EIFAC Technical Paper No. 19 EIFAC/T19

WATER QUALITY CRITERIA FOR EUROPEAN FRESHWATER FISH

Report on dissolved oxygen and inland fisheries

EUROPEAN INLAND FISHERIES ADVISORY COMMISSION
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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WATER QUALITY CRITERIA FOR EUROPEAN FRESHWATER FISH

Report on Dissolved Oxygen and Inland Fisheries

prepared by

European Inland Fisheries Advisory Commission
Working Party on Water Quality Criteria
for European Freshwater Fish

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1973

PREPARATION OF THIS DOCUMENT

The background of this paper is desoribed in the Foreword to the report itself. The paper was prepared by the European Inland Fisheries Advisory Commission (EIFAC) Working Party on Water Quality Criteria for European Freshwater Fish.
The report is being issued in this series where the first six documents of the Working Party were published: "Report on finely divided solids and inland fisheries", EIFAC Teoh.Pap., (1):21 p., 1964; "Report on extreme pH values and inland fisheries", EIFAC Teoh.Pap., (4):24 p., 1968; "Report on water temperature and inland fisheries based mainly on Slavonic literature", EIFAC Teoh.Pap., (6):32 p., 1968; "List of literature on the effect of water temperature on fish", EIFAC Teoh.Pap., (8):8 p., 1969; "Report on ammonia and inland fisheries", EIFAC Teoh.Pap., (11):12 p., 1970; and "Report on monohydric phenols and inland fisheries", EIFAC Tech.Pap., (15):18 p., 1972.

Distribution:

FAO Department of Fisheries
FAO Regional Offioers
Seleotor EI/E only

Bibliographio Entry:

EIFAC. Working Party on Water Quality Criteria for European Freshwater Fish (1973)
EIFAC Tech.Pap., (19):10 p.
Water quality oriteria for European freshwater fish. Report on dissolved oxygen and inland fisheries

FAO - reports of commissions. F. Europe. Water quality, pollution - dissolved oxygen. Effeots on fish-fauna and food organisms. Direot lethal and sublethal actions - physiology, reproduotion, development, growth, behaviour. Effeots on environment - rivers, lakes, estuaries. Laboratory researoh. Selected bibliography.

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FOREWORD

This is the seventh technical paper on water quality criteria for European freshwater fish prepared for the European Inland Fisheries Advisory Commission (EIFAC) - an inter-governmental organization with a membership of 23 countries. The Commission has been active in its efforts to establish water quality criteria for European freshwater fish since its Second Session, Paris, 1962, when it took note of a recommendation of the United Nations Conference on Water Pollution Problems in Europe, 1961, that EIFAC take the initiative in drawing up water quality requirements with respect to fisheries 1/.

As was stated in its first six reports on water quality criteria 2/, the Commission "agreed that the proper management of a river system demands that water of suitable quality be provided for each use that is made or intended to be made of it and that the attainment and maintenance of such quality is normally to be sought through the control of pollution. It was necessary, therefore, to know the standards of quality required for each particular use in order to determine the degree of pollution control necessary and to forecast the probable effect of augmented or new discharges of effluents. It was pointed out that water quality standards for drinking water had been well defined by the World Health Organization (WHO) and that standards for certain agricultural and industrial uses are also well defined. However, water quality criteria for fish have not received the attention that they deserve. All too often, water has been considered quite adequate for fish as long as there has been no obvious mortality which can be ascribed to known pollutants. Degradation of the aquatic habitat through pollution and decrease in the annual production and subsequent harvest of fish have often passed unnoted.

With such reasoning in mind, it was agreed that the establishment of water quality criteria for European freshwater fish be undertaken by the Commission. This was to be accomplished by a critical examination of the literature, and very possibly experimentation to clear up contradictions and fill in gaps of knowledge, followed by recommendations as to desirable requirements for various aquatic organisms or groups of aquatic organisms with respect to the various qualities of water. The final criteria were to be published and given wide dissemination."

To accomplish this task, the Second Session of the Commission appointed a Working Party of experts selected on the basis of their knowledge of physical, chemical and biological requirements of European freshwater fish in relation to the topics to be studied.

This Working Party prepared its first report on finely divided solids and inland fisheries (see footnote 2/) which was submitted to the Commission at its Third Session, Scharfling am Mondsee, 1964, where it was unanimously approved 3/.

1/ See, respectively: EIFAC Report, Second Session, 1962, p. 21-2
UN (1961) Conference on Water Pollution Problems in Europe, held in Geneva from 22 February to 3 March 1961
Documents submitted to the Conference. Vols. I-III, United Nations, Geneva, 600 p.

2/ Report on Finely Divided Solids and Inland Fisheries, EIFAC tech.Pap., (1):21 p., 1964
Report on Extreme pH Values and Inland Fisheries, EIFAC tech.Pap., (4):18 p., 1968
Report on Water Temperature and Inland Fisheries based mainly on Slavonic Literature, EIFAC tech.Pap., (6):32 p., 1968
List of Literature on the Effect of Water Temperature on Fish, EIFAC tech.Pap., (8):8 p., 1969
Report on Ammonia and Inland Fisheries, EIFAC tech.Pap., (11):12 p., 1970
Report on Monohydric Phenols and Inland Fisheries, EIFAC tech.Pap., (15):18 p., 1972

3/ EIFAC Report, Third Session, 1964, p. 11

The Third Session then suggested that the following studies be considered by the Working Party:

- water temperature (including a review of the effect of heated discharges);
- dissolved oxygen and carbon dioxide; pH; toxic substances including heavy metals, phenols and pesticides and herbicides.

Elevated temperature was given first priority, and a draft on this subject was prepared by the Working Party during the following inter-sessional period. (At the Third Session the work of the Commission was re-organized into three Sub-Commissions, one of which, Sub-Commission III - Fish and Polluted Water - regrouped all the activities of EIFAC in the field of water pollution. The Working Party on Water Quality Criteria for European Freshwater Fish has since functioned under this Sub-Commission.)

The Fourth Session of the Commission, Belgrade, 1966, after having studied this first draft of review of literature on the effects of water temperature on aquatic life concluded that such a review required more effort than the resources of the Commission permitted at the time. Meanwhile, it suggested that a water quality report for extreme pH values be prepared for the next Session of EIFAC, and that a report on dissolved oxygen be prepared when funds become available for a full-time consultant 4/.

The report on extreme pH values and inland fisheries (see footnote 2/) was published in 1968, in time for presentation at the Fifth Session of EIFAC, Rome, 1968, where it was unanimously approved 5/.

At its Fifth Session the Commission again reviewed priorities for future studies and decided to undertake critical reviews on the effects of ammonia and phenols on freshwater fishes.

It also recommended that guidance as to its future work in the field of water pollution control, including the development of water quality criteria, be taken from the FAO/EIFAC Symposium on the Nature and Extent of Water Pollution Problems affecting Inland Fisheries in Europe which was later held in Jablonna, Poland, 15-16 May 1970, just before the Sixth Session of EIFAC.

The Fifth Session also approved in draft a report on water temperature and inland fisheries based mainly on Slavonic literature. The report was published in November 1968 as the third in the EIFAC water quality criteria series, and was followed in 1969 by the fourth publication in the series, a list of literature on the effect of water temperature on fish. (See footnote 2/ for both papers.)

Following the Jablonna Symposium 6/, the Sixth Session of EIFAC, Krakow, 1970, again reviewed the Commission's programme with respect to water quality criteria 7/. Noting that a report on ammonia was almost complete, it approved continuance of work on phenols, and the current work begun by the Working Party on copper, zinc and mercury, and recommended the addition of cyanides, detergents, chlorine and hydrocarbons as items for future reviews. It also recommended eventual resumption of work on water temperature and the preparation of a review based on a critical worldwide report on dissolved oxygen prepared for FAO 8/.

4/ EIFAC Report, Fourth Session, 1966, p. 12

5/ EIFAC Report, Fifth Session, 1968, pp.14-5

6/ Holden, A.V. and R. Lloyd (1972), Symposium on the Nature and Extent of Water Pollution Problems affecting Inland Fisheries in Europe. Synthesis of National Reports, EIFAC tech.Pap., (16):20 p.

7/ EIFAC Report, Sixth Session, 1970, p. 13

8/ Doudoroff, Peter and Dean L. Shumway (1970), Dissolved Oxygen Requirements of Freshwater Fishes. FAO Fish.tech.Pap., (86):291 p.

Since the Sixth Session of EIFAC, the EIFAC Working Party has published reports on ammonia and monohydric phenols (see footnote 2/ for both reports) as the fifth and sixth reviews in this EIFAC series of water quality papers. They were both presented to the Seventh Session of EIFAC (Amsterdam, 1972 9/) where they were unanimously approved. The Working Party has also continued an active search on mercury, and is preparing reviews on zinc and chlorine and inland fisheries.

The seventh review, which follows, is the one on dissolved oxygen and inland fisheries. For the preparation of this report, the following experts were appointed to the EIFAC Working Party on Water Quality Criteria:

Mr. J.S. Alabaster	(United Kingdom), Convener
Dr. D. Calamari	(Italy)
Mr. M. Grande	(Norway)
Dr. T.B. Hasselrot	(Sweden)
Mr. R. Lloyd	(United Kingdom)
Dr. A.W. Lysak	(Poland)

FAO Secretariat:

Mr. J.-L. Gaudet - Acting Secretary to EIFAC
Dr. T.V.R. Pillay - Acting Chief, Inland Fishery Resources Branch
Dr. R.L. Welcomme - Inland Fishery Resources Branch

The preparation of the present report on dissolved oxygen and inland fisheries was accomplished largely by the Water Pollution Research Laboratory (Stevenage, U.K.) which prepared the basic manuscript to be reviewed by the members of the Working Party.

The Working Party used the same general basis for their work on which they had agreed for the preparation of their first report that:

"Water quality criteria for freshwater fish should ideally permit all stages in the life cycles to be successfully completed and, in addition, should not produce conditions in a river water which would either taint the flesh of the fish or cause them to avoid a stretch of river where they would otherwise be present, or give rise to accumulation of deleterious substances in fish to such a degree that they are potentially harmful when consumed. Indirect factors like those affecting fish-food organisms must also be considered should they prove to be important."

This report will be presented to the Eighth Session of EIFAC, which is scheduled to be held in Aviemore, Scotland, United Kingdom.

The Seventh Session of EIFAC (see footnote 9/) suggested as possible future subjects for reviews cadmium and lead.

9/ EIFAC Report, Seventh Session, 1973, p. 76

SUMMARY

Sensitivity of fish to low concentrations of dissolved oxygen (DO) differs between species, between the various life stages (eggs, larvae, and adults), and between the different life processes (feeding, growth, and reproduction, which in turn may depend on swimming ability, and specialized behaviour which may also be influenced by DO). Any DO standards set for fisheries must take all these into account, bearing in mind the type of fishery, the times and places the fish occur, and the likely impact on the fishery of impairment of each part of the life cycle.

Although there is a considerable volume of laboratory data on the effects of DO on fish life processes, much of it is incomplete in terms of the distribution of the responses within fish populations at given physiological and behavioural states, and difficult to interpret in terms of ecological significance. However, the general pattern which emerges is that, providing other environmental factors (including the absence of poisons) are favourable, a minimum constant value of 5 mg/l would be satisfactory for most stages and activities in the life cycle in that some processes, such as juvenile growth, fecundity, hatch of eggs, larval morphology and survival, upstream movement of migratory salmon, and schooling behaviour of some species, including shad, are not particularly susceptible to levels of DO above 5 mg/l. However, this value may be unnecessarily high merely to ensure satisfactory survival of the fish and adequate growth of the juveniles.

Difficulties arise in formulating DO criteria for fisheries because of the widely different patterns of DO fluctuations which can exist in inland waters even when unpolluted and the uncertainty of predicting their effect even when adequately described, unless the levels are so low as to be directly lethal to fish or so high as to have no effect on them. There have been few experiments made which attempt to simulate natural conditions, most being made at constant DO levels; furthermore, field data are generally inadequate in that either the fish populations present or the DO regime are poorly described, and their interpretation is complicated by the presence of other poisons. In these circumstances, only tentative criteria can be put forward.

Because DO levels in a river normally fluctuate, it is inappropriate to put forward criteria based on a single minimum value never to be violated or even as several minima each not to be violated at a certain time of year, but they should be expressed as a minimum percentile distribution (e.g., a minimum 5- and 95-percentile value) over a year or part of a year, or, with estuarine fisheries, part of a tidal cycle.

From the limited data available it is suggested that for resident populations of moderately tolerant freshwater species, such as roach, the annual 50-percentile and 5-percentile DO values should be greater than 5 mg/l and 2 mg/l respectively and for salmonids the percentiles should be 9 mg/l and 5 mg/l respectively.

These values are to be regarded as being for general guidance only, because there are special circumstances where more consideration should be given to the seasonal distribution of DO, for example in estuaries through which migrant salmonids pass. Moreover, all these minimum values might need to be considerably increased in the presence of high temperature or poisons.

To enable more satisfactory criteria to be formulated, further laboratory studies are required which would reflect natural DO regimes and more field observations are required on the status of fish populations where the DO is lowered and on the movements of adults and young of migratory species. These should be coupled with more complete analytical data on the DO, both where the fish populations are only marginal and where they are well established. The consequences of reduced fecundity, growth and reproduction, and of changed behaviour patterns, on population dynamics and production of fish and of fisheries should also be appraised.

1. INTRODUCTION

(1) Dissolved oxygen (DO) is essential, and in some cases even the limiting factor, for maintaining aquatic life; its depletion in water is probably the most frequent general result of certain forms of water pollution, and its effects on aquatic organisms, especially at low concentrations, have therefore been very extensively studied. Most of the work with freshwater species of fish has recently been thoroughly and critically reviewed by Doudoroff and Shumway (1970); their review provides the basis for the factual information presented here. References already covered by these authors will not be cited, but a selection of more recent papers will be referred to, together with some unpublished data.

(2) Sensitivity to low dissolved-oxygen concentrations differs between species, between the various life stages (eggs, larvae, and adults), and between the different life processes (feeding, growth and reproduction, which may depend on swimming ability, and specialized behaviour which may also be influenced by DO) so that the DO requirements for fisheries must take this into account, bearing in mind the type of fishery, the times and places the fish occur, and the likely impact on the fishery of impairment of each part of the life cycle.

(3) The effect of DO on fish is influenced by several other factors, including temperature, which affects the solubility of oxygen in water and also the metabolic rate of poikilotherms.

2. DIRECT LETHAL ACTION ON FISH

2.1 Age of fish

(4) Sensitivity of young salmonids is greatest around the time of hatching, high mortalities resulting, for example, from sudden reduction of DO to 2-3 mg/l for 6 d. Newly hatched pike larvae (Esox lucius) can survive for one hour in the absence of oxygen but free-swimming larvae for only a few minutes.

(5) Survival of the fry of fathead minnow (Pimephales promelas) after 30 days was only 5 percent at 3 mg/l, increasing to 66 percent at 5 mg/l (Brungs, 1971).

(6) Mature-sized fish can probably survive in DO levels in excess of 3 mg/l when other conditions are favourable, and lethal levels are often much lower than this. Generally, the maximum exposure period required to produce acute anoxia under constant conditions would be about a day for European freshwater species. Young fish tend to be less resistant, but the patterns of change in resistance with age are variable, especially in the first month.

2.2 Temperature

(7) Seasonal variation in resistance independent of temperature has not been demonstrated; in general the minimum DO that fish are able to tolerate increases with rise in temperature, particularly near the upper lethal thermal limit.

2.3 Acclimation

(8) Experiments to determine acute lethal DO values for fish have usually involved their direct transfer from well oxygenated water to the test solutions. However, there is abundant evidence that acclimation to low DO can take place, the length of time required increasing with decreasing temperature; at low temperatures acclimation may not take place. However, it is well known that common carp (Cyprinus carpio) and crucian carp (Carassius carassius) can withstand anaerobic conditions for some months at temperatures close to freezing point. Acclimation for periods up to 10 d to low DO can reduce the "tolerance threshold" of fish to 50 percent of that obtained by direct transfer from the air saturation value ([illegible]V).

(9) R. Lloyd and D.J. Swift (personal communication) suggest that acclimation by rainbow trout (Salmo gairdneri) to 3 mg/l DO at 17°C occurs in two stages; the first, involving

diuresis, reduced blood volume, and increased haematocrit, taking about 6 hours; the second, involving urine retention, increased blood volume, and erythropoesis, taking a further 16 hours. However, such DO levels also increase the permeability of rainbow trout to water.

2.4 Supersaturation

(10) Oxygen-supersaturated water resulting from phytoplankton activity is generally unlikely to be lethal except when gas-bubble disease is caused by the sum of the partial pressures of all dissolved atmospheric gases being greatly in excess of the hydrostatic pressure, or when accompanied by high pH values. Superabundant oxygen in water can produce definite improvement in the period of survival of goldfish (Carassius auratus) at a fixed lethal temperature, or in the lethal temperature reached as a result of heating. No further improvement in thermal tolerance was found at dissolved-oxygen pressures over 5 atmos. (Weatherley, 1970).

2.5 Interaction with poisons and carbon dioxide

(11) At lowered concentration of DO the rate at which water is pumped over the gills of fish may be increased, so increasing the amount of poison in contact with the gill surface where it is absorbed. For several common poisons the LC50 at a DO of 5 mg/l would be roughly halved at 10 mg/l, and a similar effect has recently been confirmed with a more complex waste (Hicks and De Witt, 1971) and with hydrogen sulphide (Adelman and Smith, 1972). Also Cairns and Scheier (1957) found that the 96-h LC50 of zinc chloride, naphthenic acid, and potassium cyanide to bluegill sunfish (Lepomis macrochirus) in soft water at 18°C with the dissolved-oxygen concentration fluctuating over several hours between 9 and 2 mg/l was approximately 0.2, 0.3 and 0.4 of the value when the fluctuations were between 9 and 5 mg/l.

(12) Sudden exposure to a moderately high concentration of CO_2 causes a normally tolerable low DO to be rapidly fatal, but prior acclimation to the CO_2 level removes much of this additional effect. In nature, however, acclimation to increasing CO_2 is likely to occur before the concomitant decreasing DO reaches a critical low level. Effects of CO_2 on DO requirements are not considered to be ascribable to decrease in pH. However, increase in temperature, CO_2, and hydrogen ions, either independently or together, cause rainbow trout blood to have a lowered affinity for oxygen (Eddy, 1971).

(13) Interesting as this information is, it is of limited value in choosing satisfactory water quality criteria for fisheries. It would seem, however, that where conditions are otherwise favourable, acutely lethal effects on fish would probably be avoided by maintaining DO levels above 3 mg/l, though for some species this limit could be much lower (Brungs, 1971), and for many species lower concentrations could be tolerated for short periods. This conclusion is embodied in the summary in Table 1 (see Section 6.).

3. SUBLETHAL ACTION ON FISH

3.1 Fertilization and fecundity

(14) Levels of DO which might affect fertilization appear to be largely unknown, but ova of pike have been fertilized in the absence of oxygen (and at temperatures between 0°C and 30°C).

(15) There is little information on the effect of low DO on fecundity, but Brungs (1971) has recently reported on experiments in which fathead minnow reared for 11 months at 1 mg/l failed to spawn, while those at 2 mg/l or more produced proportionately more eggs per female with increase in DO up to 5 mg/l. Control results at 8 mg/l seem spurious and are perhaps attributable to the slightly different experimental arrangements involved.

3.2 Embryonic development

(16) With salmonids any reduction of DO from ASV or supersaturation can retard development and embryonic growth, reduce size at the time of hatching, or delay hatching, but most will hatch successfully at between 2 and 3 mg/l to produce relatively small and underdeveloped larvae that are viable and not deformed.

(17) Embryos of some non-salmonid species can develop to produce undeformed larvae at DO below 2 mg/l but others including sturgeon (Acipenser güldenstaedti), bream (Abramis brama), Vimba vimba, and pike, apparently require well above 4-5 mg/l at their normal temperatures; those of the last species continuously exposed to 2.0 mg/l from 6 to 24 hours after fertilization showed a statistically significant reduction in percentage hatch compared with that at 6.0 mg/l (Adelman and Smith, 1970).

(18) Under hypoxic conditions hatching is often delayed, but in some species such as chum salmon (Oncorhynchus keta) it may be advanced (Trifonova, 1937); in both cases the newly hatched larvae tend to be smaller than under favourable conditions.

3.3 Respiration and metabolism

(19) The considerable respiratory and cardio-vascular adaptive responses of fish to changes in DO, given special attention by Doudoroff and Shumway (1970) and Satchell (1971), are not necessarily indicative of impairment of ecologically important functions, and probably should not be used as a basis for judgements on DO requirements. For example, diel fluctuations in DO in water were reflected 4 hours later by corresponding changes in tissue oxygen tension in trout (Garey and Rahn, 1970). Levels of DO that depress ordinary metabolic rates of normally feeding fish in nature have not been determined, but they might perhaps be ecologically meaningful. However, the "energy balance" method has been used to show that average metabolic rates of large-mouth bass (Micropterus salmoides) may be nearly independent of prey in its natural environment at favourable temperatures. Since similar amounts of energy can be expended in either seeking prey or in digestion and growth, DO requirements for metabolism may be independent of food consumption and growth rate, indicating that moderately reduced DO levels could affect growth rates at any level of food availability.

3.4 Larval growth

(20) Neither reduction in DO to about 5 mg/l nor moderately wide diurnal fluctuations about this level has much effect on growth of salmonid alevins. At 3 mg/l there may be only slight reduction of growth and, when the yolk sac has been fully absorbed, a reduction in size of about 25 percent, unless temperatures are unfavourably high. There is little information on other species, but somewhat similar results have been reported for fathead minnow (Brungs, 1971). However, since this stage is generally short, retardation of post-larval (juvenile) growth is perhaps of more importance for fish production.

3.5 Juvenile growth

(21) Any reduction in DO even to 50 percent ASV can depress food consumption and growth rate of juvenile fish, even when all other conditions are favourable. It has been shown for the pike that while food conversion is not affected at 3 mg/l, growth shows a slight decrease at 3-4 mg/l and a much greater decrease at lower values (Adelman and Smith, 1970). Also, Japanese data (Itazawa, 1971) suggest that the minimum level of DO for maintaining maximum feeding, growth and efficiency of food conversion is 4-4.5 mg/l for rainbow trout at about 10.5°C, and 3 mg/l for common carp at about 21.5°C.

(22) With carp weighing 40-250 g kept at 23°C and offered food at a rate of 5 percent of their body weight per day in nine portions, the ratio of weight of food offered to increase in weight of fish (conversion ratio) was almost 1:1 at a concentration of DO of 7 mg/l, 2:1 at about 3 mg/l, and 3:1 at about 1 mg/l (Huisman, 1970); it was thought likely that the ratio would have been higher with a lower rate of feeding.

(23) It has been found that 4 to 10 month old brook trout (Salvelinus fontinalis) subjected to fluctuating levels of DO (2.4-10.6 mg/l) do not grow as well as those exposed continuously to 10.6 mg/l (Dorfman and Whitworth, 1969). However, large diel fluctuations of DO down to minima of 2-3 mg/l impair growth and appetite almost as much as do conditions of continuous low DO.

(24) Carbon dioxide may also affect growth adversely. This is relevant where fluctuations may be caused by photosynthetic activity of aquatic plants.

(25) If, in laboratory tests, growth rates of abundantly fed fish are low and apparently dependent on DO only at levels well below saturation, other factors such as low temperature, or nutritionally-deficient or unattractive food, which may not be important under natural conditions, though they may be so in artificial intensive culture, may have been the primary cause of the depressed growth rate.

(26) Under natural conditions growth is usually limited by the availability of food, and increased exploitation of food may require excessive expenditure of energy. However, organic enrichment which often causes low DO can also help sustain a greater biomass of potential food organisms, thus reducing the metabolism required for foraging. Laboratory tests seldom simulate the bioenergetics of a natural system and therefore it is almost impossible to establish limiting levels of DO at which food consumption and growth might become dependent on oxygen under natural conditions. Nevertheless, they might be close to those restricting growth when food is unrestricted in the laboratory when ecosystems are used.

(27) On the present limited information, it appears that at moderately high temperatures the critical or limiting DO levels for natural rates of growth and metabolism may be near the ASV.

3.6 Swimming performance

(28) While swimming continues at near-lethal low levels of DO, maximum sustainable swimming speeds of salmonids normally decline with any reduction of DO below saturation. Even at cruising speeds there may be an increased tendency to fatigue as suggested by the results of recent experiments carried out by Smith et al. (1971) on adult migrant coho salmon (*Oncorhynchus kisutch*); these fish continued to swim at about 56 cm/s for an hour at 5-6.6 mg/l DO and for a further hour at 4.5-5 mg/l whereas those exposed for the second hour to 4-4.5 mg/l became fatigued. Swimming of some warm-water fish, however, is affected only by concentrations near or below 5 mg/l. Acclimating goldfish to DO deficiency does not change the effect of low DO on moderate swimming activity. The effects of reduced DO on "burst" speeds and on the frequency with which these can be repeated have not yet been studied.

(29) One can envisage that cruising speeds, maximum sustainable speeds, and "bursts" would all have survival value for fish on migration and when foraging for food, but to what extent reduction in any of these abilities would affect fish stocks and catches is not known.

3.7 Behaviour and avoidance

(30) Activity can increase or decrease at reduced DO, but if the first occurs it is often followed by the second. Brook trout for example (Dandy, 1970), showed increased activity within minutes when the DO concentration was dropped from 11 to 8 or 6 mg/l, reaching a peak within an hour and then gradually waning. An incidental result of increased activity may be avoidance of low DO concentrations, but some laboratory studies suggest deliberate avoidance of concentrations of about 1 mg/l, for example those of Stott and Cross (1973) using roach (*Rutilus rutilus*). This avoidance level was raised slightly when the lowered DO (reduced over a period of 4 hours) was accompanied by an increased CO_2, and reduced slightly when the roach were acclimated overnight to 3 mg/l DO. There is, however, considerable variation in the levels avoided by fish reported by different workers; to some extent this may reflect the experimental technique used, in particular the nature of the DO gradient and the existence of other superimposed behaviour patterns which may be important under natural conditions. While many species occur at, and do not avoid, DO levels only slightly above lethal, successful avoidance has been observed when better oxygenated water is accessible, and this is supported by field observations.

(31) Avoidance behaviour of fish under laboratory conditions raises the possibility that regions of low concentrations in estuaries could form a barrier to the movement of migratory fish. During an 11-year study, the upstream migration of adult chinook salmon (Oncorhynchus tshawysha) and coho salmon through a fish pass was apparently inhibited by DO below 4-5 mg/l, but in an exceptional year the fish proceeded even at 3 mg/l; however, the possible effects of other germane factors, such as water temperature and flow, were not taken into account. American shad (Alosa sapidissima) have been reported to pass through an estuarine zone at 2 mg/l. On the other hand there appears to be no information on whether smolts can be prevented from migrating downstream by low DO.

(32) Other behavioural reactions of fish of possible survival value for the species are also affected by reduced DO. Schooling behaviour can be altered when DO is lowered to 7 mg/l (Moss and McFarland, 1970), and for the American shad this occurs when it is less than 4.5 mg/l. Another example is the tendency of the walleye (Stizostedion vitreum vitreum) to remain quiet under cover; this behaviour is progressively changed with reduction in concentration of DO from 6 to 2 mg/l, being finally replaced by abnormally active swimming in the open (Scherer, 1971) when it is 1-2 mg/l.

4. DIRECT EFFECT ON FISH FOOD ORGANISMS

(33) While some food organisms may be harmed by reduced DO levels too high to harm fish, others thrive in waters enriched by oxygen-absorbing organic material.

(34) Larvae of the ephemeropteran (Cloeon dipterum), a species widespread in Europe at low altitude, lived longer at low concentrations of DO than the plecopteran (Perlodes intricata), one which is confined to mountainous areas, whether these were arrived at gradually or suddenly; they were able to exhaust the DO in an enclosed vessel down to 0.02 mg/l at 5.5°C whereas P. intricata died almost immediately when transferred suddenly to 26 percent ASV at 5.5 and 15.5°C (Kamler, 1971). Also, the rheotactic response of Gammarus which is at a maximum under laboratory conditions at a water velocity of 5 cm/s has been shown to be greatest at a DO of 2.7, 3.3 and 5.3 mg/l for G. pulex, G. roeseli and G. fossarum respectively (Vobis, 1972). Other examples are given by Nebeker (1972), the 30-d LC50 for ephemeroptera and chironomids ranging from 0.6 to 5.0 mg/l.

(35) Overall food resources are therefore unlikely to be impaired by organic wastes which merely reduce the DO level. Thus the oxygen requirements of fish food organisms need not necessarily be evaluated when estimating the DO levels necessary for the protection of fish or fisheries. Some organisms, however, may be of special importance because they may also comprise commercial fisheries, for example the crayfish (Astacus fluviatilis), and in this case little is known of its oxygen requirements though Höglund (1961) reported that it responded to gradients of DO under laboratory conditions.

5. FIELD OBSERVATIONS

5.1 Rivers

(36) A good mixed fish fauna has been found in inland waters having DO levels below 4-5 mg/l, and in polluted waters even where for a long time they had not exceeded 4 mg/l. However, a heavy mortality of salmon (Salmo salar) occurred in the River Don, Scotland, in 1971 at DO levels of about 4 mg/l when minimum temperatures were 18°C and maximum values about 23°C (data from E. McGregor Weir, personal communications). This is in agreement with laboratory data which indicate a higher lethal DO level at elevated temperatures (Para. 7).

(37) Further data obtained from examination of concentrations found during daylight hours in the years 1968-70 at places where fisheries are known to occur in the catchment area of the River Trent, described by Alabaster (1973), show that trout fisheries occur where the median and 5-percentile of the annual distribution of DO are greater than 8.7 and 4.8 mg/l respectively and that coarse fisheries occur where the median and 5-percentile are greater

than 3.7 and 2.1 mg/l respectively. It should be pointed out, though, that the status of these fisheries is not known, only that fish are present; there is no evidence that these populations are resident and therefore the critical levels for a permanent fishery may be higher. On the other hand, other pollutants were present in these waters, including heavy metals, which may cause an error in the opposite direction. Also, without further consideration of the sequence of changes in DO which make up the overall annual distribution found, it would be unwise to assume that these criteria would apply to other situations.

5.2 Lakes

(38) In Onondaga Lake (Onondaga County, Syracuse, New York, 1971), which is saline, studies have shown that for substantial periods of time (weeks) much of the water, sometimes the whole water column, contains less than 4 or 5 mg/l DO and yet the fisheries appear to be unharmed. According to Brodde (1972), the anaerobic region that developed near the bottom of Lake Ivösjön at the end of the summer of 1969 was apparently successfully avoided by vendace (Coregonus albula), burbot (Lota lota), and ruffe (Acerina cernua). On the other hand, larvae of pollan (Coregonus lavaretus) hatched from eggs collected in 1968-69 from Lake Constance where the minimum DO was 4.3 mg/l showed malformities absent in former years when the DO was much higher; also there was a high mortality of eggs in the lake in 1969-70 (Nümann, 1972). However, it is possible that these results are partly attributable to the toxic effect of hydrogen sulphide leached from anaerobic bottom deposits (Smith and Oseid, 1972).

5.3 Estuaries

(39) Examination of data given by Wheeler (1969) for roach collected on the intake screens of electricity generating stations using the tidal Thames for cooling purposes shows that, in the period November 1967-October 1968 where the average DO was about 78 percent ASV, catches were about 14 per month while where the average was less than 25 percent they were less than 5 per month.

(40) Information relating to the disappearance of fisheries from the Thames Estuary at the turn of the century and the return of some species over the last decade has been examined by Alabaster (1973). It suggests that for lampern (Lampetra fluviatilis) flounder (Platichthys flesus) and smelt (Osmerus eperlanus), values of at least 30-50 percent ASV are necessary for their presence. However, shad (Alosa fallax) have not yet reappeared and may have somewhat higher requirements for DO. Whether these fisheries can become thoroughly established under present conditions remains to be seen.

(41) Examination of data supplied by the Northumberland River Authority on salmon catches in the River Tyne for the year 1967 suggests that the fish were passing upstream through a zone in the estuary during March and early April where the calculated minimum DO was probably oscillating between 4.5 and 6.8 mg/l (J.S. Alabaster and M.J. Barrett, personal communication). However, it is not possible to conclude from the data what minimum would have inhibited the migration.

6. SUMMARY OF DATA

(42) Laboratory data point to certain levels of DO associated with impairment or alteration of fish survival, growth, reproduction, swimming ability and behaviour; incomplete as the data are, with respect to the distributions of the responses within fish populations in given physiological and behavioural states, they must form the present basis of any DO criteria for fish and fisheries, and have had to be used to derive the tentative minimum steady levels proposed here for normal successful fulfilment of the life cycle, assuming other environmental factors are favourable including the absence of poisons (Table 1).

Table 1. Tentative minimum sustained DO for maintaining the normal attributes of the life cycle of fish under otherwise favourable conditions

Attribute	DO (mg/l)	Paragraph
Survival of juveniles and adults for one day or longer	3	4-13
Fecundity, hatch of eggs, larval survival	5	15
10 percent reduction in hatched larval weight	7	16
Larval growth	5	20
Juvenile growth (could be reduced 20 percent)	4	21
Growth of juvenile carp (*Cyprinus carpio*)	3	21 & 22
Cruising swimming speed (maximum sustainable speed could be reduced 10 percent)	5	28
Upstream migration of Pacific salmon (*Oncorhynchus* spp.) and Atlantic salmon (*Salmo salar*)	5	31
Upstream migration of American shad (*Alosa sapidissima*)	2	31
Schooling behaviour of American shad	5	32
Sheltering behaviour of walleye (*Stizostedion vitreum vitreum*)	6	32

(43) They suggest that, in general, a minimum of 5 mg/l would be a satisfactory limit for most of the processes required for a successful fish life cycle, though it may be unnecessarily high merely to ensure satisfactory survival of the fish and growth of the juveniles. Consequently fluctuations about 5 mg/l or any reduction below 5 mg/l could have a greater effect on some processes than on others; the greater effect of fluctuations in DO on juvenile growth as compared with that on growth of larvae has already been mentioned, but clearly fecundity, hatch of eggs, and larval morphology and survival, as well as the upstream movement of migratory salmon and schooling behaviour of some species, including shad, would also be adversely affected by levels below 5 mg/l that would not necessarily affect either the survival of individuals or the upstream migration of shad. This is consistent with the mere presence of fish observed in polluted rivers and estuaries where the DO is well below saturation and exhibits a wide variation within a year (Paras. 37-41); this would suggest minimum acceptable values (for ranges of variation) of much less than 5 mg/l - probably less than 1 mg/l, for example, for coarse fish in the River Trent.

7. TENTATIVE DO CRITERIA

(44) Difficulties arise in formulating DO criteria for fisheries because of the widely differing patterns of DO fluctuations which can exist in a river. Even in an unpolluted river there can be a considerable fluctuation with peak DO values after noon and low DO values before sunrise. This pattern can be similar, though at a generally lower level, in a polluted river and on this can be superimposed a seasonal variation and changes associated

with flow. Low DO values attained for 1-2 hours each day will have less effect than the same value sustained for several days or even weeks. The true DO regime in a river is likely to be shown not by infrequent sampling during daylight hours but only where automatic monitoring stations exist.

(45) However, even where the DO regime is known with some certainty, it will be difficult to predict the effect which this is likely to have on fish and fisheries, unless the levels are so low as to be lethal to fish or so high as to have no effect on them. Although there is an extensive literature on the DO requirements of fish, few experiments have been made which even approach natural conditions, most being made at constant DO levels; further, field data are either inadequate in describing the fish populations present or the DO regime, or are complicated by the presence of other poisons.

(46) In these circumstances, only tentative criteria can be put forward. It is obvious that these cannot be based on a single minimum value never to be violated or even as several minima each not to be violated at a certain time of year, but rather as a minimum percentile distribution over a year or perhaps part of a year, or, with some fisheries, part of a tidal cycle. This idea is inherent in the criteria for monohydric phenols, suggested by the EIFAC Working Party on Water Quality Criteria for European Freshwater Fish (EIFAC, 1972) though it was not expressed as a percentile distribution.

(47) From the limited data available it is tentatively suggested, pending further information, that for resident populations of moderately tolerant freshwater species, such as roach, the annual 50- and 5-percentile DO values should be greater than 5 mg/l and 2 mg/l respectively and for salmonids the percentiles should be 9 mg/l and 5 mg/l respectively.

(48) These values are to be regarded as of general guidance only because there are special circumstances where more consideration should be given to the seasonal distribution of DO. For example, for adult migrant salmonids the values for the 50- and 5-percentiles for periods of low water during the summer months in the region of an estuary where the DO is lowest, should be 5 and 2 mg/l respectively, although with an extensive deoxygenated zone (more than a few kilometres in length) higher concentrations at these percentiles might be necessary. Moreover, because lower levels are particularly dangerous to the young stages of fish (Paras. 4, 5, 17 and 18) they should not occur when such stages are present.

(49) However, all these minimum values might need to be considerably increased in the presence of high temperature (Paras. 7, 27 and 36) or poisons (Para. 11).

(50) To enable more satisfactory criteria to be formulated, more laboratory studies and required which reflect natural DO regimes and more field observations are required on the status of fish populations and on the movements of adults and young of migratory species. These should be coupled with more complete data on the DO, both where the fish populations are only marginal and where they are well established. The consequences of reduced fecundity, growth and reproduction and of changed behaviour on population dynamics and production of fish and of fisheries should also be appraised.

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