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SUSPENDED AND DISSOLVED SOLIDS EFFECTS ON FRESHWATER BIOTA

A Review

Environmental Research Laboratory
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U.S. Environmental Protection Agency
Corvallis, Oregon 97330

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SUSPENDED AND DISSOLVED SOLIDS EFFECTS ON FRESHWATER BIOTA: A REVIEW

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report presents a review of the recent literature describing the effects of suspended and dissolved solids on aquatic organisms.

A. F. Bartsch
Director, CERL

ABSTRACT

It is widely recognized that suspended and dissolved solids in lakes, rivers, streams, and reservoirs affect water quality. In this report the research needs appropriate to setting freshwater quality criteria or standards for suspended solids (not including bedload) and dissolved solids are defined by determining the state of our knowledge from a critical review of the recent literature in this field. Common literature sources and computer searching routines were used as an initial source of information followed by detailed journal searches. Although some 185 journal articles, government reports, and other references were cited herein (about 45 percent published since 1974) and many other reports (about 300 citations) were reviewed, there is a dearth of quantitative information on the response of freshwater biota, especially at the community level, to suspended and dissolved solids.

Consequently, the major research need was defined as the development and/or application of concepts of community response to suspended and dissolved solids concentrations and loads. These concepts need to be applied especially to the photosynthetic level and the microfauna and macrofauna levels. Fish studies are of lower priority since more and better research has been reported for these organisms.

In addition, the role of suspended solids in transporting toxic substances (organics, heavy metals), aesthetic evaluation of suspended solids in aquatic ecosystems and dissolved solids in drinking water, and economic aspects of dissolved solids in municipal-industrial water were defined as research needs.

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Many persons have contributed to the successful completion of the literature review reported herein. The innovation and direction of the project by Jack H. Gakstatter, the project officer, is gratefully acknowledged. The support and extra effort by the Utah Water Research Laboratory staff has helped greatly in the performance of the work. Project business management by the Utah State University Foundation has been expeditiously performed. We gratefully acknowledge the expert assistance of the staff of the Merrill Library at Utah State University. Special recognition is due Mary Cleave who has often volunteered her time and expertise to locate materials included in the review.

SECTION I

CONCLUSIONS

Generally, the review indicates that considerable effort has been directed toward determining the freshwater ecosystem effects of dissolved and suspended solids. However there is a significant gap at the freshwater community level in our understanding of the impacts of these pollutants and research needs are principally related to developing concepts about community response to dissolved and suspended solids.

Specific major conclusions about biological effects of dissolved and suspended solids gained from the reviews were:

1. Acute effects on specific organisms were difficult to demonstrate; succession and/or adaptation can allow communities to be maintained even though specific organisms may differ.

2. The total quantity of dissolved salts and the composition of the ions are both important in terms of organism type selection and productivity. The mode of action of dissolved salts is primarily due to osmotic interactions. Cation and anion ratios seem to have important roles in succession of certain organisms.

3. Dissolved organic compounds frequently increase the availability (and toxicity or biostimulation) of specific elements.

4. Although fishes adapt somewhat to gross changes in salinity, life cycle effects may prevent specific fish from being maintained in a specific aquatic habitat. Osmoregulation is an important aspect of adaptation and biochemical changes (e.g., protein and glucose levels in blood) are evidence of salinity changes.

5. Suspended solids have significant effects on community dynamics when they interfere with light transmission because of turbidity (shading).

6. Suspended solids may have significant effects on succession due to shading, abrasive action, habitat alteration, and sedimentation. Avoidance reactions of fish, selection of species and shading impacts on community stability have been demonstrated.

7. The role of sediments in serving as a reservoir of toxic chemicals has been demonstrated but the quantitative and directional aspects of toxicant transfer are largely unknown and whether the sediments are a sink or a source of toxicants needs to be studied.

8. Relatively high suspended solids were needed to cause behavioral reactions (20,000 mg/l) or death (200,000 mg/l) in a short time in fish. Recovery is fairly rapid when fish were returned to clear water.

SECTION II

INTRODUCTION

SCOPE OF THE REVIEW

The current literature on the effects of suspended and dissolved solids on aquatic living systems is reviewed in this report. Attention was directed to the literature published since 1971 with occasional reference to especially important work on reviews published prior to 1971. The effects of suspended and dissolved solids on freshwater organisms and their habitat was emphasized. Works concerning estuarine or marine life were reviewed only when they were directly relevant or appeared to be the only work available on a given topic.

The effects of suspended and dissolved solids on the physical or chemical environment are included in the review as supportive material for the effects on biological systems. Here again the review was directed primarily toward the literature published since 1971, but was further limited to major or review type publications which had direct reference to the topic. An important recent review on methodologies for assessing streamflow requirements was not included because that report dealt only peripherally with suspended solids and salt effects on biota (Stalnaker and Arnette, 1975). However the reader should be aware that streamflow integrally affects dissolved and suspended solids and that relationship needs consideration.

DEFINITIONS OF SUSPENDED AND DISSOLVED SOLIDS

Natural surface or groundwater is never found as pure H_2O. Separation of the impurities of natural water into particulate and dissolved fractions is, in practice, made on the basis of working definitions such as those found in Standard Methods (APHA, 1975). Suspended solids are the residue in a well mixed sample of water which will not pass a standard (glass fiber) filter. The residue trapped on the filter is dried (103-105C) and reported in units of weight per volume (mg/l). Suspended solids usually impart an optical property to water called turbidity. Particulate matter causes light to be scattered and absorbed rather than transmitted in straight lines. This property (turbidity) can be measured by standardized methods but it cannot be related to weight concentrations of suspended solids because of the effects of size, shape, and refractive index of the particles. However, turbidity measurements do give an indication of the relative abundance of suspended material in a water sample.

Dissolved solids (filterable residue) are the material that pass through a standard (glass fiber) filter and remain after the water has been evaporated and the material dried (180C or 103 to 105C). Salinity is the filterable solids in water after all carbonates have been converted to oxides, all bromine and iodide have been replaced by chloride, and all organic matter have been oxidized. Salinity measurements are usually numerically smaller than dissolved solids measurements (APHA, 1975). Total dissolved solids (TDS) and salinity terminology are often used interchangeably in practice and are not distinguished as to biological or chemical-physical effects in this review.

The ionization of substances dissolved in water allows water to conduct an electric current. The numerical expression of this property is referred to as conductivity. The mobility, valence, and actual and relative concentrations of each of the dissolved ions affect conductivity. Most inorganic acids, bases and salts (e.g., HCl, Na_2CO_3, NaCl, $MgSO_4$) in solution are good conductors. Organic compounds that do not dissociate in aqueous solution are not good conductors. Conductivity is a good method for determining the degree of mineralization of water, for assessing the effect of diverse ions on chemical equilibria, and for determining physiological effects of dissolved ions on plants or animals. The dissolved ionic matter in water may be estimated by multiplying the conductivity (in μmhos/cm) by an empirically determined factor which usually ranges from 0.55 to 0.9 (APHA, 1975).

SOURCES OF SUSPENDED AND DISSOLVED SOLIDS

Natural Sources

Natural weathering and decomposition of rocks, soils, and dead plant materials and the transport or dissolution of the weathered products in water contributes a natural ''background'' of suspended and dissolved materials to natural waters. Even rain and snowfall contain such contaminants which are washed from the atmosphere. Snyder et al. (1975) observed that gross precipitation in a forest in northern Idaho contained a mean suspended solids concentration of 21.8 mg/l. Likens et al. (1970) report an annual mineral dissolved solids export from an undisturbed northern hardwood ecosystem watershed of 13.9 metric tons/km^2. In the Colorado River Basin natural diffuse sources of salt are estimated to contribute 60.5 percent and mineral springs 8 percent of the 36,393 tons (33,084 metric tons) of salt/day exported via that river (USU, 1975, part one). Geologic formations (e.g. exposed marine shales) and other factors of the watershed contribute greatly to natural salt loading of streams (Blackman et al., 1973).

Erosion of soil materials depends greatly on many watershed factors (Bennett, 1974). The protection of undisturbed forest canopies and their mats of detrital material make such forests very resistant to erosion (EPA, 1973; Debyle and Packer, 1972). Snyder et al. (1975) report natural suspended solids concentrations in a northern Idaho forest stream as 2.7 to 9.0 mg/l. Erosion and sedimentation from rangelands is expertly reviewed by Branson et al. (1972). They point out that approximately 40 percent of the world's land surface is classified as rangeland, 80 percent of which is within arid and semi-arid zones. These areas are especially subject to erosion due to extremes in the hydrologic cycle and limited plant cover. Concentrations of suspended solids in the Colorado River have been reported as high as 38,700 mg/l (USU, 1975, part four).

Fletcher et al. (in press) have reviewed the processes contributing to or controlling erosion in arid areas of the western U.S. along with the potential effect that the erosional process has on nitrogen fertility of soils in these areas.

Rural and Agricultural Sources

Sixty-four percent of the land in the U.S. is used for agriculture and silviculture. The major pollutant of water in the U.S. is sediment and it has been estimated that 50 percent or more of the sediment deposited in streams and lakes of the U.S. is contributed by cropland. This amounts to 1.8 billion metric tons of sediment annually. Local values of sediment loading vary widely as to rainfall and rainfall intensity, type of crop, soil characteristics, topography, type of tillage and conservation practices (EPA, 1973). Bowen (1972) points out the pressing need to address water pollution problems associated with runoff and to develop technology for their control. He points out that contrary to the expected dilution effect expected during periods of high flow associated with rainfall, that pollution is often worse during high flows. This suggests a large contribution of pollution due to runoff from land.

A study conducted in eastern South Dakota (Dornbush et al., 1974) measured annual soil losses from agricultural land ranging from < 10 to 1000 lb/acre/yr (< 11 to 1120 kg/ha/yr). Runoff due to rainfall accounted for 93.7 percent of the sediment losses. Most of the sediment loss was from cultivated fields. The bulk of soil losses occurred during short duration, high intensity rain storms. Feedlot runoff waters have been found to contain from 1,000 to 13,400 mg/l suspended solids as well as high levels of other pollutants (Middlebrooks, 1974). Filip and Middlebrooks (1976) observed suspended solids concentrations of approximately 20,000 mg/l in a study to evaluate the eutrophication potential of cattle feedlot runoff. In describing the nonpoint rural sources of pollution in Illinois, Lin (1972) identified suspended solids loading from feedlots as a problem. In her work in the South River Basin in Virginia, Southerland (1974) observed a suspended solids contribution ranging from 3.35 to 29.5 lb/acre/day (3.76 to 33.1 kg/ha/day) during a storm event. She estimated that agriculture, forests, and urban runoff contributed 99.99 percent of the suspended solids during periods of storm flows.

Literature published prior to 1969 dealing with dissolved and suspended solids contributions as well as other pollution problems of irrigation return flows has been reviewed by the USU Foundation (1969). Law and Skogerboe (1972), Blackman et al. (1973), and Branson et al. (1975) have reviewed the effect of irrigation usage of water on dissolved solids content of water. Irrigation water often dissolves mineral salts and organic matter as its flows over and through soils and adds these materials to the stream as it returns as tailwater (runoff) or as groundwater. Oster and Rhoades (1975) have modeled the gain in salt burden of irrigation drainage water due to mineral dissolution by waters from eight rivers used for irrigation in the western U.S. Hagius et al. (in press) observed that irrigation return flows can be inhibitory to algal growth under bioassay conditions.

The Sevier River in central Utah undergoes seven complete stream diversions for irrigation along its 200 mile course, and in the process increases in salinity 20 fold (Law and Skogerboe, 1972). It has been estimated that 15,809 tons/

day (14,372 metric tons/day) or 30.5 percent of the total salt load of the Colorado River is due to irrigation (USU, 1975, part one). Sorensen et al. (1976) have estimated that from zero to more than 35 percent of the salt loading in various subbasins of the Bear River Basin, Idaho-Utah-Wyoming is due to irrigation. Also irrigation can serve to concentrate salinity by removing diluting water from the stream by consumptive use (e.g. evapotranspiration).

King and Hanks (1975) conducted field and laboratory research to determine the effects of irrigation management and fertilizer use upon the quality and quantity of irrigation return flow. The total seasonal discharge of salts from the tile drainage system was directly related to the quantity of water discharged, because the solute concentration of the groundwater was essentially constant over time. Under such conditions, reduction of salt content of return flow is accomplished by reduced drain discharge. Field studies and computer models showed that salts may be stored in the zone above the water table over periods of several years without adversely affecting crop yields on soils with high ‘‘buffering’’ capacity. However, over the long term, salt balance must be obtained. Appreciable amounts of nitrate moved into drainage water at depths of at least 106 cm when commercial fertilizer and dairy manure were applied to the ground surface. Submergence of tile drains in the field reduced nitrate concentrations in the effluent, especially under heavy manure applications.

Urban Runoff and Stormwater Sources

Runoff waters from urban and suburban areas have been observed to contain significant amounts of pollutants. Bryan (1971) found that an urban drainage basin in North Carolina produced runoff that contained an annual load of total organic matter in excess of the load from the sewage treatment plant for the same area. This area produced 43.6 lb/acre/day (49.0 kg/ha/day) of total solids. Sartor et al. (1974) calculated that for a hypothetical city of 100,000 persons and 14,000 acres (5,666 ha) with 400 curb miles (644 km) that street runoff following a one-hour storm would yield 560,000 pounds (254,500 kg) of settleable plus suspended solids/hour. He found that the major constituent of street surface contaminants was inorganic, mineral material similar to common sand and silt. Another study (Whipple et al., 1974) estimated that suspended solids concentration doubled (from 36 mg/l to 74 mg/l) due to runoff from an urban area in New Jersey.

Sources from Forestry Practices

Undisturbed forests are virtually free of erosion, but poorly managed lumbering or forest fires can lead to significant contributions of suspended sediments from forests (EPA, 1973). Deforestation and herbicide treatment of a northern hardwood forest ecosystem (Likens et al., 1970) caused a four fold increase in particulate matter output over that of undisturbed forest. Inorganic materials in the particulates increased from a normal 50 percent to 76 percent. Negligible increases in turbidity were associated with this increase in particulate matter.

Debyle and Packer (1972) working in a Larch-Douglas Fir forest in northern Idaho on plots which had been clearcut and the logging debris broadcast burned, observed a maximum soil erosion of 168 lb/acre/year (189 kg/ha/year). In the third year of study after logging and burning of slash, erosion had been reduced to 15 lb/acre/year (17 kg/ha/year). In four years, vegetal recovery returned conditions to near prelogging status. In one steep denuded area rainfall exceeding two inches (5.1 cm) in 10 hours (0.4 inches [1.0 cm]/hour during one two-hour period) produced ''much'' (no numbers given) of the total of 1,507 pounds (685 kg) of erosion occurring on that plot in the first year after treatment.

Working in the same forest ecosystem in northern Idaho, Synder et al. (1975) found increases in suspended solids in streams on clearcut and burned plots of from 4 to 14 times higher than undisturbed areas. Buffer strips of unlogged areas between the logged and burned area and the stream effectively reduced sediment loading to the streams.

Likens et al. (1970) found a significant increase (from 13.9 to as high as 97 metric tons/km^2) in dissolved solids being exported from the disturbed forest ecosystem at Hubbard Brook. High rates of nitrification of nitrogen from decaying organic matter resulted in increased availability of hydrogen ions which replaced cations on the various exchange sites on the soil making them susceptible to leaching. Since this high rate of salt loss was the result of mining the nutrient capital of the ecosystem (nitrification) it could not be expected to continue indefinitely.

Snyder et al. (1975) found significant increases in electrical conductivity and in most major ions in streams draining clearcut and burned plots in northern Idaho. Here, high runoff yielded low concentrations and low runoff yielded high concentrations of dissolved solids.

Construction and Mining Sources

Construction and mining activities occupy 0.6 percent of the land area of the U.S. Construction activities are responsible for 99.5 percent of the sediment eroded from construction sites (EPA, 1973). Glancy (1973) found that annual sediment yields ranged from 620 to 7,600 tons/mi^2 (218 to 2,670 metric tons/km^2) from developed areas whereas undeveloped areas yielded 60 to 930 tons/mi^2 (21 to 326 metric tons/km^2) in the Lake Tahoe-Incline Village area, Nevada. Goldman (1974) has shown that bacteria associated with these sediments can be important in cycling nutrients which can lead to eutrophication. Construction activities in a development area in Florida disturbed a marsh and lake, and increased suspended solids in water draining from the area (Anderson and Ross, 1975). Here, a 0.28 inch (0.71 cm), 15 minute storm produced 0.178 lb/acre (0.20 kg/ha) of suspended solids. A recent report by the Utah Water Research Laboratory (UWRL, 1976) reviews erosion problems associated with highway construction in the U.S. Methods in use for erosion control during highway construction are reviewed and evaluated, and research needs are identified in the UWRL report.

Dissolved mineral pollutants are of primary importance to the mining industry. Acid mine drainage contributes large amounts of toxic materials to surface waters that have a devastating effect on a local basis. Neutralized acid mine drainage can also be a serious local source of salinity (EPA, 1973).

Dredging and Disposal Sources

In 1972 dredging transferred over 380 million cubic yards of dredge spoils from freshwater and marine sediments (Slotta and Williamson, 1974). A great deal of concern over the effects of the suspended and relocated sediments has been raised, and considerable research has been directed toward assessing potential hazards and developing criteria for reducing the impacts of dredging and disposal operations (Hansen, 1971; Fulk et al., 1975; Lee et al, 1975; Blom et al., 1976; Chen et al., 1976).

Municipal and Industrial Wastewater Sources

Contributions of dissolved and suspended solids from municipal and industrial sources are of concern primarily because of their local impact and composition. Southerland (1974) found that suspended solids contributions from wastewater effluents in the upper South River Basin in Virginia were always overshadowed by loads from runoff sources. However, suspended solids from municipal and industrial effluents such as those from the sugar industry (EPA, 1971), paper manufacture (EPA, 1972), and fish hatcheries (Liao, 1970) are often composed of oxidizable organic matter which can, through biodegradation, reduce the oxygen content of receiving water making it unfit for desirable aquatic life. A large paper manufacturing plant discharging 29 million gal/day (111,000 m^3/day) of treated wastewater discharged approximately 5,000 pounds (2,300 kg) of suspended solids per day (EPA, 1972). Cane sugar manufacture at one plant in Hawaii produced 1,850 pounds (841 kg) of suspended solids for each ton (0.91 metric ton) of sugar produced (EPA, 1971).

Dissolved solids from municipal and industrial effluents are of concern primarily due to their special, often toxic, composition. Biochemical oxygen demand (BOD) due to dissolved organic materials is the problem of most widespread concern. Heavy metals and other dissolved toxic materials also draw special attention to municipal and industrial wastes (McGauhey and Middlebrooks, 1972a; 1972b). Salt loading from municipal and industrial sources is usually not of great importance in a river basin. Municipal and industrial salinity loading in the Colorado River Basin contribute less than 1.7 percent of the total daily salt load (USU, 1975, part one). Consumptive use by municipalities and industries can serve to concentrate salt loads (Blackman, 1973).

COMPOSITION OF DISSOLVED SOLIDS

Inorganic dissolved solids is considered the combination of dissolved salts found in natural water. A summation of the concentrations of the major ions found in water can be and sometimes is used to approximate total dissolved solids (TDS) (APHA, 1975). These major ions are as follows: Sodium (Na^+), potassium (K^+), calcium (Ca^{++}), magnesium (Mg^{++}), carbonate ($CO_3^=$), bicarbonate (HCO_3^-), sulfate ($SO_4^=$), and chloride (Cl^-). The relative abundance of these ions in natural water and the way in which they are contributed varies widely (Hem, 1970; Likens et al., 1970; Snyder et al., 1975).

Organic matter dissolved in water varies greatly as to composition and concentration. Probably of greatest importance on a large scale is the macromolecular humic and fulvic acids and similar compounds which persist in the environment as degradation products of plant materials. These compounds can serve as chelating or complexing agents for metals and nutrients, and have been shown to be effective in solublizing chlorinated hydrocarbons (Wershaw et al., 1969; Blom et al., 1976). Dissolved organic compounds which exert a BOD are of serious local importance to aquatic life. Currently, great effort is being made to remove these compounds from wastewater effluents. However, urban run-off often goes untreated even though it is a significant source of oxygen demanding organic matter (Whipple et al., 1974). Low molecular weight organic compounds are in certain instances very important. V. D. Adams et al. (1975) have found high concentrations of low molecular weight dissolved organic compounds (i.e., acetaldehyde, methanol, ethanol, propanol, acetone, and 2-propanol) in a eutrophic reservoir in northern Utah. Possible sources of these compounds include algal by-products and algal decomposition products.

TYPES OF SUSPENDED SOLIDS

Eroded soils are the most important type of suspended solids on a large scale. Sand, silt, and clay are dislodged by rainfall and overland flow and carried into streams and lakes from rural and agricultural areas, forests, and urban areas (Likens et al., 1970; Bryan, 1971; Lin, 1972; Glancy, 1973; Sartor et al., 1974). Sediment resuspended in the course of the stream (bed load) is also an important type of suspended solids but will not be addressed in this review. A review of bed load effects is being currently prepared for EPA, Region X, by the University of Washington.

Organic suspended particulates compose an important part of suspended solids in most natural waters. Natural detrital material can be dislodged from the soil surface and enter a stream or lake. Likens et al. (1970) reported that 50 percent of the suspended solids being exported from the undisturbed area at Hubbard Brook were organic in nature. Often the less dense organic fraction of soil will be preferentially removed in runoff causing the organic fractions of the suspended solids to actually be enriched (Debyle and Packer, 1972). This organic fraction is often higher in nutrients than the inorganic fraction of the soil (Fletcher et al., in press). The suspended solids washed from feedlots are primarily organic material (Miner et al., 1966). Much of the suspended matter in urban runoff is organic (Bryan, 1971). The organic nature of suspended solids in municipal and industrial effluents has been discussed above.

SECTION III

PHYSICAL-CHEMICAL EFFECTS OF DISSOLVED SOLIDS

EFFECTS ON IRRIGATION WATER QUALITY

A great amount of research dealing with the effects of irrigation water salinity on soils and crops has been accomplished. It is beyond the scope of this report to deal extensively even with the more recent literature pertaining to the subject, but some description of the problems and management solutions is included.

The Committee on Water Quality Criteria (1973) have prepared a good review of water quality considerations for irrigation including crop tolerance to salinity and effects on soils. Methods for dealing with saline and alkaline soils (Richards, 1954) have been reviewed. Problems related to usage of high dissolved solids water in irrigation are usually found in arid and semi-arid areas such as the western U.S. and the middle east. Repeated irrigation with high salinity water in these areas increases the concentration of soluble salts in the soil due to large portions of the applied water being removed by evaporation, leaving the salts behind. High concentrations of salts in the soil solution results in high osmotic pressures which make it difficult for plants to extract water. Soil salinity is usually measured as electrical conductivity of a saturation extract. Salinity levels that may produce yield-limiting soil salinity have been calculated (Branson et al., 1975) and are shown in Table 1. These values are applicable to areas with a climate similar to southern California where soil-solution salinity levels in the active part of the rootzone are commonly threefold more than in the irrigation water due to evapotranspiration.

High ratios of sodium to calcium and magnesium in irrigation water can lead to excessive exchangeable sodium percentages in the soil. Sodium-sensitive plants can be limited in production in even slightly affected soils. Soil structure can be destroyed by excessive exchangeable sodium leading to permeability and aeration problems (Branson et al., 1975). Accumulated salts in the soil solution of soils receiving high dissolved solids irrigation water can be removed by leaching the soil with an excess of irrigation water above that required for evapotranspiration and plant growth. Soil salinity can be leached by rainfall in areas such as India where monsoon rains occur (Lal and Singh, 1973). Drainage waters containing surplus salts leached from irrigated soils may have a several fold increase in salt concentration over that of the irrigation water (Branson et al., 1975).

Bernstein and Francois (1973) have found that crop yield response for alfalfa (Medicago sativa L. cv. Sonora) appears to be related to the mean

TABLE 1. SOIL SALINITY LEVELS (EC_e) ASSOCIATED WITH VARIOUS YIELD DECREMENTS (%) AND THE CALCULATED CORRESPONDING IRRIGATION WATER ELECTRICAL CONDUCTIVITIES (EC_w).*

Crop	Yield decrements: 0% EC_e†	0% EC_w†	10% EC_e	10% EC_w	25% EC_e	25% EC_w	50% EC_e	50% EC_w
	mmhos/cm							
Field Crops								
Barley (Hordeum vulgare)	8	5.3	12	8	16	10.7	18	12
Sugarbeets (Beta vulgaris)	6.7‡	4.5	10	6.7	13	8.7	16	10.7
Cotton (Gossypium hirsutum)	6.7	4.5	10	6.7	12	8	16	10.7
Safflower (Carthamus tinctorius)	5.3	3.5	8	5.3	11	7.3	14	8
Wheat [Triticum aestivum (T. vulgare)]	4.7	3.1	7	4.7	10	6.7	14	9.3
Sorghum (Sorghum vulgare)	4	2.7	6	4	9	6	12	8
Soybean (Glycine max)	3.7	2.5	5.5	3.7	7	4.7	9	6
Sesbania [Sesbania exaltata (S. macrocarpa)]	2.7	1.8	4	2.7	5.5	3.7	9	6
Rice (Paddy) (Oryza sativa)	3.3	2.2	5	3.3	6	4	7	4.7
Corn (Zea mays)	3.3	2.2	5	3.3	6	4	7	4.7
Broadbean (Vicia faba)	2.3	1.5	3.5	2.3	4.5	3	6.5	4.3
Flax (Linum usitatissimum)	2	1.3	3	2	4.5	3	6.5	4.3
Beans (Field) (Phaseolus vulgaris)	1	0.7	1.5	1	2	1.3	3.5	2.3
Vegetable Crops								
Beets (Beta vulgaris)	5.3	3.5	8	5.3	10	6.7	12	8
Spinach (Spinacia oleracea)	3.7	2.5	5.5	3.7	7	4.7	8	5.3
Tomato (Lycopersicon esculentum)	2.7	1.8	4	2.7	6.5	4.3	8	5.3
Broccoli (Brassica oleracea)	2.7	1.8	4	2.7	6	4	8	5.3
Cabbage (Brassica oleracea)	1.7	1.1	2.5	1.7	4	2.7	7	4.7
Potato (Solanum tuberosum)	1.7	1.1	2.5	1.7	4	2.7	6	4
Sweet Corn (Zea mays)	1.7	1.1	2.5	1.7	4	2.7	6	4
Sweet Potato (Ipomoea batatas)	1.7	1.1	2.5	1.7	3.5	2.3	6	4
Lettuce (Lactuca sativa)	1.3	0.9	2	1.3	3	2	5	3.3
Bell Pepper (Capsicum frutescens)	1.3	0.9	2	1.3	3	2	5	3.3
Onion (Allium cepa)	1.3	0.9	2	1.3	3.5	2.3	4	2.7
Carrot (Daucus carota)	1	0.7	1.5	1	2.5	1.7	4	2.7
Beans (Phaseolus vulgaris)	1	0.7	1.5	1	2	1.3	3.5	2.3
Cantaloupe (Cucumis melo)	2.3	1.5	3.5	2.3	No Data		No Data	
Watermelon (Citrullus lanatus)	2	1.3	No Data		No Data		No Data	
Forage Crops								
Bermuda Grass (Cynodon dactylon)	8.7	5.8	13	8.7	16	10.7	18	12
Tall Wheat Grass (Agropyron elongatum)	7.3	4.9	11	7.3	15	10	18	12
Crested Wh. Grass (Agropyron cristatum)	4	2.7	6	4	11	7.3	18	12
Tall Fescue (Festuca arundinacea)	4.7	3.1	7	4.7	10.5	7	14.5	9.7
Barley (hay) (Hordeum vulgare)	5.3	3.5	8	5.3	11	7.3	13.5	9
Perennial Rye (Lolium perenne)	5.3	3.5	8	5.3	10	6.7	13	8.7
Harding Grass (Phalaris tuberosa stenoptera)	5.3	3.5	8	5.3	10	6.7	13	8.7
Birdsfoot Trefoil (Lotus corniculatus)	4	2.7	6	4	8	5.3	10	6.7
Beardless Wild Rye (Elymus triticoides)	2.7	1.8	4	2.7	7	4.7	11	7.3
Alfalfa (Medicago sativa)	2	1.3	3	2	5	3.3	8	5.3
Orchard Grass (Dactylis glomerata)	1.7	1.1	2.5	1.7	4.5	3	8	5.3
Meadow Foxtail (Alopecurus pratensis)	1.3	0.9	2	1.3	3.5	2.3	6.5	4.3
Clover (Trifolium repens)	1.3	0.9	2	1.3	2.5	1.7	4	2.7

TABLE 1. Continued.

Crop	Yield decrements 0% EC_e[†]	EC_w[†]	10% EC_e	EC_w	25% EC_e	EC_w	50% EC_e	EC_w
	mmhos/cm							
	Fruit Crops							
Date Palm (Phoenix dactylifera)	5.3	3.5	8	5.3			16[§]	10[§]
Fig (Ficus carica) Olive (Olea europaea) Pomegranate (Punica granatum)	2.7-4.0	1.8-2.7	4.6	2.7-4.0			9[§]	6[§]
Grape (Thompson) (Vitis venifera)	2.7	1.8	4	2.7			8[§]	5.3[§]
Grapefruit (Citrus paradisi) Orange (Citrus sinensis) Lemon (Citrus limon)	1.7	1.1	2.5	1.7			5[§]	3.3[§]
Apple [Malus pumila (Pyrus malus)] Pear (Pyrus communis)	1.7	1.1	2.5	1.7			5[§]	3.3[§]
Almond (Prunus amygdalus) Apricot (Prunus armeniaca) Peach (Prunus persica) Prune (Prunus domestica)	1.7	1.1	2.5	1.7			5[§]	3.3[§]
Walnut (Juglans regia)	1.7	1.1	2.5	1.7			5[§]	3.3[§]
Blackberry (Rubus sp.) Boysenberry (Rubus ursinus) Raspberry (Rubus sp.)	1.0-1.7	0.7-1.1	1.5-2.5	1.0-1.7			4[§]	2.7[§]
Avocado (Rubus idaeus)	1.3	0.9	2	1.3			4[§]	2.7[§]
Strawberry (Fragaria sp.)	1.0	0.7	1.5	1.0			3[§]	2.0[§]

* From Univ. of Calif. Committee of Consultants report to California State Water Resources Control Board, March 1974, based on USDA-Ag. Inf. Bull. 283 and personal communication with Dr. Leon Bernstein, U.S. Salinity Laboratory, Riverside, Calif.

† EC_e is electrical conductivity of saturation extract in millimhos per centimeter (mmho/cm): EC_w is electrical conductivity of irrigation water (in mmho/cm).

NOTE: Conversion from EC_e to EC_w assumes a threefold concentration of salinity in soil solution (ECsw) in the more active part of the root zone due to evapotranspiration. $EC_w \times 3 = ECsw$; $ECsw \div 2 = EC_e$.

‡ Tolerance during germination (beets) or early seedling stage (wheat, barley) is limited to EC_e about 4 mmho/cm.

§ Calculated values, assuming 50% decrease in yield results from doubling of salinity values for 10% yield decrement.

salinity of the soil water, and that this mean salinity is influenced more by the salinity of the irrigation water than by the salinity of the drainage water. Alfalfa and presumably other plants are affected relatively little when the plants concentrate the soil solution to nearly the limits of tolerance. This indicates that leaching requirements may be reduced from 25 percent to 40 percent of the previously recommended levels depending on salt tolerance of individual species. This would reduce irrigation drainage volume making it more easily treated or diverted from a receiving water. Since the allocation of water between irrigation and leaching can have important bearing on policy decisions in water limited areas, methodologies of reducing the leaching water requirement are important (McFarland, 1975).

EFFECTS OF SALINITY ON THE QUALITY OF DRINKING WATER FOR ANIMALS

The effects of high salinity in livestock drinking water is well reviewed in Water Quality Criteria, 1972 (CWQC, 1973). Effects on animals ranges from mild diarrhea and increased or decreased water consumption in some animals at relatively low concentrations of salt (e.g. 4,000 mg/1 total salts) to severe anorexia, anhydremia, and collapse at high concentrations (e.g. 20,000 mg/1 NaCl). Table 2 presents a guide to the use of saline waters for livestock and poultry (CWQC, 1973). Effects of salinity in the drinking water of domestic animals would be expected to be similar for wild animals of similar physiology.

Recent work by A. W. Adams et al. (1975) showed that 4,000 ppm sulfate as Na_2SO_4 or $MgSO_4$ significantly depressed feed consumption and hen-day production of laying hens. They also found that Na_2SO_4 significantly increased water consumption and fecal moisture content, while $MgSO_4$ decreased water consumption. Mortality data suggested that lethal levels of Na_2SO_4 and $MgSO_4$ for laying hens were between 16,000 and 20,000 ppm.

Digesti and Weeth (1976) found increased methemaglobin and sulfhemaglobin in beef heifers given water containing 1,250 and 2,500 mg/1 sulfate (as Na_2SO_4). Test animals would discriminate against 21 mM ($\sim$ 2000 mg/1) sulfate and reject 34.5 mM ($\sim$ 3300 mg/1) sulfate. Based on these data and the finding that no adverse effects were noted at 2,500 mg sulfate/1 Digesti and Weeth (1976) placed the ''safe'' concentration for sulfate in drinking water for cattle at 2,500 mg/1. They also found that cattle would discriminate against 45.6 m chloride and reject 115.6 m chloride.

EFFECTS ON PUBLIC WATER SUPPLY

The effects of high dissolved solids in public water supplies are primarily physiological, aesthetic (taste), and economic. High levels of mineralization in drinking water may have a laxative effect especially on transients (CWQC, 1973).

The ''California Mineral Taste Study'' conducted primarily by W. H. Bruvold has provided a functional relation between mineral content of drinking water and consumer attitude toward taste. In accomplishing this, the ''California Mineral Taste Study'' may be unique in assessing aesthetic effects of water quality.

TABLE 2. GUIDE TO THE USE OF SALINE WATERS FOR LIVESTOCK AND POULTRY (CWQC, 1973).

Total Soluble Salts Content of Waters (mg/l)	Comment
Less than 1,000	Relatively low level of salinity. Excellent for all classes of livestock and poultry.
1,000-2,999	Very satisfactory for all classes of livestock and poultry. May cause temporary and mild diarrhea in livestock not accustomed to them or watery droppings in poultry.
3,000-4,999	Satisfactory for livestock, but may cause temporary diarrhea or be refused at first by animals not accustomed to them. Poor waters for poultry, often causing water feces, increased mortality, and decreased growth, especially in turkeys.
5,000-6,999	Can be used with reasonable safety for dairy and beef cattle, for sheep, swine, and horses. Avoid use for pregnant or lactating animals. Not acceptable for poultry.
7,000-10,000	Unfit for poultry and probably for swine. Considerable risk in using for pregnant or lactating cows, horses, or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry, and swine may subsist on them under certain conditions.
Over 10,000	Risks with these highly saline waters are so great that they cannot be recommended for use under any conditions.

Using methods of psychometric scaling, taste panel studies rated general taste quality of natural waters. Waters were carefully selected which had no detectable odor, nor history of odor due to anything but common minerals. The water samples, with the exception of one, had not been chlorinated. The results show an inverse linear relationship between general taste quality and mineral content. It was also found that persons may accept water of less than neutral quality. Potability (palatability) grades for various levels of TDS were suggested as follows: Excellent, < 300 mg/l; Good, 301-600 mg/l; Fair, 601-900 mg/l; Poor, 901-1100 mg/l; unacceptable, > 1101 mg/l (Bruvold et al., 1967; Bruvold and Ongerth, 1969). The study casts doubt on the usefulness of threshold testing of aesthetics for setting standards by finding that clearly detectable mineral taste may be unacceptable for daily drinking.

A public survey of six California communities using water ranging from 50 to 1401 mg TDS/l confirmed that attitude scale scores became more negative as TDS increases. The least offensive taste was found in sulfate and bicarbonate solutions while chloride and carbonate solutions have the most offensive taste. Synergistic or inhibiting effects of ions were not observed. Each ion appeared to make a straightforward contribution to the ratings according to its concentration. Dissolved oxygen variations did not seem to have a significant effect on mineral taste. Chlorine additions at 0.8 mg/l could be detected by a special panel and did not remove mineral taste. Temperature did not have a profound effect on taste either, even though cooler water was liked a little more. Contrary to common belief, consumers did not habituate or adjust to the mineral taste with time. Distilled water was less liked than water with a low mineral content. Beverages (coffee, tea, grape, and orange) made with mineralized water showed the same taste effects as for the individual ions ($SO_4^=$ and HCO_3^- had better taste than Cl^- anc $CO_3^=$). Increasing salinity in natural water decreased the palatability of these beverages (Bruvold, 1975).

Theoretically, any water can be processed into high quality water--for a price. Desalination appears to be as much as 50 or more times the cost of typical water treatment in existing water treatment plants including softening (Hartung and Tuepker, 1969).

Lawrence (1975) has developed estimating functions for the indirect costs imposed by high TDS on urban water use including industrial water supply. He listed the principal effects of high TDS as: (1) increased potentials for corrosion of vulnerable ferrous metals, (2) dezincification of vulnerable copper alloys and (3) industrial imposition (maintenance and treatment costs) to cooling waters and critical process waters. Low levels of salinity are not undesirable since distilled water itself is corrosive generally.

Water heater life is shortened about one year for every 200 mg/l additional TDS. Water hardness causes wear and tear on laundered fabrics, increased consumption of soaps, detergents, cleaners, chelating agents or combinations of these. Estimated total impact cost curves (penalty cost) were developed for the Los Angeles River planning area for 1974. These curves show the penalty cost estimate to range between about \$25/acre-ft (2.0¢/m^3)/100 mg/l TDS at the low (∿ 200 mg/l) TDS range and about \$35/acre-ft (2.8¢/m^3)/100 mg/l TDS at the high (∿ 800 mg/l) TDS range. These costs do not include bottled water use to avoid mineral taste problems since this was considered as a non-uniformly applied cost and not of significant magnitude in the study area.

EFFECTS ON INDUSTRIAL WATER SUPPLY

Water used by the manufacturing industry in 1973 totaled approximately 15,000 billion gallons (57 billion m^3) per year. Of this large quantity of water 81.2 percent is freshwater, 9.3 percent brackish water, and 9.5 percent salt water. Of the freshwater used 62.3 percent is used for cooling and condensing, 30.9 percent is used as process water, and 5 percent as boiler feed water. Brackish and salt waters are used almost entirely (93.7 percent and 91.6 percent respectively) for cooling and condensing water (U.S. Department of Commerce, 1975). Cooling water withdrawal by steam-electric plants in 1973 totaled 273,000 cfs (64,000 billion gallons/year or 244 billion m^3/year). Saline water use accounted for 28.3 percent of the total. The approximately 46,000 billion gallons (174 billion m^3/year) of fresh water used represents 11 percent of the total streamflow of the conterminous U.S., and when this is combined with manufacturing cooling water use the total is nearly 14 percent of the total streamflow (Federal Power Commission, 1976).

The dissolved solids characteristics of water that has been used for industrial water supplies varies greatly according to the requirements of individual industries and process. Concentrations of dissolved solids in water used in industry are reported to range from 150 to 35,000 mg/l (CWQC, 1973). Boiler feed, cooling tower makeup, and industrial process waters usually require specific treatments such as softening, dealkalizing, demineralization, or ameliorative additives in order to meet specific needs. Therefore, individual industries incur different costs from a given quality water. In metropolitan San Diego, California, the average industrial costs for water treatment were slightly over \$5/acre-ft (0.405¢/m^3)/100 mg TDS/l (Lawrence, 1975). Approximately 7,400 billion gallons (27.9 billion m^3) of water received treatment prior to industrial use in the manufacturing process in 1973. The number of manufacturing establishments which employed some sort of intake water treatment totaled 5,549. Treatments used included physical treatment, coagulation, softening, ion exchange, pH control, aeration, filtration, chlorination, and others (U.S. Department of Commerce, 1975).

SECTION IV

PHYSICAL-CHEMICAL EFFECTS OF SUSPENDED SOLIDS

RESERVOIR FILLING

The loss of reservoir capacity through the accumulation of sediment is a problem with serious economic consequences. A bibliographical review of the subject for the period 1964 to December 1975 which contains 105 abstracts has been compiled by R. J. Brown (1975) of the National Technical Information Service. It is beyond the scope of this review to discuss this literature in detail.

Generally, the factors contributing to the rate of sedimentation are erosion, sediment delivery rates, trap efficiency of the reservoir, and bulk density of the sediment (Paulet et al., 1972). They found that reservoir sedimentation is significantly associated with the characteristics of the contributing watershed, particularly the soils and geomorphology. Features of reservoir sedimentation can be estimated from stream characteristics and textural properties of the soil. Sedimentation rates were greater with finer texture, more uniform particle size, and lesser clay content in the soil. Similarly, greater sedimentation rates per unit of drainage area occurred with smaller drainage areas and shorter main stream length, lower order of the main stream, and smaller stream length ratio (i.e. the ratio of the mean length of the stream segment of the order of the stream on which the reservoir is located to the mean length of the segments of the next lower order). Lund et al. (1972) found that sedimentation rate predictions using the model of Paulet et al. (1972) could not be improved by including sediment clay mineralogical parameters.

TOXIC SUBSTANCE TRANSPORT

Halogenated Organics

A great deal of research has been and is being conducted on the release to the environment and ultimate fate of halogenated organic compounds. Several of these types of compounds have been associated with ecological damage and are deleterious to human health. Selected western U.S. streams (Brown and Nishioka, 1967; Manigold and Schulze, 1969) were surveyed for pesticides (i.e., aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor epoxide) and herbicides (i.e., 2,4-D; 2,4,5-T; silvex). Both classes of compounds were found but not at all sampling stations. Herbicides were the most infrequently encountered (possibly due to degradation). DDT and its metabolites were the most commonly found. The highest concentrations of insecticide were found in samples having the highest sediment load.

Pfister et al. (1969) used liquid-liquid extraction methods on Lake Erie water and found no detectable chlorinated pesticides in the water. However, they found lindane associated with the small (size) inorganic fraction, and aldrin and endrin associated with the less dense fraction (mostly organics, detritus, and microorganisms) of the microparticulates in the water. They pointed out that not including particulates in water analysis is inadequate for pesticides.

Wershaw et al. (1969) found that DDT was 20 times more soluble in 0.5 percent sodium-humate than in water alone, and that humic acid strongly sorbs 2,4,5-T from solution. DDT was found to be concentrated 15,800 times in coloring colloidal material by Poirrier et al. (1972). This coloring colloidal material was described as allochthonous polymeric hydroxy carboxylic acids complexed with varying quantities of iron which were less than 10 μm in size. These colloids may stay in suspension for long periods of time, but may precipitate with changes in environment. It is possible that they may be transported to estuaries where contact with seawater may cause them to precipitate and adsorb to plants and/or be used by estuarine organisms as food.

The intimate association of clay and organic matter (organoclay complexes) can modify clay adsorption properties. Kahn (1974) found that 2,4-D adsorption by a fulvic acid-montmorillonite complex was smaller than previously reported values for humic acid, but was much higher than for montmorillonite alone. Low heats of adsorption by these complexes are on the order of van der Waals-type adsorption. Pierce et al. (1974) described the adsorption of DDT to clay as electrostatic attraction between the net negative charge on clay surfaces and hydrogen atoms on the aromatic rings of the DDT. Adsorption of DDT to humic acid has been attributed to hydrophobic bonding to portions of the humic polymer. Pierce et al. (1974), noting the increased adsorption capacity of humic matter, pointed out the need for knowledge of the transport and distribution of humic substances as related to the transport and distribution of chlorinated hydrocarbons in the environment.

Rizwanul et al. (1974) found that the higher the chlorine content of a PCB (polychlorinated biphenyl) the greater its solubility in water. He also found that sand and silica gel adsorbs very little PCB 1254, while kaolinite clay, montmorillonite clay, illite clay, and woodburn soil (Corvallis, Oregon) adsorbed increasingly more, respectively. The organic content of the soil was suspected as being the reason for higher adsorption.

A linear relationship has been found to exist between the concentration of chlorinated hydrocarbons and total organic carbon (as well as humic and fulvic acid material) in marine sediments (Choi and Chen, 1976). This study also found organoclay complexes to be important in adsorption of chlorined hydrocarbons. Chlorinated paraffins (suggested substitutes for PCB in many applications) have been tested for uptake by juvenile Atlantic salmon by Zitko (1974). He found that the juvenile salmon accumulated a relatively large amount of PCB (144 mg/g/144 hours) but little if any chlorinated paraffins from suspended solids. Feeding of the chlorinated paraffins to the fish did not result in accumulation, but some indications of toxicity were found.

Dredging and dredge spoil disposal operations have been suspected of freeing toxic chlorinated hydrocarbons from contaminated sediments. Slotta and

Williamson (1974) point out that the cause-effect relationship between dredging and toxic organic matter release is not well documented. Transfer of PCB and pesticide material to the water column from resuspended sediments collected near Chicago, IL; Green Bay, WI; Fall River, MA; Houston, TX; and Memphis, TN; was found to be negligible (Fulk et al., 1975). Chlorinated hydrocarbon concentrations associated with the suspended solids reached ''background'' levels after settling periods of 5 to 24 hours. The oil and grease content of the water was most important in ''describing'' the concentration of pesticides remaining in solution. Chen et al. (1976) assayed the release of chlorinated hydrocarbons from settled dredge spoil under reducing conditions and were unable to detect any after 3 months incubation. Here again the concentration of chlorinated hydrocarbons was closely correlated with macromolecular organic compounds in the sediments and to particles of 8 μm or smaller. Lee et al. (1975) have refined methods used for evaluating the hazard of toxic substance which may be released from sediments scheduled for dredging.

Toxic halogenated organic compounds may enter surface waters already adsorbed to soil or organic material. Lin (1972) suggested that agricultural erosion may be an important source for pesticides in water. The very low concentrations of pesticides found in agricultural runoff in eastern South Dakota by Dornbush et al. (1974) suggest that the contribution from agriculture may be quite variable and site specific. The processes involved in transport and distribution of toxic substances through or over a watershed have been mathematically modeled by Frere (1975). Such modeling efforts help understanding of the processes affecting loss of pesticides (or other toxics) from land to which they are applied.

Metals

Heavy metals may be adsorbed by, coprecipitated with, or complexed by suspended solids. Thus, heavy metals may be translocated or deposited with the sediment load of a natural waterway. Changes in biological, electrochemical, or physiochemical conditions in sediments such as those experienced during dredging and disposal operations could conceivably cause the release of toxic metals to the water. Slotta and Williamson (1974) pointed out that heavy metals may not be released during dredging operations due to adsorption on or coprecipitation with iron (III) oxides and iron (II) sulfides which are exposed during dredging. Blom et al. (1976) investigating the effect of sediment organic matter on the migration of chemical constituents during disposal of dredged material, found that significant amounts of heavy metals were released, but that concentrations remained below water quality criteria. They also found that oxygenation of the dredged material decreases metal release except for manganese in seawater, and to a lesser extent cadmium in both sea and freshwater. There was no evidence found that sediment or soluble carbon controls the release of metals or nutrients even in the presence of ligands.

Chen et al. (1976) found that during dredge spoil disposal, concentrations of silver, cadmium, and mercury were basically unchanged under all experimental conditions. Concentrations of chromium, copper, and lead were found from 3 to 10 times over background seawater levels. Iron, manganese, and zinc were released in even larger quantities. They also found that the release of metals from freshwater sediment in a seawater environment is somewhat larger than the release from marine sediments, but since the concentrations (except for iron) were in the sub-ppb to ppb range this was not considered to be a significant hazard. Extracted macromolecular organics such as humic and fulvic substances were found to contain from 2 to 15 times higher concentrations of trace metals than total sediment on a weight basis.

NUTRIENT TRANSPORT

Suspended solids often contain adsorbed or complexed plant nutrient compounds which, if made available for biological uptake and use, can lead to accelerated eutrophication of lakes and streams. Rural and agricultural runoff waters and their associated eroded material often contain considerable quantities of nutrients. Much of these nutrients may have been applied as fertilizer to the land. Phosphorus especially is tightly bound to soil particles and removed as sediment (Lin, 1972). With increasing trends in fertilizer application, good soil conservation practices are needed to minimize this source of pollution. Runoff water from animal feedlots contains particulate matter which is high in nutrients (Miner, 1966; Middlebrooks, 1974). Laboratory and field investigations which characterize suspended sediments from varied hydrologic, soil, and land use characteristics showed that agricultural activities in the dryland wheat region of eastern Washington contributed large amounts of sediment and dissolved nitrogen during heavy runoff periods. Urban activities provided substantial amounts of nitrogen and phosphorus during the remaining months. In excess of 90 percent of the orthophosphate exposed to the sediments was adsorbed (Carlile et al., 1974).

Anderson and Ross (1975) monitored a suburban development site and observed a significant increase in suspended solids and nutrients, especially phosphorus, associated with construction activities. Nutrient losses have been associated with increased erosion in clearcut forest areas in northern Idaho (Debyle and Packer, 1972; Snyder et al., 1975). Nutrient and suspended sediment production are greatly dependent on the patterns and magnitude of water drainage in the forested areas draining to the Lake Tahoe area, and disturbances, such as development construction activities, increase sediment production (McGauhey et al., 1971; Brown et al., 1973; Skau and Brown, 1974). Goldman (1974) reported that bacteria associated with particulate matter and nutrients eroded from the watershed into Lake Tahoe facilitate nutrient regeneration and may contribute to eutrophication. Huang and Hwang (1973) have shown that from 0 to 38 percent of the inorganic and from 63 to 89 percent of the organic phosphorus in sewage is associated with the suspended and colloidal particulates.

Nutrients released from sediments resuspended during dredging operations have given mixed results as to their algal growth stimulation ability. Larsen et al. (1975) have shown that sediment release of phosphorus has a great impact on the phosphorus budget of Shagawa Lake. Slotta and Williamson (1974) suggest that the localized nature of dredging operations, large dispersion factors, and the decrease in light penetration due to turbidity from the dredging, lower the algal bloom potential. Blom et al. (1976) observed the release of ammonia and low levels of orthophosphate from marine and freshwater dredged sediments. The numerical product of sediment organic content and the sediment organic nitrogen content was useful in predicting the release of ammonia nitrogen from dredged material. The release of other nutrients or metals from sediments was not related to any measured sediment parameter.

Chen et al. (1976) found that nitrogen and phosphorus were released in sub-ppm, and silicate in 10-20 ppm concentrations from suspended dredged sediments. Clay type sediments released nitrogenous compounds 2 to 10 times higher than silty and sandy sediments. Ammonia and organic nitrogen was released from settled spoil material under anaerobic conditions while nitrate and nitrite were released under aerobic conditions at about the same concentrations (10 ppm—N). Orthophosphate from settled sediments was released at concentrations between 0.1 to 0.8 ppm under both aerobic and anaerobic conditions.

Chemical analyses of certain systems have been interpreted to show that clays and sediments are effective in adsorbing organic compounds (heterotrophic substrates and vitamins) from solution. Button (1969) has shown that clays added to solutions of thiamine and glucose do not make these compounds unavailable to microorganisms or remove them to a significant degree from solution. Thus, it is not likely that suspended sediments influence significantly the populations of suspended microorganisms by sorbing vitamins or organic substrates.

AESTHETIC EFFECTS OF TURBIDITY

Turbidity, the optical property given to water by suspended solids, affects human perception visually. The clarity of natural water is seldom perceived alone, but is a component of the total field of vision or landscape. Most persons would probably agree that a clear mountain stream as part of an alpine landscape is pleasing and that a turbid stream in the same setting would be objectionable. However, the majestic appearance of the Green River in Utah flowing over large rapids is greatly enhanced when the river is laden with silt. Generally, however, high turbidities are considered to be unpleasing. For example, Buch (1956) described turbid reservoirs as unpleasing in the aesthetic sense, and implies that fewer anglers visited a reservoir for that reason. Forshage and Carter (1973) described the turbidity caused by gravel dredging in the Brazos River, Texas, as aesthetically unpleasing for several miles below the dredging site.

Little research on the effects of turbidity on the aesthetics of natural waters has been done. Methodologies for aesthetic measurement are still in the developmental stages. Reports of aesthetic evaluations which include turbidity in water quality assessment provide little if any data relating to the actual user or public opinion. Leopold (1969) and Hamill (1974) have used scales of ''evaluation numbers'' ranging from one to five, of water quality parameters which include turbidity. Selected panels of persons which may or may not have represented user group opinions are used in these studies. Hamill's (1974) work used a method which derived the highest aesthetic value by summing evaluation numbers from 31 environmental factors, 7 water quality factors (of which turbidity was one), 10 physical factors, and 14 human use factors. Turbidities of > 5,000 ppm were ranked ''5'' on the scale, the highest evaluation possible, with turbidities of < 25 ppm ranked ''1,'' or the lowest evaluation possible.

In identifying social goals, Gum (1974) listed water ''clarity'' as a subgroup of ''aesthetic opportunity.'' Measures of water clarity were defined as suspended silt load (ppm) and BOD (ppm). Masteller et al. (1976) reviewed current methodologies of assessing aesthetic values of streams and landscapes including those incorporating water quality factors. They state that aesthetic measuring techniques are generally inadequate, often being too judgmental and relying on panels of experts.

EFFECTS ON WATER SUPPLY

Modern water supply treatment plants are designed to remove suspended solids within the range commonly experienced in the raw water supply. Of course, as the suspended solids load that must be removed from the raw water increases, the expense of removal increases and the water supply value decreases. This is reflected in the ranges of standards promulgated for raw water resources of domestic water supply (McKee and Wolf, 1963). An excellent source of water supply, requiring only disinfection as treatment, would have a turbidity range of from 0 to 10 units. A good source of water supply, requiring usual treatment such as filtration and disinfection would have a turbidity range of 10 to 250 units. Waters with turbidities over 250 units are poor sources of water supply requiring special or auxiliary treatment and disinfection.

Robeck (1969) pointed out that waters of higher turbidity (30 JTU vs. 5 JTU) may be more easily coagulated and clay is sometimes added to raw water to give this effect. Surface area, charge density, and exchange capacity of clay mineral particles all have an effect on treatability. He also calls for protection of high quality (low turbidity) waters and states that effort should be made to minimize sudden changes in raw water turbidity since these affect coagulation, chlorine demand, and filterability of the water. The maximum contaminant level for turbidity in finished drinking water is one turbidity unit (EPA, 1975). An excellent review of 49 papers dealing with human perception and evaluation (aesthetics) of taste, odor, color, and turbidity in drinking water by Bruvold (1975) is recommended as a thorough treatment of this subject. Also Bruvold (1975) cites work in which the combined 1962 Public Health Service limits for turbidity, color, and odor were judged acceptable by only 48 percent of the respondents. He suggests that no more than 10 percent of the users should call a public water unacceptable, indicating that these standards need to be reconsidered.

SECTION V

EFFECTS OF DISSOLVED SOLIDS ON AQUATIC BIOTA

As will be seen in the review of the literature that follows, only occasionally do dissolved or suspended solids have drastic acute effects on the biology of most freshwater systems. Effects of these water quality parameters are usually subtle, seldom serving to completely eliminate (or to extremely stimulate) biological systems in streams or lakes. In assessing the impacts of a marine disposal outfall high in suspended and dissolved solids, Harville (1971) points out that it is not feasible to use the simple presence or absence of organisms as an indicator of pollution, since some resistant form of life will always be present.

EFFECTS ON PHYTOPLANKTON, PERIPHYTON, AND VASCULAR PLANTS

Dissolved solids consist of both organic and inorganic molecules and ions that are in true solution in water. Reid (1961) defined the most conspicuous materials which are found in varying quantities in natural waters to include carbonate, chlorides, sulfates, phosphorus, and nitrates. These anions occur in combination with such metallic cations as calcium, sodium, potassium, magnesium and iron to form ionized salts. Many of these dissolved materials are essential for growth and reproduction of aquatic organisms. The presence and the success of an organism in the environment is controlled by the quality and quantity of inorganic and organic nutrients; deficiency or excess or both may be limiting. When these various salts are present in suitable proportion, the different cations counteract each other, and the solution is physiologically balanced. Warren (1971) reports that the harmful effects of increased salt concentrations are caused, not by toxicity of its individual components, but by high osmotic pressure. When establishing criteria for dissolved solids in water, the importance of osmotic stress associated with increases in major cation and anion species must be considered (Provasoli, 1969).

Because unrooted aquatic plants depend entirely on dissolved solids for nutrients, any change in the nutrient level of a lake is reflected in its biota (Wetzel, 1973-1974). Algae as a group, however, are physiologically, as well as morphologically, very heterogenous. This heterogeneity makes generalization about their nutrition difficult. Therefore, when dealing with specific ecological problems it is dangerous to extrapolate data from one species to another. Ruttner (1952) reports that a limitation of the number of species in an environment begins at salt concentration exceeding that of the sea (35 g/l or 3.5 percent). Specht (1975) reports inhibition of Selenastrum at salinities in excess of 9 parts per thousand whereas Cleave et al. (1976) report inhibition of Selenastrum at salinities of between 250 and 500 mg/l. [The effects of increased salinity on mangroves and submerged marine plants will not be covered here, the reader is referred to Reimold and Queen (1972) for an introduction to this topic.]

The first report of Na as an essential nutrient for blue-green algae came from Allen and Arnon (1955) who stated that 5 ppm suffices for optimal growth of Anabaena cylindrica. Brownell and Nicholas (1967), working with this same species, found that Na deficiency led to depressed N_2 fixation. It has also been shown that Anabaena variabilis and Synechocystis aquatilis tolerate NaCl up to 23.5 percent (w/v) and Microcystis firma tolerates NaCl up to 60 percent (w/v) (Schiewer, 1974). Provasoli (1969) proposed that monovalent ions might, with other factors, be responsible for tipping the balance in favor of blue-greens. Blue-green algae have an absolute need for Na as well as K which is a pattern apparently not shared by other fresh water algal groups.

Pearsall (1932) reported that a monovalent to divalent (M/D) cation ratio below 1.5 was favorable to diatoms in oligotrophic waters and Provasoli, et al. (1954) report Synura petersenii to prefer low total solids (60-100 ppm) and M/D above 2. This would appear to explain why eutrophic lakes affected by civilization often have blue-green blooms. Urbanization adds not only organic matter but also Na and P.

Zafar (1967) concluded that dissolved organic matter directly influenced the periodicity of blue-greens. While Seenayya (1973) suggested that an increase in chlorophyll a generally coincided with increasing TDS, Kerekes and Nursall (1966) reported a definite correlation of seston biomass to an increase in TDS. They hypothesized that as TDS increased, more nutrients became available thereby increasing the productivity of the water to a certain point (Figure 1). Continued increase in TDS tended to inhibit organoproduction, so that the productivity of the water decreased. In the study lakes, the TDS and alkalinity for maximum productivity were about 1,400 ppm and 450 ppm, respectively. However, the study lakes were not corrected for different nutrient levels and this confounding prevents confirmation of their hypothesis. The need to consider nutrient level as well as other limnological variables than TDS in natural field conditions is illustrated by the results of other workers. Topping (1975) found that the maximum standing crop in British Columbia lakes occurred at about 8,200 ppm. Topping (1975) also reported that increased concentrations of TDS become osmotically limiting. Larson (1970) reported that dissolved solids in Odell Lake (Oregon) were about 1/3 of Crater Lake (Oregon) yet production in Odell Lake was 8-10 times greater. Seventy-five percent of the total dissolved solids of Crater Lake were made up of six elements suggesting that, although total dissolved solids were relatively high, certain essential ions may have been deficient and therefore limiting.

Batterton and van Baalen (1971), working with blue-green algae, reported that 1 mg NaCl/l satisfied requirements for growth and higher concentrations of NaCl apparently inhibited growth. They, however, reported that inhibition was caused more by ionic (Na^+) stress than by osmotic stress. Most of the literature, however, supports the conclusion that the osmotic pressure of the solution is responsible for the observed changes in productivity following an increase in salt concentration (Schmidbauer and Ried, 1967).

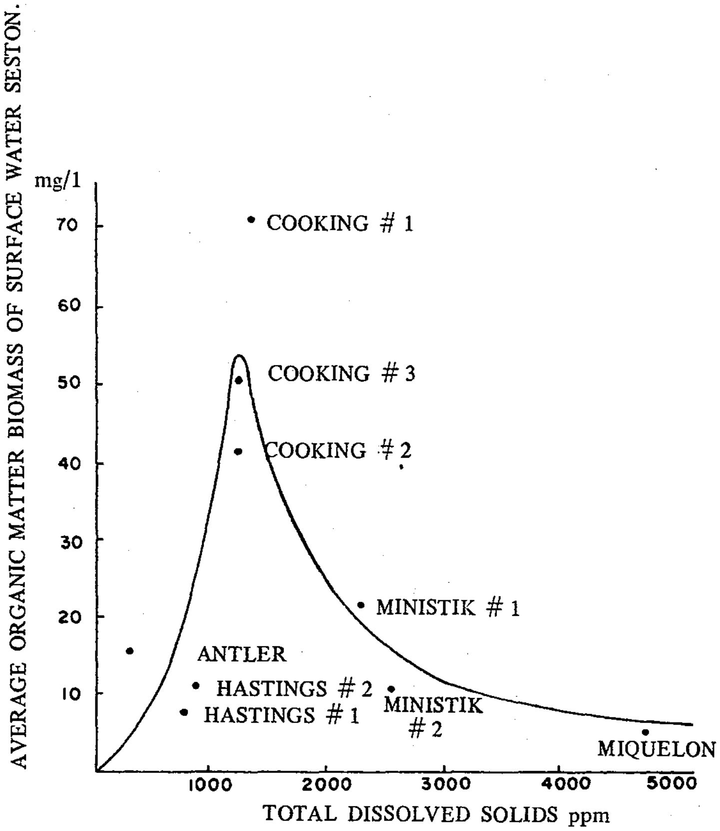

Figure 1. Relationship of organic matter biomass of surface water seston (productivity) to the total dissolved solids in nine bodies of water in central Alberta. (Kerekes and Nurshall(1966),reprinted by permission of the International Association of Theoretical and Applied Limnology.)

Dissolved organic substances can function directly as growth factors or essential micronutrients for algae. Doig and Martin (1974) report that iron associated with dissolved organic material may well cause the onset of logarithmic growth in Gymnodinium breve, the red tide alga.

The addition, in any amount of substances which cause shifts in population composition of the primary producers could adversely affect aquatic organisms farther up the food chain. Because of the close association between dissolved solids, nutrient availability and the growth of aquatic organisms, standards set forth to prescribe limits on TDS must take into account biological effects to insure maximum use of the water.

EFFECTS ON ZOOPLANKTON

Crustacean plankton populations have increased with increased total dissolved solids (TDS) and eutrophication of lakes in the Okanagan Valley, British Columbia (Patalas, 1973; Patalas and Salki, 1973). TDS in Lake Okanagan had increased by 19 mg/l between (July 4 to August 26) 1935 and 1969. The zooplankton abundance had increased from 2.8 mm^3/cm^2 in 1935 to 13.3 mm^3/cm^2 on

September 9, 1969, and to 7.8 mm^3/cm^2 on August 27, 1971. This represents a 4.8 and 2.8 fold increase respectively. There had been an 8 fold increase in bottom organisms. The increase in zooplankton populations probably are the result of increased eutrophication (related to phosphorus loading) which was reflected by the increase in TDS. No significant changes in species of plankton since 1935 were observed.

The chronic toxicity of NTA (nitrilotriacetate) to Daphnia magna was reduced with increasing water hardness (a major component of dissolved solids) up to 438 mg/l total hardness (Biesinger et al., 1974). Dissolved polyelectrolytes used as flocculants or coagulant aids in solids removal treatment of water were toxic to Mysis and Daphnia at concentrations ranging from 0.06 mg/l to 16.5 mg/l. Two polyelectrolytes (Superfloc 330 and Calgon M-500) impaired reproduction of Daphnia at low concentrations (Biesinger et al., 1976).

Faucon and Hummon (1976) found that the life expectancy, reproductive rate, and intrinsic rate of natural increase of the parthenogenic gastrotrich Lepidodermella squammata were maximal at pH 7.1 and total conductivity of 465 µmho/cm. Life expectancy was reduced to zero when acid mine waters were added to make the pH 4.6 and conductivity 825 µmho/cm. It was concluded that L. squammata is capable of living and reproducing at pH 6.0 to 6.5 under field conditions low in carbonates, providing non-carbonates are not abundant, or under field conditions high in non-carbonate ions, providing sufficient carbonates are present. This implies a dependence on anion ratios for survival of this organism.

EFFECTS ON MACROINVERTEBRATES

Five species of Odonatan nymphs, four species of Heteroptera, and three species of Coleoptera which had been adapted to freshwater, were tested by Shirgur and Kewalramani (1973) for their tolerance to various dilutions of seawater and to 3.5 percent solutions of major constituents of seawater. In general, Odonatan nymphs which survived longer than 360 hrs in dilutions of seawater below 30 percent were considered to be the least tolerant organisms, and Coleopterans, surviving greater than 360 hrs in dilutions below 60 percent were the most tolerant. The most sensitive species tested was Anisops barbata, which survived only 134.5 hrs in 10 percent seawater. The most tolerant species, Cybister cognatus, survived beyond 360 hrs in 50 percent seawater. Potassium chloride (KCl) was found to be the most toxic constituent and $MgSO_4$ the least toxic constituent of seawater.

Wichard and Komnick (1974) have shown that damselfly larvae (Zygoptera) osmoregulate against hypotonic salt solutions by virtue of rectal chloride epithelia which adsorb electrolytes from solution. Dills and Rogers (1974) observed increases in dissolved solids in streams subject to acid mine drainage in which macroinvertebrate community structure was adversely affected. However, hydrogen ion concentration was the only parameter highly correlated with species diversity.

The invertebrate fauna of two low salinity (25 to 40 mg/l), low pH (4.8-6.0) lakes on Stradbroke Island, Australia has been described (Bensink and Burton, 1975). Ninety-seven percent of the 1401 ppm TDS in one lake was due to dissolved organic (humic) matter, while the 124 ppm TDS in the other lake was only 48 percent dissolved organic matter. Littoral fauna species composition was very different in these lakes, probably due to differences in chemical-physical factors. Interference with light penetration in the brown colored humic lake may have been an important factor affecting faunal community structure.

EFFECTS ON SALMONID FISHES

McKim et al. (1973, 1974, 1975, 1976) have prepared extensive reviews which include the effects of salinity on freshwater fish. Eisler (1973), and Eisler and Wapner (1975) have also reviewed the literature dealing with salinity effects on fish in both marine and freshwater environments.

Bergström (1971) found an increase in blood glucose concentration correlated with a decrease in plasma sodium concentration in young salmon (Salmo salar) which had been placed in deionized water. It is possible that the increase in glucose may be of osmoregularity significance. Oxygen consumption rates were lowest in rainbow trout (Salmo gairdneri) maintained in a salinity of 7.5 ppt (Rao, 1971). This salinity is isosmotic with the fish plasma and the reduced oxygen requirement probably reflects a reduction in the osmotic load cost for the fish. The slope of a regression line relating fish weight to oxygen consumption, increased with increasing salinity at 15C, but no significant effect on the oxygen consumption-fish weight relationship was observed at 5C. Fish activity was not different in freshwater and 15 ppt salinity. Maximum oxygen consumption was observed at 30 ppt salinity (except for smaller fish at 15C)(Rao, 1971).

Zeitoun et al. (1973) found an increased protein requirement in rainbow trout (Salmo gairdneri) fingerlings raised in elevated (20 ppt) salinities. They related this requirement to the protection of the internal environment of the fish against a hypertonic external environment. However, the osmoregulatory capabilities of euryhaline coho salmon (Oncorhynchus kitutch) smolts did not require extra protein at 20 ppt (Zeitoun et al., 1974b). Water salinity and dietary protein concentration in rainbow trout (S. gairdneri) fingerlings did not influence serum protein (Zeitoun et al., 1974a). Hematocrit increased with increased salinity but was not affected by dietary protein levels. Leduc (1972) found that Atlantic salmon retain the same osmoregulation whether from ocean stock or from freshwater hatcheries. Block (1974) found that rainbow trout acclimated to 100 percent seawater had elevated levels of erythrocytes and tissue lipids when held at 1C, while plasma cholesterol and glucose levels remained unchanged. Seawater adapted rainbow trout accumulated urea in their plasma when held at 1 and 10C. This may have been due to the inability to excrete ammonia against the higher exterior concentration of sodium; then the ammonia would be converted to urea at colder temperatures, a less toxic substance.

Lack of oxygen brought about complete breakdown in osmoregulatory ability in the rainbow trout which was manifested by elevated levels of plasma electrolytes. Rainbow trout can be put directly into seawater cages if salinity is reduced to 22 ppt with mortalities of only one to eight percent (Landless, 1976).

EFFECTS ON OTHER FISH

With concern about the effects of impending degradation in water quality due to decreases in freshwater flows and increases in waste discharges, Turner and Farley (1971) studied the effects of temperature, salinity, and dissolved oxygen on the survival of striped bass (Morone saxitalis, Walbaum) eggs and larvae. Egg survival in salinities greater than approximately 1,000 ppm TDS is greatly reduced especially at higher temperatures unless they are hardened in freshwater. Dissolved oxygen levels of from four to five mg/l adversely affect egg and larval survival. Turner (1976) collected striped bass eggs and larvae from the Sacramento and San Joaquin Rivers in California during the period 1963 to 1972 and found that most spawning in the Sacramento-San Joaquin Delta occurred where salinities during spawning had been below 200 mg/l TDS with occasional maximum of 1,500 mg/l due to seawater intrusion. This high salinity level did not adversely affect egg survival. Turner (1976) pointed out, however, that although the ranges of salinities encountered (200 to 71,400 mg/l TDS) had a limited short term effect on egg survival and spawning, long term effects such as accumulative effects of small differences in survival or migratory preferences may reduce spawning in high total dissolved solids waters. Increased sodium chloride concentrations in freshwater hatchery ponds increased mean survival of striped bass fry to 7.65 percent as opposed to 1.7 percent survival in control ponds. The large variability in survival found in both pond types makes it difficult to determine if this difference (5.95 percent) in survival is significant.

Common carp (Cyprinus carpio) lived at salinities of 12 ppt for 10 weeks, but higher salinities were unfavorable (Al-Hamed, 1971). Fertilized carp eggs hatched at salinities from two to ten ppt, but had 'favorable' hatching success only up to 6.6 ppt.

Umminger (1971) found elevated levels of serum glucose in killifish (Fundulus heteroclitus) held at 0.1C. There was a 30 percent loss of serum sodium, a 42 percent loss of serum chloride, but only a 15 percent decrease in serum osmolarity in these fish. The relatively low decrease in osmolarity was due to a 1,967 percent increase in serum glucose. Osmoregulation ability by inorganic ion concentration adjustment is apparently inhibited at low temperatures. The turnover of sodium by the killifish (Fundulus kansae) is sharply increased by transfer to low calcium seawater from normal seawater. Mortality brought on by this phenomenon can be prevented by dilution to 80 percent (v/v) of the low-calcium seawater (Fleming et al., 1974). Rao (1974) found that incubation salinities over the range of five to 14 ppt produced the shortest incubation period, maximum yolk-conversion efficiency, largest larval size at hatching, and the maximum viable hatch of the California killifish (Fundulus parvipinnis). Lower salinities at fertilization resulted in shorter incubation periods and larger larvae at hatching indicating increased growth rates under the low salinity conditions.

Lutz (1972) studied the effect of osmotic and ionic stress on plasma, tissue, and whole body electrolyte composition of the perch (Perca fluviatilis). The perch showed a good degree of adaptive ionic regulation as it was able to survive up to one-third seawater with only potassium, magnesium, and chloride showing moderate significant rises in plasma. Attempts to acclimate perch to one-half seawater led to a total breakdown of the ionic controlling mechanisms. Osmotic rather than ionic considerations determined the lethality of the medium.

Peterka (1972), and Burnham and Peterka (1975) have studied the effects of salinity on eggs and larvae of the fathead minnow (Pimephales promelas) and other fishes. Peterka (1972) found that hatching success and sac fry survival was most successful for fathead minnow eggs fertilized in water with a conductivity of 1300 μmho/cm and held in water of 500, 1,300, 4,000, or 6,000 μmho/cm. Much lower success was found for eggs fertilized in 500 or 4,000 μmho/cm water and held in the above concentrations. Sac fry survival was similar in trend. There was no hatch of walleye (Stizostedion vitreum vitreum), approximately one percent hatch of northern pike (Esox lucius), and 22 to 93 percent hatch of fathead minnow eggs held in 4,000 μmho/cm water. No sac fry of northern pike survived 6,000 μmho/cm, while approximately one percent of the fathead minnow sac fry survived 12,000 μmho/cm water. All of the surviving fry at this concentration had physical abnormalities. The literature reviewed by Peterka (1972) indicated that ionic composition of the water seemed more important to tolerance by the fathead minnow than did TDS. The fathead minnow was unable to survive TDS > 2,000 ppm in the $NaHCO_3$, Na_2CO_3, and K_2CO_3 saline lakes of Nebraska, but survived approximately 15,000 ppm TDS in the Na_2SO_4 and $MgSO_4$ lakes of Saskatchewan and North Dakota. In the field, a North Dakota saline lake with 7,000 ppm TDS was not detrimental to reproduction and growth of the fathead minnow. The fathead minnow grew faster in lakes of 3,250 ppm TDS than at 1,060 ppm TDS.

Chittenden (1973) found that young American shad (Alosa sapidissima) could tolerate an abrupt as well as a gradual change from freshwater (five ppt) to salinities of about 30 ppt without mortality. Complete mortality occurred when the fish were abruptly transferred from 30 ppt to 0 ppt salinity but not with gradual decrease from 5 ppt to zero ppt salinity. Since these fish are euryhaline, they can use both brackish and freshwater nurseries. The American shad was formerly one of the most abundant anadromous fishes in the United States.

Digestive rates of the mosquitofish (Gambusia affins) generally increased with increasing salinity (Shakuntala, 1975).

Channel catfish (Ictalurus punctatus) and blue catfish (Ictalurus furcatus) have been collected from Gulf of Mexico waters with salinities of 11.4 ppt. Hybrids of these catfish were studied for salinity tolerance by Stickney and Simco (1971). They found that the hybrids were able to tolerate salinities between 14 and 15 ppt for periods of 96 hours. Allen and Avault (1971) found that blue catfish were more tolerant to 14 ppt salinity than were channel catfish. Size of the fish did not seem to affect the tolerance of either species. Both species of fish showed signs of distress early in the experiments, but showed some signs of recovery near the middle or end of the experiment. All the test fish lost weight indicating that neither species was able to adapt to 14 ppt salinity. Transfer of the fish from the 14 ppt to freshwater did not cause adverse effects. White catfish (I. catus) seemed to tolerate 14 ppt salinity better than blue catfish. Block (1974) found that 30 percent seawater did not change hematocrit values in channel catfish as compared to freshwater values. Tissue water of fish in freshwater and 2C was three percent above the level in freshwater and 30C. In 30 percent seawater at 2C the tissue water of the channel catfish was increased only one percent compared to 30C fish.

Osmoregulation by the catfish may be lost at low temperatures (2C) as evidenced by decreases in plasma osmolarity, sodium, and chloride levels in freshwater adapted fish. Davis and Simco (1976) observed increases in plasma sodium and chloride levels of channel catfish after five days exposure to 10 and 12 g/l sodium chloride in July (27C); at the same time there was a plasma electrolyte concentration increase for 4.8 hours after which the concentration leveled off. Catfish exposed similarly in March (9C) had a slow increase in plasma electrolyte throughout the 13 day experiment.

Hollander and Avault (1975) studied the salinity tolerance of buffalo fish (Ictiobus cyprinellus, and I. niger). They found that eggs of all fish types tolerated salinities as high as 15 ppt and hatched in 72 days. Emerging normal fry could tolerate only 9 ppt. Fry of both species of buffalo fish had the best survival time at 9 ppt and the poorest at zero ppt. Fingerlings had an upper salinity tolerance of 12 ppt, and yearlings tolerated 10 ppt salinity. Perry (1976) repored the successful spawning of black buffalo and bigmouth buffalo in ponds with salinities ranging from 1.6 to 1.8 ppt and 1.4 to 2.0 ppt respectively.

Leatherland et al. (1974) studied the regulation of plasma sodium (Na^+) and potassium (K^+) in African Tilapia fishes. Upon comparing plasma levels of Na^+ and K^+ in fishes from concentrated ''soda'' lakes to fishes from freshwaters, they found that generally Na^+ and K^+ were more concentrated in species from soda lakes. The Na^+/K^+ ratio in the serum was not related to ambient salinity. One species (Tilapia alcalica) from a saline lake tolerated a loss of plasma Na^+ in fresh water, while another saline adapted species (T. grahami) was better able to maintain plasma Na^+ levels. Fresh water species (T. zilli and T. nigra) could not tolerate salinities in excess of 2.5 percent NaCl. Mucopolysaccharide cells in Tilapia mossambica may be converted to chloride cells active in osmoregulation under conditions of hyperosmotic stress. The adsorptive surface of the intestine also increases, possibly to facilitate adsorption of water for hypoosmotic regulation in the hyperosmotic media (Narasimham and Parvatheswararao, 1974). Adaptation to osmotic stress in T. mossambica has been shown to follow a regular time course involving two phases (Bashamohideen and Parvatheswararao, 1976). There is a rapid rise in oxygen consumption in proportion to the magnitude of stress imposed by transfer of the fish into higher saline media, followed by a gradual decrease in oxygen usage which stabilizes at a new level almost equal to the original normal (freshwater) medium.

The recreational fishery of the Salton Sea, California, a terminal lake receiving irrigation return flows, presents an unusual case for salinity management in inland fisheries. Marine fish species such as sargo (Anisotermus davidsoni), orangemouth corvina (Cynoscion xanthulus), and bairdiella (Bairdiella icistia) have been introduced successfully into the saline waters which have about 36 ppt salinity. Increasing salinities seriously threaten this fishery through adverse effects on the eggs and larvae of these fish (Lasker et al., 1972; May 1976). It has been shown that bairdiella egg and larvae survival are severely inhibited in 40 ppt Salton Sea water. The unusually harmful effects of Salton Sea water may be attributed to its higher proportions of calcium and sulfate which are approximately threefold higher (percentage of total salinity) than seawater. In particular, divalent cations (e.g. Ca^{++}) may have adverse physiological effects (May, 1976).

There is considerable evidence that the pituitary gland (pars intermedia) plays a vital role in the osmoregulation of euryhaline fishes (Chidambaram et al., 1972). The bullhead (Ictalurus melas) was unable to survive longer than seven days in freshwater after removal of the pituitary gland. Prolactin treatment, isosmotic saline maintenance, or autografted pituitary glands prolonged freshwater survival. Harrison et al. (1974) immersed goldfish (*Carassius auratus* L.) in a graded series of sodium chloride solutions up to a concentration of 15 g/l and found that the rising osmolarity induced cytophysiological changes (staining reaction) in specialized cells of the pituitary gland. Singley and Chavin (1975) observed increases in cortisol and ACTH titers in goldfish subjected to saline stress.

Subramanyam (1974) studied the succinic dehydrogenase activity of the freshwater teleost, *Heteropneustes fossilis* during acclimation to elevated salinities. He found that the enzyme activity increased in the liver but not in the kidney, reflecting the metabolic response to osmotic stress. This would indicate that the effect of salinity stress varied from tissue to tissue.

SECTION VI

EFFECTS OF SUSPENDED SOLIDS ON AQUATIC BIOTA

EFFECTS ON PHYTOPLANKTON, PERIPHYTON, AND VASCULAR PLANTS

When establishing criteria concerning suspended solids it must be kept in mind that the concentration of suspended solids in natural waters is influenced by such factors as topography, geology, soil conditions, intensity, and duration of rainfall, type and amount of vegetation in the drainage basin, and man's activity in the drainage basin. Most flowing waters have considerable variation in the suspended solids concentration from day-to-day; therefore, loading of suspended solids in lakes from streams will vary from day-to-day. Since natural variation in suspended solids is so great, it is not desirable to have fixed rigid standards. For this reason, Cairns (1967) in reviewing the ecological effects of suspended solids, suggests that the effects upon aquatic organisms living in the system be used to determine the suspended solids standard.

Plants adapted to the aquatic environment include floating and benthic macroscopic plants, phytoplankton, and periphyton. The role of phytoplankton in the environment includes oxygenation of the water, conversion of inorganic material to organic material, a source of food for zooplankton and, after death, a nutrient source. Macrophytes also play an important role in nutrient cycling in addition to a major role in forming habitats for other organisms. These habitats include surfaces for attachment of bacteria, periphyton, and aquatic insects as well as providing protection and nesting sites for fish. Consequently, perturbation of the system that would adversely affect the phytoplankton, periphyton, or macrophyte community would also adversely affect other members of the food chain. Suspended solids concentration standards based on the response of this community would insure that maximum use be made of a drainage basin without impairing its ability to function beneficially in the ecosystem.

The major ecological parameters of suspended solids which would affect photosynthetic systems includes reduction in light penetration, sedimentation, and habitat alteration, abrasive action, and effects of adsorbed toxins. The importances of these effects may vary, some species being affected more than others.

Since photosynthetic organisms form the basis of the food chain, any reduction in the availability of light (regardless of nutrient concentration) which causes a decrease in photosynthetic productivity, has a widespread effect on other organisms dependent on them for food. Swale (1964) working on the River

Lee, emphasized that for most of the year, fluctuation in the concentrations of phosphorus and nitrogen could not be the factors determining the number of algae. She placed emphasis on rates of flow and detrital turbidity as major factors limiting algal production. Lund (1969), also working on the River Lee, reported that even a reduction of phosphorus and nitrogen to a tenth of their concentration could still permit very large phytoplankton populations to develop if light intensity were not limiting. Increases in suspended solids brings about reduction in light penetration and this greatly reduces the primary producers except for those species that are planktonic or living on floating debris. This reduction causes a shift from herbivores to those that are primarily detritus feeders (Patrick, 1972). Not only does reduction in light penetration restrict photosynthesis, it may also alter oxygen relationships in surface waters (Oschwald, 1972). Angino and O'Brien (1968) suggest that reduction in oxygen production due to excess turbidity may be critical in some large streams.

Light penetration is important not only with respect to productivity but also with respect to community composition. Wetzel and McGregor (1968) reported that low light intensity inhibits germination of *Najas flexilis* and *Chara* and would, therefore, eliminate these two species from the community.

Sedimentation, due to suspended solids, results in habitat destruction and abrasive action. These two effects can severely alter the photosynthetic population. Many species of plants are confined to one or a very few types of substratum because they need a special surface for attachment. Destruction of specific habitats will not only eliminate one part of the populations but may also introduce a new population to the area. Hynes (1970) reported that 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.

Adsorption of chemicals by suspended solids is particularly important if it leads to a build-up of toxic substances in a limited area with the possibility of sudden release. For some trace elements, especially copper, the limits between need and toxicity may be extremely narrow. Low concentrations of copper ($\leq 10^{-7}$ M) are essential for *Chlorella* while concentrations $\geq 10^{-7}$ M are toxic (Green et al., 1939; Greenfield, 1942).

EFFECTS ON ZOOPLANKTON AND AUFWUCHS PROTOZOANS

Published research concerning the direct effect of suspended solids on minute invertebrates is limited. It could be assumed that as turbidity limits light penetration and hence aquatic algae and plant productivity (Oschwald, 1972), the grazing microfauna would also be limited. In addition, the abrasive action of suspended sediments would be expected to have an adverse effect on attached protozoans and micrometazoans.

Response of *Daphnia magna* in suspensions of several kinds of solids was reviewed by EIFAC (1965). Harmful levels of kaolinite and montmorillonite were 102 and 82 ppm respectively. Charcoal was harmful at 82 ppm. Pond sediment was not lethal to *Daphnia* up to 1458 ppm. Toxicity of suspended solids to *Daphnia* appeared to be type specific. The reproduction rate of *Daphnia* seemed to increase at lower concentrations of suspended solids (e.g. 39 ppm kaolinite, 73 ppm pond sediment). The review also cited work in which it was found that the production of Daphnia in the Mondsee in Austria was reduced from 400,000 kg/year to 80,000 kg/year due to high clay turbidities caused by road construction. This reduction in plankton severely affected the production of whitefish (Coregonus).

Spoon (1975) found a doubling in the number of protozoan or micrometazoan species colonizing artificial substrates in the upper Potomac estuary below the Blue Plains sewage treatment plant in 1974 as contrasted to 1971. Water quality in 1974 showed an improvement over 1971 in turbidity as well as dissolved oxygen, phosphorus, nitrogen and organic carbon. It is not clear whether turbidity directly affected the colonizing protozoans and metazoans. An increase in algae was also observed in 1974 (see also Spoon, 1976). Research is needed to determine the mode and extent of the effect of suspended solids on protozoa and related organisms.

EFFECTS ON MACROINVERTEBRATES

Work by Gammon (1970) includes a review of the literature published prior to 1970 on the effect of inorganic sediment on stream macroinvertebrates (Table 3). Stream substrate may be altered by suspended silt deposition and this can have important effects on the macroinvertebrate community. Using a scale ranging from one to 452, various substrates mixed with silt rated no higher than 27. A substrate combination of moss, gravel, rubble, and Elodea rated over 400 while shifting sand supported the fewest macroinvertebrates thus rating only one. Hynes (1970) has also commented on the importance of substratum to selection and diversity of aquatic insect populations.

Field monitoring and experimental work by Gammon (1970) in a stream below a limestone quarry where the average suspended solids load was increased approximately 40 mg/l showed that there was considerable impact on the macroinvertebrate population. Suspended solids concentrations ranged from 13 to 52 mg/l above the quarry and 21 to 250 mg/l below the quarry. Species of the Tricorythoides increased somewhat below the quarry as opposed to the area above the quarry due to their preference for silt or mud substrate while net spinners (Cheumatopsyche) were reduced during periods of heavy sediment input. Drift rates of macroinvertebrates from an impacted riffle increased approximately linearly with increasing suspended solids up to 160 mg/l. There was a 25 percent increase in drift at an increase of 40 mg/l suspended solids above normal and a 90 percent increase in drift at an increase of 80 mg/l suspended solids above normal. Drift rates seemed to be more closely related to suspended solids than to settled sediment but both settled and suspended sediment reduced invertebrate populations. Drifting species were the same as those in the riffle. It appeared that the effect of suspended solids on invertebrates in the studied system was equal, i.e. there was no species selection by suspended solids.

Stream faunal recovery after strip mine reclamation has been studied by Hill (1972). He found that the pollutant limiting to populations of fish and bottom organisms in reclaimed and partially reclaimed streams was inorganic silt, and that complete reclamation of spoil areas reduces the levels of siltation and turbidity which in turn allows recovery of stream faunal communities.

TABLE 3. SUMMARY OF SUSPENDED SOLIDS EFFECTS ON AQUATIC MACROINVERTEBRATES (DATA COLLECTED FROM GAMMON, 1970; HILL, 1972; AND ROSENBERG AND WIENS, 1975).

Organism(s)	Effect	Suspended Solid Concentration	Source of Suspended Solids	Comment
Mixed Populations	Lower summer populations		Mining area	
Mixed Populations	Reduced populations to 25%	261-390 ppm (Turbidity)	Log dragging	
Mixed Populations	Densities 11% of normal	1000-6000 ppm		Normal populations at 60 ppm
Mixed Populations	No organisms in the zone of settling	>5000 ppm	Glass manufacturing	Effect noted 13 miles downstream
Chironomus & Tubificidae	Normal fauna replaced by (Species Selection)		Colliery	Reduction in light reduced submerged plants
Cheumatopsyche (Net spinners)	Number reduced	(High concentrations)	Limestone Quarry	Suspended solids as high as 250 mg/l
Tricorythoides	Number increased		Limestone Quarry	Due to preference for mud or silt
Mixed Population	90% increase in drift	80 mg/l	Limestone Quarry	
Mixed Populations	Reduction in numbers	40-200 JTU	Manganese Strip mine	Also caused changes in density and diversity
Chironomidae	Increased drift with suspended sediment		Experimental sediment addition	
Ephemoptera, Simuliidae, Hydracarina	Inconsistant drift response to added sediment		Experimental sediment addition	

Turbidities in unreclaimed streams ranged between 40 and 200 JTU with maximum levels of 32,000 JTU having been recorded. Turbidity and siltation caused an overall reduction in the number of bottom organisms which resulted in changes in density, diversity, and community structure. Six years after reclamation in one stream, faunal recovery was complete. Gravel dredging on the Brazos River, Texas, limited macroinvertebrates by causing a loss of gravel habitat which was replaced by a sand-silt bottom (Forshage and Carter, 1973). Increased turbidity may also have had an effect on macroinvertebrate populations.

Rosenberg and Wiens (1975) added bankside sediment to the Harris River in northern Canada in order to study the mode of action of suspended and settled sediments and the responses of stream fauna. Preliminary results of their study indicated that the number of Chironomidae caused to drift by sediment addition always increased with sediment addition, but that the Ephemeroptera, Simulidae, and the Hydracarina were inconsistent in their drift response to suspended sediment. Based on their data and several assumptions they estimated that it would take as long as 18 days and as short as seven hours for 50 percent of the resident macrobenthic population to leave their experimental riffle area when sediment was added as it was in their experiments (100 and 250 mg/l intended concentrations). McGaha and Steen (1974) in their study of Mississippi flood control reservoirs found that benthic fauna appeared to be more closely related to bottom type, submerged vegetation, and normal life cycles than to turbidity. Reservoir habitats appear qualitatively different with regard to effects on community responses than stream habitats, as would be expected.

EFFECTS ON SALMONID FISHES

The European Inland Fisheries Advisory Commission (EIFAC, 1965) promulgated protective standards on salmonid and other fish types and delineated five ways that finely divided solids may harm freshwater fishes. 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; and

(5) by affecting the efficiency of methods of catching fish.

A summary of their results was prepared to illustrate these effects on salmonids (Table 4).

On recommending water quality criteria for the protection of aquatic communities the Committee on Water Quality Criteria (CWQC, 1973) relied strongly on the EIFAC study. Their recommendation is as follows:

TABLE 4. SUMMARY OF EFFECTS OF SUSPENDED SOLIDS ON SALMONID FISH. (DATA TAKEN FROM REVIEW IN EIFAC, 1975).

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
Rainbow Trout (Salmo gairdneri)	Survived one day	80,000 ppm	Gravel washing	
	Killed in one day	160,000 ppm	Gravel washing	
	50% mortality in 3 1/2 wks	4,250 ppm	Gypsum	
	Killed in 20 days	1000-2500 ppm	Natural sediment	Caged in Powder River, Washington
	50% mortality in 16 wks	200 ppm	Spruce fibre	70% mortality in 30 wks
	1/5 mortality in 37 days	1,000 ppm	Cellulose fibre	
	No deaths in 4 wks	553 ppm	Gypsum	
	No deaths in 9-10 wks	200 ppm	Coal washery waste	
	20% mortality in 2-6 months	90 ppm	Kaslin and diatomaceous earth	Only slightly higher mortality than control
	No deaths in 8 months	100 ppm	Spruce fibre	
	No deaths in 8 months	50 ppm	Coal washery waste	
	No increased mortality	30 ppm	Kaslin or diatomaceous earth	
	Reduced growth	50 ppm	Wood fibre	
	Reduced growth	50 ppm	Coal washery waste	
	Fair growth	200 ppm	Coal washery waste	
	"Fin-rot" disease	270 ppm	Diatomaceous earth	
	"Fin-rot" disease	200 ppm	Wood fibre	
	"Fin-rot" disease	100 ppm	Wood fibre	Symptons after 8 months exposure
	No "fin-rot"	50 ppm	Wood fibre	
	Reduced egg survival	(Siltation)		Eggs in gravel
	Total egg mortality in 6 days	1000-2500 ppm	Mining operations	Powder River, Oregon (Not specifically rainbow trout eggs)
Pacific Salmon (Oncorhynchus)	Survived 3-4 wks	300-750 ppm (2300-6500 ppm for short periods each day)	Silt	Fingerlings

TABLE 4. Continued.

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
	Reduced survivial of eggs	(Silting)		Eggs in gravel
	Supports populations	(Heavy loads)	Glacial silt	Spawn when silt is washed from spawning beds.
	Avoid during migration	(Muddy water)		Yuba River, California
Brown Trout (*Salmo trutta*)	Do not dig redds	(Sediment in gravel)		Water must pass through gravel
	Reduced populations to 1/7 of clean streams	1000-6000 ppm	China-clay waste	
Cutthroat Trout (*Salmo clarkii*)	Abandon redds	(If silt is encountered)		
	Sought cover and stopped feeding	35 ppm		Two hours exposure
Atlantic Salmon (*Salmo salar*)	No effect on migration	Several thousand ppm		River Severn, British Isles
Brook Trout (*Salvelinus fontinalis*)	No effect on movement	(Turbidity)		

	Maximum Concentration of Suspended Solids
High level of protection	25 mg/1
Moderate protection	80 mg/1
Low level of protection	400 mg/1
Very low level of protection	over 400 mg/1

More recent work by Sykora et al. (1972) showed that suspensions of iron hydroxide of 50, 25, 12, and 6 mg/1 iron caused juvenile brook trout (Salvelinus fontinalis, Mitchell) to reach no more than 16 percent, 45 percent, 75 percent, and 100 percent of the weight of control fish, respectively. The turbidity of the water at a theoretical concentration of 50 mg/1 iron as $Fe(OH)_3$ (95.5 mg/1 $Fe(OH)_3$) averaged 86 JTU (range 130 to 60 JTU) while the average turbidity at a 'theoretical' (prepared) 6 mg/1 iron was 23 JTU (range 42 to 14 JTU). It was assumed that impaired visibility due to high turbidity prevented the fish from feeding which in turn resulted in slower growth. The review by Oschwald (1972) pointed out that angler success for most game fish species improved as turbidity decreases.

Williams and Harcup (1974) working on an industrial river in south Wales found that spawning areas for brown trout were limited by industrial and urban developments, sporadically high levels of suspended coal residues and other factors. Native trout produced in the stream showed poor growth. High levels of suspended solids in the lower reaches of the river increased the movement of fish into a downstream river. Suspended solids concentrations ranged from 0 to 22 mg/1 at an upstream station and from 7 to 1530 mg/1 at the most downstream station. Resuspended harbor sediment (subject to dredging) at concentrations of up to 5 percent wet weight (28.8 g/1 dry weight) had no observable effect on coho salmon fry (Oncorhynchus kisutch) or threespine sticklebacks (Gasterosteus aculeatus) in 96 hr bioassays (LeGore and DesVoigne, 1973). The sediments were contaminated with high levels of organic matter, oil and grease, zinc, and lead.

EFFECTS ON OTHER FISHES

The acute direct effects of turbidity on fishes was investigated by Wallen (1951). Using 14 genera and 16 species, he found that behavioral reactions to turbidity did not develop until turbidities neared 20,000 ppm. Most of the experimental fish endured more than 100,000 ppm turbidity for a week or longer, but these same fishes died at turbidities of 175,000 to 225,000 ppm. Lethal turbidities caused death in 15 minutes to 2 hours after exposure was begun. Fishes that were killed by the exposure to the suspended clay developed opercular cavities and clogged gill filaments. Some effects on selected fish used in Wallens' study are listed in Table 5. The tolerance of the test fish for such high suspended solids concentrations compared with known natural concentrations led Wallen to conclude that natural clay turbidity was not a lethal condition in the life of juvenile to adult fishes.

Buch (1956) in reporting work on the effects of turbidity on fish and fishing, stated that young bass were not found in waters with greater than 84 ppm, redear sunfish in greater than 174 ppm, and bluegills in 185 ppm turbidity.

TABLE 5. SOME EFFECTS OF TURBIDITY ON SELECTED FISH SPECIES (DATA FROM WALLEN, 1951).

Species	Turbidity at First Adverse Reaction	Turbidity at First Death
Golden Shinner (*Notemigonus crysoleucas*)	20-50,000 ppm	50-100,000 ppm
Mosquitofish (*Gambusia affins*)	40,000	80-150,000
Goldfish (*Carassius auratus*)	20,000	90-120,000
Carp (*Cyrinus carpio*)	20,000	175-250,000
Red Shinner (*Notropis lutrensis*)	100,000	175-190,000
Largemouth Black Bass (*Micropterus salmoides*)	20,000	101,000 (average)

Clear farm ponds produced from 1.7 to 5.5 times the total weight of fish in turbid ponds. Largemouth bass were most affected by turbidity. Interference with light penetration lowered plankton productivity by 8 to 12.8 times in turbid waters as opposed to clear waters. This reduction in productivity limited the amount of available food for fish. Individual channel catfish grew faster in clear ponds but greater total weights were obtained in muddy ponds due to lack of competition. The presence of carp (which increased turbidities) reduced the growth of bass and bluegills, but led to increased yields of channel catfish and bluegills. A clear reservoir attracted more anglers, yielded greater returns per unit of fishing effort, as well as desirable species, and was aesthetically more attractive.

Smith et al. (1965) found that the mortality of fish exposed to suspensions of wood fibers such as those from pulping plants, depended on the species of fish, type of wood fibre, processing method, dissolved oxygen concentration, and to a lesser degree, water temperature. Using young of the year of fathead minnows (*Pimephales promelas*) and walleyes (*Stizostedion vitreum vitreum*), they found that ground conifer wood was the most lethal and had the greatest effect on walleye fingerlings, and that ground wood pulps were more lethal than chemical pulps.

Gammon (1970) presented an excellent review of the effects of suspended solids on fishes. His review as it pertains to non-salmonid fishes is summarized in Table 6.

TABLE 6. EFFECTS OF SUSPENDED SOLIDS ON NON-SALMONID FISH (DATA COLLECTED FROM GAMMON, 1970).

Fish (Species)	Effect	Concentration of Suspended Solids	Source of Suspended Materials	Comment
Mixed fish populations	Decrease in occurence	Turbidity increase		
Mixed fish populations	Critical levels affecting populations	100-300 ppm	Industrial	England, Scotland, and Wales fisheries
Perch (*Perca flavesiens*)	High egg mortality	(Silting)		
European Pike Perch (*Lucioperca lucioperca*)	High egg mortality	(Silting)		
Zebra (*Brachyolanio rerior*)	Earlier egg hatch and no increase in egg mortality	18,000-30,000 ppm	Limestone dust	Fry died within 4 hours at 74,800
Barbel (*Barbus fluviatilis*)	Decreased migration	(Increasing turbidity)		
European eel (*Anguilla anguilla*)	Increased migration	(Increasing turbidity)		
Smallmouth bass (*Micropterus dolomieui*)	Successful nesting, spawning, hatching	(Sporadic periods of high turbidity)		

In investigating the effects of limestone quarry suspended solids, Gammon (1970) found that most fish were reduced in numbers below the quarry. Carp (Cyprinus carpio) were often seen in very turbid waters, but were seldom more than 50 percent as abundant as above the outfall. Carpsuckers (Carpiodes cyprinus) were the most sensitive to suspended solids but smallmouth bass (Micropterus dolomieni) were also sensitive. Gizzard shad (Dorosoma cepedianum) tolerated lower concentrations but avoided higher concentrations of suspended solids. Spotted bass (Micropterus punctulatus) were unaffected and did not avoid high levels of suspended solids. Golden redhorse (Moxostoma erythrurum) and spotted bass grew at significantly lower rates below the outfall than those above the outfall. Other fish species grew at about the same rate above and below the outfall. This lack of supression of growth was probably due to the tendency for these fish to avoid turbid waters.

Ritchie (1972) reviewed the effects of suspended solids (turbidity) on fish population changes and indicated that the Lake Erie fish community had changed from ciscoes (Coregonus), whitefish, and yellow perch (Perca flavescens) to sauger (Stizostedion canadense), sheepshead (Aplodinotus grunniens), catfish, and carp partly because of sediment.

Hill (1972) observed that the blacknose dace (Rhinichthys atratulus) was the most common fish collected in streams occurring in unreclaimed manganese strip mine areas; these streams were subjected to high levels of turbidity. Sculpins (Cottus sp.) that were otherwise common to the study area were always absent in unreclaimed streams.

Gravel dredging effects on the fauna of the Brazos River, Texas were studied by Forshage and Carter (1973). They concluded that habitat destruction and siltation caused a shift in fish populations from largemouth bass, green sunfish, bluegill, and redear to white crappie, warmouth, channel catfish, and flathead catfish.

Horkel and Pearson (1976) have found that green sunfish (Lepomis cyanellus) did not significantly increase their oxygen consumption rate in bentonite suspensions of as high as 26.7 ppt (2,359-3,750 formazin turbidity units (FTU)). However, ventilation rates increased 50 percent to 70 percent at the same oxygen consumption rate with turbidities above 898 FTU. Opercular movements of the green sunfish returned to the pre-treatment rates by the third day of exposure.

Although these results are sometimes difficult to interpret because of either conflicting conclusions for some fish species at different life stages or confounding due to variation in more than one independent variable, the results do indicate that 1) there are severe effects of suspended solids on species survivability largely through life cycle effects, 2) significant effects of suspended solids on habitat may prevent maintenance of or eliminate a fish species from a specific freshwater ecosystem, and 3) there is a strong relationship between land uses and suspended solids concentrations in streams that manifests its effect directly on the fish community.

SECTION VII

RESEARCH NEEDS RELATED TO STANDARDS ON SUSPENDED AND DISSOLVED SOLIDS FOR PROTECTION OF FRESHWATER BIOTA

While it has been frequently stated that the dissolved solids and suspended materials found in streams, rivers, reservoirs, and lakes affect water quality, little information is available as to just what some of these effects are on the freshwater biota. Angino and O'Brien in a 1968 paper summarizing some of the effects that the suspended load has or may have on determining water quality, recognized that the direct effect of suspended solids on organisms, chemical quality, photosynthesis, temperature and oxygen content is poorly understood. Since then, little information has been added to our knowledge of these effects.

The necessity for establishing water quality standards based on the response of the aquatic community to changes is obvious; the means for doing so are not as readily apparent. More quantitative data concerning direct and indirect effects of changes in dissolved and suspended solids on aquatic life need to be gathered before standards can aid in maintaining the maximum number of uses of the watershed. As Wolman (1971) stated in his paper on ''The Nation's Rivers,'' we are particularly weak in our ability to detect subtle initial changes from a natural to a polluted condition. More research is needed so we can understand changes in biological systems due to changes in environment. This will enable us to prescribe standards which will prevent the onset of ''the polluted condition.''

To ascertain the research needs relevant to the development of water quality standards, it is necessary to relate possible impacts of suspended and dissolved solids on freshwater biota and to prioritize the research needs on the least understood subject areas. Using the information contained in the foregoing review, a classification was developed to relate specific qualities of the suspended and dissolved solids to likely impact on freshwater ecosystems (Table 7). Primary, secondary and tertiary effects on biota of these pollutants would be expected to be observed. For example, primary includes direct life cycle effects (growth, reproduction) or toxicity (acute and chronic); secondary includes chemical effects which in turn cause biological effects, such as, the interaction of dissolved oxygen and fish; tertiary includes the effects of organisms on organisms, such as, decreased light reduces primary productivity which in turn affects the whole food chain.

Standards must reflect these different levels of effect. Because climax communities generally reflect natural conditions, we are usually concerned with changes of condition from what occurs naturally. Thus one important area of

TABLE 7. CLASSIFICATION OF SUSPENDED AND DISSOLVED SOLIDS AND THEIR PROBABLE MAJOR IMPACTS ON FRESHWATER ECOSYSTEMS.

	Biochemical, Chemical, and Physical Effects	Biological Effects*
Suspended Solids		
Clays, silts, sand	Sedimentation, erosion & abrasion, turbidity (light reduction), habitat change	Respiratory interference, habitat restriction, light limitation
Natural organic matter	Sedimentation, DO utilization	Food sources, DO effects
Wastewater organic particles	Sedimentation, DO utilization, nutrient source	DO effects, eutroph.
Toxicants sorbed to particles	All of the above	Toxicity
Dissolved Solids		
Major inorganic salts	Salinity, buffering, precipitation, element ratios	Nutrient availability, succession, salt effects
Important nutrients	DO production	Eutrophication
Natural organic matter	DO utilization	DO effects
Wastewater organic matter	DO utilization	DO effects
Toxicants	Effects on DO	Toxicity

*Some of these effects are a result of direct impacts of pollutant (primary effect) and some are a result of changes due to biochemical, chemical, or physical changes (secondary) or biological interactions (tertiary effects).

research concerns establishing the effects on natural communities of changes from natural suspended solids and dissolved solids concentrations and their patterns and time in space to a new set of conditions caused by human activities (land uses, waste disposal or water consumption and use). Thus, there is a need to develop a quantitative relationship between response parameters (biomass, diversity, growth rates) and the change in pollutant concentration. This should be the overall goal for determining research needs relevant to setting standards for suspended solids and dissolved solids. Specific research needs must be related to this goal.

In the achievement of this goal it is important to stress the need to design experiments carefully so that confounding due to multiple and uncontrolled manipulations do not invalidate the conclusions. This is particularly true for studies on suspended and dissolved solids because 1) the difficulty in isolating secondary and tertiary effects, 2) the problem of other pollutants which are either associated with or carried on suspended solids, and 3) confounding effects in field studies where increased dissolved and suspended solids are associated with increases in other pollutants.

Impacts of dissolved and suspended solids on the physical and chemical parameters are well understood. However, biological responses, particularly at the community level, are only poorly understood but are probably most relevant to setting standards. Thus most of the research needs relate to determining community responses to dissolved and suspended solids concentrations and loads. Concepts relating to community responses either need development or must be applied to the practical problem of setting standards. These concepts include diversity, successional processes, energy transfer and food web relationships and ecosystem modeling. Thus, the understanding and definition of freshwater community response parameters to dissolved and suspended solids are defined as the principal research need.

EFFECTS OF SUSPENDED AND DISSOLVED SOLIDS ON AQUATIC PHOTOSYNTHETIC SYSTEMS

Although the importance of the effects of dissolved and suspended solids on photosynthetic systems has been recognized in the literature, very little quantitative data are available. Therefore, when trying to establish dissolved (DS) and suspended solids (SS) concentration standards based on the response of the aquatic community to changes in its environment, one realizes the need for more research on their effects on photosynthetic systems.

Successional Effects--SS

The effects of reduction in light penetration due to suspended solids has been established in the literature. Very little has been reported, however, concerning levels of suspended solids and their direct effect on the plant population. We need to know what level of increase will cause shifts in populations from desirable species to less desirable species, for example, algae to macrophytes or green to blue-green algae.

Abrasive and Siltation Effects--SS

More research is also needed concerning the direct physical effects of suspended solids. Very little is known about the effects of abrasive action on attached algae and rooted plants. We also need to know what effects sedimentation has on attached and rooted plants. Good quantitative data are needed in all these areas concerning community response before standards insuring maximum use of the watershed can be established.

Successional Effects--DS

Changes in community composition due to increases in dissolved solids must also be quantified before standards dealing with dissolved solids are established.

More studies, such as the one carried out by Kerekes and Nursall (1966) dealing with seston biomass and increase in TDS, need to be done so that standards based on community response can be determined.

Primary Production Effects--DS

The effects of dissolved solids on producer organisms (algae and plants) are needed in terms of photosynthetic rate, nutrient availability and interactions, and successional effects for different concentrations.

EFFECTS OF SUSPENDED AND DISSOLVED SOLIDS ON ZOOPLANKTON AND MACROINVERTEBRATES

There is very little information available on the effects of dissolved solids per se on the microfauna of freshwater. Published information relates almost entirely to the effects of specific constituents of dissolved solids such as nutrients (and resulting primary productivity), heavy metals, and toxic organics. Suspended solids effects on protozoans and micrometazoans are also poorly understood. Therefore, it is difficult to assess the adequacy of water quality standards for protection of these organisms.

Successional Effects--Microfauna

A great deal of research is needed both in the laboratory and under field conditions to assess the tolerances of at least common species of zooplankton, attached protozoans, and micrometazoans to various concentrations and types of suspended and dissolved solids. Population composition changes should also be looked at when trying to determine the effects of changes in suspended and dissolved solids. Any shifts in the zooplankton population could adversely affect other aquatic organisms in the food chain. More knowledge in this area is needed before standards can be set based on the response of this community to changes.

Successional Effects--Macroinvertebrates

The effects of dissolved solids on macroinvertebrates also have not been documented quantitatively in the literature. Here again a great deal of research is needed to assess toxic and sublethal effects of dissolved solids on these organisms. Special attention should probably be directed toward species selection and effects on ecosystem structure. Bioassay techniques and case by case studies will probably be required to set effluent standards for protection of aquatic insect communities which may be impacted by increased dissolved solids levels.

The literature provides a fair understanding of the effects of suspended solids on macrobenthic communities. Increased turbidities cause increased insect drift and may selectively reduce insect populations, hence altering ecosystem structure. The recommended criteria of the CWQC (1973) are probably adequate to protect most aquatic communities.

Macroinvertebrates--Acute Changes in SS

Unusual increases in suspended solids concentrations probably affect established macroinvertebrate communities more than concentrations per se, especially in low suspended solids waters. Research is needed to expand the knowledge of suspended solids effects on macroinvertebrate ecosystem types as related to habitat and climate. Little, if any, information is available on physiological effects of suspended solids on aquatic insects. These effects must be studied to understand their impacts on community dynamics.

EFFECTS OF SUSPENDED AND DISSOLVED SOLIDS ON FISH

Considerable amounts of research have been published on the effects of dissolved and suspended solids on fish, consequently additional research should have a lower priority. Many fish have been shown to be able to tolerate high suspended solids or relatively high salinities for at least a short time. Eggs, larvae, and fingerling fish are generally more susceptible to stress by dissolved or suspended solids than are adult fish. Standards which are similar to the recommended criteria of the CWQC (1973) are adequate for protecting fish against suspended solids.

However, some streams probably naturally exceed the recommended low level of protection afforded by 400 mg/l suspended solids on a regular basis. In these streams, special research will be required to determine safe levels of suspended solids for the native fish population. Standards for protection of fish from dissolved solids should be designed similarly with the recommended criteria promulgated by the CWQC (1973), i.e. bioassays and field studies should be conducted to determine what levels of salinity can be tolerated without damaging ecosystem structure and function, and discharge standards should be designed to protect the water against exceeding these levels.

SECTION VIII

OTHER RESEARCH NEEDS

SUSPENDED SOLIDS TRANSPORT OF TOXIC SUBSTANCES

The fluvial translocation of suspended solids to which toxic organics or toxic metals have been adsorbed poses a significant threat to public health and ecosystems that is not well understood. The findings that humic matter and other organics by themselves or in complexes with inorganic clays can greatly increase the solubility of chlorinated organic compounds and thus increase their mobility in the environment, calls for research into the transport and distribution of humic substances and associated chlorinated organics in the environment. Only limited information is available concerning the nature of the cause-effect relationship of toxic substance release during dredging operations. Some laboratory studies have shown negligible release of toxic materials from dredged sediments, but some field observations conflict with this. Fundamental information is needed on contaminant-to-sediment attachment mechanisms so that conditions under which the contaminants might be released can be better predicted (Chen et al., 1976). Monitoring requirements for dredging operations need to be improved (Slotta and Williamson, 1974).

AESTHETIC EFFECTS OF SUSPENDED SOLIDS

A great deal of emphasis is being placed by human populations on the quality of life including aesthetic opportunity. However, methods of evaluating aesthetic preference and/or acceptance have only begun to be developed. No meaningful information is available concerning the aesthetic perception of suspended solids (turbidity) in water. Sociological research is greatly needed to develop methods of evaluating aesthetic perception of water quality (including turbidity) and then collecting sociological data so that planning efforts for upgrading or maintaining water quality can use this information.

THE EFFECTS OF SUSPENDED AND DISSOLVED SOLIDS ON PUBLIC AND INDUSTRIAL WATER SUPPLY

Bruvold (1975) has evaluated the effects of mineral taste on public acceptance of drinking water in California. This information is very valuable in setting salinity limits for public water supplies. However, more geographically widespread information on mineral taste acceptance is needed. Bruvold (1975) also points out that the presently promulgated standards for turbidity, color, and odor in drinking water may be too high and need reevaluation. Dissolved and suspended solids effects also involve corrosion and wear and tear problems in public water distribution systems, industrial equipment, and individual residence equipment. These effects are primarily of economic concern. Little information is available, however, on the exact nature and extent of this economic impact. Research is needed on a broad geographical scale into the economics of using or treating turbid or mineralized water (including treatment alternatives) for public or industrial water supply.

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16. ABSTRACT

It is widely recognized that suspended and dissolved solids in lakes, rivers, streams, and reservoirs affect water quality. In this report the research needs appropriate to setting freshwater quality criteria or standards for suspended solids (not including bedload) and dissolved solids are defined by determining the state of our knowledge from a critical review of the recent literature in this field. Although some 185 journal articles, government reports, and other references were cited herein, there is a dearth of quantitative information on the response of freshwater buita, especially at the community level, to suspended and dissolved solids.

The major research need was defined as the development and/or application of concepts of community response to suspended and dissolved solids concentrations and loads. These concepts need to be applied especially to the photosynthetic, the microfauna, and macrofauna levels. Fish studies are of lower priority since more and better research has been reported for these organisms.

In addition, the role of suspended solids in transporting toxic substances (organics, heavy metals), aesthetic evaluation of suspended solids in aquatic ecosystems, and dissolved solids in drinking water, and economic aspects of dissolved solids in municipal-industrial water were defined as research needs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
review, suspended solids, suspended sediment, turbidity, residue, dissolved solids, salinity, TDS, conductivity, freshwater, fish, invertebrates, zooplankton, algae, water supply, livestock, aesthetics, nutrients, chlorinated organics, erosion, irrigation, standards, research needs		0203 2006 0502 0603 0704 0801 0808 1407

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