WATER QUALITY CRITERIA FOR EUROPEAN FRESHWATER FISH

Report on Finely Divided Solids and Inland Fisheries

Prepared by

EIFAC Working Party on Water Quality Criteria for European Freshwater Fish

EUROPEAN INLAND FISHERIES ADVISORY COMMISSION

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Rome, 1964

PREPARATION OF THIS PAPER

The background for the preparation of this paper is described in the "Foreword" of the report itself.

The paper was first submitted to the Third Session of the European Inland Fisheries Advisory Commission (EIFAC), held at Scharfling-am-Mondsee, Austria, 20-25 April 1964, as a working paper:

> European Inland Fisheries Advisory Commission. Working Party on Water Quality Criteria for European Freshwater Fishes (1964), Water quality criteria for European freshwater fishes. Interim report on finely divided solids and inland fisheries. EIFAC 64/D:24 p.

Following unanimous approval of the report, the Commission recommended that it be transmitted to the Director-General of FAO in order to receive the widest possible distribution, including reproduction in scientific and trade journals connected with water pollution control and water quality.

In order to achieve this purpose, the report is issued here (in slightly edited form) and is being issued in French under reference: EIFAC tech.Pap. (1), 1964. Copies are also being sent to several journals granting them permission to reprint the paper.

Bibliographic Citation and Abstract

Eifac Working Party on Water Quality Criteria for European Freshwater Fish (1964), Water quality criteria for European freshwater fish. Report on finely divided solids and inland fisheries. EIFAC tech.Pap.,(1): 21 p.

First of a series of reports on water quality criteria for European freshwater fish prepared for and approved by the European Inland Fisheries Advisory Commission. The background of the project is described and reasons for establishing water quality criteria for fish explained. This is followed by a literature survey of: the direct effects of solids in suspension on death or survival of fish, their growth, and resistance to disease; suspended solids and reproduction; effects on behaviour; effect on food supply; total effect of suspended solids on freshwater fisheries. Tentative water quality criteria are suggested.

Rome, July 1964

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SUMMARY

Water quality criteria for suspended solids are needed by those who have to manage inland fisheries and must sometimes decide, for example, how much solid matter could enter a river or lake without undue risk to a fishery, or whether it is worth attempting to develop a commercial or recreational fishery in water already containing a known concentration of such materials.

EIFAC tech. Pap., (1):21 p.

There are at least five ways in which an excessive concentration of finely divided solid matter might be harmful to a fishery in a river or a lake. These are:-

(1) By acting directly on the fish swimming in water in which solids are suspended, and either killing them or reducing their growth rate, resistance to disease, etc.

(2) By preventing the successful development of fish eggs and larvae.

(3) By modifying natural movements and migrations of fish.

(4) By reducing the abundance of food available to the fish.

(5) By affecting the efficiency of methods for catching fish.

Some or all of these factors could operate together to harm a fishery.

There is evidence that not all species of fish are equally susceptible to suspended solids, and that not all kinds of solids are equally harmful. Unfortunately there is very little information on these and many other aspects of the problem, and much of the evidence which does exist is less firmly established than is desirable. It has therefore been concluded that definite water quality criteria which distinguish between the many different kinds of finely divided solids to which different sorts of inland fisheries may be subjected cannot yet be proposed. Nevertheless, when the evidence is considered as a whole certain general conclusions can be drawn.

There is probably no sharply defined concentration of a solid above which fisheries are damaged and below which they are quite unharmed. It appears that any increase in the normally prevailing concentration of suspended matter above quite a low level may cause some decline in the status and value of a freshwater fishery, and that the risk of damage increases with the concentration. Although there is not enough evidence to allow the relation between solids concentration and risk of damage to be defined at all precisely, the Working Party considers that the degree of risk to fisheries may be divided into four arbitrarily defined categories and that rough estimates may be made of the ranges of concentration to which they would generally correspond. From this approach to the problem the following tentative criteria are presented. With respect to chemically inert solids and to waters which are otherwise satisfactory for the maintenance of freshwater fisheries,

(a) There is no evidence that concentration of suspended solids less than 25 p.p.m. (parts per million) have any harmful effects on fisheries.

(b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25 to 80 p.p.m. suspended solids. Other factors being equal, however, the yield of fish from such waters might be somewhat lower than from those in category (a).

(c) Waters normally containing from 80 to 400 p.p.m. suspended solids are unlikely to support good freshwater fisheries, although fisheries may sometimes be found at the lower concentrations within this range.

(d) At the best, only poor fisheries are likely to be found in waters which normally contain more than 400 p.p.m. suspended solids.

In addition, although several thousand parts per million solids may not kill fish during several hours or days exposure such temporary high concentrations should be prevented in rivers where good fisheries are to be maintained.

The spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided solids.

FOREWORD

This is the first of a series of reports on water quality criteria for European freshwater fish prepared for the European Inland Fisheries Advisory Commission (EIFAC) an intergovernmental organization with a membership of 18 countries. At its Second Session, Paris, 1962, the Commission took note of a recommendation of the Conference on Water Pollution Problems in Europe, 1961, that EIFAC take the initiative in drawing up water quality requirements with respect to fisheries. 1/

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 then agreed that the establishment of water quality 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.

A Working Party, of members selected on the basis of their knowledge of physical, chemical and biological requirements of European freshwater fish, was appointed as follows:

Mr. J.S. Alabaster (U.K.), Convenor	- Ministry of Agriculture, Fisheries and Food, Salmon and Freshwater Fisheries Laboratory
Dr. Torsten B. Hasselrot (Sweden)	- Statens Vatteninspektion
Mr. D.W.M. Herbert (U.K.)	- Department of Scientific and Industrial Research, Water Pollution Laboratory
Prof. Dr. H. Mann (Federal German Republic)	- Bundesforschungsanstalt für Fischerei, Institut für Küsten- und Binnenfischerei

1/ See, respectively:
EIFAC Report, Second Session, 1962, p. 21-22.
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.

Mr. Paul Vivier (France) 1/		- Directeur de la Station d'Hydrobiologie continentale de Paris
FAO Secretariat:	Mr. J.L.L. Chaux	- Regional Fisheries Officer for Europe, Secretary of EIFAC
	Mr. Wm. A. Dill	- Chief, Inland Resources Section, Biology Branch, Fisheries Division

As a general basis for their work, the Working Party first agreed 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 these prove to be important.

They then proceeded to their first study, an attempt to define water quality criteria for finely divided solids and inland fisheries.

The preparation of their report on this study was accomplished largely by Mr. Herbert, who prepared the basic manuscript to be reviewed and supplemented by the other members.

The final report was presented at the Third Session of EIFAC, held at Scharfling-am-Mondsee, Austria, April 1964, where it received the full approval of the Commission. 2/ It follows.

1/ Miss M. Nisbet (France), Chef du Laboratoire de Contrôle de la Pollution, acted as alternate for Mr. Vivier

2/ EIFAC Report, Third Session, 1964, p. 10

INTRODUCTION

(1) A review of literature on, and an attempt to define water quality criteria for finely divided solids and inland fisheries was chosen as the first task of our Working Party on Water Quality Criteria for European Freshwater Fish. Although we have not been able to study the whole of the world's literature on solids and fisheries, we believe that we must have considered a large proportion of the more important research reports, and have also been furnished with unpublished information by fishery biologists in many European countries. It is considered, therefore, that this summary of the literature and our conclusions can be useful not only to the European Inland Fisheries Advisory Commission and its member countries but to all those concerned with the management of inland waters and their fisheries resources.

(2) Nearly all river and lake waters have some solid matter in suspension and some at times contain very high concentrations resulting from soil erosion, from engineering works during which large volumes of earth are disturbed, from forestry operations, and from the discharge of sewage, sewage effluents, mining wastes, pulp and paper mill wastes, and other industrial effluents. Solids of many different kinds are therefore to be found in surface waters. Some of them - basic salts of zinc for example - have toxic properties (Lloyd, 1960; Herbert and Wakeford, 1964), while organic solids are oxidized by micro-organisms which can reduce the concentration of dissolved oxygen to levels at which fish are asphyxiated. Effects of these kinds are not considered in this report, nor has particular attention been given to the effects which solids may have by altering physical characteristics of the water such as temperature. Furthermore, some waste waters contain both solids in suspension and potentially harmful substances in solution. We have not examined the possibility that suspended solids will modify the resistance of fish to poisons, or to other lethal agencies such as low dissolved oxygen, high temperature and extremes of pH value, nor have we included in our literature survey the results of laboratory studies or of observation in the field unless it was reasonably certain that any adverse effects were due only to the solids. For example, Edwards and Rolley (in preparation) have shown that dissolved oxygen may be reduced as a result of deposits of organic matter being brought into suspension, consequently we have not used some reports of fish kills during floods when the suspended-solids concentration was high and the dissolved-oxygen concentration was not measured.

(3) Some other research reports have been excluded because we considered that the conclusions reached by their authors were not fully supported by the evidence. In many research papers - especially some of those reporting studies of lakes and rivers - much of the evidence which we have used is less securely established than is desirable because the suspended-solids concentrations were not measured very often.

(4) Although most authors have reported their observations as weight of solids per unit volume of water, others have expressed them as light transmittancies of Secchi disc readings. One of these systems of measurement cannot be converted into another unless the relation between them has been determined for the particular solid under consideration. Because the appropriate relation has seldom been reported, we have not attempted to use one system of measurement throughout the literature survey, but have quoted results in the units employed by the authors.

(5) From our study of the literature it is apparent that there are at least five ways in which an excessive concentration of finely divided solid matter might be harmful to a fishery in a river or a lake. These are:-

(a) By acting directly on the fish swimming in water in which solids are suspended, and either killing them or reducing their growth rate and resistance to disease.

(b) By preventing the successful development of fish eggs and larvae.

(c) By modifying natural movements and migrations of fish.

(d) By reducing the abundance of food available to the fish.

(e) By affecting the efficiency of methods for catching fish.

In addition, some or all of these factors could operate together to harm a fishery.

These subjects (except (e)) are considered in the above order in the next section of this report.

LITERATURE SURVEY

Direct Effects of Solids in Suspension

Death or survival of fish

(6) Wallen (1951) kept several species of fish in water containing montmorillonite clay and increased the turbidity to high levels for a short time each day by stirring the sediment. Most individuals of all species - including goldfish (Carassius auratus) and carp (Cyprinus carpio) - endured maximum turbidities of 100,000 p.p.m. occurring during experiments lasting a week or more, and some individuals of these two species survived occasional exposure to 225,000 p.p.m. for one to three weeks. Herbert (personal communication) found that rainbow trout (Salmo gairdnerii) survived one day in 80,000 p.p.m. silt from gravel washing, and the concentration had to be raised to about 160,000 p.p.m. to kill them within this period. Alabaster (personal communication) found that harlequin (Rasbora heteromorpha), a tropical fish, was killed in a day by about 40,000 p.p.m. bentonite clay, but survived for a week in 6,000 p.p.m. Cole (1935) reported that some fish survived 20,000 p.p.m. wood fibre, although he said that it undoubtedly hastened the death of unhealthy or moribund individuals, and Griffin (1938) stated that Pacific salmon (Oncorhynchus) and trout fingerlings lived for 3-4 weeks in concentrations of 300-750 p.p.m. silt which were increased to 2,300-6,500 p.p.m. for short periods by stirring the sediment each day. Thus it appears that many kinds of fish are unlikely to be killed within a day or so by exposure to suspended matter unless the concentrations are extremely high. To kill within such short times the concentrations of some solids would probably have to exceed 100,000 p.p.m. However, Slanina (in press) found that although rainbow trout survived a week in 5,000 to 2-300,000 p.p.m. suspended mineral solids, the epithelium of their gills had thickened and proliferated. Similarly affected gills were observed in rainbow trout which eventually died after exposure to several hundred p.p.m. solids for longer periods (Herbert and Merkens, 1961). Exposure for relatively short periods to very high concentrations might thus be harmful eventually even though fish are not killed within the period of exposure.

(7) Concentrations of several hundred thousand p.p.m. are never likely to be present in surface waters for more than a short time, but quite high concentrations can be present for relatively long periods. From 2,000 to 6,000 p.p.m. silt, persisting for 15-20 days, have been reported for rivers in flood (Campbell, 1954; Simaika, 1940; and Kemp, 1949); 6,000 p.p.m. and 1,000 p.p.m. appear to have been average levels in two streams continuously polluted with wastes from china-clay mining (Herbert, Alabaster, Dart and Lloyd, 1961).

(8) In the laboratory, 4,250 p.p.m. gypsum in suspension produced a 50 per cent mortality among rainbow trout in about 3½ weeks (Herbert and Wakeford, 1962). Caged rainbow trout were killed in 20 days in the Powder River, Oregon, when the concentration was 1,000 to 2,5000 p.p.m. but other conditions were apparently satisfactory (Campbell, 1954). In laboratory studies there were 40 to 50 per cent kills of trout in 810 and 270 p.p.m. kaolin and diatomaceous earth after exposure periods of 10 days in some experiments, but only after 85 days in others (Herbert and Merkens, 1961). Spruce fibre at 200 p.p.m. produced 50 per cent mortality among rainbow trout after 16 weeks exposure, and 70 per cent after 30 weeks (Herbert and Richards, 1963).

(9) On the other hand, Grande (personal communication) found that only one rainbow trout out of five was killed during 37 days in 1,000 p.p.m. cellulose fibre, and Vallin (1935) reported that one individual of each of the species Carassius carassius, Leuciscus rutilis, and Thymallus thymallus was tested and survived 3 weeks in 200 p.p.m. Herbert and Wakeford (1962) found that there were no deaths among rainbow trout kept for 4 weeks in a suspension of 553 p.p.m. gypsum. There was 100 per cent survival of the same species for 9-10 months in 200 p.p.m. of solids from a coal washery (Herbert and Richards, 1963).

(10) Thus there is evidence from properly conducted experiments and reliable observations of rivers that suspended-solids concentrations from 200 to several thousand p.p.m. have caused deaths among fish exposed for several weeks or months, and other equally reliable evidence that fish have been kept with few or no deaths at concentrations in the range 200 to 1,000 p.p.m. for similar periods. These differences are probably due in part to the kind of solid: in simultaneous experiments with identical techniques, all the rainbow trout tested in 200 p.p.m. coal washery solids for 40 weeks survived, whereas nearly 80 per cent died in the same concentration of spruce fibre (Herbert and Richards, 1963). Ellis (1944) states that the larger the particles, and the greater their hardness and angularity, the greater the possibility of injury to gill structures. Another factor is that species of fish are not all equally resistant. Smith, Kramer and McLeod (personal communication) found that walleye fingerlings (Stizostedion v. vitreum) were killed within 72 hours by 100 p.p.m. of various wood pulps, although 20,000 p.p.m. did not kill fathead minnows (Pimephales promelas) exposed for 96 hours. Whether or not fish in a river or lake will eventually be killed by the continual presence of 200 p.p.m. suspended solids or more is likely to depend upon the nature of the solids and the species present. Nevertheless, the available evidence suggests that the death rate among fish living in waters which over long periods contain suspended solids in excess of 200 p.p.m. will often be substantially greater than it would have been in clean water.

(11) There are also a few studies of death rates in concentrations lower than 200 p.p.m. Smith, Kramer and McLeod (personal communication) found that the walleye (which seems to be an extremely sensitive fish) was killed within 72 hours by 100 p.p.m. wood pulp, and a rather special case is provided by ferric hydroxide which is precipitated from acid solutions containing 3 p.p.m. Fe on to the gills of trout, carp, and tench (Tinca tinca) and kills them when the pH value rises above 5.5 (Mann, personal communication, and Krämer, 1924). In the majority of reported cases, however, death rates in 100 p.p.m. and less have been little or no higher than among control fish in clean water. Herbert and Merkens (1961) found that rainbow trout kept for long periods in 90 p.p.m. kaolin and diatomaceous earth suffered a slightly higher death rate than did the control fish, but the mortality was low: in 5 out of 6 tests lasting from 2 to 6 months no more than 20 per cent died. There were no deaths of rainbow trout during 8 months exposure to 100 and 50 p.p.m. spruce fibre or coal washery waste solids (Herbert and Richards, 1963), and no significant increase over control mortality among the same species in 30 p.p.m. kaolin or diatomaceous earth (Herbert and Merkens, 1961).

Growth

(12) Laboratory experiments, in which trout were given equal quantities of food in amounts which were nearly enough to satisfy their appetites, showed that 50 p.p.m. wood fibre or coal washery waste solids reduced their growth rate, and that they grew more slowly as the suspended-solids concentration was increased (Herbert and Richards, 1963). Nevertheless the fish grew reasonably well in the presence of the abundant food supply; even in 200 p.p.m. coal washery waste solids, yearling fish more than trebled their weight in 8 months.

Resistance to disease

(13) Herbert and Merkens (1961) found that trout in 270 p.p.m. diatomaceous earth suffered more from the disease 'fin-rot' than controls in clean water. Herbert and Richards (1963) report that many of the trout dying in 200 p.p.m. wood fibre suffered from fin-rot, and that fish in 100 p.p.m. showed some symptoms after 8 months, although those in 50 p.p.m. and the control fish showed no sign of the disease.

Suspended Solids and Reproduction

(14) If solids settle from suspension and block gravel which contains eggs, high mortalities will result. Shapovalov (1937) showed that silting reduced the survival of rainbow trout eggs (Salmo g. gairdnerii) in gravel, and found the same with silver salmon (Oncorhynchus kisutch) eggs in later experiments (Shapovalov and Berrian, 1940). Hobbs (1937) states that the mortality of trout eggs in New Zealand streams was greatest in those redds which contained the greatest proportion of material smaller than 0.03 inch in diameter. According to Ward (1938) who studied the Rogue River, Oregon, where placer mining was extensively practised, "... erosion silt in some streams has been found to cover nests and spawning grounds with a blanket such that the bottom fauna was killed and eggs also suffocated in nests." Campbell (1954) planted eggs in gravel in the Powder River, Oregon, where the turbidity was between 1,000 and 2,500 p.p.m. as a result of mining operations. All the eggs died in six days, although there was only 6 per cent mortality in 20 days at a control site where the water was clean. Other instances of eggs being killed by siltation are given by Heg (1952), Hertzog (1953), Gangmark and Broad (1955 and 1956), and by Neave (1947).

(15) Stuart (1953) has shown that Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) eggs - which are buried in gravel on the stream beds - can develop successfully only if a current of water passes through the gravel, while Gangmark and Bakkala (1960) found that the survival of king salmon (Oncorhynchus tshawytscha) eggs increased with the velocity of water through the gravel in which they were laid. Fish eggs require oxygen during development. Aldedice, Wickett and Brett (1958) showed that chum salmon (Oncorhynchus keta) eggs needed at least one part oxygen per million in the surrounding water at the early stages and 7 p.p.m. at later stages if they were to hatch successfully, and Alderdice and Wickett (1958) demonstrated that the utilization of oxygen by the eggs was impaired by increasing the carbon dioxide concentration. Wickett (1954) concluded that the amount of oxygen available to eggs depends not only on its concentration in the water, but also upon the rate at which the water flows over the eggs.

(16) The foregoing observations are relevant to the silting up of spawning beds after the eggs have been laid, but there is also evidence that some salmonids will not spawn in gravel which is already blocked. Stuart (1953) found that brown trout do not dig redds in gravel if it is choked with sediment, nor will they do so even if the surface has been cleared of sediment so that it appears indistinguishable from known spawning areas; presumably this is because the fish detects that water is not flowing through the gravel. Rather similar behaviour was observed with cutthroat trout (Salmo clarkii); these fish abandon a redd if they encounter silt while they are digging (Snyder, 1959).

(17) Where the harm is done by blocking gravel spawning beds, the concentration of solids suspended in the water is apparently less important than the amount which will settle out of suspension. This will depend upon such factors as the size of the solid particles, the stream velocity and degree of turbulence. Some rivers in British Columbia support large populations of Pacific salmon (Oncorhynchus) in spite of carrying heavy loads of glacial silt. Spawning takes place, however, when the rainfall is heavy and silt is flushed out of the spawning beds (Foskett, 1958).

(18) Finely divided solids can be harmful to eggs which are not buried in spawning beds. Stuart (1953) observed that silt in suspension will adhere to the surface of eggs and kill them - probably by preventing sufficient exchange of oxygen and carbon dioxide between the respiring egg and the water. Suspended solids can damage the eggs of species which do not lay them on or in stream beds. The eggs of the yellow perch (Perca flavescens), which are laid in gelatinous strings entwined round aquatic plants, etc., were mostly destroyed over an area where silt from the construction of a road increased the turbidity to give an average Secchi disc reading of 18 inches, but hatching was reasonably successful above the silted area where the average Secchi disc reading was 33 inches (Muncy, 1962). Pikeperch (Lucioperca lucioperca) eggs are also entwined around plants and have been killed in Lake Balaton when the suspended solids content of the water rises during storms (Wynarovich, 1959).

Effects on Behaviour

(19) Quite high concentrations of suspended solids in part of a river do not stop salmonoid fish from passing through on migration between fresh and sea water. There are Atlantic salmon in the River Severn in the British Isles and they are netted in the estuary although parts of the estuary naturally contain high concentrations of suspended solids - up to several thousand p.p.m. at times (Gibson, 1933). Smith and Saunders (1958) when studying the movements of brook trout (Salvelinus fontinalis) between fresh and salt water, found that turbidity seemed to have no effect on the fish's movements. Ward (1938) said that the normal concentrations of suspended solids in several Oregon streams were 137 to 395 p.p.m. and that salmon run through them. On the other hand, when given a choice, some fish will select clear water. Thus, Summer and Smith (1939) found that king salmon avoided the muddy water of the Yuba River, California, and entered a clean tributary. These fish also chose a clear streak in a muddy river for spawning rather than more turbid areas nearby. Schools of minnows advancing down a clean tributary to a muddy river have been seen to turn back immediately their heads enter the water of the muddy stream (Moore, 1932).

(20) Bachmann (1958) found that when cutthroat trout in a river in Idaho were subjected for two hours to a turbidity of 35 p.p.m. they were unharmed, but sought cover and stopped feeding.

(21) Hofbauer (1962) when studying the factors influencing the numbers of migrating fish passing through a fish ladder, considered that the tendency for the barbel (Barbus fluviatilis) to migrate decreased with increasing turbidity of the water, even though other conditions such as temperature and water level would favour migration. The opposite tendency appeared to be the case with the European eel (Anguilla anguilla): migration occurred when there was notable turbidity, and migration intensity decreased immediately the water became clearer.

Effect on Food Supply

(22) The amount of food for fish in fresh waters depends ultimately upon the growth of green plants (algae and higher aquatic plants). Such plants may be restricted by suspended solids, but we have not considered the literature on this subject in detail in this report.

(23) We have found few laboratory studies made to discover the concentrations of suspended solids which can be tolerated by invertebrate animals on which fish feed. Stephan (1953) worked with several Cladocera and Copepoda. The harmful effect of suspended solids on these animals was thought to be partly due to clogging of their filter-feeding apparatus and digestive organs, and the critical concentrations were from 300 to 500 p.p.m.. Clay was most harmful, while earth and sand caused less damage. Robertson (1957) studied the survival and reproduction rate of Daphnia magna in suspensions of several kinds of solids. Apparently harmful levels were:-

Kaolinite	- 392 p.p.m.
Montmorillonite	- 102 p.p.m.
Charcoal	- 82 p.p.m.

Pond sediment was not lethal up to 1,458 p.p.m. After being washed with hydrochloric acid, montmorillonite, pond sediment and charcoal were more toxic. Different kinds of solids thus appear to have different toxicities, and Robertson considers that this may be attributed, at least in part, to differences in absorptive capacity. Much lower concentrations (e.g. 39 p.p.m. kaolinite, 73 p.p.m. pond sediment) appeared to increase the reproduction rate of Daphnia.

(24) Although they are often important in lakes, small planktonic invertebrates like Daphnia are a less important component of the fish-food fauna in rivers than organisms which live on the stream bed or on plants. Benthic animals are at risk not only from the solids in suspension, but from the accumulation of particles which settle on the bottom. Many authors have reported more or less severe reductions in bottom fauna from this cause. Thus, Taft and Shapovalov (1935) studied the abundance of the fauna on the beds of Californian streams into which large quantities of natural silt were washed by mining operations. In samples taken during the summer there were always fewer food organisms per unit area in the places where mining was practised than in clear streams. In the Scott River, silted areas averaged 36 organisms/ft^2, while in clean areas the average was 249/ft^2. Smith (1939) quotes earlier work by Surber and Smith which showed that silted areas in the American and Yuba Rivers of California contained only 41 to 63 per cent as many food organisms on the stream beds as did clear streams. Tebo (1955) found that in North Carolina streams heavy siltation caused by dragging logs over the ground near a small tributary resulted in turbidities from 261 to 390 p.p.m. in a trout stream, and during summer and autumn, when the flow of water was low, the stream bed was covered with a layer of sterile sand and micaceous material up to 10 inches deep. In these areas the bottom fauna was only one-quarter as abundant (as volume per ft^2) as at clean places above the point where the silt entered. Rainbow trout fed mainly on bottom fauna from January to June, but from June to December this made up only 42 per cent of their food, much of the remainder consisting of terrestrial insects. The bottom fauna (expressed as wet weight per unit area) in clean Cornish streams was found by Herbert, Alabaster, Dart and Lloyd (1961) to be present at nine times the density occurring in streams containing 1,000 and 6,000 p.p.m. suspended solids, although in a stream with an average of 60 p.p.m. the bottom fauna was about equal in abundance to that in the clean rivers. These authors found during their survey that although a substantial proportion of the food eaten by trout (in May) consisted of bottom fauna, much of the food consisted of terrestial forms. Even a complete destruction of aquatic invertebrates in these streams did not mean that no food was available for those fish, but only that the total quantity was reduced. The effects on the food supplies of other species might be more serious.

(25) Several more examples are given in unpublished reports of investigations made in France for administrative purposes and summarized for us by Mr. P. Vivier. Waste water from a sand-washing plant contained 29,900 p.p.m. suspended solids, of which 19,750 p.p.m. was settleable. When discharged to a trout stream in the Côtes du Nord it caused the disappearance of the bottom fauna of Trichoptera (Hydropsyche, Rhyacophiles), Ephemeroptera (Ecdyonurus), Crustacea (Gammarus) and Mollusca (Ancylus, Limnea) which was present upstream. Four kilometers downstream, where the suspended-solids concentrations had fallen to 29 p.p.m., the fauna reappeared except for the Ephemeroptera.

Plants and fish food fauna disappeared from another trout stream after introduction of 250 p.p.m. suspended solids from a quarry. Another small stream in the Vosges contained 11,300 p.p.m. solids just below a granite crushing mill and washing plant, and 185 p.p.m. 7 km downstream at its confluence with the River Saône. The normal fauna and flora were completely absent from the tributary below the discharge. Coal mines brought the suspended solids in a river in the Gard Department to 570 p.p.m. 1 km below the pits, and the river was virtually abiotic for 10 km. After this distance the suspended-solid concentration had fallen to about 100 p.p.m. and a sparse fauna reappeared.

(26) Although the bottom fauna of streams may be drastically reduced by finely divided solids which are chemically inert, deposits of some kinds of organic solids - humus from a sewage-disposal works for example - can support dense populations of some bottom-dwelling invertebrates, such as Chironomus riparius and Asellus aquaticus, which provide an abundant food supply for fish (Allan, Herbert and Alabaster, 1958).

The Total Effect of Suspended Solids on Freshwater Fisheries

(27) The earlier sections of this review have shown that sufficiently high concentrations of suspended solids can kill fish directly, increase their susceptibility to disease, reduce their rate of growth, modify their normal movements within fresh water, reduce the area suitable for spawning, and kill developing eggs. In addition, the quantity of natural food available to fish can be reduced. When a freshwater fishery is harmed by excessive quantities of finely divided solid matter, it is likely that many of these factors will be operating, although the relative importance of each one will probably not be the same in every case. Correlation of the status of fisheries in lakes and rivers with the concentrations of solids found in them should therefore provide data very relevant for the establishment of water quality criteria.

(28) Ellis (1937) made 514 determinations of turbidity at 202 places on rivers in the U.S.A., and classified each site as either having or not having a good mixed fish fauna. His results are summarized in Fig. 1. Precise conclusions cannot be drawn from these data, because few measurements of turbidity were made at most sites and these might not adequately represent the levels occurring in rivers where turbidity can fluctuate considerably. Furthermore, a poor fish population may not have been due to high turbidity in every case but to some other factor such as low dissolved oxygen (see Paragraph 2). Nevertheless, the data of Ellis suggest that an increase in turbidity above quite low levels will reduce the chances of maintaining a good fishery, although it should be noticed that good fish populations were found at a few places where the water was very muddy.

(29) It seems that some species of fish are much more tolerant of muddy water than others, and that an increase in suspended solids can lead to an increase in the numbers of the resistant fish as they are freed from competition with less tolerant species. Aitken (1936) said that Iowa streams which once supported trout, smallmouth black bass (Micropterus dolomeiui) and other clean-water species were transformed by excessive soil erosion so that they contained rough fish or mud-loving forms. Similar changes in parts of the Ohio river basin are reported by Trautman (1933). Rather more detailed evidence of changes which could eventually alter the species composition of a fishery is provided by an investigation made by the Institute of Freshwater Research, Drottningholm, which indicated that erosion turbidity in Lake Hotögeln, Sweden, was probably responsible for greatly reduced catches of char (Salvelinus alpinus), although the catches of trout (Salmo) and European grayling (Thymallus thymallus) were not appreciably affected. The table below shows that the catch of whitefish (Coregonus lavaretus) in Lake Aisjaur, Sweden, was reduced by turbidity due to mining wastes consisting principally of quartz sand.

Secchi disc reading	No. of nets	No. of whitefish caught per net
10–20 cm	11	0.6
40–50 cm	15	1.0
> 100 cm	10	1.9

The catches of perch (<u>Perca fluviatilis</u>) and pike (<u>Esox lucius</u>) were, however, not affected (Vallin, personal communication). Doan (1942) investigated the fishery statistics for Lake Erie where the turbidities vary between 5 and 230 p.p.m. The annual commercial catch of "yellow pickerel", i.e., the walleye (<u>Stizostedion v. vitreum</u>), was inversely correlated to a statistically significant extent with the turbidities during April and May of the same year. On the other hand the catch of sauger (<u>Stizostedion canadense</u>) was positively correlated with the turbidities prevailing three years earlier.

(30) Whitefish (<u>Coregonus</u>) have suffered severely from suspended solids in several lakes. Many species of whitefish feed mainly on plankton, and typically dwell in lakes where the water is clear and cold. Scheffel quoted in Stephan (1953) recounts the history of the fishery in the Chiemsee, Upper Bavaria, where suspended solids carried in by streams appear to have been responsible for a decline in the whitefish catch to a few under-nourished fish in 1920, and to zero over the period September 1920 to February 1921. The number of spawning fish was also severely reduced. Previously these fish had fed on zooplankton which was presumably abundant enough for their needs, but the reduced population was feeding on bottom-dwelling animals such as snails and chironomid larvae. Similar observations were made by Einsele (1963) on the Mondsee in Austria. Some large quantities of clay entered this lake during the construction of a road in 1961–62, making the water very turbid. This reduced the development of plankton, particularly <u>Daphnia</u>. Einsele estimated that the normal annual production of <u>Daphnia</u> in the Mondsee was about 400,000 kg fresh weight, and this fell to 80,000 kg in the turbid conditions. The turbidity also increased the mortality rate of the whitefish, resulting in a very low catch the following year.

(31) Schnedeberger and Jewel (1928) studied ponds in the U.S.A. which naturally contained different concentrations of suspended solids, and found that the production of fish increased as turbidity was reduced down to a value of 100 p.p.m. Buck (1956) studied the growth of fish in 39 farm ponds, having a wide range of turbidities, which were cleared of fish and then restocked with largemouth black bass (<u>Micropterus salmoides</u>), bluegill (<u>Lepomis macrochirus</u>) and red-ear sunfish (<u>Lepomis microlophus</u>). After two growing seasons the yields of fish were:-

Clear ponds	(less than 25 p.p.m. suspended solids)	161.5 lb/acre
Intermediate	(25–100 p.p.m. suspended solids)	94.0 lb/acre
Muddy	(more than 100 p.p.m. suspended solids)	29.3 lb/acre

The rate of reproduction was also reduced by turbidity and the critical concentration for all three species appeared to be about 75–100 p.p.m. In the same paper, Buck reports that largemouth black bass, crappies (<u>Pomoxis</u>) and channel catfish (<u>Ictalurus punctatus</u>) grew more slowly in a reservoir where the water had an average turbidity of 130 p.p.m. than in another reservoir where the water was always very clear.

(32) In rivers, Herbert, Alabaster, Dart and Lloyd (1961) found that 1,000 and 6,000 p.p.m. china-clay wastes had reduced the populations of brown trout to about one-seventh the density found in clean streams, but that a normal trout population was present in a river carrying 60 p.p.m. There is much additional evidence in the unpublished reports from France communicated to us by P. Vivier. In a river in the Gard Department of France which supports a cyprinid fish fauna, fish are absent from a stretch which contains up to 570 p.p.m. solids from coal mines, but a fre roach and chub reappear 10 km below the mines where the suspended-solids concentration has fallen to about 100 p.p.m. Trout, minnows and bullheads which populate the upper reaches of a stream in the Vosges, disappear completely below the entry of wash waters from a granite-crushing mill which raises the suspended-solids content to 11,300 p.p.m. immediately below the discharge. The fish do not reappear until the confluence of the stream with the River Saône: just above the confluence 185 p.p.m. suspended solids are present. Trout and dace were present in a stream in the Finistère Department of France above the entry of wash water from a tin mine, but the only fish in the polluted zone were eels. When the suspended solids were determined in this stream during a flood, 560 p.p.m. were present 500 m below the discharge, and 80 p.p.m. 4 km below. A rich fauna of Ephemeroptera, Trichoptera, Crustacea, Mollusca and worms almost completely disappeared below the discharge. However, in mountain streams fed by melting snow, some 1,000 p.p.m. suspended solids are often present for 3 to 5 months of the year and trout are found there, although not in large numbers. In the River Loirelva (Norway) which is rather muddy with an average concentration of about 50 p.p.m. suspended solids but with occasional concentrations up to 1,331 p.p.m., pike, perch, pikeperch and several species of cyprinids are common. A very similar fish fauna is found in another muddy Norwegian stream, the Nitelva, in which the concentrations range from 5.9 to 99.8 with an average of about 25 p.p.m. (M. Grande, personal communication). D.W.M. Herbert (personal communication) installed a suspended-solids recorder for a year in the River Mimram, Hertfordshire, where there was a good trout fishery, and found that the average suspended-solids concentration was 24 p.p.m. with maximum values of 80 to 100 p.p.m. occurring at times. Liepolt (1961) reports that a trout fishery exists in a stream usually containing 19 to 23 p.p.m. solids, and that this was not harmed by dredging operations which raised the concentration to about 160 p.p.m. for short periods, except that fly-fishing was impeded when the water was turbid.

(33) Herbert and Richards (1963) report the results of a questionnaire sent to River Boards in England, Scotland and Wales. Streams containing suspended solids of industrial origin were classified as either "Fish present and fish population not adversely affected" or "Fish absent or markedly reduced in abundance". Care was taken that no data were included if there was reason to suppose that a river was polluted with materials other than inert suspended solids. These data are shown in Fig. 2, together with the information summarized in Paragraph 32. Some of the concentrations shown in the figure are means or ranges of a large number of determinations made over a considerable period, whereas some of the others are based on a single observation which may not properly represent the concentrations normally to be found in that stream. However, in spite of this limitation, it may be concluded that nearly all the rivers (or parts of rivers) in which the fisheries were apparently unharmed carried distinctly lower concentrations of suspended solids than those in which the fisheries were either seriously damaged or destroyed. The concentrations in the two categories overlap to some extent and there is not a clearly defined concentration which separates them, but the critical concentration appears to be in the approximate range 100 to 300 p.p.m.

TENTATIVE WATER QUALITY CRITERIA FOR FINELY DIVIDED SOLID MATTER

(34) Water quality criteria for suspended solids are needed by those who have to manage inland fisheries and must sometimes decide, for example, how much solid matter could enter a river of lake without undue risk to a fishery, or whether it is worth attempting to develop a commercial or recreational fishery in water already containing

a known concentration of such materials. The criteria should therefore be presented in terms of the effect on a fishery which a given concentration of solids is likely to produce.

(35) There is evidence that not all species of fish are equally susceptible to suspended solids, and that not all kinds of solids are equally harmful (Paragraph 10). Unfortunately there is very little information on these and many other aspects of the problem, and, as was stated in Paragraph 3, much of the evidence which exists is less firmly established than is desirable. We have therefore come to the conclusion that we cannot yet propose definite water quality criteria which distinguish between the many different kinds of finely divided solids to which different sorts of inland fisheries may be subjected. Nevertheless, we think that when the evidence is considered as a whole, certain general conclusions can be drawn and some tentative criteria can be based upon them. We have attempted to draw these conclusions and arrive at such criteria in the following paragraphs, and put them forward as a basis for discussion and in the hope that they will provide some useful guidance, but it must be emphasized that they are provisional and may well have to be revised when more information becomes available.

(36) The spawning grounds of trout and salmon are very vulnerable to finely divided solids, and quite a small turbidity in the water or deposition of solids on or in the gravel may cause spawning fish to avoid them or prevent successful development of their eggs after they are laid (Paragraphs 14 to 17). This may be especially important where a salmon population is restricted by lack of suitable spawning areas.

(37) Except for possible effects on spawning behaviour and egg development and the special case of freshly precipitated iron hydroxide (Paragraph 11), there is no evidence that concentrations less than 25 p.p.m. have done any harm to fish or fisheries, and there are known to be good fisheries in rivers usually containing about 25 p.p.m. suspended solids (Paragraph 32).

(38) Concentrations above 25 p.p.m. have reduced the yield of fish from ponds (Paragraph 31); 35 p.p.m. have reduced feeding intensity (Paragraph 20); 50 p.p.m. have reduced the growth rate of trout under laboratory conditions (Paragraph 12); 82 p.p.m. charcoal have killed <u>Daphnia</u> (Paragraph 23). On the other, 85 p.p.m. is the lowest concentration reported for a stretch of stream containing few or no fish where other factors are satisfactory, and there are many other streams with only slightly lower concentrations where the fishery is no noticeably harmed (Paragraphs 32, 33 and Fig. 2). In laboratory tests the lowest concentration known to have reduced the expectation of life of fish is 90 p.p.m. (Paragraph 11), and the lowest concentration known to have increased susceptibility to disease is 100 p.p.m. (Paragraph 13).

(39) Some satisfactory fisheries are reported for waters containing 100 to 400 p.p.m. suspended solids, but fish are few in number, or absent, in other waters within this range (Paragraph 33 and Fig. 2). Similar concentrations of several kinds of solids have also increased susceptibility to disease (Paragraph 13), increased mortality rates (Paragraph 8), and reduced growth rates (Paragraphs 12 and 31). <u>Daphnia</u> has been killed by several solids in concentrations within this range (Paragraph 23) and, in all the studies we have seen, the abundance of the invertebrate fauna of stream beds has been drastically reduced (Paragraphs 24 and 25).

(40) We found no good evidence that plentiful and varied fish faunas exist in waters normally carrying suspended solids in excess of 400 p.p.m., although there are streams which carry even 6,000 p.p.m. in which there are very sparse populations of trout (Paragraph 32 and Fig. 2). There may be some tolerant species of fish which can provide good fisheries in very muddy waters, but we have found no evidence of such fisheries in Europe. An exception is that salmon are netted as they pass through muddy reaches when migrating (Paragraph 19).

(41) Many kinds of solids can be present for short periods (possibly up to a few days) in concentrations of at least several thousand p.p.m. and probably much higher without killing fish, but may damage their gills. This might affect their subsequent survival.

(42) The brief résumé of the evidence in Paragraphs 36 to 41 suggests to us that there is probably no sharply defined concentration of a solid above which fisheries are damaged and below which they are quite unharmed. Our impression is rather that any increase in the normally prevailing concentration of suspended matter above quite a low level may cause some decline in the status and value of a freshwater fishery, and that the risk of damage increases with the concentration. However, there is not nearly enough evidence to allow the relation between solids concentration and risk of damage to be defined at all precisely, and we think that the best that can be done at present towards the establishment of water quality criteria for this class of substance is to divide the degree of risk to fisheries into four arbitrarily defined categories and attempt to make rough estimates of the ranges of concentration to which they would generally correspond.

(43) From this approach to the problem we present the following tentative criteria for discussion and comment.

With respect to chemically inert solids and to waters which are otherwise satisfactory for the maintenance of freshwater fisheries:

(a) There is no evidence that concentrations of suspended solids less than 25 p.p.m. have any harmful effects on fisheries.

(b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25 to 80 p.p.m. suspended solids. Other factors being equal, however, the yield of fish from such waters might be somewhat lower than from those in category (a).

(c) Waters normally containing from 80 to 400 p.p.m. suspended solids are unlikely to support good freshwater fisheries, although fisheries may sometimes be found at the lower concentrations within this range.

(d) At the best, only poor fisheries are likely to be found in waters which normally contain more than 400 p.p.m. suspended solids.

(44) In addition although several thousand p.p.m. solids may not kill fish during several hours or days exposure, such temporary high concentrations should be prevented in rivers where good fisheries are to be maintained. The spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided solids.

These tentative criteria apply only to chemically inert solids and to waters which are otherwise satisfactory for the maintenance of freshwater fisheries.

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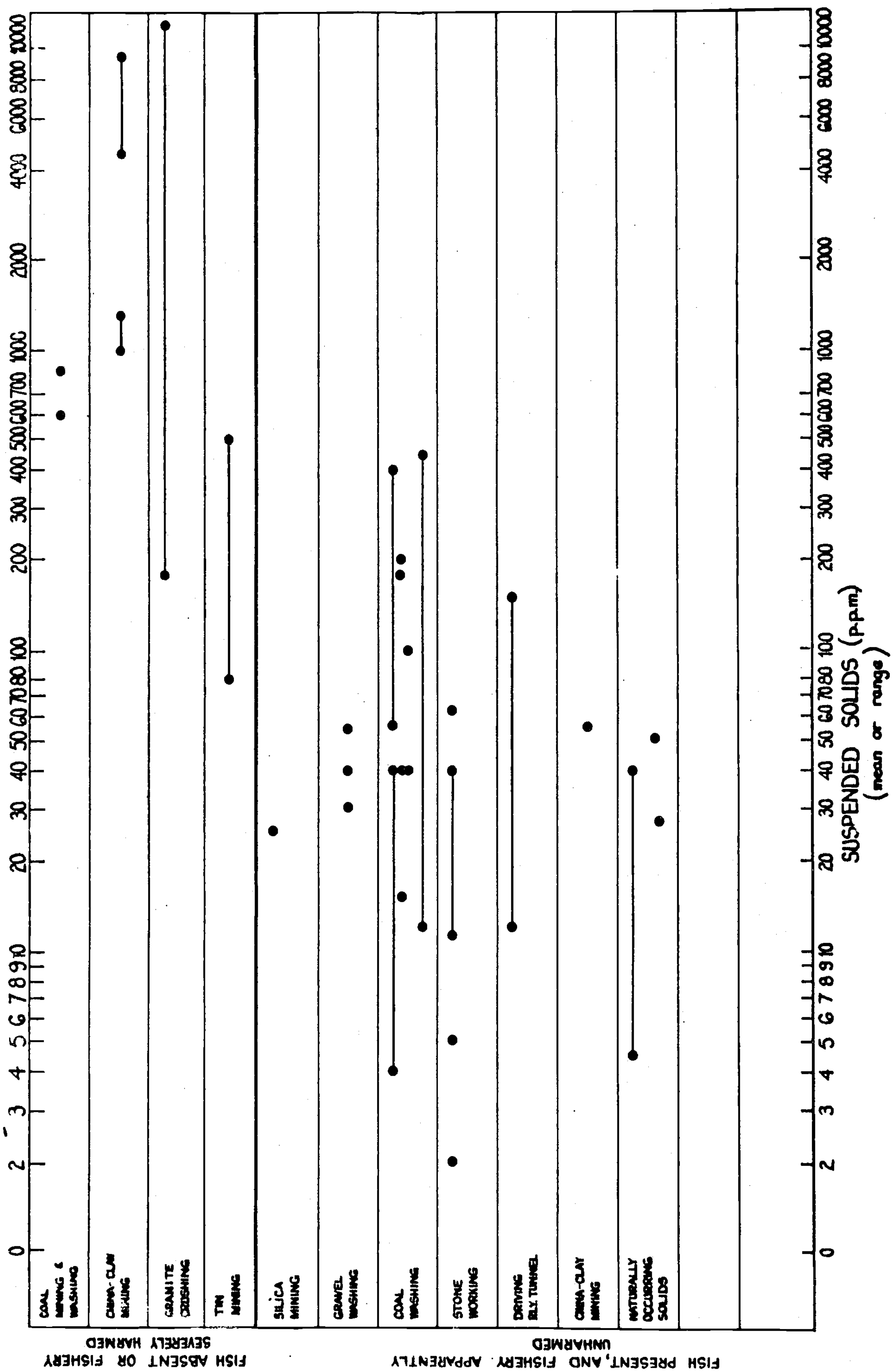
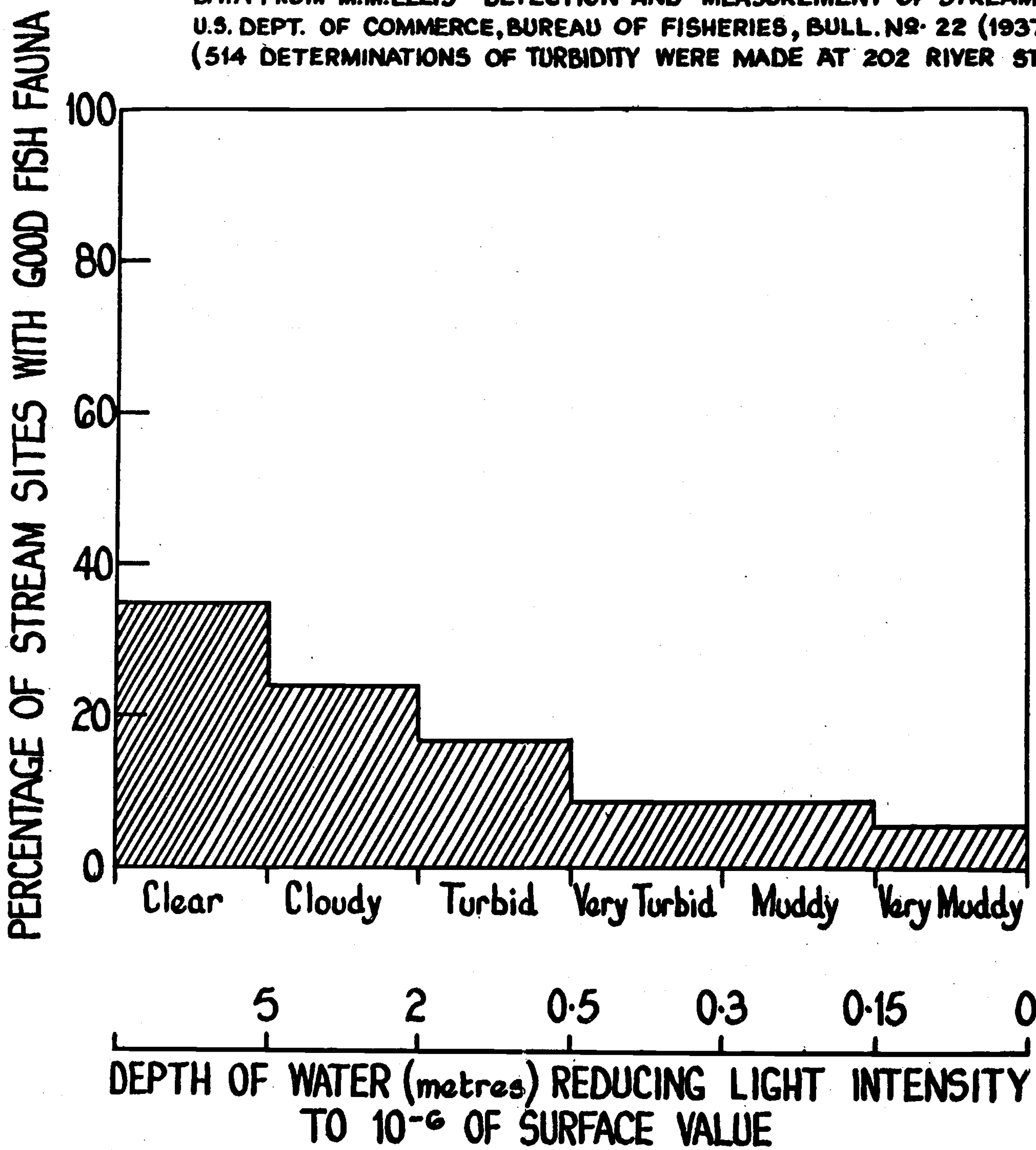


FIG. 2 REPORTED STATUS OF FRESHWATER FISHERIES RELATED TO THE SUSPENDED SOLIDS CONTENT OF THE WATER

FIG.1 TURBIDITY AND FRESHWATER FISHERIES IN THE U.S.A.
DATA FROM M.M.ELLIS "DETECTION AND MEASUREMENT OF STREAM POLLUTION"
U.S. DEPT. OF COMMERCE, BUREAU OF FISHERIES, BULL. Nº 22 (1937)
(514 DETERMINATIONS OF TURBIDITY WERE MADE AT 202 RIVER STATIONS).



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