1979-01-01

Report of the Review Committee for the Dissolved Oxygen Objective for the Great Lakes

Great Lakes Science Advisory Board. Review Committee for the Dissolved Oxygen Objective for the Great Lakes

Recommended Citation
Great Lakes Science Advisory Board. Review Committee for the Dissolved Oxygen Objective for the Great Lakes (1979). Report of the Review Committee for the Dissolved Oxygen Objective for the Great Lakes. *International Joint Commission (IJC) Digital Archive*. https://scholar.uwindsor.ca/ijcarchive/227

00227

GLC 22222 130 but

our copy is missing → so add
to collection.

REPORT
OF THE
REVIEW COMMITTEE
FOR THE
DISSOLVED OXYGEN OBJECTIVE
FOR THE
GREAT LAKES

230
1979

INTERNATIONAL JOINT COMMISSION
GREAT LAKES SCIENCE ADVISORY BOARD
100 OUELLETTE AVENUE, 8TH FLOOR
WINDSOR, ONTARIO N9A 6T3

January 1979

Great Lakes Science Advisory Board

International Joint Commission

Canada and the United States

Members of the Board:

The Review Committee for the Dissolved Oxygen Objective for the Great Lakes, as a requirement of its Terms of Reference, takes pleasure in submitting the following report on its findings prepared by the members.

Respectfully submitted,

John J. Magnuson
J. J. Magnuson, Chairman

P. O. Fromm
P. O. Fromm

J. R. Brett
J. R. Brett

F. E. J. Fry
F. E. J. Fry

TABLE OF CONTENTS

REPORT OF DISSOLVED OXYGEN OBJECTIVE
REVIEW COMMITTEE

1. We have re-examined the basis for the dissolved oxygen criterion for the Great Lakes (June 1977) and have reviewed new published and unpublished data (appendices). Our recommendation is that the objective should be as follows.

In connecting channels and in all the waters of the Great Lakes, the dissolved oxygen level should not be less than an average of 6.5 mg/liter nor less than 5.5 mg/liter at any time over 24 hours and across a temperature scale of $0^{o}C$ - $25^{o}C$.

This differs from the existing objective in Annex 1, paragraph 1 (c) of the Water Quality Agreement in that the level is decreased by 0.5 mg/liter from 6 to 5.5 mg/liter at any time, and that hypolimnetic waters are included in the objective.

It differs from the June 1977 recommendation in that we are not recommending a need for higher concentrations of dissolved oxygen at lower temperatures. Our rationale for basing the objective on concentration rather than percent saturation is presented below in Section 2 - Concentration verus percent saturation.

It also differs from the June 1977 recommendation in that we believe objectives should be based on the ideas that the threshold value of dissolved oxygen should be determined from data on growth and development, reproduction, and survival rather than on incipient sublethal response. This idea is argued below in Section 3 - Concentration in relation to vital functions.

We believe that our objective is a no-effect level in regard to causing changes in fish communities; that our objective is a level that will protect salmonids at all life stages; that previous objectives for temperatures below $4^{o}C$ may be unnecessarily high and that our objective is as precise as is warranted by existing data. Additional data are needed on the oxygen requirements for growth, development, reproduction, and ecological survival before any further refinement of the oxygen objectives for Great Lakes fishes is warranted.

2. Dissolved Oxygen Concentration Versus Per Cent Saturation:

The committee recommends that oxygen concentration in water rather than oxygen pressure be used to establish the dissolved oxygen requirements for the following reasons: the rate of oxygen transfer across fish gills is by diffusion down a concentration gradient and is directly dependent upon the mean difference in oxygen partial pressure across the gill; the minimal tissue oxygen pressure, as reflected by the oxygen pressure of venous blood necessary for normal metabolic activity in fishes, has not been established. Hence, oxygen pressure or the percent saturation of water with oxygen, does not provide a true indication of the oxygen pressure difference across the gills. Since the solubility of oxygen varies with changes in temperature and salinity a constant relationship between oxygen pressure and oxygen content does not exist.

Fish gills have been shown to be very efficient at extracting oxygen from water. This efficiency is due to morphological and physiological adaptations of the blood-vascular system and to the counter flow arrangement between blood and water. Since most of the oxygen can be removed from the water presented to the respiratory surface it follows that the total amount of oxygen delivered to the gills is a more specific limiting factor than is oxygen pressure per se. Concentration of oxygen in water rather than percent saturation of water with oxygen is the more precise indicator of the amount of oxygen available for respiratory exchange.

3. Dissolved Oxygen Concentration in Relation to Vital Functions

The decision on the DO concentrations required to support healthy fish populations was based on threshold levels concerning such vital functions as growth, development, swimming performance and reproduction of mixed freshwater populations. Emphasis, however, was placed on the full life cycle of salmonids, supplemented by recommended hatchery practices for coho salmon in British Columbia; where a daily mean level of 7.0 ppm at 10°C is considered desirable for disease and stress prevention. Other threshold responses (e.g., increased ventilation and cardiac rates were noted but only used indirectly to support a buffer margin).

The literature examined is outlined in a review by Brett (1979, in press), giving recent supporting evidence on coho and salmon growth rate; the review by Davis (1975), and two 1978 publications noted. The increase in concentration from the growth inflection in Brett (1979), (approx. 5.0 ppm), and from Davis' 1975 B-level for salmonids (6.0 ppm) recognizes: (a) the generally "pristine" environmental conditions of the laboratory experiments quoted; (b) the ecological need for metabolic scope above that necessary for growth, involving attack and escape activities common in nature; (c) the temporal, particular, circumstances of eggs and larvae, described in Davis (1975) and Garside (1966); (d) the elevating effect that many pollutants have on limiting oxygen levels defined or undefined in the Great Lakes; and, (e) a margin of protection felt necessary to meet general stress and disease; at present poorly undocumented.

APPENDIX A. COMMITTEE

- Committee Membership
- Directive to Review Committee

GREAT LAKES RESEARCH ADVISORY BOARD

REVIEW COMMITTEE FOR THE

DISSOLVED OXYGEN OBJECTIVE FOR THE GREAT LAKES

(Revised May 18, 1978)

Dr. John J. Magnuson (Chairman)
Laboratory of Limnology
University of Wisconsin
Madison, Wisconsin 53706
(608) 262-1627 or 262-2840

Dr. Paul O. Fromm
Department of Physiology and Pharmacology
Michigan State University
East Lansing, Michigan 58823
(517) 355-6475

Dr. J. R. Brett
Fisheries Research Board
Pacific Biological Station
Nanaimo, B.C. V9R 5K6
(604) 758-5202

Dr. F. E. J. Fry
10 Riverlea Road
Weston, Ontario M9P 2R9
(416) 244-6368

Secretariat Responsibilities
Dr. A. E. P. Watson
International Joint Commission
Great Lakes Regional Office
100 Ouellette Avenue, 8th Floor
Windsor, Ontario N9A 6T3
(519) 256-7821
(313) 963-9041

white

INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD
Reply to:
Environmental Research Laboratory
6201 Congdon Boulevard
Duluth, Minnesota 55804

I.J.C.
APR - 3 1978
DIR.
D. DIR.
A.C.

(AEDW al. rec'd same)
5-9

March 30, 1978

Subject: Review Committee for Oxygen Criteria

To: : Attached list of Addressees

The Great Lakes Water Quality Board, which is one of the two Boards under the International Joint Commission assigned to implement the Great Lakes Water Quality Agreement between Canada and the United States, has referred the oxygen water quality criterion to the Research Advisory Board for advice and recommendations for action. In short, a water quality criterion has been developed by a joint Committee for the Great Lakes for the protection of aquatic life. The Water Quality Board is not satisfied that it is the best criterion for the Great Lakes, and would like an opinion from the Research Advisory Board. I have discussed the matter with the Board and they have concurred in the selection of you to serve on a Committee of four to review that objective and make a recommendation as to the action that should be taken by the International Joint Commission.

I would envision that this will involve not more than two meetings, and probably one meeting, to discuss the issues and reach a decision. The International Joint Commission will pay the travel of non-federal employees and will also provide secretarial support for the meeting. I know that each of you is busy at different things, but I also know that it is only through experts, such as yourself, that we can reach the best decision.

I hope that you will be willing to help us out with this matter. If so, please let me know as soon as possible, so that we can establish a meeting date. If you agree to serve on the committee, I will provide you with a collection of papers which will give you the background of the issue in question.

For selfish reasons, I am hoping that you will be willing to meet at Duluth so that you can visit our laboratory, and give some of our staff a chance to meet each of you and talk about matters of mutual interest. However, the place of the meeting is up to the group and can be in any location. I will look forward to receiving your reply soon and I hope that it is positive.

Best regards,

Donald I Mount, Ph.D.
U. S. Chairman
Research Advisory Board

List of Addressees Attached

Review Committee for Oxygen Criteria

ADDRESSEES:

Dr. J. R. Brett ✓
Pacific Biological Station
Fisheries Research Board
Nanaimo, B.C. V9R 5K6

Dr. F. E. J. Fry
Professor of Zoology
University of Toronto
Toronto, Ontario

Dr. Peter Doudoroff
3483 N.W. Crest Drive
Corvallis, OR 97330

Dr. Paul O. Fromm
Department of Pharmacology and
Physiology
Michigan State University
East Lansing, Michigan 48823

cc:
Tom Roush
Bob White
A. L. LeFeuvre
Andy Watson

APPENDIX B. MATERIAL FOR FIRST MEETING

- Agenda and Minutes of First Meeting with Appendices 1, 2A, 2B and 3
- Chairman's Report of First Committee Meeting to the Science Advisory Board (Appendix 3 to Minutes)
- Dr. Fry's Comments on the Chairman's Report
- C. M. Fetterolf's Comments on the Chairman's Report

FIRST MEETING OF THE
INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD'S
REVIEW COMMITTEE FOR THE DISSOLVED OXYGEN OBJECTIVE
FOR THE GREAT LAKES

AT THE
LABORATORY OF LIMNOLOGY
UNIVERSITY OF WISCONSIN, MADISON
JUNE 26, 1978 -- 8:30 A.M. - 3:30 P.M.

AGENDA

1. WELCOME AND INTRODUCTIONS
2. AGENDA
3. RATIONALE FOR OBJECTIVE REVIEW AND NATURE OF PROBLEM - *A. E. P. Watson*
4. IDENTIFICATION OF THE CHARACTERISTICS OF A WORKSHOP OBJECTIVE
5. PLANS FOR ADDITIONAL COMMITTEE ACTIVITIES AND INDIVIDUAL ASSIGNMENTS
6. OTHER BUSINESS
7. NEXT MEETING
8. ADJOURNMENT

MINUTES OF THE FIRST MEETING
OF THE
INTERNATIONAL JOINT COMMISSION
RESEARCH ADVISORY BOARD'S
REVIEW COMMITTEE FOR THE DISSOLVED OXYGEN OBJECTIVE FOR THE GREAT LAKES

HELD AT THE LIBRARY
LIMNOLOGY LABORATORY
UNIVERSITY OF WISCONSIN
MADISON, WISCONSIN

June 26, 1978
8:30 A.M. - 3:30 P.M.

United States Members Present

J. J. Magnuson (Chairman)	University of Wisconsin, Madison
P. O. Fromm	Michigan State University, East Lansing

United States Members Absent

None

Canadian Members Present

J. R. Brett	Pacific Biological Research Station Fisheries & Environment Canada Nanaimo, B. C.

Canadian Members Absent

F. E. J. Fry	Weston, Ontario

Secretary

A. E. P. Watson	IJC Great Lakes Regional Office, Windsor, Ontario

1. WELCOME AND INTRODUCTIONS

The Chairman opened the meeting at 8:45 A.M. and welcomed the attendees. Introductions were made. Regrets for non-attendance had earlier been expressed by Dr. Fry.

2. AGENDA

The proposed agenda was adopted in principle.

3. RATIONALE FOR OBJECTIVE REVIEW AND NATURE OF PROBLEM

3.1 Background

With reference to the Water Quality Board's Report "Great Lakes Water Quality 1976," Appendix A, Water Quality Objectives* (See excerpt in Appendix 1), Dr. Watson outlined the problem. He stated that the Water Quality Board, unable to accept or evaluate the dissolved oxygen (D.O.) objective described in the report, had requested aid from the Research Advisory Board. The latter stated the problems as:

- o the proposed objective cannot be implemented neither, however, can the present objective; and
- o such a restrictive objective is unnecessary to protect aquatic life.

Hence, the Review Committee has been constituted to resolve these issues.

3.2 Perception of the Problem

A. Dr. Magnuson noted that a sound scientific basis would be necessary in order to recommend dissolved oxygen levels compatible with observed taxonomic relationships.

Following discussion, specific elements of the problem were identified as:

1) The validity of the criteria for the partial pressure of venous blood (i.e. pVO_2 in mm Hg) to maintain the required gradient across the gills.

2) The need for and validity of separate D.O. levels for different fish species, coupled with the perceived trophic state of a lake and the

---

*N.B. Copies of the complete report were distributed during the meeting.

selection of an appropriate management strategy.

3) Reveiw of the recent (i.e. post-1973) literature, especially that relating to the D.O. requirements of fish at low temperatures.

4) "Oxygen debt" and accountability in fish during active and resting periods.

5) Acclimation by fish to iow D.O levels.

B. An analysis was made of the development of dissolved oxygen criteria described in the report (see Appendix I - report excerpt, pp. II-27). Queries regarding the report included:

- the validity of "critical" oxygen levels;
- the significance of D.O concentrations in venous blood and their inculsion in the reported data; and
- the influence of temperature on oxygen requirements.

4. COMMITTEE ACTIVITIES

It was agreed that the members' expertise be shared in developing a rationale and that the oxygen requirements for this be developed. Moreover, it was decided to note issues resulting from this meeting and to continue the assignment by correspondence; holding the next meeting in the Fall of 1978.

5. MEMBERS' PRESENTATIONS

The Chairman invited presentation of relevant research material by the members.

5.1 Dr. Brett's Presentation on Metabolic Rates and Dissolved Oxygen Concentrations

Dr. Brett noted that growth was a valuable sublethal stress indicator. Data were presented - see Appendix 2A - illustrating relationships between oxygen and: (a) growth index (fig. 15, Appendix 2Aa); (b) food conversion efficiency (fig. 16, Appendix 2Ab); growth rate (fig. 1, Appendix 2Ac); and the haematocrit (fig. 2, Appendix 2Ad); respectively.

It was concluded that:

- a re-appraisal of earlier work on limiting D.O. concentrations is necessary since recent research indicates lower values of 4-5 ppm (i.e. 4-5 mg/L);
- good diurnal growth is observed at relatively low D.O. concentrations, with (oxygen-demanding) excreta present; and
- evidence for adaptation is demonstrated at these D.O. concentrations.

5.2 Dr. Magnuson's Presentation on D.O. and Winterkill Conditions

Two publications on this subject co-authored by Dr. Magnuson, were distributed and are reproduced in Appendix 2Ba and 2Bb; respectively. It was noted that:

- fish behaviour is similar at D.O. concentrations of .l mg/L and at 4 mg/L, implying the use of an accessory ventilation mechanism;
- fish seek a preferred temperature (e.g. 0^{o}-4^{o}C and ~ 0.7 mg/L D.O.) to conserve energy;
- bottom standards for the lake D.O. concentration apply in winter; and
- few data are available at temperatures of 5^{o}C or below.

5.3 Dr. Fromm's Presentation on Respiratory Mechanisms

Appropriate literature was cited and recent research on this topic was described by Dr. Fromm, including studies of the variation of cardiac output to increase oxygen transfer and the ventilation effect, involving utilization of secondary gill lamellae to provide additional oxygen uptake.

It was concluded that:

- adaptability by organisms to D. O. concentrations less than the maximum has largely been ignored in the report under review;
- oxygen requirements at low temperature (i.e. below 5^{o}C) have been extrapolated from information on gill activity at 20^{o}C; and

- it is unreasonable to propose such a high value for p VO_2, since the saturation of haemoglobin by oxygen is not compromised by the likely reduction in O_2 tension and the CO_2 balance must be accounted for.

Dr. Fromm was requested to provide additional information on the latter topic. FROMM

6. MAJOR CONCERNS OF THE COMMITTEE (See Appendix 3)

The Committee itemized its major concerns and the Chairman agreed to submit these as a report of the Committee to the Research Advisory Board for its July 1978 meeting. The report is reproduced in Appendix 3. MAGNUSON WATSON

7. NEXT MEETING

This will be held in November 1978 at a location convenient for Dr. Fry. The business of the Committee will meantime continue by means of correspondence involving the Chairman and Secretary. MAGNUSON WATSON

8. ADJOURNMENT

Dr. Magnuson adjourned the meeting at 4:30 P.M.

APPENDIX 1

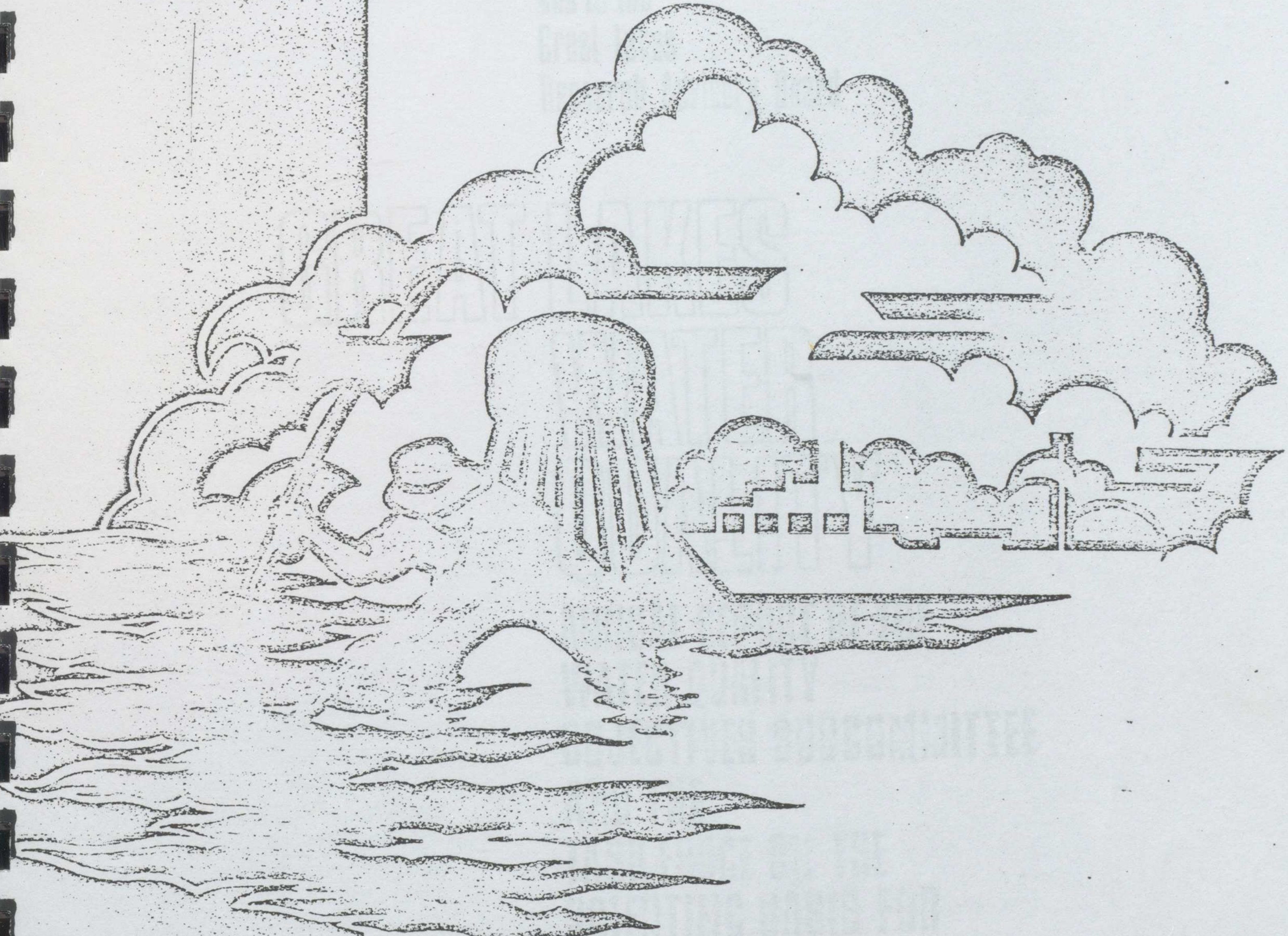
Dissolved Oxygen Excerpt from the June 1977 Report

on

Great Lakes Water Quality 1976

Appendix A, Water Quality Objectives

GREAT LAKES
WATER QUALITY BOARD
RESEARCH ADVISORY BOARD



INTERNATIONAL JOINT COMMISSION

GREAT LAKES WATER QUALITY 1976
APPENDIX A
WATER QUALITY OBJECTIVES

Presented to the
Implementation Committee
of the
Great Lakes
Water Quality Board
and to the
Great Lakes
Research Advisory Board

GREAT LAKES WATER QUALITY

ANNUAL REPORT OF THE WATER QUALITY OBJECTIVES SUBCOMMITTEE AND THE TASK FORCE ON THE SCIENTIFIC BASIS FOR WATER QUALITY CRITERIA

JUNE 1977

DISSOLVED OXYGEN

RECOMMENDATION

It is recommended that the following revised objective for dissolved oxygen be adopted to replace the existing objective in Annex 1 of the Water Quality Agreement:

> *Dissolved oxygen should not be less than the values specified below for the protection of aquatic life:*

Water Temperature °C	*Oxygen Concentration*	
	Percent Saturation	*mg/litre*
0	*69*	*10.0*
5	*70*	*9.0*
10	*70*	*7.9*
15	*71*	*7.2*
20	*79*	*7.2*
25	*87*	*7.2*

EXISTING OBJECTIVE

The above objective is recommended to replace the existing objective in Annex 1 paragraph 1 (c) of the Water Quality Agreement, which states:

> "In the Connecting Channels and in the upper waters of the lakes, the dissolved oxygen level should be not less than 6.0 milligrams per litre at any time; in hypolimnetic waters, it should be not less than necessary for support of fishlife, particularly cold water species."

RATIONALE

INTRODUCTION

Dissolved oxygen (DO) is a critical constituent which is essential for the continued healthy functioning of aquatic systems. Inadequate dissolved oxygen concentrations in surface waters may contribute to an unfavourable environment for fish and other aquatic life; the absence of dissolved oxygen may degrade the aesthetic quality of waters by giving rise to the malodorous products of anaerobic decomposition. Although supersaturated concentrations of DO which can arise from excessive algal production may affect one or more beneficial uses of water, the emphasis of the rationale is on the implications of a deficiency of dissolved oxgyen.

OXYGEN REGIMES IN THE GREAT LAKES

Table 1 summarizes summertime dissolved oxygen conditions in the hypolimnetic waters of the Great Lakes, and illustrates the variation in conditions within that system. In Lakes Superior and Huron, the hypolimnion remains essentially

TABLE 1.

SUMMARY OF DISSOLVED OXYGEN CONDITIONS IN THE GREAT LAKES' SUMMERTIME HYPOLIMNIA AS OBSERVED BY THE CANADA CENTRE FOR INLAND WATERS

(COMPILED BY HUGH F.H. DOBSON, APRIL 22, 1977)

LAKE	NUMBER OF CRUISES	YEARS OF THE OBSERVATIONS CONSIDERED	APPROXIMATE TEMPERATURES (°C)	DISSOLVED OXYGEN CONDITIONS		
				MAXIMUM VALUES (MG/L, % SATN)	MINIMUM VALUES (MG/L, % SATN)	MEAN DEPLETION RATE (MG/L/MONTH)
Superior	9	1968 - 73	3.8°	13.8/107%	12.0/93%	0.14
Huron	17	1968 - 74	3.9°	13.8/108%	11.4/88%	0.24
Georgian Bay	10	1969 - 74	4.1°	14.5/114%	11.6/90%	0.27
Central Erie	5	1970	7 to 12°	~11. /~100%	0.0/0%	3.3
Eastern Erie	6	1970	6°	~12. /~100%	5.7/48%	1.2
Ontario, main basin	21	1972 - 75	3.8°	~13. /~100%	10./80%	0.6 ?
Ontario, outlet basin	33	1966 - 75	5 to 12°	13.1/105%	4.2/39%	2.0

saturated with oxygen, though areas of oxygen depletion do occur. This depletion is generally observed during the August-September period; the reduction seldom exceeds 10%.

In contrast to the upper lakes, there is a marked seasonal variation in oxygen conditions in Lakes Erie and Ontario. The existing objective for dissolved oxygen is frequently violated in both lower lakes. Zero values of DO commonly occur during the summer months in the bottom waters of the central basin of Lake Erie; minimum values of 5.7 mg/l (48% saturation) have been observed in the hypolimnion of the eastern basin of Lake Erie. Dissolved oxygen values in the central and eastern basin are depicted in Figure 1.

In Lake Ontario, oxygen conditions are more stable, with a maximum depletion of 20% from complete saturation. However, significant reductions occur in the outlet basin of Lake Ontario. Minimum cycles of 39% saturation have been recorded. The seasonal cycle of DO in the bottom water of Prince Edward Bay is presented in Figure 2.

In contrast to the bottom waters, the eplimnetic waters throughout the Great Lakes are normally saturated with oxygen, and violations of water quality objectives, would not be expected to occur.

AESTHETIC QUALITIES OF WATER

Maintenance of aesthetic qualities of water requires sufficient dissolved oxygen to avoid the onset of septic conditions. The absence of dissolved oxygen in the water column causes the anaerobic decomposition of any organic materials present. Such decomposition results in the formation of gases such as hydrogen sulfide, carbon dioxide and methane in the sediments.

POTABLE WATER SUPPLIES

Dissolved oxygen in bodies of water used for municipal water supplies is desirable as an indicator of generally satisfactory water quality. In addition, dissolved oxygen in the water column prevents the chemical reduction and subsequent leaching of iron and manganese principally from the sediments (Environmental Protection Agency, 1973). These metals cause additional expense in the treatment of water or affect consumers' welfare by causing taste problems and staining plumbing fixtures and other surfaces which contact the water in the presence of oxygen (NAS/NAE, 1974).

Dissolved oxygen also is required for the biochemical oxidation of ammonia ultimately to nitrate in natural waters. This reduction of ammonia reduces the chlorine demand of waters and increases the disinfection efficiency of chlorination (NAS/NAE, 1974).

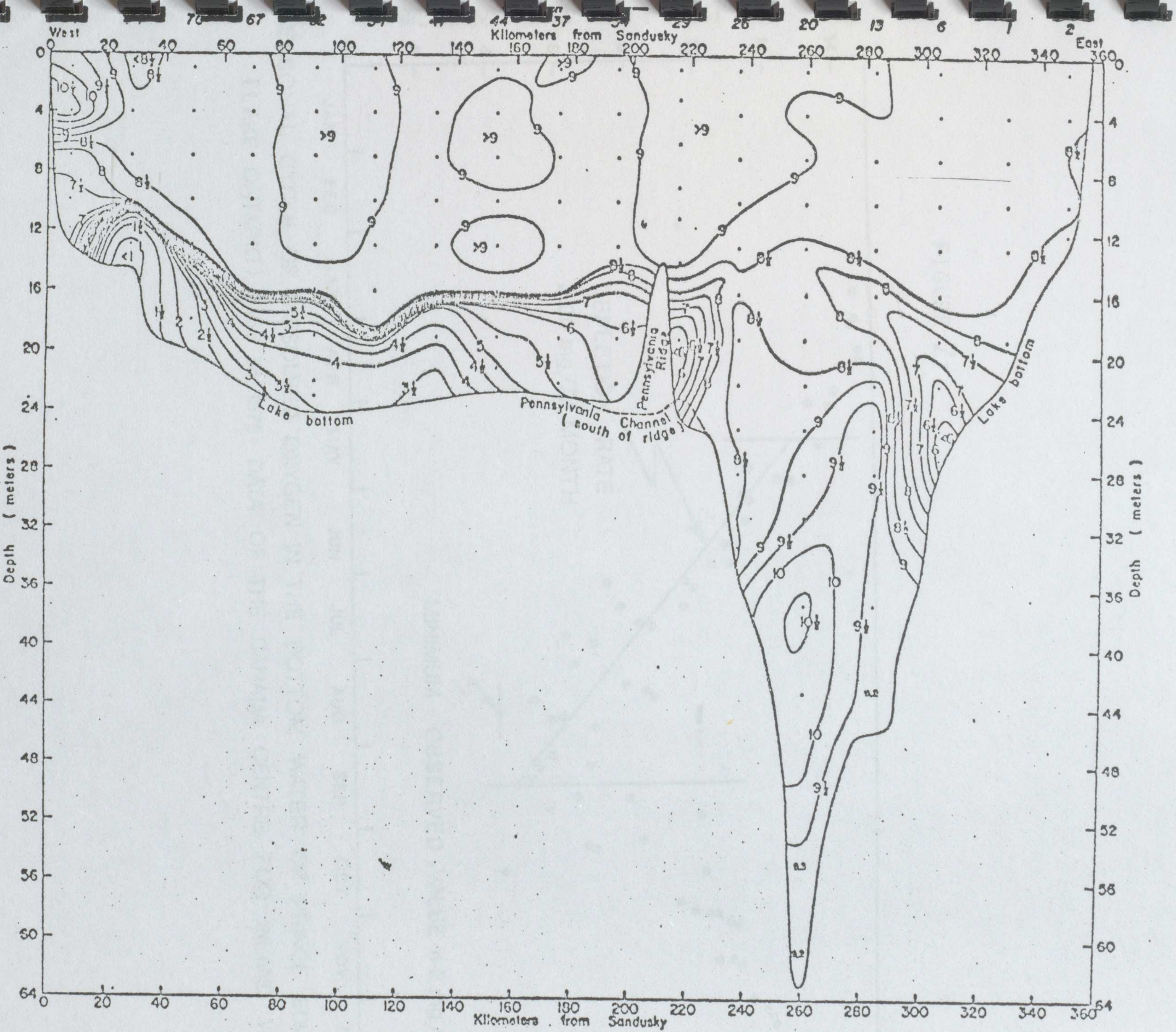
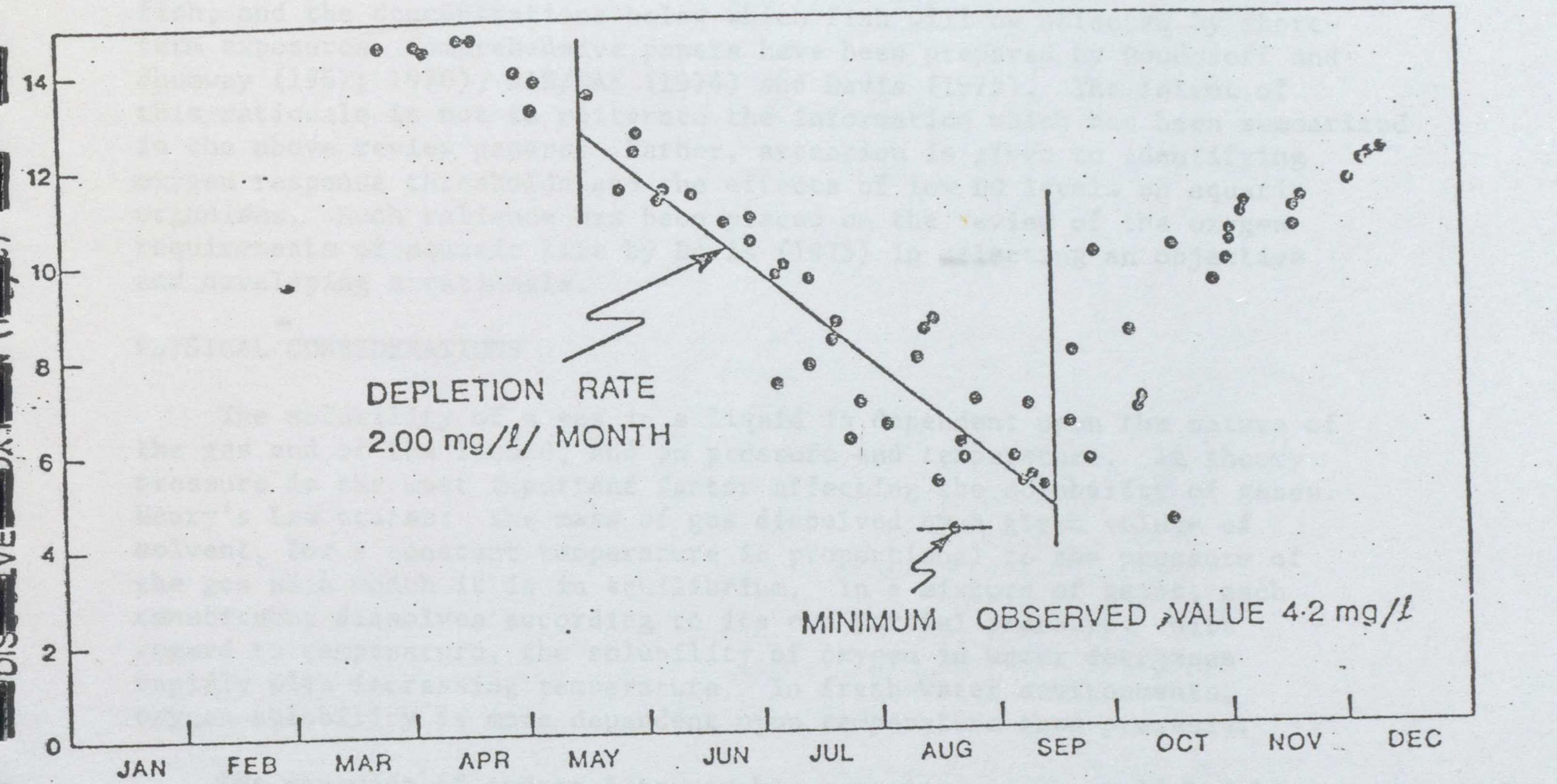


FIGURE 1: Lake Erie: Dissolved oxygen (mg/l) in a vertical section from Sandusky to Buffalo. July 29 to August 2, 1968.

FIGURE 2:



EASONAL CYCLE OF DISSOLVED OXYGEN IN THE BOTTOM WATER OF PRINCE EDWARD BA (LAKE ONTARIO), 1966 to 1975: DATA OF THE CANADA CENTRE FOR INLAND WATERS.

The disadvantage of substantial quantities of dissolved oxygen in water used as a source of municipal water supply is the increased rates of corrosion of metal surfaces in both the water treatment facilities and in the distribution system (NAS, 1974).

Such corrosion, in addition to the direct damage, can increase the concentration of iron (and other metals) which may cause taste in the water, as well as staining.

AQUATIC LIFE REQUIREMENTS

There is a large volume of literature pertaining to the minimum dissolved oxygen concentration necessary to sustain aquatic life, especially fish, and the concentrations below which fish will be affected by short-term exposures. Comprehensive papers have been prepared by Doudoroff and Shumway (1967; 1970), NAS/NAE (1974) and Davis (1975). The intent of this rationale is not to reiterate the information which has been summarized in the above review papers. Rather, attention is given to identifying oxygen response thresholds and the effects of low DO levels on aquatic organisms. Much reliance has been placed on the review of the oxygen requirements of aquatic life by Davis (1975) in selecting an objective and developing a rationale.

PHYSICAL CONSIDERATIONS

The solubility of a gas in a liquid is dependent upon the nature of the gas and of the liquid, and on pressure and temperature. In theory pressure is the most important factor affecting the solubility of gases. Henry's Law states: the mass of gas dissolved by a given volume of solvent, for a constant temperature is proportional to the pressure of the gas with which it is in equilibrium. In a mixture of gases, each constituent dissolves according to its own partial pressure. With regard to temperature, the solubility of oxygen in water decreases rapidly with increasing temperature. In fresh-water environments, oxygen solubility is more dependent upon temperature than pressure.

The movement of oxygen into aerobic organisms is accomplished by a process of diffusion which depends upon an internal - external oxygen pressure gradient. It is the oxygen tension gradient between tissues and the external medium that is critical to the gas exchange process.

Water which is equilibrated with the atmosphere at sea level will have an oxygen partial pressure of about 154 - 158 mm Hg. In fish, the internal oxygen tension usually ranges from 50 - 110 mm Hg, and oxygen therefore diffuses across the gills into the blood down an O_2 gradient of 40 - 100 mm Hg (Randall, 1970). A decrease of the external oxygen partial pressure (P_{O_2}) reduces the gradient or depresses arterial P_{O_2}.

As temperature increases, oxygen solubility decreases, but oxygen partial pressure drops only slightly. In warm water, a fish must pump e water over the gills to provide a given volume of oxygen per unit time, even though the oxygen partial pressure gradient between water and blood has changed but little. Metabolic demand for oxygen increases with elevated temperatures. Therefore, severe respiratory problems can be associated with a combination of high temperature and reduced oxygen tension (i.e. water not saturated) as both oxygen availability and the gradient for oxygen diffusion are reduced. To provide protection for aquatic life, oxygen objectives must aim to maintain a critical oxygen content and necessary oxygen tension as well as provide for the effects of temperature on metabolism.

OXYGEN REQUIREMENTS OF FISH

The blood oxygen dissociation curve (relating percent saturation of the blood to the P_{O_2} applied) for rainbow trout indicates that the blood remains nearly 100% saturated until P_{O_2} drops below 80 mm Hg (Cameron, 1971). The oxygen tension where the blood ceases to be fully oxygen saturated is indicative of a limiting oxygen condition for fish. Under these conditions more circulatory and ventilatory work must be done to meet the oxygen requirement of the tissues. Jones (1971) suggested that a P_{O_2} of 118 mm Hg was necessary to maintain a proper gradient for oxygen uptake. Randall (1970) has calculated that the internal - external gradient for trout should be 20 mm Hg.

Under conditions of reduced oxygen availability, fish attempt to maintain oxygen uptake by increasing the rate and amplitude of breathing and decreasing heart rate (Holeton and Randall 1967 a, b; Garey, 1967). In addition, the stroke volume output of the heart increases to maintain cardiac output, and the gill transfer factor for oxygen increases. The responses of fish to hypoxia represent some form of compensation or adjustment of bodily processes. Fish are able to tolerate reduced levels of oxygen for short periods. The success of such tolerance depends upon the species, the oxygen levels, and on environmental factors. The use of compensation mechanisms requires an expenditure of energy, and will consequently reduce energy reserves required for swimming, feeding, avoiding predators and other activities.

Much work has been conducted in the laboratory to determine oxygen concentrations which are in some way harmful to fish maintained in quiescent conditions. However, Fry (1957) recognized that identification of oxygen thresholds (where metabolic rate ceases to be dependent upon available oxygen) should be studied in relation to active metabolism of the test organism. He states:

> "Any reduction of the oxygen content below the level where the active metabolic rate begins to be restricted is probably unfavourable to the species concerned. From the ecological point of view this "incipient limiting level" (the critical level under conditions of activity) can be taken as the point where oxygen content becomes unsuitable".

Brett (1970) determined the oxygen requirements for fingerling sockeye salmon during various important activities. His data indicate that a reduction in oxygen to 50% saturation (at 20°C) would severely limit energy expenditure for migrating or maximum feeding. Similarly, 30 and 43% reductions of maximal swimming speed in rainbow trout resulted when environmental oxygen fell to 50% of saturation at 21-23°C and 8-10°C, respectively (Jones, 1971). Davis et al. (1963) reported that any reduction from ambient oxygen at 10-20°C usually reduced maximum sustained swimming speed in coho and chinook salmon. In contrast, Katz et al. (1959) has reported that the swimming ability in reduced oxygen may be affected by season and temperature, based upon experiments with large mouth bass.

The ability of fish to avoid hypoxic water has been reported by Randall (1970). Whitmore et al. (1960) have observed a seasonal variability in behavioral sensitivity of juvenile chinook salmon to low dissolved oxygen. Juvenile fish avoided DO concentrations of 1.5 - 4.5 mg/l in the summer, but showed little avoidance of 4.5 mg/l in the fall when temperatures were lower. Other behavioral responses to hypoxia include a negative phototaxis in walleye (Scherer, 1971), and violent bursts of activity and attempts to surface (Shepard, 1955).

Growth rate of fish is dependent upon dissolved oxygen. Growth rate and food consumption in juvenile largemouth bass and coho salmon increased as DO concentrations approached air-saturation levels (Stewart et al., 1967; Herrman, 1958). Herrman (1958) concludes that minimal oxygen concentrations to which juvenile coho can be exposed for relatively long periods without markedly affecting growth, feeding, food conversion and general activity, lie within the range of 4-6 mg/l. Exposure to fluctuating DO levels reduced growth of juvenile largemouth bass (Stewart, et al., 1967), and Whitworth (1968) observed loss of weight in brook trout to daily oxygen fluctuations.

The ability to acclimate to low DO would be a useful factor for populations regularly exposed to such conditions. However, the ability of fish to acclimate to low DO has not been clearly demonstrated, and there is a lack of field data to demonstrate that this ability would markedly improve the survival chances of fish populations. The ability to acclimate would be useful if the transition to a low DO regime were sufficiently slow to enable acclimation to occur without a severe physiological stress. Acclimation would be of no value if fish encounter a rapid downward shift of oxygen.

In addition to the direct impact of low oxygen levels in fish, there is evidence that low oxygen enhances the lethal effect of toxicants by producing a metabolic stress, thus lowering the resistance of the animal, and by increasing toxicant uptake as the result of elevated water flow across the gills. Alderdice and Brett (1957) observed an apparent increase in the toxicity of kraft pulpmill waste to young sockeye salmon in the presence of low oxygen. Similarly, Lloyd (1961) reported an increase in the toxicity of a number of chemical species (ammonia, lead, copper, zinc, phenols) to rainbow trout when oxygen levels fell below 60% saturation at 17.5°C. In tests with rainbow trout, Downing (1954) demonstrated that at 17°C, any reduction in DO below 100% saturation (9.74 mg/l) led to a significant enhancement of the lethal effect of cyanide.

Developing fish eggs and larvae show a number of responses to low oxygen including respiratory dependence, retarded growth, reduced yolk sac adsorption, developmental deformities, and mortality. As development proceeds, the oxygen requirements of both eggs and larvae increase. Alderdice et al. (1957) observed that eggs at early stages of incubation required oxygen concentrations of approximately 1 mg/l, while those about to hatch required about 7 mg/l. It is apparent that hatching eggs and larval fish represent the most sensitive stage in the life history. Davis (1975) has calculated the mean threshold of incipient oxygen response for salmonid larvae to be 8.09 mg/l.

OXYGEN REQUIREMENTS OF AQUATIC INVERTEBRATES

Available data on the responses of freshwater invertebrates to low dissolved oxygen have been summarized by Davis (1975). Davis indicated that a great range of tolerance responses and requirements for oxygen exist amongst aquatic invertebrates, and concluded that insufficient evidence exists at this time to allow meaningful dissolved oxygen objectives to be established for aquatic invertebrates. He suggests that any depression of natural oxygen conditions can result in a change in an aquatic invertebrate community. However, as many invertebrates are able to temporarily withstand periods of low oxygen, it is likely that establishment of objectives to protect fish will also ensure the protection of aquatic invertebrates.

APPROACHES TO THE DEVELOPMENT OF A DISSOLVED OXYGEN OBJECTIVE FOR AQUATIC LIFE

There are currently two philosophies with regard to establishment of an objective for dissolved oxygen to protect aquatic life. One view is that any reduction of DO can reduce the efficiency of oxygen uptake by aquatic animals and hence reduce their ability to meet the demands of their environment. This approach espouses the view that there is no DO concentration or percentage saturation to which the oxygen content of natural waters can be reduced without causing or risking some adverse effects on the reproduction, growth and productivity of resident fish populations. This view has been endorsed by Doudordoff and Shumway (1970), NAS/NAE (1974) and Davis (1975). Objectives which are based upon this approach generally are expressed as percent saturation or concentration minima and are in effect a continuum of values dependent upon temperature.

The opposing view is that the response of organisms to DO concentrations below 100% saturation simply reflects an acclimation response which has no negative impact on the continued survival or productivity of the aquatic community. Based largely upon field observations of fish populations which have been found at oxygen concentrations considerably below that considered suitable for a thriving population, single minimum concentrations of DO are believed to adequately protect aquatic populations. This view has been adopted by the EPA "Quality Criteria for Water" (EPA, 1976) which recommends an objective of 5 mg/l for dissolved oxygen in freshwater.

There are merits to both of these philosophies. However, the approach which has been adopted for establishment of a DO objective for the Great Lakes is that any change in the DO regime is likely to have some effect on the ecosystem and the magnitude of that effect will depend on the severity and duration of the change. It is felt that this approach is justified for the following reasons.

1. The objective provides both the correct oxygen tension gradient to move oxygen into the blood and sufficient oxygen to fulfill the requirements of metabolism.
2. The objective recognizes the greater metabolic demand for DO at elevated temperatures.
3. A reduction of DO levels to below saturation limits active metabolism, reduces maximum swimming speed of fish and causes a physiological, behavioral or other stress induced response. While the consequences of the chronic occurrence of such stress are not well understood, there is a reasonable likelihood that it is an important factor in the long term survival of the organism.
4. There is a small safety factor included between the objective and the concentration causing measurable harm to aquatic biota.

DEVELOPMENT OF OXYGEN CRITERIA FOR FISH POPULATIONS

In line with the above discussion, the approach proposed by Davis (1975) for deriving DO criteria to protect fish has been adopted here. His approach involved the establishment of mean thresholds of incipient oxygen response thresholds by averaging data on oxygen levels for various assemblages of fish where sublethal responses to hypoxia first become apparent. Using the calculated mean threshold level, three levels of protection (A, B, and C) were devised as follows:

1. Level A: This level is one standard deviation above the mean average oxygen response level for a fish community (e.g. freshwater fish, including salmonids). It represents a high degree of safety for important fish stocks and permits 13-20% depression of oxygen from full saturation.

2. Level B: This level is the caluclated mean oxygen response threshold, and represents the oxygen value where the average member of a species of a fish community starts to exhibit symptoms of oxygen distress. Oxygen concentrations are allowed to be depressed from 35 to 45% below saturation.
3. Level C: This level is one standard deviation below the mean oxygen response threshold, and permits a large portion of a fish population to be affected. Oxygen concentrations may be depressed to 60% below saturation.

The calculated oxygen response thresholds for freshwater fish populations is presented in Table 2 (abridged from Davis, 1975).

TABLE 2.

INCIPIENT DISSOLVED OXYGEN RESPONSE THRESHOLDS FOR FRESHWATER ASSEMBLAGES OF FISH

GROUP	PROTECTION LEVEL	P_{O_2} MMHG	MG O_2/LITER
Mixed freshwater fish population including salmonids (15 °C)	A	113	7.27
	B	86	5.26
	C	58	3.25
Mixed freshwater fish population with no salmonids (18 °C)	A	92	5.63
	B	73	3.98
	C	54	2.33
Freshwater salmonids (including steelheads) (15 °C)	A	119	7.84
	B	90	6.00
	C	61	4.16
Salmonid larvae and mature eggs (9 °C)	A	115	9.74
	B	120	8.09
	C	85	6.44

On the basis of the calculated critical partial oxygen pressures presented in Table 2, extrapolated objectives over the range of 0-25 °C were calculated as percent of saturation required to provide a desirable oxygen partial pressure and content. These values are intended to be minimum oxygen levels of body of water. Oxygen criteria based upon percent saturation are provided in Table 3 (abridged from Davis, 1975).

These objectives expressed as percent saturation over a range of temperatures, are intended to protect fish by providing both the correct oxygen gradient to move oxygen into the blood and sufficient oxygen to

TABLE 3.

CRITICAL CONCENTRATIONS OF OXYGEN REQUIRED TO MAINTAIN DIFFERING LEVELS OF PROTECTION FOR VARIOUS ASSEMBLAGES OF FRESHWATER FISH

GROUP	PROTECTION LEVEL	P_{O_2} MMHG	ML O_2 /LITER	MG O_2 /LITER	% SATURATION AT °C REQUIRED TO MAINTAIN PROTECTION LEVEL					
					0°	5°	10°	15°	20°	25°
Freshwater mixed fish population including salmonids	A	110	5.08	7.25	69	70	70	71	79	87
	B	85	3.68	5.25	54	54	54	54	57	63
	C	60	2.28	3.25	38	38	38	38	39	39
Freshwater mixed fish population with no salmonids	A	95	3.85	5.50	60	60	60	60	60	66
	B	75	2.80	4.00	47	47	47	47	47	48
	C	55	1.75	2.50	35	35	35	35	35	36
Freshwater salmonid population (including steelhead)	A	120	5.43	7.75	76	76	76	76	85	93
	B	90	4.20	6.00	57	57	57	59	65	72
	C	60	2.98	4.25	38	38	38	42	46	51
Salmonid larvae and mature eggs of salmonids	A	155	6.83	9.75	98	98	98	98	100	100
	B	120	5.60	8.00	76	76	76	79	87	95
	C	85	4.55	6.50	54	54	57	64	71	78

Figure 3: Oxygen objective expressed as mg/litre at various temperatures (interpolated between points)

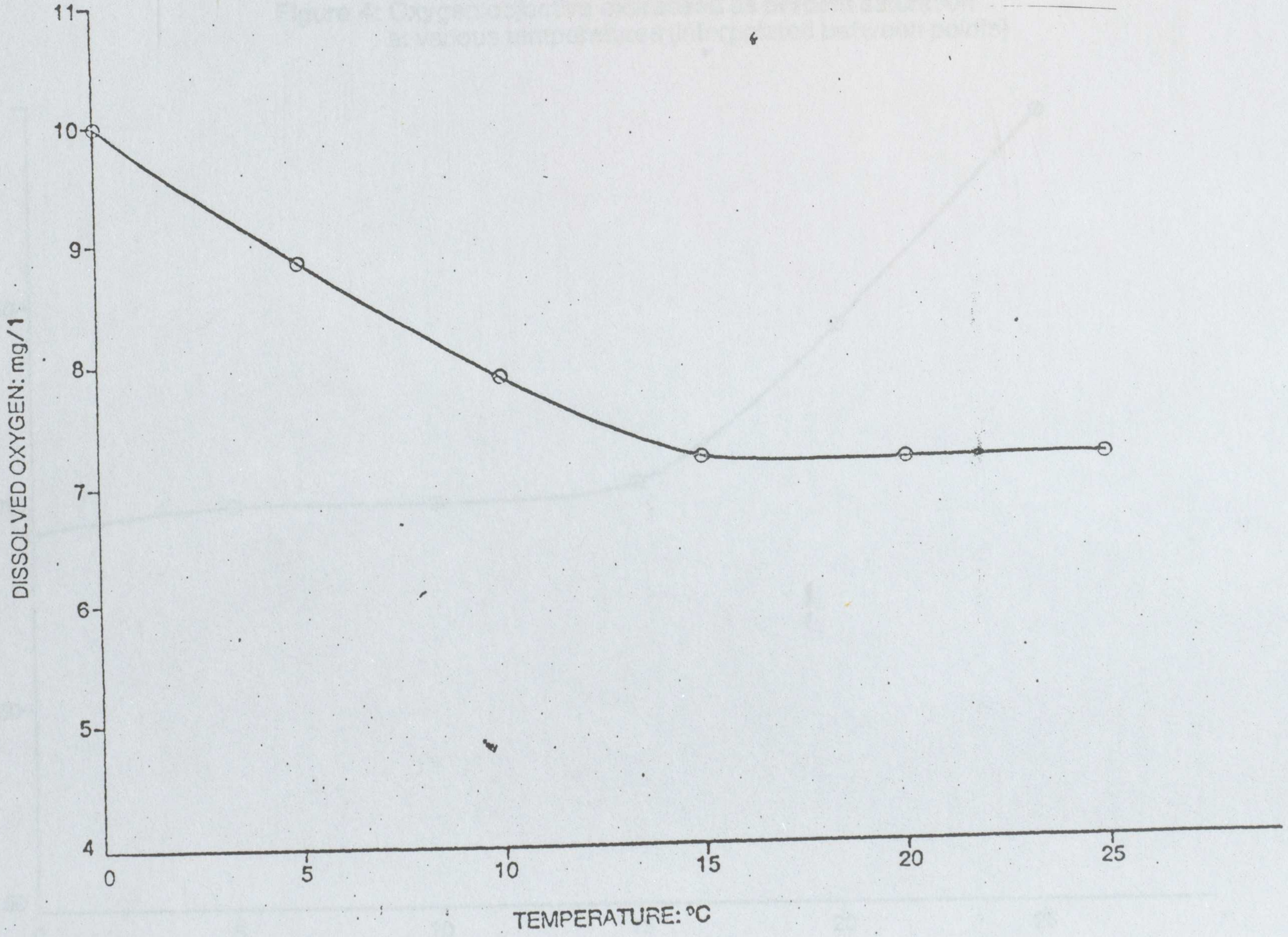
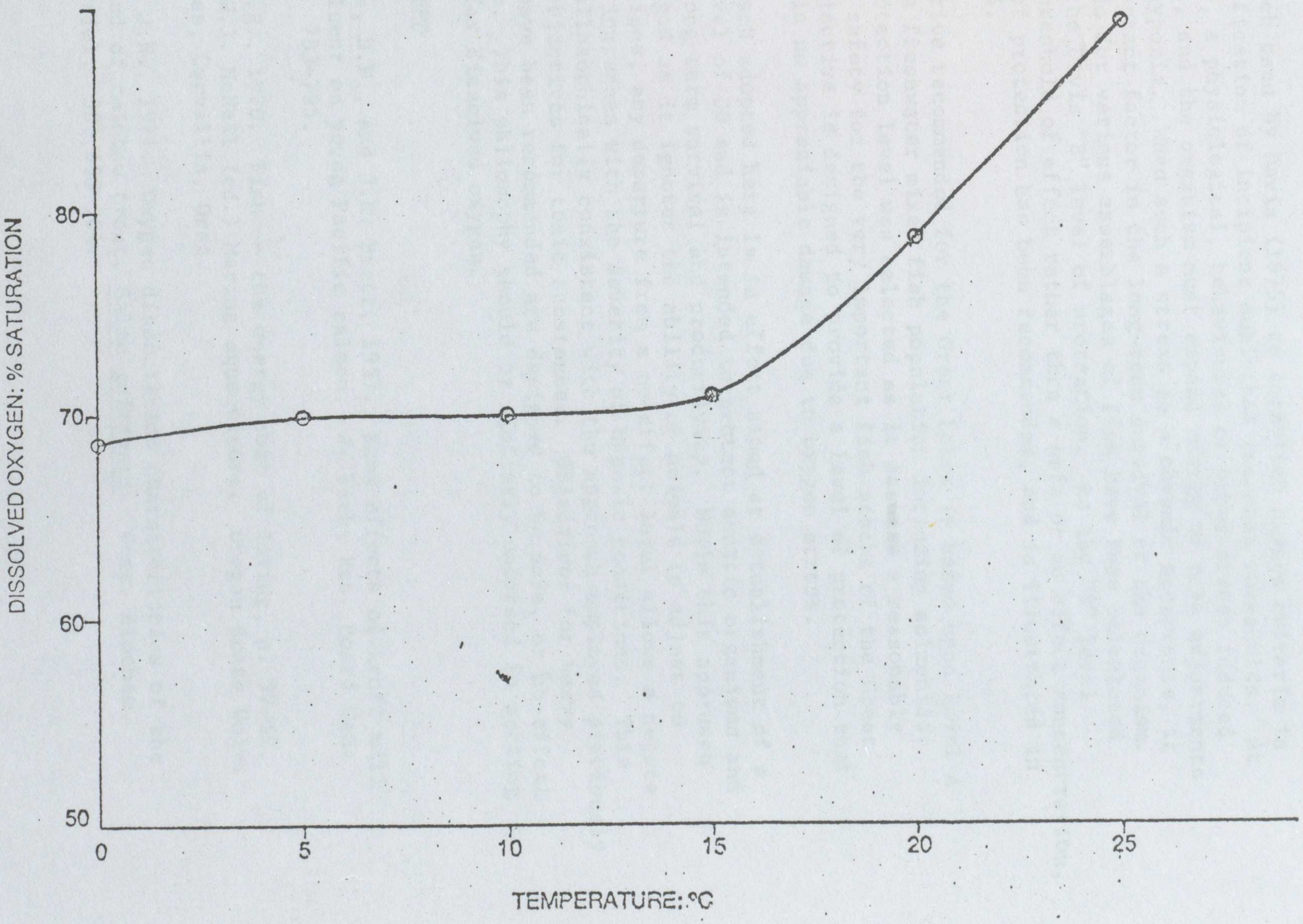


Figure 4: Oxygen objective expressed as percent saturation at various temperatures (interpolated between points)



fulfill the requirements of metabolism. At the lower temperatures where water solubility of oxygen is high, the criteria are based upon the P_{O_2} values (Table 3) to ensure that a percent saturation value consistent with the required P_{O_2} gradient was present. At the higher temperatures, higher percentage saturation values were necessary to provide the oxygen content requirements.

The approach used by Davis (1975) to establish oxygen criteria is aimed at identification of incipient sublethal response thresholds. At such thresholds, a physiological, behavioural or other stress induced response occurs, and the organism must expend energy or make adjustments to counteract hypoxia. When such a stress is a chronic occurrence, it becomes an important factor in the long-term survival of the organism. These thresholds for various assemblages of fish have been calculated and represent the Davis "B" level of protection. As the "B" level represents a threshold of effect rather than a safe or no effect concentration, the "A" level of protection has been recommended, and is illustrated in Figures 3 and 4.

The objective recommended for the Great Lakes is based upon Level A protection of a freshwater mixed fish population including salmonids. The maximum protection level was selected as it assures a reasonably high degree of safety for the very important fish stocks of the Great Lakes. The objective is designed to provide a level of protection that should result in no appreciable damage due to oxygen stress.

The approach adopted here is in effect aimed at establishment of a "no-effect" level of DO and is intended to protect aquatic organisms and ensure their long-term survival and productivity. While this approach can be challenged as it ignores the ability of animals to adjust to altered conditions, any departure from a no-effect level allows a degree of risk which increases with the severity of hypoxic conditions. This approach is philosophically consistent with the approach employed previously to establish objectives for toxic substances. Objectives for heavy metals which have been recommended are designed to be safe, or "no-effect concentrations. This philosophy should be similarly endorsed in setting an objective for dissolved oxygen.

LITERATURE CITED

Alderdice, D.F., and J.R. Brett, 1957. Some effects of kraft mill effluent on young Pacific salmon. J. Fish. Res. Board Can. 14: 783-795.

Brett, J.R., 1970. Fish -- the energy cost of living, p. 37-52. In W.J. McNeil (ed.) Marine aquaculture. Oregon State Univ. Press, Corvallis, Oreg.

Cameron, J.N., 1971. Oxygen dissociation characteristics of the blood of rainbow trout, Salmo gairdneri. Comp. Biochem. Physiol. 38: 699-704.

Davis, G.E., J. Foster, C.E. Warren, and P. Doudoroff, 1963. The influence of oxygen concentration on the swimming performance of juvenile Pacific salmon at various temperatures. Trans. Am. Fish. Soc. 92: 111-124.

Davis, J.C., 1973. Sublethal effects of bleached kraft pulpmill effluent on respiration and circulation in sockeye salmon (Oncorhynchus nerka). J. Fish. Res. Board Can. 30: 369-377.

Davis, J.C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species : a review. J. Fish. Res. Bd. Can. 32(12): 2295-2332.

Doudoroff, P., and D.L. Shumway, 1967. Dissolved oxygen requirements for the protection of fish. In: A Symposium on water quality criteria to protect aquatic life. Spec. Pub. No. 4, Amer. Fish. Soc.

Doudoroff, P., and D.L. Shumway, 1970. Dissolved oxygen requirements of freshwater fishes. Food Agric. Organ. U.N., FAO Tech. Pap. 86: 291.

Downing, K.M., 1954. The influence of dissolved oxygen concentration on the toxicity of potassium cyanide to rainbow trout. J. Exp. Biol. 31: 161-164.

Environmental Protection Agency, 1973. The control of pollution from hydrographic modifications. EPA 430/9-73-017. U.S. Government Printing Office, Washington, D.C.

Fry, F.E.J., 1957. The aquatic respiration of fish, p. 1-63. In M.E. Brown (ed.) The Physiology of fishes. Vol. 1. Academic Press Inc., New York, N.Y.

Garey, W.F., 1967. Gas exchange, cardiac output and blood pressure in free swimming carp (Cyprinus carpio). Ph.D. Dissertation. Univ. New York, Buffalo, N.Y. 123 p.

Herrman, R.B., 1958. Growth of juvenile salmon at various concentrations of dissolved oxygen. M.Sc. Dissertation. Oregon State Univ., Corvallis, Oreg.

Holeton, G.F., and D.J. Randall., 1967a. Changes in blood pressure in the rainbow trout during hypoxia. J. Exp. Biol. 46: 297-305.

Holeton, G.F. and D.J. Randall, 1967b. The effect of hypoxia upon the partial pressure of gases in the blood and water afferent and efferent to the gills of rainbow trout. J. Exp. Biol. 46: 317-327.

Jones, D.R., 1971. The effect of hypoxia and anemia on the swimming performance of rainbow trout (Salmo gairdneri). J. Exp. Biol. 55: 541-551.

Katz, M., A. Pritchard and C.E. Warren, 1959. Ability of some salmonids and a centrarchid to swim in water of reduced oxygen content. Trans. Am. Fish. Soc. 88: 88-95.

Lloyd, R., 1961. Effect of dissolved oxygen concentrations on the toxicity of several poisons to rainbow trout (Salmo gairdneri Richardson). J. Exp. Biol. 38: 447-455.

NAS/NAE, 1974. Water Quality Criteria, 1972. National Academy of Sciences, National Academy of Engineering, U.S. Environmental Protection Agency, Ecological Research Series, EPA-R3-73-033, 594 pp. Superintendent of Documents, Washington, D.C.

Randall, D.J., 1970. Gas exchange in fish. p. 253-292. In: W.S. Hoar and D.J. Randall (ed.) Fish physiology. Vol. IV. Academic Press Inc., New York, N.Y.

Shepard, M.P., 1955. Resistance and tolerance of young speckled trout (Salvelinus fontinalis) to oxygen lack, with special reference to low oxygen acclimation. J. Fish. Res. Bd. Can. 12: 387-446.

Scherer, E., 1971. Effects of oxygen depletion and of carbon dioxide buildup on the photic behavior of the walleye (Stizostedion vitreum vitreum). J. Fish. Res. Board Can. 28: 1303-1307.

Stewart, N.W., D.L. Shumway, and P. Doudoroff, 1967. Influence of oxygen concentration on the growth of juvenile largemouth bass. J. Fish. Res. Board Can. 24: 475-494.

Whitmore, C.M. C.E. Warren and P. Doudoroff, 1960. Avoidance reactions of salmonids and centrarchid fishes to low oxygen concentrations. Trans. Am. Fish. Soc. 89: 17-26.

Whitworth, W.R., 1968. Effects of diurnal fluctuations of dissolved oxygen on the growth of brook trout. J. Fish. Res. Board Can. 25: 579-584.

APPENDIX 2 A

Dr. Brett's Presentation

(a) Figure 15: Growth Index (%) vs. Oxygen (mg/L)
(b) Figure 16: Food Conversion Efficiency (%) vs. Oxygen Concentration (ppm)
(c) Figure 1: Growth Rate (% per day) vs. Oxygen (ppm)
(d) Figure 2: Haematocrit (%) vs. Oxygen (ppm)

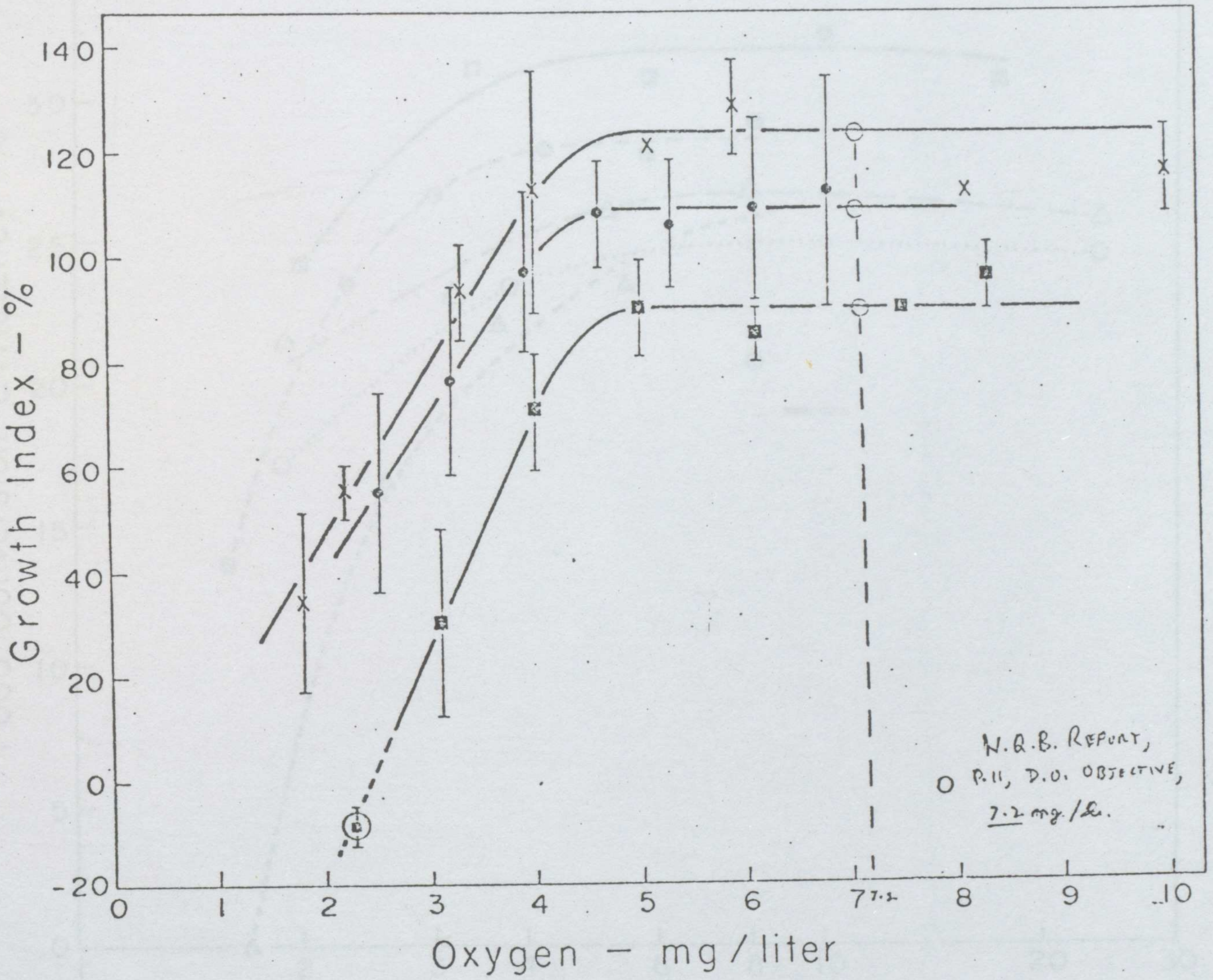


Fig. 15. Relation of oxygen concentration to growth rate expressed as the percentage of the "growth index" developed by each author. Limits = ± ISD. Data for Micropterus salmoides (26°C; 2.5-4.5 g - upper curve) from Stewart et al. (1967), for Cyprinus carpio (22°C; 0.5-3.4 g - middle curve) from Chiba (1966), and for Oncorhynchus kisutch (20°C; 2-6 g - lower curve) from Herman et al. (1962); circled point was accompanied by significant mortalities. The vertical positioning by species has no relative significance. Lines drawn according to interpretation presented in text.

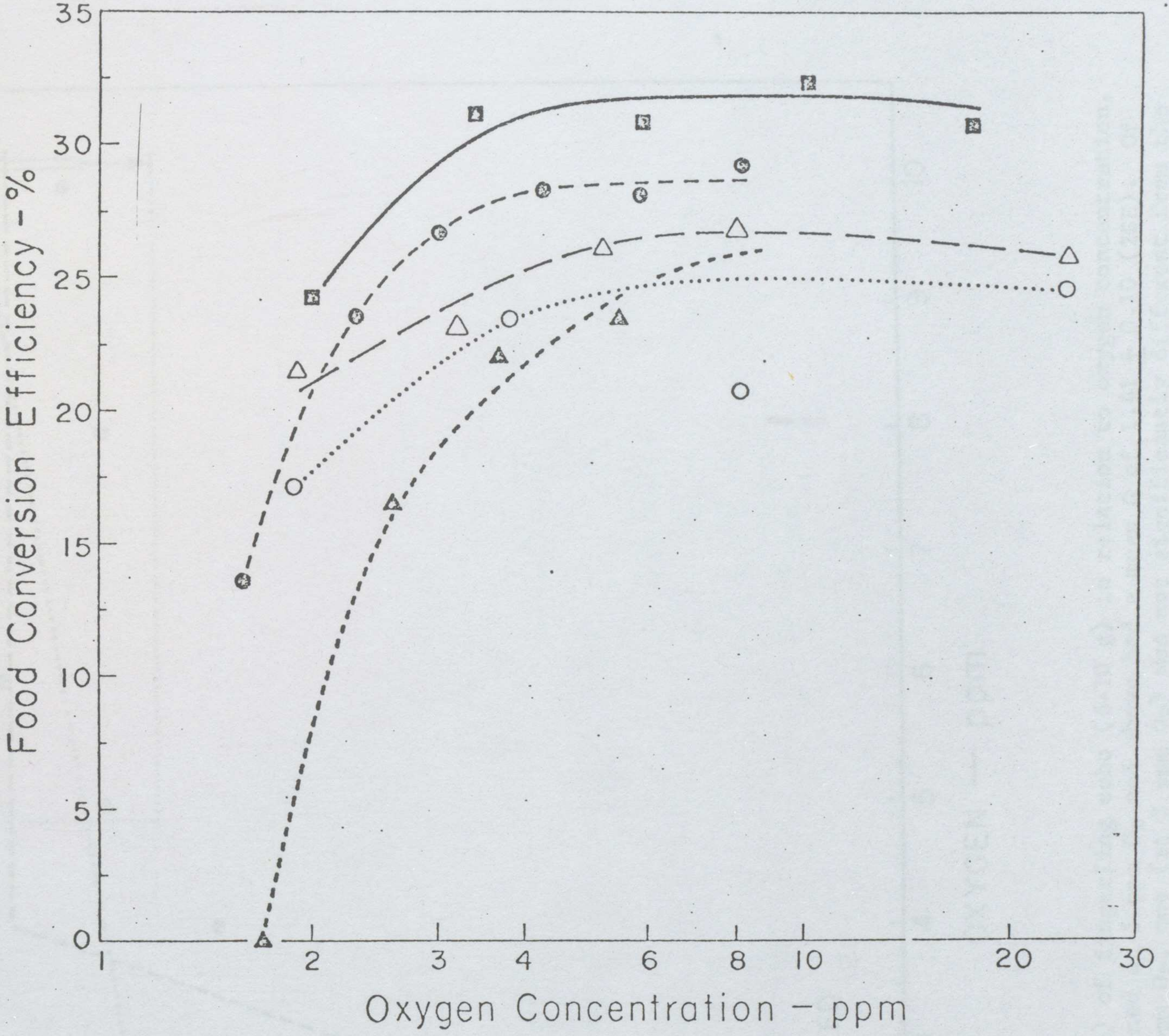
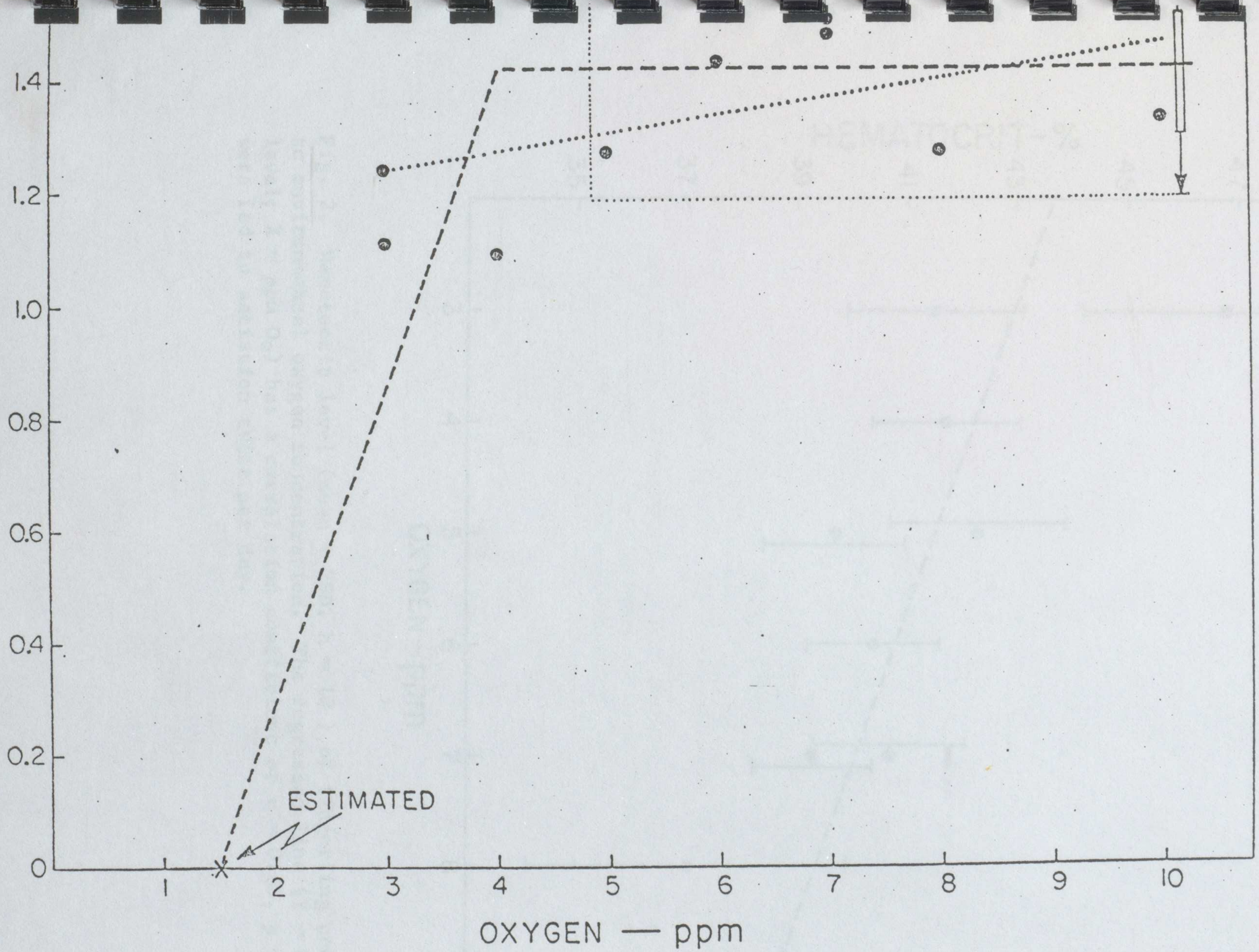


Fig. 16. Food conversion efficiency in relation to oxygen concentration. Results are for separate experiments conducted on *Micropterus salmoides* at 26°C. From Stewart *et al*. (1967).



ig. 1. Specific growth rate (G) of fingerling coho (6-10 g) in relation to oxygen concentration, t 15°C. The seven values obtained at 5 ppm O_2 and above had a mean G of 1.41 ± 0.10 (2SE). Of he three growth rates below 5 ppm O_2, one (at 3 ppm O_2) was not significantly different from the alues for 5 ppm and above. Limits are shown as mean ± 2SD, ± 2SE, n = 25. The dotted line is the egression relation of growth rate and oxygen concentration. The broken line is the interpreted elation, using an observed distress response to a steady reduction in ppm O_2 at the termination of he 42-day experiment.

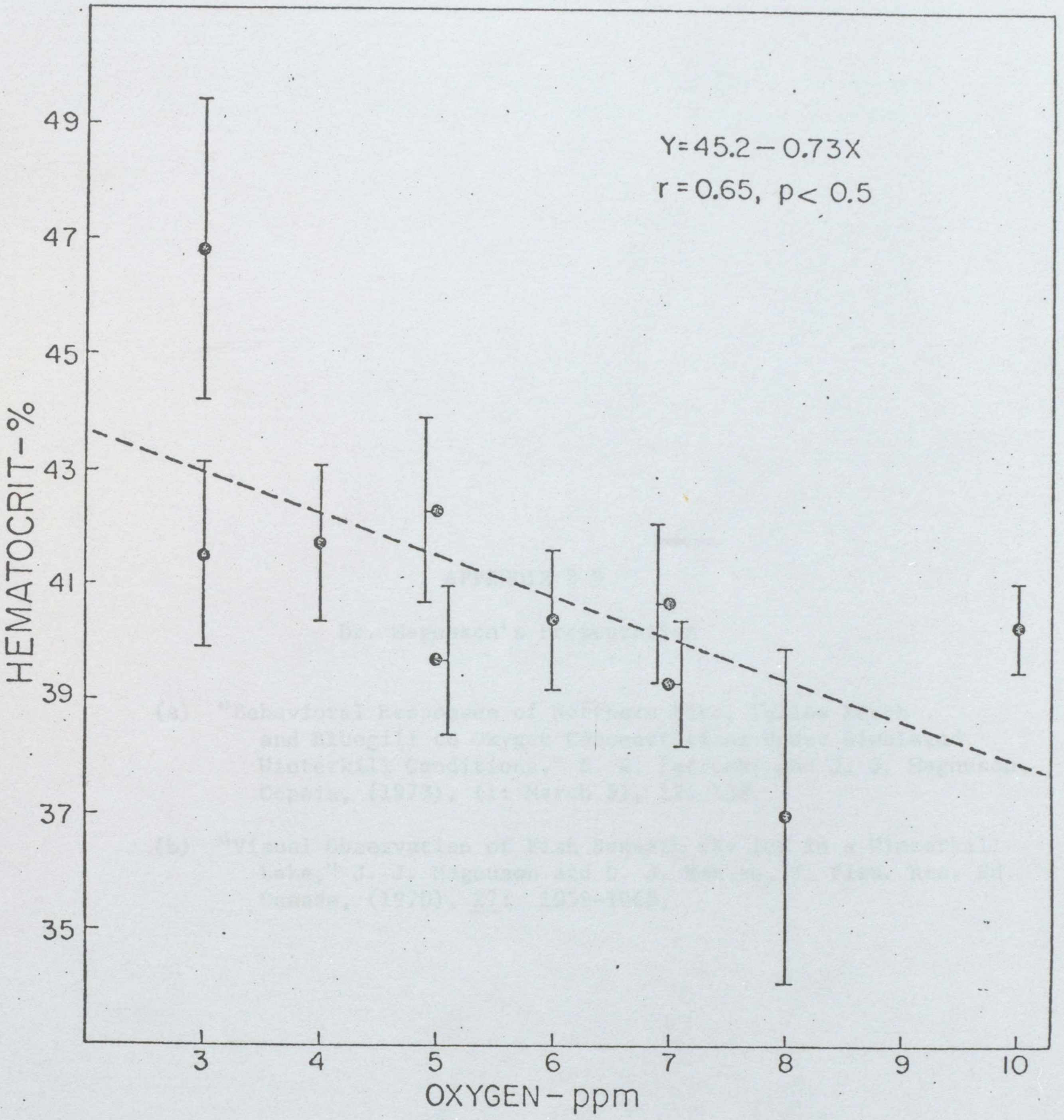


Fig. 2. Hematocrit level (mean ± 2SD, h = 10) of fingerling coho in relation to environmental oxygen concentration. The regressed line (Y = hematocrit level; X = ppm O_2) has a correlation coefficient of $r = 0.65$, $p < 0.5$. Fish were fed to satiation twice per day.

APPENDIX 2 B

Dr. Magnuson's Presentation

(a) "Behavioral Responses of Northern Pike, Yellow Perch and Bluegill to Oxygen Concentrations Under Simulated Winterkill Conditions," B. R. Petrosky and J. J. Magnuson, Copeia, (1973), (1: March 5), 124-133.

(b) "Visual Observation of Fish Beneath the Ice in a Winterkill Lake," J. J. Magnuson and D. J. Karlen, J. Fish. Res. Bd. Canada, (1970), <u>27</u>: 1059-1068.

Behavioral Responses of Northern Pike, Yellow Perch and Bluegill to Oxygen Concentrations under Simulated Winterkill Conditions

BERNARD R. PETROSKY AND JOHN J. MAGNUSON

Reprinted from COPEIA, 1973, No. 1, March 5
pp. 124–133
Made in United States of America

Behavioral Responses of Northern Pike, Yellow Perch and Bluegill to Oxygen Concentrations under Simulated Winterkill Conditions

Bernard R. Petrosky and John J. Magnuson

Northern pike (*Esox lucius*), yellow perch (*Perca flavescens*), and bluegill (*Lepomis macrochirus*), were exposed to successively lower oxygen concentrations 4.0, 2.0, 1.0, 0.5, and 0.25 mg/liter) each day for five days in aquaria sealed above with simulated "ice." Water temperature varied from 2.5 to 4.0 C and light intensity and photoperiod simulated conditions in an ice-covered lake.

Gill ventilation rates increased in response to lowered oxygen, doubling for bluegill and yellow perch but quadrupling for northern pike. Maximum ventilation rates occurred at 0.5 mg/liter D.O. for northern pike and yellow perch and at 1.0 mg/liter D.O. for bluegill. Locomotory activity was greatest at 0.25 mg/liter D.O. for northern pike but at 0.5 mg/liter D.O. for yellow perch and bluegill. Northern pike and yellow perch began to move toward the ice at 0.5 mg/liter D.O. At 1.0 mg/liter D.O., bluegill kept sinking to the bottom of the aquaria; they continually made forays upward only to sink again. Northern pike and yellow perch nosed at the under surface of the ice at the lowest oxygen concentrations while bluegill seldom did. The fish never aggregated more than 10 percent of the time even at the lowest concentrations of dissolved oxygen. Almost all northern pike and yellow perch were still alive at 0.25 mg/liter D.O. while all bluegill were dead.

Evidently northern pike are best adapted for survival in winterkill lakes and bluegill the least. The upward movement takes the fish to the highest oxygen available in the immediate vicinity. Detection of an oxygen gradient is not a requirement of this response because in the aquaria the fish move to the ice at low oxygen concentrations in absence of a gradient. High free CO_2 and dissolved H_2S are also not necessary to stimulate or orient the upward movement. Increased locomotory activity, if coupled to reduced activity when respiratory distress is alleviated, also provides an effective mechanism for locating higher oxygen. The increases in gill ventilation have obvious survival value.

FISH winterkill is common in shallow northern lakes. Respiration of the biotic community consumes oxygen that is not replaced by wind mixing or photosynthesis because ice and snow cover the lake. Concomitant with the decrease in dissolved oxygen are increases in the concentrations of toxic respiratory and decomposition products; however, inadequate dissolved oxygen is considered the principal cause of winter

TABLE 1. MEAN DISSOLVED OXYGEN (MG/LITER) IN SIX TEST AQUARIA DURING THREE EXPERIMENTAL RUNS. $\bar{x}$ = mean; S.D. = standard deviation; n = 54 per mean, 18 determinations per run.

Day	1	2	3	4	5
Nominal $D.O_2$ (mg/liter)	4.0	2.0	1.0	0.5	0.25
	Dissolved Oxygen mg/liter				
$\bar{x}$	3.95	2.08	1.05	0.54	0.24
S.D.	0.21	0.11	0.33	0.12	0.04

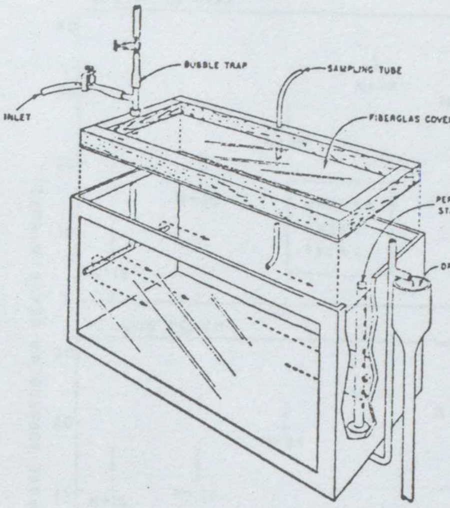


Fig. 1. Detail of test tank.

fish mortality (Greenbank, 1945; Scidmore, 1957; Johnson, 1965).

Winterkill seldom produces complete mortality in a fish population (Moore, 1942; Greenbank, 1945; Mooreman, 1957; Bennett, 1962; Johnson, 1965). While fish species differ in their tolerance of low oxygen (Moore, 1942; Cooper and Washburn, 1949; Johnson, 1965), survival is not simply a function of this tolerance. Mooreman (1957) and Bennett (1962) both concluded that nonuniform conditions within winterkill lakes allowed some individuals of less tolerant species to survive. Survival would be augmented by significant reductions in dissolved oxygen requirements or the ability to locate areas of more favorable conditions.

Purposes of the present experiments were to describe the behavioral responses of fishes to lowered dissolved oxygen under simulated winter conditions in the laboratory and to clarify the functional significance of these responses to winter survival. Data describing behavioral responses are presented, compared with previous reports, and discussed as adaptive responses to winter oxygen depletions.

MATERIALS AND METHODS

Fish held at 2.5 to 4.0 C, were subjected to successively lower dissolved oxygen concentrations on each of five days. Nominal oxygen levels were 4.0, 2.0, 1.0, 0.50, and 0.25 mg/liter. This scheme provided a series of oxygen concentrations that was regularly ordered and had an adequate range with two concentrations below 1.0 mg/liter. Mean daily oxygen concentrations are shown in Table 1.

The continuous flow of Trout Lake water to the tanks passed in series through two nitrogen gas stripping columns for control of dissolved oxygen. Nitrogen gas bubbled up from aquarium air diffusers while the water flowed down through the columns. For oxygen concentrations of 1.0 mg/liter or greater only the second column was operated. The system delivered approximately four liters of water/min.

Test tanks were molded fiberglass aquaria with glass faces and inside dimensions of 60 × 28 × 25 cm deep. A panel of white, translucent fiberglass mounted on an epoxy-covered wooden frame was inserted into the top of each aquarium to exclude the atmosphere and to simulate ice.

Inlets and drains in the test tanks were designed to prevent stratification and "dead" water areas (Fig. 1). Experiments with dyes demonstrated that good mixing occurred. Water siphoned from 4 depths including within 2 mm of the ice had average concentrations that were all within 0.03 mg/liter of each other when dissolved oxygen (D.O.) in a tank was 0.30 mg/liter. Oxygen concentrations were 0.10 to 0.15 mg/liter higher within 5 mm of the edge of the aquarium at the ice water interface. These measurements were with the modified Winkler technique described by Broenkow, W. W. and J. D. Cline, 1969. Flow rate through each aquarium was approximately 600 ml/min. Tanks were arranged in two banks of three, both facing a central observation blind. From the darkened blind the observer viewed the fish in each tank through a one-way mirror set at 45° so the fish could not see their own reflections. Black opaque curtains covered those mirrors not in use to reduce the amount of light entering the blind. Fish showed little reaction to the observer's presence.

The experimental room was at the University of Wisconsin's Trout Lake Biological Station. It was windowless and a black curtain covered the door. Incandescent bulbs mounted above each aquarium and controlled by time switches provided light. Photoperiod was 10 hours light (0830–1830 hrs.), 14 hours dark. Nine hours (0900–1800 hrs.) were at full light intensity. Illumination at the under-surface of the "ice" was 0.1 lux at "night," 35 lux during the "twilight" period and 110 lux at full light intensity. Water temperatures varied from 2.5 to 4.0 C. Free carbon dioxide varied from 0.0 to 2.5 mg/liter. The higher carbon dioxide concentrations occurred at higher oxygen levels (less nitrogen stripping).

Northern pike (*Esox lucius*), 19–38 cm total length; yellow perch (*Perca flavescens*), 14–21 cm T.L.; and bluegill (*Lepomis macrochirus*), 14–19 cm T.L. were selected for these experiments. The fish were collected from lakes in Vilas Co., Wisconsin during September, 1969 and were held in a pond. Intermittently from 29 December 1969 to 28 February 1970 the fish were recaptured and transferred to 300 liter holding aquaria. These aquaria were supplied with flowing water from Trout Lake at 2 to 3 C with 10 to 13 mg/liter dissolved oxygen. Large exterior windows in the holding room provided prevailing late winter photoperiods. Fish were held in the laboratory for at least 3 weeks and were used in experiments only once.

Three experiments were conducted between 27 February and 27 March 1970. In each, 12 fish were observed.

Northern pike and yellow perch were observed in the first experiment, northern pike and bluegill in the second, and yellow perch and bluegill in the third. Fish were assigned randomly to the six test aquaria with the restriction that a large and a small fish of the same species were placed in each of three aquaria. The size difference facilitated individual recognition. Fish were introduced at about 2200 hours on the day preceding an experiment. At that time the oxygen content of the incoming water was set to 4.0 mg/liter.

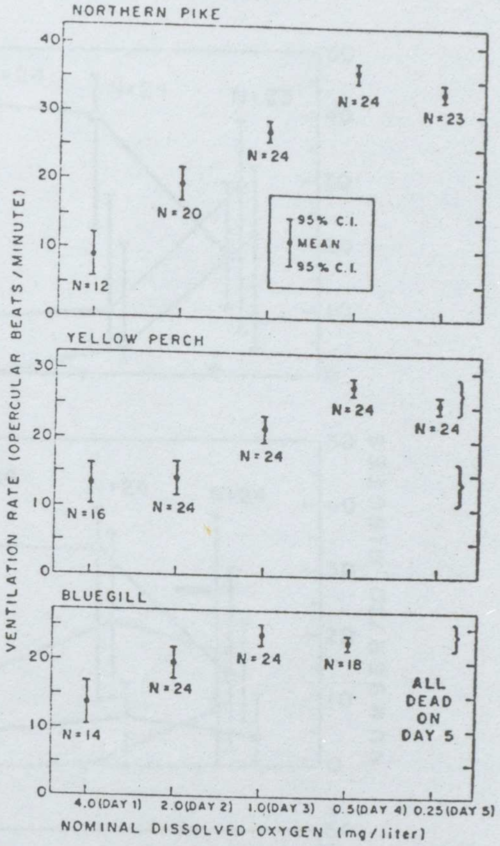


Fig. 2. Mean ventilation rates of northern pike, yellow perch, and bluegill at dissolved oxygen concentrations from 4.0 to 0.25 mg/liter. Vertical brackets on the right enclose means not significantly different ($p \leq 0.05$) by Kramer's (1956) extension of Duncan's multiple range test.

Dissolved oxygen samples were siphoned from the tanks, and water temperatures were measured at 0830, 1300 and 1800 hrs. Oxygen was measured by Winkler titration (azide modification) or with a direct reading oxygen meter (YSI model 5420) standardized against Winkler determinations. At 1800 hrs. free CO_2 in each tank was measured by titration with sodium carbonate.

Behavior observations were made on all fish twice daily. Between 0900 and 1300 hrs. each fish was watched ten minutes and its behavior recorded. Ventilation rates were also counted over a one minute interval for each fish. These observations were repeated between 1400 and 1800 hrs. At 2100 hrs. the nitrogen stripping columns were set to the next day's oxygen level.

Kramer's (1956) extension of Duncan's multiple range test was used to evaluate the

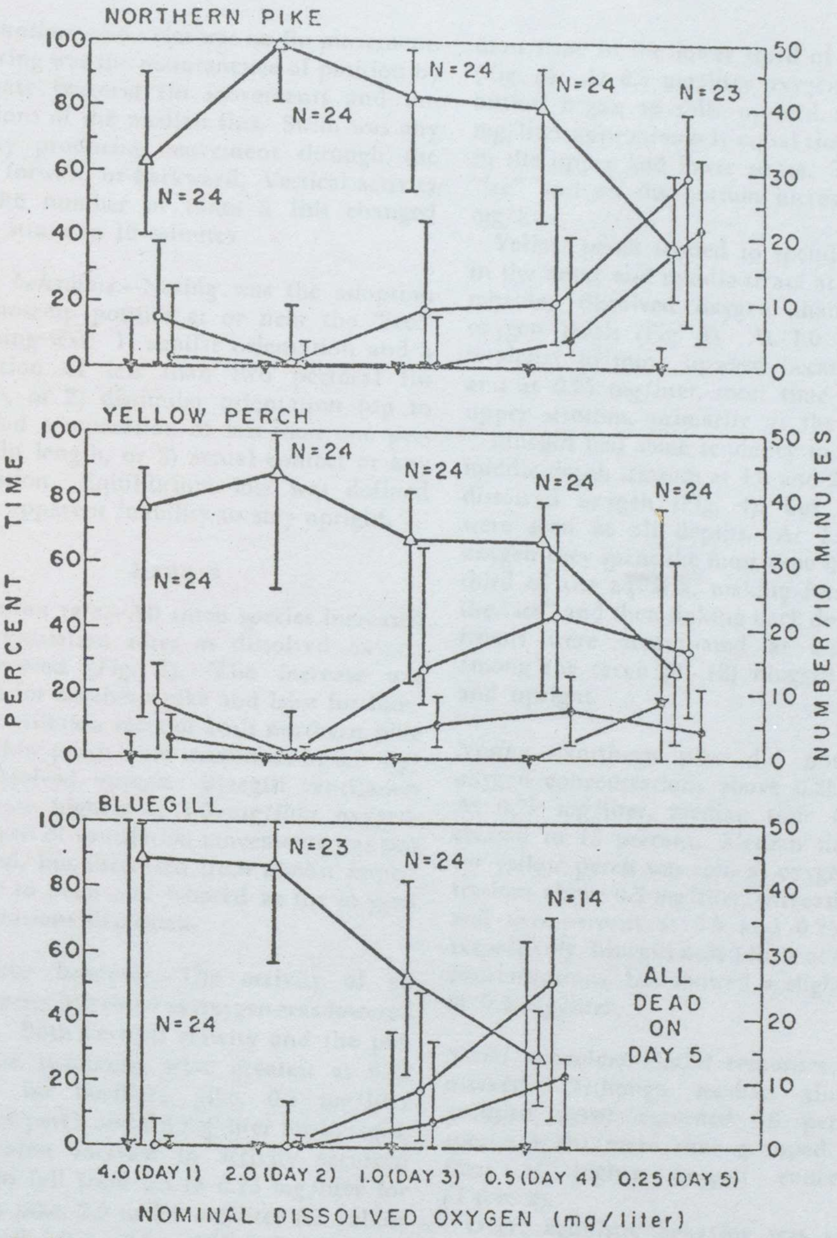


Fig. 3. Medians and quartiles of locomotor activity of northern pike, yellow perch, and bluegill at dissolved oxygen concentrations from 4.0 to 0.25 mg/liter. Medians are for the 10 min observations. The number near each group of medians is the number of 10 min observations included in the medians. △ percent time hover, ○ percent time swim, ⊙ vertical activity-number of depth stratum changes, ▽ percent time no-swim.

significance of differences in mean ventilation rate at the different oxygen levels. Other behavioral data were described by medians and quartiles because the distributions were not normal. After equilibrium loss was continuous, observations other than ventilation rate and equilibrium loss were excluded from results. The analysis did not include values for fish after they had died.

Depth distribution.—Horizontal lines divided each tank into three equal depth strata. Occupation of a stratum was based on the position of the fish's eye. We also recorded contact with either "ice" or bottom.

Locomotion.—No-swim was no fin movement. Hovering was the maintanence of position by alternate pectoral fin movements and undulations of the median fins. Swim was any activity producing movement through the water forward or backward. Vertical activity was the number of times a fish changed depth strata in 10 minutes.

Other behaviors.—Nosing was the adoption of a nose-up posture at or near the "ice." Grouping was: 1) similar orientation and a separation of less than two pectoral fin lengths, or 2) dissimilar orientation (up to 45°) and a separation of less than one pectoral fin length, or 3) actual contact at any orientation. Equilibrium loss was defined by the apparent inability to stay upright.

Results

Ventilation rate.—All three species increased their ventilation rates as dissolved oxygen was lowered (Fig. 2). The increase was greatest for northern pike and least for bluegill. Ventilation rates of both northern pike and yellow perch were maximum at 0.5 mg/liter dissolved oxygen. Bluegill ventilation rates were highest at 1.0 mg/liter oxygen. The depth of ventilation movements was not measured, but increased from almost imperceptible to deep and labored as the oxygen concentrations decreased.

Locomotor behavior.—The activity of all three species increased as oxygen was lowered (Fig. 3). Both vertical activity and the percent time swimming were greatest at 0.25 mg/liter for northern pike, 0.5 mg/liter for yellow perch and 0.5 mg/liter for bluegill. The greatest increase in activity occurred as oxygen fell from 0.5 to 0.25 mg/liter for northern pike, 2.0 to 1.0 mg/liter for yellow perch, and 1.0 to 0.5 mg/liter for bluegill. The percent time "no-swim" was low at all oxygen concentrations and the percent time hovering declined as swimming activity increased (Fig. 3). Northern pike and yellow perch spent most of their time hovering at all oxygen concentrations greater than 0.25 mg/liter. Bluegill spent most of their time hovering at all oxygen concentrations greater than 0.5 mg/liter.

Depth distribution.—At higher oxygen levels, 4.0 to 1.0 mg/liter, northern pike spent the most time in the lower third of the aquaria (Fig. 4). At 0.5 mg/liter oxygen, the distribution began to shift upward and at 0.25 mg/liter approximately equal time was spent in the upper and lower strata. Time at the "ice" and on the bottom increased at 0.25 mg/liter.

Yellow perch tended to spend more time in the lower and middle strata at 4.0 and 2.0 mg/liter dissolved oxygen than at lower oxygen levels (Fig. 4). At 1.0 mg/liter, a tendency to move upward became evident, and at 0.25 mg/liter, most time was in the upper stratum, primarily at the "ice."

Bluegill had some tendency to occupy the middle depth stratum at 4.0 and 2.0 mg/liter dissolved oxygen (Fig. 4), but individuals were seen at all depths. At 1.0 mg/liter oxygen they spent the most time in the lower third of the aquaria, making forays toward the "ice" and then sinking back down. These trends were accentuated at 0.5 mg/liter among the seven (of 12) bluegill still alive and upright.

Nosing.—Northern pike did not nose at oxygen concentrations above 0.25 mg/liter. At 0.25 mg/liter, median time nosing increased to 13 percent. Median time nosing for yellow perch was zero at oxygen concentrations above 0.5 mg/liter, increasing to one and two percent at 0.5 and 0.25 mg/liter respectively. Bluegill nosed little at all oxygen concentrations, but showed a slight increase at 0.5 mg/liter.

Social behaviors.—Social responses were not marked. Although median time spent grouped never exceeded 10 percent, all species spent more time grouped at lower than at higher oxygen concentrations (Table 2).

Overt agonistic behavior was seen only once and involved a threat by a yellow perch toward its larger tank-mate. Although fin postures were not regularly recorded, the larger fish in each pair of yellow perch and bluegill tended to hold its dorsal fin more fully erect. At lower oxygen levels the large and small fish behaved more similarly. At oxygen concentrations below 1.0 mg/liter both large and small yellow perch usually extended their fins. At oxygen concentrations below 2.0 mg/liter both large and small bluegill tended to appress their fins.

At 4, 2, and 1 mg/liter dissolved oxygen

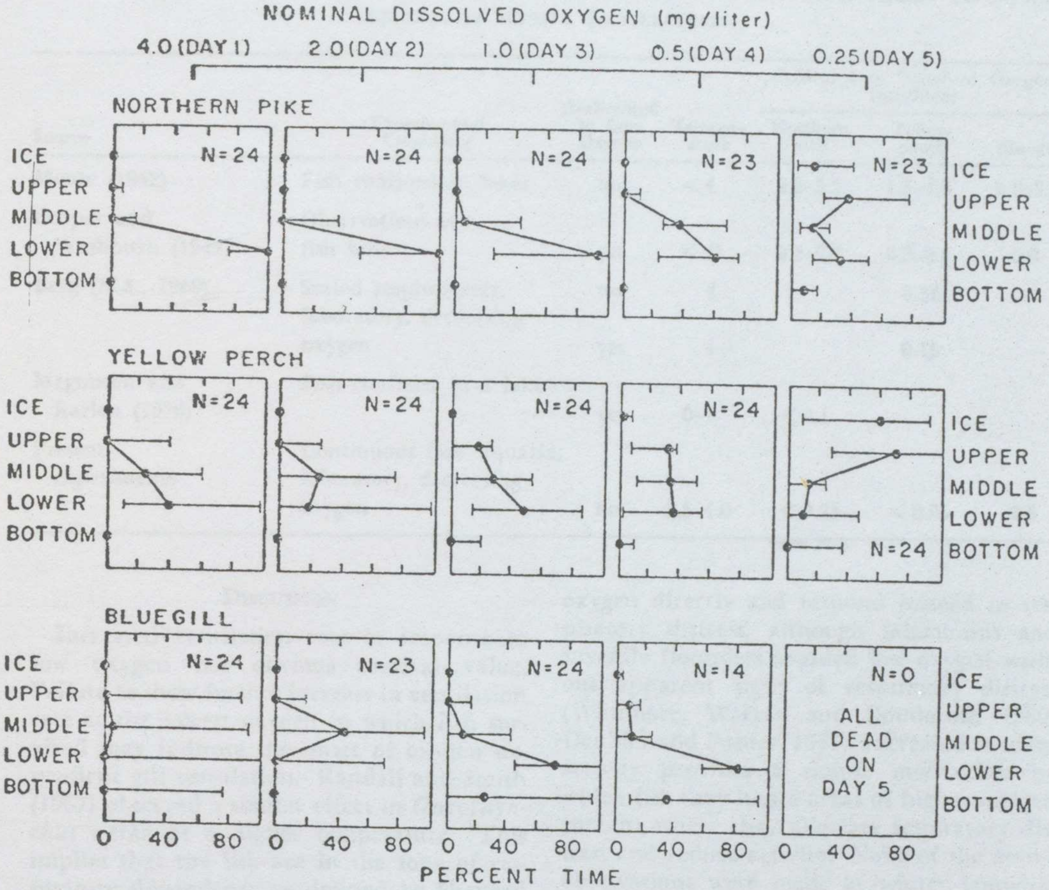


Fig. 4. Percent times (medians and quartiles) spent at various depths by northern pike, yellow perch, and bluegill at dissolved oxygen concentrations from 4.0 to 0.25 mg/liter. Time in the upper stratum includes time at the "ice" and time in the lower stratum includes time on the bottom. N = number of 10 min observations included in each distribution.

northern pike usually hovered near the tank bottom, oriented at right angles to one another, tail to tail, facing the front glass.

Equilibrium loss.—Only one northern pike lost equilibrium completely. One yellow perch lost equilibrium for a brief period. Bluegills all exhibited equilibrium loss before death and all had died by the time oxygen concentration reached 0.25 mg/liter. They typically spent several hours lying on their sides before respiratory movements ceased and were negatively bouyant.

Low oxygen tolerance.—Low oxygen tolerance in our experiments may be compared with data from the literature (Table 3). Only one northern pike and none of yellow perch died. All bluegill died before the observations at 0.25 mg/liter oxygen were made. About half of them died before the observations at 0.5 mg/liter were completed. Our estimates of low oxygen tolerance are as low as or lower than the others.

Table 2. Median Percent Time Spent Grouped in the 10 Min Observations by Northern Pike, Yellow Perch, and Bluegill at Dissolved Oxygen Concentration from 4.0 to 0.25 mg/liter. Number of 10 min observations in median is 23 or 24 except for bluegill at 0.5 mg/liter where n = 14.

Nominal dissolved oxygen (mg/liter)	4.0	2.0	1.0	0.5	0.25
	Percent Time Grouped				
Northern pike	1.8	0.0	0.0	1.8	9.4
Yellow perch	0.6	0.0	2.0	8.9	5.9
Bluegill	0.0	0.0	3.8	2.6	Dead

TABLE 3. LETHAL CONCENTRATIONS OF DISSOLVED OXYGEN FOR NORTHERN PIKE, YELLOW PERCH, AND BLUEGILL AT WINTER TEMPERATURES.

Source	Experimental Conditions	Acclimated to Low Oxygen	Temperature	Critical Low Dissolved Oxygen (mg/liter)		
				Northern pike	Yellow perch	Bluegill
Moore (1942)	Fish confined in lakes	no	<4	2.3–3.2	1.5–4.8	0.8–3.6
Cooper and Washburn (1949)	Observations of fish kills	yes	<4?	0.3–0.4	0.3–0.4	0.6
Berg (M.S., 1969)	Sealed respirometer, laboratory, decreasing oxygen	no	4		0.38	
		yes	4		0.15	
Magnuson and Karlen (1970)	Fish confined in a lake	yes	0–1	<0.1		
Present experiments	Continuous flow aquaria, laboratory, decreasing oxygen	no	2.5–4.0	<0.25	<0.25	0.5

DISCUSSION

Increased ventilation rate in response to low oxygen has obvious survival value. Failure to show further increase in ventilation rate at the lowest oxygen in which fish survived may indicate the onset of oxygen dependent gill ventilation. Randall and Smith (1967) observed a similar effect in *Oncorhynchus nerka* at a higher temperature. This implies that the fish are in the zone of respiratory dependence as defined by Shepard (1955) and are probably near the incipient lethal level. The earlier ventilation rate peak and subsequent earlier death of the bluegill support this interpretation.

Because the aquaria were so small, the locomotor activity of the fish may have been altered. On many occasions, horizontal movement was transformed into vertical, but much vertical activity seemed voluntary and may correspond to the sounding of northern pike and perch seen by Magnuson and Karlen (1970). The lowered activity of yellow perch below 0.5 mg/liter may be a result of oxygen limitation.

Increases in swimming activity in response to lowered oxygen have been described for various fish species by Shelford and Allee (1913), Jones (1952), Shepard (1955), Alabaster and Robertson (1961), Hoglund (1961) and Hill (1968). The consensus of these authors is that increased activity is random and undirected appetitive behavior. Apparently, fish are unable to sense dissolved oxygen directly and respond instead to respiratory distress, although salamonids and juvenile flounders avoided low oxygen without apparent signs of respiratory distress (Whitmore, Warren and Doudoroff, 1960; Deubler and Posner, 1963). Increased random activity provides a simple mechanism by which fish may locate areas of higher oxygen content where they alleviate respiratory distress and reduce activity. None of the above observations were made at winter temperatures, but Johnson and Moyle (1969) noted increasing fish activity as conditions deteriorated in a winterkill lake.

Movement upward in response to low oxygen has been reported for a number of different fishes and is usually associated in some way with the nosing activity discussed below (Shelford and Allee, 1913; Shepard, 1955; Hoglund, 1961; Lowe, Hinds and Halpern, 1967; Lewis, 1970; Magnuson and Karlen, 1970; and Scherer, 1971). Evidently upward movement is a response released by low oxygen, but oriented by other environmental parameters (such as light, gravity or pressure). The response is clearly adaptive because in natural situations of oxygen depletion, upper waters (even in ice covered lakes) contain more dissolved oxygen. If fish are unable to sense dissolved oxygen directly, this response allows immediate movement toward water with more oxygen without a slow process of random search.

The absence of vertical gradients may have altered laboratory responses compared with field conditions where these gradients do occur. If the fish in the aquaria had found higher oxygen levels near the "ice," they might have consummated appetitive behavior or been reinforced in the tendency to move upward.

Nosing is part of the vertical response described above and functions as an adaptation to utilize thin layers of oxygenated water occurring at the interface with the atmosphere (Lowe et al., 1967; Dorfman and Westman, 1970, Lewis, 1970) or ice (Magnuson and Karlen, 1970). Ability to use these thin layers effectively is determined in part by head and mouth morphology (Lowe et al., 1967; Lewis, 1970). The northern pike's long flat snout is well adapted to this function. The bluegill, with its small mouth and high "forehead" is poorly suited for nosing, while the yellow perch's morphology is intermediate. Head shape probably was important in the longer survival of northern pike reported by Magnuson and Karlen (1970). Like movement to the surface, nosing seems to be released (but not directed) by low dissolved oxygen since it occurred in the absence of a vertical gradient. Some individuals of all three species occasionally nosed at the edge of the aquarium and may have obtained water with oxygen concentrations 0.1 mg/liter greater than elsewhere beneath the ice. Only a small portion of the time nosing was spent at the edge.

Social behavior does not seem to be an important factor in the winter survival of these fishes. Large aggregations of fish reported in streams (Cooper and Washburn, 1949) or open holes in the ice (Greenbank, 1945) probably result from individual fish responding independently to the abiotic environment. Possibly if some individuals had found more favorable conditions, others could benefit by approaching them. In the examples cited, however, the large masses of fish caused local oxygen depletions.

In bluegill, fin erection has a function in dominance display (Miller, 1963). Normally two buegill in a small area exhibit frequent agonistic behavior. Breder and Nigrelli (1935) reported schooling of redbreast sunfish (*Lepomis auritus*) only at low temperatures. Perhaps the absence of overt agonistic behavior in our experiments was a result of low temperatures. Furthermore, it has been shown that fish will abandon certain nonessential activities when stressed. When placed under oxygen stress, Atlantic salmon parr ceased territorial defense (Hoglund, 1961) and walleye abandoned their normal negative phototaxis (Scherer, 1971). The changes we observed in yellow perch and bluegill fin postures and in northern pike orientation may represent analogous responses.

Although equilibrium loss represents an early stage in death, a fish may survive in this state for a number of hours and even recover if conditions improve. In a winterkill situation, equilibrium loss must be fatal if a fish becomes negatively buoyant (as the bluegill did) and sinks into the anoxic bottom waters. If a fish floats unconscious near the ice where oxygen concentrations are highest as the single northern pike did, an increase in dissolved oxygen might allow it to recover.

The differences in low oxygen tolerance seen in Table 3 are largely explicable by different techniques, conditions, and criteria for critical concentrations. Moore's (1942) higher estimates probably resulted from his use of unacclimated fish. In our experiments and Berg's (1969) experiments with unacclimated fish, the fish may have acquired partial acclimation during their exposure to lowered oxygen, but they cannot be considered fully acclimated. Low carbon dioxide concentrations in the aquaria may have contributed to the low estimates we obtained.

Behavior and survival.—The results of our experiments and the literature we reveiwed suggest that fish have two responses to low oxygen which enable them to locate higher oxygen concentrations. Although fish apparently can not sense dissolved oxygen directly they respond to respiratory distress with upward movement and increased locomotor activity. Upward movement takes the fish to the highest oxygen available in the immediate vicinity since surface waters usually contain more oxygen. Increased locomotor activity when coupled to reduced activity upon alleviation of respiratory distress, provides an effective mechanism for locating higher oxygen without a gradient response. In addition, increases in gill ventilation have obvious survival value in low oxygen environments.

The observed behavioral responses of northern pike were most adaptive for survival under simulated winterkill conditions, those of yellow perch were intermediate, and the behavior of bluegill was least adaptive. This same general conclusion was reached in preliminary field observations on the same species (Magnuson and Karlen, 1970) but the behavior of the species differed somewhat in the laboratory and the field.

Northern pike, yellow perch and bluegill respond to lowered dissolved oxygen, under winter conditions, by modifying their behavior. Because these behavioral changes occur at above-lethal oxygen concentrations, they provide more sensitive indicators of low oxygen stress than equilibrium loss or death. Presumably these behavioral responses occur above lethal oxygen concentrations because they have an adaptive function and because at lower, near-lethal levels, fish activity becomes oxygen limited.

ACKNOWLEDGMENTS

We thank James Herbert and Ann Neidermeier for their help in collecting and analyzing data, and William M. Lewis, Jr., Indiana University, and John G. Hale, U. S. Environmental Protection Agency, for their critical review of the manuscript. We also thank Arthur D. Hasler, William R. Schmitz, and Robert Brocks, University of Wisconsin, for facilitating our research at the Trout Lake Station. The assistance of the Wisconsin Department of Natural Resources at Woodruff, in the collecting and storing of fishes, was greatly appreciated. Support for this research was from Grant No. GB 18272, National Science Foundation and a Federal Water Quality Traineeship.

LITERATURE CITED

Alabaster, J. S., and K. G. Robertson. 1961. Effect of diurnal changes in temperature, dissolved oxygen, and illumination on the behaviour of roach (*Rutilus rutilus* L.), bream (*Abramis brama* L.), and perch (*Perca fluviatilus* L.). Anim. Behav. 9:187–192.

Bennett, G. W. 1962. Management of artificial lakes and ponds. Reinhold Publ. Corp., New York.

Berg, R. J. 1969. Low oxygen tolerance by yellow perch (*Perca flavescens*) from winterkill and non-winterkill lakes. M. S. Thesis, Univ. of Wisconsin, Madison.

Breder, C. M., Jr., and R. F. Nigrelli. 1935. The influence of temperature and other factors on the winter aggregations of the sunfish, *Lepomis auritus*, with critical remarks on the social behavior of fishes. Ecology 16:33–47.

Broenkow, W. W., and J. D. Cline. 1969. Colorimetric determination of dissolved oxygen at low concentrations. Limnol. Oceanog. 14: 450–454.

Cooper, G. P., and G. N. Washburn. 1949. Relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Trans. Amer. Fish. Soc. 76:23–33.

Deubler, E. E., Jr., and G. S. Posner. 1963. Response of post-larval flounders, *Paralichthys lethostigma*, to water of low oxygen concentrations. Copeia 1963:312–317.

Dorfman, D., and J. Westman. 1970. Responses of some anadromous fishes to varied oxygen concentrations and increased temperatures. Partial Completion Rept., OWRR Proj. No. B-012-N.J.

Greenbank, J. 1945. Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. Ecol. Monogr. 15:343–392.

Hill, L. G. 1968. Oxygen preference in the spring cavefish, *Chologaster agassizi*. Trans. Amer. Fish. Soc. 97:448–454.

Hoglund, L. B. 1961. The reactions of fish in concentration gradients. Fish. Bd. Sweden, Inst. Freshwater Res., Rept. No. 43.

Johnson, F. H., and J. B. Moyle. 1969. Management of a large shallow winterkill lake in Minnesota for the production of pike (*Esox lucius*). Trans. Am. Fish. Soc. 98:691–697.

Johnson, M. G. 1965. Limnology of Ontario ponds in relation to winterkill of largemouth bass. Prog. Fish. Cult. 27:193–198.

Jones, J. R. E. 1952. The reactions of fish to water of low oxygen concentration. J. Exp. Biol. 29:403–415.

Kramer, C. Y. 1956. Extension of multiple range tests to group means with unequal numbers of replications. Biometrics 12:307–310.

Lewis, W. M., Jr. 1970. Morphological adaptations of cyprinodontoids for inhabiting oxygen deficient waters. Copeia 1970:319–326.

Lowe, C. H., D. S. Hinds and E. A. Halpern. 1967. Experimental catastrophic selection and tolerances to low oxygen concentrations in native Arizona freshwater fishes. Ecology 48: 1013–1017.

Magnuson, J. J., and D. J. Karlen. 1970. Visual observation of fish beneath the ice in a winterkill lake. J. Fish. Res. Bd. Canada 27:1059–1068.

Miller, H. C. 1963. The behavior of the pumpkinseed sunfish, *Lepomis gibbosus* (Linnaeus), with notes on the behavior of other species of *Lepomis* and the pigmy sunfish, *Elassoma evergladei*. Behaviour 21:88–151.

Moore, W. G. 1942. Field studies on the oxygen requirements of certain freshwater fishes. Ecology 23:319–329.

Mooreman, R. B. 1957. Some factors related to the success of fish populations in Iowa farm ponds. Trans. Amer. Fish. Soc. 86:361–370.

Randall, D. J., and L. S. Smith. 1967. The effects of environmental factors on circulation and respiration in teleost fish. Hydrobiology 29:113–124.

Scherer, E. 1971. Effects of oxygen depletion and carbon dioxide buildup on the photic behavior of the walleye (*Stizostedion vitreum vitreum*). J. Fish. Res. Bd. Canada 28:1303–1307.

Scidmore, W. J. 1957. An investigation of carbon dioxide, ammonia, and hydrogen sulfide as factors contributing to fish kills in ice-covered lakes. Prog. Fish Cult. 19:124–127.

SHELFORD, V. E., AND W. C. ALLEE. 1913. The reactions of fish to gradients of dissolved atmospheric gases. J. Exp. Zool. 14:207–266.

SHEPARD, M. P. 1955. Resistance and tolerance of young speckled trout (*Salvelinus fontinalis*) to oxygen lack, with special reference to low oxygen acclimation. J. Fish. Res. Bd. Canada 12:387–446.

WHITMORE, C. M., C. E. WARREN AND P. DOUDOROFF. 1960. Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. Trans. Am. Fish. Soc. 89:17-

BERNARD R. PETROSKY, ICHTHYOLOGICAL ASSOCIATES, R.D. #2, BOX 35, MIDDLETOWN, DELAWARE, 19709 AND JOHN J. MAGNUSON, LABORATORY OF LIMNOLOGY, UNIVERSITY OF WISCONSIN, MADISON, WISCONSIN 53706.

Visual Observation of Fish Beneath the Ice in a Winterkill Lake

JOHN J. MAGNUSON AND DUANE J. KARLEN

Laboratory of Limnology, Department of Zoology
University of Wisconsin, Madison, Wis. 53706, USA

MAGNUSON, J. J., AND D. J. KARLEN. 1970. Visual observation of fish beneath the ice in a winterkill lake. J. Fish. Res. Bd. Canada 27: 1059–1068.

A device is described to directly observe fish behavior beneath the ice of a shallow lake. The viewing device, a 1.9-m tall plexiglass tube (14.0 cm inside diameter) sealed at the bottom, worked on the principle of a periscope. It was frozen into place in the center of a net enclosure. A man in a darkened hut lowered a mirror into the tube to observe the fish in the enclosure.

Vertical distributions and behavior of 5 adult northern pike (*Esox lucius*), 6 yellow perch (*Perca flavescens*), and 13 bluegill (*Lepomis macrochirus*) were compared with the levels of dissolved oxygen, free carbon dioxide, hydrogen sulfide, and water temperature. Observations in Mystery Lake, Wisconsin, were from December 29, 1968, through January 30, 1969, during a period when environmental conditions worsened beneath the ice and resulted in a winterkill.

Yellow perch were the most active, northern pike the least. Bluegill remained farther beneath the ice than did the other two species. Northern pike took up residence in domes that they formed in the undersurface of the ice. Northern pike and yellow perch frequently sounded into the anoxic layers.

We conclude that differences in fish behavior were significant in prolonging survival. A combination of little locomotory activity and a position immediately beneath the ice apparently favored the longer survival of northern pike over bluegill and yellow perch.

Received December 16, 1969

INTRODUCTION

THE WINTER ENVIRONMENT of shallow northern lakes can be lethal to fishes because oxygen is depleted during periods of snow cover and is not necessarily replaced by photosynthetic activity (Greenbank, 1945). Even with the low oxygen concentration, some fish usually survive. According to Cooper and Washburn (1949) some survived in a lake containing no more than 0.2 mg/liter dissolved oxygen. In 31 winterkills cited by Moorman (1957) largemouth bass (*Micropterus salmoides*) were eliminated but bluegill (*Lepomis macrochirus*) survived; in two other cases the reverse was true. Moorman and also Bennett (1962) believed that differential survival was due in part to nonuniform distributions of adverse conditions and the presence of some fishes in more favorable areas. When conditions became severe, many fish were observed to move into an inlet that had higher oxygen concentrations than the lake (Cooper and Washburn, 1949). A position near the ice would also favor survival in a winterkill lake because oxygen depletion begins at the lake bottom and moves up as winter progresses.

Printed in Canada (J1677)

The present paper describes the design of and first experiences with a device used to observe fishes directly in a lake with severe winter oxygen depletion. The device was used to observe behavior that may favor winter survival. Vertical distributions of yellow perch (*Perca flavescens*), northern pike (*Esox lucius*), and bluegill are reported in relation to that of dissolved oxygen and hydrogen sulfide, free carbon dioxide, and water temperature. Qualitative data are also presented on the locomotor activity, aggregation, and behavior of the three species beneath the ice.

METHODS

DESCRIPTION OF VIEWING DEVICE, NET ENCLOSURES, AND OBSERVATION HUT

Viewing devices (Fig. 1), working on the principle of a periscope, were inserted through a hole in the ice and allowed to freeze in place. From a darkened hut, observations were made of fishes enclosed in a net that kept them close enough to be seen.

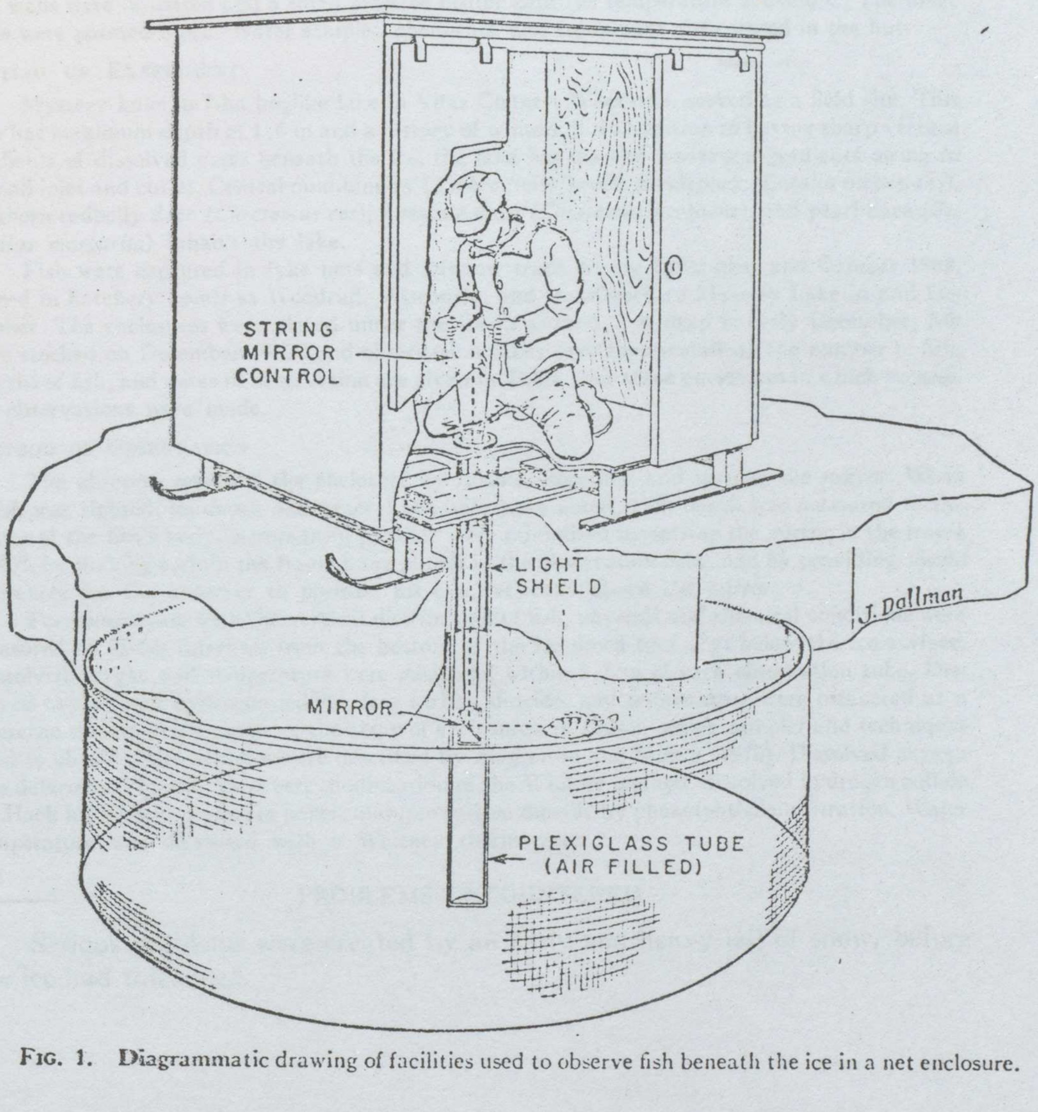


FIG. 1. Diagrammatic drawing of facilities used to observe fish beneath the ice in a net enclosure.

The devices were 1.9-m long plexiglass tubes sealed at the bottom (15.2 cm outside diameter and 14.0 cm inside diameter). The coefficient of expansion of plexiglass is approximately the same as that of ice. None of the tubes broke owing to expansion and contraction of the ice, even when the ice cracked.

To prevent the air-filled tubes from rising owing to buoyancy, each was weighted with cement blocks placed on boards through which the upper 10 cm of the tubes protruded. Styrofoam caps on the tubes kept out snow and insulated the enclosed air.

An elliptical mirror at 45° from the vertical was fastened on a frame made from a cutaway cylinder of plexiglass that fitted into the observation tube. The mirror was raised, lowered, and turned by manipulating two strings tied to the frame. A cylindrical light shield pushed into a tube during observation blocked light coming from the ice and from the space between the ice and the hut floor. This reduced glare and made it easier for the observer to become dark-adapted.

Cylindrical net enclosures, 3 m in diameter, 1.5 m deep, and open at the top, kept fish close enough to observe from the central tube. A ring of 1.9-cm diameter black polyethylene pipe attached to the top of the net froze in the ice and made the enclosure secure. A ring of fiberglass weighted the bottom edge of the net and kept it circular. The netting was 1.3-cm bar nylon treated with tar.

The aluminum observation hut mounted on wooden skis weighed 130 kg. It could be pulled by one man on clear ice, but three or four men were needed to move it through 20 cm of wet snow. The walls were insulated and a small propane heater kept the temperature above 0 C. The inner walls were painted black. Water samples, chemicals, and equipment were stored in the hut.

SETTING UP EXPERIMENT

Mystery Lake, a 7-ha boglike lake in Vilas County, Wisconsin, served as a field site. This lake has maximum depth of 1.6 m and a history of winterkill. In addition to having sharp vertical gradients of dissolved gases beneath the ice, the lake has marked horizontal gradients owing to a small inlet and outlet. Central mudminnow (*Umbra limi*), brook stickleback (*Eucalia inconstans*), northern redbelly dace (*Chrosomus eos*), finescale dace (*Chrosomus neogaeus*), and pearl dace (*Semotilus margarita*) inhabit the lake.

Fish were captured in fyke nets and minnow traps during September and October 1968, placed in hatchery ponds at Woodruff, Wisconsin, and transferred to Mystery Lake in mid-December. The enclosures were placed under the ice in water 1.5 m deep in early December; fish were stocked on December 19–20 and observation tubes were then installed. The number of fish, lengths of fish, and dates of observation are given in Table 1 for those enclosures in which successful observations were made.

METHOD OF OBSERVATION

The observer searched the enclosure by raising, lowering, and turning the mirror. When a fish was sighted, its depth and general behavior were noted. Fish depth was measured to the center of the fish's body. Errors from parallax were minimized by setting the mirror in the frame at 45°, by making certain the frame hung plumb in the observation tube, and by providing visual references for the observer to position his eye vertically above the mirror.

For comparison with the vertical distribution of fish, physical and chemical conditions were measured at 25-cm intervals from the bottom of the ice down to 1.5 m below the ice surface. Dissolved oxygen and temperature were measured within 2.5 m of each observation tube. Dissolved oxygen and hydrogen sulfide, free carbon dioxide, and temperature were measured at a reference station in the center of the array of enclosures. A siphon water sampler and techniques used to obtain water samples were described by Magnuson and Stuntz (1970). Dissolved oxygen was determined by the Alsterberg modification of the Winkler method, dissolved hydrogen sulfide by Hach kit with lead acetate paper, and free carbon dioxide by phenolphthalein titration. Water temperature was measured with a Whitney thermometer.

PROBLEMS ENCOUNTERED

Serious problems were created by an early and heavy fall of snow, before the ice had thickened.

TABLE 1. Numbers and total lengths of fish placed in enclosures, number later observed in the enclosure, and dates of observations. Nets in which no successful observations were made are not shown.

		Fish length (*cm*)		No. in enclosure		Dates of successful observation			
Species	Enclosure	Median	Range	Stocked	Observed	Dec. 25–Jan. 2	Jan. 11–19	Jan. 25–26	Jan. 30
Northern pike	I	40	36–54	5	3	×	×	×	×
Northern pike	II	44	41–53	5	2	×	×	None seen	
Bluegill	III	16	14–18	10	6	×	×	"	
"	IV	16	15–17	10	5	×	×	"	
"	V	17	15–17	10	2+		×	×	
Yellow perch	VI	13	9–20	10	2	×	×	×	Dead
"	VII	12	10–15	10	1	×	None seen		
"	VIII	16.5	12–19	10	1	–	×	–	
"	IX	11	9–16	10	2	×	–	–	

Early snows resulted in a depletion of dissolved oxygen sooner than had been anticipated and no observations were obtained prior to the establishment of sharp vertical gradients of dissolved gases. The early snows insulated the lake from further freezing, and the top ring of the nets did not freeze securely into the ice as soon as anticipated. Many fish escaped from the nets before the seal was complete.

Heavy snow and frozen slush on top of the clear ice reduced light to a level that made under-ice observations difficult and even impossible. This was countered by clearing the snow from above each enclosure and in severe cases, drilling holes part way through the ice. The stained water also hampered good visibility. It usually took at least an hour to obtain six fish-depth estimates. Although snow removal may have changed the rate of oxygen depletion beneath the ice, the study area became anoxic by late January. Under the poorest conditions on January 18, the ice was covered with 13 cm of water, 8 cm of slush, and 7 cm of snow. This flooding filled the observation tubes with water. Each tube had to be removed from the ice several times during the winter, emptied, dried, and reset.

Deposits, algae growths, and gas bubbles formed on the outside of the observation tubes especially at the boundary between oxygenated and anoxic water. These obstructions to good viewing were removed by forcing the tubes up and down in their holes. The deposits were scraped off by the ice.

VERTICAL DISTRIBUTION OF ENVIRONMENTAL CONDITIONS

Vertical distributions of dissolved oxygen, dissolved hydrogen sulfide, free carbon dioxide, and water temperature at the reference station provided a graphic picture of the changes that occurred in the study area (Fig. 2). The environment deteriorated rapidly for fish during mid-December when

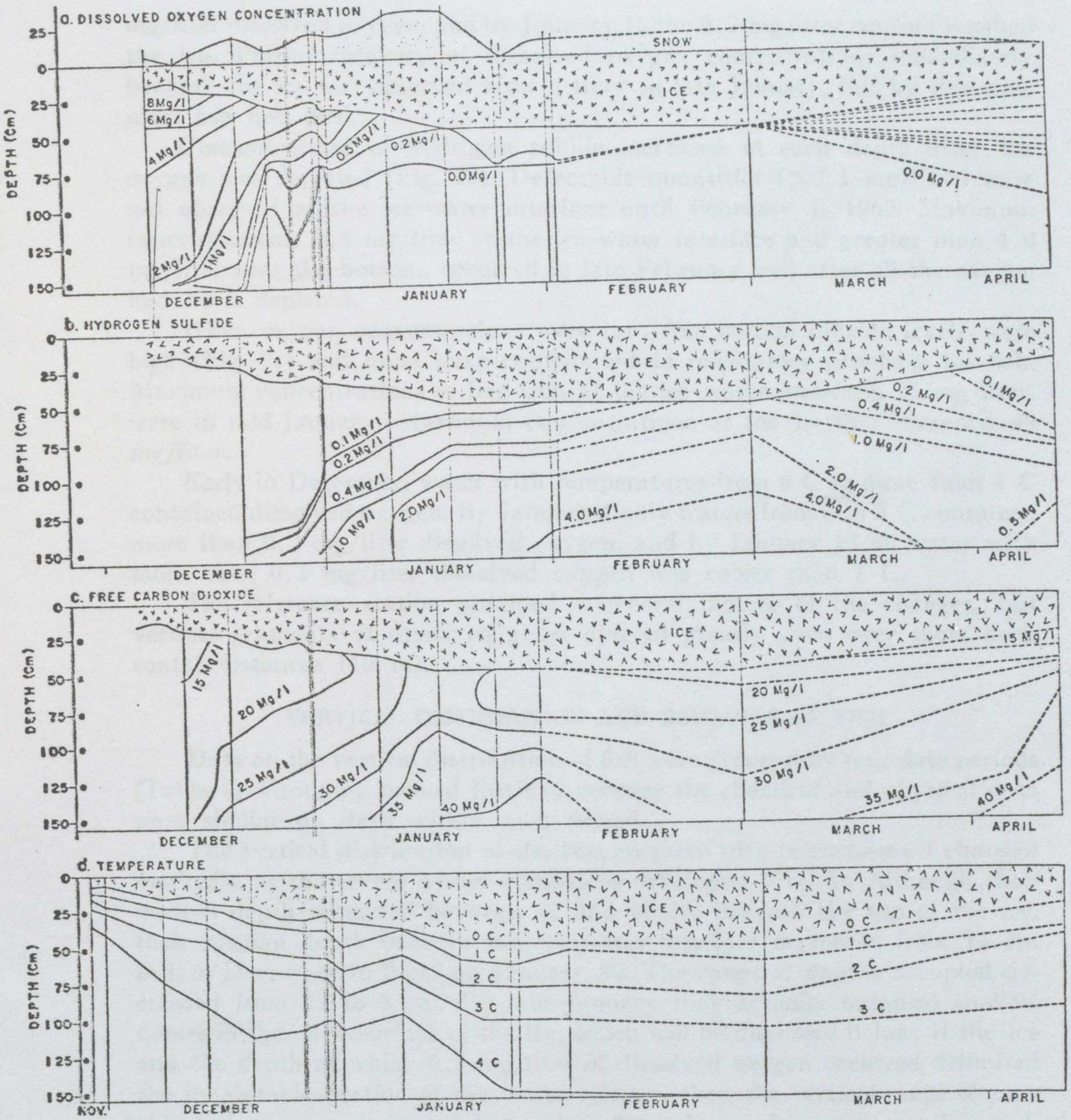


FIG. 2. Vertical distribution of dissolved oxygen, dissolved hydrogen sulfide, free carbon dioxide, and water temperature along with ice and snow depth at reference station on Mystery Lake during the winter of 1968–69. Dots on ordinate are sampling depths; vertical lines are dates of sampling; broken lines represent rather gross interpolations.

snow began to accumulate on the ice. The 1- and 0.2-mg/liter contours of dissolved oxygen rose as far as 10 cm per day (Fig. 2*a*). This plus the thickening of the ice rapidly reduced the water volume suitable for fishes. By the end of December only 40 cm of water just beneath the ice contained more than 0.2

mg/liter dissolved oxygen, and by January 18 the 0.2-mg/liter contour reached the ice. Partial recovery of dissolved oxygen concentrations immediately beneath the ice was observed after a thaw in late January, but by this time most fish had died.

Concentrations of hydrogen sulfide increased at each depth after the oxygen was depleted (Fig. 2*b*). Detectable quantities (>0.1 mg/liter) were not observed at the ice-water interface until February 1, 1969. Maximum concentrations, 0.4 mg/liter at the ice-water interface and greater than 4.0 mg/liter near the bottom, occurred in late February well after all the oxygen had been depleted.

When oxygen concentrations were low, free carbon dioxide levels were high (Fig. 2*c*) and must have contributed to respiratory problems for fish. Maximum concentrations of free CO_2 at the ice-water interface, 25 mg/liter, were in mid-January. Maximum concentrations at the bottom exceeded 40 mg/liter.

Early in December, water with temperatures from 0 C to more than 4 C contained dissolved oxygen. By January 1 only waters from 0 to 3 C contained more than 0.2 mg/liter dissolved oxygen, and by January 15 all water with more than 0.2 mg/liter dissolved oxygen was cooler than 1 C.

The reference station provided a general picture of the changes, but vertical gradients of dissolved gases differed greatly even over short horizontal distances (10 m).

VERTICAL DISTRIBUTION AND BEHAVIOR OF FISH

Data on the vertical distribution of fish were grouped by four date periods (Table 1). Grouping seemed justified because the chemical and physical data were similar on days within each period.

The vertical distribution of the two northern pike in enclosure I changed markedly as the severe winter conditions developed (Fig. 3). Although their median depth remained between 42 and 46 cm beneath the top of the ice, their median depth beneath the ice-water interface decreased from 14 cm in late December to 0 cm on January 30. The range of depths occupied decreased from 22 to 8 cm. By late January they actually occupied shallow domes in the undersurface of the ice, which will be discussed below. If the ice and the depth at which 0.2 mg/liter of dissolved oxygen occurred delimited the inhabitable portion of the water column, then the vertical range of suitable living space decreased from 44 to 0 cm during January at enclosure I. Ice thickened by 11 cm and the anoxic zone thickened by approximately 31 cm.

Conditions at the northern pike's median depth also changed. Dissolved oxygen in the four successive date periods were 2.0, 0.2, 1.3, and <0.1 mg/liter (estimated from Fig. 3). Water temperature at the median depth was also lower as winter progressed — 0.6, 0.4, 0.2, and 0.0 C in the four successive periods. Dissolved hydrogen sulfide and free CO_2 were not measured at enclosure I. If we assume data from the reference station apply to enclosure

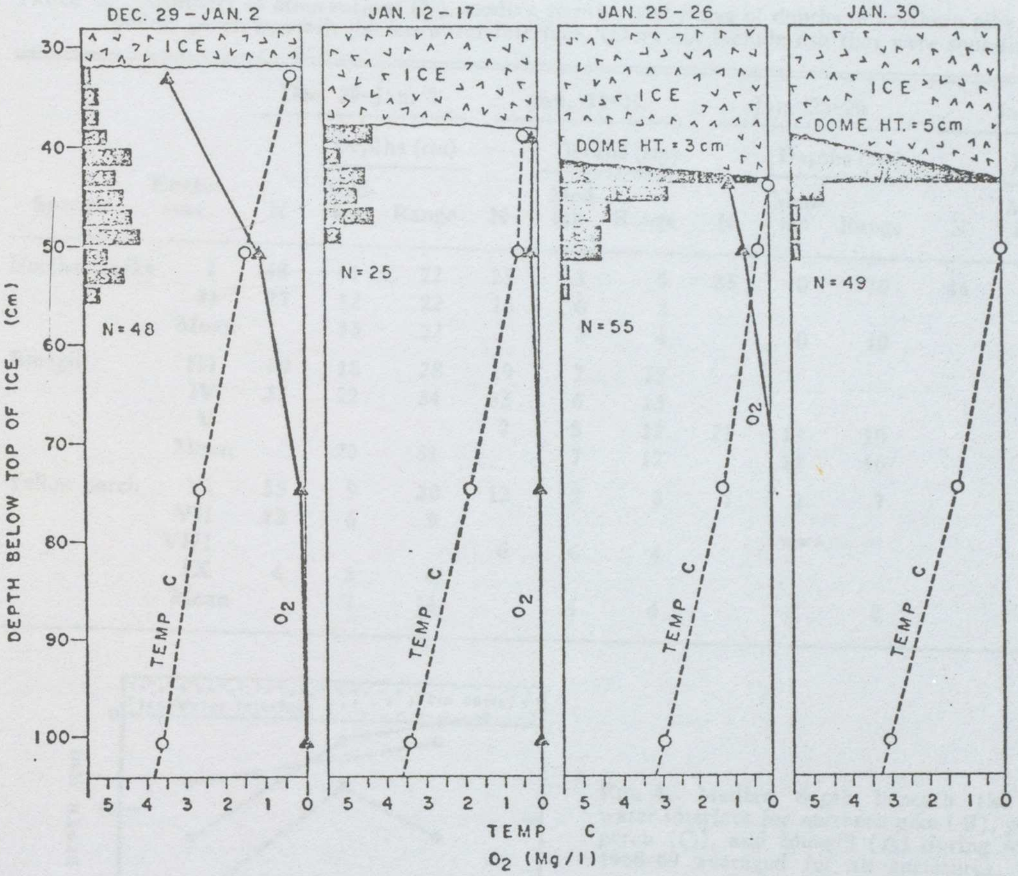


FIG. 3. Vertical distribution of northern pike, dissolved oxygen, and water temperature at enclosure I. Number of fish observed at each depth is given on histogram. Dissolved oxygen at undersurface of ice on January 30 was 0.07 mg/liter.

I, the concentration of hydrogen sulfide was zero at the median depth until February 1 when 0.1 mg/liter was present. Whether this contributed to the death of northern pike on that date is uncertain because by that time the maximum oxygen level was certainly critically low, <0.1 mg/liter. Free carbon dioxide at the median depth was estimated to change from 18 mg/liter on December 30, to 28 mg/liter on December 18, to 22 mg/liter on February 1. The most adverse levels of free CO_2 apparently occurred several weeks before the fish died.

The median depth and range of depths occupied also decreased for yellow perch and bluegill in January (Table 2, Fig. 4). However, neither yellow perch nor bluegill formed and occupied domes in the ice, even though the yellow perch often swam with their backs at the undersurface of the ice.

The bluegill's median depth in any period averaged 3–13 cm deeper than yellow perch or northern pike (Table 2, Fig. 4). Thus, the water they inhabited was slightly warmer and contained less dissolved oxygen. Perhaps bluegill

TABLE 2. Numbers of observations (N), median depths, and range of depths of northern pike, bluegill, and yellow perch beneath the ice–water interface. (Does not include fish that were sounding.)

		Dec. 29–Jan. 2			Jan. 11–19			Jan. 25–26			Jan. 30		
			Depths (*cm*)			Depths (*cm*)			Depths (*cm*)			Depths (*cm*)	
Species	Enclosure	N	Median	Range	N	Median	Range	N	Median	Range	N	Median	Range
Northern pike	I	48	14	22	25	3	6	55	0	10	44	0	8
	II	27	12	22	16	6	2						
	Mean		13	22		2	4		0	10		0	8
Bluegill	III	40	18	28	19	7	12						
	IV	31	22	34	33	6	13						
	V				7	8	12	21	12	10			
	Mean		20	31		7	12		12	10			
Yellow perch	VI	55	9	30	12	2	3	7	2	7			
	VII	12	6	9									
	VIII				6	6	4						
	IX	4	5	4									
	Mean		7	14		4	4		2	7			

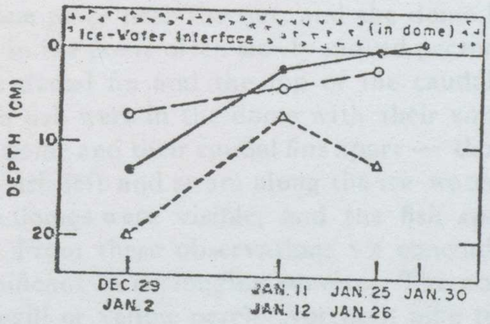


FIG. 4. Median depth beneath the ice–water interface for northern pike (ʘ), yellow perch (○), and bluegill (△) during winter 1968–69 averaged for all enclosures. Data from Table 2.

avoided the coldest water immediately beneath the ice and were unable to sense that this placed them in water with less oxygen. Bluegill have a more southerly distribution than yellow perch or northern pike (Trautman, 1957) and in summer prefer warmer temperatures than yellow perch and *Esox* sp. (Ferguson, 1958).

All three species occasionally swam into the deeper, anoxic water that contained hydrogen sulfide. This behavior was most pronounced in northern pike on the last few days before they died and was least developed in bluegill. Northern pike swam actively down to depths 30–100 cm beneath the bottom of the ice and remained from a few seconds to several minutes. Sounding activity was not concentrated at the edge of the enclosure. As many as nine soundings were observed in 1 hr (4.5/fish per hr). Only once did both northern pike in enclosure I sound together. The yellow perch in enclosure VI behaved the same way during the last few days they were seen alive. Bluegill often swam just above the anoxic water and several times without actually sounding, they swam slowly down and then up out of this zone. This behavior did not appear analogous to the active sounding. Sounding by northern pike and yellow perch appeared to be one of their final responses when the severe stress conditions reached the ice-water interface. The possible function of this activity was not apparent, nor can we be certain that it was not an artifact of confinement.

Marked qualitative differences in the locomotory activity and the aggregating behavior were observed among the three species. When conditions were severe, yellow perch never stopped swimming, bluegill were relatively active, and northern pike were relatively motionless for long periods. Yellow perch always swam rapidly, bluegill slowly. Yellow perch or bluegill were usually in a group, and a solitary fish was rarely seen, whereas the northern pike behaved more independently even though two fish often occupied the dome together.

During their last week, the two northern pike in enclosure I usually remained in a dome in the undersurface of the ice. When first noticed on January 26, the dome was 3 cm high and about 30 cm in diameter. By February 1 the height reached 5 cm. In late January the northern pike rested with head slightly higher than tail and snout almost touching the ice. Opercular movements and pectoral fin movements apparently created a weak but steady flow of water along the ice that melted the dome. The fish usually remained at one place near the net, and the dome became increasingly larger. The two fish in the dome often slowly moved pectorals and caudal fin to retain stability. The dorsal fin and the top of the caudal fin often touched the ice. Usually both fish were in the dome with their snouts almost touching at the apex of the dome and their caudal fins apart — their bodies forming a V. Occasionally, one fish left and swam along the ice-water interface or sounded. On January 30 two domes were visible, and the fish spent time in each.

From these observations we conclude that differences in behavior were significant in prolonging survival. The northern pike lived longer than either bluegill or yellow perch. Northern pike took a position immediately beneath the ice where dissolved oxygen concentrations were the greatest; they were also the least active. In contrast, yellow perch, also at the ice-water interface, were always swimming rapidly. Bluegill usually swam 5–15 cm below the ice, suffering the double disadvantage when conditions were most severe of being moderately active in an environment with less oxygen. The combination of little locomotor activity and a position immediately beneath the ice apparently favored the longer survival of northern pike. The aggregational tendencies of yellow perch and bluegill, if advantageous at low dissolved oxygen levels, did not outweigh the other behavioral advantages of the northern pike.

ACKNOWLEDGMENTS

Our special thanks go to Messrs W. E. Stuntz and R. R. Brocks without whose extra effort we would not have made it. We thank the hardy men who made the trip to Mystery Lake — Messrs P. C. Baumann, G. G. Chipman, A. E. Dizon, and S. S. Engel, Dr B. L. Haase, Messrs

C. M. Kaya, J. M. Miller, R. E. Mullen, W. H. Neill, E. K. Olsen, B. R. Petrosky, and F. El Shamy, and Drs A. B. Stasko, R. V. Thurston, and T. E. Wissing.

We thank the Wisconsin Department of Natural Resources at Woodruff for assistance in collecting, storing, and transporting fish. This project was supported with funds from the University of Wisconsin Graduate School.

REFERENCES

Bennett, G. W. 1962. Management of artificial lakes and ponds. Reinhold Publishing Corp., London. xvii + 283 p.

Cooper, G. P., and G. N. Washburn. 1949. Relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Trans. Amer. Fish. Soc. 76: 22–33.

Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada 15: 607–624.

Greenbank, J. 1945. Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. Ecol. Monogr. 15: 343–392.

Magnuson, J. J., and W. E. Stuntz. 1970. A siphon water sampler for use through the ice. Limnol. Oceanogr. 15: 156–158.

Moorman, R. B. 1957. Some factors related to success of fish populations in Iowa farm ponds. Trans. Amer. Fish. Soc. 86: 361–370.

Trautman, Milton B. 1957. The fishes of Ohio with illustrated keys. Ohio State University Press, Columbus, Ohio. viii + 683 p.

APPENDIX 3

Report to the Research Advisory Board

of the

First Committee Meeting

TO: The International Joint Commission
Great Lakes Advisory Board

ROM: The Review Committee for the Dissolved Oxygen Objectives
for the Great Lakes

SUBJECT: Report of our first meeting on June 26, 1978 at the Laboratory
of Limnology, University of Wisconsin-Madison

Attending: J. R. Brett, P.O. Fromm, J.J. Magnuson (Chairman),
A. E. P. Watson (Secretariat Responsibility).
Absent: F. E. J. Fry.

In setting adequate criteria for environmental oxygen, the Committee wishes to emphasize:

(1) That some account should be taken of evidence for physiological compensation by fishes exposed to reduced environmental oxygen, e.g., recent data on increased hematocrits of coho salmon growing at oxygen concentrations from 10 to 3 ppm O_2.

(2) That little data on oxygen requirements exist for water temperatures characteristic of the deeper waters of the Great Lakes, but that populations in smaller lakes persist at levels of dissolved oxygen much below the recognized incipient limiting levels.

(3) That a re-examination of the literature on critical oxygen levels, supplemented by new information, indicates that the mean incipient limiting tension for good growth occurs between 4 and 5 ppm O_2. This applies to normal habitat temperatures, and in the absence of any recorded or detected interfering excretory products.

(4) That despite reduced environmental O_2 the naturally lowered pO_2 of venous blood (rarely documented) can help maintain the necessary gradient (such as 20 mm Hg) for oxygen uptake across the respiratory surface (ΔP_G), and also that the carrying capacity of blood is decreased relatively little from near saturation by a considerable decrease in environmental oxygen, e.g., a reduction from 80 to 50 mm Hg pO_2 environmentally, results in a decrease in the blood oxygen saturation of trout of not more than 15%.

(5) That fish at cooler temperatures have a lower scope for activity and a lower demand for oxygen and would not be expected to require higher levels of dissolved oxygen than at warmer temperatures.

The above comments suggest that some reduction in the proposed dissolved oxygen objectives are justified, especially for those temperatures below 15°C. Our review committee will document the basis of our views and report back to the Research Advisory Board by December 1, 1978. We hope that our December 1978 report will be sent to the committee that developed the dissolved oxygen criteria and that our report be used at their discretion.

The three committee members who met regretted the unfortunate absence of Dr. Fry and will attempt to seek his views on the above deliberation.

John J. Magnuson

INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD

100 OUELLETTE AVENUE, 8TH FLOOR
WINDSOR, ONTARIO N9A 6T3

File No. 3000-5-9

July 19, 1978

MEMORANDUM

TO: Members, IJC Great Lakes Research Advisory Board's Review Committee for the Dissolved Oxygen Objective

FROM: A. E. P. Watson, Secretary

SUBJECT: DR. FRY'S COMMENTS ON THE COMMITTEE'S JUNE 1978 REPORT

Enclosed, please find a copy of Dr. Fry's comments on the report of the Committee's first meeting, June 1978; made during a telephone conversation of July 14, 1978.

A.P. Watson

AEPW:jl

Enclosure (1)
As Noted

Addressees: (w/encl.)
J. J. Magnuson
J. R. Brett
P. O. Fromm

cc: F. E. J. Fry

Dr. Fry's Telephoned Comments on Dissolved Oxygen Review Committee's June 1978 Report

I have reviewed the Dissolved Oxygen Criteria and I think there is a major fallacy which is a very common one in the strict adherence to the expression of oxygen dissolved in water by partial pressures. With the counter current exchange in the gill, whereby a gradient is formed relatively constant throughout the mouth of the passage, the mass of oxygen presented to the gill is often of greater significance than the immediate pressure. In fact Davies, in his review, makes the difference clear in his comparison in Figures 16 and 17. You will note that, when mass is used as the expression of oxygen in Figure 16, there is no correlation between his index of sensitivity and temperature. In other words, with that measurement, the index is independent of temperature.

The remarks above are meant to be perfunctory rather than a dissidentive comment on Magnuson's report. From the point of view of his report, I see no need to add any specifics at this time in view of his final promise that we will document our concerns in a report that hopefully will be sent to the committee that developed the Dissolved Oxygen Criteria. At that time I would wish to present an extensive critique of the Dissolved Oxygen section.

Dr. F. E. J. Fry

Great Lakes Fishery

ESTABLISHED BY CONVENTION BETWEEN CANADA AND THE UNITED STATES TO IMPROVE AND PERPETUATE FISHERY RESOURCES

I.J.C.
Windsor
JUL 28 1978
DIR.
D. DIR.
A.O.
[illegible] (25 VII 78)
FILE 3[illegible]5-9

Review Committee
Dissolved Oxygen
Objectives on the Great Lakes

25 July 1978

Dr. A. E. P. Watson
International Joint Commission
100 Ouellette Avenue
Windsor, Ontario, Canada N9A 6T3

Dear Andy:

I was interested to hear the report of the first meeting of the RCDOOGL as presented to the RAB on 18 July 1978.

Without referring to the DOO under review I offer the following for the consideration of the Committee. There is no need for you or the Committee to respond to this letter. The Committee emphasized five points.

Point 1. When considering physiological compensation to reduced oxygen, remember that fish of the Great Lakes will be exposed for long periods of time to the levels recommended in the objectives. The situation is not similar to streams with their diel cycles where a debt incurred can be repaid quickly.

Point 2. It sure isn't the goal of the Great Lakes Fishery Commission and its cooperators that fish populations "persist" in the Great Lakes, and I hope it isn't the goal of the IJC and its cooperators. We're striving for self-sustaining, thriving populations.

Point 5. Yes, fish at cooler temperatures have a lower scope for activity, but remember that most Great Lakes species will be very active at 15°C (mentioned in the next paragraph) and lower.

After writing this I have the feeling I've carried coal to Newcastle, but please send it on to the members.

I'm glad to know there's such a competent group working to resolve the issue.

Sincerely,

Carlos

Carlos M. Fetterolf, Jr.
Executive Secretary

cc: Don Mount
Al LeFeuvre
Robert White
Andy Robertson

1451 Green Road • Ann Arbor, Michigan 48105 • Telephone: (313) 662-3209 / FTS 378-2077

APPENDIX C. INFORMATION EXCHANGE

- Dissolved Oxygen Criterion Proposed for Mississippi Waters (Watson)
- Ontario Guidelines and Criteria for Water Quality Management (Watson)
- Summary of Data on Behavioral Responses of Fishes to Low D.O. (Magnuson)
- Dissolved Oxygen Objective Comments (Fromm)
- "Bioenergetics and Growth, (D.) Oxygen." (Brett)

INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD
100 OUELLETTE AVENUE, 8TH FLOOR
WINDSOR, ONTARIO N9A 6T3

September 15, 1978

File No. 3000-5-49

MEMORANDUM

TO: Members, Great Lakes Research Advisory Board's Review Committee for the Dissolved Oxygen Objective for the Great Lakes

FROM: A. E. P. Watson, Secretary

SUBJECT: D.O. CRITERION PROPOSED FOR MISSISSIPPI WATERS

For your information, I have enclosed a copy of the proposed criterion for Mississippi waters, reported on pages 495 and 495 of the Environmental Reporter, (1978), 9, (12: July 21). The U.S. Environmental Protection Agency, in making this proposal, refers to the "fishable, swimmable" requirement of the U.S. Clean Water Act and the support of a balanced fish population.

A.E.Watson

AEPW/hk

Enclosure (1): As noted

Addressees:
J. J. Magnuson
J. R. Brett
P. O. Fromm
F. E. J. Fry

cc: w/encl.
A. R. LeFeuvre
D. I. Mount
R. E. White

Environmental Reporter, (1978), 9, (12: July 21), 495-496.

Rauch pointed specifically to the group's efforts to influence development of the Environmental Protection Agency's prevention of significant deterioration regulations and the Occupational Safety and Health Administration's standards for workplace cotton dust (June 9, p. 187).

"It is our hope that these were only 'transitional' cases and that all of the group's activities will be confined to the public comment period in the future," Rauch said.

He questioned the review group's authority to contact an agency head after the public comment period has closed, pointing to the decision of the U.S. Court of Appeals for the District of Columbia Circuit in *Home Box Office, Inc., v. Federal Communications Commission* (April 15, 1977, p. 1918).

Ex parte contacts by Executive Branch officials with no statutory responsibility for regulations "pose many of the same problems as *ex parte* contacts from private parties," Rauch said.

"Indeed, the possibility that an *ex parte* contact from an Executive Branch will 'materially influence the action ultimately taken' is substantially more likely than a similar *ex parte* contract from a private party," he said.

"We feel that such contacts create special problems particularly where the purpose of the contact is to influence a major regulatory decision."

To buttress his argument, Rauch quoted from an August 4, 1977, memorandum from EPA Administrator Douglas M. Costle to other agency officials regarding *Home Box Office.*

"I do not believe that EPA should base or appear to base its regulatory decision on information or arguments presented informally that do not appear on the public record," Costle said in that memorandum.

To resolve the "potential problem" of *ex parte* contacts, Rauch suggested the review group make sure its review of proposed regulations "will be completed by the end of the public comment period and that no further attempts to influence the form or substance of the proposed regulations will be made after that time."

Rauch suggested also that the group keep written records — to be inserted in agency records for public review — of meetings between the group and the agency. He said such meetings should be open to the public.

Chemicals

EPA REGIONS APPROVE PCB DISPOSAL FACILITIES

The Environmental Protection Agency July 18 said (43 FR 30882) it has approved facilities in EPA Regions IV and X for disposal of polychlorinated biphenyls (PCBs).

EPA explained that regional administrators must approve all disposal facilities for PCBs, in accordance with a regulation adopted under Section 6 of the Toxic Substances Control Act.

The rule on disposal and marking of PCBs, adopted February 17 (Current Developments, February 24, p. 1650), prohibits disposal of many PCBs, as defined in the regulation, after April 18, 1978, except at EPA-approved facilities.

The list of disposal facilities includes one Alabama facility approved by Region IV, and two facilities, one in Oregon and one in Idaho, approved by Region X.

Following is a list of the approved facilities:

EPA REGION IV (345 COURTLAND STREET NE., ATLANTA, GA. 30308)

1. Facility: Waste Management of Alabama, Inc. Facility Address: P.O. Box 1200, Livingston, Ala. 35470. Facility Telephone No.: 205-652-9529. Type of Facility Approved: Chemical Waste Landfill. Type of PCB Waste Handled: Capacitors (small and large). Properly drained transformers. Contaminated soil, dirt, rags, and other debris. Dredge spoils. Municipal sludges. Properly drained containers (drums). Expiration Date of Approval: Open-ended.* EPA Regional Office Contact: Mr. James Scarbrough. EPA Telephone No.: 404-881-3116.

NOTE.—After January 1, 1980, PCB capacitors and contaminated soil, rags, and other debris cannot be disposed of in chemical waste landfills. A special provision does permit without time limits, the disposal in chemical waste landfills of contaminated soil and debris resulting from spills or from old disposal sites that predate the PCB regulations.

EPA REGION X (1200 SIXTH AVENUE, SEATTLE, WASH., 98101)

1. Facility: Chem-Nuclear Systems, Inc. Facility Address: P.O. Box 1269, Portland, Oreg. 97205. Main office (site located in Arlington, Oreg.). Facility Telephone No.: 503-223-1912. Type of Facility Approved: Chemical Waste Landfill. Type of PCB Waste Handled: Capacitors (small and large). Properly drained transformers. Contaminated soil, dirt, rags, asphalt, and other debris. Properly drained containers (drums). Expiration Date of Approval: January 1, 1980. EPA Regional Office Contact: Mr. Roger Fuentes. EPA Telephone No.: 206-442-1260.

2. Facility: Wes-Con, Inc. Facility Address: P.O. Box 564, Twin Falls, Idaho 83301. Main office (site located in Grand View, Idaho). Facility Telephone No.: 208-734-7711. Type of Facility Approved: Disposal in Missile Silos. Type of PCB Waste Handled: Capacitors (small and large). Properly drained transformers. Contaminated soil, dirt, rags, asphalt and other debris. Properly drained containers (drums). Expiration Date of Approval: January 1, 1980. EPA Regional Office Contact: Mr. Roger Fuentes. EPA Telephone No.: 206-442-1260.

EPA said it will continue to publish lists of approved facilities for disposal of PCBs on a monthly basis.

Further information on EPA approval of the facilities is available from the appropriate agency regional offices.

Water Pollution

DISSOLVED OXYGEN CRITERION PROPOSED FOR MISSISSIPPI WATERS

The Environmental Protection Agency is proposing a dissolved oxygen criterion for Mississippi's water quality standards to encourage fish propagation, and help achieve the Clean Water Act's "fishable, swimmable" requirement.

The rule proposed July 13 (43 FR 30076) by EPA would amend Mississippi's intrastate, interstate, and coastal water quality standards (40 CFR 120) to provide for a minimum dissolved oxygen concentration of five milligrams per liter in flowing streams and estuarine waters, including tidally affected portions of streams.

The five mg/1 dissolved oxygen concentration requirement would apply also to the epilimnion, or surface layer, of thermally stratified lakes and impoundments, or five feet from the surface in water not thermally stratified.

EPA Region IV notified the Mississippi Air and Water Pollution Control Commission in 1975, 1976, and 1977 that its dissolved oxygen standard was too low and that the state criterion would not support a balanced fish population.

EPA disapproved the state standard.

Mississippi Criterion Rejected

Section 303(c) of the Water Act provides that EPA publish revised or new water quality standards when necessary to meet requirements of the Act. Within 90 days after publishing the proposed standard, the EPA administrator must promulgate a new standard unless a state adopts its own revised or new standard consistent with the requirements of the Act.

EPA explained that Mississippi had proposed a dissolved oxygen criterion of four mg/1 as a minimum daily average applicable at the seven-day, 10-year flow, while EPA Region IV had urged the state to adopt a criterion of five mg/1 applicable at the seven-day, 10-year low flow and all greater flows.

Mississippi's criterion was too low to ensure protection of a balanced fish population and was not consistent with national quality criterion for water, EPA Region IV told the state.

In proposing the rule to amend Mississippi criterion, EPA referred to research indicating that Mississippi sport fish, including large- and small-mouth bass, striped bass, bream, and crappie require "substantial concentrations" of dissolved oxygen for favorable propagation conditions.

The five mg/1 minimum daily criterion would support a balanced fish population while the Mississippi standard would not, EPA said. The Mississippi criterion would favor survival of rough and forage fish rather than sport fish, EPA said.

The EPA proposed criterion would apply to all Mississippi waters, EPA said, even though certain waters may not achieve that criterion. EPA said it would consider modifications to the proposed criterion on a case-by-case basis, with proper justification required for a lower dissolved oxygen criterion.

EPA said the criterion proposed by Mississippi would provide for greater waste emissions and consequent water degradation than would the EPA-proposed standard. Thus, the proposed criterion reflects the requirements of the Act that state standards protect fish propagation and the statutory requirement of "fishable, swimmable" use designations for all waters by 1983, EPA said.

EPA tentatively is planning hearings in Jackson and Biloxi, Miss., on the proposed rule and will publish a notice of the hearings in the Federal Register.

The proposed rule is published in the Full Text section of this issue.

Litigation

FREEWAY SEGMENT CHALLENGE TERMINATED BY COURT RULING

The U.S. District Court for the District of New Jersey June 9 ruled against several environmental and citizens groups in a suit to halt a two-and-one-quarter mile freeway extension involving construction of a bridge over the Raritan River in New Brunswick, N.J. (*Citizens' Committee for Environmental Protection v. U.S. Coast Guard*, No. 77-1719).

The various plaintiff groups sued both state and federal governments over the proposed segment of Route 18 which was designed in 1965 as an improvement to traffic flow in the city.

The proposed Route 18 project includes construction of a bridge over the Raritan River and placement of fill in both the Raritan River and the Delaware and Raritan Canal.

State and Federal Permits Obtained

The New Jersey Department of Transportation obtained a permit from state authorities to build bridge piers in the river in 1970.

The U.S. Coast Guard, pursuant to a memorandum of agreement with the Corps of Engineers, prepared an environmental impact statement for the project in accordance with the Department of Transportation Act, Section 4(f), and the National Environmental Policy Act.

In 1976, the Coast Guard issued the bridge construction permit, and in 1977 the Corps of Engineers authorized the associated fill and rip-rap work in the river and canal.

The plaintiffs challenged these state and federal approvals on several theories.

Claims Against State Agency

The environmental plaintiffs contended that the New Jersey Department of Transportation violated Sections 9 and 10 of the Rivers and Harbors Act of 1899.

The court disagreed for three reasons.

Sections 9 and 10 of the Rivers and Harbors Act, the court said, do not create a private right of action. The Act provides for assessment of civil and criminal penalties and not the injunctive relief sought in this action, the court said.

The suit against state defendants also is barred by the Eleventh Amendment to the U.S. Constitution, the court said, unless the state consents to be sued in federal court. The court found no such waiver of constitutional protection by New Jersey in this case.

Even if there were a right of action under the Rivers and Harbors Act not barred by the Eleventh Amendment, the court said, there has been no factual showing of construction or fill activities in violation of Sections 9 and 10.

The court also found the plaintiffs' attempt to rely on a breach of the memorandum of agreement between the Corps of Engineers and the Coast Guard inappropriate as a basis for injunction of the freeway extension.

The court said the plaintiffs had neither the privity of contract to enforce the terms of the agreement nor standing based on some injury in fact to seek redress for breach of the agreement.

Claims Against Federal Agencies

The plaintiffs contended that the Coast Guard violated the Department of Transportation Act by not considering feasible and prudent alternatives to the proposed freeway route, which involves the taking of some public park land.

The court concluded on the basis of the evidence at trial, which included exhibits and testimony on the Coast Guard's decisionmaking process, that the agency had acted reasonably in considering alternatives to the project and by rejecting those proffered by plaintiffs.

The court also rejected the contention that federal agencies violated NEPA by preparing an impact statement which evaluates only a segment of the freeway project approved by the New Jersey legislature.

The court found that three criteria to determine the proper length of a segment to be considered in an impact statement were satisfied:

INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD
100 OUELLETTE AVENUE, 8TH FLOOR
WINDSOR, ONTARIO N9A 6T3

Windsor (519) 256-7821
Detroit (313) 963-9041

October 5, 1978

File No. 3000-5-9

MEMORANDUM

TO: Members, Great Lakes Research Advisory Board's Review Committee for Dissolved Oxygen Objective for the Great Lakes

FROM: A. E. P. Watson, Secretary

SUBJECT: PREPARATIONS FOR DECEMBER 1 MEETING: EXCHANGE OF INFORMATION

During the June 26, 1978 meeting of the Review Committee, it was decided that members would exchange appropriate information for review and comment prior to our fall (1978) meeting. In this regard, I would appreciate receiving from you any such material which will be distributed to the other members from the IJC Regional Office. If initiated, this process will, I am sure, facilitate the committee's task of writing its report during the December 1 meeting and your early consideration of this would be appreciated.

For your information and by the way of an example, I have enclosed excerpts (pp. 85-90) of the Ontario Guidelines and Criteria for Water Quality Management, February 1973, as reproduced in the International Environment Reporter, (1978), September 10, Supplement No. 7. In Section 2, Water Quality Criteria for the Protection of Fish, Other Aquatic Life and Wildlife, pages 86-90, reference is made to Temperature (1) General; (2) Great Lakes and Connecting Channels; (3) Inland Waters and to Dissolved Oxygen (1) Warm-Water Biota; (2) Cold-Water Biota, as well as to "Free" Carbon Dioxide. I have been reassured that, in the proposed (1979) update of the Guideline and Criteria, the Ontario Ministry of the Environment foresees no changes in the current Dissolved Oxygen levels prescribed.

The complete text of Section 2 has been reproduced to include data on Toxic Substances - especially biocides - and miscellaneous surfactants and inorganic ions, pages 87-90. This information may be of value in gauging the potential levels of chemically-induced stress likely to be found in the species to be protected by the dissolved oxygen objective under consideration.

AEPW/hk

Enclosure (1): Excerpts from Ont. Guidelines and
Criteria for Water Quality Management

Addressees:
J. J. Magnuson P. O. Fromm J. R. Brett F. E. J. Fry

cc: (w/encl.)
D. I. Mount, RAB Chairman, U.S. Section
[illegible] RAB Chairman, Canadian Section

INTERNATIONAL ENVIRONMENT REPORTER

September 10, 1978 THE BUREAU OF NATIONAL AFFAIRS, INC. Supplement No. 7

FILING INSTRUCTIONS

NOTE: The instructions below should be followed carefully. The boldface headings on the left correspond to the tab sections in the International Environment Reporter binders. Obsolete pages are listed in the column headed "Take Out Pages." New and replacement pages in this supplement are listed in the column headed "Put In Pages." It is important to follow instructions in both columns. Retain the instructions sheet for this supplement in the front of the Reference File 1 binder.

REFERENCE FILE 1

	Take Out Pages	Put In Pages
01 – CONTENTS		
Table of Contents (Revision)	01:0001–01:0009	01:0001–01:0009
11 – INDEX		
Master Index (Revision)	11:1001–11:1014	11:1001–11:1015
21 – TREATIES		
Tab Section Contents (Revision)	21:0001	21:0001
Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution (Revision)	21:2721–21:2722	21:2721–21:2722
1978 Amazon Pact Treaty (New material)	....	21:2901–21:2903
31 – BILATERAL AGREEMENTS		
Tab Section Contents (Revision)	31:0001	31:0001
1978 Memorandum of Understanding Between the Subsecretariat for Environmental Improvement of Mexico and the Environmental Protection Agency of the United States for Cooperation on Environmental Programs and Transboundary Problems (New material)	....	31:1201–31:1202
51 – CANADA		
Tab Section Contents (Revision)	51:0001–51:0004	51:0001–51:0004
Alberta Clean Water (General) Regulations (New material)	....	51:5245–51:5246
British Columbia Pollution Control Objectives for the Forest Products Industry (New material)	....	51:5481–51:5492
British Columbia Pesticide Control Act (New material)	....	51:5541–51:5544
British Columbia Pesticide Control Regulation (New material)	....	51:5551–51:5553
British Columbia Motor Vehicle Act (New material)	....	51:5565
Ontario Sewage Systems Regulation (New material)	....	51:7311–51:7319
Ontario Containers for Carbonated Soft Drink Regulations (New material)	....	51:7381
Ontario Guidelines and Criteria for Water Quality Management (New material)	....	51:7711–51:7720

ONTARIO GUIDELINES AND CRITERIA FOR WATER QUALITY MANAGEMENT

February 1973

GUIDELINES FOR THE CONTROL OF WATER QUALITY

1 The water resources of Ontario must meet many needs, some of which are in conflict. The standards established, therefore, must be based on the best interests of the people of Ontario. These interests require the preservation, and restoration where necessary, of the quality of our water for the greatest number of uses. The use of water for the assimilation and dilution of treated waste effluents must take into consideration the variety of uses, including public, agricultural and industrial supply, recreation, aesthetic enjoyment and the propagation of fish and wildlife.

2 For each use of water there are certain water quality characteristics, identified as criteria, which should be met to ensure that the water is suitable for that use.

3 Water quality standards will be established by the Ministry of the Environment for waters of drainage basins or parts thereof with important water uses, following consultation with agencies or persons having an interest or responsibility in the present or future use of the water in the basin for which the standards are to be established.

4 Water of a higher quality than that required by the standards will be maintained at that higher quality unless in the public interest an alteration of the quality is consistent with the protection of all uses which are in accordance with the water quality standards established.

There should be a constant effort to improve the quality of water, for it is recognized that the improvement of the quality of water makes it available for more uses.

5 Requirements for effluents and land drainage based on the applicable water quality standards, or criteria where such standards do not exist, will be established by the Ministry in order to maintain acceptable water quality. More stringent methods of control and/or treatment of waste inputs and land drainage may become necessary as the use of water changes or increases, or as standards are re-defined.

6 In establishing effluent requirements from water quality standards a reserve capacity of the receiving water should be set aside to provide an adequate margin of protection in recognition of the limitations of water management theory and practice.

7 All wastes prior to discharge to any receiving watercourse must receive the best practicable treatment or control. Such treatment must be adequate to protect and wherever possible upgrade water quality in the face of population and industrial growth, urbanization and technological change.

8 Criteria and standards of water quality and effluent requirements will be defined quantitatively only where sound numerical information is available; otherwise, they will be described in appropriate detail. They will be re-defined from time to time in the light of new evidence.

WATER QUALITY CRITERIA

The following criteria for water quality are a set of numerical and descriptive characteristics, carefully defined, and applicable to each major water use category such as agriculture; fish, other aquatic life and wildlife; industrial water supply; public water supply; recreation and aesthetics. The criteria are described for use in establishing Water Quality Standards for drainage basins which in turn will be used to determine Effluent Requirements for discharges of wastes and land drainage.

The responsibility for demonstrating that a waste effluent is harmless to water uses in the concentrations to be found in the receiving waters, rests with those producing the discharge. Zones of passage and/or mixing adjacent to outfalls at the limit of which water quality may be critical, will be prescribed by the Ministry.

Reference is frequently made in the Criteria to the Report of the Committee on Water Quality, Federal Water Pollution Control Administration, U.S. Department of the Interior (1968). Acknowledgement of the report is gratefully given in recognition of its basic reference value.

ZONES OF PASSAGE AND MIXING

Mixing zones in the vicinity of outfalls should be restricted as much as possible in extent and should provide for the safe passage of both fish and free-floating and drift organisms. Every precaution should be taken to ensure that at least two-thirds of the total cross-sectional area of a river or stream is characterized by a quality which is entirely favourable to the aquatic community at all times. In most cases this would preclude the use of a diffuser outfall which would distribute effluent uniformly across the river or stream. The water quality standard which defines the acceptable concentration of a substance contained in a waste discharge will apply at the periphery of the mixing zone or other specified sampling location.

Within mixing zones, it should be recognized that toxic wastes which will not evoke an avoidance response on the part of fish or other organisms should not be permitted. Where toxic materials are being discharged it should be assumed that the various components in the waste, regardless of the form in which they are present, may eventually be altered to the most toxic form in the aquatic environment. Adequate treatment of all wastes should be provided and mixing zones should not be considered as a substitute for proper treatment.

STATISTICAL PROBLEMS IN SETTING LIMITS

The systematic surveillance of water and waste sources requires the collection of data to clearly represent the problems being studied. The problems are many and varied. In one case the average condition over a period of time may be required and the question arises over what period shall the average or median be taken; in another, the limit may be a figure that should not be exceeded at any time. If a standard for a certain constituent is "none", the question arises "how small an amount does this mean?" The answers vary with the type of standard and the circumstances governing the fluctuation of the indicator. In ground water problems, only the average over a considerable period of time is significant. Where required in the setting of standards and effluent requirements, definitions of limits will include the applicable sampling conditions, quantitative values and rates of discharge.

1 WATER QUALITY CRITERIA FOR AGRICULTURAL USES (AGR)

Agricultural production requires water of suitable quality for a variety of uses. Criteria for the major uses are given under three headings: Dairy Sanitation, Livestock Watering, and Irrigation.

Requirements for domestic and other farmstead uses and the common requirements for dairy sanitation are given elsewhere in the criteria for Private Water Supplies and Public Water Supplies.

AGR-1 Dairy Sanitation

Modern methods for bulk handling of milk on farms require large volumes of good quality water to ensure a premium product. The quality of water needed for good dairy sanitation requires criteria for certain parameters that are additional to, or more stringent than, those required for private water supplies. These are summarized under the headings "Permissible Criteria" and "Desirable Criteria". They should be used in conjunction with the criteria for public and private water supplies.

Treatment may prove satisfactory in meeting the criteria for certain of the inorganic chemicals such as iron and total hardness.

Waters that meet the desirable microbiological criteria can be used without disinfection. Those meeting the permissible criteria require disinfection (chlorination), or chlorination and filtration, before use to reduce bacteria to levels where they will not cause deterioration of the quality of milk. Waters used for dairy sanitation should be sampled and tested at least monthly, in some cases daily, to ensure that they meet the microbiological criteria.

TABLE AGR-1

Water Quality Criteria for Agricultural Uses
Dairy Sanitation

Constituent or Characteristic	Permissible Criteria	Desirable Criteria
Inorganic Chemicals:		
Copper	0.1 mg/l	
Iron	0.1 mg/l	
pH (range)	6.8 to 8.5	
Potassium	20 mg/l	
Total hardness as $CaCO_3$	150 mg/l	100 mg/l
Microbiological:		
Proteolytic and/or lipolytic bacteria (20°C) (individual results)	500/100 ml	0/100 ml
Yeast		Absent
Mould		Absent
Physical:		Clear Colourless Good taste

AGR-2 Livestock Watering

The health and productivity of livestock are affected by the quantities of various substances ingested as feed and as water. Accordingly, the amounts of certain substances that can be present without harm in water consumed by livestock will depend in part on the amounts of the same substances that are present in the feed in addition to a number of other factors which include: the daily water requirements and the species, age, and physiological condition of the animals, and the nature and quantities of other constituents of the feed and water.

Animals may be able to tolerate a fairly high level of total dissolved solids or bacteria if they are accustomed to such levels, but may be unable to tolerate a sudden change from waters with low dissolved solids or bacteria to waters with high dissolved solids or bacteria.

In addition to direct effects on the animals, certain substances may contaminate animal products to the point where they will not be acceptable for human consumption.

The variability of the factors that influence the acceptability of water for livestock-watering purposes must be considered when using the water quality criteria. Although the criteria provide a general guide to the quality of water that will be acceptable for most livestock, there may be cases where water of different quality than that indicated by the criteria will be required or acceptable because of the nature, age, or condition of species being raised or because of special rearing conditions or feed components. In such cases, or where the quality of an individual supply is in doubt, the quality should be assessed in relation to the specific use.

Water meeting the permissible criteria will be satisfactory for most livestock under normal rearing conditions. Water meeting the desirable criteria should provide a palatable and safe source for all normal livestock-watering purposes.

TABLE AGR-2

Water Quality Criteria for Agricultural Uses
Livestock

Constituent or Characteristic	Permissible Criteria	Desirable Criteria
General Quality		ideally should meet the desirable criteria for private water supplies.
Inorganic Chemicals:		
Total Dissolved Solids	2500 mg/l	< 500 mg/l
Arsenic	0.05 mg/l	Absent
Cadmium	0.01 mg/l	Absent
Chromium (hexavalent)	0.05 mg/l	Absent
Fluoride	2.4 mg/l	1.2 mg/l
Lead	0.05 mg/l	Absent
Nitrate plus Nitrite (as N)	20 mg/l	< 10 mg/l
Selenium	0.01 mg/l	Absent
Sulphate	1000 mg/l	< 250 mg/l
Radioactivity:		
Radium-226	3 pc/l	< 1 pc/l
Strontium-90	10 pc/l	< 2 pc/l
Gross beta activity in the known absence of strontium-90 and alpha-emitting radionuclides.	1000 pc/l	< 100 pc/l
Microbiological: (1)		
Enterococci (35°C)	< 40/100 ml	0/100 ml(1)
Algae	No heavy growth of blue-green algae	

(1) The supply should be free of barnyard runoff and of effluent contamination from either man or animals. The geometric mean of sample results should not exceed the values given.

AGR-3 Irrigation

The suitability of water for irrigation cannot be defined precisely because the effects of the water on the crop being irrigated depend on many factors. These include: soil types, climatic conditions, irrigation practices, variations in the relation between the concentration and composition of the irrigation water and the soil solution, variations in the tolerance of different plants to the combined or individual constituents in the irrigation water or the soil solution, and the modifying effects of interrelations between and among the constituents. In general, for satisfactory irrigation, soils with poor drainage characteristics require water of higher quality than better drained soils.

In humid areas, excessive concentrations of salts or individual elements will normally be leached from the soil during periods of heavy rainfall or snowmelt before or after the growing season. This leaching action is another factor affecting the quality of water that can be used for irrigation. It may allow the use of water of poorer quality than that listed in these criteria for some crops and conditions without serious detrimental effects. Also through proper timing and adjustment of frequency and volumes of water applied, detrimental effects of poorer quality water may often be mitigated. Good drainage of soil may be a factor of similar importance as the quality of the water used.

The presence of sediment, pesticides, or pathogenic organisms in irrigation water, which may not specifically affect plant growth, may affect the acceptability of the product. Larger sediment particles could lead to plugging of sprinkler nozzles.

Although there are many variations in the quality of water that is suitable for specific irrigation uses, water quality criteria have been assembled as a guide to the quality of water that will meet many irrigation needs. The criteria are listed as permissible and desirable. Water meeting the desirable criteria should be satisfactory for irrigation of most crops in most soil types for long periods of time. Water meeting the permissible criteria, while suitable for many crops, soil and climatic conditions, could result in decreased yields for some crops if it is used repeatedly, unless there is dilution or leaching by precipitation or the application of excess irrigation water under favourable drainage conditions. Special crops or conditions, such as the growing of plants in greenhouses, may require irrigation with water of higher quality than that indicated by the desirable criteria.

The suitability of a given source of water for specific crops, soil types, and climatic conditions should be judged on an individual basis if its suitability has not been demonstrated by practice.

2 WATER QUALITY CRITERIA FOR THE PROTECTION OF FISH, OTHER AQUATIC LIFE AND WILDLIFE (F & W)

The following criteria are considered to be satisfactory for fish, other aquatic life and wildlife. Reference is made to aspects of water quality considered to be most important in the light of current knowledge. Narrative guidelines are offered where quantification is not yet possible.

Dissolved Materials

Dissolved materials should not be added to increase the concentration of dissolved solids by more than one-third of the natural condition of the receiving water, owing to potentially harmful osmotic effects of high concentrations. Dissolved materials that are harmful in relatively low concentrations are discussed in the section "Toxic Substances".

pH, Alkalinity, Acidity

(1) pH should be maintained within a range of 6.5 to 8.5.

(2) To protect the carbonate system, and thus the productivity of the water, acid should not be added in sufficient quantity to lower the total alkalinity to less than 20 mg/l.

Temperature

(1) General

Unless a special study shows that discharge of a heated effluent into the hypolimnion of a lake will be desirable, such practice is not recommended and water for cooling should not be pumped from the

TABLE AGR-3

Water Quality Criteria for Agricultural Uses

Irrigation

Constituent or Characteristic	Permissible Criteria	Desirable Criteria
Physical:		
Temperature		55°F to 85°F
Microbiological: (1)		
Fecal Coliforms (44.5°C)	100/100 ml	0/100 ml
Enterococci (35°C)	20/100 ml	0/100 ml
Total bacteria (20°C)	100,000/100 ml	< 10,000/100 ml
Inorganic Chemicals:		
Aluminum	20.0 mg/l	< 1.0 mg/l
Arsenic	10.0 mg/l	< 1.0 mg/l
Beryllium	1.0 mg/l	< 0.5 mg/l
Boron	0.5 mg/l	0.3 mg/l
Cadmium	0.05 mg/l	< 0.005 mg/l
Chloride	150 mg/l	< 70 mg/l
Chloride—special requirement for tobacco	70 mg/l	< 20 mg/l
Chromium	20.0 mg/l	< 5.0 mg/l
Cobalt	10.0 mg/l	< 0.2 mg/l
Copper	5.0 mg/l	< 0.2 mg/l
Lead	20.0 mg/l	< 5.0 mg/l
Lithium	5.0 mg/l	< 5.0 mg/l
Manganese	20.0 mg/l	< 2.0 mg/l
Molybdenum	0.05 mg/l	< 0.005 mg/l
Nickel	2.0 mg/l	< 0.5 mg/l
pH (range)	4.8 to 9.0	
Residual Sodium Carbonate $=(CO_3^{--}+HCO_3^{-})-(Ca^{++}+Mg^{++})$ expressed as mg eq/l	1.25 mg eq/l	< 1.25 mg eq/l
Selenium	0.05 mg/l	< 0.05 mg/l
Sodium Adsorption Ratio $=\frac{Na^{+}}{\sqrt{\frac{Ca^{++}+Mg^{++}}{2}}}$ expressed as mg eq/l	6	< 4
Total dissolved solids	500 mg/l	< 200 mg/l
Vanadium	10.0 mg/l	< 10.0 mg/l
Zinc	5.0 mg/l	< 5.0 mg/l
Organic Chemicals:		
Pesticides	Insecticides, herbicides, fungicides, and rodenticides must not be present in waters used for irrigation in concentrations that are detrimental to crops, livestock, wildlife or man.	Absent

(1) The geometric mean of sample results should not exceed the values given.

hypolimnion to be discharged to the same body of water.

The normal daily and seasonal temperature variations that were present before the addition of heat due to other than natural causes should be maintained.

Wherever possible, heated discharges should be located where elevated temperature will enhance public utilization of the water by supporting a wider variety of water uses.

(2) Great Lakes and Connecting Waters

(a) Heated discharges are not permitted that may stimulate production of nuisance organisms or vegetation or that are or may become injurious to wildlife, waterfowl, fish or other aquatic life or the growth and reproduction thereof. For each discharge of a heated effluent, acceptable mixing zones will be established on the basis of features and facts pertinent to that specific situation.

(b) Heat may not be discharged in the vicinity of spawning areas or where increased water temperature might interfere with recognized movements of spawning or migrating fish populations.

(3) Inland Waters

(a) Heated discharges to inland waters will not be permitted unless it is clearly demonstrated that heated effluents will enhance the usefulness of the water resource without endangering the production and optimum maintenance of wildlife, fish and other aquatic species. It shall be the responsibility of the user to provide evidence to support the acceptability of the discharge under these terms.

(b) Inland trout streams, salmon streams, trout and salmon lakes and the hypolimnion of lakes and reservoirs containing salmonids and other cold water forms should not be warmed.

(c) Heat may not be discharged in the vicinity of spawning areas or where increased temperature might interfere with recognized movements of spawning or migrating fish populations.

Dissolved Oxygen

(1) Warm-water Biota

The dissolved oxygen (DO) concentration should be above 5 mg/l at all times, except that in certain situations concentrations may range between 5 and 4 mg/l for short intervals within any 24-hour period provided that water quality is favourable in all other respects.

(2) Cold-water Biota

In spawning areas, DO levels must not be below 7 mg/l at any time. Elsewhere DO concentrations should not be below 6 mg/l. In certain situations, they may range between 6 and 5 mg/l for short intervals within any 24-hour period, provided the water quality is favourable in all other respects.

Carbon Dioxide

The 'free' carbon dioxide concentration should not exceed 25 mg/l.

Oil

Oil, petrochemicals or other immiscible substances that will cause visible films or toxic, noxious or nuisance conditions should not be added to water.

Turbidity

(1) Turbidity associated with waste inputs should not exceed 50 Jackson units in warm-water streams or 10 Jackson units in cold-water streams.

(2) There should be no discharge which would cause turbidities exceeding 25 Jackson units in warm-water lakes or 10 Jackson units in cold-water or oligotrophic lakes.

Settleable Materials

Substances should not be added that will adversely affect the aquatic biota or will create objectionable deposits on the bottom or shore of any body of water.

Colour and Transparency

For effective photosynthetic production of oxygen, it is required that 10 per cent of the incident light reach the bottom of any desired photosynthetic zone in which adequate dissolved oxygen concentrations are to be maintained.

Floating Materials

All floating materials, other than those of natural origin, should be excluded from streams and lakes.

Tainting substances

All materials that will impart odour or taste to fish or edible invertebrates should be excluded from receiving waters at levels that produce tainting.

Radionuclides

Radioactive materials should not be present in natural waters as a consequence of failure to exercise necessary controls of radioactivity releases to keep exposure to a minimum.

Experience has shown that standards established for drinking water assure that people will receive no more than currently acceptable amounts of radioactive materials from aquatic sources and that fish and other aquatic life will not receive an injurious dose of radiation.

Thus, present standards accepted for the protection of fish and other aquatic life are as follows.

	pc/l
Gross beta emitters	1000
Radium-226	3
Strontium-90	10

Where other radioisotopes occur, the significance of the exposure of aquatic species to these forms of radiation should be assessed for each situation, both with respect to potential damage to the organisms themselves and to humans where fish or other edible forms are utilized.

Plant Nutrients and Nuisance Growths

(1) Nutrients from unnatural sources that will stimulate production of algae, nuisance vegetation or offensive slime growths should not be added to water. The addition of sulphates or manganese oxide to a lake should be limited if iron is present in the hypolimnion as these substances may increase the quantity of available phosphorus.

(2) Organic or other materials that will promote an increased zone of anaerobic decomposition within a lake, reservoir or other body of water should not be allowed to enter the water.

(3) The naturally-occurring ratios of nitrogen (particularly NO_3 and NH_4) to total phosphorus, and their amounts, should not be radically changed by the addition of materials from waste sources and land drainage.

Toxic Substances

Toxic substances must not be added to water in concentrations or combinations that are toxic or harmful to human, animal, plant or aquatic life, except where the application of approved substances for the control of nuisance organisms has been authorized by the Ministry (Section [illegible] OWRC Act).

The evaluation of toxicity for aquatic organisms is based on use of the TLm or median tolerance limit. This represents the concentration at which half the test organisms will succumb over a given period of exposure such as 24, 48 or 96 hours. It does not, therefore, represent the safe concentration an application factor is applied to ensure a safe c ation, including allowance for sub-lethal effects.

(1) Substances of Unknown Toxicity

All effluents containing foreign materials should be considered harmful and not permissible until bioassay tests have shown otherwise. The onus for demonstrating that an effluent is harmless in the concentrations to be found in the receiving waters rests with those responsible for the discharge. Information concerning acceptable bioassay procedures is available from the Ministry.

(2) Application Factors

Concentration of materials that are non-persistent (that is, have a half-life of less than 96 hours), or have non-cumulative effects after mixing with the receiving waters, should not exceed 1/10 of the applicable 96-hour TLm value at any time or place based on species representative of local conditions. The 24-hour average of the concentration of these materials should not exceed 1/20 of the TLm value after mixing. For other toxicants, the concentrations should not exceed 1/20 and 1/100 of the TLm value under the aforementioned conditions.

(3) Additive Effects

When two or more toxic materials that have additive effects are present at the same time in the receiving water, some reduction is necessary in the permissible concentrations as derived from bioassays on individual substances or wastes. The amount of reduction required is a function of both the number of toxic materials present and their concentrations in respect to the derived permissible concentration. An appropriate means of assuring that the combined amounts of the several substances do not exceed a permissible concentration for the mixture is through the use of the following relationship:

$$\left(\frac{C_a}{L_a} + \frac{C_b}{L_b} \ldots + \frac{C_n}{L_n} \leq 1\right)$$

where C_a, C_b, ... C_n are the measured concentrations of the several toxic materials in the water and L_a, L_b, ... L_n are the respective permissible concentration limits derived for the materials on an individual basis. Should the sum of the several fractions exceed one, then a local restriction on the concentration of one or more of the substances is necessary.

(4) Pesticides

(a) Chlorinated Hydrocarbons:

Any addition of chlorinated hydrocarbon insecticides is likely to cause damage to some desired organisms and their use should be avoided.

(b) Other Chemical Pesticides:

Other pesticides and herbicides gaining access to water can cause damage to desirable organisms and should be used with utmost discretion and caution. Tables F & W-1 and F & W-2

TABLE F & W-1 INSECTICIDES*

(48-hour TLm values from static bioassay, in micrograms per litre. Exceptions are noted.)

Pesticide	Stream Invertebrate[1] Species	Stream Invertebrate[1] TLm	Cladocerans[2] Species	Cladocerans[2] TLm	Fish[3] Species	Fish[3] TLm	Gammarus Lacustris,[1] TLm
Abate	Pteronarcys californica	100			Brook trout	1,500	640
Aldrin[4]	P. californica	8	Daphnia pulex.	28	Rainbow trout	3	12,000
Allethrin	P. californica	28	D. pulex	21	- do -	19	20
Azodrin					- do -	7,000	
Aramite			D. magna.	345	Bluegill	35	100
Baygon[3]	P. californica	110			Fathead	25	50
Baytex[3]	P. californica	130	Simocephalus serrulatus	3.1	Brown t.	80	70
Benzene hexachloride (lindane)	P. californica	8	D. pulex	460	Rainbow t.	18	88
Bidrin	P. californica	1900	D. pulex	600	- do -	8,000	790
Carbaryl (sevin)	P. californica	1.3	D. pulex	6.4	Brown t.	1,500	22
Carbophenothion (trithion)			D. magna	0.009	Bluegill	225	26
Chlordane[3]	P. californica	55	S. serrulatus	20	Rainbow t.	10	80
Chlorobenzilate			S. serrulatus	550	- do -	710	
Chlorthion			D. magna	4.5			
Coumaphos			D. magna	1			0.14
Cryolite			D. pulex	5,000	Rainbow t.	47,000	
Cyclethrin			D. magna	55			
DDD (TDE)[3]	P. californica	1100	D. pulex	3.2	Rainbow t.	9	1.8
DDT[4]	P. californica	19	D. pulex	0.36	Bass	2.1	2.1
Delnav (dioxathion)					Bluegill	14	690
Delmeton (systex)				14	- do -	81	
Diazinon[4]	P. californica	60	D. pulex	0.9	- do -	30	500
Dibrom (naled)	P. californica	16	D. pulex	3.5	Brook t.	78	160
Dieldrin[3]	P. californica	1.3	D. pulex	240	Bluegill	3.4	1,000
Dilan			D. magna	21	- do -	16	600
Dimethoate (cygon)	P. californica	140	D. magna	2500	- do -	9600	400
Dimethrin					Rainbow t.	700	
Dichlorvos[4] (DDVP)	P. californica	10	D. pulex	0.07	Bluegill	700	1
Disulfoten (di-syston)	P. californica	18			- do -	40	70
Dursban	Pteronarcella badia	1.8			Rainbow t.	20	0.4
Endosulfan (thiodan)	P. californica	5.6	D. magna	240	- do -	1.2	64
Endrin[4]	P. californica	0.8	D. pulex	20	Bluegill	0.2	4.7
EPH			D. magna	0.1	- do -	17	36
Ethion	P. californica	14	D. magna	0.01	- do -	230	3.2
Ethyl guthion[4]			D. pulex		Rainbow t.		
Fenthion	P. californica	39	D. pulex	4			
Guthion[4]	P. californica	8	D. magna	0.2	Rainbow t.	10	0.3
Heptachlor[3]	P. badia	4	D. pulex	42	- do -	9	100
Kelthane (dicofel)	P. californica	3000	D. magna	390	- do -	100	
Kepone					- do -	37.5	
Malathion[4]	P. badia	6	D. pulex	1.8	Brook t.	19.5	1.8
Methoxychlor[4]	P. californica	8	D. pulex	0.8	Rainbow t.	7.2	1.3
Methyl parathion[4]			D. magna	4.8	Bluegill	8000	
Morestan	P. californica	40			- do -	96	
Ovex	P. californica	1500			- do -	700	
Paradichlorobenzene					Rainbow t.	850	
Parathion[4]	P. californica	11	D. pulex	0.4	Bluegill	47	6
Perthane			D. magna	9.4	Rainbow t.	7	
Phosdrin[4]	P. californica	9	D. pulex	0.16	- do -	17	310
Phosphamidon	P. californica	460	D. magna	4	- do -	8000	3.8
Pyrethrins	P. californica	64	D. pulex	25	- do -	54	18
Rotenone	P. californica	900	D. pulex	10	Bluegill	22	350
Strobane[4]	P. californica	7			Rainbow t.	2.5	

* From Report of the Committee on Water Quality Criteria, Federal Water Pollution Control Administration, U.S. Department of the Interior (1968).

TABLE F & W-1—continued

Pesticide	Stream Invertebrate[1] Species	Stream Invertebrate[1] TLm	Cladocerans[2] Species	Cladocerans[2] TLm	Fish[3] Species	Fish[3] TLm	Gammarus Lacustris,[4] TLm
Tetradifon (tedion)					Bluegill	1100	140
TEPP[5]					Fathead	390	52
Thanite			D. magna	450			
Thimet					Bluegill	5.5	70
Toxaphene[5]	P. californica	7	D. pulex	15	Rainbow t.	2.8	70
Trichlorofon (dipterex)[5]	P. badia	22	D. magna	8.1	- do -	160	60
Zectran	P. californica	16	D. pulex	10	- do -	8000	76

TABLE F & W-2

HERBICIDES, FUNGICIDES, DEFOLIANTS, ALGICIDES*

Pesticide	Stream Invertebrate[1] Species	Stream Invertebrate[1] TLm	Cladocerans[2] Species	Cladocerans[2] TLm	Fish[3] Species	Fish[3] TLm	Gammarus Lacustris,[4] TLm
Ametryne					Rainbow t.	3400	
Aminotriazole							
Aquathol					Bluegill	257	
Atrazine			Daphnia magna	3600	Rainbow t.	12,600	
Azide, potassium					Bluegill	1400	10,000
Azide, sodium					- do -	980	9000
Copper chloride					- do -	1100	
Copper sulphate					- do -	150	
Dichlobenil	Pteronarcys californica	44,000	Daphnia pulex	3700	- do -	20,000	1500
2,4-D PGBEE			D. pulex	3200	Rainbow t.	960	1800
2,4-D BEE	P. californica	1800			Bluegill	2100	760
2,4-D isopropyl					- do -	800	
2,4-D butyl ester					- do -	1300	
2,4-D butyl + isopropyl ester					- do -	1500	
2,4,5-T isooctyl ester					- do -	16,700	
2,4,5-T isopropyl ester					- do -	1700	
2,4,5-T PGBE					- do -	560	
2(2,4-DP) BEE					- do -	1100	
Dalapon	P. californica Very low toxicity		D. magna	6000	Very Low Toxicity		
Dead-X	P. californica	5000	D. pulex	3700	Rainbow t.	9400	5600
DEF	P. californica	2300			Bluegill	36	230
Dexon	P. californica	42,000			Bluegill	23,000	6000
Dicamba					non-toxic		5800
Dichlone			D. magna	26	Rainbow t.	48	11,500
Difolitan	P. californica	150			Channel Cat	31	6500
Dinitrocresol	P. californica	560			Rainbow t.	210	
Diquat					Rainbow t.	12,300	
Diuron	P. californica	2800	D. pulex	1400	- do -	4300	380
Du-ter					Bluegill	33	
Dyrene			D. magna	490		15	
Endothal, copper					Rainbow t.	290	
Endothal dimethylamine					Rainbow t.	1150	
Fenac, acid	P. californica	70,000			- do -	16,500	
Fenac, sodium	P. californica	80,000	D. pulex	4500	- do -	7500	18,000
Hydram (molinate)	P. californica	3500			- do -	290	
Hydrothol 191					- do -	690	1000
Lanstan (Korax)					- do -	100	5500
LFN					- do -	79	
Paraquat	P. californica Very low toxicity		D. pulex	3700	Very low toxicity		18,000
Propazine					Rainbow t.	7800	
Silvex, PGBEE			D. pulex	2000	- do -	650	
Silvex, isoctyl					Bluegill	1400	
Silvex, BEE					- do -	1200	
Simazine					Rainbow t.	5000	21,000
Sodium arsenite	P. californica P. californica Very low toxicity	50,000	Simocephalus serrulatus	1400	- do -	36,500	
Tordon (picloram)					- do -	2500	48,000
Trifluralin	P. californica	4200	D. pulex	240	- do -	11	5600
Vernam[5] (vernolate)					- do -	5900	25,000

---

1 Stonefly bioassay was done at Denver, Colo., and at Salt Lake City, Utah. Denver tests were in soft water (35 mg/l TDS), non-aerated, 60 F. Salt Lake City tests were in hard water (150 mg/l TDS), aerated, 48-50 F. Response was death.

2 Daphnia pulex and Simocephalus serrulatus bioassay was done at Denver, Colo., in soft water (35 mg/l TDS), non-aerated, 60 F. Daphnia magna bioassay was done at Pennsylvania State University in hard water (145 mg/l TDS), non-aerated, 68 F. Response was immobilization.

3 Fish bioassay was done at Denver, Colo., and at Rome N.Y. Denver tests were with 2-inch fish in soft water (35 mg/l TDS), non-aerated, trout at 55 F.; other species at 65 F. Rome tests were with 2-2½ inch fish in soft water (5 mg/l TA; pH 3.65-6.4), 60 F. Response was death.

4 Gammarus bioassay was done at Denver, Colo., in soft water (35 mg/l TDS), non-aerated, 60 F. Response was death.

5 Becomes bound to soil when used according to directions, but highly toxic (reflected in numbers) when added directly to water.

* From Report of the Committee on Water Quality Criteria, Federal Water Pollution Control Administration, U.S. Department of the Interior (1968)

list t [illegible] hour TLm values of a number of pesticides for various types of fresh water organisms. To provide reasonably safe concentrations of these materials in receiving waters, application factors ranging from 1/10 to 1/100 should be used with these values depending on the characteristic of the pesticide in question and used as specified in (2) above. Concentrations thus derived may be considered tentatively safe under the conditions specified. TLm values and related application factors are subject to revision as additional bioassay information is obtained for species which may be more representative of local conditions.

(5) Other Toxic Substances

(a) ABS:	The concentration of ABS should not exceed 1/7 of the 48-hour TLm at any time or place.
(b) LAS:	The concentration of LAS should not exceed 1/7 of the 48-hour TLm at any time or place.
(c) ARSENIC:	An application factor of 1/100 should be applied to the 96-hour TLm value as a tentative safe concentration for continuous exposure. An environmental level of .01 mg/l should not be exceeded under any circumstances.
(d) AMMONIA:	Permissible concentrations of ammonia should be determined by the flow-through bioassay with the pH of the test solution maintained at 8.5, DO concentrations between 4 and 5 mg/l, and temperatures near the upper allowable levels.
(e) CADMIUM:	The concentration of cadmium must not exceed 1/500 of the 96-hour TLm concentration at any time or place.
(f) CHROMIUM:	The concentration of chromium should not exceed 1/100 of the 96-hour TLm at any time or place.
(g) COPPER:	The maximum copper (expressed as Cu) concentration at any time or place shall not be greater than 1/12 of the 96-hour TLm value. The maximum permissible concentration for continuous exposure is between 3 per cent and 7 per cent of the 96-hour TLm.
(h) LEAD:	The concentration of lead should not exceed 1/20 of the 96-hour TLm at any time or place and the 24-hour average should not exceed 1/100 of the 96-hour TLm concentration after mixing.
(i) MERCURY:	Owing to demonstrated cumulative effects of mercury in fish, and the attendant hazard to other animals, discharges of mercury to water should be avoided.
(j) NICKEL:	The concentration of nickel should not exceed 1/50 of the 96-hour TLm concentration at any time or place.
(k) ZINC:	The concentration of zinc should not exceed 1/100 of the 96-hour TLm concentration at any time or place.

3 WATER QUALITY CRITERIA FOR INDUSTRIAL WATER SUPPLIES (IWS)

Desired water quality criteria are tabled for the major industrial classifications as follows:

Brewing and Soft Drinks	— IWS-1
Chemical and Allied Products	— IWS-2
Industrial Cooling	— IWS-3
Food Processing	— IWS-4
Electroplating and Metal Finishing	— IWS-5
Iron and Steel	— IWS-6
Petroleum	— IWS-7
Pulp and Paper	— IWS-8
Leather Tanning and Finishing	— IWS-9
Textiles	— IWS-10

While the values listed should not normally be exceeded, these water quality criteria can vary considerably for the same industrial process depending on factors such as the technological age of plant design.

A raw surface water and/or ground water supply which is used by many different industries may not satisfy the widely varying criteria for each use. However, water treatment technology in its present state of development permits the utilization of surface water of literally any available quality to produce water of any desired quality at the point of use in industry.

Most industries located on municipal water supply systems find the quality of water provided to be satisfactory. If the water quality requirements of an industry are such that water of higher quality than that provided by the municipality is required for specific process use, the industry generally accepts the additional costs involved to produce the higher quality water.

TABLE IWS-1

WATER QUALITY CRITERIA FOR THE BREWING AND SOFT DRINK INDUSTRIES

(Unless otherwise indicated, units are mg/l)

Characteristic	Concentration
Alkalinity ($CaCO_3$)	65
pH, units	(1)
Hardness ($CaCO_3$)	(1)
Chloride (Cl)	250(2)
Sulphate (SO_4)	250(2)
Iron (Fe)	0.3(3)
Manganese (Mn)	0.05
Fluoride (F)	1(3)
Dissolved solids	(1)
Organics: carbon chloroform extract (CCE)	0.15(3)
Coliform bacteria, count/100 ml	(3)
Colour, units	5(4)
Taste, threshold number	(4, 5)
Odour, threshold number	(4, 5)

(1) Controlled by treatment for other constituents
(2) For brewing, value should not exceed 100 mg/l.
(3) Not greater than OWRC Drinking Water Objectives.
(4) In general, public water supplies are given conventional treatment such as coagulation, filtration and chlorination. Any additional requirement for higher quality, for example, deionized water, is the responsibility of the industry. To ensure low organic content, activated carbon treatment is used by industry.
(5) Zero, not detectable by test.

TABLE IWS-2

WATER QUALITY CRITERIA FOR THE CHEMICAL AND ALLIED PRODUCTS INDUSTRIES*

(Unless otherwise indicated, units are mg/l)

Characteristic	Concentration[1]
Alkalinity (as $CaCO_3$)	150
Iron (Fe)	0.3
Manganese (Mn)	0.1
Calcium (Ca)	50
Magnesium (Mg)	25
Bicarbonate (HCO_3)	250
Sulphate (SO_4)	250
Chloride (Cl)	250
Nitrate (NO_3) as N	10
Hardness (as $CaCO_3$)	250
pH, units	6.5-8.5
Dissolved solids	750
Silica	50
Colour, units	20
Suspended solids	15

* Industries include the manufacture of synthetic rubber, plastics, fertilizers, soap and detergents, organic and inorganic chemicals, etc.

(1) Because of the varying requirements of the many uses in the vast number of chemical industries, more stringent restrictions are placed on several of the above noted characteristics. In some cases, any concentration can be handled, while in others, the raw water is accepted as received provided it meets total solids or other limiting values. The above concentrations are suggested guidelines that should be suitable for the majority of uses in the chemical industry.

TABLE IWS-3

WATER QUALITY CRITERIA FOR COOLING WATER*

(Unless otherwise indicated, units are mg/l)

Characteristic	Concentration
Turbidity	50
Hardness	50
Iron	0.5
Manganese	0.5

* Cooling waters should have appropriate initial temperatures and should not deposit scale, be corrosive or encourage the growth of slimes. Among the constituents of natural water that may prove detrimental to its use for cooling purposes are hardness, suspended solids, dissolved gases, acids, oil and other organic compounds and slime-forming organisms.

TABLE IWS-4

WATER QUALITY CRITERIA FOR THE FOOD PROCESSING INDUSTRY

(Unless otherwise indicated, units are mg/l)

Characteristic	Concentration
Alkalinity ($CaCO_3$)	150
pH, units	6.5-8.5
Hardness ($CaCO_3$)	150
Chloride (Cl)	250
Sulphate (SO_4)	250
Iron (Fe)	0.2
Manganese (Mn)	0.2
Chlorine (Cl)	(1)
Fluoride (F)	1(2)
Silica (SiO_2)	50
Phenol	(3, 4)
Nitrate (NO_3) as N	10(2)
Nitrite (NO_2) as N	(3)
Organics:	
Carbon chloroform extract (CCE)	0.15
Odour, threshold number	(3)
Taste, threshold number	(3)
Turbidity	(6)
Colour, units	5
Dissolved solids	500
Suspended solids	10
Coliform, count/100 ml	(6)
Total bacteria, count/100 ml	(7)

(1) Process waters for food canning are purposely chlorinated to a selected, uniform level. An unchlorinated supply must be available for preparation of canning syrups.
(2) Waters used in the processing and formulation of foods for babies should be low in fluorides concentration. Also, because high nitrate intake is alleged to be involved in infant illnesses, the concentration of nitrates in waters used for processing baby foods should be low.
(3) Zero, not detectable by test.
(4) Because chlorination of food processing waters is a desirable and widespread practice, the phenol content of intake waters must be considered. Phenol and chlorine in water can react to form chlorophenol, which even in trace amounts can impart a medicinal off-flavour to foods.
(5) Maximum permissible concentration may be lower depending on type of substance and its effect on colour and taste.
(6) As required by Ministry Drinking Water Objectives
(7) The total bacterial count must be considered as a quality requirement for waters used in certain food processing operations. Other than aesthetic considerations, high bacterial concentration in waters coming in contact with frozen foods may significantly increase the count per gram for the food. Waters used to cool heat-sterilized cans or jars of food must be low in total count for bacteria to prevent serious spoilage due to aspiration of organisms through container seams. Chlorination is widely practised to assure low bacterial counts on container cooling waters.

WATER QUALITY CRITERIA FOR THE ELECTROPLATING AND METAL FINISHING INDUSTRIES — IWS-5

Plating-room processes that utilize water include the stripping or pickling operations, cleaning by organic solvents or alkaline solutions, rinsing, and electrochemical plating. For acid stripping or for alkaline cleaning, the quality of water used in the baths is seldom critical, for the added chemicals far outweigh the natural constituents of the water. Hardness of water may be detrimental when soaps or alkaline cleaning agents are used.

THE UNIVERSITY OF WISCONSIN
MADISON, WISCONSIN 53706

LABORATORY OF LIMNOLOGY

IJC
Windsor
NOV 21 1978
DIR.
DIR.
A.O.
A.E.W. - New (21-XI-78)
FILE 3000-5-9

M E M O R A N D U M

TO: J.R. Brett, P.O. Fromm, F.E.J. Fry, and A.E.P. Watson

FROM: John J. Magnuson

DATE: November 15, 1978

SUBJECT: Summary of Data on Behavioral Responses of Fishes to Low Dissolved Oxygen

I have summarized my data on behavioral responses of fishes to low dissolved oxygen at temperatures below 4°C. Each of the behaviors indicated is interpreted to be adaptive to surviving low dissolved concentrations in winter.

Ventilation rate is the first to respond to lowered dissolved oxygen. Seven out of nine fishes exhibited faster ventilation rates when the concentration dropped from 4 to 2 mg/liter. An early decrease as concentrations were lowered to 4 mg/liter cannot be discounted because observations were not made at higher oxygen concentrations. Regardless, the increase in ventilation rate was usually the only behavioral change noted at 2 mg/liter.

Fish began moving upward in the water column at concentrations of 1.0, 0.5, and 0.25 mg/liter. This behavior would also be adaptive as it would tend to move the fish into water containing more oxygen in most winter habitats. Approximately half of the species increased their swimming activity when oxygen was present at 2.0, 1.0, 0.5, or 0.25 mg/liter, and six of the nine species decreased their swimming activity at concentrations of 1.0, 0.5, or 0.25 mg/liter. The central mudminnow and finescale dace increased locomotory activity at 2.0 mg/liter and then reduced activity at 0.5 mg/liter. Increased activity would appear to be search behavior for better habitats and the reduced activity could be conservation of energy or perhaps even an indication of deterioration of vital functions.

An oxygen concentration of 4 mg/liter did not result in these fishes employing their behavioral adaptations for surviving low oxygen habitats. Many of these species may be more tolerant than some of the Great Lakes species. Presumably, increases in ventilation rates at 1 and 2 mg/liter compensate for the change in oxygen. Consequently little impairment would be expected to occur to fish at these levels. Ventilation appears to become oxygen dependent at 0.25 mg/liter or even lower for some species.

These data suggest that a number of fishes can deal with oxygen levels below 4 mg/liter and above 2 mg/liter with little difficulty at temperatures below 4°C.

Enclosure

RESPONSES OF NINE FRESHWATER FISHES TO DECREASES IN DISSOLVED OXYGEN CONCENTRATIONS AT WATER TEMPERATURES BELOW 4°C

Oxygen concentrations were decreased on five successive days from 4-2 mg/liter, 2-1, 1-0.5, 0.5-0.25 in 42-liter aquaria covered with simulated ice. (See methods in Petrosky and Magnuson 1973.)

	OXYGEN CONCENTRATION WHERE CHANGE FIRST OCCURRED (mg/liter)				
	Ventilation Rate			Locomotory Activity	
Family Species	Increase	Decrease	Move Up In Water Column	Increase	Decrease
Umbridae					
Central mudminnow (*Umbra limi*) [1]	1.0	----	0.5	2.0	0.5
Esocidae					
Northern pike (*Esox lucius*) [2]	2.0	0.25	0.5	0.25	Did Not
Cyprinidae					
Fathead minnow (*Pimephales promelas*) [1]	2.0	----	1.0	Did Not	1.0
Northern redbelly dace (*Phoxinus eos*) [1]	2.0	0.25	0.25	Did Not	0.25
Finescale dace (*Phoxinus neogaeus*) [1]	2.0	----	0.25	2.0	0.5
Gasterosteidae					
Brook stickleback (*Culea inconstans*) [1]	2.0	----	1.0	Did Not	0.5
Centrachidae					
Bluegill (*Lepomis macrochirus*) [2]	2.0	0.5	Did Not	1.0	Did Not
Percidae					
Iowa darter (*Etheostoma exile*) [1]	2.0	0.25	Did Not	Did Not	1.0
Yellow perch (*Perca flavescens*) [2]	1.0	0.25	0.5	0.5	Did Not
Total Range	1.0-2.0	0.25	0.25-1.0	0.25-2.0	0.25-1.0

---

[1] Magnuson, J.J. (unpublished data).

[2] Data Source: Petrosky, B.R. and J.J. Magnuson 1973. Behavioral responses of northern pike, yellow perch, and bluegill to oxygen concentrations under simulated winterkill conditions. Copeia (1973):124-133.

Date: October 19, 1978

To: Members of Review Committee for D.O. (GLRAB)

From: Dr. Paul O. Fromm P.O. Fromm

The committee agrees that the water quality objective for dissolved oxygen should provide protection for the aquatic life and in order to do this the objectives must aim to maintain a critical oxygen content and necessary oxygen tension taking into consideration the physical and biological effects of temperature. With respect to oxygen tension the authors apparently relied heavily on statements made by Davis (1975) where he quoted Jones et al. (1970), not Jones (1971), and Randall (1970), (see paragraph 2 page 17 of the IJC report). Relying to such great extent on the oxygen tension of water in setting the dissolved oxygen requirements at lower environmental temperatures is open to question.

Paragraph 3, page 17 of the IJC report can be amplified as follows: The transfer factor (T_{O_2}) of gills is a measure of their capacity to transfer oxygen from water to blood. T_{O_2} can be calculated by dividing the total oxygen uptake per minute ($\dot{V}_{O_2}$) by the mean difference in oxygen partial pressure across the gill, ΔPg. ΔPg is determined in large part by $P_{v_{O_2}}$, the partial pressure of oxygen in venous blood. Oxygen transfer and arterial oxygen tension (Pa_{O_2}) are maximized by ensuring maximum blood flow to those portions of the gill receiving maximum water flow. Thus the transfer factor may be increased by (a) enlarging the effective surface area of the gills or (b) by reducing the diffusing distance between blood and water. These may be accomplished by altering the patterns of blood flow through the gill and water flow across the surface of gills.

The relation between water and blood flow to ΔPg is rather complex. With water oxygen tension and ventilation volume ($\dot{V}g$) constant, change in gill blood flow($\dot{Q}$) and/or the number of gill capillaries open to blood flow will alter the residence time of blood in gills and raise or lower the partial pressure of arterial blood leaving the gills. With constant internal perfusion ($\dot{Q}$) changes in ventilation volume and inhalent water P_{O_2} will likewise alter Pa_{O_2}. The total oxygen uptake and arterial oxygen saturation can be maintained in the face of a decrease in environmental oxygen content by (a) an increase in the ventilation volume ($\dot{V}g$), (b) a reduction in ΔPg, and (c) a decrease in Pv_{O_2}.

Randall (1970) did not make the statement that the internal-external gradient for trout should be 20 mm Hg. He did state that direct measurements of the mean P_{O_2} difference across the gill (ΔP_{O_2}) have never been made. And that, "In the absence of measurements, if one assumes that ΔP_{O_2} is 20 mm Hg, then the water shunt in the trout based on the data of Stevens and Randall (1967B) is 60% of the total ventilation volume." This is in line with a statement (p.261, Randall, 1970) that the P_{O_2} in water leaving the gills is not in equilibrium with that of venous blood thus not all of the oxygen that theoretically can be removed from water is utilized. Critical perusal of two 1971 papers by Jones (J. Theor. Biol. 32: 341-459 and J. Exp. Biol. 55:541-551) revealed no suggestion that a P_{O_2} of 118 mm Hg is necessary to maintain a proper gradient for oxygen uptake (by fish). However, Jones et al. (1970) did show theoretically that (when the mean P_{O_2} difference across the gill is 75 mm Hg and venous P_{O_2} is 20 mm Hg) trout at 5C maintain 95% saturation of arterial blood until the P_{O_2} of inhalent water falls below 118 mm Hg. When fish are exposed to an hypoxic environment they can increase their ventilation volume or reduce the P_{O_2} difference across the gill in order to maintain arterial P_{O_2}. Holeton and Randall (1967) demonstrated in trout that below an environmental P_{O_2} of 120 mm Hg, ΔP_{O_2} decreases almost linearly. Too, fish can reduce $P_{V_{O_2}}$ when exposed to hypoxic conditions, i.e., increase oxygen extraction from the blood by the tissues. The reduced venous oxygen tension facilitates oxygen nsfer across the gills and permits a lowering of gill blood flow.

When fish are subjected to lowered environmental temperatures, their standard metabolism is decreased. It is theoretically possible that blood does not need to be fully saturated (95% or above) to provide an adequate amount of oxygen for delivery to the tissues. Oxygen dissociation curves for rainbow trout (Cameron, 1971) indicates that at 10C the blood is 75 to 90% saturated with oxygen at a P_{O_2} of 40 mmHg. The lower value was determined at abnormally high P_{CO_2} levels so that in vivo the % saturation would probably be nearly 90%. Even at 20C the % saturation was found to be around 70 at the same P_{O_2} and normal P_{CO_2}. Currently, we do not know the tissue oxygen tension necessary to sustain the normal level of metabolic activity in fishes. This value would set the lower limit for $P_{v_{O_2}}$. Venous oxygen tensions are variable and those fish such as carp with a normally low $P_{v_{O_2}}$ have a limited capacity to regulate oxygen uptake by altering venous oxygen tension.

As stated earlier, the above comments suggest that some reduction in the proposed dissolved oxygen objectives are justified, especially for those temperatures below 15C.

C

FISH PHYSIOLOGY — Academic Press, 1979

Volume VIII

Bioenergetics and Growth

J. R. Brett
Pacific Biological Station
Fisheries and Marine Service
Department of the Environment
Nanaimo, British Columbia

Peters (1971) and Peters and Boyd (1972) have used restricted rations in experiments on the combined effects of temperature, salinity and food availability on the growth of young flatfish, *Trinectes maculatus*. By examining the response at an intermediate temperature (20°C) it is apparent that the slope of the GR curve increases with increasing salinity such that, from a common pivot point of similar maintenance rations, an increase in salinity induced a higher G_{max} when on *ad libitum* feeding. When starved, at 15°C, *Trinectes maculatus* lost weight faster in fresh water than at higher salinities; the reverse was observed at 35°C.

These illustrations serve to point up the complexity and diversity of the growth response to salinity, a circumstance that is likely to require searching physiological analysis for adequate explanation. Whatever this may be, it is of interest to note that in nature these species of flatfish occur most frequently at salinities where they grow fastest (Peters, 1971).

It can be concluded that, with the possible exception of the smolting stage in salmonids, evidence for any substantial increase in growth accompanying isosmotic conditions is lacking (isionic conditions have not been examined). Pronounced decreases in G_{max} with increasing salinity, among freshwater adapted species, appear to be the result of large increases in R_{maint}. As the limit of salinity tolerance is approached and regulation becomes progressively inadequate, R_{max} falls to the level of R_{maint} blocking further growth.

D. OXYGEN

At the time of feeding and for some hours thereafter the metabolic rate of fish is elevated (Chapter 4). Some authors deduced that for maximum rations the increased demand for oxygen could reach as high as the active metabolic rate (Paloheimo and Dickie, 1966). While this may be true in nature where the daily encounter of predator and prey can involve numerous bursts of activity, in the laboratory the maximum metabolic requirement does not appear to exceed two or three times the standard rate (about one-third active metabolism). The total daily increase in oxygen consumption is directly related to the size of the meal; like any other activity, as the load increases the energy expenditure goes up (Chapter 4b). One aspect of the metabolic process, *specific dynamic action*, has not always been clearly defined and measured for fish (Warren, 1971; Beamish, 1974). Despite the sequence of complex digestion-absorption-transformation steps in food processing, environmental oxygen can be shown to act as a simple Limiting Factor, sharply curtailing growth and food conversion efficiency at critical oxygen levels, usually well below the air-saturation point. However, oxygen cannot be confined *a priori* to this single role. It is conceivable that reduced oxygen content could act as a cue (Directive Factor) for reduction of appetite -- or more likely some associated change accompanying lowered oxygen, since the existence of O_2-sensors among fish has yet to be confirmed.

1. Maximum Growth Rate (G_{max}) × Oxygen

While many studies have been conducted on the effects of oxygen supply on the growth rate of fish, these are very varied in relation to duration, size and survival of fish, nature of diet, temperature applied, and the level and precision of environmental oxygen control, such that useful systematic tabulation is difficult if the comparability is to be preserved (see: Brungs, 1971; Swift, 1963, 1964; Doudoroff and Shumway, 1967, 1970; Warren, 1971; Ebeling and Alpert, 1966; Davison *et al*., 1959). The studies involving late embryonic and early larval stages, where first feeding occurs, are complicated by the change in developmental state during the test period and the initiating of an adequate feeding response. Further, there is a bias introduced where only the size of the surviving fish can be used to determine growth. Some increased sensitivity to reduced oxygen is apparently present at the larval stage in comparison with the juvenile stage; the margin, however, is not great (Carlson and Siefert, 1974; Carlson _et al_., 1974).

From three well-documented studies on juveniles it has been possible to determine the mean and variance of the "growth index" applied in each case (Chiba, 1966; Stewart _et al_., 1967; Herrmann _et al_., 1962). This was done by grouping according to concentration* intervals of 0.5 ppm O_2, and plotting the results as the mean of G_{Dax} against the mean value of the concentrations within each of the O_2-intervals (Fig. 15). Where only two values occurred in a given interval, the range was used. Despite the considerable deviation accompanying each mean determination (partly due to experimental variability in O_2-level) it is clear that an oxygen concentration of close to 5 ppm is critical for growth, below which increasing suppression of G_{Dax} is directly proportional to decreasing O_2-concentration -- a drop of 1 ppm causes a 30% reduction in growth rate. The analysis bears further comment. None of the authors would dispute the O_2-dependent segment of the curves as depicted. However, the balance of the relation might be contested, here shown as forming a plateau beyond the critical transition zone (depicting complete _independence_ of O_2-concentration above 5 ppm, as in simple limiting cases). In two of the original sources (Stewart _et al_., 1967; Herrmann _et al_., 1962) and again in Doudoroff and Shumway (1970) the data for largemouth bass are interpreted by the authors as rising to a peak of growth close to 8 ppm (100% saturation) and falling off at concentrations far in excess of this, e.g., 17 ppm at 26°C (212% saturation). It is known that excessive oxygen

---

*Since fish have a great ability to extract oxygen from water, concentration is a better indicator of available amount than saturation.

concentrations can even be lethal (Hubbs, 1930). However, from the variance of the small samples involved above the 5 ppm critical level, there is insufficient evidence to negate the present interpretation. Support for the latter can be gained from the fact that oxygen concentration would have to be reduced to the critical level indicated (approximately 5 ppm) in order to act as a Limiting Factor to the associated metabolic rate (see Chapter 4b). It should be noted that experimentally reduced oxygen concentration is maintained in the complete absence of any change in the rest of the controlled environment. In nature, and in hatcheries, decreased oxygen would likely be accompanied by an increase in other environmental factors such as ammonia, urea and nitrites which would act antagonistically to growth.

The presence of a definite upper plateau, supporting the Limiting Factor concept, is clearly depicted in the conversion efficiency relation 16 in Fig. 16. The values obtained above 5 ppm are in keeping with the high efficiency that usually accompanies good growth when young fish are fed a nutritious diet. Tests conducted on a small number of juvenile Northern pike, Esox lucius, by Adelman and Smith (1970) follow the same pattern as the three species illustrated in Fig. 15. Evidence for reduction in food consumption and conversion efficiency for this species suggests a critical level between 3 and 4 ppm O_2 (at 19°C).

2. Restricted Rations × Oxygen

Since ration is the "driving force" any restriction obviously reduces the growth opportunity to a lower level; the GR curve is truncated. As was pointed out, a restricted ration is also accompanied by a lowering of the daily metabolic rate and consequently a reduced demand for oxygen. Thus, it might be expected that the critical oxygen level would fall. Fisher (1963) 17 demonstrated this clearly for underyearling coho salmon (Fig. 17). On a limited ration, which resulted in approximately 0.4 G_{max}, the critical oxygen level dropped to between 3 and 4 ppm. If the positions of inflection inferred by Fisher (1963) are used, intermediate levels of restricted ration would be expected to follow the paths indicated in Fig. 17 (dotted lines).

The general phenomenon witnessed under these circumstances is the interrelation of two Limiting Factors -- food and oxygen -- acting *in series*. Successive plateaus below G_{max} are set by the degree of restricted ration. But as oxygen is reduced, an O_2-dependent stage enters to depress the growth rate below that previously dictated by the limited ration (depicted by the slope of the line below the plateau, Fig. 17)

This phenomenon can be identified in the response of channel catfish exposed to three oxygen concentrations and two feeding regimes (Andrews *et al.*, 1973). At 26.6°C the saturations imposed convert to the following concentrations: 100% = 7.9 ppm O_2, 60% = 4.7 ppm O_2, and 30% = 2.8 ppm O_2. On *ad libitum* feeding (R_{max}) there was a significant reduction in growth rate between each O_2-level, which would be expected for concentrations below the critical O_2-level of 5 ppm (results: G = 3.1% wt/day at 7.9 ppm, 2.7% at 4.7 ppm, and 1.8% at 2.8 ppm). When fed a fixed ration of 3% wt/day there was no significant difference between the two higher O_2-concentrations (avg. G = 1.8% wt/day); only the growth rate at 2.8 ppm O_2 was depressed (G = 1.3% wt/day). Thus, the limiting effect of reduced oxygen was shifted to a lower concentration when on restricted ration.

3. Varying Oxygen × Growth

Daily oscillations in oxygen content are not unusual in nature, frequently produced through the light cycle on photosynthesis. Stewart *et al.* (1967) subjected largemouth bass to alternately low (2-4 ppm) and higher (4-8 ppm) oxygen concentrations and showed that growth was markedly impaired. The reduction was greater than that which would have occurred if kept at the mean O_2-level, showing the detrimental consequences of the low concentrations when these were below the critical level. When the variation was entirely below the critical value (e.g, 1.8 to 3.7 ppm) the growth was only 32% of that expected for a concentration equivalent to the mean daily O_2-level.

Whitworth (1968) demonstrated a similar inhibiting effect on the growth of brook trout, *Salvelinus fontinalis*. When subjected to fluctuating oxygen levels (10.6 ppm reduced to either 5.3 or 3.6 ppm) the fish lost weight and were approximately 75% of the weight achieved by a control group at 10.6 ppm (for 49 days). Diurnal fluctuations from 3.0 ppm O_2 rising to either 9.5 or 18 ppm O_2, applied by Fisher (1963) to underyearling coho, resulted in an almost equally depressed growth rate, similar to that which would have occurred at fixed levels of 3.5 and 3.9 ppm respectively.

It is apparent from these few but revealing studies on fluctuating O_2 that high concentrations above air-saturation do not confer any substantial benefit compensating for the periods of low concentration. Further, an exposure to subcritical levels of oxygen for only a portion of the day (e.g., 8-12 hr) is sufficient to depress the growth rate to that comparable with the constant low-O_2 level. And this is despite feeding during the high-O_2 period. There is obviously not a simple on-off effect without a carryover of serious consequences into the higher O_2-period.

E. SUMMARY CONFIGURATIONS

More information is available on the effects of temperature on growth than any other abiotic factor; oxygen is next, with light and salinity not at all well documented. Within these limitations an attempt has been made to present the various patterns that the GR curves follow for each environmental factor, and the consequent path of the major parameter G_{max} (see Fig. 1 19
These illustrate the categories of effect (Factors) postulated by Fry (1947).

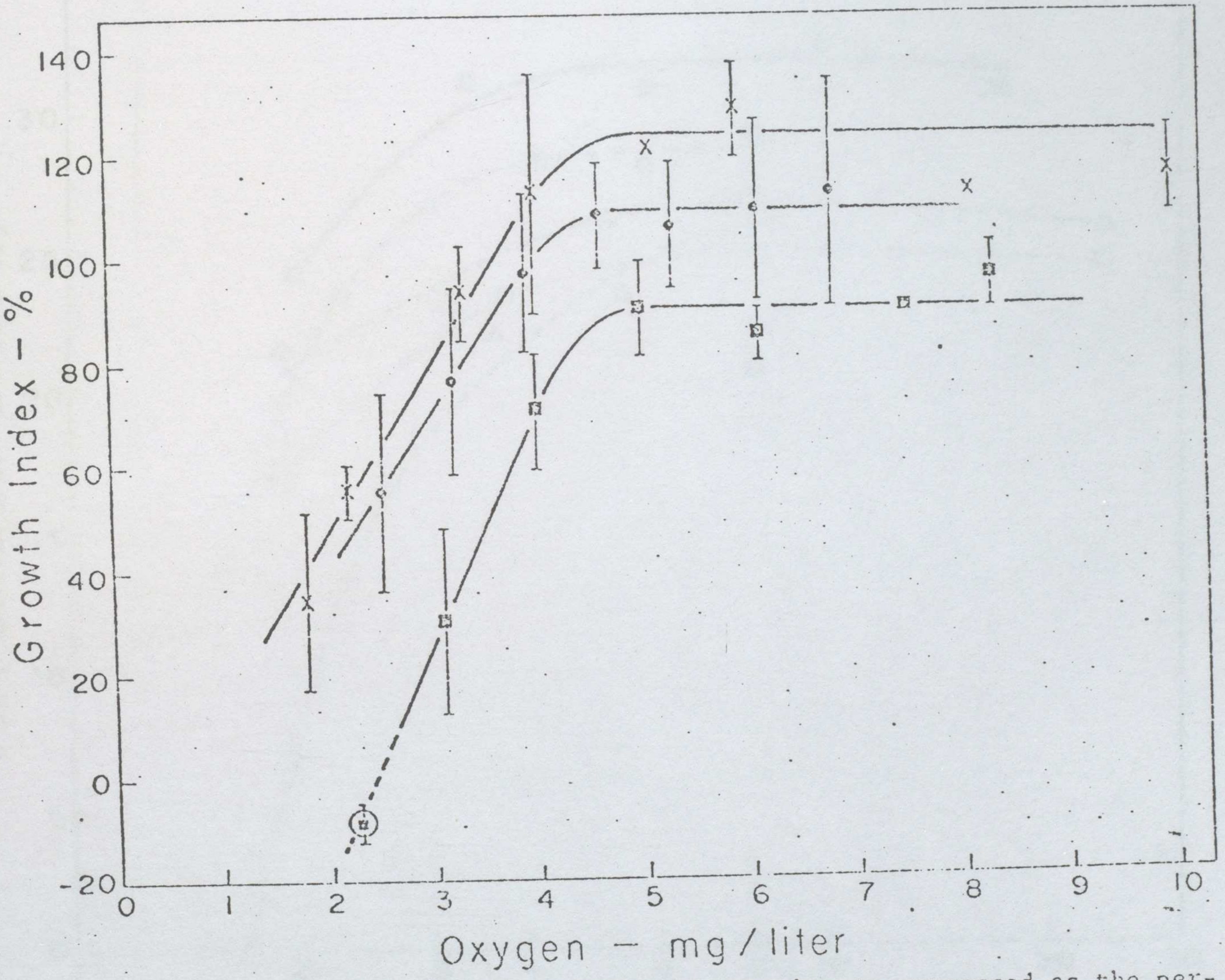


Fig. 15. Relation of oxygen concentration to growth rate expressed as the percentage of the "growth index" developed by each author. Limits = ± 1SD. Data for *Micropterus salmoides* (26°C; 2.5-4.5 g - upper curve) from Stewart *et al.* (1967), for *Cyprinus carpio* (22°C; 0.5-3.4 g - middle curve) from Chiba (1966), and for *Oncorhynchus kisutch* (20°C; 2-6 g - lower curve) from Herman *et al.* (1962); circled point was accompanied by significant mortalities. The vertical positioning by species has no relative significance. Lines drawn according to interpretation presented in text.

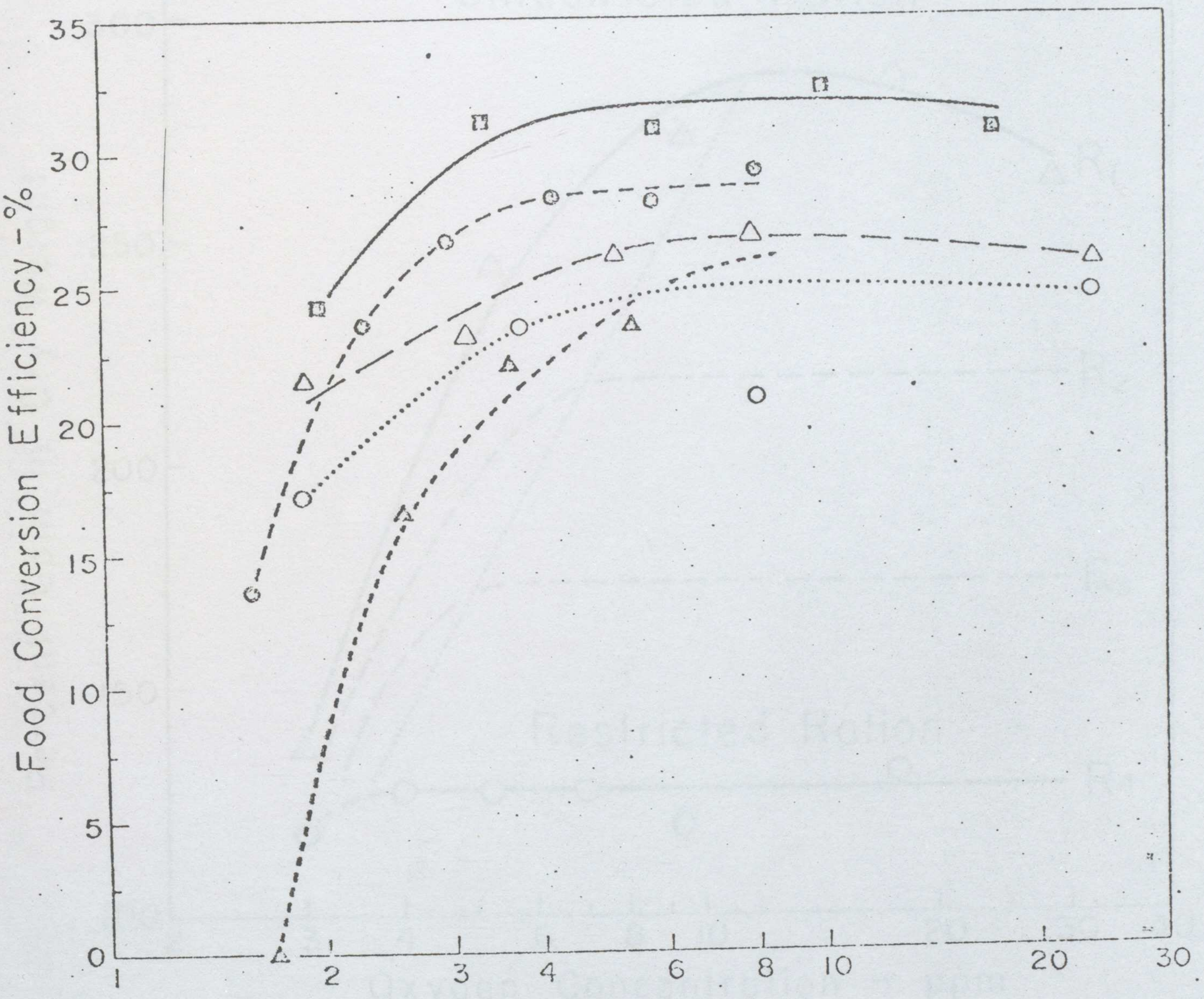


Fig. 16. Food conversion efficiency in relation to oxygen concentration. Results are for separate experiments conducted on Micropterus salmoides at 26°C. From Stewart *et al.* (1967).

C

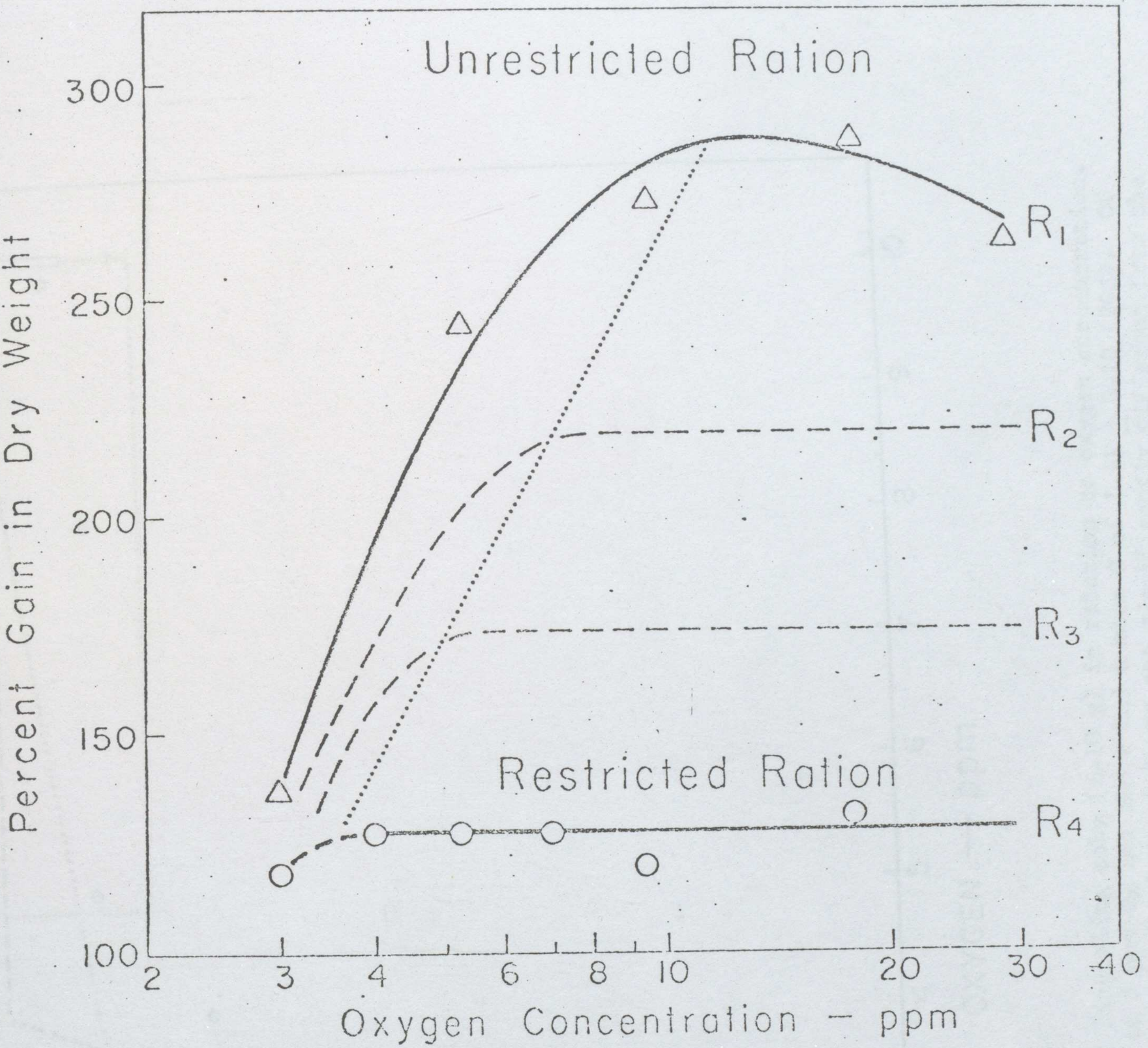
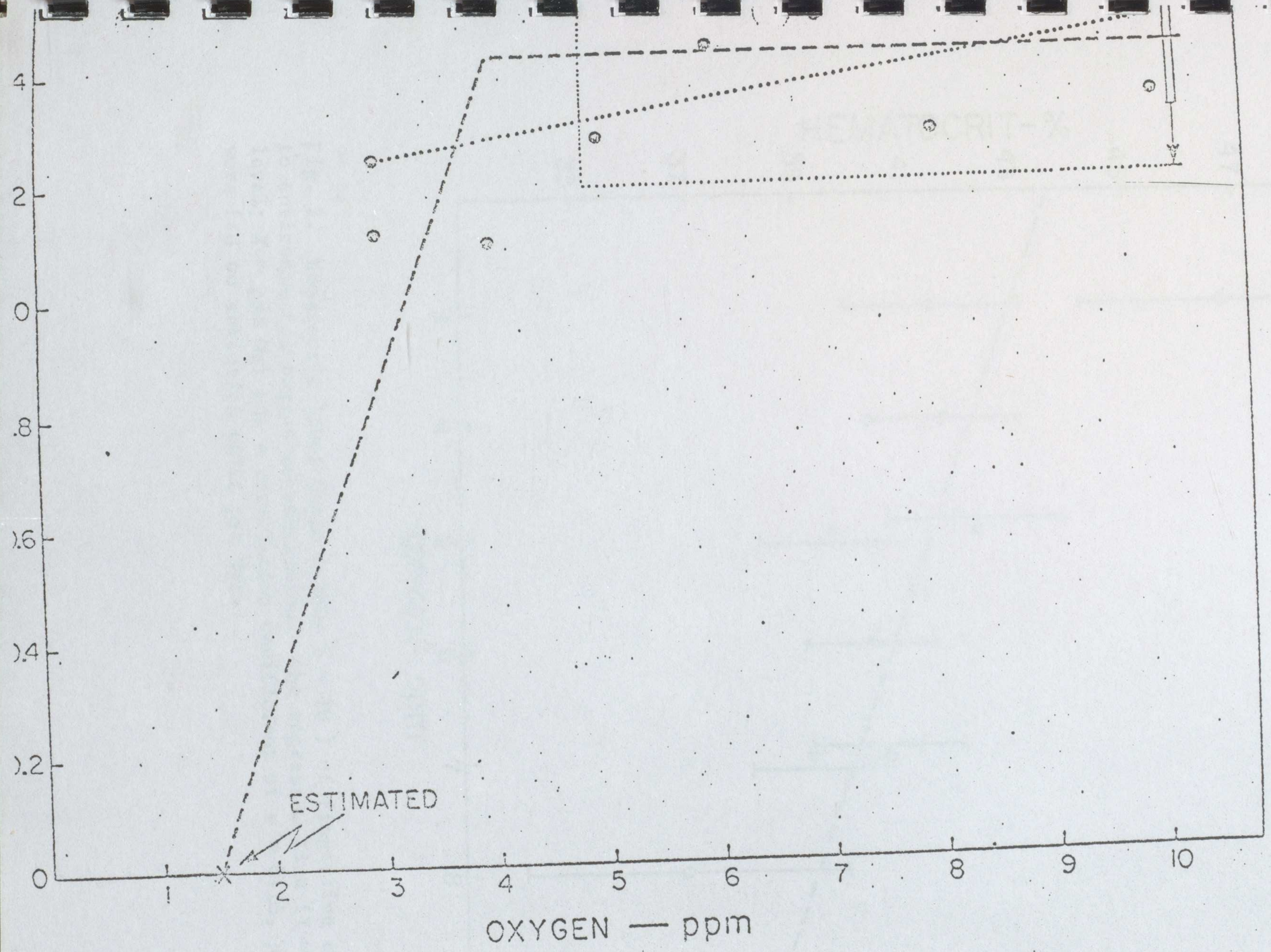


Fig. 17. Growth rate of coho salmon, *Oncorhynchus kisutch*, on unrestricted ration (R_1) and restricted ration (R_4) in relation to oxygen concentration (modified from Fisher, 1963; reproduced in Doudoroff and Shumway, 1967). The dotted construction line has been added, joining the points of inflection for R_1 and R_4. The expected relations for intermediate restricted rations (R_2 and R_3) have been drawn as broken lines.



.g. 1. Specific growth rate (G) of fingerling coho (6-10 g) in relation to oxygen concentration, : 15°C. The seven values obtained at 5 ppm O_2 and above had a mean G of 1.41 ± 0.10 (2SE). Of ıe three growth rates below 5 ppm O_2, one (at 3 ppm O_2) was not significantly different from the alues for 5 ppm and above. Limits are shown as mean ± 2SD, ± 2SE, n = 25. The dotted line is the egression relation of growth rate and oxygen concentration. The broken line is the interpreted elation, using an observed distress response to a steady reduction in ppm O_2 at the termination of

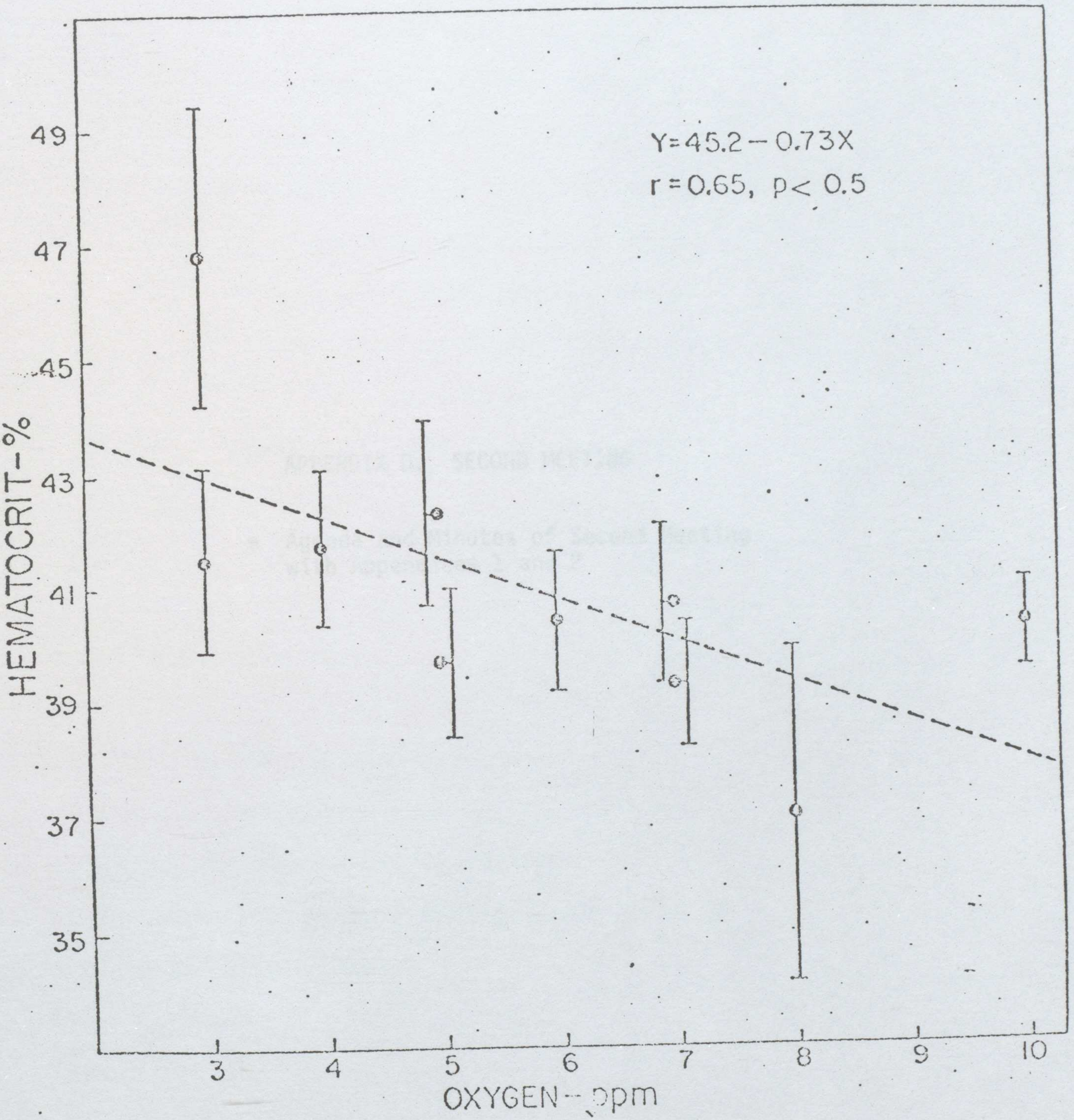


Fig. 2. Hematocrit level (mean ± 2SD, h = 10) of fingerling coho in relation to environmental oxygen concentration. The regressed line (Y = hematocrit level; X = ppm O_2) has a correlation coefficient of $r = 0.65$, $p < 0.5$. Fish were fed to satiation twice per day.

APPENDIX D. SECOND MEETING

- Agenda and Minutes of Second Meeting with Appendices 1 and 2

SECOND MEETING OF THE
INTERNATIONAL JOINT COMMISSION
GREAT LAKES RESEARCH ADVISORY BOARD'S
REVIEW COMMITTEE FOR THE DISSOLVED OXYGEN OBJECTIVE
FOR THE GREAT LAKES AT THE
IJC GREAT LAKES REGIONAL OFFICE

100 OUELLETTE AVENUE, 12TH FLOOR
WINDSOR, ONTARIO

DECEMBER 1, 1978; 9:30 A.M. - 4:30 P.M.

AGENDA

1. WELCOME AND INTRODUCTIONS
2. AGENDA
3. MINUTES OF PREVIOUS MEETING
4. RATIONALE FOR OBJECTIVE REVIEW - *A. E. P. Watson*
5. COMPARISON OF DISSOLVED OXYGEN CRITERIA
6. DISCUSSION OF RECOMMENDED DISSOLVED OXYGEN STANDARDS
7. DRAFTING OF COMMITTEE REPORT
8. OTHER BUSINESS
9. ADJOURNMENT

MINUTES OF THE SECOND MEETING
OF THE
INTERNATIONAL JOINT COMMISSION
SCIENCE ADVISORY BOARD'S
REVIEW COMMITTEE FOR THE DISSOLVED OXYGEN OBJECTIVE
FOR THE GREAT LAKES

HELD AT THE
INTERNATIONAL JOINT COMMISSION'S GREAT LAKES REGIONAL OFFICE
100 OUELLETTE AVENUE, 12TH FLOOR
WINDSOR, ONTARIO

DECEMBER 1, 1978
9:30 A.M. - 4:30 P.M.

United States Members Present

J. J. Magnuson (Chairman)	University of Wisconsin, Madison, Wisconsin
P. O. Fromm	Michigan State University, East Lansing, Michigan

United States Members Absent

None

Canadian Member Present

J. R. Brett	Pacific Biological Research Station, Fisheries and Environment Canada, Nanamimo, B.C.

Canadian Member Absent

F. E. J. Fry	Weston, Ontario

Secretary

A. E. P. Watson	IJC Great Lakes Regional Office, Windsor, Ontario

WATSON

1. WELCOME AND INTRODUCTIONS

The meeting was opened by the chairman at 9:30 a.m. and the attendees welcomed. The secretary conveyed regrets for non-attendance from Dr. Fry and explained the arrangements for a conference telephone call with Dr. Fry later in the meeting.

2. AGENDA

The agenda for the meeting was unanimously adopted.

3. MINUTES OF PREVIOUS MEETING

The following revisions to the minutes of the first meeting were suggested.

3.1 Item 5.1, p. 3. Dr. Brett's presentation on Metabolic Rates and Dissolved Oxygen Concentrations. It was concluded that: (omit the statement) .... "good diurnal growth, etc."

3.2 Item 5.2, p. 3. Dr. Magnuson's presentation on D.O. and Winterkill Conditions. It was noted that:

- fish behaviour is similar at D.O. concentrations of 0.1 mg/L and at 4 mg/L;
- Bluegill will move toward more preferred temperatures as soon as the D.O. falls below 0.7 mg/L at temperatures below 4°C; and
- the eggs of a large number of fish species incubate on the bottom at the substrate/water interface.

The minutes of the previous meeting were adopted with the inclusion of the above revision.

4. RATIONALE FOR OBJECTIVE REVIEW - A. E. P. WATSON

Dr. Watson briefly reviewed the rationale earlier articulated at the committee's first meeting (see Agenda Item 3, p. 1 of the minutes for that meeting) and drew attention to two relevant documents, viz.:

- "Natural Convection: A Mechanism for Transporting Oxygen to Incubating Salmon Eggs," R. N. O'Brien, S. Visaisouk and R. Raine, J. Fish. Res. Bd. of Canada, (1978), 35, (10), 1316-1321; and

- "Dissolved Oxygen" (in raw water sources), U.S. EPA Water Quality Criteria, 1972; EPA-43-73.033, March 1973.

Both documents, see Appendix 1, were distributed. The problems of implementation of D.O. standards for the most sensitive Great Lakes use were discussed and included references to land use activities. The committee agreed to establish a sound scientific basis for the D.O. objective.

5. COMPARISON OF DISSOLVED OXYGEN CRITERIA

Comments by Dr. J. C. Davis, Fisheries and Environment Canada, on the D.O. levels proposed were read by Dr. Brett from a personal communication, November 1978. The "B" level, ranging from 5.3 to 8.1 ppm O_2 depending on life stage, was recommended. Reference was made to two U.S. EPA books on water quality criteria, viz:

- the "Blue Book," 1972, see Agenda Item 4 (above) Appendix 1; and
- the "Red Book," Quality Criteria for Water," U.S. EPA, July 1976, EPA-440/9-76-023.

The section on Dissolved Gases, pp. 131-139, of the "Blue Book" was noted, especially the criteria listed on pp. 134-135 (see Appendix 1). Davis' three threshold levels of protection (A, B, C from highest to lowest) see the Water Quality Report's Appendix A, pp. 20 <u>et</u> <u>seq.</u>, were debated (see Appendix 1).

The following points were listed for discussion:

(1) The incipient sublethal level is the best basis for a criterion.

(2) Davis' level A (one standard deviation above mean level is necessary to protect aquatic life.

(3) One set of criteria is justified for all the Great Lakes.

(4) The oxygen mass is a better basis than percent saturation.

(5) A threshold which is a function of acclimation.

(6) Base the threshold on:
  - growth and development;

- reproduction, stages in life cycle;
- survival, lethal and ecological;
- swimming performance, decline in scope for activity;
- any changes in the percent saturation in arterial and venous blood;
- detection of avoidance;
- adaptive behavioural responses;
- acclimation response.

Items arising from the discussion of selecting D.O. thresholds included:

- "no effect" level comparisons with other contaminants for D.O.;
- scope of activity and the implications of the oxygen debt incurred; and
- chemical interactions (e.g., cyanide) and temperature effects.

6. <u>DISCUSSION OF RECOMMENDED DISSOLVED OXYGEN STANDARDS</u>

Dr. Brett distributed the following documents (see Appendix 2) for discussion:

- Dr. Brett's graph of Growth Rate (%/day) vs. Oxygen Concn. (ppm.) at 15°C for Sockeye and Coho Salmon and an excerpt from Fish Physiology, Vol. VIII, Bioenergetics and Growth, Eds. Hoar, Randall and Brett, Academic Press, (1979) in press;

- "Reactions of Some Great Plains Fishes to Progressive Hypoxia," J. H. Gee, R. F. Tallman, and Heather J. Smart, Can. J. Zool., (1978), <u>56</u>, 1962-1966; and

- "Effect of Long-Term Reduction and Diel Fluctuation in Dissolved Oxygen on Spawning of Black Crappie, *Promoxis nigromaculatus*," A. Carlson and L. J. Herman, Trans. Amer. Fish. Soc. (1978), <u>107</u>, (5), 742-746.

The dissolved oxygen requirements presented in the graph were also supported by the partial pressures for dissolved oxygen in water ($p_{w}O_{2}$) given in Table 1, p. 1963, of the paper by Gee, <u>et al</u>., <u>loc. cit</u>., and tended to substantiate the lower values cited by Davis in November 1978, (<u>loc. cit</u>.).

It was noted that British Columbia salmon hatchery levels are 7 ppm. D.O. and that, under winder conditions, Lake Erie displays a D.O. range of 7.0 ± 0.2 ppm. Also, few data exist for temperatures below 5°C.

The committee agreed to:

(a) a 7 mg/L D.O. concentration, 0°-25°C, this recommendation differing from the Water Quality Board's in that the criteria are not increased at lower temperatures; and

(b) utilize Davis' B level as distinct from the A level.

7. DRAFTING OF COMMITTEE REPORT

The committee's report would be submitted in memorandum format, the earlier material and minutes of both meetings being included in an Appendix.

Writing assignments during this meeting were apportioned as follows:

- Section 1, Recommendation - Dr. Magnuson;
- Section 2, Concentration versus Percent Saturation - Dr. Fromm; and
- Section 3, Dissolved Oxygen Concentration in Relation to Vital Functions - Dr. Brett.

In reference to Agenda Item 5, above, it was agreed that the following categories be chosen with thresholds based on:

A. Growth and Development
Reproduction
Survival__(physiological) and (ecological)

B. Swimming Performance
Decline in Scope for Activity
Any Changes in the Relative Percent Saturation of Arterial and Venous Blood
Detection of Avoidance
Adaptive Behavioural Responses
Acclimation Responses

Two telephone discussions were held with Dr. Fry re: the committee's recommendations.*

As a result of the input from Dr. Fry and the questions by the committee members, the following recommendation resulted:

---

*Reference was made to the article by E. T. Garside, J. Fish. Res. Bd. Can., (1966), 23, (8), 1121-1134, concerning dissolved oxygen levels and trout embryo survival.

In connecting channels and in all waters of the Great Lakes, the dissolved oxygen level should not be less than an average of 6.5 mg/L nor less than 5.5 mg/L at any time over 24 hours and across a temperature scale of 0^{o}*-*25^{o}*C. It was agreed that the secretary would distribute the draft report to committee members. The draft report (i.e., Sections 1-3) constitutes Appendix 3 to these minutes.*

8. ADJOURNMENT

The meeting was adjourned by the chairman at 4:00 p.m.

APPENDIX 1

- "Natural Convection: A Mechanism for Transporting Oxygen to Incubating Salmon Eggs," R.N. O'Brien, S. Visaisouk, R. Raine, J. Fish. Res. Bd. of Canada, (1978), 35, (10), 1316-1321;
- "Dissolved Oxygen," U.S. EPA Water Quality Criteria, 1972;
- "Dissolved Gases," ibid, pp. 134-135, dissolved oxygen criteria; and
- Water Quality Board Annual Report, June 1977, Appendix A, pp. 20-22.

Natural Convection: A Mechanism for Transporting Oxygen to Incubating Salmon Eggs

R. N. O'Brien, S. Visaisouk, R. Raine

Department of Chemistry, University of Victoria, Victoria, B.C. V8W 2Y2

and D. F. Alderdice

Department of Fisheries and the Environment, Fisheries and Marine Service, Pacific Biological Station, Nanaimo, B.C. V9R 5K6

O'Brien, R. N., S. Visaisouk, R. Raine, and D. F. Alderdice. 1978. Natural convection: a mechanism for transporting oxygen to incubating salmon eggs. J. Fish. Res. Board Can. 35: 1316–1321.

Respiratory exchange at the surface of developing fish eggs is influenced by two processes: diffusion and convection. The respiring egg acts as an oxygen sink, removing dissolved oxygen from the diffusion layer surrounding the outer surfaces of the egg capsule. To maintain the oxygen gradient in the diffusion layer, oxygen must be delivered to it by convection. This paper describes two components of convective transport: that provided by *forced* convection — the bulk transport of oxygenated water to the egg; and a newly recognized component, *natural* convection. Salmon normally spawn in gravel environments. Mass transfer of oxygen to incubating eggs, resulting from forced convection, is provided by subsurface water moving with a velocity related primarily to properties of the gravel and the hydraulic gradient. Egg-induced natural convection is seen as a component embedded in these relations. Acting as an emergency oxygen transport and metabolite disposal mechanism at low water velocities, natural convection could maintain perfusion of respiring eggs at some minimum water velocity in the event of diminution or interruption of natural water flow. The relevance of natural convection as a possible mechanism affecting several other respiring systems is discussed.

Key words: respiration, forced convection, density of water, bulk transport, diffusion, diffusion layer, oxygen gradient

O'Brien, R. N., S. Visaisouk, R. Raine, and D. F. Alderdice. 1978. Natural convection: a mechanism for transporting oxygen to incubating salmon eggs. J. Fish. Res. Board Can. 35: 1316–1321.

Deux processus influent sur les échanges respiratoires à la surface d'oeufs de poisson en voie de développement : la diffusion et la convection. L'oeuf qui respire agit comme un piège à oxygène, enlevant l'oxygène dissout de la couche de diffusion qui entoure les surfaces extérieures de la capsule de l'oeuf. Pour que le gradient d'oxygène se maintienne dans la couche de diffusion, il lui faut recevoir de l'oxygène par convection. Nous décrivons dans cet article deux composants du transport convectif : la convection *forcée* — le transport en masse d'eau oxygénée vers l'oeuf et un composant récemment reconnu, la convection *naturelle*. Les saumons frayent normalement sur des substrats de gravier. Le transport en masse de l'oxygène aux oeufs en voie d'incubation, résultant de la convection forcée, est fourni par l'eau de la sous-surface se déplaçant à une vitesse qui dépend surtout des propriétés du gravier et du gradient hydraulique. Nous considérons la convection naturelle provoquée par les oeufs comme un composant inhérent à ces relations. La convection naturelle agit comme un mécanisme de transport d'urgence de l'oxygène et de rejet des métabolites à de faibles vitesses de l'eau, et elle peut ainsi maintenir la perfusion des oeufs qui respirent à une vitesse minimum de l'eau dans le cas d'une diminution ou d'une interruption du débit naturel. Nous examinons la convection naturelle comme mécanisme possible affectant plusieurs autres systèmes qui respirent.

Received March 7, 1978
Accepted July 13, 1978

Reçu le 7 mars 1978
Accepté le 13 juillet 1978

Dissolved oxygen is provided to the living teleost egg by two processes: diffusion and convection. The first of these is a statistical molecular process that procee
ward equilibrium between two regions of diffe
oxygen concentration. The respiring egg, acting a
oxygen sink, removes oxygen from the perivitelline
beneath the egg capsule, thereby establishing an a

Printed in Canada (J5180)
Imprimé au Canada (J5180)

n gradient between the interior of the egg nal microenvironment surrounding the egg. roenvironment, metabolic activities of the en consumption and metabolite excretion — entration gradient between the capsule and vironment, known as the diffusion layer. To e gradient, oxygen must be supplied con- the diffusion layer. This is provided by con- second process, which is a bulk movement perfusing the egg. In general, transport of he diffusion layer depends primarily on con- city and the concentration of oxygen in the ater.

ently, it was assumed that supply of oxygen sion layer was dependent entirely on *forced* (Daykin 1965) — bulk movement of water he egg in relation to properties of the sur- ravel and the hydraulic gradient. We now nother component, *natural* convection, also ygen to the diffusion layer. We have ob- n coho salmon (*Oncorhynchus kisutch*) eggs ng, respiring in air-saturated water. Natural results from density differences produced at face, through removal of dissolved oxygen excretion of metabolite into the diffusion of these activities result in an increase in the water in the macroenvironment. Natural as well as the causes of the density increase te it, to our knowledge have been unsus- their potential influence on the function of y surfaces.

convection itself is a well-documented phe- especially in the electrochemical behavior of lectrodes (Wagner 1949; Wilke et al. 1953; al. 1963; O'Brien and Mukherjee 1964; 72). Convection due to removal of dissolved less well known; only recently has it been at oxygen solutions are less dense than pure Brien and Hyslop 1975). They found that ns to a vertical fringe system were produced pressure of oxygen was raised over water in an meter. The perturbed fringes could be fitted by n of Fick's Second Law of Diffusion with the e boundary conditions. That is

$$C_{(x,t)} = (C - C_o)\,\mathrm{erfc}\,(x/(2(Dt)^{\frac{1}{2}}) + C_o$$

$_{,t)}$ is the concentration of oxygen (mol·cm^{-3}) nce x (cm) perpendicular to the water surface (s), C_o is the bulk or zero concentration, erfc r function complement, and D is the diffusion of oxygen (cm^2·s^{-1}). Both theory and ex- with fringes perturbed by convection (O'Brien dicate that the observed fringe pattern pertur- ere not caused by convection. Experiments there is a negative slope for the relation be- fractive index and concentration (or pressure) and Hyslop 1975). This is consistent with the a decrease in density would be coupled with increased concentration or pressure, as seen in the Lorentz–Lorenz expression

$$R = M/\rho((n^2 - 1)/(n^2 + 2)) \tag{2}$$

where R is the molar refraction (cm^3), M is the molecular weight of the solute (g), n is the measured refractive index of the solution, and ρ is the density (g·cm^{-3}). Since R and M are constants, it follows that if n decreases with concentration, then so must ρ.

On the other hand, $(NH_4)_2CO_3$ can be assumed to result from the metabolic products

$$2NH_{3(aq)} + CO_{2(aq)} + H_2O \rightleftharpoons (NH_4)_2CO_3 \rightarrow 2NH_4{}^+{}_{(aq)} + CO_3{}^{2-}{}_{(aq)}. \tag{3}$$

Experiments have shown that solid $(NH_4)_2CO_3$ and its solutions are heavier than water (unpublished data, O'Brien 1978). We also have found carbon dioxide solutions to be heavier than water. We have not conducted experiments on the density of NH_3 solutions; however, they are listed (Handbook of Chemistry and Physics, Chemical Rubber Publ. Co., 1958; p. 1963) as being less dense than water. It is assumed that the CO_2 and NH_3 produced during egg development originate largely from protein metabolism; apart from water, protein is the dominant constituent of the salmon egg (Hayes 1949). Since the C/N ratio in protein can be expected to be at least 10:1, it seems likely that CO_2 will be present in greater quantity than NH_3. That being the case, the equilibrium in equation 3 will be far to the right, and no light ammonia solution is likely to be generated to oppose downward convection. Certainly no visible effects contrary to this assumption have been detected. Therefore, both processes would contribute to and be responsible for the observed convection. Further, it appears that oxygen uptake by the egg is responsible for the initial convective propelling force over short experimental elapsed times (0–5 min), and the excretion of metabolites is the main continuing convective force.

Under normal conditions the rate of oxygen consumption of salmon eggs increases, as embryonic development proceeds, and reaches a maximum just prior to hatching. As with the eggs of most species of Pacific salmon, those of the coho hatch after an incubation period of about 50 d at 10°C (500 degree-days). The coho eggs used in these studies were between 450 and 500 degree-days old, and hatching did occur during experiments in some of the later tests. The rate of oxygen uptake of salmonid eggs just prior to hatching varies with temperature, and ranges from about 1.5×10^{-3} to 5.5×10^{-3} mg/egg per h (Hayes et al. 1951; Wickett 195 Alderdice et al. 1958; Marckmann 1958; J. O. T. Jen Pacific Biological Station, personal communication. Rates of oxygen uptake of the coho eggs in the current tests at 10°C would be expected to be about 3×10^{-3} to 5×10^{-3} mg/egg per h.

This paper demonstrates natural convection. It shows that the process, embedded in forced convective transport, could provide a substantial portion of the total

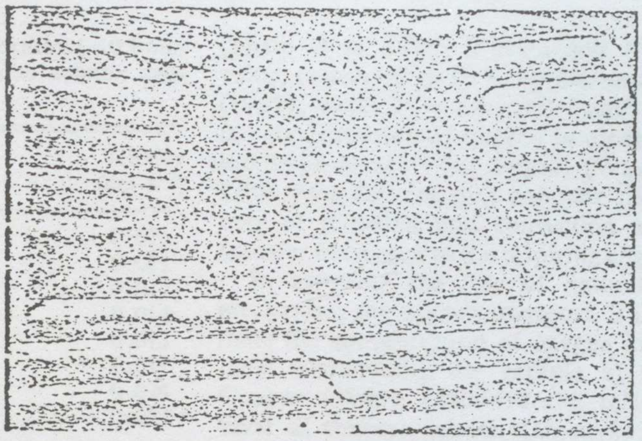


FIG. 1. Interferogram of coho salmon eggs near hatching. Three eggs, in a row perpendicular to the plane of the paper, are held in a thin, open-sided holder, which appears as a dark, curved line on each side of the eggs. The interference fringes bend at the egg surface, indicative of a concentration change in that region. There also is a slight discontinuity in the fringes immediately below the eggs; the series of "dips" in the fringes result from downward convective streaming of water in the diffusion layer at the egg surface to a point at the bottom of the eggs. There the layer breaks free and flows vertically away from the eggs.

respiratory requirements of incubating salmon eggs under circumstances where forced convection suffers either brief interruptions, or reductions due to decreased bulk water movement over longer periods. The process also helps to explain differences between bulk transport requirements estimated on the basis of forced convection mass transfer of oxygen (Daykin 1965; Wickett 1975), and those presumed lower requirements sometimes reported in practical incubation situations (Bams and Simpson 1977).

Materials and Methods

Coho salmon eggs obtained from Rosewall Creek, Vancouver Island, on November 30, 1976, were fertilized and incubated at 6°C at the Pacific Biological Station, Nanaimo. When the eggs were about 400 degree-days old, and well eyed, they were transported to the University of Victoria, Department of Chemistry, and held at 8°C until needed.

Two types of experiments were conducted: interferometry, and measurement of particle movement in the water containing the eggs in the interferometer. For each experimental run, three eggs were first washed in terramycin solution (50 mg/L for 5 min at 8°C) to remove bacterial contamination, then rinsed in water at 8°C. Next, the eggs were placed in an open-sided aluminum rack inserted lengthwise into a thermostated (10°C) Fabry-Perot interferometer, similar in design to that described by O'Brien and Hyslop (1975). The interferometer then was carefully filled with air-saturated water at 10°C.

The first type of experiment, interferometric measurement, used 90% reflecting optically flat surfaces for the ends of the interferometer cell and a laser source emitting coherent light at 632.8 nm to produce interference fringes. Perturbations to the fringes developing at the egg surfaces (Fig. 1) are related to changes in the concentration of solut
volved in respiration and metabolite excretion. The se
type of experiment measured the direction and veloci
particle movement in the water in the interferomete
this instance, clear end windows replaced the refle
surfaces on the ends of the interferometer cell, and
particles of Plexiglas® (<0.1 mm diam) were suspe
in the air-saturated water. Movement of the particles
noting convection, was readily observed and photogra
(Fig. 2A).

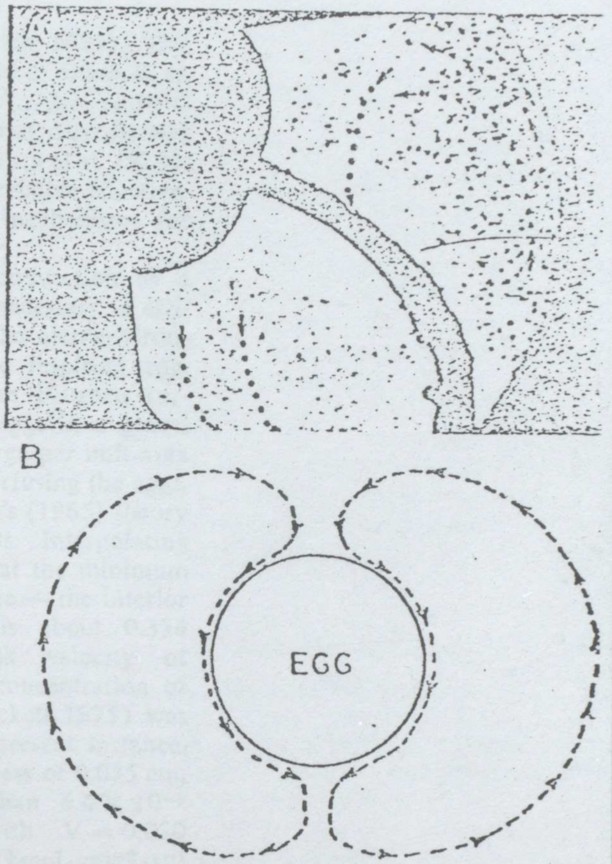


FIG. 2. A, Photograph of coho eggs, as in Fig. 1, r
using clear end windows in the interferometer cell.
paths of six fine particles of plastic suspended in the v
surrounding the eggs are shown in composite from seri
photographs taken consecutively. The arrows indicat
direction of movement. B, Stylized depiction of to
motion of water surrounding a respiring egg under th
fluence of natural convection in a "static" environment
out substrate or constraining boundaries. The moveme
lustrated would be altered substantially by the presen
forced convection (bulk movement of water) and
characteristics of natural substrate (gravel) surroundin
egg.

Results

The configuration in Fig. 1 shows a typical inte
ence fringe pattern 5 min after the beginning of a
The bends in the fringes at the egg surface indicat
presence of a larger concentration gradient and,

ypical velocities of Plexiglas ® particles (<0.1 mm
ended in water surrounding coho salmon eggs
ural convection.

	Time observed (s)	Velocity ($cm \cdot s^{-1}$)
	9	0.026
	7	0.021
	21	0.019
	24	0.014
	12	0.015
	28	0.017
	18	0.024
	13	0.022
ighted)		0.020

higher convective velocities. In that region
sed gradient, the diffusion layer decreases in
The denser solution in the gradient flows
the surface of the eggs to converge at the
the eggs into a rapidly downflowing stream,
by the "dip" in the fringes directly beneath

2A shows successive positions of a series
es photographed within the cylindrical inter-
cell with the eggs placed axially. Figure 2B
d interpretation of the toroidal motion that
xpected in the absence of the cylindrical walls
terferometer, and without substrate particles
l) surrounding the egg. This configuration, of
uld be greatly modified under natural con-
ypical measured particle velocities (Table 1)
about 0.020 $cm \cdot s^{-1}$ (72 cm/h). In a control
where teflon balls of the same size replaced
either perturbation to the fringes nor convec-
suspended particles occurred.

Discussion

sion and convection studies, the general form
nsport equation for uncharged particles is

$$\vec{J} = \vec{J}_D + \vec{J}_C = -D\frac{\partial c}{\partial x} + cV$$

and $\vec{J}_C$ are the diffusion and convection com-
spectively, of the total dissolved oxygen flux
$n^{-2} \cdot s^{-1}$), D is the diffusion coefficient for
n water ($cm^2 \cdot s^{-1}$), c is concentration of dis-
gen in the bulk fluid ($mol \cdot cm^{-3}$), x is the
om the surface of the egg capsule (cm), and
lk velocity of the perfusing water ($cm \cdot s^{-1}$).
iguration of our cell necessitates using a factor
he convective term: as approximately half of
n the interferometer cell appears to be rising,
the basis of particle movement, then the
f must be sinking.

st acceptable value of the diffusion coefficient
in water is 2.0×10^{-5} $cm^2 \cdot s^{-1}$ at 22°C (Tham et al. 1970; O'Brien and Hyslop 1975). This value, converted to 10°C by the method of Davis et al. (1967), yields $D = 1.4 \times 10^{-5}$ $cm^2 \cdot s^{-1}$. Also, at 10°C the concentration of oxygen in air-saturated freshwater is 0.35 $\mu mol \cdot cm^{-3}$ (11.2 ppm) (Washburn et al. 1928). With these data we may compare the relative effectiveness of diffusion and convection as mechanisms for transfer of oxygen to the respiring eggs.

In assessing the role of natural convection as a mechanism for oxygen transport, it is necessary to estimate the concentration of oxygen in the nicroenvironment surrounding the capsule of the respiring egg. Cooper (1965) examined the relation between survival of sockeye salmon (*O. nerka*) eggs in a gravel medium and the bulk velocity (discharge per unit area of gravel, eggs, and water) of water perfusing the eggs. Wickett (1975, table 1) applied Daykin's (1965) theory of mass transfer to Cooper's results. Interpolating Wickett's tabled values, we assume that the minimum oxygen concentration at the egg surface — the interior boundary of the diffusion layer — is about 0.334 $\mu mol \cdot cm^{-3}$ (10.7 ppm) at a bulk velocity of 0.020 $cm \cdot s^{-1}$ (Table 1), where the concentration of oxygen in the macroenvironment (Wickett 1975) was 0.39 $\mu mol \cdot cm^{-3}$ (12.5 ppm). In the present instance, using a measured diffusion layer thickness of 0.035 cm, we calculate $\vec{J}_D$ to be no more than 6.4×10^{-6} $mol \cdot cm^{-2} \cdot s^{-1}$. For convection, with $V = 0.020$ $cm \cdot s^{-1}$, $\vec{J}_C$ is calculated to be 3.5×10^{-3} $mol \cdot cm^{-2} \cdot s^{-1}$ of dissolved oxygen. It is seen that $\vec{J}_C/\vec{J}_D = 5.5 \times 10^2$. Therefore, convection is estimated to be about 500 times more effective than diffusion in providing oxygen to the respiring egg in our "static" water experiment. The actual mechanism of increased transport, of course, is the reduction by natural convection of the thickness of the diffusion layer — the diffusion distance.

Furthermore, the magnitude of perturbation of the fringes (Fig. 1) cannot be accounted for solely on the basis of oxygen depletion in the diffusion layer. We conclude that the remainder of the refractive index (concentration) change is a result of the presence of metabolites, which also must contribute to convection. From these considerations, $\vec{J}$ must be in the range of $3\text{–}4 \times 10^{-3}$ $\mu mol \cdot cm^{-2} \cdot s^{-1}$.

Our interferometer cell is designed so that convection, if present, is optimized. For salmon eggs respiring in a gravel substrate, the less symmetrical environment could reduce the convective mode by an order of magnitude. The overall effect, we believe, is that convection in a natural situation may result in a rate of oxygen transport at least one order of magnitude greater than that associated with diffusion. Of course, our results serve primarily to indicate the potential value of natural convection. A fuller evaluation of the phenomenon must await further analyses, particularly for eggs at different temperatures, stages of embryonic development, and at various environmental levels of dissolved oxygen.

Natural convection as an oxygen transport mechanism is different from, and would be embedded in, the forced convection of mass transfer as treated by Daykin (1965). Bams and Simpson (1977), on the basis of available evidence, suggest that forced transport of water past incubating eggs under practical conditions should be about 200 cm/h, with a minimum permissible limit of 150 cm/h. Nevertheless, these authors mention that satisfactory results appear to have been obtained at lower bulk velocities in some instances. At these lower bulk velocities it now appears that natural convection may assume a significant role in oxygen transport. However, at this time natural convection alone should be considered realistically only as an emergency system, providing oxygen to respiring eggs in the event of an interruption or diminution in bulk flow. Natural convection can oxygenate eggs only within the limited macroenvironment surrounding the egg that is subject to convective transport. If oxygen in the macroenvironment were not replenished — either in our interferometer cell or under natural conditions — then succeeding convective cycles (e.g. Fig. 2B) would slowly deplete dissolved oxygen in the limited water volume presented to the egg, and the egg eventually would die from lack of oxygen.

In general, natural convection is seen as a mechanism that could supply a substantial portion of oxygen requirements to stationary wetted vertical or near-vertical respiring surfaces. Hence, we conclude that oxygen-absorbing surfaces are likely to be predominantly vertical or inclined in all stationary aquatic organisms. Natural convection may be involved in the supply of oxygen to various tissues hitherto thought to depend primarily on diffusion. These may include the osteocytes in the extravascular canalicules of the Haversian system of compact bone, tissues such as those surrounding the fluid-filled synovial capsule of diarthroidal joints (e.g. knee joint), and some types of connective tissues. Possible applications of natural convection might be found in methods of manipulating and treating such tissues following disease or injury.

Natural convection may also be associated with oxygenation of eggs in the interior of egg masses laid on fixed substrate. For example, the Pacific herring (*Clupea pallasi*) lay its eggs in irregular masses largely on submerged aquatic marine vegetation. Irregularities in packing of the eggs in the mass produce discontinuities, or voids, among the eggs. A linking of voids into channels, if they occur, would provide a means by which natural convection could supply oxygen to eggs in the interior of the mass. Further, such convection probably would be more successful for egg masses on vertical surfaces such as the eelgrass normally used by spawning herring, compared with survival of eggs in masses laid on flat thallus-like surfaces of other forms of marine vegetation that are sometimes used.

Finally, in salmon egg respiration the vertical streaming of water over the egg surface, and the downward flow resulting from natural convection, raise certain questions regarding the efficiency of current designs of salmon egg incubators. Most salmon egg incubation
boxes (Bams and Simpson 1977) and hatcher
trays force water to upwell through the eggs or
gravel mixture. Under such conditions, the vectors
ciated with natural and forced convection are op
and may tend to cancel each other. In a "downwe
system, the two vectors may in part reinforce
other, suggesting a means of increasing the effi
of oxygen transfer while using lower bulk tra
velocities. If such lower bulk transport rates
proven not to compromise egg and alevin qual
artificial incubators, then the reduced water re
ments would lead to lower power and filtration
Alternatively, alternating downwelling and upw
modes of operation of gravel incubation boxes
also assist in maintaining higher permeability
gravel through removal of accumulating fine pa
We believe these possibilities deserve further
nation.

Acknowledgments

This work was funded by Environment Canada, Fi
and Marine Service, grant OSS76-02160. We ackno
F. P. J. Velsen and other members of the staff of the
Biological Station for their assistance in obtainir
incubating the eggs used in this study.

Alderdice, D. F., W. P. Wickett, and J. R. Brett
Some effects of temporary exposure to low di
oxygen levels on Pacific salmon eggs. J. Fis
Board Can. 15: 229–249.

Bams, R. A., and K. S. Simpson. 1977. Substrate inc
workshop — 1976. Current state-of-the-art. Fis
Serv. Tech. Rep. 689: v, 68 p.

Cooper, A. C. 1965. The effect of transported strea
ments on the survival of sockeye and pink salm
and alevin. Int. Pac. Salmon Fish. Comm. Bull.
71 p.

Davis, R. E., G. L. Horvath, and C. W. Tobias. 19
solubility and diffusion coefficient of oxygen i
sium hydroxide solutions. Electrochemica A
287–297.

Daykin, P. N. 1965. Application of mass transfer th
the problem of respiration of fish eggs. J. Fis
Board Can. 22: 159–171.

Hayes, R. F. 1949. The growth, general chemist
temperature relations of salmonid eggs. Qua
Biol. 24: 281–308.

Hayes, F. R., I. R. Wilmot, and D. A. Livingston
The oxygen consumption of the salmon egg in
to development and activity. J. Exp. Zool. 11
395.

Marckmann, K. 1958. The influence of the temper
the respiratory metabolism during the develop
the sea-trout. Meddelelser fra Danmarks Fi
Havundersgelser. New Series: Vol. 2, No. 21:

O'Brien, R. N. 1972. Low current density microce
sion layer thickness at shallow vertical electr
Electrochem. Soc. 119: 589–590.

O'Brien, R. N., and W. F. Hyslop. 1975. A Fab
interferometer for monitoring gas–liquid exch
326–336. *In* W. A. Adams, G. Greer, G. S. K
Desnoyers, K. B. Oldham, G. Atkinson, and J.

emistry and physics of aqueous gas solutions.
trochemical Society, Inc., Princeton, N.J., xi,

. N., AND L. M. MUKHERJEE. 1964. Correlation
ing currents; electrodeposition of copper in
ctrolytic cells. J. Electrochem. Soc. 111: 1358–

. N., W. F. YAKYMYSHYN, AND J. LEJA. 1963.
rometric study of Zn/ZnSO$_4$/Zn System. I. Rela-
sition of electrodes and convective effects. J.
chem. Soc. 110: 820–825.
K., R. D. WALKER, AND K. E. GUBBINS. 1970.
ion of oxygen and hydrogen in aqueous potas-
ydroxide solutions. J. Phys. Chem. 74: 1747–

. 1949. The role of natural convection in elec-
ic processes. J. (and Trans.) Electrochem. Soc.
–173.

WASHBURN, E. W., C. J. WEST, N. E. DORSERY, N. R. BICHOWSKY, AND A. KELMENC [ed.] 1928. International critical tables of numerical data, physics, chemistry, and technology. Vol. 3. p. 257. McGraw-Hill Inc., New York, N.Y., xiv, 444 p.

WICKETT, W. P. 1954. The oxygen supply to salmon eggs in spawning beds. J. Fish. Res. Board Can. 11: 933–953.

1975. Mass transfer theory and the culture of fish eggs, p. 419–434. *In* W. A. Adams, G. Greer, G. S. Kell, J. E. Desnoyers, K. B. Oldham, G. Atkinson, and J. Walkley [ed.] Chemistry and physics of aqueous gas solutions. The Electrochemical Society Inc., Princeton, N.J., xi, 521 p.

WILKE, C. R., M. EISENBERG, AND C. W. TOBIAS. 1953. Correlation of limiting currents under free convection conditions. J. Electrochem. Soc. 100: 513–523.

U.S. EPA WATER QUALITY CRITERIA, 1972.

CYANIDE

ndards for cyanide in water have been published by
World Health Organization in "International Stand-
for Drinking Water" (1963)[148] and the "European
ards for Drinking Water" (1970).[149] These standards
r to be based on the toxicity of cyanide to fish, not
an. Cyanide in reasonable doses (10 mg or less) is
y converted to thiocyanate in the human body and in
orm is much less toxic to man. Usually, lethal toxic
s occur only when the detoxifying mechanism is over-
ned. The oral toxicity of cyanide for man is shown in
llowing table.

oper chlorination with a free chlorine residual under
al or alkaline conditions will reduce the cyanide level
ow the recommended limit. The acute oral toxicity
nogen chloride, the chlorination product of hydrogen
de, is approximately one-twentieth that of hydrogen
de (Spector 1955).[146]

the basis of the toxic limit calculated from the
hold limit for air (Stokinger and Woodward 1958),[147] and assuming a 2-liter daily consumption of water containing 0.2 mg/l cyanide as a maximum, an appreciable factor of safety would be provided.

TABLE II-1—Oral Toxicity of Cyanide for Man

Dosage	Response	Literature citations
2.9–4.7 mg/day	Noninjurious	Smith 1944[143]
10 mg, single dose	Noninjurious	Bodansky and Levy 1923[143]
19 mg/l in water	Calculated from the safe threshold limit for air	Stokinger and Woodward 1958[147]
50–60 mg, single dose	Fatal	The Merck Index of Chemicals and Drugs 1963[144]

Recommendation

Because of the toxicity of cyanide, it is recommended that a limit of 0.2 mg/l cyanide not be exceeded in public water supply sources.

DISSOLVED OXYGEN

olved oxygen in raw water sources aids in the elimi-
n of undesirable constituents, particularly iron and
anese, by precipitation of the oxidized form. It also
s the biological oxidation of ammonia to nitrate,
revents the anaerobic reduction of dissolved sulfate
drogen sulfide. More importantly, dissolved oxygen
aw surface water supply serves as an indicator that
ve quantities of oxygen-demanding wastes are prob-
not present in the water, although there can be sig-
t exceptions to this. Therefore, it is desirable that
in the water be at or near saturation. On the other
oxygen enhances corrosion of treatment facilities,
uting systems, and household appurtenances in many

ygen depletion in unmixed bodies of water can result
he presence of natural oxygen-demanding substances
l as from organic pollution. Lakes and reservoirs may contain little or no oxygen, yet may be essentially free of oxygen-demanding wastes. This is because contact with the air is limited to the upper surface, and because thermal stratification in some lakes and reservoirs prevents oxygenation of lower levels directly from the air. Similar conditions also occur in ground waters.

Conclusion

No recommendation is made, because the presence of dissolved oxygen in a raw water supply has both beneficial and detrimental aspects. However, when the waters contain ammonia or iron and manganese in their reduced form, the benefits of the sustained presence of oxygen at or near saturation for a period of time can be greater than the disadvantages.

TABLE III-4—Example of Recommended Minimum Concentrations of Dissolved Oxygen

Estimated natural seasonal minimum concentration of oxygen in water	Corresponding temperature of oxygen-saturated fresh water	Recommended minimum concentrations of O_2 for selected levels of protection			
		Nearly maximal	High	Moderate	Low
5	(*a*) (*a*)	5	4.7	4.2	4.0
6	45C(a) (115F)(a)	6	5.6	4.8	4.0
7	36C (96.8F)	7	6.4	5.3	4.0
8	27.5C (81.5F)	8	7.1	5.8	4.3
9	21C (69.8F)	9	7.7	6.2	4.5
10	16C (60.8F)	10	8.2	6.5	4.6
12	7.7C (45.9F)	12	8.9	6.8	4.8
14	1.5C (34.7F)	14	9.3	6.8	4.9

^a^ Included to cover waters that are naturally somewhat deficient in O_2. A saturation value of 5 mg/l might be found in warm springs or very saline waters. A saturation value of 6 mg/l would apply to warm sea water (32 C=90 F).

Note: The desired kind and level of protection of a given body of water should first be selected (across head of table). The estimated seasonal minimum concentration of dissolved oxygen under natural conditions should then be determined on the basis of available data, and located in the left hand column of the table. The recommended minimum concentration of oxygen for the season is then taken from the table. All values are in milligrams of O_2 per liter. Values for natural seasonal minima other than those listed are given by the formula and qualifications in the section on recommendations.

Examples

- It is desired to give moderate protection to trout (*Salvelinus fontinalis*) in a small stream during the summer. The maximum summer temperature is 20 C (68 F); the salt content of the water is low and has negligible effect on the oxygen saturation value. The atmospheric pressure is 760 millimeters (mm) Hg. Oxygen saturation is therefore 9.2 mg/l. This is assumed to be the natural seasonal minimum in the absence of evidence of lower natural concentrations. Interpolating from Table III-4 or using the recommended formula, reveals a minimum permissible concentration of oxygen during the summer of 6.2 mg/l. If a high level of protection had been selected, the recommendation would have been 7.8 mg/l. A low level of protection, providing little or no protection for trout but some for more tolerant fish, would require a recommendation of 4.5 mg/l. Other recommendations would be calculated in a similar way for other seasons.
- It is decided to give moderate protection to largemouth bass (*Micropterus salmoides*) during the summer. Stream temperature reaches a maximum of 35 C (95 F) during summer, and lowest seasonal saturation value is accordingly 7.1 mg/l. The recommendation for minimum oxygen concentration is 5.4 mg/l.
- For low protection of fish in summer in the same stream described above (for largemouth bass), the recommendation would be 4.0 mg/l, which is also the floor value recommended.
- It is desired to protect marine fish in full-strength sea water (35 parts per thousand salinity) with a maximum seasonal temperature of 16 C (61 F). The saturation value of 8 mg/l is assumed to be the natural dissolved oxygen minimum for the season. For a high level of protection, the recommendation is 7.1 mg/l, for a moderate level of protection it is 5.8 mg/l, and for a low level of protection it is 4.3 mg/l.

It should be stressed that the recommendations are minimum values for any time during the same season.

Recommendations

(a) For nearly maximal protection of fish a other aquatic life, the minimum dissolved oxy in any season (defined previously) should not less than the estimated natural seasonal minim concentration (defined previously) characteristi that body of water for the same season. In e mating natural minima, it is assumed that wat are saturated, unless there is evidence that t were lower in the absence of man-made influen

(b) For a high level of protection of fish, minimum dissolved oxygen concentration in season should not be less than that given by following formula in which M=the estima natural seasonal minimum concentration ch acteristic of that body of water for the same seas as qualified in (a):

$$\text{Criterion}^* = 1.41M - 0.0476M^2 - 1.11$$

(c) For a moderate level of protection of fish, minimum dissolved oxygen concentration in season should not be less than is given by following formula with qualifications as in (b):

$$\text{Criterion}^* = 1.08M - 0.0415M^2 - 0.202$$

(d) For a low level of protection of fish, minimum O_2 in any season should not be less t given by the following formula with qualificati as in (b):

$$\text{Criterion}^* = 0.674M - 0.0264M^2 + 0.577$$

(e) A floor value of 4 mg/l is recommended exc in those situations where the natural level of solved oxygen is less than 4 mg/l, in which case further depression is desirable.

(f) For spawning grounds of salmonid fis higher O_2 levels are required as given in the foll ing formula with qualifications as in (b):

$$\text{Criterion}^* = 1.19M - 0.0242M^2 - 0.418$$

(g) In stratified eutrophic and dystrophic la the dissolved oxygen requirements may not ap to the hypolimnion and such lakes should be c sidered on a case by case basis. In other strati lakes, recommendations (a), (b), (c), and (d) ap and if the oxygen is below 4 mg/l, recommenda (e) applies. In unstratified lakes recommendati apply to the entire circulating water mass.

(i) All the foregoing recommendations appl all waters except waters designated as mixing zo

---

* All values are instantaneous, and final value should be expr to two significant figures.

ee section on Mixing Zones p. 112). In locations here supersaturation occurs, the increased levels oxygen ould conform to the recommendations the discussion of Total Dissolved Gases, p. 139.

OTAL DISSOLVED GASES (SUPERSATURATION)

Excessive total dissolved gas pressure (supersaturation) is relatively new aspect of water quality. Previously, super- turation was believed to be a problem that was limited to water supplies of fish culture facilities (Shelford and lee 1913).[135] Lindroth (1957)[126] reported that spillways hydroelectric dams in Sweden caused supersaturation, d recently Ebel (1969)[112] and Beiningen and Ebel (1968)[103] ablished that spillways at dams caused gas bubble disease be a limiting factor for aquatic life in the Columbia and ake Rivers. Renfro (1963)[133] and others reported that essive algal blooms have caused gas bubble disease in ntic water. DeMont and Miller (*in press*)[110] and Malous al. (1972)[127] reported gas bubble disease among fish and llusks living in the heated effluents of steam generating ations. Therefore, modified dissolved gas pressures as a sult of dams, eutrophication, and thermal discharges sent a widespread potential for adversely affecting fish d aquatic invertebrates. Gas bubble disease has been udied frequently since Gorham (1898,[119] 1899[120]) pub- ed his initial papers, with the result that general knowl- e of the causes, consequences, and adverse levels are lequate to evaluate criteria for this water quality char- eristic.

as bubble disease is caused by excessive total dissolved s pressure *but it is not caused by the dissolved nitrogen gas ne* (Marsh and Gorham 1904,[125] Shelford and Allee 3,[135] Englehorn 1943,[115] Harvey et al. 1944a,[121] Doudoroff 7,[111] Harvey and Cooper 1962).[123] Englehorn (1943)[115] alyzed the gases contained in the bubbles that were ned in fish suffering from gas bubble disease and found t their gas composition was essentially identical to air. is was confirmed by Shirahata (1966).[136]

logic Factors

Gas bubble disease (GBD) results when the uncompen- ed total gas pressure is greater in the water than in the but several important factors influence the etiology of D. These factors include: exposure time and physical tors such as hydrostatic pressure; other compensating es and biological factors such as species or life stage rance or levels of activity; and any other factors that luence gas solubility. Of these factors perhaps none are c commonly misunderstood than the physical roles of dissolved gas pressure* and hydrostatic pressure. The lowing discussion is intended to clarify these roles.

Each component gas in air exerts a measurable pressure, and the sum of these pressures constitutes atmospheric or barometric pressure, which is equivalent per unit of surface area at standard conditions to a pressure exerted by a column of mercury 760mm high or a column of water about 10 meters high (at sea level, excluding water vapor pressure). The pressure of an individual gas in air is called a *partial pressure*, and in water it is called a *tension*; both terms are an acknowledgement that the pressure of an individual gas is only part of the total atmospheric pressure. Likewise, each component gas will dissolve in water independently of all other gases, and when at equilibrium with the air, the pressure (tension) of a specific dissolved gas is equivalent to its partial pressure in the air. This relationship is evident in Table III–5 which lists the main constituents of dry air and their approximate partial pressures at sea level.

When supersaturation occurs, the diffusion pressure imbalance between the dissolved gas phase and the atmospheric phase favors a net transfer of gases from the water to the air. Generally this transfer cannot be accomplished fast enough by diffusion alone to prevent the formation of gas bubbles. However, a gas bubble cannot form in the water unless gas nuclei are present (Evans and Walder 1969,[116] Harvey et al. 1944b[122]) and unless the total dissolved gas pressure exceeds the sum of the compensating pressures such as hydrostatic pressure. Additional compensating pressures include blood pressure and viscosity, and their benefits may be significant.

Gas nuclei are probably unavoidable in surface water or in animals, because such nuclei are generated by any factor which decreases gas solubility, and because extreme measures are required to dissolve gas nuclei (Evans and Walder 1969;[116] Harvey et al. 1944b).[122] Therefore, hydrostatic pressure is a major preventive factor in gas bubble disease.

The effect of hydrostatic pressure is to oppose gas bubble formation. For example, one cannot blow a bubble out of a tube immersed in water until the gas pressure in the tube slightly exceeds the hydrostatic pressure at the end of the tube. Likewise a bubble cannot form in water, blood, or

TABLE III–5—Composition of Dry Air and Partial Pressures of Selected Gases at Sea Level

Gas	Molecular[a] percentage in dry air	Times atmospheric pressure	Individual gas[b] pressure in air or water at sea level
N_2...........	78.084	×760 mm Hg	=593.438 mm Hg
O_2...........	20.946	"	159.189 "
Ar...........	0.934	"	7.098 "
CO_2..........	0.033	"	0.250 "
Ne...........	0.00181	"	0.0138 "
He...........	0.00052	"	0.0039 "
			759.9927 mm Hg

[a] Glueckauf (1951[118]).
[b] At standard conditions excluding corrections for water vapor pressure.

---

n this Section gas tension will be called gas pressure and total ension will be called total dissolved gas pressure (TDGP). This ing done as a descriptive aid to readers who are not familiar with erminology and yet need to convey these principles to laymen.

Presented to the
Implementation Committee
of the
Great Lakes
Water Quality Board
and to the
Great Lakes
Research Advisory Board

GREAT LAKES WATER QUALITY

ANNUAL REPORT OF THE WATER QUALITY OBJECTIVES SUBCOMMITTEE AND THE TASK FORCE ON THE SCIENTIFIC BASIS FOR WATER QUALITY CRITERIA

JUNE 1977

The opposing view is that the response of organisms to DO concentrations below 100% saturation simply reflects an acclimation response which has no negative impact on the continued survival or productivity of the aquatic community. Based largely upon field observations of fish populations which have been found at oxygen concentrations considerably below that considered suitable for a thriving population, single minimum concentrations of DO are believed to adequately protect aquatic populations. This view has been adopted by the EPA "Quality Criteria for Water" (EPA, 1976) which recommends an objective of 5 mg/l for dissolved oxygen in freshwater.

There are merits to both of these philosophies. However, the approach which has been adopted for establishment of a DO objective for the Great Lakes is that any change in the DO regime is likely to have some effect on the ecosystem and the magnitude of that effect will depend on the severity and duration of the change. It is felt that this approach is justified for the following reasons.

1. The objective provides both the correct oxygen tension gradient to move oxygen into the blood and sufficient oxygen to fulfill the requirements of metabolism.
2. The objective recognizes the greater metabolic demand for DO at elevated temperatures.
3. A reduction of DO levels to below saturation limits active metabolism, reduces maximum swimming speed of fish and causes a physiological, behavioral or other stress induced response. While the consequences of the chronic occurrence of such stress are not well understood, there is a reasonable likelihood that it is an important factor in the long term survival of the organism.
4. There is a small safety factor included between the objective and the concentration causing measurable harm to aquatic biota.

DEVELOPMENT OF OXYGEN CRITERIA FOR FISH POPULATIONS

In line with the above discussion, the approach proposed by Davis (1975) for deriving DO criteria to protect fish has been adopted here. His approach involved the establishment of mean thresholds of incipient oxygen response thresholds by averaging data on oxygen levels for various assemblages of fish where sublethal responses to hypoxia first become apparent. Using the calculated mean threshold level, three levels of protection (A, B, and C) were devised as follows:

1. Level A: This level is one standard deviation above the mean average oxygen response level for a fish community (e.g. freshwater fish, including salmonids). It represents a high degree of safety for important fish stocks and permits 13-20% depression of oxygen from full saturation.

2. Level B: This level is the caluclated mean oxygen response threshold, and represents the oxygen value where the average member of a species of a fish community starts to exhibit symptoms of oxygen distress. Oxygen concentrations are allowed to be depressed from 35 to 45% below saturation.
3. Level C: This level is one standard deviation below the mean oxygen response threshold, and permits a large portion of a fish population to be affected. Oxygen concentrations may be depressed to 60% below saturation.

The calculated oxygen response thresholds for freshwater fish populations is presented in Table 2 (abridged from Davis, 1975).

TABLE 2.

INCIPIENT DISSOLVED OXYGEN RESPONSE THRESHOLDS FOR FRESHWATER ASSEMBLAGES OF FISH

GROUP	PROTECTION LEVEL	P_{O_2} MMHG	MG O_2/LITER
Mixed freshwater fish population including salmonids (15 °C)	A	113	7.27
	B	86	5.26
	C	58	3.25
Mixed freshwater fish population with no salmonids (18 °C)	A	92	5.63
	B	73	3.98
	C	54	2.33
Freshwater salmonids (including steelheads) (15 °C)	A	119	7.84
	B	90	6.00
	C	61	4.16
Salmonid larvae and mature eggs (9 °C)	A	115	9.74
	B	120	8.09
	C	85	6.44

On the basis of the calculated critical partial oxygen pressures presented in Table 2, extrapolated objectives over the range of 0-25 °C were calculated as percent of saturation required to provide a desirable oxygen partial pressure and content. These values are intended to be minimum oxygen levels of body of water. Oxygen criteria based upon percent saturation are provided in Table 3 (abridged from Davis, 1975).

These objectives expressed as percent saturation over a range of temperatures, are intended to protect fish by providing both the correct oxygen gradient to move oxygen into the blood and sufficient oxygen to

TABLE 3.

CRITICAL CONCENTRATIONS OF OXYGEN REQUIRED TO MAINTAIN DIFFERING LEVELS OF PROTECTION FOR VARIOUS ASSEMBLAGES OF FRESHWATER FISH

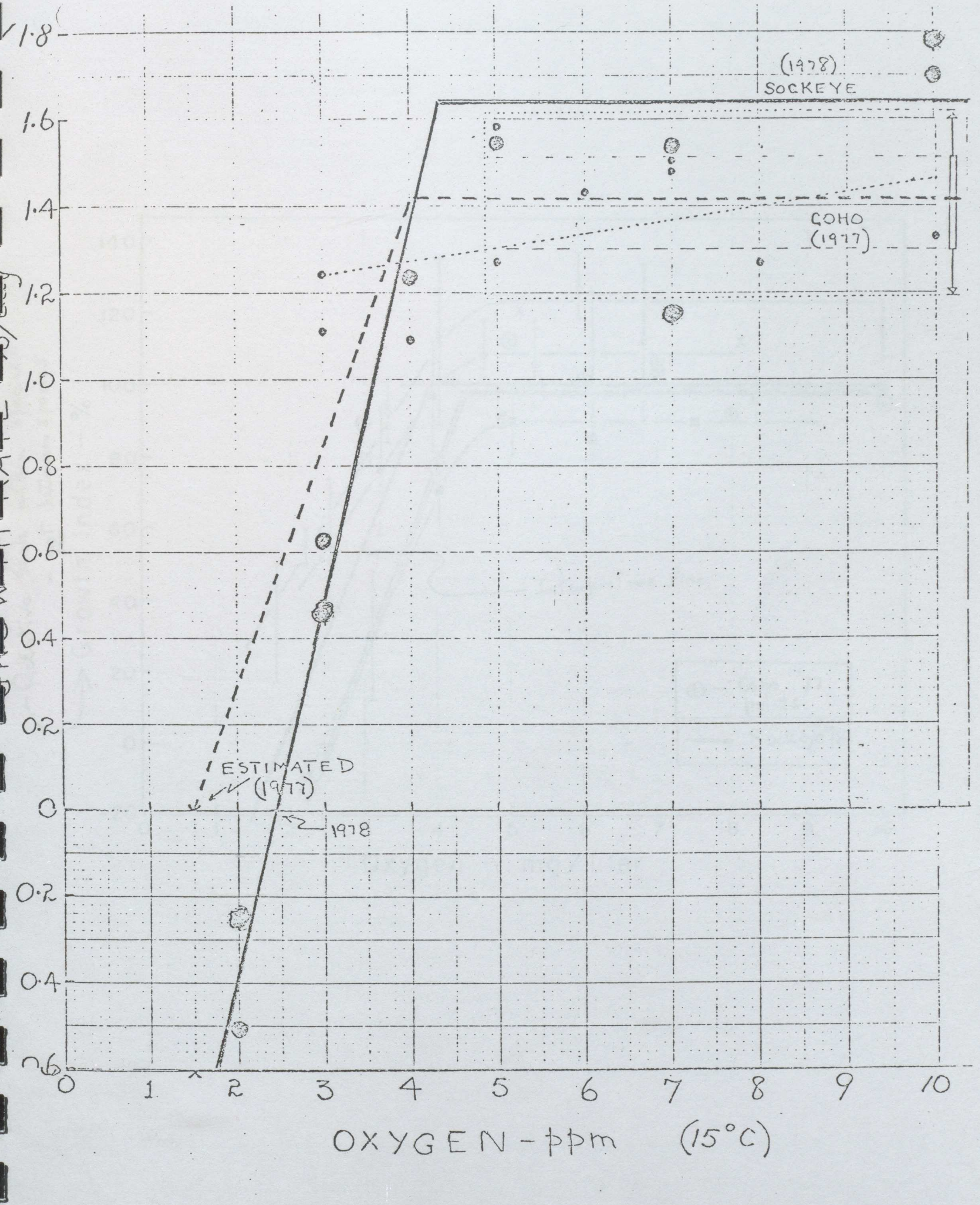
GROUP	PROTECTION LEVEL	P_{O_2} MMHG	ML O_2 /LITER	MG O_2 /LITER	% SATURATION AT °C REQUIRED TO MAINTAIN PROTECTION LEVEL					
					0°	5°	10°	15°	20°	25°
Freshwater mixed fish population including salmonids	A	110	5.08	7.25	69	70	70	71	79	87
	B	85	3.68	5.25	54	54	54	54	57	63
	C	60	2.28	3.25	38	38	38	38	39	39
Freshwater mixed fish population with no salmonids	A	95	3.85	5.50	60	60	60	60	60	66
	B	75	2.80	4.00	47	47	47	47	47	48
	C	55	1.75	2.50	35	35	35	35	35	36
Freshwater salmonid population (including steelhead)	A	120	5.43	7.75	76	76	76	76	85	93
	B	90	4.20	6.00	57	57	57	59	65	72
	C	60	2.98	4.25	38	38	38	42	46	51
Salmonid larvae and mature eggs of salmonids	A	155	6.83	9.75	98	98	98	98	100	100
	B	120	5.60	8.00	76	76	76	79	87	95
	C	85	4.55	6.50	54	54	57	64	71	78

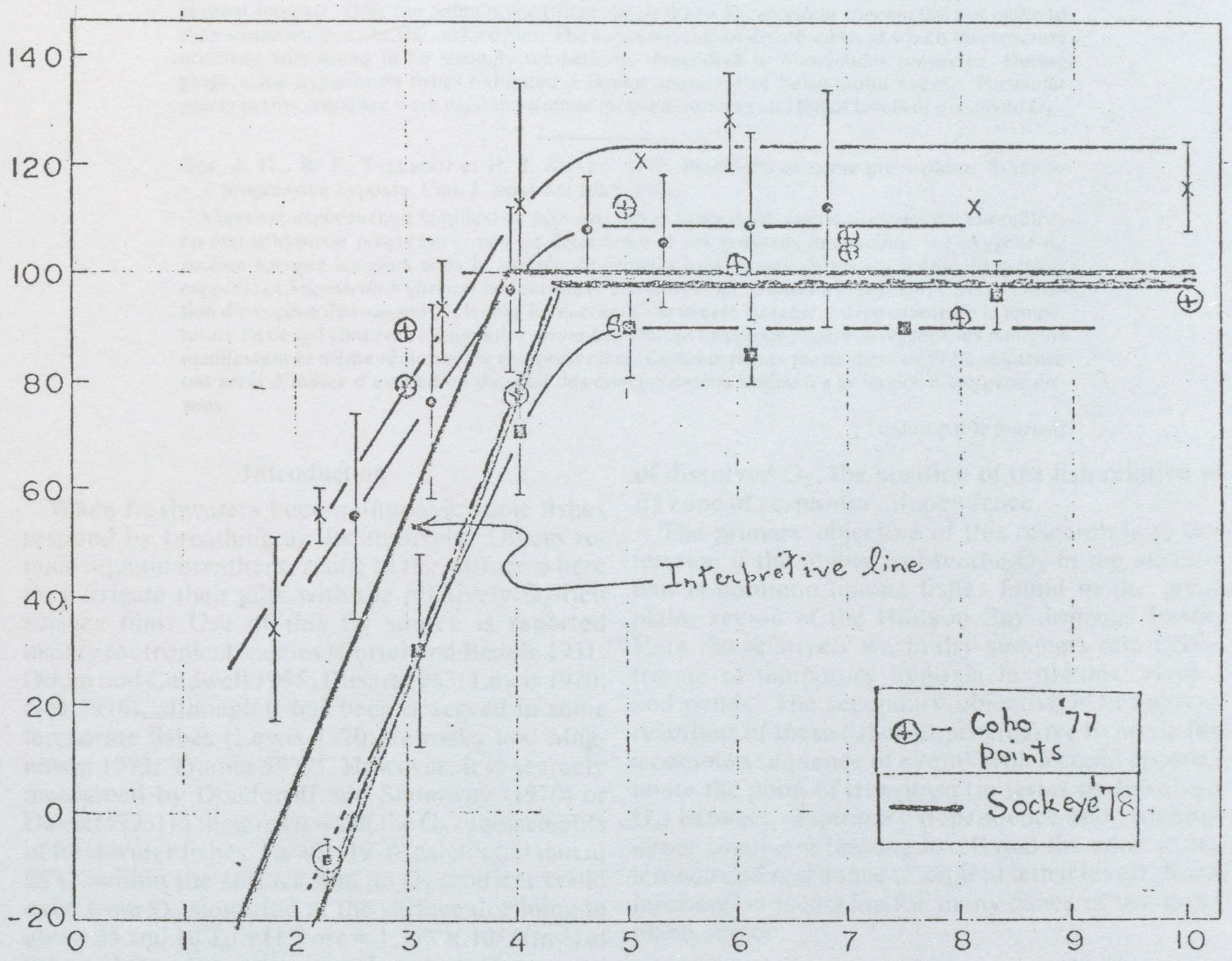
APPENDIX 2

- Dr. R. Brett's graphs of Growth Rate (%/day) vs. Oxygen Concn. (ppm.) at 15°C for Sockeye and Coho Salmon and species comparisons, from Brett (1979) in press;

- "Reactions of Some Great Plans Fishes to Progressive Hypoxia," J. H. Gee, R. F. Tallman and Heather J. Smart, Can. J. Zool., (1978), 56, 1962-1966; and

- "Effect of Long-Term Reduction and Diel Fluctuation in Dissolved Oxygen on Spawning of Black Crappie, *Pomoxis nigromoculatus*," A. R. Carlson and L. J. Herman, Trans. Amer. Fish. Soc., (1978), 107, (5), 742-746.


(1978)
SOCKEYE
COHO
(1977)
ESTIMATED
(1977)
1978
GROWTH RATE %/day
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0
1
2
3
4
5
6
7
8
9
10
OXYGEN - ppm (15°C)



Relative scale within species –
– not between species.

Reactions of some great plains fishes to progressive hypoxia

JOHN H. GEE, ROSS F. TALLMAN, AND HEATHER J. SMART
Department of Zoology, University of Manitoba, Winnipeg, Man., Canada R3T 2N2

Received December 14, 1977

GEE, J. H., R. F. TALLMAN, and H. J. SMART. 1978. Reactions of some great plains fishes to progressive hypoxia. Can. J. Zool. 56: 1962–1966.

Twenty-six species from eight families of great plains fishes were examined in progressive hypoxia to see if the use of dissolved O_2 in the surface film was common when subsurface waters became hypoxic. Only the Salmonidae (three species) and *Stizostedion vitreum* did not move to the surface and breathe the surface film. The concentration of dissolved O_2 at which this reaction occurred was found to be strongly temperature dependent in *Pimephales promelas*. During progressive hypoxia all fishes exhibited a similar sequence of behavioural events. Particular points in this sequence were used to estimate incipient limiting and lethal levels of dissolved O_2.

GEE, J. H., R. F. TALLMAN et H. J. SMART. 1978. Reactions of some great plains fishes to progressive hypoxia. Can. J. Zool. 56: 1962–1966.

Vingt-six espèces (huit familles) de poissons des prairies nord-américaines ont été surveillées en état d'hypoxie progressive, afin de déterminer si ces poissons ont recours à l'oxygène de surface lorsque les eaux sous la surface deviennent hypoxiques. Seuls les Salmonidae (trois espèces) et *Stizostedion vitreum* restent sous l'eau sans venir respirer à la surface. La concentration d'oxygène dissous qui déclenche la réaction s'est avérée fortement dépendante de la température en ce qui concerne *Pimephales promelas*. Durant l'hypoxie progressive, tous les poissons manifestent la même séquence de comportement. Certains points particuliers de cette séquence ont servi d'indice d'estimation du seuil des concentrations limitantes et létales d'oxygène dissous.

[Traduit par le journal]

Introduction

When freshwaters become hypoxic some fishes respond by breathing air facultatively. Others remain aquatic breathers, rising to the surface where they irrigate their gills with the relatively O_2-rich surface film. Use of this O_2 source is reported mainly for tropical species (Carter and Beadle 1931; Odum and Caldwell 1955; Dusart 1963; Lewis 1970; Gee 1976), although it has been observed in some temperate fishes (Lewis 1970; Petrosky and Magnuson 1973; Tramer 1977). However, it is scarcely mentioned by Doudoroff and Shumway (1970) or Davis (1975) in their reviews of the O_2 requirements of freshwater fishes. Lewis (1970) calculated that at 25°C, within the surface film an O_2 gradient could exist from O_2 saturated at the surface declining to about 55 and 10 Torr (1 Torr = 1.333×10^2 N/m^2) at 0.5 and 1 mm, respectively, below the surface, even when there was no detectable O_2 in deeper waters. He found that this source of O_2 was exploited to varying degrees by different species of fish according to the extent of morphological adaptations.

Upon encountering a gradual reduction in dissolved O_2 (progressive hypoxia) many fishes increase the frequency and amplitude of opercular movements (Marvin and Heath 1968) and alter activity and depth distribution (Petrosky and Magnuson 1973) prior to utilizing O_2 in the surface film. Petrosky and Magnuson (1973) suggested that particular changes in the above could indicate, in terms of dissolved O_2, the position of the fish relative to its zone of respiratory dependence.

The primary objective of this research is to determine if the ability to breathe O_2 in the surface film is common among fishes found in the great plains region of the Hudson Bay drainage basin. Here the relatively warm dry summers often contribute to temporary hypoxia in streams, rivers, and ponds. The secondary objective is to analyse reactions of these fishes to progressive hypoxia for a common sequence of events which could approximate the point of transition (in terms of dissolved O_2) between respiratory dependence and independence (incipient limiting level) and the zone of tolerance and resistance (incipient lethal level). Such information is lacking for many fishes of the great plains region.

Materials and Methods

Fishes were collected from southern Manitoba waters and held in the laboratory up to 4 weeks at 16°C (±3°C) in a 12 h light : 12 h dark photoperiod. They were fed Tetramin flakes and frozen brine shrimp. To describe their reactions to hypoxic water they were observed as dissolved O_2 (P_wO_2) declined from normoxic ($P_wO_2 \triangleq 150$ Torr) to hypoxic ($P_wO_2 < 50$ Torr) conditions. Pelagic species were observed in a large aquarium ($45 \times 45 \times 90$ cm) and benthic species in a smaller one ($25 \times 25 \times 50$ cm) with a sloping bottom (about 45°) surfaced with small pebbles (2–6 mm diameter). This ramp permitted fish access to surface water while resting on the bottom. Both aquaria were painted black on three sides and illuminated with a 100-W light from above; observations were made from behind a blind to reduce

TABLE 1. Reactions of fishes to hypoxic water showing estimated incipient lethal levels (A) for fishes utilizing O_2 in surface film and estimated incipient limiting levels (B) that were indicated by a decline in either opercular movements, activity, or both

	Fork length, mm	(A) P_wO_2 when 50% breathing surface film, Torr	(B) P_wO_2 (Torr) at start of decline in: opercular movements (OM)	activity (Act.)	P_wO_2 mean where OM and Act. both occurred, Torr
Salmonidae					
Salmo gairdneri[a]	104–150	[f]	42.8	42.8	42.8
Savelinus alpinus[b,c]	135–165	[f]	48.3	48.3	48.3
Coregonus clupeaformis[c,d]	112–126	[f]	[g]	23.7	
Esocidae					
Esox lucius	89–115	6.3	42.1	[h]	
Cyprinidae					
Chrosomus eos	44–51	9.5	20.6	15.8	18.2
Hybognathus hankinsoni	54–61	11.3	32.2	32.2	32.2
Nocomis biguttatus	64–112	13.7	20.1	17.1	18.9
Notropis atherinoides	51–76	15.6	21.8	21.8	21.8
Notropis cornutus	38–51	16.1	23.1	23.1	23.1
Notropis hudsonius	63–112	17.2	[g]	19.5	
Pimephales promelas	40–63	13.7	[g]	13.7	
Rhinichthys atratulus	63–76	15.1	28.0	19.0	23.5
Rhinichthys cataractae[e]	45–78	8.0	16.9	16.9	16.9
Semotilus atromaculatus	63–89	14.0	39.0	32.0	35.5
Semotilus margarita	88–115	7.9	15.1	11.4	13.3
Catostomidae					
Catostomus commersoni	63–114	13.6	23.3	17.5	19.9
Ictaluridae					
Ictalurus melas	76–115	10.3	52.3	15.8	34.1
Noturus gyrinus	38–64	3.4	18.9	[i]	
Gasterosteidae					
Culaea inconstans	38–53	18.7	34.1	34.1	34.1
Pungitius pungitius	31–38	49.9	[g]	58.7	
Centrarchidae					
Ambloplites rupestris	26–88	19.5	[g]	35.9	
Percidae					
Perca flavescens	50–127	11.7	35.1	23.0	29.1
Stizostedion vitreum	63–76	[f]	32.8	32.8	32.8
Etheostoma exile[e]	31–63	12.2	38.6	[h]	
Etheostoma nigrum[e]	37–50	16.8	26.5	[h]	
Percina maculata[e]	51–58	8.3	[g]	[h]	

[a] Obtained from Caddy Lake Hatchery, Manitoba.
[b] Tested at 10°C.
[c] Obtained from Freshwater Institute, Winnipeg, Manitoba.
[d] Tested at 7°C.
[e] Benthic species.
[f] Not observed to use O_2 in surface film.
[g] No decline in frequency of opercular movement prior to breathing O_2 in surface film.
[h] Inactive all the time.
[i] No decline in activity prior to breathing O_2 in surface film.

visual disturbance. A gently bubbling air stone maintained normoxic conditions. By bubbling N_2 through this air stone the P_wO_2 could be reduced from 156 to 10 Torr within 120 min (P_wO_2 measured by a YSI O_2 meter; model 57 at 10–15 cm below the water surface). Experiments were conducted in a well-ventilated room which prevented the accumulation of N_2 above the surface water.

Once accustomed to the test aquarium (at least 18 h at 16.5 ± 1°C), 10 individuals of each species were observed. Observations in progressive hypoxia continued until there was evidence of either breathing surface water or a loss of coordinated movement and distress. Every 5 min the following were recorded: P_wO_2; number of fish in top, middle, and bottom thirds of the test aquarium; number of fish swimming (activity index); and number of fish breathing the surface film. Frequency of opercular movements was recorded for five fish every 10 min. The position of fish while breathing the surface film was described. Exceptions to this procedure are noted in Table 1.

As hypoxia can occur at any temperature, the effect of temperature on the P_wO_2 at which *Pimephales promelas* commenced to breathe the surface film was examined at 6, 10, 15.5, 20, 24, 27.5, and 30°C (±0.5°C). Fish were taken from the field in monidae would be classified as category 1 fishes. The remainder are category 2 except Gasterosteidae and *E. lucius* which are category 3. Their pointed heads and somewhat dorsal mouths would facilitate use of surface waters.

The typical sequence of responses of fishes encountering progressive hypoxia is the following: an initial increase in frequency of opercular movements with either sustained or increased activity; then a decline in frequency of opercular movements and (or) activity; and finally, either breathing the surface film or loss of coordinated movements. Particular stages in this sequence could be used to estimate the incipient limiting level (Shepard 1955) or critical level (Hughes 1973) and the incipient lethal level (Fry 1947). The incipient limiting level could be approximated by the P_wO_2 at which either the decline in frequency of opercular movement or activity is initiated (or when both occur, their mean). Here the declining P_wO_2 available is just sufficient to meet the demands of the fish. With a further decrease the fish must compensate by reducing O_2 uptake as it passes from the zone of respiratory independence into the zone of dependence. To use this estimator we assume that the initial reduction in opercular movements and (or) activity signals the start of a reduction in O_2 uptake. These estimates vary between 13.3 and 58.7 Torr (Table 1). Their mean of 24 Torr corresponds well to that of 30 Torr given by Davis (1975) as an average incipient limiting level for aquatic vertebrates.

Marvin and Heath (1968) reported that *Salmo gairdneri* and *Lepomis machrochirus* increased O_2 uptake during progressive hypoxia but passed into the zone of respiratory dependence at about 95 and 120 Torr respectively, much higher incipient limiting levels than those reported here. The differences could be caused by confined experimental conditions that did not permit swimming. During progressive hypoxia both species swim actively (Table 1; Petrosky and Magnuson 1973), most likely contributing to gill irrigation and O_2 uptake. Confinement would restrict O_2 uptake and raise the incipient limiting level.

The P_wO_2 at which 50% of the fish breathe the surface film could be used to approximate the incipient lethal level. To use this estimator, one must assume that breathing the surface film is a last resort for survival. This seems likely for species in category 2 and possibly category 3 which are not well adapted morphologically for using surface-film O_2 and which could be vulnerable to aquatic and aerial predators while at the surface.

The mean value of P_wO_2 at which breathing the surface film was initiated by species studied by Lewis (1970) was 11.9 Torr (range: 7.2–22.4 Torr). This corresponds well with the mean P_wO_2 at which 50% of the fish studied here had commenced to utilize surface film O_2 of 14.2 Torr (range: 3.4–49.9 Torr, Table 1).

Incipient limiting and lethal levels of P_wO_2 represent conditions of extreme O_2 stress and should not be used to establish O_2 criteria to safeguard fish populations. The beginning of O_2 stress occurs when P_wO_2 reaches the incipient O_2 response threshold (Davis 1975), i.e., the level at which a lowered P_wO_2 first affects either the physiological, biochemical, or behavioural processes of the fish. Such levels of P_wO_2 for five nonsalmonid species and four salmonid species averaged 73 and 90 Torr respectively (Davis 1975).

We conclude that the ability to utilize dissolved O_2 in surface waters during hypoxia is a common response among fishes of the great plains. These species are not well adapted to use this O_2 source indefinitely. During progressive hypoxia, a sequence of events common to most species occurs that could be used to estimate incipient limiting and lethal levels of dissolved O_2.

Acknowledgements

This study was supported by the National Research Council of Canada. We thank Drs. R. M. Evans, D. L. Kramer, and E. Scherer for constructive comments on an earlier draft of the manuscript.

Carter, G. S., and L. C. Beadle. 1931. The fauna of the swamps of the Paraguayan Chaco in relation to its environment. II Respiratory adaptations in the fishes. J. Linn. Soc. London, Zool. 7: 327–368.

Davis, J. C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32: 2295–2332.

Doudoroff, P., and D. L. Shumway. 1970. Dissolved oxygen requirments of freshwater fishes. FAO (F.A.O.U.N.) Tech. Pap. 86.

Dusart, J. 1963. Contribution à l'étude de l'adaptation des Tilapia (Pisces Cichlidae), à la vie en milieu mal oxygéné. Hydrobiologia, 21: 328–341.

Fry, F. E. J. 1947. Effects of the environment on animal activity. Univ. Toronto Stud. Biol. Ser. No. 55. Publ. Ont. Fish. Res. Lab. No. 68.

Gee, J. H. 1976. Buoyancy and aerial respiration: factors influencing the evolution of reduced swim-bladder volume of some Central American catfishes (Trichomycteridae, Callichthyidae, Loricariidae, Astroblepidae). Can. J. Zool. 54: 1030–1037.

Hughes, G. M. 1973. Respiratory responses to hypoxia in fish. Am. Zool. 13: 475–489.

Lewis, M. W. 1970. Morphological adaptations of cyprinodon-

Trans. Am. Fish. Soc., 107(5): 742–746, 1978

Effect of Long-term Reduction and Diel Fluctuation in Dissolved Oxygen on Spawning of Black Crappie, *Pomoxis nigromaculatus*

ANTHONY R. CARLSON AND LAWRENCE J. HERMAN

U.S. Environmental Protection Agency, Environmental Research Laboratory-Duluth
6201 Congdon Boulevard, Duluth, Minnesota 55804

ABSTRACT

Mature black crappies were exposed over winter in the laboratory to constant dissolved oxygen concentrations near 2.5, 4.0, 5.5, and 7.0 mg/liter. Starting on 26 April during a simulated spring-to-summer rise in water temperature, some were continued at the original oxygen concentrations while others were subjected to mean diel fluctuations ranging from 0.8 to 1.9 mg O_2/liter above and below the original concentrations. Controls were maintained at concentrations near air saturation. No spawning occurred at the lowest fluctuating treatment of 1.8 to 4.1 mg/liter. This treatment also caused behavioral aberrations as the water temperature reached 20 C. Successful spawning occurred during all other treatments.

Diel fluctuations of dissolved oxygen (DO) concentrations in aquatic habitats are often enhanced by organic pollutants. Although a large literature exists on the DO requirements of freshwater fish, the relationship between diel fluctuations in DO concentrations and fish spawning success is unknown. Such information is essential for the establishment of meaningful water-quality criteria. Exposure of fish for short periods of time to diurnal fluctuations in DO concentration, from relatively high to low levels, can cause behavioral aberrations, deformities, and death of larvae (Spoor 1977), impaired growth of juveniles (Fisher 1963; Stewart et al. 1967; Whitworth 1968) and behavioral aberrations and changes in several components of the blood in larger fish (Bouck and Ball 1965; Bouck 1972).

The objective of this laboratory study was to determine the spawning success of the black crappie, *Pomoxis nigromaculatus*, exposed to diel fluctuations of DO concentration after exposure over winter to one of four constant reduced DO regimes. Black crappie spawning success was unaffected by 2-mo exposure to several constant reduced DO concentrations ranging from 2.5 to 6.6 mg/liter (Siefert and Herman 1977), although the time of first spawning appeared to be advanced at the lower concentration. Brungs (1971) found that fathead minnow *Pimephales promelas* spawning was inhibited at a constant 11-mo exposure to 1 mg O_2/liter and was reduced at 2 mg/liter; resulting larvae died within 2–5 days after hatching. Survival of larvae was reduced at concentrations up to and including 4 mg/liter. To our knowledge no other work has been reported on the effects of experimental long-term reductions in DO concentration on fish spawning success.

METHODS

The test apparatus, black crappie culture and rearing techniques, and chemical characteristics of the water supply have been described previously (Siefert and Herman 1977).

Black crappies were obtained from the Mississippi River near Genoa, Wisconsin, and transported to the laboratory in Duluth, Minnesota, on 30 September and 7 October 1976 at 13 C. Thereafter they were provided with Lake Superior water and were subjected to a simulated seasonal decrease in water temperature to an overwinter temperature of 4.5–7 C. On 26 April 1977 a simulated spring rise in temperature was initiated; at the end of the test on 1 July 1977 the temperature reached 23 C. The natural light cycle of Duluth, Minnesota was simulated.

To obtain the desired DO concentrations degassed water was mixed with air-saturated water in glass mixing chambers. This water was drawn by in-line pumps through four-way valves that were timer-controlled

---

and let wate
centration i
pumped thr
water bath t
and delivere
flow meters a
was delivere
drical screen
gases.

On 9 Nove
of 8 C, fish r
graded into
uted one at a
each contain
some fish fr
diameter fi
approxi
tained
the DO conc
ered to const
5.5, 4.0, and
trols) retained
air saturation.
the fish in ea
centrations w
ditional dupli
remained at t
until the end
problems and
completing
study, the mo
erally larger
tanks and we
in DO conce
highs at 1800
liter above a
(Fig. 1). This
April and co
of the rise in

Two artifici
1977) were pl
when water
These nests
bryos. If em
spawning act
were removed
were conside
hundred emb
cubated and
and "survival
Each sample
screened-bott
tank where s

mouth bass (*Micropterus salmoides*); and rock bass (*Ambloplites rupestris*) (Bouck and Ball 1965; Bouck 1972).

Spawning did not occur among four males and one female in one tank with a mean diel fluctuation of 2.6–5.6 mg DO/liter, but was apparently uninhibited (15 spawnings) under similar conditions in the duplicate tank (mean diel fluctuation 2.7–5.7 mg/liter) containing three males and two females. No behavioral deviations of the fish were seen in these treatments.

The selection of the healthy appearing and generally larger fish for exposure to the fluctuating DO treatments should not have biased the results. At the end of the test, mature males at the constant treatments were smaller (mean weight 167.6 g; range 70–265 g) than those at the fluctuating treatments (mean weight 226.5 g; range 156–492 g). However, small and large males were observed defending nests and spawning. There was little difference among the average weights of the mature females. Mean weights in the constant and fluctuating treatments were 184.3 g (range 125–276 g) and 196.1 g (range 125–447 g), respectively. We also believe the number of females (three, ranging from 200–224 g) at the lowest fluctuating DO treatment was adequate for determining the effects on spawning because spawning occurred in 12 of 13 tanks containing from one to four females.

This study indicates that dissolved oxygen concentrations near 2.6 mg/liter or above are sufficient to provide the DO requirements of mature black crappie prior to (overwinter) and during the spawning period; and that diel fluctuations below this concentration to about 1.8 mg/liter during the spring water temperature rises can cause hypoxic stress and inhibit reproduction.

ACKNOWLEDGMENTS

We thank John Blocker for assistance during the study, Richard Siefert for technical guidance, Virginia Snarski for identifying the bacterial pathogen, and the Genoa National Fish Hatchery personnel for providing the fish.

REFERENCES

Bouck, G. R. 1972. Effects of diurnal hypoxia on electrophoretic protein fractions and other health parameters of rock bass *Ambloplites rupestris*. Trans. Am. Fish. Soc. 101:448–493.

———, and R. C. Ball. 1965. Influence of a diurnal oxygen pulse on fish serum proteins. Trans. Am. Fish. Soc. 94:363–370.

Brungs, W. A. 1971. Chronic effects of low dissolved oxygen concentrations on the fathead minnow *Pimephales promelas*. J. Fish. Res. Board Can. 28:1119-1123.

Fisher, R. M. 1963. Influence of oxygen concentration and of its diurnal fluctuation on the growth of juvenile coho salmon. M.Sc. Thesis. Oregon State Univ., Corvallis. 48 pp.

Siefert, R. E., and L. J. Herman. 1977. Spawning success of the black crappie *Pomoxis nigromaculatus* at reduced dissolved oxygen concentrations. Trans. Am. Fish. Soc. 106:376–378.

Spoor, W. A. 1977. Oxygen requirements of embryos and larvae of the largemouth bass, *Micropterus salmoides* (Lacépède). J. Fish Biol. 11:77–86.

Stewart, N. E., D. L. Shumway, and P. Doudoroff. 1967. Influence of oxygen concentration on the growth of juvenile largemouth bass. J. Fish. Res. Board Can. 24:475–494.

Trussell, R. P. 1972. The percent un-ionized ammonia in aqueous ammonia solutions at different pH levels and temperatures. J. Fish. Res. Board Can. 29:1505–1507.

Whitworth, W. R. 1968. Effects of diurnal fluctuations of dissolved oxygen on growth of brook trout. J. Fish. Res. Board Can. 25:579–584.

Trans. Am. Fish. S
© Copyright by the A

Inf

Yearlin
relatively
peratures
temperat

Mammalia
shown to inc
fish species
1957; Cheste
enhancement
carpio L.) d
(bGH) was fo
perature as
perature for
influence eff
One objectiv
test an expa
include effec
well as abo
tures. Since
Markert et a
malian grow
position of
objective of
effect of bo
composition

Yearling c
in May 1976.
C until the
mation in A
tion period c
then mainte
ture. The ex
22-liter aqua
flowing wate
proximately
tained in eac

---

[1] Paper 9941.
Agricultural E