UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

April 18, 1986

OFFICE OF
THE ADMINISTRATOR

Honorable Lee M. Thomas
Administrator
U. S. Environmental Protection Agency
401 M Street, S. W.
Washington, D. C. 20460

Dear Mr. Thomas:

The Water Quality Subcommittee of the Environmental Effects, Transport and Fate Committee of the Science Advisory Board has completed its review of the Agency's Ambient Water Quality Criteria for Dissolved Oxygen—Fresh Water Aquatic Life. The Subcommittee addressed the issue of whether the document comprises a scientifically adequate discussion and evaluation of the scientific literature concerning dissolved oxygen in fresh water aquatic systems.

The Subcommittee assessed six major scientific issues including: the invertebrate problem; laboratory-field implications; additive stresses and chemical interactions; growth rate reductions; oxygen criteria levels; and dissolved oxygen monitoring conditions. The Subcommittee recommended that EPA staff make various modifications to the treatment of these and other issues. In general, however, the Subcommittee concludes that the document is well-organized and research whose logic and conclusions are scientifically defensible.

We appreciate the opportunity to review this document and request an Agency response to the attached report.

Sincerely,

John Neuhold, Chairman
Water Quality Subcommittee
Environmental Effects, Transport
and Fate Committee

Norton Nelson, Chairman
Executive Committee

SAB-EETFC-86-020

SCIENCE ADVISORY BOARD REVIEW OF THE WATER QUALITY CRITERIA DOCUMENT FOR DISSOLVED OXYGEN

Water Quality Subcommittee

Environmental Effects, Transport and Fate Committee

Science Advisory Board

April 1986

EPA NOTICE

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Water Quality Criteria Subcommittee

Dr. John M. Neuhold, Chairman
College of Natural Resources
Utah State University
Logan, Utah 84322

Dr. Terry F. Yosie, Director
Science Advisory Board
United States Environmental
Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

Dr. Melbourne R. Carriker
Professor of Marine Science
College of Marine Studies
University of Delaware
Lewes, Delaware 19958

Dr. Dan Coble
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Research Unit
University of Wisconsin
Stevens Point, Wisconsin 54481

Dr. Rolf B. Hartung
Professor, Environmental
and Industrial Health
School of Public Health
University of Michigan
Ann Arbor, Michigan 48109

Dr. Kenneth Jenkins
Professor of Biology
California State University
at Long Beach
Long Beach, California 90804

Dr. Charles Norwood
4958 Escobedo Drive
Woodland Hill, California 91364

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University of Georgia
Athens, Georgia 30602

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Virginia Institute of Marine
Science
Gloucester Point, VA 23696

Dr. Kenneth Jenkins
Professor of Biology
California State University
at Long Beach
Long Beach, CA 90804

Dr. John Laseter
Enviro-Health Systems
Suite 800
990 North Bowser Road
Richardson, Texas 75081

Dr. John Neuhold
Department of Wildlife Science
College of Natural Resources
Utah State University
Logan, Utah 84322

I. Executive Summary

A water quality criteria document assesses and articulates the scientific basis for establishing levels of a substance at which specific organism and ecosystem effects will result. Selecting the level of that substance permitted in fresh water systems represents a policy decision based upon decision maker judgments of acceptable risks. In view of the fragmentary nature of the evidence concerning this risk, the Subcommittee recommends EPA maintain a conservative approach by upwardly revising criteria levels for dissolved oxygen.

The levels for dissolved oxygen stated in the criteria document derive primarily from laboratory toxicity studies of fish species, while field studies of fish and invertebrates, which provide the food base for these fish, receive minimal discussion. The Subcommittee recommends that EPA give greater emphasis to available published field studies. If EPA judges the current field study data base as too limited, it should carry out and/or sponsor research to obtain the needed information.

Chemical interactions and additive stresses are critical factors in establishing criteria levels for oxygen and other substances. The Subcommittee recommends that EPA provide a more thorough discussion of how these factors were considered and integrated with other information in preparation of the oxygen criteria document.

Inconsistencies appear in the documentation relating to growth rate reduction by oxygen deprivation and what is termed to be "slight, moderate or severe" growth impairment.

The Subcommittee recommends that EPA upwardly revise the criteria levels presented in Table 6 of the criteria document. This recommendation is based upon a recognition of the limitations caused by the lack of data for organisms other than fish, the possibility of deleterious effects of lower dissolved oxygen levels (besides those determined for fish), the fact that the proposed dissolved oxygen levels that would impair fish production and the likelihood of deleterious effects on fish resulting from the interaction between dissovled oxygen levels and other stressors.

Effective monitoring is essential if the states are to successfully implement water quality criteria. The sampling and analysis plans for monitoring data should, therefore, conform to the biological criteria. In the case of a criteria that is expressed as a periodic function, the sampling plan should require: samples to be equally spaced in time, sampling rates that are high enough to avoid aliasing, and total sample sizes large enough so that the lowest frequency of importance can be observed.

The monitoring guidance included in the dissolved oxygen criteria document would be significantly improved by supplying guidance on sampling ambient dissolved oxygen. The suggested calculation procedure, while different from the classically used technique, is reasonable if modified to account for monitoring periods longer than one week, and if based on a sampling frequency that can detect significant deviations from the function that defines the no unacceptable effect level.

II. Introduction

A. Historical Perspective

The Federal government promulgates water quality criteria for the purpose of controlling pollutant toxicity in aquatic ecosystems. The intent of these criteria is to control excess concentrations of a toxicant by establishing maximum permissible levels that will protect aquatic life. Scientists and state and Federal agencies do not define oxygen in the aquatic system as a toxicant and, rather than being concerned with having excess oxygen, they are concerned with not having enough to protect and/or sustain aquatic life.

Oxygen is an essential element for the maintenance of aerobic life in any biotic system. Oxygen enters the aquatic environment through diffusion from the atmosphere and is produced by aquatic plants in the process of photosynthesis. Pollutants in the aquatic environment, particularly organic pollutants, provide the substrate for the production of microbial communities which use the oxygen in their metabolic activities and compete with fish, aquatic invertebrates and other aquatic organisms. Waste heat, when discharged into aquatic systems, also has the direct effect of reducing the amount of oxygen that can dissolve in the water column and thus affect its availability to organisms. It also reduces oxygen indirectly through creating a temperature environment amenable to the proliferation of microbial organisms.

Since organic materials and heat cause the reduction of oxygen in water columns, a logical step would be to set upper limits for them.

However, the organic materials are many and varied, and are often not toxic. Though maximum heat tolerances can be defined for various species, these levels are often greater than those that will materially affect oxygen concentrations. Thus, oxygen becomes the substance for which criteria are established, and the criteria express the result of complex interactions of physical, chemical and biological factors. In turn, these oxygen levels produce effects on organisms within the ecosystem and, consequently, on the ecosystem itself.

The criteria development strategy used by the Environmental Protection Agency sets limits for oxygen concentration in the water column to protect aquatic organisms as well as the ecosystem. This strategy was first formulated in a criteria format with the publication of Water Quality Criteria 1972 (NAS/NRC 1973) and implemented by EPA four years later in Quality Criteria for Water (EPA 1976). Section 304(a)(1) of the Clean Water Act [33 U.S.C. 1314(a)(1)] requires that EPA publish and periodically update ambient water quality criteria reflecting the latest scientific information available on the effects of pollutants on public health and welfare, aquatic life and recreation. The draft document, Ambient Water Quality Criteria for Dissolved Oxygen: Fresh-Water Aquatic Life, critiqued in this review is EPA's latest effort to fulfill the requirements of the Clean Water Act for this particular criteria.

B. Charge to the Subcommittee

On July 29, 1985 the Division of Criteria and Standards of the Office of Water requested the Science Advisory Board to review the draft document, for the purpose of improving its scientific quality. The Executive Committee of the Science Advisory Board accepted this request and assigned the task of reviewing the document to the Water Quality Subcommittee of its Environmental Effects, Transport and Fate Committee.

Members of the Subcommittee received copies of the document in September, 1985 and met in public session to review it at EPA's Environmental Research Laboratory - Duluth on October 10-11, 1985. The Subcommittee discussed and evaluated the scientific adequacy of the document with its principal author and other EPA staff and arrived at a concensus during the meeting. Subsequently, individual Subcommittee members wrote individual sections of this report and subjected their analyses for review and editing by their colleagues. This final report articulates the scientific concensus derived during the public meeting and follow-up discussions of successive draft reports.

The report is organized into three major sections involving general comments, and a discussion of philosophical issues and scientific issues.

III. General Comments on the Dissolved Oxygen Criteria Document

The Subcommittee concludes that this is the best prepared criteria document the Science Advisory Board has reviewed to date. The document is well-organized, researched and referenced. Generally, its arguments, logic and conclusions are scientifically defensible although its premises were sometimes arguable. The overall quality of the thinking, research and writing is commendable.

There are several areas in which the document can be further improved. These include: 1) the philosophical basis for a criteria document that reflects, in part, how the material in such a document is presented, and

2) the validity of some of the premises upon which the scientific arguments rest.

IV. Philosophical Issues for the Criteria Document

A criteria document is a scientific document in which scientific data are presented and arguments synthesized to provide evidence for the effect of some substance on organisms and systems of organisms. This particular document concerns the effects of lowered oxygen concentrations on freshwater aquatic life. The levels that affect, partially affect or do not affect aquatic life define criteria levels that are supported by evidence from the scientific literature based upon laboratory experiments and field observations.

The choice of one of these criteria levels as the level at which it is either permissible or not permissible to allow an effect is a policy decision. The Subcommittee believes that the document blurs the distinction between scientific and policy issues and choices. Specifically, on pages 24-25, criteria levels are defined for production impairment of organisms during "embryo and larval stages" and "other life stages" for salmonid and non-salmonid waters. These levels are supported by documentation in previous pages although it is questionable whether the ordinal levels of growth impairment used (slight, moderate, severe) have any real meaning. On Table 6 (page 26), however, the criteria levels selected fall into the "impairment allowed" area. Table 6, therefore, presents a policy decision stating that it is permissible to allow production impairment of individual organisms, but no evidence is presented that the aquatic system itself will not also be affected.

The Subcommittee believes that the water quality criteria for dissolved oxygen should be designed to protect the entire aquatic ecosystem. Fish are only one component of this ecosystem, but they receive virtually exclusive attention in the criteria document. The justification for this focus includes: 1) the assumption that the protection of fish will also ensure the protection of other organisms or groups of organisms, and 2) little information exists upon which to base inclusion of other biota in considerations underlying the proposed criteria. The first of these assumptions is not supported by documentation; it is an article of faith (but a strong one since most scientists would accept the premise that health of a water body is reflected in the status of its ichthyofauna). The second is largely true, but EPA should assess what literature exists and state the conclusions that could be drawn from it. The relative lack of information about microbial, plant and invertebrate responses does not justify completely ignoring them.

The ecosystems in question are complex, organized networks of biotic and abiotic interactions. About such networks, including food webs and feedback control loops, there is growing knowledge that indirect effects propagated over time may be more important than instantaneously experienced direct effects. The dissolved oxygen criteria document focuses on the direct effects of oxygen upon fish. Such direct (but unknown) effects on other groups may propagate as the result of indirect effects to the fish over a long period of time through the ecosystem's interconnecting network. Thus, after a period of years, fish populations could become seriously impacted by slowly induced changes in other groups even though no standards based on fish requirements were ever violated.

Given the goal of protecting all biological forms and the integrity of their vital interactions within the aquatic ecosystem, the responsible pragmatic response to the lack of relevant knowledge is to employ a conservative approach. Accordingly, the low dissolved oxygen levels recommended in Table 6, justified solely by ichthyofaunal considerations, should be adjusted upwards to achieve at least the protective level afforded by the present Redbook standards.

V. Review of Scientific Issues in the Criteria Document

A. The Invertebrate Problem

The concensus position of the document states that if all stages of fish are protected, invetebrate communities, although not necessarily unchanged, should be adequately protected. The document does not state the scientific support for this position. Rather, it asserts that some invertebrate species are as sensitive as "moderately susceptible" fish.

Because biotic communities consist of many species at various trophic levels, and since the role of these species in the metabolism of the community is not fully known with reference to the production of food resources for fin fish, it is important to recognize the potentially significant role of at least "dominant" invertebrate species and their tolerance to low levels of dissolved oxygen.

At a minimum, the document should refer to the literature on requirements for dissolved oxygen by those invertebrate species that have been studied. Groups of invetebrates that should be checked and that are important directly as prey species for fish with commercial or recreational value, or indirectly as important processors of energy in the ecosystem, include:

unionid clams, fingernail clams, Amphipods, crayfish and insects of the orders of Plecoptera and Ephemeroptera. The document reports that few appropriate data are available that address the effects of reduced dissolved oxygen on freshwater invertebrates. These data should, nevertheless, be reviewed and briefly summarized.

B. Laboratory-Field Implications

It is not at all clear that the methods used to achieve oxygen levels in experimental units in order to determine oxygen requirements for fish and invertebrates did not produce spurious results evoking other biological responses. A statement clarifying the methodology would be useful.

Laboratory tolerance tests for oxygen are most often designed to hold all extraneous variables constant to ascertain the main effect of oxygen. Even if efforts are made to determine the interactive effects of other physical, chemical and biological factors with oxygen levels, scientists seldom succeed in duplicating the natural environment experimentally. Thus, the comparability between laboratory and field results remains unknown unless field observations are designed to verify laboratory results. A discussion of the advantages and disadvantages of laboratory tests and field observations in the document's "Introduction", while eliminating a discussion of disadvantages after each of the sections, would considerably enhance the scientific presentation of the document.

Coupled with this addition to the Introduction should be removal or modification of the negative statements in the text. The available data are much better than the document suggests. Numerous laboratory studies of fish in which experimental conditions (e.g., species, temperature, duration) varied have produced conclusions for the effects of dissolved oxygen upon fish for a number of variables. These results provide a stronger basis upon which to develop confidence in the data than if all the experiments had uniform designs. Added to this factor are the results of the field studies which support, to a large extent, the results of the laboratory studies. The combination of laboratory hypothesis testing and field verification is a very powerful one.

Statements in the document complaining about the variability of testing conditions, suggesting that scientists investigating dissolved oxygen had unusual whims and preferences, stating that the data base is fraught with inconsistency, and denigrating metabolic and physiologic studies because they require extrapolation and assumptions, are unjustified and counter-productive. Similarly, statements that belittle laboratory studies at the beginning of the presentation of laboratory results and field studies after the presentation of field results do nothing but reduce confidence in the document and should either be eliminated or rephrased to emphasize the power of similar conclusions from varying laboratory and field approaches.

The negative tone referred to above also gives the impression that violation of the criteria is permissable. Specifically, pages 28-29 include such statements as "Some deviation below acceptable concentrations would probably not cause significant harm"; discussion of significance (importance) of conditions that fail to meet recommended criteria"; and "excursions below minimum recommended values are likely to be appreciable". Such statements cast doubt upon how seriously EPA considers the criteria and, in the opinion of the Subcommittee, should be stated more carefully.

C. Additive Stresses and Chemical Interactions

The dissolved oxygen criteria document breaks important ground for EPA in that it attempts to deal with the effects of both physical and chemical stresses on the sensitivity of organisms to low dissolved oxygen concentrations. Particular emphasis is placed on the adverse effects of high temperatures and tolerance to low dissolved oxygen. The document states that "Concern for this temperature effect was a consideration in establishing these criteria, especially in the establishing of those criteria intended to prevent short-term lethal effects" (page 19). Section VI elaborates on this statement by noting that "The dissolved oxygen concentrations in the criteria are intended to be protective at typically high seasonal environmental temperatures" even though these temperatures "are often higher than those used in the research from which the criteria were generated" (pages 25-26).

In spite of this assertion, the document does not discuss the methods used to factor the temperature effects into the actual criteria numbers. Instead, the reader is told that the criteria derive from the production impairment estimates (pages 24-25), "which are in turn based primarily upon growth data and information on temperature, disease and pollution stresses." It is appropriate and important to incorporate a discussion on additive stesses in a criteria document, but these data should not be factored into the final criteria numbers without clearly defining the underlying rationale. Without that rationale, it is not possible to critically evaluate the inclusion of these data. The alternative is to accept at face value that the criteria numbers adequately address the problems of temperature, disease and pollution stresses.

In general, the discussion of additive chemical stresses on sensitivity to low concentrations of dissolved oxygen is well presented. It includes a review of data on metals (Zn, Pb, Cu), xenobiotics (monohydric phenols), cyanide and ammonia. More importantly, though the document addresses the importance of chemical stresses in section IV B, it is mentioned only in passing in discussion of the National Criteria in Section VI, and is not addressed at all in the discussion of the relationship between criteria and monitoring and design conditions. These deficiences should be remedied.

This document successfully articulates the complex issues of chemical interactions and additive stresses, issues that should receive consideration in all of the criteria documents developed by EPA. More thorough discussion of how these data were applied in deriving the criteria numbers and how they should be used in monitoring and experimental design, however, would help to integrate and strengthen the document.

D. Growth Rate Reduction

The document should accompany data entries in Tables 1-5 with a fuller discussion of the variation surrounding the values because, as currently presented on page 6, the arguments are not well substantiated. One can conclude from Table I that a "slight" growth impairment occurs at an oxygen concentration of 7 mg/l and that growth impairment of 4%-9% at 6 mg/l might better be termed "moderate" for the following reasons: 1) the absolute weight of fish (and probably invertebrate) flesh lost in natural waters can be significant at such levels, particularly considering the economic loss of commercially exploited populations such as the salmon produced in the Columbia River drainage basin; and 2) the likelihood of temperatures in natural waters exceeding those of the experiments (Table 1,) during critical periods of low dissolved oxygen. At dissolved oxygen levels below 6 mg/l, growth of salmonids was reduced by 10% or more. One should conclude from this table that values of dissolved oxygen concentration listed at the top of page 25 for slight, moderate and severe production impairment should be 7, 6 and 5 mg/l, respectively.

E. Oxygen Criteria Levels

The Subcommittee believes that the dissolved oxygen criteria in Table 6 are too low because the criteria listed for the 7-day mean minimum derive from studies which have shown sublethal deleterious effects on fish. According to the statement on page 24, nearly all data on the effects of low dissolved oxygen on aquatic organisms relate to continuous exposures for periods of hours to weeks. A 7-day mean minimum is a period of hours to a week. Therefore, the deleterious effects observed in the various studies should be expected to occur in a 7-day period. In fact, according to the conclusions stated on page 25, the 7-day mean minimum values recommended in Table 6 would cause moderate impairment of production. Such values can hardly be protective of our nation's aquatic resources.

Moreover, the recommended dissolved oxygen criteria derive mainly from laboratory studies in which stresses that occur as the rule rather than the exception in nature were eliminated and other stresses peculiar to the laboratory setting were substituted, thus creating substantial uncertainties. Low dissolved oxygen exacerbates effects of such commonly occurring stresses on fish as temperature fluctuation, presence of ubiquitous pathogenic organisms, competitive interactions, and presence of toxic chemicals (pp. 19-21). Based upon studies which eliminated stresses, the dissolved oxygen criteria cannot be expected to be protective for the interactions of low or marginal dissolved oxygen levels and environmental stresses that occur commonly in nature.

Under these circumstances the Subcommittee concludes that current scientific data demonstrates that the proposed dissolved oxygen criteria are unacceptably low and recommends that higher (i.e. more protective) values supported by the information on pages 24-25 be substituted as in the table below:

Water Quality Criteria for Ambient Dissolved Oxygen Concentration (mg/l)

	Cold Water Criteria		Warm Water Criteria	
	Early Life	Other Life	Early Life	Other Life
30 day mean	NA	8.0	NA	6.0
7 day mean	11.0 (8.0)	NA	6.5	NA
7 day mean minimum	NA	7.0	NA	5.0
1 day minimum	9.0 (6.0)	3.0	5.5	3.0

F. Dissolved Oxygen Criteria and Monitoring Conditions

One of the best features of this criteria document is its discussion of the biological effects of cyclic and other variations in dissolved oxygen. The document points out that dissolved oxygen varies continuously in a daily cycle, and it seems clear that seasonal and annual cycles exist.

The ambient value of dissolved oxygen consists of the sum of these natural cycles, plus the effects of any human activities. The criteria document also notes that the sensitivity of some species to low dissolved oxygen levels varies during the course of their life cycle.

Since dissolved oxygen levels, and the organism's sensitivity to these levels, follows cycles, the natural way to describe the dissolved oxygen criteria is as a periodic function that does not produce unacceptable effects. Assuming that the acceptable dissolved oxygen level represents a sinusoidal function of time, the criteria would be expressed as an average value, an amplitude, and a period. These three numbers would determine the minimumally acceptable dissolved oxygen value, the average acceptable value, and the time between minima.

The dissolved oxygen criteria rest on the assumption that the acceptable effect level defines a function whose dominant component is a sinusoid with a period of one day. For example, to protect the early life stages of cold water species, this assumption can be expressed as:

$$DO(t) = 6.5 + 1.5 \cos[(2\pi/24)t] + \xi \qquad (1)$$

where DO(t) is the acceptable dissolved oxygen level in mg/l, t is time in hours measured from a maximum, and $\xi > -2$.

Section IV of the criteria document addresses the important problem of calculating with monitoring data to determine whether ambient dissolved oxygen is below the acceptable levels described by an equation like (1). In the following paragraphs the Subcommittee discusses monitoring issues raised by the calculation approach developed in Section IV.

The calculation approach suggested in the criteria document assumes that dissolved oxygen is measured twice daily, once at the maximum and once at the minimum value. The example calculations (Table 7) assume the availability of only seven pairs of observations, and from these pairs are defined:

(1) daily maximum = minimum of measured dissolved oxygen and air saturation concentration;

(2) daily mean = average of that day's minimum and maximum;

(3) 1-day minimum = minimum of the minima;

(4) 7-day mean minimum = average of 7 minima; and

(5) 7-day mean = average of 7 daily means.

The criteria are violated if any of the quantities 2 through 5 fall below values judged to be acceptable.

The guidance on monitoring does not specify the sampling plan for acquiring the monitoring data. In the following paragraphs two sampling plans will be considered. The first monitors dissolved oxygen continuously, with the required maxima and minima found from the observed time history. The second possibility assumes that dissolved oxygen is measured by grab samples taken at widely spaced time intervals.

1. Continuous Monitoring

With continuous monitoring, the suggested calculation procedure is reasonable if the concentration of ambient dissolved oxygen is nearly sinusoidal with a period of twenty-four hours. However, the calculation procedure does not address how to deal with more than seven pairs of points, as will be the case if monitoring lasts more than a week. Nor does it address cases where the observed time function is either not very sinusoidal, or has a frequency greater than one cycle per day.

If the concentration of ambient dissolved oxygen is periodic, but not sinusoidal, it may happen that the daily minimum value persists for unacceptably long periods. If ambient dissolved oxygen has components the periods of which are less than one day, it is possible the daily minimum will be achieved more than once.

Based on the data presented in the criteria document, both of these situations could lead to unacceptable effects, while not necessarily violating the criteria. However, when ambient dissolved oxygen is continuously monitored, sufficient information exists to determine, on a site specific basis, what modifications (such as limiting the time at the minimum) might be required to avoid unacceptable effects.

2. Grab Sampling

When ambient dissolved oxygen is monitored by grab sampling at widely spaced intervals, the calculation procedure may produce misleading results. By sampling out of phase with the minima and maxima, it is possible to consistently obtain a pair of daily measurements that correctly estimates the average concentration but give essentially no information about the true amplitude of fluctuations around the mean. If as few as two samples per day are taken, events with frequencies higher than one cycle per day will actually appear as components with frequencies lower than one cycle per day. This could lead to a misinterpretation of the detection of adverse effects.

Another problem with estimating the criteria's parameters with widely spaced samples results from the paucity of information about the length of time over which ambient dissolved oxygen remains near critical concentrations, since many physically possible continuous functions will pass through the measured points.

From the discussion in the previous paragraphs, the Subcommittee concludes that the suggested calculations (assuming monitoring lasts only one week) are reasonable when the daily maxima and minima are sampled rapidly enough to detect deviations that have unacceptable biological effects. However, EPA could significantly improve the monitoring guidance by explicitly addressing the sampling rate that is required to determine the acceptability of ambient dissolved oxygen levels. In the next section, the Subcommittee discusses a classical approach to determining this rate.

3. Fourier Analysis

The purpose of monitoring dissolved oxygen levels is to verify that ambient levels satisfy the bounds expressed by a biologically determined sinusoidal function like equation (1). To do this requires estimation of the mean, amplitude, and frequency of the ambient concentration, and comparison of these values with those judged acceptable. The classical approach to this problem is called Fourier analysis.

Fourier analysis expresses a function, X_t, sampled at equally spaced time intervals, as the sum of periodic components:

$$X_t = A_0 + \Sigma\,[A_j \cos(\omega_j t) + B_j \sin(\omega_j t)] \qquad (2)$$

where $0 < j < n/2$,

$0 < t < n - 1$,

$\omega_j = 2\pi j/n$,

$A_0 = X_t/n$, and

$R_j = A_j^2 + B_j^2$.

A_0 is the mean of the X_t, and R_j is the amplitude of the jth component. The analysis solves for the n coefficients of (2) using ordinary least squares.

By using Fourier analysis, it is possible to identify the amplitudes of selected frequencies with periods between two times and n times the sampling rate. To determine a sampling plan for the Fourier analysis of data, it is necessary to select a sampling interval, Δ, so that no frequencies higher than 0.5Δ are present. One also needs to select n, the number of samples, so that n times Δ is equal to the fundamental period of X_t.

Because the sum of the R_j^2 is proportional to the mean square of the X_t, under appropriate statistical assumptions, it is possible to use regression techniques together with the magnitudes of the R_j^2 to determine which of the ω_j contributes most to the total variability of the X_t.

One of the advantages of using Fourier analysis to examine a time series for periodic components is the ability to know the consequences of misspecifying the sampling interval and the fundamental period. When the sampling interval Δ is too large, frequencies higher than $0.5\ \Delta$ are aliased down to frequencies less than $0.5\ \Delta$. For each frequency greater than $0.5\ \Delta$, the alias can be explicitly identified. When the period of the sampled data is incorrect, there are frequency components that are not equal to one of the ω_j. This effect is called leakage and, as with aliasing, its effect can also be precisely calculated.

Depending on the frequency band of interest, one should process several thousand data points in a Fourier analysis. Historically, this posed a practical limitation on the use of this technique. However, many current software packages can perform the required calculations, accounting for both aliasing and leakage.

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