus-based detergents. Considerable numbers of studies were undertaken to determine the causes of eutrophication, and to document the consequences of lake and stream enrichment (e.g. National Academy of Sciences 1969).

One of the key results which emerged from the body of knowledge which came into existence was the confirmation of the primary role of phosphorus in the eutrophication process. The emphasis in this report on phosphorus is a reflection of the role of that element in algal growth. In lakes, the relationship between phosphorus (concentration and/or loading) and algae (growth rates and/or standing crop) has been well established (Vollenweider 1968; Wetzel 1983a) and is discussed in detail in section 5.1. Nitrogen is also an important nutrient, however only in uncommon cases can it become the nutrient which assumes highest importance.

There are a variety of negative effects on water use and fresh water biology caused by excessive algal growth. These negative effects must be viewed in the human perspective of pollution (i.e. an impairment of the use- fullness of water for human use).

2.1 Taste and Odour in Drinking Water

Objectionable taste and odours can be caused both by algae and actinomycete bacteria growing in water, and the presence of both groups of organisms appears to be related to the trophic state of the lake. Niemi et al. (1982) reported that algae and actinomycetes were more abundant in eutrophic and mesotrophic lakes than oligotrophic lakes. Silvey and Wyatt (1971) report a maximum density of actinomycetes in rivers and reservoirs after algal blooms. The algal species responsible for taste and odour in water supplies are listed and discussed by Taylor et al. (1981).

2.2 Fish Tainting

Fish from water with large amounts of algal biomass are reported to have poor tasting flesh (muddy, etc) (Persson 1978, 1980, 1982; Lovell and Sackey 1973). Several lakes in B.C. which have relatively high amounts of summer algal biomass (generally coincident with high surface water temperature) have been the object of complaints of poor tasting trout flesh. These include Wood, Ellison, Kathlyn, St. Mary, Dutch and others.

2.3 Allergies

Physiological reaction to algae contained in drinking water has also been reported in a variety of situations. Unexplained outbreaks of gastroenteritis involving thousands of people using water supplies with heavy algal growth were reported by Tisdale (1931), Veldee (1931), and Dean and Jones (1972). Decomposing algae on sand filters of water treatment plants were also suggested as a cause of gastrointestinal disturbances (Nelson 1941). Diarrhea can be caused by algae in water supplies (Aziz 1974), and inadvertent drinking of water from lakes with blue-green algal blooms can cause severe diarrhea and vomiting (Schwimmer and Schwimmer 1955; Dillenberg and Dehnel 1960). Other medical problems caused by algae in water supplies have been described by Hindman et al. (1975) and Libby and Erb (1976). Allergic reactions (dermatitis and symptoms of hay fever) have been reported to be caused by blue-green algae (Cohen and Reif 1953; Helse 1951). Allergic reaction to the biological content of potable water was described by Muittari et al. (1980) and Atterholm et al. (1977). General aspects of health related to eutrophication are discussed by Suess (1981).

2.4 Filter Clogging and Corrosion

Clogging of filters by algae in water treatment plants is a common occurrence, and increased algal content increases the cost of treating the water and maintaining acceptable quality. Increased backflushing of sand filters and additional settling times and volumes of chemicals are generally needed. Corrosion of concrete and steel is described by Palmer (1977) and is quoted below.

> "Corrosion of concrete and of metals in pipes and boilers is a continual problem. Algae sometimes contribute to corrosion either directly in localized places where they may be growing, or through their modification of the water by physical or chemical changes. Green and blue-green algae, along with lichens and mosses growing on the surface of submerged concrete, have caused the concrete to become pitted and friable (Oborn and Higginson 1954).
>
> Typical algae are unlikely to be the direct cause of corrosion of iron or steel pipes in a distribution system because most are incapable of active growth in the absence of light. However, algae have been reported to cause corrosion in metal tanks or basins open to sunlight. *Oscillatoria* growing in abundance in water in an open steel tank has caused serious pitting of the metal. When the steel tank was covered to prevent entrance of light, the algae disappeared and the corrosion stopped (Myers 1947)."

Algae can also cause problems in industrial cooling systems.

2.5 Toxicity/Carcinogenicity

Toxicity to domestic animals by blue-green algae has received considerable attention. There are many records of cattle, horses, sheep, dogs, rabbits and poultry being poisoned by drinking water predominantly from small ponds where blue-green algal blooms were present (Ingram and Prescott 1954; Gorham 1964; Schwimmer and Schwimmer 1968; Moore 1977).

The most serious problem as far as human health is concerned is the formation of trihalomethanes (THM's) from chlorination and bromination of organic compounds. This group of compounds has been identified as being carcinogenic (Maugh 1981). The potential problem was identified in the early 1970's (Rook 1974; Bellar et al. 1974), and since then considerable efforts have been expended in defining the extent of these compounds in drinking water (Symons et al. 1975; Foley and Missingham 1976; Health and Welfare Canada 1977). The risk presented by THM's would appear to be relatively low (risk factors 1.13-1.96) (Crump and Guess 1982) and chlorination because of it's widespread use and high purification efficiency ls unlikely to be curtailed because of the presence of THM's. A reduction in THM' s appears to be best achieved by a reduction in organic precursors (reduction of the nutrients causing excessive algal growth) or modified treatment procedures (e.g. additional clarification or prefiltration).

Trihalomethanes and associated compounds can be formed from a variety of organic precursors. Humic substances (Christman et al. 1981) and algal metabolites and decomposition products have been identified as organic materials which, when chlorinated as part of the disinfection process in a water treatment plant, are transformed into potential carcinogens. The number of algae in the raw water supply has been shown to be correlated with the production of THM's (Oliver and Schindler 1980; Hoehn et al. 1982), and in general, THM's have been correlated with the level of eutrophication in water bodies (Dorin 1981).

No defined relationship between algal standing crop and concentrations of THM's exists, nor has any threshold level of algae been identified above which an unacceptable risk exists for the formation of THM's. What appears to be generally understood is that increasing algal standing crop is correlated with the potential for formation of THM's.

2.6 Effects on Fishery Resources

One effect of eutrophication on fish (tainting) has been noted above. Although increased algal production in lakes may be a benefit by increasing fisheries production, eutrophication beyond a certain point can be harmful to fisheries, primarily by causing a shift in species of fish from more desirable species (i.e. sport fish such as salmonids) to less desirable species such as suckers, squawfish, etc.

In lakes this change in species composition can take place in a number of ways: alteration of habitat (increased hypolimnetic oxygen depletion), change in food species (change in zoo plankton or benthos), decrease in survival at any of the life stages, or increased competitive position by other species. Hypolimnetic oxygen depletion has been noted as a cause of fish community change in the Grosser Ploner See in Germany (Morawa 1958), and a combination of oxygen depletion and a related change in benthic food organisms caused substantial changes in fish communities in Lake Erie (Price 1961; Britt 1961). Bregazzi and Kennedy (1982) noted a steep decline in perch in response to eutrophication. Many examples of the effects of eutrophication on fish have been reviewed by Larkin and Northcote (1969) and Beeton (1969). The effects of the changing water quality of the Okanagan Lakes on fish are documented in Northcote et al. (1972).

In streams, excessive nutrient increases and consequent algal growth can also cause major losses in fish habitat and changes in fish food organisms. Heavy algal growth can cause physical alteration by covering or cementation of spawning areas (Mundie 1974). Oxygen depletion can be caused by algal respiration or decomposition and, by physically blocking the flow of water through gravel, algae can reduce dissolved oxygen. Changes in algal biomass or composition can often lead to changes in invertebrate food organisms, and this leads generally to less desirable food organisms (Grimas 1963). This problem is of special concern in B.C. because of the economic and recreational value of salmonid species which use streams to spawn or rear.

Nutrient addition to lakes does not always have negative consequences. In many unproductive lakes, nutrients have been intentionally added to enhance fisheries production. Intentional fertilization of lakes and streams (for example Great Central Lake, Nimpkish Lake, Morice Lake - Stephens and Stockner 1983; and the Keogh River - Perrin and Bothwell 1984) has been carried out as part of the Salmonid Enhancement Program (Parsons et al. 1972; LeBrasseur et al. 1978; Stockner 1977; Stockner et al. 1980) and is also discussed in more detail in section 5.2.

2.7 Effects on Recreation

A major consequence of eutrophication is the loss of recreational potential due to decreased water clarity and/or presence of algal growth. Although public perception of water quality differs from area to area even within B.C., depending on availability of recreational waters, there is a decided preference for good water clarity where some choice exists.

It is difficult to quantify the effect of increasing eutrophication, .in terms of resource loss, but in many cases it is very substantial. McNeill (1983) presents examples of changing water quality in the Okanagan and the economic value of improvement or decline of water quality. In his analysis the value of lost or gained recreation due to modest water quality change amounts to changes in value of millions of dollars to the tourism industry of the Okanagan. Young (1984) examined the impact of degraded water quality of a lake in Vermont. He concluded that the property values were depressed by 20% compared to values around a lake with better water quality. The net effect was a loss of more than two million dollars.

3. MEASUREMENTS

In attempting to discuss a technical subject such as nutrients and algae, it is necessary to give a brief description of those methods which are used to measure both the nutrients and algae. Quantification is central to the subject, and a variety of measurement techniques are available, some of which are applicable to particular situations, and some of which are superior techniques in particular situations.

3.1 Nutrients

The measurement of phosphorus and nitrogen in their various forms is primarily a matter of analytical chemistry, but there are important aspects of this subject which require definition,

3.1.1 *Analytical Methods*

There are a number of analytical techniques which are now well established and accepted (A.P.H.A. 1980). The principal techniques used by the Ministry of Environment Laboratory are described in McQuaker (1976) and Shera (1984). Follows (1982) reviewed the Ministry techniques, as well as the methods used by the Inland Waters Directorate of Environment Canada.

The most important aspect of analytical procedure is relating analytical results to what is termed "biologically available phosphorus" and "biologically available nitrogen". A variety of other factors can also affect the analysis of samples and interpretation of results. These include field filtration and handling of samples. The subject of bioavailability as related to specific analytical fractions of phosphorus is discussed in more detail in section 3.1.3.

Handling of samples between the time they are taken and when they are analysed is particularly important. Other than the obvious procedure of keeping the samples cool and dark and minimizing transit time, a decision must be made as to whether the sample should be field filtered. For both nitrogen and phosphorus, particularly when the water sample originates from a productive lake or stream, significant transformation can take place in the interval between sampling and analysis for dissolved and particulate fractions, and for different inorganic forms (e.g. nitrate and ammonia), Therefore, when accurate knowledge of nutrient fractions is required, field filtration should be carried out.

There has also been some concern expressed about the use of polyethylene bottles for sampling, because of potential adsorption of phosphorus onto the walls of the container. The use of hard glass (Pyrex) sampling bottles would minimize this potential problem.

Another method of preventing changes in phosphorus fractions is by using a preservative immediately on collection of the sample. The most used preservative at present is chloroform and should be considered in all cases where accurate quantification of phosphorus fractions is required. Freezing of samples has also been used, however, the freezing and thawing is likely to cause some transformation in phosphorus fractions, particularly if cellular material (algae, zooplankton) comprises a portion of the sample.

Neilson and El-Shaarawi (1984) tested the effect of storage on the analytical results for nutrients from samples collected in Lake Ontario. They concluded that unpreserved samples, analysed for soluble reactive phosphorus, nitrate plus nitrite, and ammonia, showed significant change after storage.

There have been a number of reports which have raised questions as to what some of the chemical analyses represent. Rigler (1968) felt that orthophosphorus was not measured accurately by the molybdenum blue technique. Tarapchak et al. (1982a) noted significant differences in orthophosphorus depending on minor differences in the acidification (strength and exposure) during analysis. Another problem which has been identified is the filtration technique used. Tarapchak et al. (1982b) noted that variations in volume filtered, pressure used, and pore size could have a significant effect on the results of soluble phosphorus analysis.

3.1.2 *Detection Limits*

In many cases, it is necessary to be able to measure forms of nitrogen and phosphorus to relatively low levels. The following should be the detection limits used in evaluating nutrient supply to algae:

phosphorus (all forms)	1 µg/L
nitrogen (total)	5 µg/L
nitrate – N	2 µg/L
ammonia – N	5 µg/L

Achievement of these detection 1evels is particularly important when considering impacts on streams with low ambient levels of nutrients, where otherwise innocuous inputs (e.g. < 5 µg/L of phosphorus) could cause a very large increase in algae. In more productive water bodies (e.g. a eutrophic lake), higher detection limits may be acceptable.

3.1.3 *Bioavailability of Phosphorus*

Some differentiation between bioavailability in streams and lakes is necessary. Dissolved inorganic forms of nutrients (orthophosphorus, nitrate, nitrite and ammonia) are available directly for uptake. However, other fractions (organics, particulates, bound material) are transformed to more bioavailable forms at a variety of rates dependent on microbial action or environmental conditions. The key to the bioavailability is the rate at which these non-biological forms are mineralized. In streams with relatively short water residence times, the kinetics of mineralization are unlikely to be a factor in making available to attached algae any forms other than those which are dissolved and inorganic. This is generally measured analytically as orthophosphorus or soluble reactive phosphorus (and nitrate and ammonia). In examining what is available for periphyton at a specific time and place, these fractions are the most accurate estimate of biologically available nutrients.

In lakes, however, where water residence times are longer, many more forms will be available within a length of time which is relevant to phytoplankton (ie. within the growing season assuming this is longer than the water residence time). With short residence time lakes, the amount of material which can be mineralized and made available to algae is reduced. However, in most lakes a pool of phosphorus and nitrogen is present which is cycled by undergoing incorporation into cells and then mineralization, and as such, much more than the soluble inorganic fractions are available. The best approximation in lakes of bioavailable nutrients is generally considered to be total phosphorus, although this is discussed in more detail below.

3.1.3.1 *Introduction*

Since phosphorus is generally the limiting nutrient in freshwater, the vast majority of investigations on nutrient bioavailability have been carried out on phosphorus associated with particulate material. This is the fraction which has the highest variability in terms of bioavailability.

Estimation of the fraction of total phosphorus which is biologically available represents the object of most investigations published in the literature. Gray and Kirkland (1982), working in the Okanagan, estimated that biologically available phosphorus contributed to the lakes consisted of 15 to 98% of total phosphorus, depending on time of year and creek sampled. Other investigators have reported similarly wide biologically available phosphorus percentages of total phosphorus. The phosphorus loading to Kamloops Lake was estimated by St. John et al. (1976) to be largely unavailable to phytoplankton, since 80% of the particulate phosphorus was inert apatite. The IJC (1983) felt that, in general, no more than 0% of suspended sediment total P from Great Lakes tributaries was potentially bioavailable. For northwestern Ohio tributaries that carry a large sediment load into Lake Erie, about 25% of the sediment phosphorus was potentially available.

There are a variety of fractions of phosphorus which can be analysed, but three fractions which are typically reported are orthophosphorus[*] (also called soluble reactive phosphorus), total dissolved phosphorus, and total phosphorus. Orthophosphorus (dissolved mineral phosphorus) is generally felt to be almost totally available for algal growth. Total dissolved phosphorus includes soluble reactive phosphorus, as well as a fraction consisting of dissolved organic phosphorus which originates as cellular contents, breakdown products or extrametabolites of biota as well as dissolved polyphosphates. Much of the organic material is in the process of re-mineralization by bacteria. Total dissolved phosphorus is partially available for algal growth, the percentage which is bioavailable depending on a number of factors, including the origin of the parent material, the rate of mineralization, etc. Total phosphorus includes the two fractions noted above, as well as particulate phosphorus (generally arbitrarily defined as being greater than 0.45 microns diameter) which is both organic and mineral in origin. The total phosphorus also has a variable portion which is bioavailable - again depending on the origin of the material, residence time of the material in the water column, kinetics, and other factors.

The particulate mineral phosphorus (at least in part, minerals such as apatite) is often considered unavailable as a source of phosphorus for algal growth, but some reports contradict this assumption.

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[*] orthophosphorus is used here as a term to designate that fraction of phosphorus defined by analytical procedures outlined in Ministry of Environment standard procedures (McQuaker 1976). Orthophosphorus is considered to be functionally equivalent to soluble reactive phosphorus and quite distinct from the chemically defined orthosphosphate.

Smith et al. 1977, 1978) used apatite (30-100 micrometers) as a source of phosphorus for algal cultures. They found that apatite was a good source of phosphorus, and that orthophosphorus was derived from the apatite and could serve as an important source of P for algae, particularly in oligotrophic systems. This finding was disputed by Williams et al. (1 980). They felt apatite was a very poor source of biologically available phosphorus.

Particulate organic phosphorus can consist of reactive phosphorus adsorbed onto particles and intact living or non living bacteria, algae and zooplankton, as well as partially decomposed biological matter (which may be allochthonous in origin). This material is generally not immediately available, but because of the rapid recycling of phosphorus in the aquatic environment (Lean 1973), particulate phosphorus and adsorbed reactive phosphorus may be bioavailable within a relatively short time.

A representation of phosphorus fractions is shown in Table 1. Most efforts to quantify bioavailable phosphorus are directed towards the particulate fractions rather than the dissolved fractions. In the literature, attention is given almost exclusively to suspended sediments in rivers or particulate phosphorus flowing into lakes.

Table 1. Particulate and dissolved phosphorus forms in water and sediments (from Logan 1982).

Phosphorus Fraction		**Chemical Characteristics**	**Percent Bioavailability**
Total P	Total dissolved P	Dissolved inorganic P (ortho/SRP)	>90
		Dissolved organic P	<50
	Total particulate P	Labile P Includes adsorbed, exchangeable, easily dissolved, easily hydrolyzed	Potentially - 100 Immediately - ?
		Inorganic P Relatively stable, primary and secondary minerals with Fe, Al, Ca.	Potentially - ? Immediately - 0
		Organic P Relatively stable humus compounds such as inositols Living and non-living organisms and partly decomposed organisms.	Potentially - ? (<50) Immediately - 0

3.1.3.2 *Algal Bioassays*

There are two general types of techniques used in attempts to quantify bioavailable P. The first uses the response of algal cultures - the EPA Algal Assay bottle test (USDI 1969; USEPA 1971; and modifications). Additions of sediment to cultures of *Selanastrum capricornutum* are made, and growth rates are compared to· parallel cultures to which known amounts of phosphorus have been added. The responses can be compared and an estimate made of the amount of phosphorus in the suspended sediment tested. Examples of this approach are given in Perry and Stanford (1982), Depinto et al. (1981), Saghar et al. (1975), Dorich et al. (1980), Golterman et al. (1969), Fitzgerald (1970), Cowen and Lee (1976), Young et al. (1981), Verhoff and Heffner (1979), and Nelson (1977).

Many algal bioassay results are difficult to interpret since total al gal growth, in the presence of sediments, is compared to standard phosphorus-spiked algal cultures to estimate available phosphorus levels. In view of the variable stoichiometry of phosphorus in algae (Rhee 1978; Young and King 1980), phosphorus uptake by the test organism would appear to be a poor measure of available particulate phosphorus, particularly if the kinetics of the available phosphorus released are desired to be understood (Young and DePinto 1982).

3.1.3.3 *Chemical Extractions*

The difficulties, time and cost associated with incubation techniques have led many researchers to investigate chemical extraction procedures which simulate algal removal or mineralization processes (Saghar et al. 1975; Cowen and Lee 1976; Golterman et al. 1969; Nelson 1977). Since phosphorus from particulate (and organic dissolved) fractions is transformed by both chemical and biological processes into biologically available fractions, many workers have used chemical extractions of various strengths to approximate the amount of phosphorus which algae can extract directly from particulate phosphorus, or which bacteria are likely to make available within a short time for algae to use. This approach has been used by soil scientists to estimate phosphorus available to crops (Chang and Jackson 1957; Olsen et al. 1954). The use of this technique on lake sediments was pioneered by Williams (Williams et al. 1971a, 1976b), and applied to an assessment of bioavailability by Williams et al. (1980). A considerable number of variations of the type of extraction and length of extraction have been proposed, and no “standard” method exists due to a lack of consensus on methodology.

ln the original scheme from soil science methodology of Chang and Jackson (1957), an initial extraction was with ammonium fluoride, which was considered to remove aluminum-bound phosphorus. However, Williams et al. (1971b) indicated that ammonium fluoride extraction is not selective for aluminum-bound phosphorus since it. extracted a high amount of iron-bound phosphorus. Extraction with sodium hydroxide after ammonium fluoride extraction was considered to remove iron-bound phosphorus. However, Williams et al. (1971a) found that sodium hydroxide extracted both iron and aluminum-bound phosphorus from calcareous sediment. Reductant-soluble phosphorus (occluded phosphorus) and apatite phosphorus were extracted sequentially with citrate-dithionite-bicarbonate and hydrochloric acid respectively.

The fractionation scheme was simplified by Williams et al. (1976b) and Allan and Williams (1978) for lake sediments. They proposed two inorganic sediment phosphorus fractions: non-apatite inorganic phosphorus that is extracted with citrate-di thionate-bi carbonate, and apatite phosphorus that is extracted with hydrochloric or sulphuric acid.

Other extraction schemes have employed anion exchange resin (Cowen and Lee 1976), aluminum-saturated cation exchange resin (Huettl et al. 1979) and nitrilotriacetic acid (NTA) (Golterman et al. 1969). Both resin methods were shown to correlate well with sodium hydroxide extraction (Logan et al. 1979).

The scheme used by Williams et al. (1976b), and Allan and Williams (1978) assumes that non-apatite inorganic phosphorus is bioavailable. While non-apatite inorganic phosphorus probably represents the maximum potentially available sediment phosphate, much of it probably will be available only over long periods of time. Citrate-dithionate-bicarbonate extraction used by Williams et al. (1976b) to estimate non-apatite inorganic phosphorus has been shown in soils to measure less labile phosphorus than that extracted by sodium hydroxide (Robertson et al. 1966). Sagher et al. (1975) found that 60-80% of sodium hydroxide extractable sediment phosphorus was removed by the alga *Selenastrum* in incubation studies, while only small amounts of hydrochloric acid extractable phosphorus were utilized. Dorich et al. (1984) estimated that 93% of sodium hydroxide extractable phosphorus was bioavailable.

Logan et al. (1979) considered bioavailable sediment phosphate to be present in two forms: short-term, as estimated by sodium hydroxide extraction, and maximum potentially bioavailable, as estimated by the sum of sodium hydro xi de and citrate-di thionate-bi carbonate sequential extractions. The latter form is equivalent to non-apatite inorganic phosphorus estimated by Williams et al. (1976b) by a single citrate-dithionate-bicarbonate extraction. Cowen and Lee (1976) found considerable variation in bioavailability of sediment phosphorus between New York and Wisconsin suspended sediments. Wisconsin sediments had approximately one third more available sediment phosphorus than those from New York, as estimated by sodium hydroxide extraction.

Young and DePinto (1982) used an extraction sequence for particulate phosphorus consisting of base-extractable, reductant-extractable, and acid- extractable fractions. They found that 63% of sewage treatment plant influent and effluent phosphorus was biologically available. Available P from tributary streams (to Lake Erie) was best approximated by the NaOH extraction (0.1 N), and represented 70% of the non-apatite P.

Workers using extraction have included Klapwijk et al., (1982) who used a sequential extraction with ammonium chloride, sodium hydroxide, and hydrogen chloride. The strongest extraction (NaOH) resulted in 27-62% extraction of total P. Klapwijk et al. also compared this extraction to P uptake by algae (0.4 - 36% of total P) and extraction by NTA (36-69%).

Gray and Kirkland (1982) investigated the bioavailability of N and Pin tributary streams in the 0kanagan Basin. They found that biologically available P was 15-98% of total P, and biologically available N was 58-98% of total N. They defined biologically available phosphorus as the sum of dissolved P plus particulate P which was not apatite.

Several investigators have used a combination of extraction techniques and bioassays to estimate available algal P. (DePinto et al. 1981; Dorich et al. 1980; Williams et al. 1980; Klapwijk et al. 1982).

Biologically available P was felt by the IJC (1983) to be represented by dissolved inorganic P plus the inorganic particulate P that is extracted with 0.1 N NaOH (soil to solution ratio of 1:1 000).

Peters (1981) used two other techniques to define biologically available phosphorus. First, he determined the degree to which a series of phosphorus fractions (total, particulate, soluble, large and small molecular weight) interacted with radioactive orthophosphorus in long term incubations.. Because orthophosphorus is a highly available form (Lean 1973; Rigler 1964), any fraction which exchanges with orthophosphorus, and so becomes radioactive itself, must be available. Second, by taking samples of lake and river water saturated with chloroform to stop biological uptake, but allowing enzymatic breakdown of P substrates (Berman 1970), an estimate of P available from particulate phosphorus can be obtained.

Recent reviews of phosphorus availability have been done by Hegemann et al. (1983) and Sonzogni et al., (1982).

3.1.3.4 *Conclusions*

From the previous sections, it can be seen that estimating bioavailable phosphorus is a complex subject, and that no consensus exists on how to do it.

For British Columbia, with its variety of geological parent materials, it may be difficult to establish a standard procedure for estimating biologically available phosphorus in water and in suspended sediment. However, it is important to evaluate available P and consequent potential algal related problems, so it should be a very high priority to establish a standard procedure for estimating biologically available phosphorus. Until standard procedures are established, the following should be considered.

In reviewing the methods for estimating biologically available phosphorus three general approaches (fractionation, bioassay, radioisotope) can be taken. The first is the fractionation/extraction approach which has been used extensively. Because of the variety of techniques, a recommendation is made to adopt one method as standard so some degree of comparability might be achieved. The method which appears to be most useful in terms of simplicity and general use for dealing with the problematical particulate fraction is the procedure set out by Williams et al. (1976b).

The use of bioassay techniques appears to be a less desirable way of estimating bioavailable phosphorus.

The radioisotope interaction technique of Peters (1981) represents the most promising technique for estimating bioavailability. It has received less use because of its recent development, however the inherent advantages of the approach are strong enough to recommend it for adoption to more routine use.

3.1.4 *Bioavailability of Nitrogen*

A second major nutrient required by algae is nitrogen, and although phosphorus limits algal growth in the majority of cases, nitrogen can be the limiting form in some circumstances. Nitrogen occurs in the aquatic environment in a number of forms, and analytical results can be reported in several ways. The nitrogen cycle is a key in understanding the transformations which take place in water. For discussions of the nitrogen cycle refer to Wetzel (1983a), Likens and Bormann (1972) or Martin and Goff (1972).

The forms most important to algae are nitrate and ammonia. Nitrite is generally not present in large quantities in undisturbed lakes or streams but can be transformed to nitrate or ammonia and serve as a nutrient. Preference for either of the inorganic nitrogen forms (nitrate, ammonia) seems to- be somewhat dependent on species or algal groups. However, both forms are generally considered to be entirely bioavailable.

A third major nitrogen component is organic nitrogen. This can be composed of a variety of materials with nitrogen content, both dissolved and particulate. Dissolved organic nitrogen generally accounts for more than 50% of the total dissolved nitrogen. Of the dissolved organic nitrogen, most is in the form of polypeptides and complex organics with a smaller portion present as free amino nitrogen.

Particulate organic nitrogen is comprised largely of phytoplankton, zooplankton, and detritus however, particulate organic nitrogen is generally a very small fraction of organic nitrogen. In some situations (turbid streams or in agricultural areas) a larger portion of the total nitrogen may be made up of particulate inorganic nitrogen. Some nitrogen fractions (e.g. ammonia and nitrate) may be adsorbed to particulate matter and released when conditions change.

A significant portion of the dissolved organic nitrogen may be biologically available, particularly compounds such as amino acids which are utilized by bacteria and mineralized quickly. Particulate nitrogen (whether organic or inorganic) tends to be much less available to algae even indirectly through bacterial breakdown.

There is considerable difficulty understanding the bioavailability of various nitrogen fractions. A diagrammatic tabulation of nitrogen forms and bioavailability is given as Table 2. Due to the less common occurrence of nitrogen limitation, less work on nitrogen bioavailability, particularly of particulate nitrogen, has been undertaken. Nitrogen limitation of freshwater algal growth is less common than phosphorus limitation because of potential for nitrogen fixation by blue-green algae (cyanobacteria) from the atmosphere when nitrogen becomes limiting.

3.1.5 *Other Essential Nutrients*

Many other elements are necessary for algal growth, however, all are less important than nitrogen or phosphorus. Carbon is the element which is required in the highest amounts, however, carbon dioxide is abundantly available from the atmosphere and readily equilibrates into surface waters. Carbon is, only under very unusual circumstances, a limiting factor for photosynthesis. A large number of trace elements are required by algae and in rare circumstances one of these may be a limiting factor for algal growth. Goldman (1972) reviewed some of these examples.

Table 2. Forms of nitrogen in water.

Nitrogen Fraction		**Chemical Characteristics**	**Percent Bioavailability**
Total Nitrogen	Dissolved Nitrogen	nitrate (NO_3)	very high (>95%)
		nitrite (NO_2)	very high (>95%)
		ammonia (NH_3)	very high (>95%)
		dissolved organic nitrogen - low molecular weight compounds such as amino acids	variable (20-80%)
	Particulate Nitrogen	particulate organic nitrogen - phytoplankton cells, zoo plankton, detritus, bacteria	variable (10-60%)
		particulate inorganic nitrogen - soil particles	very low (< 15%)

3.2 Algal Measurements

In evaluating the effect that algae are having on a waterbody (whicl1 must relate to water use), the most appropriate method for measuring algae in the waterbody must be determined. The measurements can be divided into two basic categories: techniques designed to measure standing crop (biomass), and techniques for measuring growth rates (production).

3.2.1 *Algal Biomass*

There are a number of techniques which have been used as a measure of algal biomass or standing crop. It is not intended to review the techniques here, but rather to mention some methods which are in common use, which are typically encountered in the literature, and which must be part of any criteria for algal growth.

Vollenweider (1969a) gives methods for both phytoplankton and periphyton, Wetzel and Likens (1979) review phytoplankton methods, and Clark et al. (1979) review periphyton biomass methods.

Typical measurements of biomass include numbers of organisms (per unit volume or area), dry weight and ash free dry weight (gravimetric), chlorophyll a (pigments), and adenosine triphosphate (biochemical indicator). Each measurement has advantages and disadvantages, depending on the application and circumstances.

Biomass samples collected sequentially over a specific period of a study can be used (with some reservations) to estimate attached algal production. This method, (accrual rate estimation) is a valuable and widely used technique. There are a number of considerations which have to be made to ensure that accrual rates provide acceptable estimates. The most important aspect is to have sampling done at short intervals - one to two days. Longer intervals between sampling greatly reduce accuracy. Some control is needed of settlement (colonization) rates as well as losses (sloughing, sedimentation) which should not be included in growth rates. In experimental situations for periphyton this can be done by using a darkened trough or growth area. Grazing must also be controlled or quantified if algal growth rate is to be estimated.

3.2.2 *Algal Growth Rates*

Another group of measurements which is typically used to measure algae are those concerned with algal production. The distinction between production, which is a time-related rate function, and biomass, which is a value with no implied time frame, is an important one.

Production of lake phytoplankton is typically measured by carbon (^{14}C) uptake (Steeman-Nielsen 1951; Strickland and Parsons 1972). Changes in oxygen concentration over time (using light/dark bottles) can also be used.

Measurement of production of stream periphyton directly is more difficult, and no standard accepted technique has been developed. Some proposed techniques use ^{14}C or oxygen evolution, but enclose the peri phyton in some type of container which unquestionably changes the physiology of organisms normally exposed to moving water. The most common technique for estimation of peri phyton production is using the biomass accrual method - typically using chlorophyll *a*, as a measure of biomass. This technique, as noted earlier requires consideration of both accrual by growth and by passive settlement for valid estimates of production and control of invertebrate grazing (Bothwell and Jasper 1983). Biomass production which is lost by respiration, removal or mortality is not included in the estimate. In measuring algal production, it has become apparent (Wetzel 1983b) that frequent sampling (every 1 to 2 days) is necessary for periphyton biomass changes to be characterized, and accurate production estimates made.

Quantification of growth rates is, in a technical sense, more valuable than the measurement of algal biomass, since it can be more easily related to algal responses and environmental changes. The difficulty with growth-rate measurements is that they are, in general, more difficult to make, require a higher level of capability, and demand more time and expense on the part of the investigator. In lakes, there is generally a reasonable correlation between growth rates and biomass, however, there is a general uncoupling of biomass and growth rate.s for stream periphyton. The potential exists for very high rates of periphyton growth occurring, but low biomass being present due to sloughing, diurnal cycles of growth, high respiration rates or grazing. Since most water uses are affected by the amount of algal material present rather than the rate at which the algae are growing, it would seem more appropriate to use measurements of biomass rather than growth rates in establishing water quality criteria. Al tf”\ough the techniques for measuring biomass are, in general, easier than growth rates, they are not without a substantial number of shortcomings, the primary one being the difficulty in obtaining a representative measurement.

3.2.3 *Spatial Variability*

Algae, particularly in streams, tend to be very patchy in their distribution. In regard to the problem of *in situ* heterogeneity, Wetzel (1975) states that satisfactory confidence limits in production measurements, to a point where variability was delineated sufficiently to permit analyses of changes in production in response to environmental variables, is very difficult to obtain. Sokal and Rohlf (1969) give some guidance on sample size which is required for statistical evaluation of means. An example in this regard, al though concerning sampling of invertebrates, is instructive. Within a single stream riffle, over 400 replicate samples were required to achieve a sample mean within 5% of the population mean at a 95% level of confidence (Needham and Usinger 1956; Chutter 1972). While some of the variance can be attributed to the sampling device and its use, most is simply a reflection of natural heterogeneity. Variations among populations of microflora are less likely, as indicated, for example, by the detailed analyses of Roff (1969) Variations in microdistribution are still, however, very large. The effort of replication and manipulation required is great and has not been often, if ever, attained.

Several alternative approaches to sampling have been under ta ken, none of which is without inherent difficulties. *In situ* heterogeneity has led to employment of artificial substrates of uniform composition.

The variety of artificial substrate techniques is very large, ranging from simply immersing glass slides in the stream to very sophisticated stream-side technology designed to reduce the number of variables which are affecting algal growth (e.g. Bothwell 1983; Jasper et al. 1984). An apparatus such as used by Bothwell appears to be necessary to elucidate the important relationships between the growth rates or biomass and the major factors which govern these processes, particularly nutrient concentration and water velocity.

Although artificial substrates provide some advantages for reducing substrate as a variable for growth and in some ways simplifying sampling, measurement of algal biomass or growth on natural substrates has many advantages (section 4.5.1.1). However, in some situations artificial substrate sampling may be the most appropriate choice. The choice between natural and artificial substrates should be made on the basis of the type of data required or the situation which must be assessed.

3.2.4 *Physiological Indicators of Algal Growth Status*

There are a variety of measurements which have been used to gain insight into particular characteristics of algal species or algal communities. Generally, no one indicator can be used by itself to provide an unqualified answer, but rather a number of different measurements, when considered together provide the best information for an interpretation of growth rate, relative state of health, limiting nutrients, etc. A review of many physiological indicators has been done by Healy (1973, 1975) and Healy and Hendzel (1980). A number of these indicators are discussed below since they have applicability to the criteria for algal growth which are proposed. They also serve to predict effects in cases where potentially heavy algal growth could result due to a proposed waste discharge. If the general characteristics of the discharge were known, a prediction of algal growth could be made. The information also is useful in evaluating cases where sufficient phospl1orus is apparently available and physical conditions are suitable, but algal growth is not occurring. Limiting factors which could trigger algal blooms can be identified.

3.2.4.1 *Nitrogen to Phosphorus Ratios*

Algae require nitrogen and phosphorus in specific proportions to meet their metabolic needs. A number of investigators have proposed, on the basis of a variety of physiological and environmental data, ranges of N:P ratios which are representative of conditions for algal growth under different circumstances. There are two methods of expressing N: P ratios, as an atomic weight ratio and as an actual weight ratio. Only the latter is used here, with literature values for atomic weight ratios converted to the actual weight ratios.

a) N:P ratios in water

The N:P ratio in the water provides an indication of the relative availability of these two important nutrients. Algae require nitrogen and phosphorus in particular ratios, and comparing these to what is available is a particularly valuable diagnostic tool.

The ratio of N:P in water in lakes appears to be a better indication of relative limitation than in streams. Running water systems with large flow to algal biomass ratios would likely not show any alteration in ambient nitrogen or phosphorus caused by periphyton. In contrast, phytoplankton in lakes can affect ambient nutrient concentrations, thus N:P ratios in water are likely to be indicative of actual nutrient concentration. In rivers or streams, the N:P ratio in water represents only a potential nutrient limitation rather than an actual limitation (Bothwell 1985a).

Vollenweider (1968) (cited in Hickman 1980) stated that algae require nitrogen and phosphorus in a ratio of 7.2:1. Dillon and Rigler (1974) suggest that water with an N:P ratio of greater than 12:1 is phosphorus limited. The data of Schindler (1977) indicate that 5:1 produced algal growth (blue-greens) symptomatic of nitrogen limitation, Forsberg (1980) felt that an N:P ratio in water of greater than 17:1 indicated P limitation, 10-17:1 indicated N and/or P limitation, and less than 10:1 indicated N limitation. However, no statement was made by Forsberg (1980) as to whether the ratios represent atomic weight or actual weight ratios.

Chiandani and Vighi (1974) investigated algal growth in relation to N:P ratios of algal culture media. They found that additional phosphorus only stimulated growth at N:P ratios greater than 10:1, and that nitrogen only stimulated growth at less than 5:1, indicating that these were the critical ratios for nitrogen and phosphorus limitation.

Stockner (1981) aimed at a loading rate of 6.8:1 of N:P for B.C. lake fertilization to enhance fish production. Rhee and Gotham (1980) felt the optimum ratio of N:P, based on nutrient uptake studies, was approximately 8:1. Sakamoto (1966) noted that ·chlorophyll. yield was best correlated with both nitrogen and phosphorus· over a range of 10-17:1 with N limitation at less than 10:1 and P limitation at greater than 17:1.

Smith and Shapiro (1981) used the criteria of a total N: total P of less than 10, or total inorganic nitrogen: soluble reactive phosphorus less than 5 to indicate nitrogen limitation. These criteria were taken from Forsberg et al. (1978), Few authors have indicated which forms of nitrogen and phosphorus were used to calculate N: P ratios although in most ·cases it would appear to be total nitrogen to total phosphorus.

From the examples presented, and the data cited below on cellular N: P ratios, the interpretation is made that ratios of N:P in water (in available forms) of less than 5:1 are indicative of nitrogen limitation, ratios of 5-15:1 indicate no limitation or co-limitation and ratios of greater than 15:1 indicate phosphorus limitation. Smith (1982) uses a much wider range of N:P values (4:1 to 38:1) for co-limitation however the high N:P values seem to be out of agreement with most literature values. This wide range and even the range cited above (5:1 to 15:1) probably reflect the preference of a variety of algal species. For single species the optimum N:P ratio is probably much narrower.

The nitrogen and phosphorus fractions used in calculating N:P ratios for water will be different for lakes and streams. Ideally, only biologically available N and p should be considered. However, since defining these fractions is difficult (Section 3.1.3), it is best at present to use total N to total *P* in lakes (providing that the lake has good water transparency, indicating little input of suspended sediment). An alternative would be to use total dissolved phosphorus compared to the sum of dissolved inorganic plus dissolved organic nitrogen (TDN:TDP). The TN:TP ratio probably overestimates both biologically available forms, and the TDN:TDP likely underestimates them. In contrast, for streams, N:P ratios should be calculated differently. They should be based on soluble reacti.ve (ortho) phosphorus and dissolved inorganic nitrogen (DIN) (nitrate plus ammonia). Since there are biologically available fractions of both organic phosphorus and nitrogen, the ratio of total dissolved phosphorus (TDP) to total dissolved nitrogen (nitrate plus ammonia plus dissolved organic nitrogen) could also be used, however this second ratio is far less desirable.

b) N:P Ratios in Algal Cells

The first N: P ratios were proposed on the basis of a consistent ratio of C:N:P in marine plankton (Redfield 1934, 1958). Redfield reported that the ratios of available N and P in the ocean and in the cells of phytoplankton are about the same (7: 1). Since that time, a variety of researchers have reported ratios of N:P in algae. Studies of marine phytoplankton give cellular N:P ratios of 7-8:1 (Perry 1976; Goldman et al. 1979). Golterman (1975) felt that a mean N:P ratio of 10:1 was representative of freshwater algae. Vallentyne (1974) felt that typical algal cells had a N: P ratio of 7:1. Rhee and Gotham (1980) give a mean N:P ratio of several species as 8:1. Schindler (1971) cites seston N:P ratios of 11-13:1. Healey and Hendzel (1980) report N:P ratios of plankton as 6.6 and seston as 5.7.

Healey (1973, 1975) categorized algal nutrient deficiency by using the N:P ratio of algal cells. He felt that algae with an N:P tissue ratio of less than 10:1 had a deficiency of either Nor P. With N:P ratios in the 10-20:1 range, algae were characterized as being “moderately deficient” in phosphorus, and with N:P tissue concentrations of greater than 20:1, they were called “severely deficient” in phosphorus.

One difficulty in using cellular nutrient concentrations as an index of nutrient availability is the phenomenon of luxury uptake. It has been noted by various workers that in many cases there is poor correlation between algal biomass and concentrations of nitrogen and phosphorus in the water column (Stewart et al. 1978). This appears to be a consequence of the ability of many algal species to store cellular reserves of nitrogen and phosphorus (luxury uptake) when high concentration of nutrients are available, which can be used at a later time when conditions for growth are more favourable. However, if other measurements of algal nutrient stat us are also used, this uptake can be ·taken into account.

A difficulty in the analysis of cellular nitrogen and phosphorus is choosing an analytical technique which specifically measures the cellular nitrogen and phosphorus. In streams particularly, sediment adhering to the outside of algae must not be included if an accurate measurement, particularly of phosphorus, is to be made. Measurement of organic phosphorus using the technique of Solorzano and Strickland (1968), but omitting the acid hydrolysis step, appears to be tl1e best technique at present (Bothwell 1985a).

On the basis of the examples cited previously it would be appropriate to use the following guideline for assessing nutrient limitation by algae: that tissue N:P ratios of greater than 10:1 generally indicate phosphorus limitation. Some caution should be used in applying this guideline since different algal species may have N:P cellular ratios which deviate from this.

As noted earlier, in evaluating nitrogen or phosphorus limitation, no single criterion (e.g. N:P ratio) should be used. Rather a number of evaluative criteria, (e.g. radiotracer uptake, alkaline phosphatase, growth rate analysis) used together, provide the only reliable way of assessing nutrient limitation.

3.2.4.2 *Algal Physiology*

a) Radiotracer Uptake

A number of radiotracer techniques are available which can be used to evaluate growth or nutrient limitations in algae. In assessing phosphorus demand, the rate at which carrier-free radioactive phosphate ($32 P- P0_4$) is taken up by algae can be used. This uptake rate is generally defined as turnover time (Rigler 1956). When the orthophosphate turnover time is rapid (i.e. <20 minutes or <1 hour), phosphorus is considered to be limiting for phytoplankton growth (Lean and Pick 1981; Lean et al. 1983; Prepas 1983; Chow-Fraser and Duthie 1983). Longer turnover times are associated with surplus phosphorus or physical limitation (Rigler 1964; Peters 1979; Lean and Nalewajko 1979; White et al. 1982). Phosphorus demand must be normalized for biomass and temperature to convey an accurate value for demand.

b) Alkaline Phosphatase

This enzyme is produced by algae when the supply of phosphorus becomes low. Thus, high levels of alkaline phosphatase (corrected for biomass) are a good indicator of phosphorus deficiency. The technique has been used for several years (Overbeck 1961; Fitzgerald and Nelson 1966; Berman 1970; Healey and Hendzel 1979; Pettersson 1980; Smith and Kalff 1981), and is a particularly valuable tool in assessing the relative supply of phosphorus. However, in lake water, it has been reported by Stewart and Wetzel (1981) that non-algal (bacterial) alkaline phosphatase can be present in very significant amounts, and may cause an overestimate of phosphorus deficiency of algae. A physiological measurement such as alkaline phosphatase is most useful when used in an experimental context e.g. affected or treatment population versus a control. Relative differences are more meaningful than absolute values used in comparing separate algal communities at different times. Absolute values can be affected by age of the algal community, light, temperature and other factors so comparison of samples from different locations or times without some reference values is invalid. The sampling design must take into account the strengths and limitations of the technique to be useful.

4. NUTRIENTS/ALGAE IN STREAMS

4.1 Introduction

Aquatic ecologists generally consider actively moving water (rivers and streams) to be distinctly different from lakes. There is a considerable technical basis for this. From the perspective of this report (i.e. phosphorus and algae), it is also very desirable to make this distinction. The growth rate, and (sometimes) biomass accumulation can be substantially greater in flowing water than in standing or quiescent waters. Consequently, streams are sometimes felt to be more "sensitive" to inputs of nutrients.

Many workers have noted that attached algae are more abundant in areas of swift flow. Hynes (1970), Blum (1956), Gessner (1955) and Ruttner (1937) suggested that the current made water "physiologically richer" because of the constant renewal of materials and dissolved oxygen near the surface of the organisms. Whitford (1 960) mentioned that this one particular habitat factor (current), of considerable importance in stream ecology, seemed to be misunderstood by many limnologists. Whitford and Schumacher (1 961) noted that lotic (flowing water) species of fresh water algae have a higher mineral uptake and rate of respiration in a current than in quiet water. Cedergren (1938) reported that some species of algae which grow in still water during the cool season are found only in rapids in summer.

Whitton (1975) stated that flow may benefit particular groups of algae in a number of ways, For example, a fast current reduces the flora to only those algal species such as *Lemanea* that are very firmly attached to the substratum and also resistant to mechanical damage, thereby eliminating some competition.

Whitford (1960), and Whitford and Scr1Umacher (1961, 1964) showed in laboratory studies that some species require flowing water, and that others showed enhanced growth with higher flows. *Oedogonium kurzii* had ten times more ^{32}P uptake at a water velocity of 18 cm/s than in still water. Uptake increased up to a water velocity of 40 cm/s.

Another important distinction between streams and lakes, which is relevant to the above information, is the relationship between growth rates and biomass accumulation. In lakes there is a general correlation between the two measurements (with some notable exceptions). Thus categorization of lake types is possible using either biomass (cell volume, chlorophyll, etc.) or growth rate (oxygen evolution, carbon uptake), and both of these measurements are generally correlated with either nutrient concentration or loading.

However, in rivers there may be a definite distinction between growth rate and biomass accumulation since the two processes may be governed by different factors. As noted above, the growth rate seems to be primarily controlled by nutrient concentration, at least up to some level of saturation with some secondary effect by stream velocity, but biomass accumulation appears to be governed by stream velocity, nutrients, and invertebrate grazing. Stream velocity may also have an effect on colonization rate.

In low velocity streams, biomass may accumulate in proportion to growth rate since less biomass would be sloughed by the slow water velocity. Thus, velocity becomes very important in evaluating which variable (growth or biomass) should be used in measuring algal growth in a stream. It also becomes a major consideration in determining whether or not high concentrations of nutrients are likely to manifest themselves as high biomass, or whether a high rate of algal growth with a high rate of sloughing is likely to occur.

4.2 Trophic Classification of Streams

A number of authors (e.g. Cushing et al. 1980) have expressed the desire to be able to categorize streams using a system analogous to the oligotrophy-eutrophy system now well accepted by lake limnologists. Several previous at tempts have been made to categorize streams using different methods, for example early works by Naumann (1932), Brinck (1949) and Schmassmann (1955). These at tempts were somewhat unsuccessful because of their wide scope or difficult criteria (Brinck used stoneflies as the basis for classification).

A classification including algal growth or biomass and nutrients could provide a means of evaluating stream sensitivity to nutrient input. Nutrients are an important factor in stream classification; however, stream velocity, annual hydrologic pattern, substrate and light availability are also major factors determining both algal production and biomass.

Cushing et al. (1980) evaluated a number of physical and chemical variables for 34 streams in North America and Europe. The most important factors in determining stream types were (not in order of importance) watershed area, ratio of channel length to watershed area, terrestrial litter input, total dissolved solids and phosphate-phosphorus. The importance of phosphorus is not unexpected and several variables related to phosphorus (watershed area, total dissolved solids, annual precipitation, stream length/watershed area ratio) give some support to using phosphor us as a key factor in a stream classification scheme. It should be emphasized that the perspective here is much narrower (dealing with algae and nutrients) than the larger and far more complex subject of stream ecosystem dynamics (Newbold et al. 1981, 1982; Elwood et al. 1983).

Although there is a general understanding that many streams are basically heterotrophic (consumers of organic carbon) and the base of the food chain originates allochthonously (outside the stream - i.e., leaves, wood, grass etc.) (Hynes, 1970), in many other cases there are indications of differences in energy supply. Westlake et al. (1972) estimated the autochthonous (in-stream) organic production to be approximately 40% of the total organic supply in Bere Stream, a typical chalkstream. In many B.C. streams, autotrophy (production of organic carbon) is the dominant process and hence nutrients and algae are important factors in stream characterization. Cushing (1967) and Cummins et al. (1966) have pointed out the importance of the periphyton community in small streams as a source of energy.

It is difficult to find information which provides correlation between important components of the stream ecosystem, such as benthic invertebrates or fish, and primary production (or standing crop). Consequently, any judgements on the quantitative effects of additional nutrients on benthic invertebrates or fish tend to be very tenuous. One B.C. example where nutrient addition to streams resulted in increased fish production is the Keogh River (Perrin and Slaney 1982). This is in spite of general characteristic differences in streams with high versus low nutrients, because so many other factors are present. What does appear to be possible however, is to identify those factors which modify the relationship between phosphorus and algal production (section 4.3). This would serve as the basis for some criteria for protection of those aspects of water quality in streams affected by algal growth directly.

When a trophic classification system for streams is developed, it may provide a major assistance to developing criteria to protect water quality. Such a system does appear to be very useful for lakes (section 5.1). Since most streams have a carbon supply which originates both from autotrophic production and heterotrophic processes, a first step could be to, 1) measure total carbon processed and, 2) apportion the contribution of organic carbon to autotrophic and heterotrophic processes as a ratio (e.g. 90:10, 60:40, 5:95). Such characteristics seem to be fundamental in characterizing the nature of a stream.

4.3 Factors Controlling Algal Growth and Biomass in Streams

Several major factors control al gal growth and bi amass in streams. These are light, velocity, substrate, nutrients, grazing and temperature. These factors are discussed in the following sections, and summarized in Table 3 (page 42) with respect to the risk of excessive stream algal biomass.

If streams responded directly to nutrient input, cause and effect relationships would be much easier to elucidate. However, these other factors have major influences on algae, and can override the potential of nutrients to cause visible algal biomass.

4.3.1 *Light*

In streams which are shaded by stream-side vegetation, insufficient light may be available for algal growth to reach full potential. Considering the variety of factors which may attenuate light, there are very few data to make generalizations about intensities which would limit algal growth since different species require different optimal ranges of light.

In the water, the usual cause for light attenuation is suspended particulate matter. Suspended sediments can be measured as weight/volume or as turbidity. Suspended sediments can physically abrade algal biomass as well as reduce light penetration. In areas such as the Fraser River, spring freshet turbidity may reduce periphyton standing crop significantly (Northcote et al. 1975). Colour can also be a factor in light attenuation, and ultraviolet light may affect the growth of algae in streams (Bothwell 1985b), although most species of stream algae are adopted to high levels of light. Other species or communities may be adapted to low light. Welch (1980) reviews several aspects of light and periphyton.

4.3.2 *Velocity*

It is generally considered that a very important factor for algal growth is stream velocity (Traaen and Lindstrom 1983). Hickman et al. (1982) studied algal production in rivers in the north-east area of Alberta and felt that the major factor affecting both algal standing crops and production was current velocity. A wide range of current velocities can be encountered in streams. Whitton (1975) proposed the following classification for current velocities: very strong, greater than 10 cm/s; strong, 5-10 cm/s; moderate, 2.5-5 cm/s; slight, 1-2.5 cm/s; very slight, <1 cm/s.

However, in the light of other workers' experience, this classification appears biased toward a low scale, particularly from a B.C. perspective. McIntire (1966) used two velocities in his experiment with streams. He considered 38 cm/s to be a "high" velocity and 9 cm/s to be a "reduced" velocity. Horner (1978) felt that 50 cm/s represented a velocity above which loss of algal biomass through erosion becomes greater than growth. Welch (1980) described 20-40 cm/s as a moderate velocity at which no scouring occurs. Bothwell (1983) used a velocity of 50 cm/sin a trough apparatus which was designed for comparison of peri phyton settlement and net growth between sites in the Thompson River. However, because of the uniform and low turbulent flow, scouring in his apparatus would be very minimal compared to a natural stream with turbulent and fluctuating flow. Stockner and Shortreed (1978) maintained a velocity of 40 cm/sin their periphyton trough experiments. Traaen and Lindstrom (1983) reported that certain species of algae were associated with particular water velocities (i.e. that several algal species have a defined niche within the current velocity spectrum). They felt that many macroscopically visual algal colonies have best development at velocities greater than 20 cm/s but only a few can thrive at very high velocities (> 100 cm/s). Horner et al. (1983) stated that velocities of up to 75 cm/s did not cause scouring or loss of biomass, but this was in artificial stream channels with steady velocities and more or less smooth flow. Horner and Welch (1981) examined six natural streams in Washington State, and found that increasing velocity up to 50 cm/s increased diatom accrual rates at high phosphorus concentrations (35 µg/L). They also noted that incremental velocity increases above 50 cm/s eroded an increasingly greater proportion of the periphyton growth. The excessive periphytic algal growth in the Thompson River (Kussat and Olan 1975) occurred at velocities of 11-45 cm/s (Langer and Nassichuk 1975).

From this information, some conclusions can be drawn about the velocities at which algal growth may occur (assuming nutrient concentrations are suitable). At low stream velocities (less than 10 cm/s), it would appear that the risk of excessive algal biomass accumulation would be moderate to low. At high stream velocities (greater than 50 cm/s) the risk is low because abrasion and the high rate of export (sloughing) can offset any high rate of growth. The highest risk of accumulation would be at moderate velocities (10-50 cm/s), where renewal of nutrients is taking place, but where velocities are not so high as to cause scouring.

In the literature, little detail is given as to the methods of velocity measurement. Some data may represent mean cross-sectional values however the best location for reference to algae would be close to the substrate adjacent to the algae.

The other factor which must be considered is the constancy of velocity. In systems where velocities (and flows) fluctuate significantly, algal growth can be dislodged from the surface by occasionally high velocities, or even by bed movement where the algal substrate is disturbed. The highest risk then would be on stream systems with very steady flows - for example downstream from a lake or in watersheds which, because of their morphometry, have very steady flows. Periphyton problems are generally manifested at periods of low flow when nutrients are highest, clarity is highest and flows are steady.

4.3.3 *Substratum*

For stream periphyton to accumulate to undesirable levels, the stream substrate must be suitable. Substrates such as mud, sand or fine gravel generally are not sufficiently stable for colonization and growth. In cases where large amounts of algal biomass have accumulated, the substrate has generally been gravel, cobbles, boulders or bedrock.

4.3.4 *Temperature*

Water temperature is a factor to consider, however it appears to be less important than some other factors. The effect of higher temperature is to increase algal growtr1 rates and an increase of 10° would likely result in a doubling of growth rates. Low temperatures (near zero) are not a limitation to growth (Bothwell 1985a) and nuisance levels of growth can occur at low temperatures if other factors are favourable.

4.3.5 *Invertebrate Grazing*

Grazing by insects or snails can be a major factor in the amount of biomass which is present in a stream (Kehde and Wilhm 1978; Eichenberger and Schlatter 1978; Sumner and McIntire 1982; Lamberti and Resh 1983). High growth rates accompanied by high grazing rates can result in a low standing crop of periphyton and conversely low growth rates in the absence of significant grazing pressure can result in a high standing crop which could cause a water or habitat deterioration. The latter situation (low grazer population) could occur where low populations of drift invertebrates were available to populate the area. This could occur in streams below lake outlets or in streams fed by groundwater. Low grazer populations could also be caused by fish predation.

A summary of factors governing algal growth is given in Table 3.

Table 3. Factors Contributing to High Risk of Excessive Stream Algal Biomass

1. Temperature
    a. warm water temperatures (>15°) increase risk of heavy algal growth and biomass
2. Hydrology
    a. smooth flow (i.e. stream has a more or less smooth gradient) as opposed to a stream with turbulent flow (i.e. rapids and falls)
    b. stream velocity of 10-50 cm/s
    c. annual flow variability is low (mean monthly high flow: mean monthly low flow is less than 10:1)
    d. stream velocity during potential growing period is relatively steady (little “flashiness”, effect of storm events is minor)
3. Light
    a. water clarity is high (< 5 NTU turbidity, < 3 mg/L suspended sediments)
    b. stream is open to direct sunlight (not shaded by trees or high stream banks)
4. Substrate
    a. substrate is stable and has a relatively high surface area (i.e. gravel and cobble as opposed to mud or sand which are poor algal substrates due to instability)
5. Invertebrate Grazers
    a. a high risk exists if numbers of invertebrate grazers are low
6. Nutrients biologically available phosphorus greater than 3 µg/L (with phosphorus the limiting
    a. nutrient) or inorganic nitrogen greater than 25 µg/L (N-limited)

4.3.6 *Nutrients*

If all of the physical factors are within a suitable range for algal growth, nutrients then become a very important factor. In ideal circumstances (i.e. ideal physical conditions), algal growth can be related to phosphorus (or nitrogen) alone.

Horner et al. (1982) felt that 25 µg/L orthophosphate represented a threshold, above which nuisance levels would occur. Jacoby et al. (1983) reported that several Swedish streams developed heavy localized filamentous mats at SRP of 20 µg/L or greater. Horner et al. (1983) suggested that concentrations of phosphorus (SRP) of 15-25 µg/L were the threshold of critical phosphorus concentrations for running water. Perrin and Bothwell (1984) showed that no significant differences existed in biomass accumulation rates between phosphorus concentrations of 15 and 20 µg/L. They felt that these concentrations were too high to detect gradients of periphyton growth, implying that the threshold (i.e. critical level) was less than 15 µg/L. Wuhrmann (1974) describes results of an experiment using nutrient additions to a trough system in Switzerland which give some support for this interpretation. Wuhrmann used groundwater with a concentration of 15 µg/L of P and 700 µg/L of N in various forms. He noted that there was no difference in the accumulation of biomass when the nutrients were raised to 100 µg/L P and 3600 µg/L N. However, there is evidence that much lower concentrations of phosphorus can cause excessive algal growth. In the Thompson River (see section 4.4) the concentrations of both SRP and TOP at which very high amounts of biomass occurred were less than 5 µg/L - perhaps as low a 3-4 µg/L (Bothwell 1985a; Langer and Nassichuk 1975; Bothwell and Daley 1981). High algal biomass has also been reported from the Cowichan River (Derksen 1981) and Sakwi Creek (Gough 1975) where SRP concentrations were less than 5 µg/L.

The recent work of Bothwell (1985a) indicates that under nutrient limited conditions, even at low temperatures (<10), algae only became phosphorus limited when SRP falls below 3-4µg/L.

The interpretation of these data is that phosphorus at very low concentrations can stimulate high growth rates and cause nuisance accumulations of periphyton. Concentrations of ortho-phosphorus at greater than 3 µg/L must be regarded as having the potential to cause a deterioration in stream quality.

4.4 Impairment of Stream Water Use by Algae in B.C.

A number of problems have occurred in B.C. where heavy algal biomass has had a negative effect on water quality or water uses. Most of these have not been documented in the published scientific literature or even in written reports , but it is useful to make reference to them to place in perspective the type and magnitude of problem which has occurred, and the circumstances which caused the algal growth.

Another area which requires some exploration is a definition of what constitutes an “excessive” level of algal growth, i.e. the amount of algal biomass which is likely to cause impairment of the use of the water (fish habitat, water supply, recreation potential). Very few attempts have been made to quantify this level of biomass, but recently some suggestions have been made. Jacoby et al. (1983) and Horner et al. (1983) have suggested that 100 - 150 mg/m^2 of chlorophyll *a* constitutes a “nuisance” biomass. Biggs (1985) suggested a level of biomass of 50 g/m^2 (organic biomass) represented a threshold of nuisance growth. No exact conversion is available but 50 g/m^2 is approximately 250 mg/m^2 chlorophyll *a* if a conversion of 0.5% is used (Horner et al. 1983).

From a British Columbia perspective, a location where a serious problem existed with regard to heavy algal growth was the Thompson River in the early 1970’s (reviewed in the following section). Langer and Nassichuck (1975) reported an algal biomass from natural substrates in the lower Thompson River of 45 mg/m2 of chlorophyll (4.5 µg/cm^2). Higher biomass occurred later in that sampling year as well as in other years. Holmes (1984) found biomass as high as 280m g/m^2 in 1975 and 1976. The <u>mean</u> chlorophyll concentration for the reaches of the river which had heavy algal growth would be significantly less, implying that the threshold at which a problem was perceived to exist would be much lower than 45 mg chlorophyll *a*/m^2 reported by Langer and Nassichuk. This is lower than the 100 mg chlorophyll *a*/m^2 suggested by Jacoby et al. (1983) and Horner et al. (1983).

Problems with excessive algal biomass have been reported from several locations in British Columbia, and the sources of nutrients are varied. Unfortunately many of these studies have not quantified the algal biomass so no judgements can be made as to the degree of the problem, and to the consequences of particular levels of growth. Crozier (1984 pers. comm.) observed very heavy growth in Toby Creek downstream from a sewage treatment plant discharge. The biomass was very heavy (almost totally covering the stream- bed) with the dominant alga being *Hydrurus*. Heavy algal growth occurred in Peachland Creek (B.C. Research 1978), apparently as a result of nitrogen from explosives use and phosphorus from land disturbance. A very large biomass of floating and attached algae was observed in the essentially stagnant Serpentine and Nicomekl Rivers. In this latter case, the algae are suspected as the possible cause of oxygen depletion and fish kills (Gough 1984, pers. comm.). Heavy algal accumulations in the Cowichan River below the Duncan sewage treatment plant were documented by Derksen (1981a).

A problem with heavy algal growth in an artificial spawning channel adjacent to the Fulton River near Babine Lake is presently a major concern (Bothwell 1985b; Bowman 1985). The algal growth occurs at very low orthophosphorus concentrations (<5 µg/L) and a very heavy standing crop occurs (no quantification data available). The reason for the present heavy biomass has not yet been determined. No problems occurred for many years after the channel was constructed in 1962 and an adjacent channel displays no problem with algal biomass, however, the sources of water are different (groundwater for the problem channel and lake water for the other channel). Possible factors which may play a role are the lack of upstream “seed” invertebrate drift population for the problem (groundwater-fed) channel, or some long-term buildup of nutrients from organics in lower gravel depths which both augment inflow nutrients and provide a reservoir of resting stages for algae. The spawning channel has shown a marked reduction of egg-to-fry survival coincident with the heavy algal biomass (1983-84).

There are, however, several areas where quantification of algal biomass has been done and a problem identified. These are discussed below.

One B.C. example which does offer sufficient detailed documentation to interpret causes of algal growth is the Thompson River. This was also clearly the most serious degradation of a stream in B.C. since it involved major changes in the stream. Numerous studies were undertaken to determine the extent of the problem and the possible causes (Anonymous 1973; Olan 1974; Langer and Nassichuk 1975; Kussat and Olan 1975; St. John et al. 1976; Kamloops Waste Management Task Force 1981; Bothwell and Daley 1981).

The algal growth problem had several effects. There was some evidence (Langer and Nassichuk 1975) that significant changes had taken place in the numbers and species composition of stream invertebrates. The Savona and Walhachin areas, which had the heaviest algal growth, had more oligochaetes than other river sites. Some anecdotal evidence, presented by fishermen who had fished on the Lower Thompson for a long period indicated that large emergences of stoneflies, which are a high quality fish-food item, had declined markedly. The heavy algal growth in this heavily used salmon and steelhead spawning and rearing area was of concern because of the possibility of damage to the eggs or spawning gravel. Damage would be due to deoxygenation by algal respiration and decay or reduced water-flow through the gravel. There were also numerous complaints regarding the aesthetic change in the river, and the difficulty (and danger) to fishermen who were wading and walking on the thick layer of diatom slime on the bottom.

The algal growth was due to increased phosphorus concentration, largely caused by discharges from the Kamloops sewage treatment facilities and the Weyerhaeuser pulp mill. These phosphorus discharges have been significantly reduced since the highest levels of algal growth in the early and mid 1970's.

Al though the phosphorus increase triggered the heavy growth, there were several other conditions present which allowed the phosphorus to be manifested as algal growth. These included:

(a) favourable flow conditions, consisting of moderate stream velocity (which allowed high accumulations of biomass due to high uptake and growth rates, without erosion of algae from the substrate and consequent high export rates).
(b) the location below Kamloops Lake, providing a very steady stream flow well buffered from peaks of flow which could otherwise remove algal biomass from the stream bottom.
(c) clear water (because of Kamloops Lake upstream), su ny climate, and an open stream channel, so light supply was good. The algal growth was possible because of the Slli ny winters and good light intensity typical of the Kamloops area.
(d) ideal substratum (gravel and cobbles) with little stream-bed movement.

The coincident occurrence of all these factors together in the presence of adequate phosphor us is the likely reason for the excessive al gal growth in the Thompson River. A reduction in the phosphorus loading since the late 1970's has significantly reduced the amount of algal biomass normally present in the winter low-flow period when the problem occurs.

Other situations in B.C. where excessive stream periphyton growth have been reported are at Galen Creek and Sakwi Creek. At Galen Creek, north of Williston Reservoir (Carmichael 1983), sampling was carried out to determine the effect of tailing pond and treated sewage effluents. The peak algal biomass recorded was 24.5 and 32.2 mg/m2 of chlorophyll at two particular stations. Visually, the amount of biomass was described as heavy, and would have been of concern if it had occurred in a recreational stream rather than at a remote minesite.

At Sakwi Creek (near Harrison Hot Springs), measurements of periphyton (Gough 1975) showed a very high standing crop under undisturbed conditions (up to 94 mg/m^2 of chlorophyll *a*). A concern was expressed over possible additional impact of treated sewage on a salmon spawning channel. This biomass would be unacceptable in a recreational stream or where high aesthetic values existed. It is unclear whether or not this amount of biomass would have affected fisheries habitat or food supply. Macroinvertebrates were also sampled, but the data do not indicate any obvious change in species composition between stations with heaviest algal biomass and stations with less algae. Gough (1984 pers. comm.) observed that invertebrate biomass correlated best with the presence of allochthonous intergravel leaf debris. The phosphorus concentration in Sakwi Creek during the summer growing period was generally less than 3 µg/L for both total dissolved and ortho phosphorus.

The Nicola River receives agricultural drainage as well as having relatively high natural nutrient levels. Data collected by Holmes (1980) showed very high algal standing crops for three stations on the Nicola. Three stations sampled with artificial substrates had peak biomass of 107, 147 and 220 mg/m^2 of chlorophyll *a*, and mean chlorophyll over a two-year period of 17, 23 and 35 mg/m^2. The Coldwater River below a sewage treatment plant also had high algal standing crops. Holmes (1980) found maximum biomass of 250 mg/m^2 and mean chlorophyll *a* of 14.7 mg/m^2.

The Bonaparte River also receives agricultural runoff and municipal sewage effluent. Maximum and mean chlorophyll *a* standing crop for two stations were 45-70 mg/m^2 and 4.4 - 6.6 mg/m^2, respectively (Holmes and Bernard 1982).

The level of algal biomass on the Nicola and Coldwater Rivers was of concern to several agencies. It represents unacceptable algal biomass from the view point of aesthetics and is a potential problem for fish.

On the Kootenay River below a pulp mill discharge, increased algal biomass was noted by Langford (1974) and Crozier (1984, pers. comm.). A significant increase occurred below the pulp mill and another increase below the St. Mary River, a tributary which contained additional nutrients. The maximum biomass was generally less than 30mg/m^2.

4.5 Algal Biomass and Water Uses: Proposed Criteria

4.5.1 *Introduction*

Criteria can be specified both for nutrients (the only practical controllable cause for algal growth) or for the algae themselves (the visible consequence). Both types of criterion can be used in particular circumstances.

4.5.1.1 *Algae*

For both algae and nutrients there are preliminary questions which need clarification. For algae, it must be decided whether biomass or growth rate should be measured. Routine monitoring which would be used. to determine water quality would appear to preclude growth rate measurements. The more appropriate method would be to measure algal biomass. Although several means of measuring biomass are available, the most frequently used is chlorophyll *a*. Ash-free dry weight is also used, and acceptable since a conversion to chlorophyll *a* is available (Horner et al. 1983). Using chlorophyll *a* has some disadvantages since there is variability between different algal species' chlorophyll *a* content in terms of chlorophyll/cell or chlorophyll/unit mass. Dead algae, with little or no chlorophyll can represent problem accumulations. However these are exceptions to the general acceptance of chlorophyll *a* being a good general indicator of algal biomass. As well there are insufficient periphyton ash-free dry weight biomass data on which to base a criterion. Chlorophyll *a* has the advantage of being routinely available and readily comparable to much of the data in the scientific literature. For specifying criteria, biomass measured as chlorophyll *a* is recommended.

Another problem related to specifying criteria for algal biomass in streams is how the measurement should be taken. There are two schools of thought regarding measurement of algal biomass - one advocating artificial substrates - the other advocating natural substrates. The latter approach is recommended since the criteria are intended to protect actual, observed water quality and artificial substrates do not necessarily reflect actual stream conditions. Sampling the algal biomass which is growing naturally on the substrate appears to be the best way of providing a fair assessment of al gal growth. The use of artificial substrates has a number of disadvantages: colonization times differ markedly between different sites, so a standard immersion time is not possible nor has one ever been proposed; no immediate evaluation of a site is possible with artificial substrates since incubation from a few days to a few weeks is required; artificial substrates are to some degree selective in terms of species composition since they do not have the spectrum of light, velocity, aspect (direction), and texture provided by natural substrates; artificial substrates are prone to loss by accidents or vandalism; no standard artificial substrate has been universally accepted (there are advocates of glass, plexiglass, styrofoam, open-celled plastic, and others); and biomass of algae is generally lower on artificial substrates than natural substrates.

Artificial substrates are useful in a number of applications, particularly upstream/ downstream work, or where experimental work demands the reduction of variables in the experimental design.

In obtaining samples from natural substrates, a number of options exist. At the sampling site, the sampling locations in the stream can be picked using a streamside reference point and a random numbers table (or by using any accepted method for random point sampling or grid sampling - for examples see Cochran 1977; Poole 1974). Individual rocks can be removed and quadrants or entire rocks sampled, or the substrate can be sampled *in situ*. Because of the heterogeneity of biomass. at least five and preferably ten replicate samples should collected. If the analytical cost of having each sample analysed is a factor, samples can be combined.

4.5.1.2 *Phosphorus*

In considering criteria for phosphorus in streams, it is possible to use several analytical fractions. Total phosphorus is not desirable because in many cases suspended phosphorus is present, much of which is not biologically available. Similarly, the total dissolved phosphorus fraction overestimates that which is biologically available. It would seem that the best fraction for assessing risk of algal growth in streams would be soluble reactive phosphorus (or its equivalent, orthophosphorus), particularly when the residence time of nutrients in streams and mineralization kinetics are taken into account.

4.5.1.3 *Nitrogen*

Nitrogen can be of concern if nitrogen limitation is indicated. In streams the best indicator of bioavailable nitrogen is the sum of nitrate plus ammonia. Criteria could be proposed using nitrogen concentrations if it were justified.

4.5.2 *Criteria Levels for Recreation and Aesthetics in Flowing Waters*

(a) Algal Biomass

One extremely difficult problem is defining the level of algal biomass that constitutes a nuisance or problem. It can be assumed that some level of biomass represents a threshold of acceptance for a particular water use. What is attempted here is to suggest possible algal biomass values which would affect recreation and aesthetics (drinking water and fisheries are considered in sections 4.5.3 and 4.5.4).

In the previous sections, a number of studies were cited giving documentation of algal biomass under various conditions. In a number of cases, some problem with public acceptance was also documented. These data can be used for determining a level of biomass which could serve as a criterion. All of the following results are periphyton chlorophyll *a*.

Derksen (1981b) implied that 8 mg/m^2 of periphyton chlorophyll did not represent visible growth, whereas 26 mg/m^2 was visible. Sheehan et al. (1980) felt that a concentration of less than 20 mg/m^2 was representative of oligotrophic conditions. Most biomass values from the Flathead area reported by Sheehan et al. were less than 1 mg/m^2. Other samples showed higher values and they characterized biomass of approximately 10 mg/m^2 as "light growth" and of approximately 35 mg/m^2 as "typically dense growth". Two creeks with higher phosphorus concentrations had relatively high standing crop Howell Creek approximately 45 mg/m^2 in August and Cabin Creek approximately 75 mg/m^2 in August. However most streams had standing crops which averaged less than 10 mg/m^2. These streams were certainly unproductive by any standard. Similarly Stockner and Shortreed (1975, 1976) reported a very low mean standing crop from Carnation Creek on Vancouver Island (1.9 mg/m^2) . For the Capilano and Seymour Rivers, Derksen (1981b) reported background levels of 2-7 mg/m^2, and 12-24 mg/m^2 below the Capilano hatchery. Similarly for Lynn Creek, Derksen (1980) reported algal standing crop of 2.4-13.6 mg/m^2. All of the preceding values were below what might be considered objectionable levels from the view point of recreation and aesthetics.

In the Fording River, Nordin (1982b) reported algal standing crops of 2.7-35.1 mg/m^2. It is unclear whether this level of biomass would be considered objectionable. The stream was within a minesite, so no public access was allowed, precluding any public judgements. The biomass was localized to very specific areas and to very short times of the year, but 35 m g/m2 chlorophyll a algal biomass might be objectionable in a highly utilized stream near a population centre, particularly if the algae were present as the dark green gelatinous strands encountered in the Fording River.

An area where a clear problem with excessive algal growth was evident was in the lower 7hompson River (Langer and Nassichuk 1975). They reported algal biomass (chlorophyll *a*) of 23-45 mg/m^2. However, as noted previously, these concentrations did not represent maximum concentrations. Holmes (1984) used artificial substrates and reported samples with chlorophyll values as high as 280 mg/m^2. Means exceeded 100 mg/m^2 for two Thompson River sites in 1976-1977. This level of algal biomass caused many complaints about the appearance of the river, and reduced the enjoyment of the use of the river by fishermen. The algal growth, predominantly filamentous diatoms, was brown or brownish green, slimy, and often occurred as long trailing strands. The growth coated the rocks, making footing hazardous, and fouled fishermen's lures, making angling difficult.

From these reports it is recommended that 50 mg/m^2 chlorophyll *a* on natural substrates be used as a criterion for algal growth to protect streams used for recreation, or which have important aesthetic values. This value is less than the 100 mg/m^2 suggested by Horner et al. (1983) as representing a nuisance condition. However, on the basis of the experiences in British Columbia noted previously it would appear that 50 mg/m^2 is more reasonable for this particular (and sensitive) water use. As noted in the preface, the site specific water quality objectives may be modified from this criterion based on environmental conditions at a particular location.

Assessing a level of algal biomass which is acceptable from the perspective of aesthetics is difficult and involves a certain individual subjective judgement. One way of conveying information as to the relative aesthetic effect, either with or without technical quantification, is simply by using photographs. The information conveyed in a good photograph is very valuable, particularly in upstream/downstream problems, and particularly if a measurement such as biomass or chlorophyll is included.

(b) Phosphorus Concentration

Another possible criterion which could be used to protect water quality would be to specify phosphorus concentrations below which acceptable biomass accumulation will occur. The difficulty with this is that several other factors (Section 4.2) are also determinants of algal biomass accumulations. These other factors (stream velocity, water clarity, substrate) must be within certain limits to allow phosphorus to become an important factor. As such, establishment of a phosphorus criterion is only applicable if all the other factors controlling algal biomass can be defined.

A criterion of 15 µg/L phosphorus has been suggested by Horner et al. (1983), but they based this concentration partially on a biomass of 100 mg/m^2 chlorophyll *a*, which would appear to be higher than would be acceptable.

Several other agencies have also proposed objectives for phosphorus to protect water quality where the predominant use is for recreation and aesthetics. Ontario (1979) specifies a phosphorus concentration of less than 30 µg/L (total P) to protect against excessive plant growth in rivers and streams. However this concentration was chosen to avoid heavy growth of macrophytes (vascular plants). The document states that “algal growth is not generally a problem simply because algae float away with the river flow.” This situation does not appear to be applicable to B.C. because of the different substrate, gradient, and generally open stream channels. As a consequence our streams may be more susceptible to algal growth.

Saskatchewan (1975) does not differentiate between lakes and rivers, and suggests an objective of 50 µg/L. This would appear to be unrealistic for British Columbia.

Regarding phosphorus concentrations from the lower Thompson River, the problem algal biomass accumulations occurred at 4 - 5 µg/L (total dissolved phosphorus) according to Oguss and Erlebach (1976). The phosphorus concentrations reported by Bothwell and Daley (1981) were 3.6-4.0 µg/L (SRP) and 6.1-8.7 µg/L (total dissolved phosphorus). In the Cowichan River (Derksen 1981 a), heavy visible algal biomass was present at 4-5 µg/L SRP (no quantification of algae is available, but photographs serve to illustrate the heavy growth). This algal growth is likely to be objectionable if it were in a reach of stream frequented by the public for recreation, or in an area of notable aesthetic appeal.

On this basis, in streams with ideal physical characteristics, phosphorus (as SRP) would have to be less than 3 µg/L. However, because of the complexity of the stream environment, the interaction of other factors, and the lack of understanding of this problem, no criterion for phosphorus can be recommended.

4.5.3 *Criteria for Drinking Water Supplies for Flowing Waters*

(a) Algal Biomass

For flowing waters where drinking water supply is an important use, it is difficult to determine what level of algal growth is acceptable, i.e. would not interfere with water supply. Because the algal biomass is attached to the bottom of the stream and only becomes a problem when dislodged and drawn into the water intake, algal biomass is only one factor, and stream velocity may be a more important factor.

No guidance from the literature or from experiences in British Columbia is available, and so it would seem prudent to defer the setting of a criterion until more information is available.

(b) Phosphorus Concentration

The reason for setting a phosphorus criterion would be to prevent excessive algal growth. However, in the absence of any defined goal for algal growth, or any defined relationship between phosphorus and algal biomass, no phosphorus criterion is proposed.

4.5.4 *Criteria for Protection of Aquatic Life in Flowing Waters*

(a) Algal Biomass

To determine what constitutes an acceptable biomass in a stream used by fish for spawning or rearing, a number of factors must be considered.

First, it must be assumed that a certain level of production in a stream is necessary to provide a food base for fish. This production may arise from either heterotrophic or from autotrophic production in the stream. In general there is a correlation between autotrophic production or standing crop and fish standing crop (Binns and Eiserman 1979; Perrin and Slaney 1982). However, many streams in British Columbia are very unproductive, and additional biological productivity in the form of algal biomass would be beneficial for fisheries production. Additions of nutrients to streams have been used to enhance fisheries production (Perrin and Bothwell 1 984). It would appear, however. that insufficient data are available to specify a minimum level of algal biomass or nutrients which would support a reasonable level of fishery production.

However, excessive amounts of algal biomass accumulation can be detrimental to fish in streams. Heavy algal biomass can cause the following problems:

(i) Change in the invertebrate community. A change from more desirable food items for fish such as stoneflies or trichopterans to less desirable groups such as chironomids or oligochaetes (Grimas 1963) can reduce growth rates and/or survival of fish.

(ii) Change in oxygen concentration in stream bed gravels. With heavy algal biomass, algal respiration or the decomposition of algal tissue in the gravel can damage or destroy incubating eggs. The oxygen concentration can also be affected by restriction of water flows through the gravel. The sensitivity of fish appears to vary according to developmental stage. Rombough (1985 in press) indicates that dissolved oxygen requirements for steel head trout are relatively low at fertilization (1 mg/L) but very high at hatching stage (7.5-9.7 mg/L). If steelhead are typical of salmonid requirements, these data would indicate the need to maintain sub- gravel dissolved oxygen at high levels to protect the sensitive life stages (Nassichuk 1985 pers. comm.). Barns and Lam (1983) report reduced larval development and growth of Chum salmon at relatively high dissolved oxygen concentrations (6.2 mg/L).

(iii) Fry rearing and overwintering may be impaired by algal growth as well. Excellent habitat for fry (e.g. cobble) where fry rear and overwinter in the spaces between the cobbles provides high survival. Reduction in oxygen could reduce survival particularly for some species (Tredger 1984, pers. comm.).

(iv) Change in the survival of invertebrates or the forage success of fish. Heavy algal biomass may provide additional shelter for stream invertebrates from fish, and consequently affect fish growth rates or survival. Heavy algal growth may cause loss of invertebrate habitat (Paterson and Nursall 1975).

(v) Change in spawning gravel characteristics. Heavy algal growth can cause difficulty to fish in preparing an area of gravel for spawning by causing cementation of the gravel, or restricting the flow of water through gravels (Mundie 1974).

To suggest a concentration of algal biomass which would prevent these examples of damage, it is necessary to have information on the levels of biomass which cause such changes. Very little information exists in the literature which would serve as guide, and it is difficult to establish a direct cause and effect relationship between these changes and algal biomass.

From the Thompson River, Langer and Nassichuck (1975) and Servizi (1976) reported th t more desirable fish food organisms (Ephemeroptera and Plecoptera) were considerably lower at Walhachin, where heavy algal growth occurred, than at other sites where benthic invertebrates were sampled. Oligochaetes (considered pollution tolerant) were in very high numbers both at Walhachin and Savona, where heavy algal growth also occurred. Langer and Nassichuk felt that these changes could have serious consequences on the food chain dynamics of salmonids ·rearing in these areas. The algal biomass in these areas (Savona and Walhachin) was very high. For three years peak values exceeded 200 mg/m^2 chlorophyll *a*, and possibly were considerably higher.

Derksen (1982) reported a potential for change in benthic invertebrates caused by depression of intragravel dissolved oxygen (D.0.) in the Cowichan River. The oxygen depression was at least partially caused by decomposing algal growth, but no quantification of algal biomass is available. Derksen felt that low summer intragravel oxygen might cause a loss of more sensitive organisms, and could be deleterious to rearing juvenile salmon. The reduction of D.O. was 2.6-2.7 mg/L during August and September. Spawning and egg mortality were unlikely to occur in this situation since algal growth and oxygen depletion would be minimal in late fall and winter due to higher river flows when spawning occurs and eggs are present. However, in the interior of B.C. low flows occur in fall and winter and the benefit of flushing may not occur.

Perrin and Bothwell (1934) measured maximum algal biomass in the intentionally fertilized Keogh River of greater than 100 mg/m^2 chlorophyll a without any apparent negative consequences to fish. The salmonids in the river showed enhanced growth, and the fish appeared to benefit significantly. However, the high algal biomass noted was not maintained at high levels for long periods. The biomass built up quickly over an experimental period, typically two weeks, and then declined, sometimes for reasons which are not yet understood. The consequences of a high level of biomass over an extended period of time might be different and cause problems of invertebrate species composition change or gravel oxygen depletion.

A recent detailed study of the effects of fish hatchery effluents on stream biota (Munro et al. 1985) gives some additional insight into the effects of different levels of periphytic algal biomass particularly on benthic invertebrates. They found that bent hos were affected from 60-700 m downstream from some hatchery discharges. The changes which occurred were felt to represent nutrient enrichment rather than a degradation of habitat and the streams were still suitable for fish production. In most streams which were sampled (e.g. Quinsam, Big Qualicum, Capilano) the mean annual biomass was less than 50 mg/m^2 chlorophyll *a*. One stream (Puntledge) had very high mean annual algal standing crop in pool areas (120 mg/m^2). The peak biomass for two streams (Puntledge and the Big Qualicum) reached very high values (140 - 150 mg/m^2) for at least short periods ·of time. The quantities given are for artificial substrates and may or may not be directly comparable to periphyton on natural substrates. Munro et al. did note that, at higher levels of algal biomass, chironomids and oligochaetes increased more than other benthic invertebrate groups. This could have some effect on salmonids' feeding success and growth since they prefer drift invertebrates to those living on or in the substrate such as chironomids or oligochaetes. Although the study provides data on algal and benthos communities, there are no direct data to provide information on fishery response.

In the general case, it can be interpreted from this study that high algal standing crops (probably those exceeding approximately 100 mg/m^2 chlorophyll *a*) provide some significant risk of a change in the invertebrate community which may be of consequence to salmonids. Much more research is needed to quantify the linkage between periphyton, invertebrates and fish.

In considering the previous data, a recommended criterion for protection of streams with a fishery value is an algal biomass concentration of less than 100 m g/m2 of chlorophyll *a*.

To reiterate a point which was made in the preface, a criterion such as the 100 mg/m^2 cited here serves only as a basic starting point for future water quality objectives for periphyton in streams. Many other factors interact with nutrient supply to govern fish production so, in an evaluation of fish stream habitat, other factors certainly must be taken into account (eg. Binns 1978, 1982). A major factor which must be considered in setting an objective is its applicability to the site which is being considered, and the effect of factors such as nutrient concentration, substrate, stream gradient and velocity, and fish species and life stage. A detailed analysis would be necessary before an objective is proposed.

An example of the type of problem which might be encountered is the occurrence of algal growth primarily at the stream edge where numbers of juvenile fish are concentrated and where excessive algal growth could negatively affect the growth and survival of the fish. In such a case, the objective value which was determined could be measured on the basis of the important area of the stream rather than as a mean for the entire stream width. Other modifications such as diff'erent objectives for different times of the year or. objectives keyed to environmental conditions may need to be considered. However the 100 mg/m^2 serves as a reference and a starting point for an objective of this type.

(b) Phosphorus Concentration.

As noted previously, it is far more difficult to suggest a criterion for phosphorus than for biomass since so many other factors can act to modify the growth potential which is available. It would seem then that suggesting a criterion for phosphorus would be extremely difficult and likely of less value than a criterion for algal biomass.

However, some guidelines would be useful in evaluating phosphorus concentrations in streams with moderate or high fishery value, so that potential problems can be assessed. It is clear from some of the data discussed in section 4.5.2(b) that very low phosphorus concentrations (less than 5 µg/L) can cause amounts of algal growth which affect many water uses, including fisheries. The Thompson River data have been discussed at length in section 4.4, and Derksen (1981a) noted that a depression of intragravel oxygen in the Cowichan River was coincident with total dissolved phosphorus concentrations of 4-5 µg/L (no biomass measurements are available at present). It is unclear how much damage would be done to salmon eggs or fry by a depression of 2-3 mg/L of dissolved oxygen, but some increased mortality would be expected.

It would appear then that even at concentrations as low as 3 4 µg/L SRP, given suitable conditions of water velocity, water clarity and substrate, very high algal biomass (and consequences of algae, e.g. changes in benthos or oxygen depletion) can occur. However, without the appropriate accompanying physical conditions, nuisance algal growth might not occur even at relatively high phosphorus concentrations. If a criterion were to be specified for phosphorus to protect fisheries for all situations, a concentration of less than 3 µg/L SRP might be necessary, but this would be entirely impractical. For streams with fish and/or aquatic biological resources, criteria appear to be best specified as algal biomass.

5. NUTRIENTS/ALGAE IN LAKES

In contrast to streams, there is a far better understanding of lakes as ecosystems, and particularly the relationship between nutrients and algal growth and the consequences of algal growth. A major advantage over streams is the general acceptance of a trophic state concept which is in present use.

5.1 Trophic Classification of Lakes

The concept of trophic levels in lakes (Naumann 1919) is based on the grouping of lakes into categories (oligotrophy, mesotrophy and eutrophy) based on the level of biological production of lakes. Trophic levels can be characterized in a variety of ways, and some of these are summarized in Table 4.

A principal value of the trophic system is that there is a basis on which persons dealing with lakes can communicate the basic chemical and biological conditions of a lake. For instance, “mesotrophic” conveys a variety of lake characteristics, including water clarity, oxygen depletion, algal biomass, phosphorus concentration, etc., (see Table 4) and transition from, for instance, oligotrophy to mesotrophy is generally associated with a number of significant changes (algal biomass, water clarity, oxygen depletion).

It should also be noted that the limnological terms of oligotrophy, mesotrophy and eutrophy carry with them synonyms of value judgement which are also used in a qualitative way: good, fair and poor (Chapra and Dobson, 1981). Similar value judgements were used by Vollenweider (1968) in describing phosphorus loadings. He designated the oligotrophic and eutrophic loading rates as “permissible” and “dangerous”, respectively.

Bernhardt (1983) made specific connections between the trophic state and the water use. For instance he felt that for drinking water supply the required trophic state was oligotrophy but mesotrophy could be tolerated. Other Bernhardt guidelines are shown in Table 5.

The combination of some judgement on appropriate trophic levels for particular water uses and good quantification of the trophic levels gives some starting point for suggesting quantitative criteria for different land uses. However, many lakes are multiple use and uses may have conflicting water requirements. Oligotrophy (<10 µg/L phosphorus or 2 µg/L chlorophyll *a*) maybe an acceptable state for water supply for drinking water, however, oligotrophy may not provide sufficient production to support fisheries (particularly some species) at a desired level.

Table 4. Typical ranges of nutrient and phytoplankton parameters for different trophic levels in lakes.*

	total p µg/L at spring overturn	**total N µg/L at spring overturn**	**chlorophyll *a* µg/L growing season mean**	**Secchi disc m growing season mean**	**Hypolimnetic oxygen depletion rate mg O_2/m^2/day**	**phytoplankton (#/mL) growing season mean**	**phytoplankton biomass (mg/m^3) (wet weight) growing season mean**	**phytoplankton biomass mgC/m^3 growing season mean**	**primary production mgC/m^2/day growing season mean**	**primary production gC/m^2/yr**
Oligotrophic	1-10	<100	0-2	>6	<250	<1000	0-500	<100	50-300	<150
Mesotrophic	10-30	100-500	2-7	3-6		1000-5000	500-2000	100-300	250-1000	150-250
Eutrophic	>30	500-1000	>7	<3	>500	>5000	>2000	>300	>1000	>250

The purpose of this table is to provide a point of reference in establishing general lake water quality as related to open water biological production.

*Modified from a number of sources.

Table 5. Connection between the trophic state of an impoundment and the way in which it can be used (From Bernhardt 1983)

Type of Use	**Required Trophic State**	**Tolerated Trophic State**
drinking-water reservoir	oligotrophic	mesotrophic
bathing	mesotrophic	slightly eutrophic
raising of low water discharge with long distance water supply lines		mesotrophic
without long distance water supply lines		slightly eutrophic
industrial water supply	mesotrophic	slightly eutrophic
cooling water		eutrophic
water sports (no bathing)	mesotrophic	eutrophic
landscaping in recreational areas		slightly eutrophic, natural eutrophic
irrigation		strongly eutrophic
energy production		strongly eutrophic+)

+) without considering the quality required in the receiving water and without river-impoundments.

5.2 Factors Controlling Algal Growth and Biomass in Lakes

In lakes, algal biomass and/or production can generally be related to phosphorus concentration (generally measured at spring overturn) or loading (corrected for lake and hydrologic characteristics).

There are exceptions to this general response to phosphorus. These generally are cases where nitrogen is the limiting nutrient, or where physical factors are overriding (e.g. turbidity preventing light penetration). However, the relationship between phosphorus loading and lake production does hold in the general case and for reference, Vollenweider (1968) Vollenweider and Kerekes (1980) or Stockner and Shortreed (1985) are useful.

The key role of phosphorus in determining lake algal production makes the exercise of proposing water quality criteria much easier than for streams. A variety of relationships have been described which allow correlation of phosphorus loading with chlorophyll *a*, with water clarity and with hypolimnetic oxygen depletion (Vollenweider 1968; Janus and. Vollenweider 1981; Rast and Lee 1978; Rast et al. 1983). Phosphorus/ chlorophyll and phosphorus/water clarity correlations for British Columbia are described in Nordin and McKean (1984), Since these relationships are well documented, the use of phosphorus as the key water quality variable appears to be justified, but algal biomass can also provide a useful means of evaluating biological water quality and corroborating conclusions reached using phosphorus, if necessary.

5.3 Impairment of Lake Water Uses by Algal Growth in B.C.

There are several examples of lakes in B.C. where excessive algal growth caused by nutrient input has damaged water use values. Since most lakes have multiple uses of the water (potable water supply, fisheries, recreation, irrigation, industrial use) it is useful to review, at least briefly, what use was affected and the circumstances.

Kootenay Lake in the 1960’s was the recipient, from a fertilizer plant, of heavy phosphorus loading which consequently increased algal growth (Northcote 1972, 1973; Daley et al. 1980). The major concern appeared to be with a deterioration in aesthetics (algal blooms) and interference with recreation (fouling of beaches, slime on fishermen’s lines). During the period of highest loading, spring overturn total phosphorus was estimated to be 90 µg/L, but biological response was relatively minor - largely because of nitrogen limitation. With the combined construction of the Libby Dam upstream and the reduction of the discharge of phosphorus from the fertilizer plant, algal biomass in the lake decreased. Since 1975 the lake has become less productive, and it would appear that the primary and secondary production is presently below a level which would be considered desirable by fishery managers for fish production. Many lakes in B.C., particularly coastal lakes, are similarly naturally deficient in nutrients and intentional addition of N and P has been made to many lakes to increase salmon production (Stockner 1977; Stockner et al. 1980).

The Okanagan lakes came under scrutiny in the late 1960’s due to public complaints about decreasing water clarity, algal blooms and a general perception of deteriorating water quality (Coulthard and Stein 1968; Stein and Coulthard 1971). A major Federal-Provincial study (the Okanagan Basin Study) was undertaken in the early 1970’s in part to determine the condition of the lakes and the cause of eutrophication. The limnological results (Pinsent and Stockner 1974; Stockner and Northcote 1974) indicated that the sewage treatment plants were major contributors to the changes in water quality. Reduction of phosphorus loading from sewage treatment plants was achieved, and the improvement in lake quality documented by Truscott and Kelso (1979), Jensen (1981), Alexander (1982), and Nordin (1983).

The major areas which were affected were the Vernon Arm (by the City of Vernon discharge), Skaha Lake (by the City of Penticton discharge) and Osoyoos Lake (by the Town of Oliver and the Penticton discharges). The levels of algal biomass and phosphorus which caused these problems are useful in determining the acceptable levels of algal biomass and phosphorus for these lakes.

For Vernon Arm, phytoplankton standing crop (chlorophyll) prior to diversion of Vernon’s effluent from the lake (complete diversion began in August 1977) averaged 5 µg/L in 1976. In 1978 and 1979 (Jensen 1981), the mean chlorophyll *a* was 2.5 and 1.6 µg/L. Data for periphyton chlorophyll *a* standing crop showed a decrease from 8.5 µg/cm^2 (1971) to 2.3 µg/ cm^2 (1977-78), a factor of approximately 3.7. Total phosphorus concentrations in Vernon Arm were very high (42 and 50 µg/L in 1976 and 1977 and decreased after diversion to 13.6 µg/L in 1978 and 14.5 µg/L in 1979).

In Skaha Lake, blue-green algal blooms in the late 1 9601 s prompted the City of Penticton to upgrade its sewage treatment to remove phosphorus in 1972-73, and an improvement in lake water quality followed. The total phosphorus concentration (spring overturn) before phosphorus removal was 20-40 µg/L while the 1974-77 data indicated concentrations in the 10-25 µg/L range. Data for algal biomass indicate a chlorophyll *a* concentration of 13 g/L in 1971, and 3.0 - 4.5 µg/L chlorophyll *a* in the 1976-78 period. Hypolimnetic oxygen depletion data are incomplete, but there is some indication that dissolved oxygen concentrations had been sufficiently low to be of concern for fisheries prior to the removal of phosphorus.

Osoyoos Lake also appears to have responded to the reduction of phosphorus from Penticton. Truscott and Kelso (1979) reported a reduction in algal standing crop, but noted that any changes in phosphorus concentration were difficult to ascertain. The algal biomass for 1971 was reported to average approximately 20 µg/L of chlorophyll *a* while in 1976-78 mean summer chlorophyll *a* averaged 4-6 µg/L. Representative phosphorus concentrations for 1969-71 were 15-17 µg/L, compared to 12-18 µg/L for 1976-78.

St. Mary Lake on Saltspring Island was studied by Nordin et al. (1983). The lake has experienced increased nutrient concentrations and algal standing crop, partially at least from increasing watershed development. Spring overturn total phosphorus concentration was approximately 40 µg/L and mean summer chlorophyll *a* was about 8 µg/L. The lake is used as a water supply and the level of algal biomass interferes with water treatment, and causes taste and odour problems. The lake is also used for recreation (boating, swimming), and fisheries production is limited by the hypolimnetic oxygen depletion.

Dutch Lake near Clearwater was sampled in 1980 and the results reported in Nordin (1982a). The lake is used for recreation and supports an important fishery. Heavy algal growth was the cause of complaints of taste and odour of fish flesh, and for general complaints regarding nutrient related lake characteristics (algal scums, water clarity, floating weeds). The phosphorus concentration was variable (from 8-40 µg/L TP), as was the chlorophyll *a* (from< 0.5 to 135 µg/L).

At Tie Lake near Cranbrook, McDonald (1984) carried out a study to ascertain the causes of unacceptable levels of algal growth which were interfering with recreation and causing complaints about impacts on aesthetics. The peak total phosphorus and chlorophyll concentrations in this case were approximately 40 µg/L and 10 µg/L respectively.

McKean (1982) described the water quality of Dragon Lake near Quesnel, where there were complaints regarding algal growth. The lake is used recreationally, for water supply, as a source of rainbow trout eggs for hatcheries, and is a high value fly-fishing lake. Phosphorus concentration over the summer of 1980 averaged 33 µg/L.

Charlie Lake near Fort St. John is a eutrophic lake which is used for recreation, water supply, and supports an important sports fishery (Nordin and Pommen 1984). The high total phosphorus and chlorophyll *a* concentrations (96 and 31 µg/L annual mean concentrations respectively) present problems for all water uses and are clearly above desirable levels.

It should be noted that most of the perceived problems occurred when lakes acquired the phosphorus or biomass which would place them into a mesotrophic or eutrophic category (greater than 10 µg/L phosphorus, or 2 µg/L chlorophyll *a*). Oligotrophic lakes are rarely a subject of concern in terms of algal growth or water clarity.

5.4 Phosphorus and Water Uses: Proposed Criteria

5.4.1 *Introduction*

In addition to the data cited above for phosphorus and chlorophyll in B.C. lakes, there are numerous examples from the literature and from other geographical areas which can be used as guidelines for setting water quality criteria for phosphorus in lakes.

Because of the positive and significant correlation between phosphorus and algal standing crop/water clarity/oxygen depletion, it is possible to specify criteria for phosphorus concentrations in most cases. However, some situations may require specifying criteria for other properties (algal biomass/water clarity/oxygen depletion), and this can be accommodated by using correlations such as those given in Table 6. Similarly, criteria for nitrogen ·could be established using the ratio between total nitrogen and phosphorus from algal demand (7 or 8:1) to provide the basis for a criterion in a nitrogen limited environment.

Table 6. Conversions for phosphorus to chlorophyll, water clarity and hypolimnetic oxygen depletion

A. Phosphorus:Chlorophyll	
$\log_{10}(\mathrm{Chl}\,a) = 1.168 \log_{10}(P) + 2.783$	(Reckhow 1978)
$\log_{10}(\mathrm{Chl}\,a) = 1.449 \log_{10}(P) - 1.136$	(Dillon and Rigler 1974)
$\log_{10}(\mathrm{Chl}\,a) = 0.9873 \log_{10}(P) - 0.6231$	(Nordin and McKean 1984)
$\log_{10}(\mathrm{Chl}\,a) = 0.92 \log_{10}(P) - 0.09$	(Stockner and Shortreed 1985)
B. Chlorophyll: Water Clarity (Secchi depth)	
$\text{Secchi depth} = 17.28 \times (1 + 0.963\,\mathrm{Chl}\,a)^{-1}$	(Chapra 1978)
$\log_{10}(\text{Secchi depth}) = -0.473 \log10(\mathrm{Chl}\,a) + 0.803$	(Rast and Lee 1978)
C. Phosphorus: Water Clarity	
$\mathrm{Log}_{10}(P) = 0.818 - 1.307 \log_{10}(\text{Secchi depth})$	(Reckhow 1978)
D. Phosphorus: hypolimnetic oxygen depletion (HOD)	
$\text{areal HOD } (\mathrm{g/m^2/d}) = 0.467 \log_{10}\left(\frac{L(P)}{q_s} + \frac{1}{TW}\right) - 1.07$	(Rast and Lee 1978)

P = phosphorus concentration in mg/L (generally at spring overturn)
Chl *a* = growing season mean of chlorophyll *a* in $\mathrm{mg/m^3}$
q_s = water overflow rate (m/yr)
L = phosphorus loading (in $\mathrm{g/m^2}$/year)
TW = water retention time (yr)
Secchi depth = water clarity (in meters)

Phosphorus criteria need not necessarily be specified as a concentration, but can be specified in terms of loading. Many lakes have had phosphorus criteria specified as annual loads (e.g. Okanagan Basin Study, Great Lakes). The Canadian Federal Government (Dept. of Environment 1972) specified permissible nutrient additions to lakes in terms of the Vollenweider loading formula, or used an algorithm to specify permissible loading.

One difficulty in specifying criteria for lakes is that lakes are not homogeneous in their water quality. Descriptions of most lake water quality apply to the open water area. However, nearshore water quality is very often quite different than the open water part of the lake due to influences from the bottom and rooted vegetation and stream and groundwater inputs (with higher nutrients). Phytoplankton, peri phyton and aquatic macrophytes in littoral or nearshore areas have considerably higher production (on a per area basis) than in the open water. The nearshore area has a much higher level of public visibility, and may represent a disproportionately pessimistic representation of the overall lake water quality. The nearshore area also happens to be that part of the lake which receives the most intensive uses, by recreationists, water withdrawals and valued biota such as fish and birds. Coincidentally, this portion is most subject to influences by contaminants originating from the land or from human and animal users and proliferation of nuisance aquatic weeds. It may be necessary in the future to consider criteria for the nearshore area (depth less than 7 m) of a lake, but no such attempt is made in this document.

In suggesting criteria, one must also consider how the concentrations are to be measured. For phosphorus concentrations in lakes, the standard point of reference is spring overturn. This time period, when a lake is free of ice and the water column is isothermal, is assumed to give a good representation of the ·supply of phosphorus to the lake over the following summer growing period. The good general correlation between spring overturn phosphorus and mean summer chlorophyll does bear this out (Sakamoto 1966; Dillon and Rigler 1974). However, there is a limitation to this general rule. To use spring overturn phosphorus, the summer epilimnetic water residence time of the lake should be longer than about six months. Otherwise, as inflow phosphorus concentrations change (as they generally do with inflow volume), the spring overturn P no longer accurately represents the P supply to phytoplankton in the summer. Thus, in lakes with epilimnetic water residence times of less than six months, phosphorus concentrations for criteria should be measured as mean growing season values.

When sampling at spring overturn is carried out, at least three samples from the water column should be obtained: near bottom, mid-depth and near surface. Chlorophyll samples should be taken to insure biological activity has not begun. Biomass (as chlorophyll *a*) should be less than 0.5 µg/L. For sampling over the growing season to measure mean summer phosphorus, samples should be taken at approximately three week intervals at least three depths in the epilimnion and, if possible one depth in the hypolimnion.

The form of phosphorus used in criteria must also be specified. For lakes, the fraction which should be used is total phosphorus. In most lakes (except those with heavy suspended sediment load), total P is the fraction which best represents biologically available P. Most non-available particulate P from inflow streams is lost from the water column relatively quickly. Total P is largely particulate P during most of the growing season, but this is made up of algae, zooplankton and detrital material which are major components of the phosphorus cycle. Generally, only at spring overturn is SRP or total dissolved P a major fraction of total P. Although total phosphorus is not an ideal form to use as the basis of a criterion, it has considerable advantages over the other possible fractions (SRP or total dissolved P).

5.4.2 *Non-Specific Criteria*

Several early suggestions for concentrations of nutrients which would control algal problems have been made. Sawyer (1970) suggested that concentrations above 20 µg/L phosphorus and 350 µg/L nitrogen would likely cause algal blooms. Mackenthun (1965) felt concentrations of inorganic phosphorus of 10 µg/L, and inorganic nitrogen of 300 µg/L, should be used as goals to prevent algal blooms.

There are criteria which have been set by governments or other agencies for a variety of locations. Several jurisdictions have criteria for which no particular water use is specified. Saskatchewan (1975) and Alberta (1977) suggest a general criterion (presumably to cover all water uses) of 50 µg/L. Other jurisdictions do specify water uses, but make no distinction between applying the criteria to lakes or streams.

Some water quality standards are, in the B.C. perspective, very high. For instance, the State of North Carolina adopted a chlorophyll a standard for lakes and reservoirs of 40 µg/L for warm waters and 15 µg/L for cold waters (both are given as growing season maxima). No water use was attached to these standards (Duda and Johnson 1983).

5.4.3 *Criteria for Drinking Water from Lakes*

For drinking water, British Columbia (1969) specified a phosphorus objective of less than 65 µg/L (total phosphorus). Later drinking water standards (British Columbia, 1982) do not specify an objective. In England, the Anglian Water Authority (1982) specified a criterion for drinking water of 310 µg/L (90th percentile). This latter criterion would seem very high in comparison to other criteria.

A major problem associated with drinking water from lakes is the presence of algae. As noted in section 2, algae can cause increased cost of water treatment, complaints regarding taste and odour and some health risk. It can be assumed that eutrophic lakes (phosphorus greater than 20 µg/L) would be poor sources of drinking water. Lakes with hypolimnetic oxygen depletion are undesirable since the preferred location for the water intake would be in the hypolimnion where algal biomass is low and water temperatures are cool. If oxygen falls to zero in the hypolimnion, water drawn from this zone would have a variety of undesirable water quality characteristics (presence of hydrogen sulphide, iron, manganese, etc.). The phosphorus concentration at which problems begin to be encountered with oxygen depletion of the hypolimnion is generally about 10 µg/L. This can vary depending on lake depth and flushing rate, but 10 µg/L would appear to be an acceptable estimate. Both Ontario (1979) and the International Joint Commission (1980) use 10 µg/L as the phosphorus criterion based on the assumption that this is the concentration at which hypolimnetic oxygen depletion may begin to occur. The change from oligotrophy to mesotrophy also occurs at approximately 10 µg/L. Maine (1979) uses a criterion of 15 µg/L.

The recommended criterion to protect lakes which serve as drinking water supplies in British Columbia is 10 µg/L of total phosphorus during spring overturn (lake residence time > 6 months) or as the mean summer epilimnion concentration (lake residence time< 6 months) (refer to section 5.4.1 for monitoring guidelines), In the situation where evidence for nitrogen limitation has been found, a criterion of 80 µg/L total nitrogen could be applied. For other water uses, the phosphorus criteria can be used as a means of estimating nitrogen objectives by using the 8:1 correspondence between N and P demand by algae as a guide (see Section 5.4.1)

If compelling reasons for setting objectives for chlorophyll a are present, one can use the mean summer chlorophyll *a* concentration which corresponds to a phosphorus concentration of 10 µg/L. The chlorophyll *a* value is 2.0 to 2.5 µg/L and could be used as a provisional objective. Because the individual characteristics of lakes are different and the relationship between phosphorus and chlorophyll *a* is variable, some detailed knowledge or a lake would be necessary. Another corollary to the phosphorus criterion, coming from the demonstrated relationships between phosphorus and water clarity, is the potential application to water quality objectives for water clarity (Secchi disc depth). The Secchi depth corresponding to 10 µg/L phosphorus is 5-6 meters. This is again dependent on the individual lake.

5.4.4 *Criteria for Aquatic Life*

For protection of aquatic life in lakes, Ontario (1979) proposed a total phosphorus concentration for the ice-free period of 10 µg/L or less. This value was specified to prevent oxygen depletion in lake hypolimnia. The International Joint Commission (1930) also suggested that 10 µg/L should be used as a concentration which should not be exceeded to prevent deoxygenation of the hypolimnion of Lake Erie.

The 10 µg/L concentration of total phosphorus to prevent oxygen depletion has some technical support from other sources as well. Walker (1979) showed that hypolimnetic oxygen depletion (HOD) was correlated with the trophic state of the lake. Cornett and Rigler (1979) felt that HOD could be predicted from the phosphorus retention of the lake. Mathias and Barica (1980) noted that the rate of winter HOD was related to the trophic status of the lake, but that the relationship should also consider basin morphometry. Welch et al. (1976) also showed a correlation between winter HOD and phosphorus. Welch and Perkins (1979) describe the correlation between HOD and P loading.

The best correlations with HOD are found with phosphorus loading, and examples of these are given in Jones and Lee (1982) and Rast et al. (1983), However, because of the difficulty in using loading as a factor in protection of aquatic life, it would seem acceptable to use phosphorus concentration as the most convenient quantification for a criterion.

In the correlations and models above, concentration has a poorer fit with HOD than loading because of the range of morphometry and hydrology of any large data set. However, in the general case, concentration, loading and biological response (of which HOD is one component) are well correlated.

Using lakes with "typical" morphometry and hydrology, the occurrence of anaerobic or near anaerobic conditions in the hypolimnion are usually encountered at phosphorus concentrations of 10 to 12 µg/L, Large lakes, or lakes with large hypolimnia generally do not respond as directly (in terms of hypolimnetic oxygen deficit) to higher nutrient concentrations or loadings.

Oxygen demand can originate from organic material or inorganic chemicals. An input of one mg of phosphorus will result in 0.1 g of algal biomass (dry weight) in one limnological cycle, After settling into the hypolimnion, 0.1 g exerts a biochemical oxygen demand of 140 mg for mineralization. Ammonia has an oxygen demand when it is nitrified. Two moles of ammonia requires three moles of oxygen for oxidation (Stumm and organ 1970).

Rast and Lee (1978) suggested that an average summer chlorophyll a of 2 µg/L and a corresponding mean summer Secchi disc of 4, 5 m imply a hypolimnetic oxygen depletion of 0.3 g O_2/m^2/day at a loading rate on the threshold between oligotrophy and mesotrophy (Vollenweider's "permissable" loading rate). Corresponding approximate values for the "excessive" loading rate are: 6 µg/L average summer chlorophyll, 2.7 m average summer Secchi and a hypolimnetic oxygen depletion of 0.6 g 0_2 / m2 / da y . With these very approximate depletion rates or the oxygen depletion relationships noted above, risk of oxygen depletion in lakes can be assessed.

The onset of anaerobiosis at the bottom of the hypolimnion is a major change for lake biota. Generally, a change in benthos can be observed with the onset of even partial anaerobiosis. Zooplankton vertical migration (and consequent growth, reproduction and survival) are affected by low hypolimneti0c oxygen. Fish can be affected by a change in food organisms (benthos, zooplankton), and directly by loss of a summer cool water refuge due to low oxygen concentrations. Low oxygen concentration at the sediment/water interface can initiate release of P from the sediments, and begin a general acceleration of the eutrophication process.

In some cases it may be necessary to suggest concentrations of phosphorus. which can be directly related to conditions which affect aquatic organisms other than fish. However, when protection of aquatic life is considered, fish are the group which generally receives the most attention.

No criteria exist for a minimum concentration of phosphorus which would enhance the level of biological production to benefit fish production but create minimal consequences to other aquatic biota.

In evaluating the effects of nutrient additions *on* aquatic life, what is required is information on food web shifts caused by increasing production. Where salmonids are the group of interest, the concentration at which the food organisms of preference are affected would be a key piece of information. However studies of this type are only rarely carried out. Some general information has been collected by workers documenting the eutrophication process.

The program for fertilizing lakes in British Columbia to enhance production of salmon, uses the following method for calculating the amount of nitrogen and phosphorus to be added (Stockner 1981). The annual phospi1orus loading rate is calculated from spring overturn phosphorus concentrations using Vollenweider's (1969b) relationship between phosphorus loading and spring overturn phosphorus. Phosphorus application rates are generally a 50 - 80% increase over natural loading. Because of the low natural spring phosphorus concentrations (1 - 3 µg/L in many coastal lakes) a 50-80% increase does not raise the lake volume-weighted concentration more than 1 or 2 µg/L. However, this increase in phosphorus loading has resulted in significant improvement in salmon production. Thus, it would appear that a minimum of 5 µg/L of total phosphorus. would in general be beneficial to salmon production. A concentration of 5-10 µg/L would be unlikely to stimulate any level of algal biomass which would detract from aesthetic or recreational values, and would not interfere with any water supply system which used the lake as a source. The large hypolimnion as a percentage of total lake volume in the deeper of these lakes is a moderating factor reducing the tendency to hypolimnetic oxygen depletion. However, a lake concentration of 5 µg/L should provide a base level of phosphorus for enhanced fisheries production. The level of fisheries production in many ultra-oligotrophic B.C. lakes is probably far below its potential due to lack of nutrients.

Interior lakes in B.C. where trout are the important species, generally have nutrient concentrations which are higher than the coastal salmon lakes, even when these are fertilized. Smaller interior lakes which are very productive (in terms of trout) often have phosphorus concentrations exceeding 10 µg/L, and in some cases several times this value. A key consideration in an acceptable level of nutrients appears to be whether or not a lake is thermally stratified. A small lake which is stratified and has a phosphorus concentration greater than 10 or 15 µg/L generally has some degree of hypolimnetic oxygen depletion which may be a constraint to fish habitat (loss of cool water refuge) or food supply (particularly change in benthos). Shallow lakes which do not stratify do not have this oxygen depletion problem and a higher level of nutrients may be tolerable, although with increasing productivity the risk of winter kill increases. Two major factors determine winter oxygen depletion. Mathias and Barica (1980) and Welch et al. (1976) note the effects of lake productivity (nutrients/ chlorophyll) and of morphometry (primarily lake depth).

Warm water fisheries (e.g. bass) must also be considered in another category. With species such as bass, hypolimnetic oxygen is of minor concern since temperature preferences are higher and habitat requirements are different. For warm water fish a phosphorus concentration below 10 µg/L is likely to be undesirable since the level of fish production would be quite low. Lake phosphorus concentrations up to 40 µg/L may be tolerable, depending on lake characteristics and the species considered. The lack of either empirical or experimental data is a major impediment to suggesting criteria for nutrient concentrations for fish or aquatic life as noted above, except for salmonids and perhaps only for coastal lakes.

For lakes where salmonids are the important species of aquatic life, a maximum of 15 µg/L of total phosphorus and a minimum of 5 µg/L are recommended during spring overturn (lake residence > 6 months) or as the mean summer epilimnion concentrations (lake residence < 6 months) (See section 5.4.1 for monitoring guidelines). No attempt is made here to propose a range of optimum phosphorus concentrations for lakes where other groups of sport or commercial fisheries are important, and several factors must be taken into account to apply the criterion which is suggested above. Some lakes, for example, may have marginal hypolimnetic oxygen concentrations at concentrations of phosphorus as low as 7 or 8 µg/L (Nordin and McKean 1984). In such a case an objective would have to be chosen at the low end of the criterion range suggested. In contrast, some lakes may be amenable to a concentration as high as 15 µg/L *if* a favourable food chain response exists and the lake had a sufficiently large hypolimnion volume, such that no serious oxygen depletion would occur. Such a concentration would mean that uses such as drinking water or recreation might be impaired to some degree. The chlorophyll *a* concentration range which corresponds to 5-15 µg/L phosphorus is 1.0-3.5 µg/L.

5.4.5 *Criteria for Recreation and Aesthetics*

For protection of water used for recreation and aesthetics, a number of criteria have been proposed. Ontario (1979) used 10 and 20 µg/L of total phosphorus during the ice-free period as criteria for lakes. It was felt that 10 µg/L provided a high level of protection against aesthetic deterioration. The 10 µg/L criterion would apply to lakes with natural concentrations of less than 10 µg/L. The 20 µg/L criterion was a more general one, intended to avoid nuisance concentrations of algae in lakes.

The International Joint Commission (1980) proposed total phosphorus objectives ranging from 5-15 µg/L, depending on the nature of the lake (eg. 5 µg/L for Lake Superior and the main basin of Lake Huron, and 15 µg/L for western Lake Erie). Maine (1979) uses 15 µg/L as a criterion.

In considering a criterion for recreation and aesthetics, the trophic classification concept can also be used. As noted earlier, oligotrophic lakes are generally regarded as having characteristics (good water clarity, low algal growth) which are suited to the use by the population for swimming or for general aesthetic enjoyment. Since the upper limit of oligotrophy has been generally defined as 10 µg/L, and other agencies have also used similar concentrations as criteria, the recommended British Columbia criterion for recreation and aesthetics is 10 µg/L of total phosphorus during spring overturn (lake residence time > 6 months) or as the mean summer epilimnion concentration (lake residence time< 6 months) (See section 5.4.1 for monitoring guidelines).

5.5 Marine and Estuarine Waters

No criteria for protection of estuarine or marine waters from eutrophication are proposed due to the lack of information available on levels of nutrients or algal standing crop which would be desirable in British Columbia coastal waters. There have been too few documented locations where nutrients have caused water quality deterioration. In general an input of nutrients into the marine environment is regarded as a desirable situation. Nitrogen is the limiting nutrient in the marine environment so inputs of fresh water which has a surplus of nitrogen cause the localized rich areas in estuaries and generally enhance the coastal zone productivity. Since drinking water as a designated use is irrelevant, recreation/aesthetics and aquatic life become the only two water uses on which judgements of desirability can be made. Insufficient information is the major constraint in developing criteria for the marine environment as was done for freshwater.

6. RESEARCH AND DEVELOPMENT NEEDS

One major shortcoming in the understanding of algal related problems is a clear definition of biologically available phosphorus. The fractions which are presently routinely analysed do not adequately approximate what is available to algae for uptake. This is the most obvious area where more information is required. Further work is needed to both determine what is available and to propose a method for routine measurement of biologically available phosphorus.

Although orthophosphorus is a commonly used analytical fraction for reporting values of what ls generally considered to be biologically available phosphorus, there seems to be little question that it is only an approximation (Rigler 1968). A need is evident to have improved analytical techniques developed.

As well as the analytical techniques, much more effort is required to aid in the understanding of phosphorus kinetics. The ease and speed at which different phosphorus forms are transformed are an integral part of the bioavailability question.

An area which requires further investigation in general is determination of statistically acceptable sample sizes for natural algal biomass in streams. In taking into account variables of the stream, better guidance for sampling may be derived. For individual sites sample size can also be determined from sampling done for this purpose to determine variance, However, in general, much more work on the problem of standardized methods for stream periphyton from natural substrates is required.

The usefulness of the concept of trophic states in lakes would indicate that the development of some similar classification for streams would be very desirable. The classification would, by necessity, be more complex, but a great deal of benefit would be derived from it.

The relationship between biological production at the lower end of the food chain (phytoplankton, zooplankton) and fish production is only beginning to be examined (McConnell et al. 1977; Oglesby 1977; Ploskey and Jenkins 1982). More work in this area would be very useful in defining means of optimizing fish production and preventing water quality deterioration which might affect fish production. A particular need is to develop information on the effect of increasing nutrients on fisheries production and on the food chain which supports the fish.

It may be necessary in the future to consider more detailed criteria to protect water uses. The criteria suggested here are very simplistic, and do not deal with such problems as peak algal concentrations in lakes - rather average summer concentrations are used. The problem of assessing littoral (rather than pelagic) nutrients and algae needs to be resolved. In this connection both peri phyton and phytoplankton must be dealt with. The predominant species or group of algae contributing to algal biomass may also need to be considered since equal biomass of blue-green algae and diatoms are neither ecologically or aesthetically equivalent,

A mechanism of nutrient transport which requires more investigation is the input of nutrients via groundwater. Quantification of this difficult (to measure) source is necessary to assess relative contributions, particularly to lakes, and obtain accurate estimates of nutrient input.

The Pacific and Yukon Branch of the National Water Research Institute of Environment Canada has a major research program underway which will provide answers to a number of very important questions and preclude a number of research needs being listed here. It is useful to state these research questions here to indicate that this information will be forthcoming in the near future (Bothwell, 1985b). The questions being considered by this research project are: 1. relationship between water concentration of orthophosphorus and the growth rate of periphyton; 2. Relationship between growth rate and biomass; 3. factors influencing alkaline phosphatase activity in periphyton; 4. factors controlling phosphorus uptake rate; 5. quantification of the relationship between light intensity and algal growth rate; 6. concentrations of inorganic nitrogen limiting growth; 7. bioavailability of different forms of organic phosphorus; 8. effect of current velocity on accumulation and growth.

7. GLOSSARY

accrual rate	- measurement of the growth of a periphyton community using sequential measurement of biomass to derive growth per unit time.
allochthonous	- the organic matter forming the base of the food chain which is produced outside a community or ecosystem.
apatite	- a group of minerals of which the principal elements are calcium and phosphorus.
autochthonous	- the organic material forming the base of the food chain which is produced within a community or ecosystem.
autotrophic	- requiring only inorganic carbon, sunlight and minerals as the basis for metabolic synthesis.
epilimnion	- the warmer surface layer of a thermally stratified lake.
hypolimnion	- the cool deep portion of a thermally stratified lake; that portion below the thermocline.
heterotrophic	- requiring complex organic compounds as the basis for metabolic synthesis.
loading	- the amount of material which enters a water body, usually expressed as a mass per unit time or mass per unit area.
lithotrophic	- requiring only inorganic carbon and minerals as the basis for metabolic synthesis.
seston	- all particulate matter in water, both alive (plank- ton) and non-living (detritus, inorganic sediment).

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