

FINELY DIVIDED SOLIDS

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Foreword

A review of the literature on, and an attempt to define, tentative water quality criteria for finely divided solids and inland fish and fisheries were chosen as the first task of the Working Party on Water Quality Criteria for European Freshwater Fish and set a pattern for future reports. The preparation of the original report on which this chapter is based was accomplished largely by Mr D. W. M. Herbert, who prepared the basic manuscript for review by other members of the Working Party. It was not possible to study the whole of the world's literature on the subject, but a large proportion of the more important research reports was considered, together with unpublished data provided by fishery biologists in many European countries. Since then much more has been published including several reviews, e.g. by Hollis *et al.* (1964), Shelton and Pollock (1966), Gammon (1970), Ritchie (1972), and Sorensen *et al.* (1977); the data support the conclusions drawn in the original EIFAC report and therefore are not reviewed again here, except in a few cases where European species are concerned. In addition, hitherto unpublished data are included.

1.1 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.

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, resistance to disease, etc.

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- (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.

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 concentrations of suspended solids less than 25 mg/l have any harmful effects on fisheries.
- (b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25–80 mg/l 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 80–400 mg/l 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 mg/l suspended solids.

In addition, although concentrations of several thousand mg/l 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.

1.2 Introduction

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 chapter, 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.

The possibility that suspended solids will modify the resistance of fish to poisons, or to low dissolved oxygen, high temperature and extremes of pH value has not been examined, nor are there included in the chapter 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, Rolley and Owens (1967) 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.

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.

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.

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 next section of this chapter.

1.3 Literature survey

1.3.1 DIRECT EFFECTS OF SOLIDS IN SUSPENSION

Death or survival of fish

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 common carp (*Cyprinus carpio*)-endured maximum turbidities of 100 000 mg/l occurring during experiments lasting a week or more, and some individuals of these two species survived occasional exposure to 225 000 mg/l for one to three weeks. Herbert (personal communication) found that rainbow trout (*Salmo gairdneri*) survived one day in 80 000 mg/l silt from gravel washing, and the concentration had to be raised to about 160 000 mg/l to kill them within this period. J. S. Alabaster (personal communication) found that harlequin (*Rasbora heteromorpha*), a tropical fish, was killed in a day by about 40 000 mg/l bentonite clay, but survived for a week in 6000 mg/l. Resuspended harbour sediment (containing organic matter, oil and grease, and heavy metals at concentrations of up to 28 000 mg/l) had no observable adverse effects on stickleback (*Gasterosteus aculeatus*) and fry of coho salmon (*Oncorhynchus kisutch*) in 4 days (Le Gore and Des Voigne, 1973). Cole (1935) reported that some fish survived 20 000 mg/l 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 mg/l silt which were increased to 2300-6500 mg/l 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 mg/l. However, Slanina (1962) found that although rainbow trout survived a week in 5000-300 000 mg/l 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 mg/l solids for longer periods (Herbert and Merckens, 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.

Concentrations of several hundred thousand mg/l 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 2000 to 6000 mg/l silt, persisting for 15-20 days, have been reported for rivers in flood (Campbell, 1954; Simaika, 1940; and Kemp, 1949); 6000 mg/l and 1000 mg/l appear to have been average levels in two streams continuously polluted with wastes from china-clay mining (Herbert *et al.*, 1961).

In the laboratory, 4250 mg/l gypsum in suspension produced a 50 per cent mortality among rainbow trout in about $3\frac{1}{2}$ weeks (Herbert and Wakeford, 1962). Caged rainbow trout were killed in 20 days in the Powder River, Oregon, when the concentration was 1000 to 2500 mg/l but other conditions were apparently satisfactory (Campbell, 1954). In laboratory studies there were 40-50 per cent kills of trout in 810 and 270 mg/l kaolin and diatomaceous

earth after exposure periods of 10 days in some experiments, but only after 85 days in others (Herbert and Merckens, 1961). Spruce fibre at 200 mg/l produced 50 per cent mortality among rainbow trout after 16 weeks exposure, and 70 per cent after 30 weeks (Herbert and Richards, 1963).

On the other hand, M. Grande (personal communication) found that only one rainbow trout out of five was killed during 37 days in 1000 mg/l cellulose fibre, and Vallin (1935) reported that one individual of each of the species *Carassius carassius*, *Leuciscus rutilus*, and *Thymallus thymallus* was tested and survived 3 weeks in 200 mg/l. Herbert and Wakeford (1962) found that there were no deaths among rainbow trout kept for 4 weeks in a suspension of 553 mg/l gypsum. There was 100 per cent survival of the same species for 9 to 10 months in 200 mg/l of solids from a coal washery (Herbert and Richards, 1963).

Thus there is evidence from properly conducted experiments and reliable observations of rivers that suspended-solids concentrations from 200 to several thousand mg/l 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 200-1000 mg/l 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 mg/l 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 (1965) found that walleye fingerlings (*Stizostedion v. vitreum*) were killed within 72 hours by 100 mg/l of various wood pulps, although 20 000 mg/l did not kill fathead minnow (*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 mg/l 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 mg/l will often be substantially greater than it would have been in clean water.

There are also a few studies of death rates in concentrations lower than 200 mg/l. Smith, Kramer and McLeod (1965) found that the walleye (which seems to be an extremely sensitive fish) was killed within 3 days by 100 mg/l wood pulp, and a rather special case is provided by ferric hydroxide which when precipitated from acid solutions containing 3 mg/l Fe on to the gills of trout, carp, and tench (*Tinca tinca*) kills them when the pH value rises above 5.5 (H. Mann, personal communication; Krämer, 1924). More recent work by Sykora, Smith and Synak (1972) showed that suspensions of ferric hydroxide of about 96, 48 and 24 mg/l caused juvenile brook trout (*Salvelinus fontinalis*) to reach no more than 16 per cent, 45 per cent and 75 per cent of the weight of control fish and they attributed the effect to reduced feeding caused by impaired visibility of the food.

In the majority of reported cases, however, death rates in 100 mg/l and less have been little or no higher than among control fish in clean water. Herbert and Merckens (1961) found that rainbow trout kept for long periods in 90 mg/l kaolin and diatomaceous earth suffered a slightly higher death rate than did the control fish, but the mortality was low: in five out of six tests lasting for 2-6 months no more than 20 per cent died. There were no deaths of rainbow trout during 8

months exposure to 100 and 50 mg/l spruce fibre or coal washery waste solids (Herbert and Richards, 1963), and no significant increase over control mortality among the same species in 30 mg/l kaolin or diatomaceous earth (Herbert and Merkens, 1961).

Growth

The growth (and survival) of larval lake herring (*Coregonus artedii*) were not affected during exposure for 62 days to a concentration of red-clay of up to 28 mg/l (Swenson and Matson, 1976). Laboratory experiments, in which trout were given equal quantities of food in amounts which were nearly enough to satisfy their appetites, showed that 50 mg/l 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 mg/l coal washery waste solids, yearling fish more than trebled their weight in 8 months.

Resistance to disease

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

1.3.2 SUSPENDED SOLIDS AND REPRODUCTION

If solids settle from suspension and block gravel which contains eggs, high mortalities will result. Shapovalov (1937) showed that siltation reduced the survival of rainbow trout eggs (*Salmo 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 1000 and 2500 ppm as a result of mining operations. All the eggs died in 6 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 Neave (1947).

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. Alderdice, 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 ppm 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.

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).

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).

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 0.46 m, but hatching was reasonably successful above the silted area where the average Secchi disc reading was 0.84 m (Muncy, 1962). Pikeperch (*Stizostedion 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 (Wynárovich, 1959). On the other hand the survival of eggs of walleye was not affected by wood fibre at a concentration of 250 mg/l, even when the concentration of dissolved oxygen was 33 per cent of the air saturation value (Kramer and Smith, 1966).

1.3.3 SUBLETHAL EFFECTS AND EFFECTS ON BEHAVIOUR

Quite high concentrations of suspended solids in part of a river do not stop salmonid 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 mg/l at times (Gibson, 1933). Smith and Saunders (1958), when studying the movements of brook trout 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 137–395 mg/l and that salmon run through them. On the other hand, when given a choice, some fish will select clear water. Thus, Sumner 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 minnow 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).

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

Hofbauer (1963), when studying the factors influencing the numbers of migrating fish passing through a fish ladder, considered that the tendency for the barbel (*Barbus barbus*) 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. Ventilation rates of green sunfish (*Lepomis cyanellus*) were affected by concentrations of bentonite clay suspensions greater than about 17 800 mg/l at 5 °C, 13 300 mg/l at 15 °C and 6700 mg/l at 25 °C, but rates of oxygen consumption were not affected by concentrations as high as about 26 700 mg/l (Horkel and Pearson, 1976). However, Heimstra and Damkot (1969) found that turbid conditions reduced the activity and affected normal hierarchical behaviour of this species.

1.3.4 EFFECT ON FOOD SUPPLY

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; for example, severe abrasive leaf damage by coal dust to the aquatic moss (*Eurhynchium riparioides*) was observed at 500 mg/l after one week and at 100 mg/l after three weeks (Lewis, 1973). On the other hand, Hynes (1970) reported that a fairly even discharge, containing silt, can create great stable areas of weed development which can completely alter the substratum (directly and indirectly) and with it the animal population. The considerable literature on this indirect effect on fisheries is not considered in detail in this chapter.

We have found few laboratory studies on 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 300–500 mg/l. 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 mg/l
Montmorillonite	102 mg/l
Charcoal	82 mg/l

Pond sediment was not lethal up to 1458 mg/l. 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 mg/l kaolinite, 73 mg/l pond sediment) appeared to increase the reproduction rate of *Daphnia*.

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 about 300 organisms m^{-2} (36 ft^{-2}), while in clean areas the average was about 2000 m^{-2} (249 ft^{-2}). Smith (1940) quotes earlier work by Surber and Smith which showed that silted areas in the American and Yuba Rivers of California contained only 41-63 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 of 261-390 mg/l 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 254 mm (10 inches) deep. In these areas the bottom fauna was only one-quarter as abundant (as volume per unit area) 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 *et al.* (1961) to be present at nine times the density occurring in streams containing 1000 and 6000 mg/l suspended solids, although in a stream with an average of 60 mg/l 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 terrestrial 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. Gammon (1970) studied a stream where the concentration of suspended solids increased from a range of 13-52 mg/l upstream of a limestone quarry to a range of 21-250 mg/l downstream. Although the numbers of some invertebrate species (of the Trichocorythoides)

that preferred a silt or mud substrate increased below the quarry, those of others (the net-spinning species of *Cheumatopsyche*) were reduced during periods of high concentrations. Also the drift rate of macroinvertebrates from an impacted riffle increased with concentration of suspended solids, the increase being 25 per cent with a concentration increase of 40 mg/l above normal and 90 per cent at 80 mg/l above normal.

Several more examples are given in unpublished reports of investigations made in France for administrative purposes and summarized for us by M. P. Vivier. Waste water from a sand-washing plant contained 29 900 mg/l suspended solids, of which 19 750 mg/l 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 were present upstream. Four kilometres downstream, where the suspended-solids concentration had fallen to 29 mg/l, the fauna reappeared except for the Ephemeroptera. Plants and fish-food fauna disappeared from another trout stream after introduction of 250 mg/l suspended solids from a quarry. Another small stream in the Vosges contained 11 300 mg/l solids just below a granite crushing mill and washing plant, and 185 mg/l 7 km downstream at its confluence with the R. 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 mg/l 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 mg/l and a sparse fauna reappeared.

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, Herber: and Ajabaster, 1958).

1.3.5 THE TOTAL EFFECT OF SUSPENDED SOLIDS ON FRESHWATER FISHERIES

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.

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 *Figure 1.1*. 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

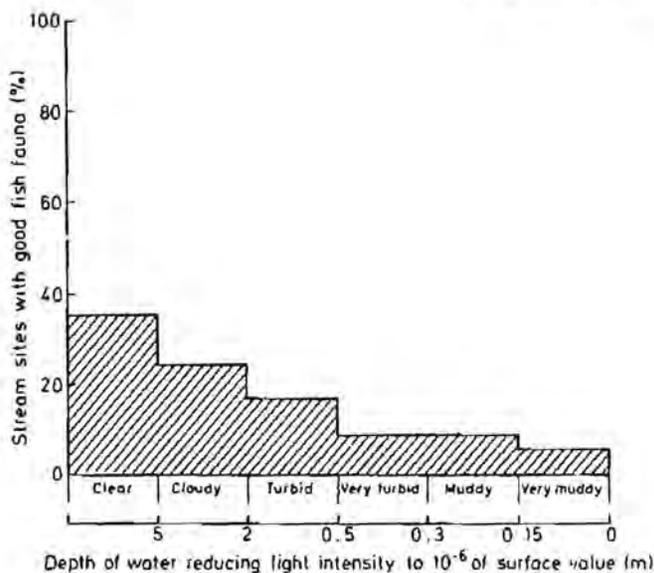


Figure 1.1 Turbidity and freshwater fisheries in the U.S.A. Data from Ellis (1937) (514 determinations of turbidity were made at 202 river stations)

ivers 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 p. 3, para. 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.

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 dolomei*), 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,

Table 1.1

Secchi disc reading (mm)	No. of nets	No. of whitefish caught per net
100-200	11	0.6
400-500	15	1.0
> 1000	10	1.9

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 and European grayling (*Thymallus thymallus*) were not appreciably affected. Table 1.1 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. The catches of perch (*Perca fluviatilis*) and pike (*Esox lucius*) were, however, not affected (Vallin, personal communication). Doan (1942) investigated the fishery statistics for Lake Erie where the turbidities vary between 5 and 230 mg/l. The annual commercial catch of 'yellow pickerel', i.e., the walleye (*Stizostedion v. vitreum*), 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 (*Stizostedion canadense*) was positively correlated with the turbidities prevailing three years earlier.

Whitefish (*Coregonus* sp.) 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 *Daphnia*. Einsele estimated that the normal annual production of *Daphnia* 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.

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 mg/l. 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 (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*) and red-ear sunfish (*Lepomis microlophus*). After two growing seasons the yields of fish were:

Clear ponds	(< 25 mg/l suspended solids)	161.5 kg/ha
Intermediate	(25-100 mg/l suspended solids)	94.0 kg/ha
Muddy	(> 100 mg/l suspended solids)	29.3 kg/ha

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

In rivers, Herbert *et al.* (1961) found that 1000 and 6000 mg/l 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 mg/l. 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 mg/l solids from coal mines, but a few roach and chub reappear 10 km below the mines where the suspended-solids concentration has fallen to about 100 mg/l. Trout, minnow and bullhead 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 mg/l immediately below the discharge. The fish do not reappear until the confluence of the stream with the R. Saône: just above the confluence 185 mg/l 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 mg/l were present 500 m below the discharge, and 80 mg/l 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 1000 mg/l suspended solids are often present for three to five months of the year and trout are found there, although not in large numbers. In the R. Loirelva (Norway), which is rather muddy with an average concentration of about 50 mg/l suspended solids but with occasional concentrations up to 1331 mg/l, 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 concentration range is 5.9-99.8 with an average of about 25 mg/l, and in the R. Leira where the median and 95 percentile values were 58 and 250 mg/l (M. Grande, personal communication). In the R. Trent catchment (U.K.) the maximum annual 50 and 95 percentile concentrations of suspended solids during the period 1968 to 1972 in areas where fish occurred were 18 and 412 mg/l respectively for trout, and 62 and 965 respectively for coarse fish (J. S. Alabaster and I. C. Hart, personal communication). D. W. M. Herbert (personal communication) installed a suspended-solids recorder for a year in the R. Mimram, Hertfordshire, where there was a good trout fishery, and found that the average suspended-solids concentration was 24 mg/l with maximum values of 80-100 mg/l occurring at times. Liepolt (1961) reports that a trout fishery existed in a stream usually containing 19-23 mg/l solids, and that this was not harmed by dredging operations which raised the concentration to about 160 mg/l for short periods, except that fly-fishing was impeded when the water was turbid. Peters (1957) studied a trout stream containing suspended solids of agricultural origin and found good populations at one station where the median and 95 percentile values were 18 and 35 mg/l, slightly reduced numbers where the percentiles were 70 and 180 mg/l respectively, and a 75 per cent reduction where they were 160 and 300 mg/l respectively. More recently Gammon (1970) found that in a stream in which the concentration of suspended solids increased from a range of 13-52 mg/l upstream of a limestone quarry, to a range of 21-250 mg/l below it, most fish, including common carp, were reduced in numbers downstream.

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 popula-

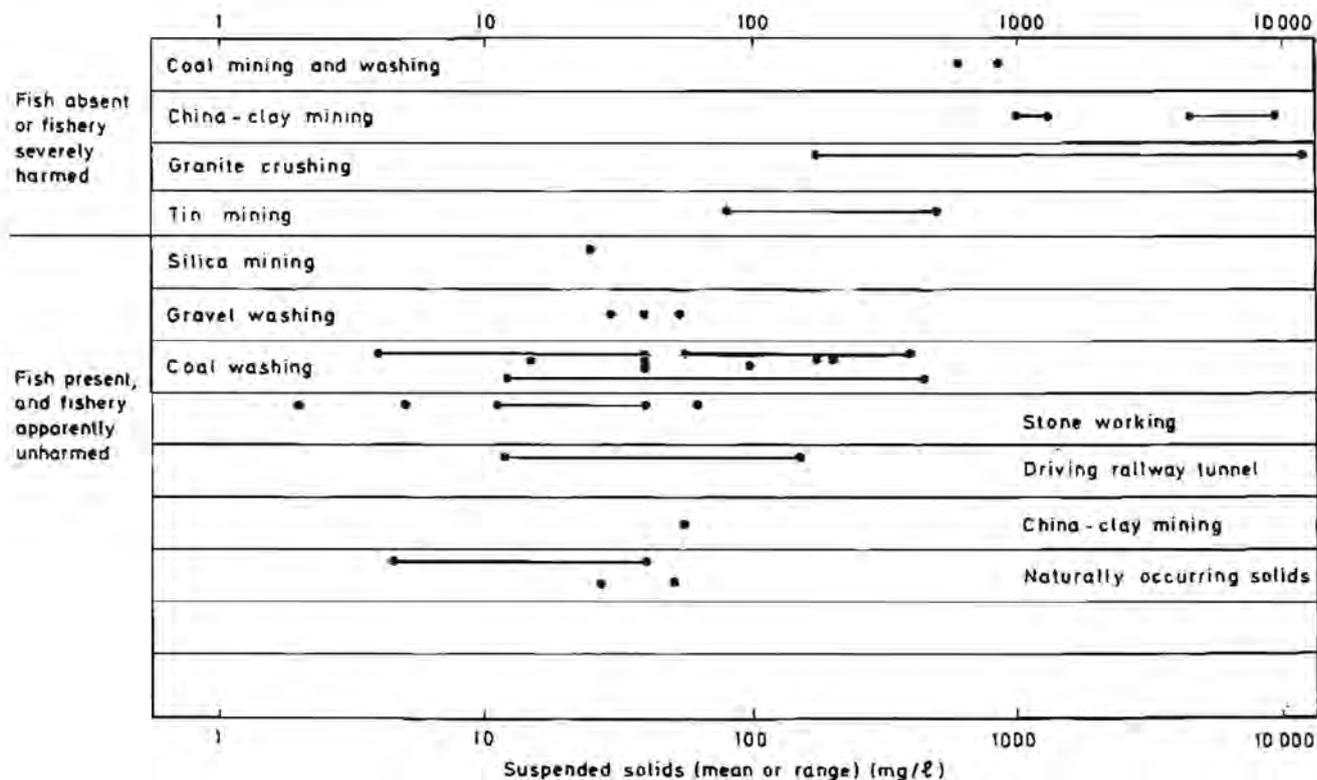


Figure 1.2 Reported status of freshwater fisheries related to the suspended solids content of the water

tion 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 *Figure 1.2*, together with the information summarized on p. 12, para. 5. 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 100-300 mg/l.

1.4 Tentative water quality criteria for finely divided solid matter

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

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 (p. 5, para. 3). Unfortunately there is very little information on these and many other aspects of the problem, and, as was stated on p. 3, para. 3, much of the evidence which exists is less firmly established than is desirable. The conclusion is that no proposals can be put forward for 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, when the evidence is considered as a whole, certain general conclusions can be drawn and some tentative criteria can be based upon them. These are summarized in the following paragraphs, and then are put forward as a basis for discussion and to 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.

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 (Section 1.3.2). This may be especially important where a salmon population is restricted by lack of suitable spawning areas.

Except for possible effects on spawning behaviour and egg development and the special case of freshly precipitated iron hydroxide (p. 5, para. 4), there is no evidence that average concentrations less than 25 mg/l have done any harm to fish or fisheries, and there are known to be good fisheries in rivers usually containing about 25 mg/l suspended solids (p. 12, para. 5).

Concentrations above 25 mg/l have reduced the yield of fish from ponds (p. 12, para. 4); 35 mg/l have reduced feeding intensity (p. 8, para. 2); 50 mg/l have reduced the growth rate of trout under laboratory conditions (p. 8, para. 2); 82 mg/l charcoal have killed *Daphnia* (p. 8, para. 5). On the other hand, 85 mg/l 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 not noticeably harmed (p. 12, para. 5 and *Figure 1.2*). In laboratory tests the lowest concentration known to have reduced the expectation of life of fish is 90 mg/l (p. 5, para. 4), and the lowest concentration known to have increased susceptibility to disease is 100 mg/l (p. 6, para. 3).

Some satisfactory fisheries are reported for waters containing 100–400 mg/l suspended solids, but fish are few in number, or absent, in other waters within this range (p. 13, para. 2 and *Figure 1.2*). Similar concentrations of several kinds of solids have also increased susceptibility to disease (p. 6, para. 3), increased mortality rates (p. 4, para. 3), and reduced growth rates (p. 6, para. 2 and p. 12, para. 3). *Daphnia* has been killed by several solids in concentrations within this range (p. 8, para. 5) and, in all the studies considered, the abundance of the invertebrate fauna of stream beds has been drastically reduced (pp. 9, 10).

There is no good evidence that plentiful and varied fish faunas exist in waters normally carrying suspended solids in excess of 400 mg/l although there are streams which carry even 6000 mg/l in which there are very sparse populations of trout (p. 12, para. 5 and *Figure 1.2*). There may be some tolerant species of fish which can provide good fisheries in very muddy waters, but there is no evidence of such fisheries in Europe. An exception is that salmon are netted as they pass through muddy reaches when migrating (p. 7, para. 5).

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

The brief résumé of the evidence on pp. 15, 16 indicates that there is probably no sharply defined concentration of a solid above which fisheries are damaged and below which they are quite unharmed. The 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 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.

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 concentrations of suspended solids less than 25 mg/l have any harmful effects on fisheries.

- (b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25-80 mg/l 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 80-400 mg/l 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 mg/l suspended solids.

In addition, although several thousand mg/l 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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