TURBIDITY IN FRESHWATER HABITATS OF ALASKA

A Review of Published and Unpublished Literature Relevant to the Use of Turbidity as a Water Quality Standard

by

Denby S. Lloyd

Report No. 85-1

Alaska Department of Fish & Game

Division of Habitat

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EXECUTIVE SUMMARY

Turbidity is an optical property of water, wherein suspended sediments and other material in the water scatter and absorb light. Turbidity measurements can be used to estimate both the penetration of light into a body of water and the concentration of suspended material in water. The value of water quality standards based upon specific turbidity criteria has been questioned, and the Alaska State Water Quality Standards (18 AAC 70) are currently being reevaluated. This paper attempts to outline relationships between turbidity and a suite of parameters that are most relevant to sustained increases of turbidity in clear-water systems. Specifically, examples from recent studies performed in Alaska, and elsewhere, provide ample illustration that turbidity criteria can be used as reasonable and effective water quality standards which, if implemented, can prevent or ameliorate the following adverse effects caused by suspended sediments in water:

1. Extinction of light in lakes and streams
2. Reduction or loss of primary (plant) production in lakes and streams
3. Reduction or loss of secondary (zooplankton and aquatic insect) production in lakes and streams
4. Reduction or loss of fish production in lakes and streams
5. Reduction in recreational fishing use of streams
6. Reduction in efficiency of fishery management techniques

Furthermore, because turbidity can be directly related to the concentration of suspended sediments in water, with adequate data predictive relationships between turbidity and suspended sediment concentration can be developed. This type of relationship can allow for the use of turbidity standards to address and regulate the direct physical effects of suspended material on aquatic life, which have also been described in available literature.

Productivity in Lakes

Studies conducted by the Alaska Department of Fish and Game (Koenings 1984) on the production of sockeye salmon in lakes provide the following information on clear and naturally turbid (glacial) lakes, i.e. lakes ranging in turbidity from approximately 0 nephelometric turbidity units (NTU) to an average of approximately 52 NTU:

1. Increases in turbidity from 0-1 NTU to approximately 10 NTU cause a dramatic reduction in the depth to which one percent of available surface light penetrates into water. Such compensation depths for clear-water lakes were measured at approximately 16-17 meters, while compensation depths for lakes with turbidity of between 2-10 NTU were measured at only 2-6 meters. The compensation depth for a lake averaging 52 NTU occurred at less than 1 meter. A 5 NTU increase of turbidity can reduce the productive volume of a clear-water lake by approximately 75 percent.

2. Abundance of zooplankton in naturally turbid lakes was observed to be lower than that in clear-water lakes. Moreover, abundance of preferred food items (Cladocera) for juvenile sockeye salmon was observed to be dramatically reduced in turbid lakes.

3. Production of juvenile sockeye salmon and returns of adult sockeye salmon were observed to be lower in turbid lake systems than in clear-water lake systems.

A study conducted by R&M Consultants (1982b) also compares the extinction of light and turbidity in a glacial lake. The results describe a similar dramatic reduction in light penetration with small increases of turbidity above 0-1 NTU.

Productivity in Streams

Studies conducted by the University of Alaska-Fairbanks (LaPerriere et al. 1983, Van Nieuwenhuyse 1983, LaPerriere 1984, Simmons 1984, Wagener 1984) describe the following set of adverse effects associated with human-induced turbidity and sedimentation in clear-water streams:

1. Light penetration is reduced by turbidity, and light extinction is directly related to turbidity.

2. Primary production in streams is reduced or eliminated by turbidity. Calculations derived in this report using equations relating turbidity, light availability, and primary productivity indicate that a turbidity of 5 NTU may reduce primary production in a normally clear-water stream 0.5 meters (1.5 feet) deep by approximately 13 percent; a 25 NTU increase in turbidity over normally clear-water conditions may reduce plant production by 50 percent. These effects may be even more pronounced in deeper streams.

3. Abundance of macroinvertebrates in turbid and sedimented streams is much lower than that in clear-water streams.

4. Abundance of fish (arctic grayling) in turbid and sedimented streams is reduced or eliminated. Also, physiological stress is exhibited by grayling in highly turbid streams.

Observations by the Alaska Department of Fish and Game (Townsend 1983, Ott 1984b) indicate that recreational use of streams for sportfishing is reduced in normally clear-water streams when turbidity increases above 8 NTU, and that aerial survey techniques employed in the management of commercial fisheries are hampered at turbidities of 4-8 NTU and above.

Suspended Sediment Concentration

Turbidity can be directly related to suspended sediment concentration. Therefore turbidity standards can be used to control the direct physical effects of sediment on aquatic life. Using data retrieved from statewide sampling conducted by the U.S. Geological Survey (USGS 1984), we have calculated a general relationship between turbidity and suspended sediment concentration. This relationship indicates that 25 mg per liter is associated with turbidity on the order of 5 NTU and that 100 mg per liter is associated with turbidity on the order of 25 NTU. A regression equation derived by Peratrovich et al. (1982) illustrates a similar relationship for the Susitna River. From recent data compiled from selected streams in interior Alaska (Post 1984, Toland 1984) we have calculated a more specific relationship indicating a one-to-one correspondence between turbidity in NTU and suspended sediment concentration in mg per liter.

Turbidity Standards

Based upon the information summarized in this report, derived from studies conducted in Alaska and elsewhere, the current State Water Quality Standard for turbidity to protect the propagation of fish and wildlife (25 NTU above natural conditions in streams, 5 NTU above natural conditions in lakes) may be sufficient to provide a moderate level of protection for clear-water aquatic habitats. A 25 NTU increase in turbidity in shallow clear-water systems may potentially reduce stream primary productivity by 13 to 50 percent or more, depending on stream depth and ambient water quality, and be associated with an increase in suspended sediment concentration of approximately 25 to 100 mg per liter.

A higher level of protection will require the application of a stricter turbidity standard. The standard presently applied to drinking water is 5 NTU above natural conditions in streams and lakes. A 5 NTU increase in turbidity in clear-water systems may reduce the primary productive volume of lakes by approximately 75 percent, reduce stream productivity by 3 to 13 percent or more, depending on stream depth and ambient water quality, and be associated with an increase in suspended sediment concentration of approximately 5 to 25 mg per liter. The current Interagency Placer Mining Guidelines (State of Alaska 1984) use turbidity of 3 NTU or less as a criterion to specify high priority streams. Application of a 5 NTU above ambient standard would bring total turbidities in these streams to 8 NTU, the level at which recreational fishing may decline and at or above the level at which efficiency of aerial surveys for fishery management are affected.

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PREFACE

This paper has been prepared by the Alaska Department of Fish and Game (ADF&G) to present a comprehensive examination of the most recent information available from studies conducted in Alaska and elsewhere addressing the effects of turbidity on freshwater aquatic habitats. Although few systematic studies have been performed directly quantifying the effects of turbidity on aquatic habitats, there is a large body of information that examines individual aspects of these effects. This paper is a synthesis and interpretation of the information currently available. The reader interested only in a summary of this information and possible conclusions regarding the use of turbidity as a water quality standard may choose to refer directly to the EXECUTIVE SUMMARY and the section on STANDARDS AND CONCLUSIONS REGARDING WATER QUALITY.

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TURBIDITY IN FRESHWATER HABITATS OF ALASKA

A Review of Published and Unpublished Literature Relevant to the Use of Turbidity as a Water Quality Standard

Few water quality characteristics are as easy to observe and as difficult to define as turbidity (Koeppen 1974). Simply put, however, turbid waters are those that are muddy or cloudy as a result of having sediment added or stirred up (Guralnik 1980). More precisely, turbidity is considered a measure of water clarity, an expression of the optical property of water that causes light to be scattered and absorbed rather than transmitted in straight lines, and is caused by the presence of suspended material such as clay, silt, finely divided organic and inorganic matter, plankton and other microscopic organisms (APHA 1980). The definition illustrates two important uses of turbidity as a water quality criterion: first as a measure of water clarity and light penetration and second as a measure of the amount of suspended material, particularly sediment, in a body of water.

Purpose

There currently exists some disagreement about the value of turbidity as a water quality criterion and standard (Pickering 1976, Wilber 1983). However, to date there has not been a detailed interpretation of available information regarding the specific effects associated with turbidity in aquatic systems. The purpose of this paper is to review and interpret recent information on turbidity as it relates to freshwater aquatic habitats in Alaska, and to provide guidance for establishing reasonable water quality standards to protect aquatic habitats from potentially adverse effects of human-induced turbidity. Largely at issue is whether or not turbidity should be retained as a simple and effective indicator of light penetration and suspended sediment concentration, to be used as a statewide water quality standard in regulating the discharge of wastewater to freshwater aquatic habitats.

Scope

This paper includes information developed in Alaska and relevant information developed elsewhere that addresses turbidity and its effects on freshwater aquatic habitats. This paper specifically addresses turbidity as it affects light penetration, primary production, secondary production, fish production, and the human use of freshwater habitats. Also, relationships between turbidity and the concentration of suspended sediment in water are discussed and related to information on the direct effects of these suspended sediments. Even though it is often difficult to distinguish between sediments suspended within a body of water and those deposited on lake bottoms or stream beds, this paper does not intend to discuss deposited materials or bedload (settleable solids).

Limitations

There are many physical and chemical parameters that affect or control the productivity of aquatic habitats, such as solar radiation, water depth, temperature, flow regime, bed stability, and nutrient concentration. This paper is not intended to portray turbidity as the only parameter responsible for different levels of productivity but to illustrate how, and to what extent, increased levels of turbidity can affect aquatic habitats.

BRIEF HISTORY

Turbidity, as a measure, was originally derived to provide a quick estimation of the amount of suspended sediment within a water sample. The original Jackson Candle Turbidimeter, developed in the late nineteenth century, was used to determine that length of a path of light passed through a suspension of sediment and water at which an observer just fails to detect the flame of a beeswax/spermaceti candle (APHA 1980). The light path in centimeters was standardized against known concentrations of diatomaceous earth in water, in parts per million, to yield Jackson Candle Units (JCU) (Pickering 1976); measurements were also expressed as parts per million (ppm) of SiO_2.

It was realized, however, that sediment particle size fractionation in addition to total concentration of suspended particles and other factors, affected the scattering and absorption of light. Therefore, formazin polymer subsequently became an accepted standard because of its more uniform particle size and ease of preparation; Formazin Turbidity Units (FTU) were derived. Other materials have also been used to standardize measurements, such as titanium dioxide and polystyrene latex microspheres, and many units have been derived, including Jackson Turbidity Units (JTU), Hellige units, severity, and Nephelometric Turbidity Units (NTU) (Freeman 1974, Pickering 1976, Stern and Stickle 1978, LaPerriere 1983, Wilber 1983).

This last unit, NTU, has recently replaced all of the others (EPA 1979, APHA 1980), and is based upon the use of a nephelometer, an instrument that measures the amount of light scattered by a water sample at 90° to the path of the incident light. This measurement is calibrated against the scattering of light in a standard suspension of formazin polymer and is reported in Nephelometric Turbidity Units (NTU).

TURBIDITY, LIGHT PENETRATION, AND PRODUCTIVITY

As an optical measurement, turbidity most directly represents the extent to which light can penetrate into a body of water. However, turbidity has not often been used to measure light penetration. Perhaps the most rigorous and comprehensive study investigating the relationship of turbidity and light penetration was performed as long ago as the 1930's (Ellis 1936). However, most recent studies have stressed the use of turbidity measurements only to estimate suspended sediment concentrations.

Using presently archaic terms, Ellis (1936) summarized that the depth at which turbidity screened out 99.9999 percent of the light entering at the water surface, or the "millionth intensity depth" (m.i.d.), decreased from 15 to 34 meters in clear inland streams to 0.3 to 1.0 meters or less in streams such as the Mississippi, which carry a high erosional silt load. Ellis (1936) also looked at particle settling and light penetration over time. His study showed that even after 96 hours of undisturbed settling, which would not occur under natural river conditions, the m.i.d. of Mississippi River water increased only from 0.157 to 1.5 meters, as compared to a calculated m.i.d. of 15 meters for the same water with its silt load artificially removed by filtering.

Light is needed in aquatic systems to provide energy for photosynthesis by plants. Photosynthesis is the beginning of energy transfer within food webs in lakes and streams; other energy may be provided by terrestrial material. Photosynthesis is often a crucial determinant of the ultimate production of fish or other higher life forms in aquatic environments. Although contributions of detritus from terrestrial sources, such as leaf litter and other organic debris, may supply a large amount of energy to lake and stream ecosystems, the importance of this terrestrial energy source is often overstated (Minshall 1978), particularly in waters with little or no terrestrial vegetation along the banks (Vannote et al. 1980). Recent studies have confirmed the importance of aquatic primary production over terrestrial input in many aquatic systems. High turnover rates of aquatic plant production (McIntire 1973, McIntire and Colby 1978, Lamberti and Resh 1983) and high food quality of aquatic plants (McCullough et al. 1979, Benke and Wallace 1980, Hornick et al. 1981) are cited as reasons to believe that many aquatic food chains are largely supported by aquatic plants. A recent study conducted by the University of Alaska-Fairbanks (Anderson 1984) concludes that aquatic plant production is likely very important to maintenance of stream ecosystems and that changes to this production may have many effects on other biological components in stream systems.

Chapman and Knudsen (1980) and Murphy et al. (1981) state that increased light availability to streams in the Pacific northwest translates through aquatic food webs to higher abundance of salmonid fishes.

Another recent study conducted by the University of Alaska - Fairbanks has shown that contributions of detritus from terrestrial sources into subarctic Alaska streams is relatively low compared to that in temperate streams (Cowan and Oswood 1983), and that seasonal pulses of energy associated with seasonal variations in aquatic primary production may be critical to the maintenance of invertebrate and fish populations (Oswood, pers. comm.). The value of seasonal pulses of aquatic primary production to stream food webs is corroborated by studies conducted in Appalachian mountain streams (Hornick et al. 1981) and in Oregon coastal streams (Chapman and Demory 1963).

In lakes and reservoirs the majority of aquatic plant production is generally derived from phytoplankton, which are microscopic or other small plants suspended in the water column. In contrast, in rivers and streams much of the primary production is available as periphyton or macrophytes, which are algae and larger plants attached to rocks and other components of the substrate. However, regardless of the type of water body or the predominant mode of plant production, the depth to which light penetrates into the water, or the amount of light which penetrates to any specific depth, will have a direct influence on the amount of biological production occurring within that body of water.

The rate at which light is naturally scattered or absorbed in a body of water is theoretically constant with depth. Therefore, the intensity of light penetrating to depth decreases exponentially. This relationship (Reid and Wood 1976) is described by the equation:

$$I_d = I_0 e^{-kd} \qquad (1)$$

where

I_d = light intensity at a particular depth, d
I_0 = light intensity at the water surface
e = base of the natural logarithm
k = extinction coefficient, which is dependent on the clarity of the water
d = depth of interest

Figure 1 presents theoretical curves of light intensity at depth for two degrees of water clarity (Reid and Wood 1976). It is apparent from these curves that light is extinguished fairly rapidly with depth and much more rapidly in turbid water.

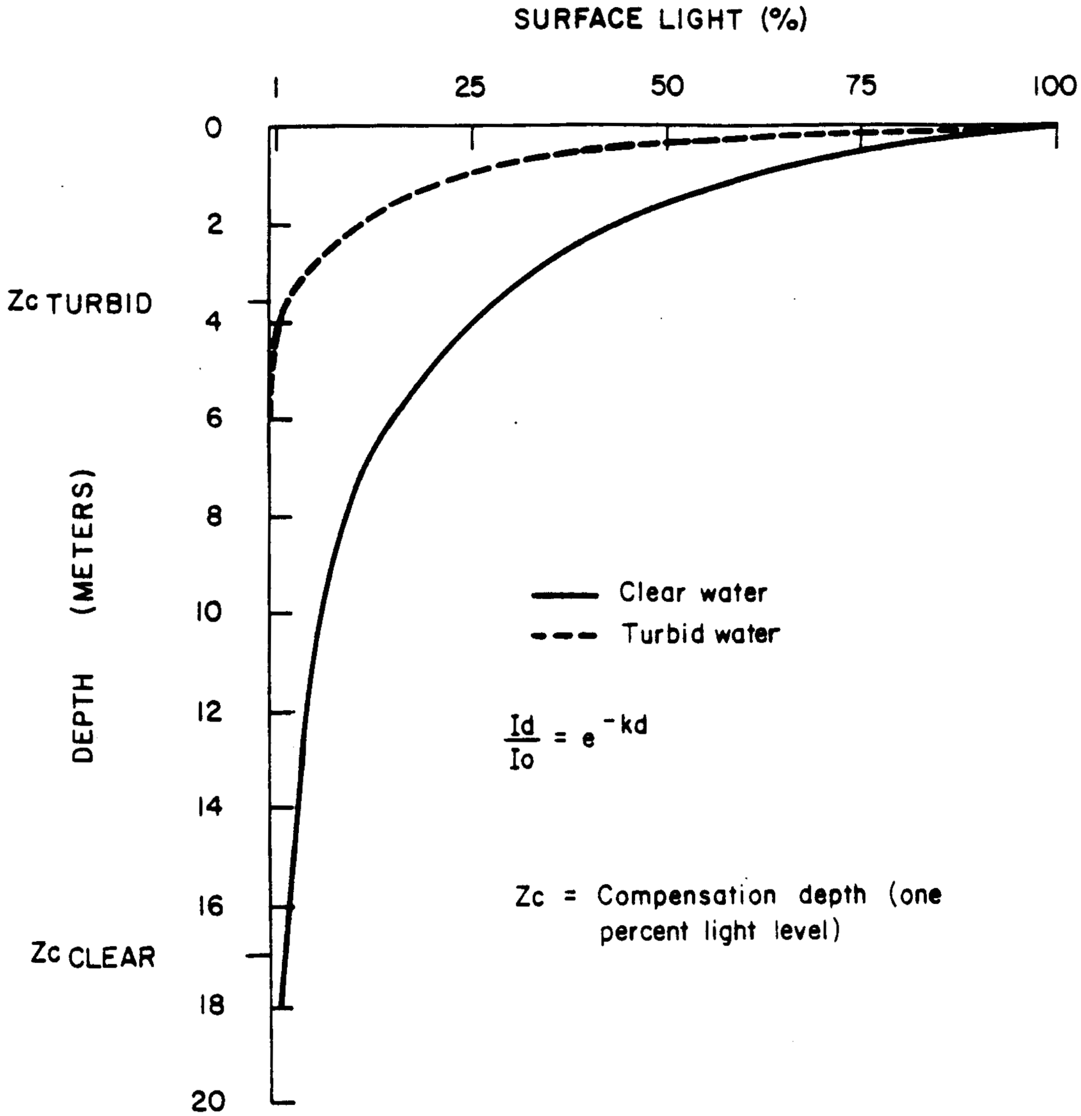

Figure 1. Theoretical curves of light intensity versus depth in a body of water, showing compensation depth (adapted from Reid and Wood, 1976).

The depth to which only one percent of the light available at the surface of a lake penetrates is generally considered the compensation depth. This compensation depth is the depth at which light intensity is just sufficient to promote photosynthesis equal to the respiratory requirements of most phytoplankton. Above the compensation depth light intensity promotes net primary production; below the compensation depth there is little or no net production of plant material. The compensation depth, then, as influenced by surface light intensity and water clarity or turbidity, determines the volume of water available in an aquatic system for the production of plant material, upon which the rest of the food web depends. Disregarding the contributory effects of inorganic nutrient concentrations, the shallower that the compensation depth occurs in a lake the less productive the system will be.

The concept of a compensation depth, per se, is more meaningful when applied to lakes, where water depth commonly exceeds the compensation depth. In streams, water depth is usually considerably shallower than the compensation depth. However, the decrease in light intensity with water depth and turbidity can still be used to indicate expected plant production in the water or on the bottom of streams, since plant production is related to the intensity of light as well as depth of penetration.

Naturally Turbid, Glacial Lake Systems in Alaska

Freshwater systems in Alaska exhibit a range of turbidities, from extremely low (less than 1 NTU) in clear-water drainages, through intermediate levels (near 50 NTU) in glacially-influenced lakes, to naturally high levels (50-4000 NTU) in several major rivers. Although no systematic study of the relationship between turbidity and productivity in freshwater lakes in Alaska has been completed to date, the Fisheries Rehabilitation Enhancement and Development (FRED) Division of the ADF&G has compiled information on several salmon-producing lake systems in the state (Koenings 1984). Figures 2 - 7 illustrate their findings, showing that increased levels of turbidity are responsible for dramatic decreases in light penetration and correspond with decreases in primary production, decreases in the production of fish food organisms, and ultimately decreases in production of juvenile sockeye salmon in and return of adult sockeye salmon to lake systems.

Figure 2 depicts the depth within several lake systems in the Cook Inlet region to which one percent of the surface light intensity penetrates. The compensation depth, which is the depth to which one percent of available surface light penetrations, shows a strong inverse

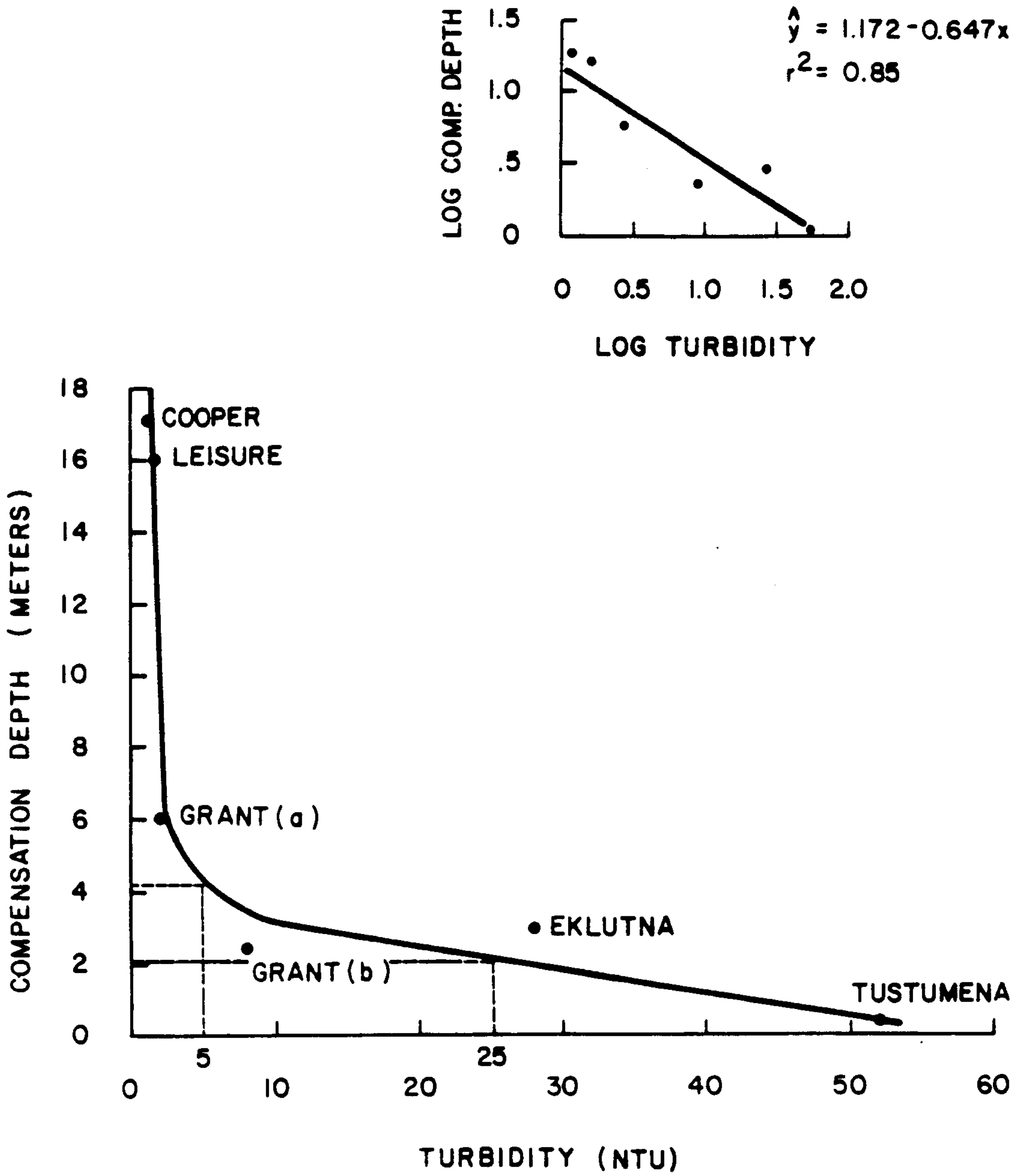

Figure 2. Empirical relationship of compensation depth (1% light level) versus turbidity for lakes in southcentral Alaska (from Koenings, 1984).

relationship (r^2 = 0.85, for log/log transform) with recorded turbidity levels in NTU. Therefore, turbidity is a good indicator of light penetration and intensity at depth. Tustumena Lake, which is a turbid, glacially-influenced water body, has a compensation depth of less than 1 meter (approximately 3.3 feet) at mean natural turbidities of 52 NTU. By contrast, the clear-water Cooper and Leisure lakes have compensation depths greater than 16 meters (approximately 52.5 feet) at natural turbidities of less than 2 NTU. The relationship between compensation depth and turbidity is reflected in a sharp decrease in compensation depth, and potential lake productivity, between turbidities of 2 and 10 NTU (Figure 2). Apparently, only very small increases in turbidity are required to dramatically reduce the penetration of light energy into aquatic systems and thereby reduce their potential productivity. According to Figure 2, a 5 NTU increase in turbidity may reduce the productive volume of a clear-water lake by approximately 75 percent.

These observations of reduced light penetration with increasing turbidity are corroborated by other studies in Alaska (R&M Consultants 1982b), where a strong relationship (r^2 = 0.96) was found between light extinction coefficients and turbidity in Eklutna Lake:

$$N_t = 0.064(T) - 0.093 \qquad (2)$$

where

N_t = extinction coefficient (meters^{-1})
T = turbidity (NTU)

By using Equation 2 to calculate light extinction coefficients corresponding to specific turbidity levels and then plugging these extinction coefficients into Equation 1, we can calculate the depth to which one percent of available surface light penetrates. Table 1 presents the values of compensation depth derived in this way for turbidities in Eklutna Lake. The resulting relationship of compensation depths and turbidity (Table 1) is very similar to the empirical data plotted in Figure 2: there is a dramatic decrease in compensation depth at turbidities just above 5 NTU and a more gradual decline after turbidities of 25 NTU. Values in Table 1 also agree with studies by Barsdate and Alexander (1971) on Tangle Lakes in the Alaska Range. Similar findings in Lake Superior (Swenson 1978) indicate that the depth of one percent light level was reduced from approximately 16.5 meters in clear water to an average of 2.5 meters at turbidities of 10 to 12 FTU. Studies in North Carolina showed that each unit (NTU) increase in turbidity caused a 0.06 unit (meter^{-1}) increase in light extinction coefficient (Reed et al. 1983), very similar to results presented in Table 1.

Table 1. EFFECT OF TURBIDITY ON LIGHT EXTINCTION AND COMPENSATION DEPTH IN AN ALASKA LAKE (derived in this report from data provided by R&M Consultants, 1982b)

TURBIDITY (NTU)	EXTINCTION* COEFFICIENT ($meter^{-1}$)	COMPENSATION** DEPTH (meters)
5.5	0.26+	17.71
15	0.87	5.29
25	1.51	3.05
35	2.15	2.14
50	3.11	1.48

* Calculated from Equation 2:

$$N_t = 0.064\,(T) - 0.093$$

where

N_t = total extinction coeff. ($meter^{-1}$)
T = turbidity (NTU)

** Derived from Equation 1:

$$I_d = I_o e^{-kd}$$

using:

$\frac{Id}{Io} = 0.01$ = Compensation point of 1% light level
$k = N_t$ = total extinction coeff. ($meter^{-1}$)
d = depth (meters)

\+ Equation 2 does not apply to turbidity less than 15 - 20 NTU, but R&M Consultants (1982b) also present an extinction coefficient of 0.26 m^{-1} for turbidity of 5.5 NTU based upon light transmissivity information at low turbidities in Eklutna Lake.

Figure 3 plots various clear-water lake and glacial lake systems in Alaska onto a generalized graph of north temperate clear-water lake systems developed by Vollenweider (1976), where primary production, or more precisely standing crop, expressed as chlorophyll a concentration is compared to phosphorus loading. Phosphorus is typically the limiting nutrient in north temperate freshwater lakes (Dillon and Rigler 1974, Oglesby 1977a, Shindler 1977), so if light penetration levels are similar, as they are in clear-water systems, it has been demonstrated that phosphorus concentrations usually control plant production. Clear-water systems in Alaska conform to this relationship; all of those investigated fall within the 99% confidence limits found on Figure 3. The glacially-turbid systems, however, do not conform. Rather, for a given level of phosphorus loading each of the glacial systems shows significantly reduced levels of primary production as expressed by chlorophyll a concentrations. It is likely that reduced light availability caused by high turbidities limits the production of phytoplankton even when sufficient nutrients are available (Koenings 1984).

Similar effects on primary production caused by turbidity in lakes have been described by studies of Lake Erie (Meyer and Heritage 1941, Chandler 1942) of ponds in Oklahoma (Claffey 1955) and of a pond in North Carolina (Reed et al. 1983). A recent study performed in a large reservoir in Oklahoma (Hunter and Wilhm 1984) suggests that even low levels of turbidity, between 4 and 15 NTU, can disrupt expected relationships between compensation depth, phosphorus and chlorophyll a exhibited in clear-water systems. As stated by Oglesby (1977a), published literature amply indicates that turbidity limits primary production below otherwise expected levels (Gulati 1972, Marzolf and Osborne 1972, Cheng and Tyler 1976). Brylinsky and Mann (1973) credit variables related to solar energy input, and turbidity, rather than nutrient concentration with the major control over primary production in lakes and reservoirs worldwide. Disregarding the influence of different nutrient concentrations, Goldman (1960) observed significant decreases in compensation depth and primary productivity with increased turbidity in large salmon producing lakes in southwest Alaska.

Although in some instances the photosynthetic efficiency of plants may compensate for low light conditions, compensatory mechanisms are limited and will not maintain plant production under conditions of high turbidity. Recent work in northern Canada (Hecky 1984, Hecky and Guildford 1984) indicates that aquatic plants will not overcome extinction coefficients of approximately 2 $meters^{-1}$. As shown earlier in Table 1, an extinction coefficient of 2 $meters^{-1}$ corresponds to turbidity on the order of 30 NTU; therefore, we cannot expect

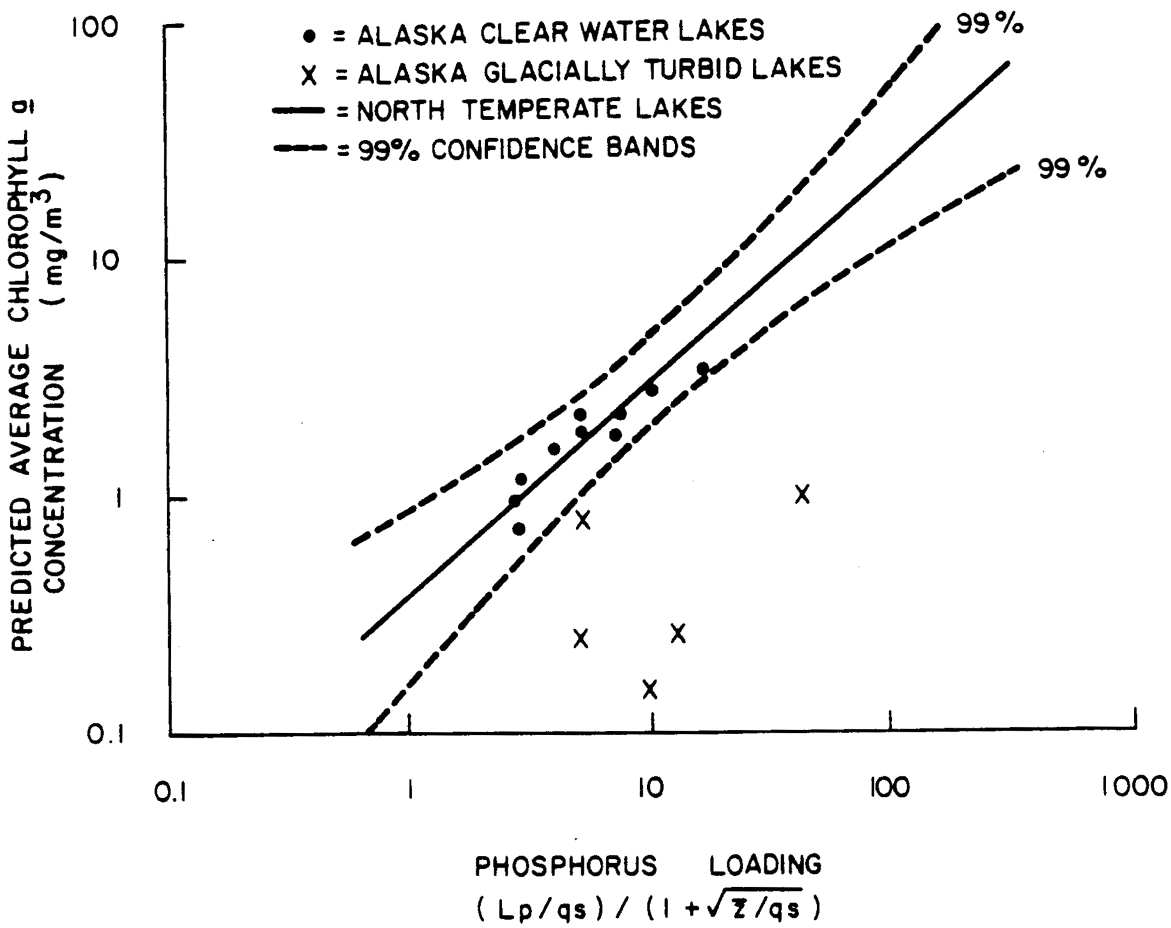

Figure 3. Conformance of lakes in Alaska to a general relation of phytoplankton production versus phosphorus availability in north temperate lakes (curves adapted from Vollenweider, 1976; data for Alaskan lakes plotted by Koenings, 1984).

compensatory mechanisms to overcome turbidities above approximately 30 NTU.

Figure 4 illustrates a translation of energy to higher trophic levels in Alaska lakes of different turbidities. Zooplankton densities within the glacially-turbid lakes are as little as one-twentieth of those densities within clear-water lakes. Furthermore, Figure 4 shows that decreasing zooplankton density with increasing turbidity corresponds with decreasing compensation depth. Reduced zooplankton abundance in turbid waters has been corroborated by other studies, particularly in Oklahoma (Matthews 1984).

Recent studies by the ADF&G (Koenings 1984) indicate that densities of zooplankton fall with increased turbidity in lakes. In addition, these studies indicate that particular species of zooplankton which are preferred by juvenile sockeye salmon as a food source are partially or completely eliminated. In the eight glacially-turbid lakes inspected none had populations of Cladocera, a group of highly favored food organisms for juvenile fish (Foerster 1968, Hoag 1972, Carlson 1974, Craddock et al. 1976, Jaenicke and Kirchhofer 1976, Manzer 1976), while all five clear-water lakes investigated supported these zooplankters. McCabe and O'Brien (1983) observed that a turbidity level of 10 NTU resulted in significant declines in the feeding rate and food assimilation capability of a common Cladoceran in Kansas. Furthermore, their calculations indicate that even low levels of turbidity, caused by low suspended sediment concentrations, reduced the reproductive potential of that Cladoceran species from that exhibited in clear water. Mills and Schiavone (1982) noted reduced abundance of Cladocerans in lakes of lower primary productivity in upstate New York. Recent work in northern Canada documents reduced abundances of Cladocerans after impoundment of a large reservoir, due to decreased water transparencies as well as reduced chlorophyll concentrations and lower temperatures (Patalas and Salki 1984).

Given that turbid lakes in Alaska have a reduced volume in which photosynthesis can occur, as determined by the compensation depth, and that they exhibit lower levels of primary production and zooplankton density because of their turbid characteristics, it is reasonable to conclude that fish production in turbid lakes is correspondingly reduced as a consequence of turbid conditions. Results of analyses which are depicted in Figures 5, 6, and 7 support this conclusion.

Figure 5 plots mean annual return of adult sockeye salmon in certain Alaska lakes against the euphotic volume of those lakes. The euphotic volume is simply the surface area of the lake multiplied by the

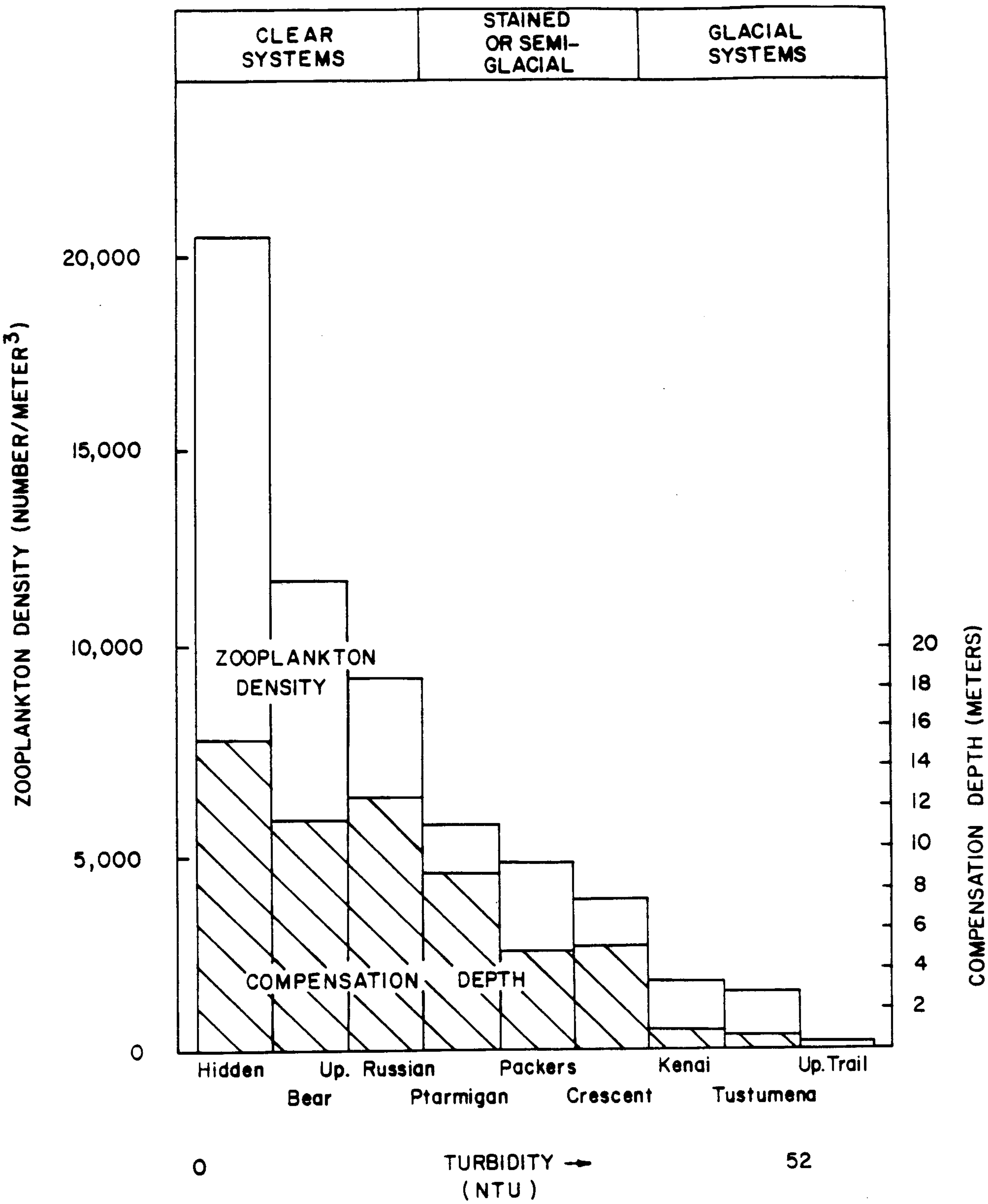

Figure 4. Zooplankton density and compensation depth for clear-water and glacially-turbid lakes in southcentral Alaska (from Koenings, 1984). Turbidity measurements for each lake are not available; clear lakes are assumed to have turbidities near 0 NTU, Tustumena Lake has been measured at 52 NTU.

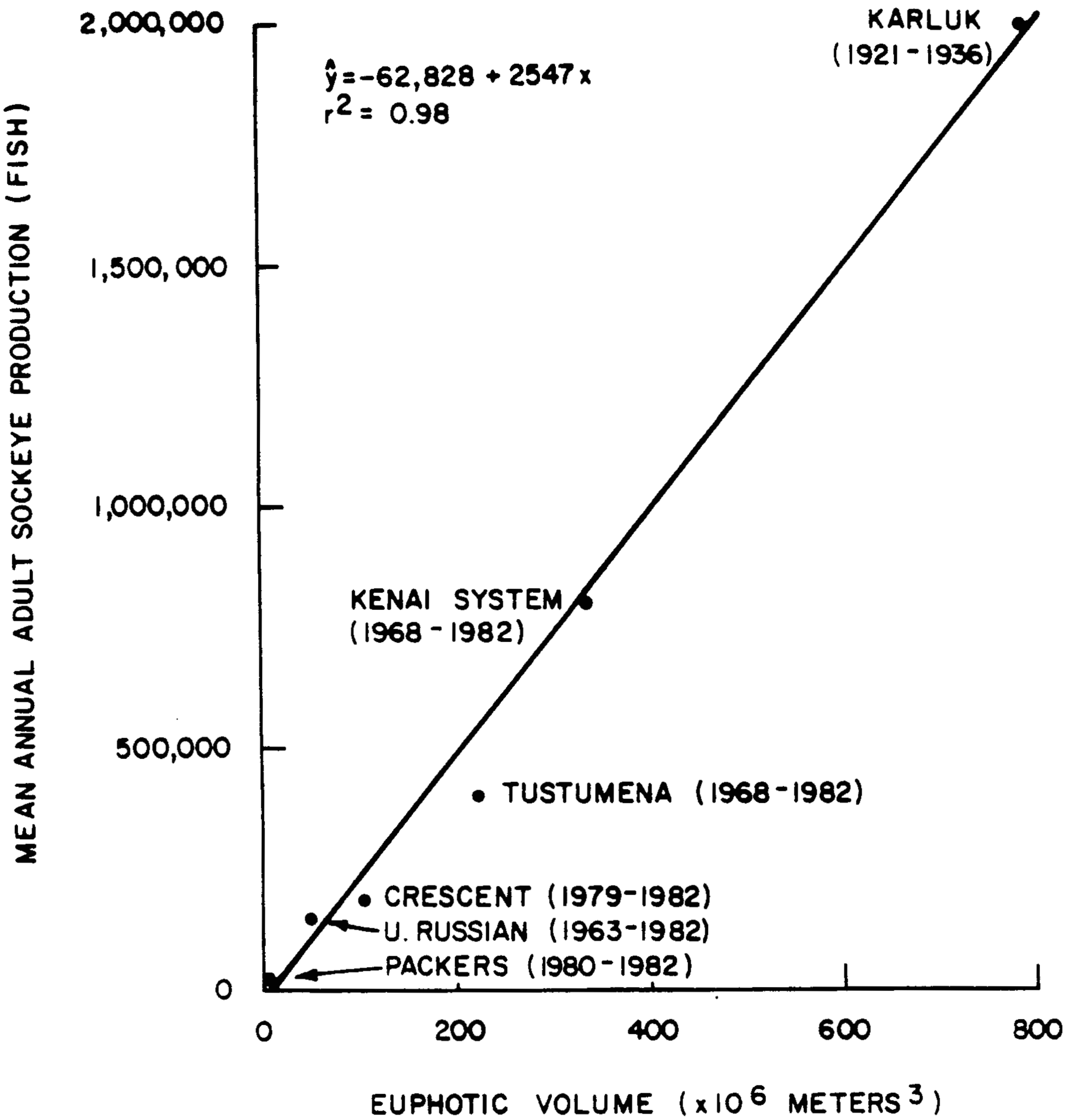

Figure 5. Relationship of annual production of adult sockeye salmon to euphotic volume (surface area multiplied by compensation depth) for lakes in southcentral Alaska (from Koenings, 1984).

compensation depth; it is the volume of biologically productive water in any particular lake. Turbidity reduces the euphotic volume of any lake by decreasing the compensation depth. So, for any two lakes with the same surface area the more turbid lake will have less euphotic volume. A regression of salmon production against euphotic volume in different sized lakes results in an extremely good relationship (r^2 = 0.98). Mean annual adult sockeye production decreases with decreasing euphotic volume. The effect of turbidity and light penetration can be seen by noting turbid Tustumena Lake, which is almost six times as large as clear Karluk Lake in surface area, averages a return of only one-fifth as many adult sockeye salmon (see Table 3).

The relationship between fish production and turbidity in lakes is more easily understood by examining Figures 6 and 7 (see also Tables 2 and 3). Although turbidity measurements are not available for all of the lakes discussed, Tustumena Lake has been observed to have a mean turbidity of 52 NTU; the clear lakes have turbidities close to 0 NTU and semi-glacial lakes have turbidities in between (see Figure 2). Trends for production of juvenile (smolt) sockeye salmon and returns of adult sockeye salmon per unit area of lake surface decline appreciably with increased turbidity. In other words, turbid lakes (ranging to approximately 50 NTU) are observed to produce far fewer fish than clear-water lakes per unit surface area.

These results of reduced fish production in turbid water are confirmed by other investigations, particularly Buck (1956), who detected reduced individual growth rates, reduced reproduction rates, and lower population sizes of fish in turbid versus clear-water ponds in Oklahoma. A positive relationship between primary production and warm-water fish production has been observed by Mills and Schiavone (1982), and they propose that assessment of zooplankton populations and measures of primary production can be used to develop fish management strategies. Moreover, they conclude that lake productivity is directly related to algae, or phytoplankton, abundance and inversely proportional to water clarity. Several other studies on lakes throughout the world confirm positive and predictive relationships between primary production and abundance or yield of fish (Melack 1976, McConnell et al. 1977, Oglesby 1977b).

Nelson (1958) reported a close relationship between increased rates of photosynthesis in Bare Lake, Kodiak Island and increased growth of juvenile sockeye salmon. Burgner et al. (1969) suggest that lakes in southwestern Alaska with high primary productivity rates may produce more salmon per unit area than lakes with lower plant production.

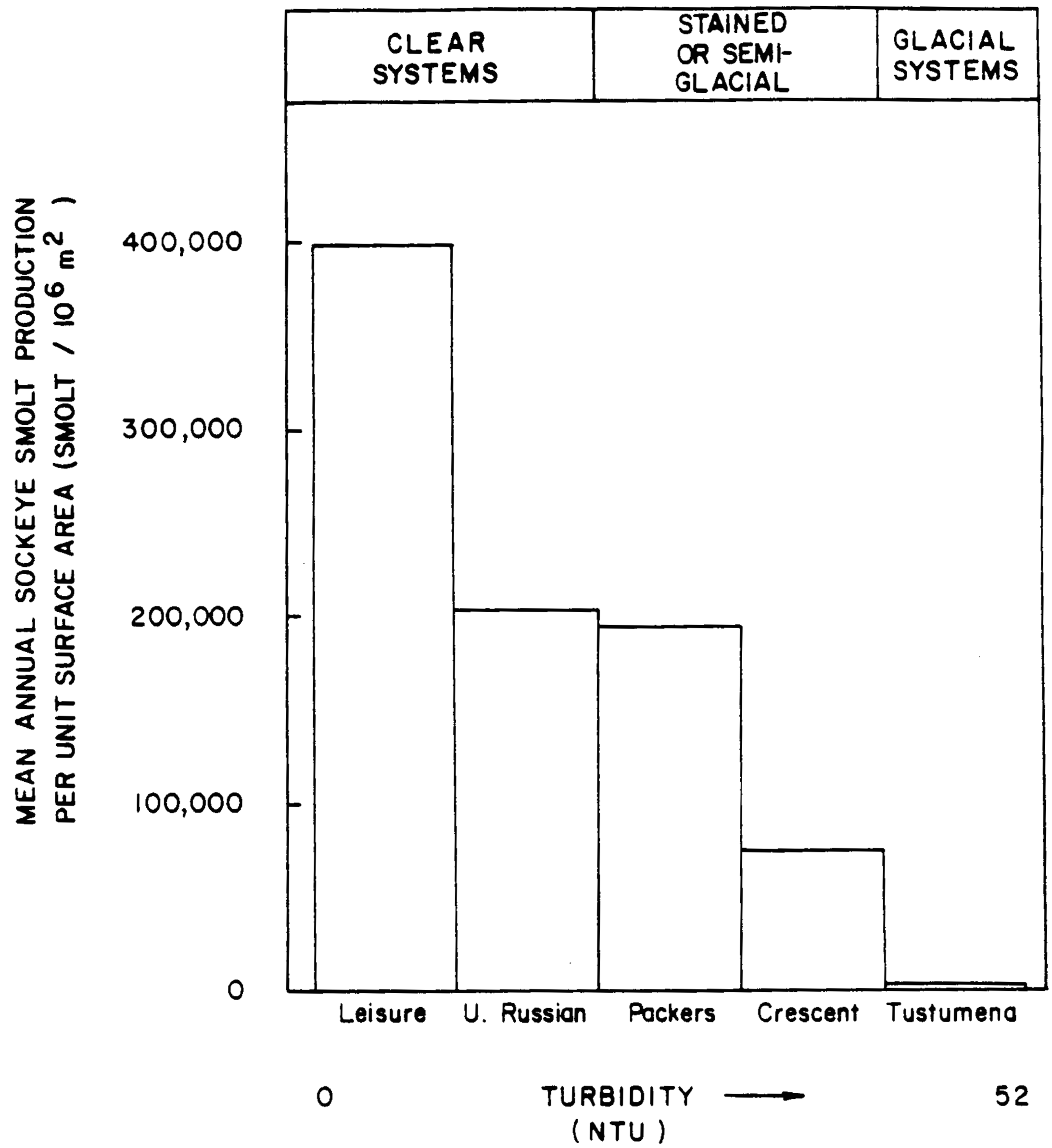

Figure 6. Annual production of juvenile sockeye salmon per unit of surface area for clear-water and turbid lakes in southcentral Alaska (from Koenings, 1984).

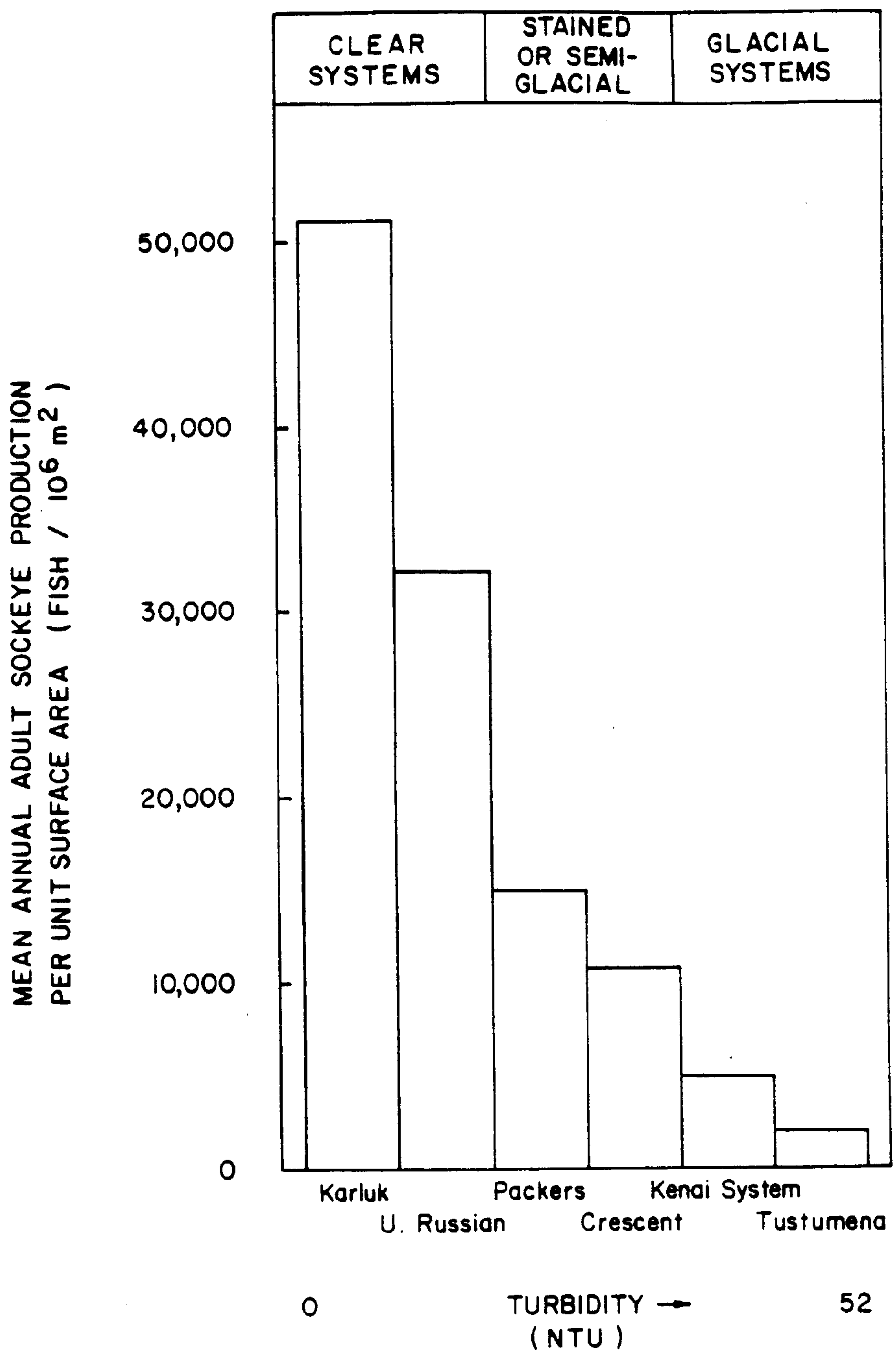

Figure 7. Annual production of adult sockeye salmon per unit of surface area for clear-water and turbid lakes in southcentral Alaska (from Koenings, 1984).

TABLE 2. SIZE AND JUVENILE SOCKEYE PRODUCTION OF SELECTED LAKE SYSTEMS IN SOUTHCENTRAL ALASKA (from Koenings, 1984)

LAKE	DATES OF PRODUCTION ESTIMATES	RELATIVE TURBIDITY	SURFACE AREA ($x10^6 m^2$)	EUPHOTIC VOLUME ($x10^6 m^3$)	TOTAL ANNUAL SOCKEYE SMOLT PRODUCTION (number of smolt)	ANNUAL SOCKEYE SMOLT PER UNIT AREA ($smolt/10^6 m^2$)	ANNUAL SOCKEYE SMOLT PER UNIT EUPHOTIC VOLUME ($smolt/10^6 m^3$)
Tustumena	1980 - 1982	Glacial	225.0	225.0	2,710,000	12,044	12,000
Crescent	1981 - 1982	Semi-glacial	16.2	105.0	1,236,000	76,296	11,800
Packers	1981 - 1982	Stained	2.1	8.4	400,000	190,000	47,000
Upper Russian	1978 - 1979	Clear	4.6	51.0	940,700	204,500	18,445
Leisure	1983	Clear	1.1	16.3	417,000	397,143	23,167

TABLE 3. SIZE AND ADULT SOCKEYE PRODUCTION OF SELECTED LAKE SYSTEMS IN SOUTHCENTRAL ALASKA (from Koenings, 1984)

LAKE	DATES OF PRODUCTION ESTIMATES	RELATIVE TURBIDITY	SURFACE AREA ($x10^6 m^2$)	EUPHOTIC VOLUME ($x10^6 m^3$)	TOTAL ANNUAL ADULT RETURN SOCKEYE (number of fish)	ANNUAL ADULT SOCKEYE PER UNIT AREA ($no./10^6 m^2$)	ANNUAL ADULT SOCKEYE PER UNIT EUPHOTIC VOLUME ($no./10^6 m^3$)
Tustumena	1968 - 1982	Glacial	225.0	225.0	400,000	1,800	1,800
Kenai System+	1968 - 1982	Glacial	162.0	377.0	800,000	4,900	2,100
Crescent	1979 - 1982	Semi-glacial	16.2	105.0	180,000	11,100	1,700
Packers	1980 - 1982	Stained	2.1	8.4	32,000	15,000	3,800
Upper Russian	1963 - 1981	Clear	4.6	51.0	150,000	32,600	2,900
Karluk	1921 - 1936	Clear	39.0	780.0	2,000,000	51,000	2,500

+ Kenai System includes Kenai, Skilak and Upper Trail lakes.

Artificially Turbid Stream Systems in Alaska

The foregoing analysis of naturally-turbid and clear-water lake systems described differences in the productivity of turbid and clear-water aquatic habitats in Alaska. There are apparently no published results of studies on the primary productivity of naturally turbid and clear-water streams in Alaska, beyond observations made by Milner (1983). in streams near Glacier Bay and Anderson (1984) in streams near Fairbanks. Milner (1983) observed mats of filamentous algae in glacially-turbid streams with turbidity up to 160 NTU, but few benthic invertebrates and no fish. Unfortunately, Milner provided little data on physical parameters, such as depth, with which to evaluate the effects of turbidity alone on aquatic plant production. Anderson (1984) measured productivity of periphyton in interior Alaska clear-water streams, but made no comparisons to production in turbid streams.

As a water quality criterion turbidity is used as a measure of the environmental impact resulting from various land use activities, such as placer mining, timber harvest and road or pipeline construction, and is most often of concern with respect to impacts to streams. The most complete suite of information on the effects of human-induced turbidity, siltation, and sedimentation in waters of Alaska is presented in preliminary reports and theses from the University of Alaska-Fairbanks for studies conducted in streams of interior Alaska in 1982-1983. These studies show for streams similar negative relationships between turbidity and light penetration as shown earlier for lakes. That is, increasing turbidity results in decreasing light penetration and light intensity at depth which causes reductions in primary production, and is associated with reduced production of fish food organisms and ultimately the reduced abundance of fish (LaPerriere et al. 1983, Van Nieuwenhuyse 1983, LaPerriere 1984, Simmons 1984, Wagener 1984) (see Table 4).

In stream systems, as opposed to lake systems, most primary production is derived from benthic algae or larger plants attached to the stream bottom, although energy may also be contributed from terrestrial sources of detritus. Primary production by benthic algae or macrophytes can occur only if light penetrates all the way to the bottom of the stream. A reduction in the amount, or intensity, of light reaching the bottom of a stream, other factors remaining the same, will cause corresponding reductions in primary production.

The discharge of placer-mining wastewater often increases the turbidity of receiving waters by hundreds or thousands of NTU (R&M 1982a, Sexton

TABLE 4. SUMMARY OF IMPACTS RESULTING FROM INCREASED TURBIDITY AND SEDIMENTATION DUE TO PLACER MINING IN INTERIOR ALASKA STREAMS (adapted from LaPerriere et al., 1983)

CHARACTERISTIC	INTERIOR ALASKA STREAMS	
	NATURAL	MINED
Turbidity	Low (0.4 - 1.1 NTU)	High (721 - 2250+ NTU)
Suspended Sediment Concentration[+]	Low (<100 - 152 mg/liter)	High (462 - 1388 mg/liter)
Settleable Solids	Low (not detectable)	High (trace - 3.5 ml/liter)
Light Penetration	High	Low
Primary, Plant, Productivity	Higher (0.38 - 1.09 g-O_2/m^2/day)	Low (0.1 - 0.39 g-O_2/m^2/day)
Density of Macroinvertebrates	Higher (460 - 693 /m^2)	Low (8 - 206 /m^2)
Abundance of Grayling	High	None - Low

\+ Suspended sediment concentrations reported in LaPerriere et al. (1983) were actually total residues. The difference is that total residue includes both dissolved solids (filtrable residue) and suspended solids (nonfiltrable residue); dissolved solids can comprise a substantial proportion of the total residues reported under these natural conditions.

feed. This may be a result of observed reductions in the abundance of macroinvertebrates in mined streams on which grayling feed or a reduction in the capability of these fish to feed. Simmons (1984) observed an absence of internal fat reserves and parr-mark development in grayling caged in turbid waters and attributed these effects to dietary deficiencies.

Another recent Alaska study, performed on arctic grayling at Toolik Lake in the Brooks Range, has shown that the reactive distance, which is the distance between a fish and its prey within which a positive feeding response occurs, of grayling decreases with decreasing levels of available light (Schmidt and O'Brien 1982). This implies that reductions in light penetration caused by turbidity in waters containing grayling may hamper their ability to capture food. Studies in the Yukon Territory indicate that grayling appear to avoid turbid waters except when driven by migrational impulses (Knapp 1975) and that numbers of grayling below sources of suspended sediment have been observed to be consistently lower than clear-water areas upstream of these turbid discharges (Birtwell et al. 1984).

Preliminary studies conducted by ADF&G show that juvenile coho salmon prefer clear-water habitats over turbid waters in the Susitna River drainage (ADF&G 1983a) and in the Stikine River drainage (Shaul et al. 1984), and that juvenile chinook salmon exhibit faster growth in clear-water tributaries than in the mainstem of the glacially-turbid Taku River (Kissner 1983). Other Alaska studies have illustrated that arctic grayling prefer clear-water tributaries and migrate to deeper mainstem rivers primarily to overwinter when sediment and turbidity levels are significantly reduced (Tack 1980, ADF&G 1983b), and that grayling avoid streams carrying silt produced by mining (Wojcik 1955, Warner 1957, Durtsche and Webb 1977, Meyer and Kavanaugh 1982). The most recent studies conducted in the Susitna River drainage (Suchanek et al. 1984a, 1984b) indicate that adult rainbow trout and arctic grayling avoid turbid water above 30 NTU and that juvenile chinook salmon use turbid waters but only in the absence of other object-type cover. An older study, conducted on the Taku River (Meehan and Siniff 1962), suggests that turbidity acts to mask differences in light between night and day and thus alters the daily pattern of downstream migration for salmon smolts.

The avoidance of turbid water by some salmonid fishes is corroborated by field studies in California (Sumner and Smith 1940), and by laboratory studies conducted by Weyerhaeuser Company in Washington (Bisson and Bilby 1982) where juvenile coho salmon exhibited significant avoidance of water with turbidities of 70 NTU and above.

$$P = 0.01491\ (PAR) \quad (5)$$

where

P = gross productivity ($g - O_2 m^{-2} d^{-1}$)

PAR = incident photosynthetically active radiation ($E\ m^{-2} d^{-1}$)

This relationship was derived only from unmined streams where there was very little light extinction, because most mined streams investigated were highly turbid and essentially no productivity could be detected.

Unfortunately, Van Nieuwenhuyse (1983) did not relate primary production to light available at depth, and thus did not account directly for natural light extinction or that caused by turbidity. However, subsequent to release of his thesis, the University of Alaska has developed an equation ($r^2 = 0.80$) relating primary production to light at depth (LaPerriere 1984):

$$P = 0.0021\ (PAR_{\bar{z}}) \quad (6)$$

where

P = gross productivity ($kcal\ m^{-2}\ d^{-1}$)

$PAR_{\bar{z}}$ = photosynthetically active radiation available at mean depth z ($kcal\ m^{-2}\ d^{-1}$)

$\bar{z}$ = mean depth (meters)

This equation allows a comparison of primary production occurring at a particular depth between 0 and 0.5 meters for waters of varying turbidities by utilizing Equations 3 and 4. Since gross productivity is described as directly proportional to light available at depth, any reduction in light penetration caused by turbidity above clear-water conditions would be expected to cause a corresponding decrease in plant production. Therefore, we have used Equations 3 and 4 to calculate the effect of various turbidity levels on light available at depth and consequently on production of plant material. This information is presented in Table 5 and plotted in Figure 8. Calculations from these relationships indicate that a turbidity level of only 5 NTU can decrease the primary productivity of shallow clear-water streams by approximately 3 to 13 percent. An increase of 25 NTU may decrease primary production in shallow streams by 13 to 50 percent. Production in streams of depth greater than 0.5 meters (1.5 feet) would be reduced even further.

This conclusion is corroborated by studies in Great Britain (Swale 1964, Westlake 1966, Lack and Berrie 1976, Lund 1969) which reported turbidity and light intensity, as opposed to nutrient concentrations, as the most commonly limiting factors to primary production in streams.

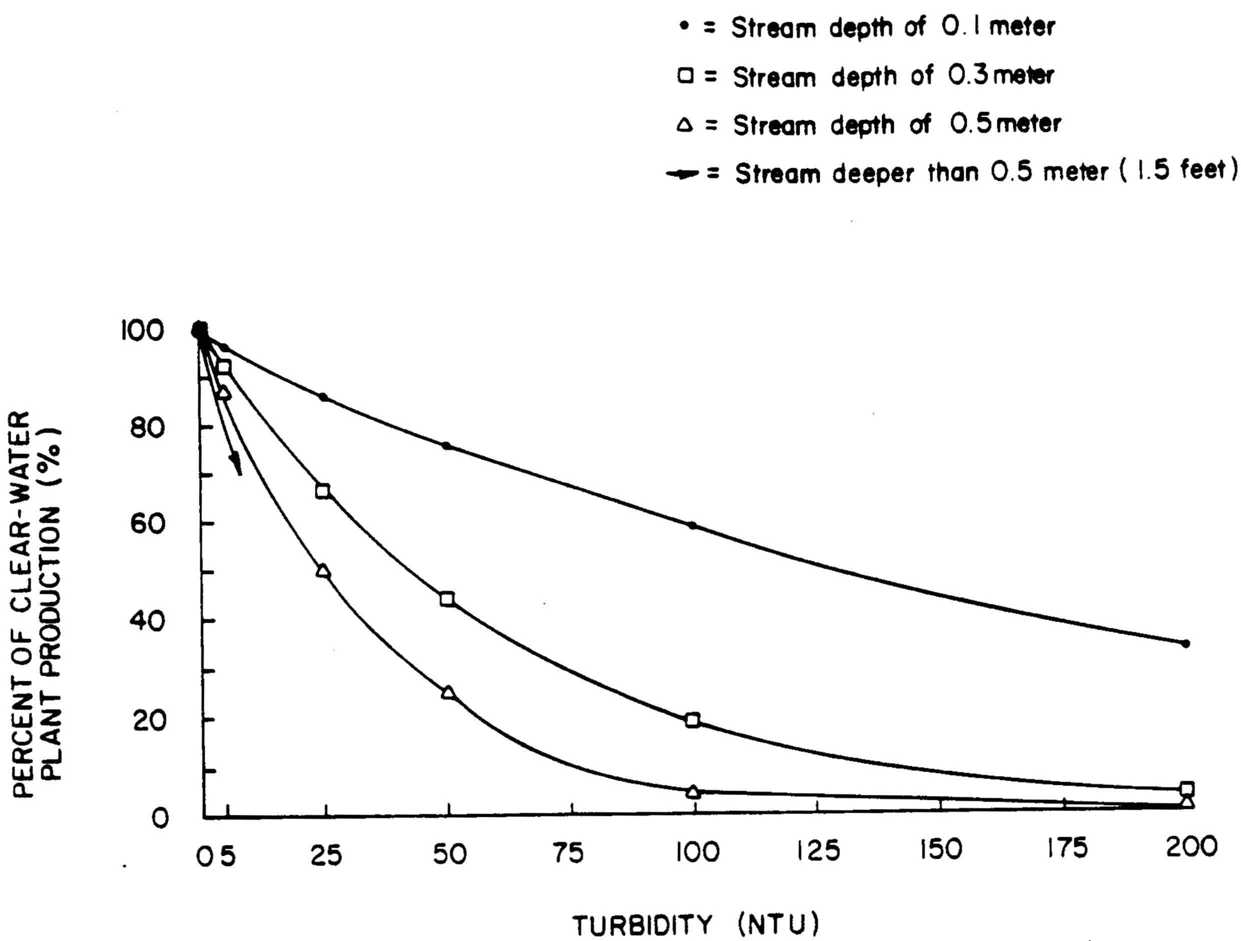

Figure 8. Potential effect of increased turbidity on plant production for shallow streams in interior Alaska (derived in this report from data presented by Van Nieuwenhuyse, 1983; La Perriere, 1984.)

TABLE 5. POTENTIAL EFFECT OF INCREASED TURBIDITY ON LIGHT PENETRATION AT DEPTH AND PLANT PRODUCTION IN SHALLOW INTERIOR ALASKA STREAMS (derived in this report from data presented by Van Nieuwenhuyse, 1983; LaPerriere, 1984)

DEPTH (meters)	TURBIDITY (NTU)	PERCENT OF SURFACE LIGHT AT DEPTH* (%)	PERCENT OF CLEAR-WATER PLANT PRODUCTION** (%)	PERCENT REDUCTION FROM CLEAR-WATER PLANT PRODUCTION (%)
0.1	0	79.4	100	0
	5	77.3	97	3
	25	69.2	87	13
	50	60.3	76	24
	100	45.7	58	42
	200	26.3	33	67
	500	5.0	6	94
0.3	0	50.1	100	0
	5	46.1	92	8
	25	33.1	66	34
	50	21.9	44	56
	100	9.6	19	81
	200	1.8	4	96
	500	0.1	0.2	99.8
0.5	0	31.6	100	0
	5	27.5	87	13
	25	15.8	50	50
	50	7.9	25	75
	100	2.0	6	94
	200	0.1	0.3	99.7
	500	0	0	100

* Calculated from Equations 3 and 4:

$$N_t = 1.00 + 0.024(T)$$

where

N_t = total extinction coeff. (meter^{-1})
T = turbidity (NTU)

$$I_z = 10^{(2.00 - N_t z)}$$

where

I_z = percent of incident PAR at depth Z
Z = depth (meters)

** Calculated from Equation 6:

$$P = 0.0021\ (PAR_{\bar{z}})$$

where

P = gross productivity (kcal m^{-2}d^{-1})
$PAR_{\bar{z}}$ = incident photosynthetically active radiation (kcal m^{-2}d^{-1}) at mean depth z

Note: $PAR_{\bar{z}} = I_z$

Stross and Stottlemeyer (1965) reported lower primary production per unit surface area in the Patuxent River, Maryland due to elevated turbidity; Hancock (1973) reported lower production and altered plant species composition caused by turbidity in South Africa. Although conducted in a shallow pond rather than a stream, studies in North Carolina (Reed et al. 1983) have shown that a reduction in turbidity from only 12 NTU to 6 NTU resulted in a significant increase in growth of plants attached to the pond bottom. Van Nieuwenhuyse (1983) concluded in his thesis on interior Alaska streams that the demonstrated importance of light in controlling a stream's productivity argues that increased turbidity is the single most important disruption to that productivity.

The University of Alaska also investigated the abundance of macroinvertebrates in mined and unmined streams of interior Alaska (LaPerriere et al. 1983, Wagener 1984). These macroinvertebrates comprise the basic food supply of stream-dwelling salmonid fishes. LaPerriere et al. (1983) summarized their studies by reporting that unmined streams supported significantly higher densities of benthic invertebrates than did mined streams and that with a high degree of mining most taxa became very rare or were completely eliminated. Wagener (1984) also reported that biomass was substantially reduced in mined streams. Although reduced invertebrate densities were hypothesized to have resulted from habitat alteration caused by settleable solids (LaPerriere et al. 1983), Wagener (1984) concluded that turbidity comprised the strongest descriptor of reduced density and biomass of macroinvertebrates in those mined streams. Similar reductions in the abundance of macroinvertebrates due to sediment input have been observed in the Yukon and Northwest Territories, Canada (Rosenberg and Snow 1975, Mathers et al. 1981, Soroka and McKenzie-Grieve 1983, Birtwell et al. 1984). The direct effects of those sediments will be more fully discussed in the next section of this paper.

Finally, the University of Alaska studies considered the effects of mining on fish (LaPerriere et al. 1983, Simmons 1984). Throughout their sampling, investigators caught many grayling within unmined streams and none in the mined streams, except during the presumed autumn migration of some fish through streams influenced by mining. The direct physical effects of sediment on fish will be discussed in the following section, but one hypothesized effect of turbidity is to reduce the feeding capability of grayling since these fish feed by sight (Simmons 1984). The researchers examined stomachs of caged grayling in mined and unmined streams and found that grayling in the turbid waters were not capable of locating aquatic insects on which to feed. This may be a result of observed reductions in the abundance of macroinvertebrates in mined streams on which grayling feed or a reduction in the capability of these fish to feed. Simmons (1984) observed an absence of internal fat reserves and parr-mark development in grayling caged in turbid waters and attributed these effects to dietary deficiencies.

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This avoidance of turbid water has been commonly attributed to the sight-feeding requirements of salmonids (Bachmann 1958, Sykora et al. 1972, Langer 1980, Berg 1982). A recent study by Crecco and Savoy (1984) suggests that turbidity may reduce feeding success of larval shad in the Connecticut River. Brett and Groot (1963) state that turbidity may directly affect the migration of salmon through interference with visual cues.

Turbidity also has an effect on the human use of aquatic systems. It is generally acknowledged that turbid water is less acceptable than clear water for consumption, contact recreation, and perhaps aesthetic enjoyment. In many cases turbidity reduces the range of opportunities available for the use of a water body (NAS 1973, EPA 1976). An analysis of angler-effort on the Chatanika River in interior Alaska, performed by ADF&G (Townsend 1983), indicates that turbidity ranging from 8 to 50 NTU, 25 miles downstream from mine discharges, coincided with and may have contributed to a 55 percent decline in sportfishing. In 1977 and 1978, the Chatanika River was the second most popular water body for sportfishing in interior Alaska; but in 1979, when increased mining activity caused muddy-water conditions, the Chatanika fell to seventh in popularity. A study in Denali National Park and Preserve (Miller 1981) also reports reduced sportfishing in streams made turbid by mining activities. Avoidance of turbid waters by sport fishermen and reduced angler success in turbid waters have been described outside Alaska as well (Buck 1956, Tebo 1956, Bartsch 1960, Oschwald 1972, Ritter and Ott 1974, Langer 1980).

Furthermore, the efficient management of fisheries can be directly affected by turbidity (Tait et al. 1962, Cousens et al. 1982). Biologists from the Commercial Fisheries and Sport Fisheries Divisions of ADF&G in western, southcentral, and interior Alaska have reported specific instances where wastewater discharges from placer mines have obstructed aerial escapement surveys for adult salmon (Schneiderhan 1982, Barton 1983a, Barton 1983b, Hepler 1983). An informal consensus from ADF&G biologists indicates that an absolute turbidity of 4-8 NTU is sufficient to interfere with these aerial surveys (Ott 1984b).

TURBIDITY AND SUSPENDED SEDIMENT

Sediment in water is generally considered in two broad classes: 1) suspended sediment, which remains in the water column due to water turbulence, particle shape, and/or the low specific gravity of individual particles, and 2) settleable solids, which rapidly settle to the lake or stream bottom and move only if rolled along the bottom or resuspended by currents. A large number of original investigations and literature reviews have identified the effects of an increase in suspended sediment or settleable solids on primary production, on the production of fish-food organisms, and ultimately on various aspects of the production of fish in aquatic habitats (Shaw and Maga 1943, Bartsch 1960, Cordone and Kelley 1961, Herbert et al. 1961, King and Ball 1964, Cooper 1965, EIFAC 1965, Saunders and Smith 1965, Peters 1967, Angino and O'Brien 1968, Chutter 1969, Hall and Lantz 1969, Gammon 1970, McDonald and Thomas 1970, Koski 1972, Oschwald 1972, Ritchie 1972, Gibbons and Salo 1973, Hynes 1973, Clarke 1974, Williams and Harcup 1974, Phillips et al. 1975, Rosenberg and Snow 1975, Horkel and Pearson 1976, Swenson and Matson 1976, Zemansky et al. 1976, Bjornn et al. 1977, Iwamoto et al. 1978, Noggle 1978, Walmsley 1978, Redding and Schreck 1980, Cederholm et al. 1981, Crouse et al. 1981, Mathers et al. 1981, Singleton et al. 1981, Berg 1982, Hesse and Newcomb 1982, Hall and McKay 1983, McLeay et al. 1983, Reed et al. 1983, Birtwell et al. 1984, McLeay et al. 1984).

Several studies and reviews have also described the importance of sediments in transporting other pollutants (Grissinger and McDowell 1970, Morris and Johnson 1971, Alabaster 1972, Feltz and Culbertson 1972, NAS 1973, Lehmann 1977, Metsker 1982, Soroka and MacKenzie-Grieve 1983, West 1983).

Although it is beyond the scope of this paper to fully describe these impacts, the following briefly outlines the various effects attributed to or coincident with increases of suspended and settleable solids in aquatic habitats. Increased sediments in water may:

- Reduce the penetration of light and intensity of light in water
- Alter the spectral composition of light penetrating in water
- Increase water temperatures by absorption of radiation or decrease water temperatures by back-radiation, depending on amount of insolation and thermal stratification
- Alter pH, alkalinity, and conductivity
- Decrease oxygen availability through increased chemical oxygen demand, increased water temperature, and/or reduced exchange between surface flow and groundwater in the streambed

- Alter nutrient availability through absorption or complexation
- Transport heavy metals and other potential toxicants
- Reduce primary production through decreased light penetration and/or preferential extinction of specific spectra of light required by plants
- Alter plant species composition and abundance through changes in light levels, smothering, scouring, and other physical effects
- Reduce zooplankton production and abundance
- Alter zooplankton species composition
- Reduce benthic invertebrate production and abundance
- Alter benthic invertebrate species composition
- Cause "drift" of benthic invertebrates
- Embed and cement spawning gravels
- Coat and suffocate incubating eggs
- Decrease survival of newly hatched fish
- Promote premature emergence of fry from stream gravels
- Reduce successful emergence of fry from stream gravels
- Reduce feeding efficiency of fish
- Decrease growth rate and production of fish
- Physically abrade and clog fish tissues, such as gill filaments
- Promote contact of absorbed pollutants with sensitive tissues, such as gill filaments
- Promote other physiological stress in fish
- Reduce amount of suitable rearing, feeding habitat of juvenile salmonids
- Interfere with migrational movements of salmon
- Reduce the aesthetic quality and recreational use of previously productive recreational fishing waters
- Reduce the efficiency of fishery management efforts to determine salmon escapements

Studies performed in Alaska have substantiated many of these effects (McNeil et al. 1962; McNeil 1964; McNeil and Ahnell 1964; Shapley and Bishop 1965; Schallock 1966; Vaux 1968; Phillips 1971; Tyler and Gibbons 1973; Meehan 1974; Meehan and Swanston 1977; R&M Consultants 1982a; Schmidt and O'Brien 1982; Van Nieuwenhuyse 1983; Simmons 1984; Wagener 1984; West and Deschu 1984; Bjerklie and LaPerriere, unpubl. ms.; LaPerriere et al., unpubl. ms.).

While there is a temporal relationship between suspended sediment and settleable solids, as well as an overlap in particle size, we are concerned in this paper with only the measurement of and impacts associated with those sediments suspended in the water column. If turbidity can be used to estimate the concentration of suspended sediment in water, then we can relate impacts associated with suspended sediment concentration to turbidity measurements.

Turbidity actually measures the scattering of light within a sample of water, but the turbidity measure was developed primarily to be used as an index of the concentration of suspended material in water (Hardenbergh 1938, in McCluney 1975). However, some investigators have criticized the use of turbidity as a measure of suspended sediment concentration on the grounds that precise estimation of natural suspended sediment concentrations by light scattering is not possible because of the variable particle size, angularity or shape, refractive index, and other properties of sediments that affect the amount of light scattered or absorbed by any particular amount of material, as well as the variability of different units of turbidity measurement and the variability in sediment particle sizes carried at different flow regimes in streams (Duchrow and Everhart 1971, McCluney 1975, Pickering 1976, Beschta 1980).

Detailed criticism (Beschta 1980) has acknowledged that good predictive relationships between suspended sediment concentration and turbidity can be developed on a drainage-by-drainage basis, however, since any particular drainage will erode similar sediment material over a period of time, but that between-drainage comparisons are not as useful since different drainages are comprised of different sediment material.

One problem with using turbidity as a measure of the concentration of suspended sediment, as illustrated by Duchrow and Everhart (1971), is that turbidity is a result of the total amount of sediment suspended in the water at any particular time. At any point in time, the suspended load includes large particles that may soon settle out (settleable solids) and smaller particles that may remain in suspension for considerable lengths of time (suspended sediment), depending on specific gravity, particle shape, and water turbulence. As long as there is sediment suspended in the water column turbidity, and thus reduced light penetration, will continue downstream from the source of sediment input, even as the settleable solids fall onto the lake or stream bottom, producing effects associated with sedimentation (Hall and McKay 1983). It should be noted, however, that suspended sediment can also be deposited in stream gravels by being filtered out during intragravel flow (Cooper 1965, Einstein 1968, Vaux 1968).

The use of mixing zones in monitoring and enforcement of sediment and turbidity standards, however, seeks to accommodate the temporal suspension of larger size fractions. Most of the larger solids will fall out of the water column within the mixing zone, so that turbidity measured at the perimeter of a mixing zone should be produced by suspended sediments that will continue to contribute to turbidity for considerable distances downstream.

The usefulness of turbidity measurement has been supported by a consensus of environmental scientists at a workshop on sediment and water quality conducted by the U.S. Environmental Protection Agency (Iwamoto et al. 1978). Turbidity has been used to estimate sediment loads in streams by the Pennsylvania Department of Transportation (Truhlar 1976) and has been recommended for use in monitoring suspended solids in wastewater treatment processes (Liskowitz 1974). A detailed analysis of suspended sediment concentration versus turbidity, conducted by Kunkle and Comer (1971) in Vermont, showed extremely good correspondence between drainages. They concluded that using turbidity measurements to estimate suspended sediment concentration can be a very useful technique.

It is apparent, then, that while a single relationship between turbidity measurements and suspended sediment concentration (SSC) may not be extremely accurate for a wide spectrum of streams, the impacts caused by specific levels of SSC can be associated with a range of turbidity levels. Conversely, turbidity standards based upon impacts such as reduced light penetration and aquatic productivity can be further justified by direct effects caused by levels of SSC associated with those turbidity standards.

Turbidity and Suspended Sediment in Alaska Streams

Many natural waters in Alaska have been sampled for turbidity and suspended sediment concentration, and the U.S. Geological Survey (USGS) maintains a computer database (WATSTORE) on these water analyses. A regression analysis of information from WATSTORE for the period 1976 to 1983 (May - October), involving 229 samples from 37 stations on 34 rivers, yields a relatively good relationship ($r^2 = 0.83$, for log/log transform) between turbidity and suspended sediment concentration (Figure 9):

$$\log T = -0.357 + 0.858 \log SSC \qquad (7)$$

where

T = turbidity (NTU)
SSC = suspended sediment concentration (mg/liter)

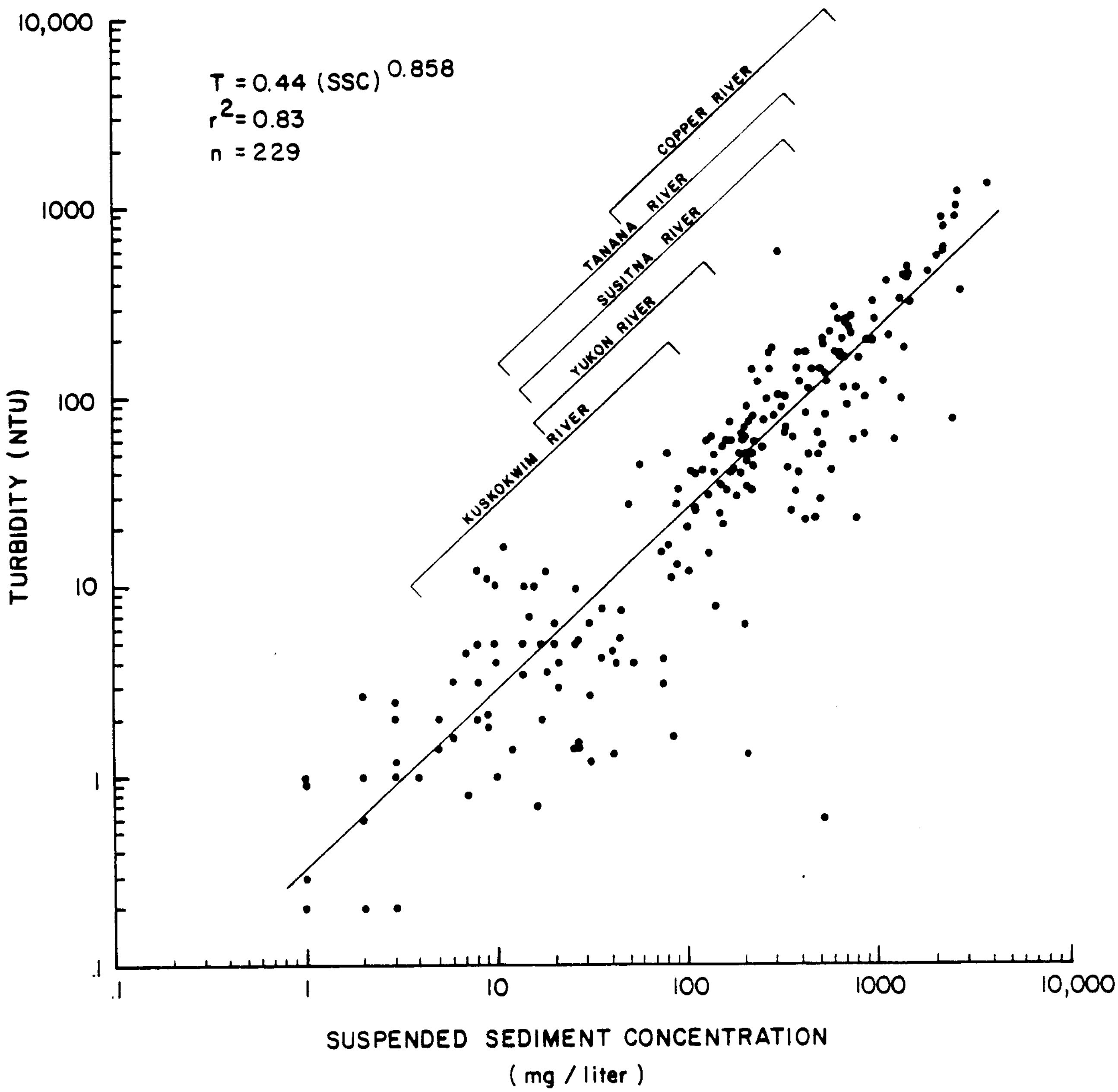

Figure 9. Empirical relationship of naturally occurring turbidity versus suspended sediment concentration for rivers and streams in Alaska, sampled during May-October, 1976-1983 (derived in this report from data provided by USGS, 1984).

This log/log equation can be transformed back to:

$$T = 0.44\ (SSC)^{0.858} \quad (8)$$

Although this relationship is driven by a high proportion of samples from larger silt-laden rivers, a diversity of stream types and locations are represented in the data. For this sample set, the regression shows that turbidity and SSC are related. The relationship shown in Equation 8 can be used to illustrate, for example, that a suspended sediment concentration of 25 mg per liter may be associated with turbidities around 7 NTU and that a SSC of 100 mg per liter corresponds to a turbidity of approximately 23 NTU.

A similar relationship between turbidity and SSC was developed by Peratrovich et al. (1982) using data from the Susitna River. Their relationship is given in Equation 9.

$$T = 0.185\ (SSC)^{0.998} \quad (9)$$

$(r^2 = 0.92$, for log/log transform)

Using this equation for Susitna River sediments, 25 mg per liter SSC corresponds to turbidities of only 4.6 NTU, and a SSC of 100 mg per liter yields a turbidity level of 18.3 NTU.

Using data gathered from placer-mined and neighboring unmined streams in interior Alaska we derive the relationship given in Equation 10 (Figure 10):

$$\log T = 0.0425 + 0.9679 \log SSC \quad (10)$$

$(r^2 = 0.92)$

This log/log equation can be transformed back to:

$$T = 1.103(SSC)^{0.968} \quad (11)$$

This equation was derived from data for the following drainages near Fairbanks: Chatanika River, Upper Birch Creek, Crooked Creek, Goldstream Creek, Tolovana River, and Chena River, gathered by Post (1984) and Toland (1984). Table 6 outlines values of turbidity estimated for various concentrations of suspended sediment in Alaska streams from the equations listed above.

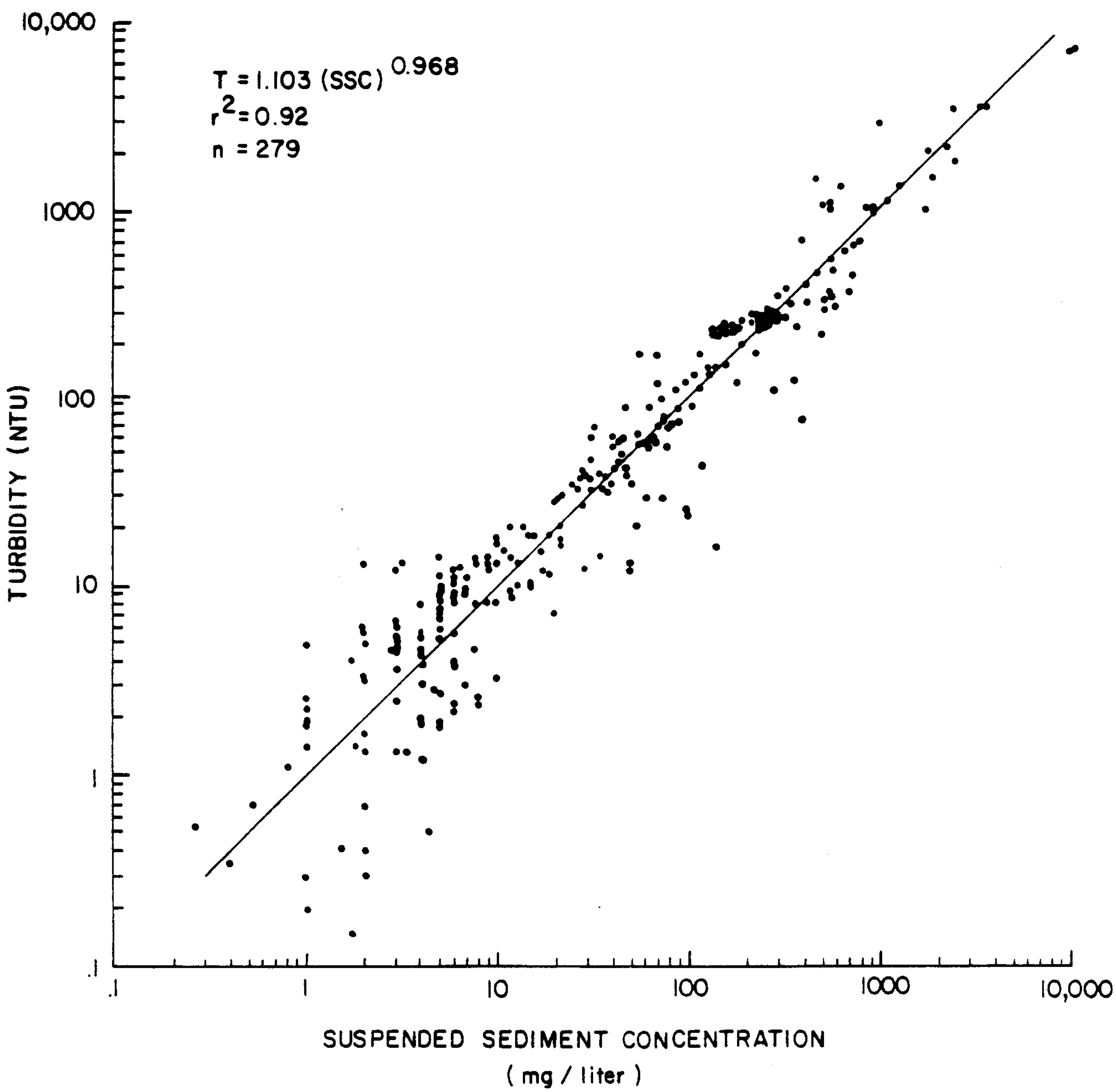

Figure 10. Empirical relationship of turbidity versus suspended sediment concentration for placer-mined and neighboring unmined streams in interior Alaska, sampled during summer, 1983-1984 (derived in this report from data provided by Post, 1984; Toland, 1984).

TABLE 6. PREDICTION OF TURBIDITY CAUSED BY SUSPENDED SEDIMENT CONCENTRATIONS IN STREAMS THROUGHOUT ALASKA, SUSITNA RIVER, AND INTERIOR ALASKA STREAMS

SUSPENDED SEDIMENT CONCENTRATION (mg/liter)	ESTIMATED* TURBIDITY (NTU) FROM STATE-WIDE EQUATION	ESTIMATED** TURBIDITY (NTU) FROM SUSITNA RIVER EQUATION	ESTIMATED*** TURBIDITY (NTU) FROM INTERIOR ALASKA EQUATION
1	0.45	0.20	1.1
10	3.2	1.8	10.
20	5.8	3.7	20.
25	7.0	4.6	25.
50	13.	9.2	49.
80	19.	15.	77.
100	23.	18.	95.
400	75.	73.	364.

* Equation derived in this report from USGS WATSTORE water records for Alaska, May - October 1976 - 1983 (see Equation 8): $T = 0.44(SSC)^{0.858}$

** Equation from Peratrovich et al., (1982) for Susitna River (see Equation 9): $T = 0.185(SSC)^{0.998}$

*** Equation derived in this report from data provided by Post (1984) and Toland (1984) for placer-mined and neighboring unmined streams in interior Alaska, summer 1983-1984 (see Equation 11): $T = 1.103(SSC)^{0.968}$

Turbidity, Suspended Sediment, and Land Use in Alaska

Land use activities such as timber harvest, agriculture, mining, and road and pipeline construction can contribute to elevated sediment loads in streams (Stern and Stickle 1978, Farnworth et al. 1979). In Alaska, studies associated with wastewater discharges from placer mines provide the most comprehensive data base on the production of turbidity and suspended sediment by land use activities.

R&M Consultants (1982a) performed a study on wastewater discharge from sixteen placer mines in interior Alaska. These mines, like most others in Alaska, are located on naturally clear-water streams. From data presented in their report it is possible to calculate mean mine-induced increases of turbidity and SSC of 2500 NTU and 3600 mg per liter, respectively. A plot of natural upstream levels and downstream effluent levels of turbidity and SSC measured at these mines is presented in Figure 11. Examination of this plot and that presented for natural streams in Alaska (Figure 9) illustrates that placer mining can increase turbidity and SSC well above natural clear-water levels and above levels found in naturally turbid rivers such as the Copper, Susitna, Kuskokwim, and Yukon. It should be noted that the wide range in values for placer mining effluents reflects the different degrees of wastewater treatment employed at various mines and possibly differences in sediment characteristics evident at those mines.

A study performed by the Alaska Department of Environmental Conservation (Sexton 1983) in the Kantishna Hills area found that mean mine-induced increases of turbidity and SSC were approximately 3600 NTU and 6500 mg per liter, respectively. Other reports on studies conducted in Alaska have illustrated or discussed various similar effects of placer mining on water quality (FWPCA 1969, Frey et al. 1970, Morrow 1971, Dames & Moore 1976, EPA 1977, ADEC 1979, Bainbridge 1979, Chang 1979, Cook 1979, Yang 1979, Blanchet 1981, Madison 1981, Wolff and Thomas 1982, KRE 1984, Peterson et al. 1984, Toland 1984).

The R&M Consultants study (1982a) also developed a relationship ($r^2 = 0.89$) between turbidity and SSC from settling column tests performed with the sluice box discharge of selected placer mines in interior Alaska:

$$\log T = 1.13 + 0.68 \log SSC \qquad (12)$$

This log/log equation can be transformed back to:

$$T = 13.49\ (SSC)^{0.68} \qquad (13)$$

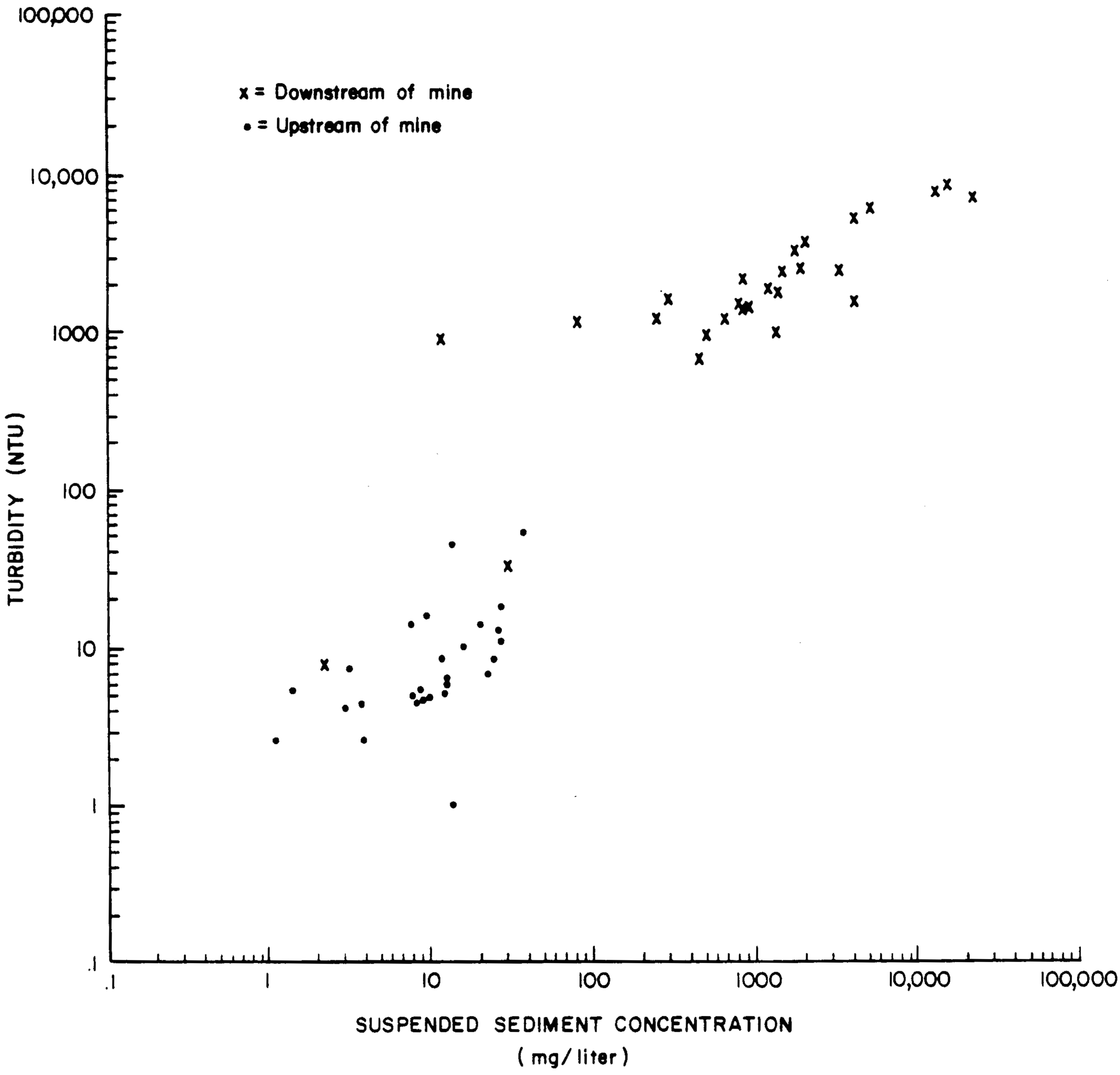

Figure 11. Plot of turbidity and suspended sediment concentration for certain placer-mined streams in Alaska (plotted in this report from data presented in R&M Consultants, 1982a).

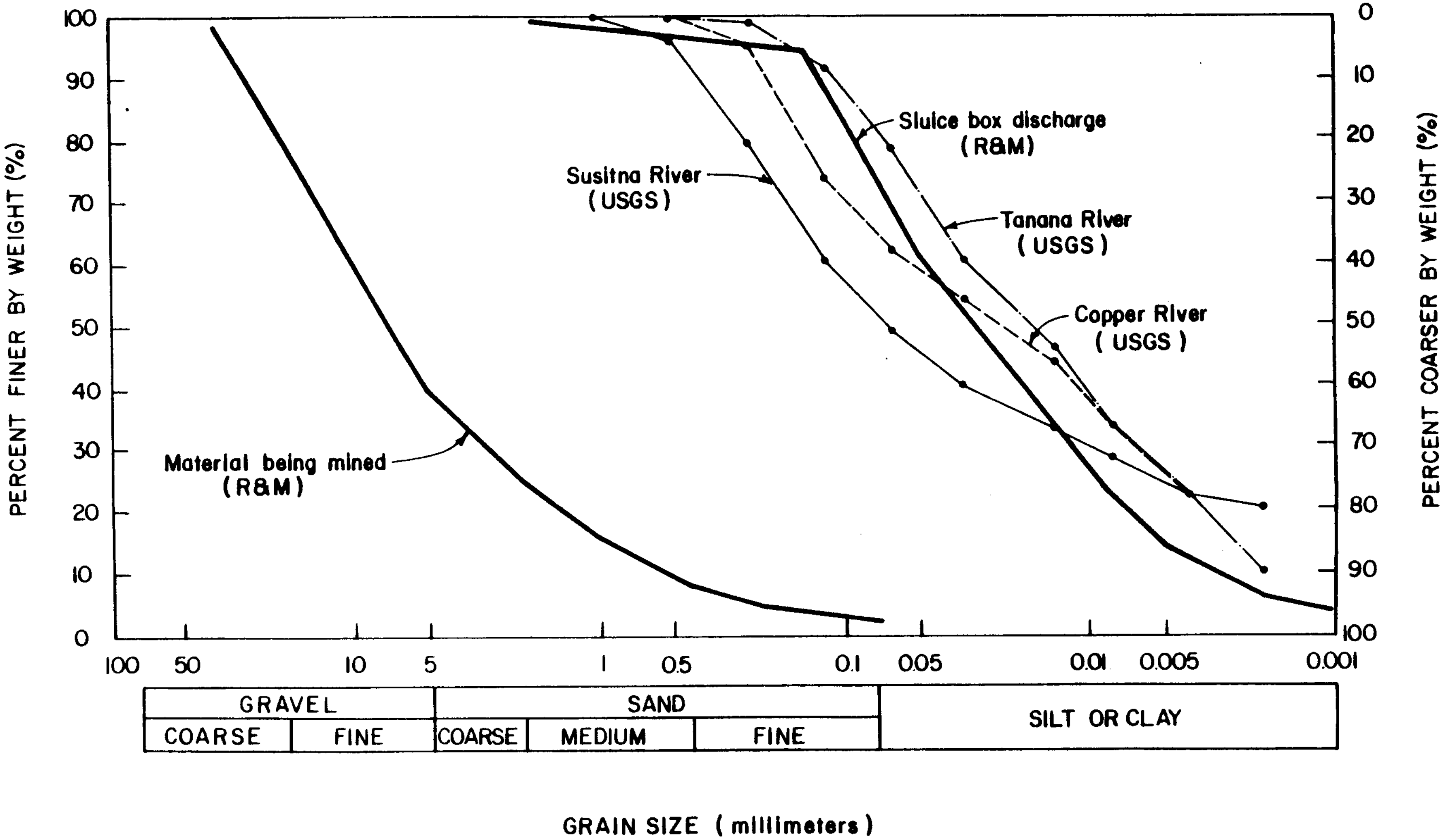

Figure 12. Grain size analysis of sediment from placer mines compared to natural suspended sediment in Alaska streams (adapted from R&M Consultants, 1982a and data derived from USGS, 1981).

Equation 13 predicts a substantially higher level of turbidity for any given level of SSC in the settling columns than do the equations presented earlier for natural waters statewide (8), the Susitna River (9), and streams in interior Alaska (11). Since the particle size fractionation of measured sluice box discharges is reasonably comparable to that described for information available from some natural waters in Alaska (Figure 12), the higher levels of turbidity associated with any particular level of SSC may be due to the undisturbed settling of sluice box effluent for up to three days in the settling column tests. Under natural conditions of stream turbulence, or within settling ponds with less than a three-day quiescent residence time, larger particles, which intuitively are believed to produce less turbidity per unit SSC, would remain in suspension. The result, under conditions other than within artificial settling columns, may be a relationship between NTU and SSC in mine effluents more closely resembling Equations 8, 9 or 11, with lower levels of turbidity per unit SSC. Therefore, relationships developed from settling column testing likely do not represent conditions in streams.

The establishment of relationships between turbidity and SSC allows us to associate impacts caused by suspended sediment to specific levels, or ranges, of turbidity measurements. In this way turbidity standards can be used not only to control adverse effects to light penetration and aquatic productivity, but also to some extent the direct impacts associated with suspended sediment.

RELEVANCE OF TURBIDITY AND SUSPENDED SEDIMENT TO FISH

The recent studies summarized in this report illustrate the effects that turbidity has on freshwater aquatic habitats in Alaska. As outlined in Table 7, increasing levels of turbidity dramatically reduce light penetration and are associated with decreased production of plant material (primary production), decreased abundance of fish food organisms (secondary production), and ultimately with decreased production and abundance of fish. Turbidity resulting from suspended sediment introduced to naturally clear-water streams also adversely affects the human use of these streams, for recreational fishing and management of fish resources. Moreover, there are useable relationships between turbidity and the suspended sediment concentration of Alaska waters, wherein turbidity can be used as a reasonable estimator of suspended sediment concentration. Elevated suspended sediment concentrations have been directly related to adverse impacts on aquatic systems in studies performed outside of Alaska. The numerous effects of sediment that settles out of suspension are not discussed here; for a description of these effects the reader is referred to Hall and McKay (1983).

The fact that turbid waters produce fewer fish may on first impression appear contradictory to the common knowledge that large, muddy rivers in Alaska, such as the Copper, Susitna, Kuskokwim, and Yukon rivers, contain massive salmon runs. To explain this apparent contradiction we need only look at the way these fish utilize their aquatic environment. Pacific salmon and other anadromous fish migrate from the ocean to fresh water to spawn, and although millions of these fish ascend large muddy rivers they almost invariably seek out the clear-water tributaries, sloughs, or areas of groundwater upwelling to deposit their eggs. Juvenile fish that hatch from these eggs generally remain in clear-water habitats for periods ranging from days to years and then descend through the turbid rivers to reach the ocean. The larger turbid rivers, then, serve primarily as migration corridors to and from the headwaters and tributaries of these systems.

It is sometimes held that land use activities contribute sediment loads to clear-water streams and account for turbidity levels that are comparable to those of our naturally silt-laden and turbid rivers. An analysis of available data, however, indicates that placer mining without proper wastewater treatment can elevate suspended sediment loads and turbidity levels of naturally clear-water streams up to an order of magnitude (ten times) above those of our large muddy rivers and perhaps three orders of magnitude (one thousand times) above natural clear-water conditions (see Figures 9 and 11).

TABLE 7. RECENTLY DOCUMENTED EFFECTS AND RELATIONSHIPS OF TURBIDITY AND SUSPENDED SEDIMENT IN FRESHWATER HABITATS OF ALASKA

CHARACTERISTIC	SYSTEM	DOCUMENTED EFFECTS OR RELATIONSHIPS	RANGE OF REPORTED TURBIDITY (NTU)	CITATION
Light Penetration	Lakes	Reduced light penetration, Increased light extinction: Extinc. Coeff. = 0.064 (Turbidity) - 0.093	17 - 38	R&M Consultants, 1982b
	Lakes	Reduced compensation depth, Reduced euphotic volume: log Comp. Depth = 1.172 - 0.647 (log Turbidity)	0 - 52	Koenings, 1984
	Streams	Reduced light penetration, Increased light extinction: Extinc. Coeff. = 1.00 + 0.024 (Turbidity)	0 - 1500	Van Nieuwenhuyse, 1983
Primary Production	Lakes	Reduced plant production, Reduced chlorophyll a concentration at any particular phosphorous loading	0 - 52	Koenings, 1984
	Streams	Reduced plant production, Reduced oxygen production by plants at any particular surface light intensity: P = 0.01491 (PAR) Reduced incorporation of energy by plants $P = 0.0021 (PAR_z)$	0 - 1500	Van Nieuwenhuyse, 1983 LaPerriere, 1984
Secondary Production	Lakes	Reduced zooplankton abundance, Reduced or eliminated preferred foods of juvenile sockeye salmon	0 - 52	Koenings, 1984
	Streams	Reduced benthic invertebrate abundance	0 - 2250+	LaPerriere et al., 1983

(Continued)

TABLE 7. (Continued)

Fish Production	Lakes	Reduced production of juvenile sockeye salmon per unit area	0 - 52	Koenings, 1984
		Reduced return of adult sockeye salmon per unit area	0 - 52	Koenings, 1984
	Streams	Reduced food intake by arctic grayling	1150 - 4825	Simmons, 1984
		Increased physiological stress in arctic grayling	1150 - 4825	Simmons, 1984
		Reduced or eliminated abundance of arctic grayling	0 - 4825	LaPerriere et al., 1983; Simmons, 1984
Fish Distribution	Streams	Coho salmon prefer clear water Rainbow trout prefer clear water Arctic grayling prefer clear water Chinook salmon use turbid water in absence of object-type cover	30	ADF&G 1983a Suchanek et al. 1984a Suchanek et al. 1984b
Recreational Use	Streams	Reduced angler effort: Use of Chatanika River dropped 55%	8 - 50	Townsend, 1983
Fishery Management	Streams	Reduced efficiency of aerial escapement surveys	<8 - +	Schneiderhan, 1982; Barton, 1983a, 1983b; Hepler, 1983; Ott, 1984b
Suspended Sediment Concentration (Natural)	Lakes, Streams	Turbidity related to SSC in Eklutna Lake system, including tributaries	0 - 320	R&M Consultants, 1982b
	Streams	Turbidity related to SSC in Susitna River: Turbidity = 0.185 $(SSC)^{0.998}$	0 - 170	Peratrovich et al., 1982
	Streams	Turbidity related to SSC in streams throughout Alaska: Turbidity = 0.44 $(SSC)^{0.858}$	0 - 4050	USGS, 1984; Analysis in this report

(Continued)

TABLE 7. (Continued)

Suspended Sediment Concentration (Placer Mining vs. Natural)	Streams	Turbidity related to SSC in sluice box discharge: Turbidity = 13.49 $(SSC)^{0.68}$ Turbidity and suspended sediment concentration drastically increased over natural levels due to placer mining Turbidity and SSC from placer mining in clear-water streams exceed turbidity and SSC of Alaska's muddiest natural streams Turbidity related to SSC in interior Alaska streams: Turbidity = $1.103(SSC)^{0.968}$	Upstream of placer mines 0 - 55 Downstream of placer mines 8 - 13,000	R&M Consultants, 1982a; Sexton, 1983; Post, 1984; Toland, 1984; Analysis in this report

At what levels of suspended sediment concentration or turbidity are aquatic habitats adversely affected? In addition to the studies conducted in Alaska, which are summarized earlier in this report and indicate that reductions in aquatic productivity can translate to reduced abundance of fish, there is a large albeit disjointed body of literature regarding the effects of turbidity and suspended sediments. Hollis et al. (1964), Sherk 1971, Sorensen et al. (1977), Stern and Stickle (1978), Farnworth et al. (1979), Muncy et al. (1979), and Wilber (1983) provide recent reviews of this literature, including a description of studies performed by Wallen (1951).

Wallen (1951) reported that lethal levels of turbidity, measured in parts per million (ppm, roughly equivalent to mg per liter), range in the tens of thousands of ppm. These high levels of turbidity, which are actually proxies for SSC, required to kill fish led Wallen (1951) to conclude that natural turbidity levels do not represent a lethal threat to fish. Wallen's information, however, is generated primarily from tests of acute effects on warm-water non-salmonid fishes, including carp, bass, and bullheads, and likely is not applicable to cold-water salmonid fishes which are prevalent in Alaska. Moreover, other more recent studies on bass and sunfish (Heimstra et al. 1969) indicate that lower levels of turbidity, of 4-16 JTU, alter fish behavior, including decreased levels of activity. Studies on cold-water salmonids indicate that low levels of turbidity or SSC may stress, alter behavior patterns, or kill these fish.

The following citations, and Table 8, briefly summarize relevant literature from studies conducted outside of Alaska on the effects of turbidity or sediments measured as suspended material on cold-water salmonid fishes.

Herbert and Merkens (1961), in a study on the effect of mineral solids on rainbow trout in Great Britain, concluded that concentrations of kaolin and diatomaceous earth at 270 ppm negatively affect ability to survive and that concentrations of 90 ppm appear to have some adverse effect. Herbert et al. (1961) found reduced densities of brown trout at SSC of 1000 and 6000 ppm. Herbert and Richards (1963) found that 50 ppm of wood fiber or coal washery waste caused reduced growth in juvenile rainbow trout, and that concentrations of 100 and 200 ppm wood fiber promoted fin-rot in these fish.

In a study on juvenile coho salmon, Noggle (1978) noted that changes from clear-water conditions resulted in a decrease in feeding, and that a complete cessation of feeding occurred at SSC above 300 mg per liter. He also estimated an acute lethal concentration causing 50 percent

TABLE 8. SOME REPORTED EFFECTS OF TURBIDITY AND SUSPENDED SEDIMENT ON SALMONID FISH OUTSIDE OF ALASKA

EFFECT	SPECIES	LOCATION	REPORTED TURBIDITY OR SUSPENDED SEDIMENT CONCENTRATION	CITATION
Mortality (96 hour LC_{50})	Coho salmon (juvenile)	Washington	1200 mg/liter	Noggle 1978
Reduced survival (marked)	Chum salmon (eggs)	Canada	97 mg/liter	Langer 1980
Reduced survival (marked)	Rainbow trout (eggs)	Great Britain	110 mg/liter	Scullion and Edwards 1980
Reduced survival (marked)	Rainbow trout (juvenile)	Great Britain	270 ppm	Herbert and Merkens 1961
Reduced survival (marked)	Rainbow trout (juvenile)	Great Britain	200 ppm	Herbert and Richards 1963
Reduced survival (slight)	Rainbow trout (juvenile)	Great Britain	90 ppm	Herbert and Merkens 1961
Reduced survival (marked)	Coho salmon (juvenile)	Pennsylvania	6, 12 mg Fe/liter 15-27 JTU	Smith and Sykora 1976
Reduced abundance (marked)	Brown trout	Great Britain	1000, 6000 ppm	Herbert et al. 1961
Reduced growth (marked)	Brook trout (juvenile)	Pennsylvania	50 mg Fe/liter 86 JTU	Sykora et al. 1972
Reduced growth (slight)	Brook trout (juvenile)	Pennsylvania	12 mg Fe/liter 32 JTU	Sykora et al. 1972
Reduced growth (slight)	Rainbow trout (juvenile)	Great Britain	50 ppm	Herbert and Richards 1963

(Continued)

TABLE 8. (Continued)

Reduced growth	Coho salmon (juvenile)	Idaho	25 NTU	Sigler et al. 1984
Reduced growth (marked)	Arctic grayling (juvenile)	Yukon	1000 mg/liter	McLeay et al. 1984
Reduced growth (slight)	Arctic grayling (juvenile)	Yukon	100, 300 mg/liter	McLeay et al. 1984
Reduced food conversion	Rainbow trout (juvenile)	Arizona	<70 JTU	Olson et al. 1973
Reduced feeding (cessation)	Coho salmon (juvenile)	Washington	300 mg/liter	Noggle 1978
Reduced feeding	Coho salmon (juvenile)	Washington	100 mg/liter	Noggle 1978
Reduced feeding	Coho salmon (juvenile)	British Columbia	10-60 NTU	Berg 1982
Reduced feeding (cessation)	Cutthroat trout	Idaho	35 ppm	Bachmann 1958
Reduced feeding	Rainbow trout (juvenile)	Arizona	70 JTU	Olson et al. 1973
Reduced feeding	Arctic grayling (juvenile)	Yukon	100, 300, 1000 mg/liter	McLeay et al. 1984
Reduced condition factor	Rainbow trout (juvenile)	Great Britain	110 mg/liter	Scullion and Edwards 1980
Altered diet (terrestrial instead of aquatic)	Rainbow trout (juveniles)	Great Britain	110 mg/liter	Scullion and Edwards 1980

(Continued)

TABLE 8. (Continued)

Stress (increased plasma cortisol, hematocrit, and susceptibility to pathogens)	Coho salmon, Steelhead trout (juvenile)	Oregon	500, 2000 mg/liter	Redding and Schreck 1980
Stress (increased metabolic rate, susceptibility to toxicants)	Arctic grayling (juvenile)	Yukon	300 mg/liter	McLeay et al. 1984
Stress (increased plasma glucose)	Arctic grayling (juvenile)	Yukon	50 mg/liter	McLeay et al. 1983
Stress (respiratory distress)	Coho salmon (juvenile)	Pennsylvania	6, 12 mg Fe/liter 15-27 JTU	Smith and Sykora 1976
Disease (fin rot)	Rainbow trout (juvenile)	Great Britain	270 ppm	Herbert and Merkens 1961
Disease (fin rot)	Rainbow trout (juvenile)	Great Britain	100, 200 ppm	Herbert and Richards 1963
Avoidance	Chinook salmon (adult)	California	"Natural turbidity"	Sumner and Smith 1940
Avoidance (sensitivity)	Lake trout	Lake Superior	6 FTU	Swenson 1978
Avoidance	Coho salmon (juvenile)	Washington	70 NTU	Bisson and Bilby 1982
Avoidance	Coho salmon, Steelhead trout (juvenile)	Idaho	22-265 NTU	Sigler 1981 Sigler et al. 1984

(Continued)

TABLE 8. (Continued)

Displacement	Coho salmon, Steelhead trout (juvenile)	Idaho	40-50 NTU	Sigler 1981
Displacement	Arctic grayling (juvenile)	Yukon	300, 1000 mg/liter	McLeay et al. 1984
Displacement	Rainbow trout (juvenile)	Great Britain	110 mg/liter	Scullion and Edwards 1980
Altered behavior (feeding)	Trout		25 JTU	Langer 1980
Altered behavior (less use of overhead cover)	Brook trout	Wisconsin	7 FTU	Gradall and Swenson 1982
Altered behavior (visual)			25-30 JTU	Bell 1973
Altered behavior (visual)	Coho salmon (juvenile)	British Columbia	10-60 NTU	Berg 1982
Altered behavior (loss of territoriality)	Coho salmon (juvenile)	British Columbia	10-60 NTU	Berg 1982
Altered behavior (listlessness)	Coho salmon (juvenile)	Pennsylvania	6, 12 mg Fe/liter 15-27 JTU	Smith and Sykora 1976
Change in body color	Arctic grayling (juvenile)	Yukon	300, 1000 mg/liter	McLeay et al. 1984
Change in body color	Coho salmon (juvenile)	Pennsylvania	6, 12 mg Fe/liter 15-27 JTU	Smith and Sykora 1976

mortality (LC 50) for coho salmon at 1200 mg per liter during summer. He concluded that human-induced sediment in waters during summer poses a greater possibility of harm to juvenile salmonids than generation of sediment in phase with natural hydrologic cycles (Noggle 1978).

Langer (1980) reports from Canada that SSC of 97 mg per liter caused by a release of sediment in the Coquitlam River resulted in only a 23 percent survival of chum salmon eggs, whereas SSC of 10 mg per liter in a tributary stream allowed almost 94 percent survival. In a recent study on the effects of placer mining effluents on arctic grayling in the Yukon Territory, McLeay et al. (1983) found that a SSC level of as low as 50 mg per liter may cause identifiable stress. Redding and Schreck (1980) observed several stress responses to suspended sediment and turbidity by juvenile coho salmon and steelhead trout at SSC of 500 and 2000-3000 mg per liter, and suggested that effects of chronic exposure to sediment are more severe than effects of acute exposure.

Sykora et al. (1972) demonstrated marked reductions in growth of juvenile brook trout in Pennsylvania at concentrations of 50 mg Fe per liter neutralized iron hydroxide and slight reductions in growth at concentrations as low as 12 mg Fe per liter. Smith and Sykora (1976) also found reduced survival of juvenile coho salmon at 6 and 12 mg Fe per liter concentrations of neutralized iron hydroxide, with associated turbidity of 15 to 27 JTU, as well as respiratory distress and listlessness. These authors (Sykora et al. 1972, Sykora and Smith 1976) attribute these effects to the reduced visibility and other impacts caused by the suspended iron hydroxide rather than to any toxic qualities of the material.

Bachmann (1958) found that cutthroat trout in Idaho sought cover and stopped feeding at turbidities measured at 35 ppm. Scullion and Edwards (1980) found that rainbow trout in Great Britain exhibited increased egg mortality, altered diets, lower condition factors, and downstream displacement caused by human-induced SSC averaging 110 mg per liter.

Based upon an extensive review of available literature commissioned by the Food and Agriculture Organization of the United Nations, the European Inland Fisheries Advisory Commission concluded that waters containing 0 to 25 ppm of chemically inert solids should not adversely affect freshwater fisheries but that SSC of 25 to 80 ppm may lower the production of fish and that waters containing SSC exceeding 80 ppm are unlikely to support good fisheries (EIFAC 1964). Moreover, they emphasize that "the spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided sediments" (EIFAC 1964). Gammon (1970) stated in a report to the U.S. Environmental Protection Agency on studies conducted in Indiana, for warm-water systems, that the suspended solids criteria proposed by EIFAC (see Table 10) may be too liberal for fish populations in the United States.

As noted earlier, studies in California show that adult chinook salmon may generally avoid entering turbid waters (Sumner and Smith 1940), and turbidity may interfere with migrational movements of salmon (Brett and Groot 1963). Lake trout have also been observed to avoid turbid water in Lake Superior, and associated laboratory studies indicate that lake trout are sensitive to turbidities as low as 6 FTU (Swenson 1978). Although brook trout exhibited no avoidance in laboratory experiments of turbidities up to an average of 61 FTU (Gradall and Swenson 1982) these studies did note behavioral changes caused by turbidity of 7 FTU. Laboratory studies conducted with juvenile coho salmon illustrate avoidance of water with turbidities of 70 NTU and above (Bisson and Bilby 1982). Studies conducted at a hatchery in Arizona indicate that the feeding activity of rainbow trout drops off sharply at 70 JTU (Olson et al. 1973); moreover, they documented a much lower food energy conversion ratio for fish in turbid water compared to those in clear water.

Most recently, laboratory studies conducted in Idaho on the chronic, as opposed to short-term, effects of turbidity illustrate that juvenile steelhead trout and coho salmon tend to avoid turbid waters of between 22 and 265 NTU, that these fish are displaced downstream at turbidity levels between 40 and 50 NTU, and that steelhead and coho salmon remaining in these turbid waters exhibit slower growth than similar fish in clear water (Sigler 1981, Sigler et al. 1984). Moreover, they conclude that turbidities of 25 NTU caused a reduction in fish growth, presumably due to reduced ability to feed (Sigler et al. 1984). A reduction in the sight-feeding ability of salmonid fishes due to reduced light intensity or increased turbidity is discussed in several previously referenced reports (Bachmann 1958, Sykora et al. 1972, Langer 1980, Schmidt and O'Brien 1982). Langer (1980) specifically notes 25 JTU as a turbidity at which trout may cease to feed; Bell (1973) states that fish food production declines and visual references are lost at turbidities of 25 to 30 JTU. Berg (1982) determined that turbidity of 60 NTU had a marked effect on the visual ability of juvenile coho salmon, and that turbidities between 10 and 60 NTU caused reduced feeding, reduced territoriality, and loss of aggressive interactions among juvenile coho salmon.

For comparative purposes, the reactive distance of bluegills, a warm water fish, has been observed to decrease with increases of turbidity from 1 to 30 JTU (Vinyard and O'Brien 1976), and the feeding rate of bluegills has been observed to drop 20 percent at turbidities of 60 NTU (Gardner 1981).

As stated earlier, research in Kansas on a common Cladoceran, which is a preferred food item of juvenile fishes including salmon, has shown that a turbidity level of 10 NTU can cause significant declines in feeding rate, food assimilation, and reproductive potential (McCabe and O'Brien 1983). Robertson (1957) found reduced reproduction in Cladocera at clay and charcoal concentrations between 82 and 392 ppm. Arruda et al. (1983) observed that suspended sediment concentrations of 50 to 100 mg per liter reduced the algal carbon ingested by Cladocerans to potential starvation levels.

Perhaps the most comprehensive study completed recently on the direct effects of suspended sediment, and resulting turbidity, on salmonid fish was conducted on arctic grayling and placer mine sediments from the Yukon Territory (McLeay et al. 1984). They conducted controlled experiments in laboratory streams maintained at nominal suspended sediment concentrations of 0, 100, 300 and 1000 mg per liter; actual mean values were <5, 86-93, 273-286 and 955-988 mg per liter respectively. Although overall survival of fish during the tests was not affected by these levels of SSC several other sublethal effects were observed. Fish growth was depressed by 6 to 10 percent in SSC of 100 and 300 mg per liter and by 33 percent in SSC of 1000 mg per liter. Distribution of the grayling was unaffected by SSC of 100 mg per liter, but fish were displaced downstream at SSC of 300 and 1000 mg per liter. Feeding responses of grayling were slower at SSC of 100, 300 and 1000 mg per liter, particularly responses to food available at the water surface. Coloration of fish was paler at SSC of 300 and 1000 mg per liter. Tolerance of fish to a reference toxicant was reduced at SSC of 300 and 1000 mg per liter, and oxygen uptake rates were increased.

McLeay et al. (1984) conclude that SSC of 100 mg per liter can affect fish growth and feeding responses, and that SSC of 300 mg per liter or higher can increase metabolic rate, lower tolerance to toxicants and cause displacement of fish downstream from the source of sediment discharge. They (McLeay et al. 1984) continued to emphasize that sustained SSC of 100 mg per liter may prove harmful to the long-term well-being of grayling in natural streams and that short-term pulses of SSC of 100 mg per liter, or turbidity on the order of 40 to 50 NTU (Sigler 1981), may cause downstream migration of otherwise resident fish.

It is apparent from this information, derived from outside of Alaska, as well as information obtained in Alaska described earlier, that introductions of even small amounts of sediment and turbidity in freshwater habitats can adversely affect fish and other aquatic life and that effects short of fish mortality may be a factor in reducing the productive potential of fish resources.

STANDARDS AND CONCLUSIONS REGARDING WATER QUALITY

The use of turbidity as a water quality criterion and standard has been criticized, principally because of a lack of readily available information on the impacts associated with elevated turbidities in natural waters. A more provincial argument against the use of turbidity is that there have been no studies conducted in Alaska to demonstrate effects. This report, however, contains Alaska illustrations of the effects of turbidity on clear freshwater habitats, and the relationship between turbidity and suspended sediment concentration. We also report effects of turbidity and suspended sediment documented from studies conducted outside of Alaska.

The State Water Quality Standards for Alaska (18 AAC 70) impose limits to allowable human-induced alterations of natural waters. These limits are specified for various water quality parameters with respect to the designated use or classification of a particular body of water. Most of Alaska's freshwaters have been classified as suitable for drinking and other consumptive uses. The turbidity standard for drinking water is:

> Shall not exceed 5 NTU above natural conditions when the natural turbidity is 50 NTU or less, and not have more than 10% increase in turbidity when the natural condition is more than 50 NTU, not to exceed a maximum increase of 25 NTU. [18 AAC 70.020(b)(1)(A)(i)(4)]

Although there are few, if any, waters in Alaska designated only for use by fish and wildlife, because of their already more restrictive classification for human consumption, the State Water Quality Standards do contain a separate standard for waters classified for the growth and propagation of fish, shellfish, other aquatic life, and wildlife including waterfowl and furbearers:

> Shall not exceed 25 NTU above natural condition level. For all lake waters, shall not exceed 5 NTU over natural conditions. [18 AAC 70.020(b)(1)(c)(4)]

For simplicity in considering allowable increases of turbidity in clear-water systems, we can restate the above standards:

Drinking water: no more than 5 NTU above natural

Fish and wildlife: no more than 25 NTU above natural - streams
no more than 5 NTU above natural - lakes

Alaska does not have a numerical standard for suspended sediment concentration or for settleable solids in drinking waters, but the state does have a generic narrative standard for sediment. The sediment standard for drinking water is:

> No measurable increase in concentrations of sediment above natural levels. [18 AAC 70.020(b)(1)(A)(i)(7)]

The sediment standard for the propagation of fish and wildlife is much more complex. That part of the standard dealing with settleable solids is difficult to enforce, and that part addressing suspended sediment is difficult to define:

> The percent accumulation of fine sediment in the range of 0.1 mm to 4.0 mm in the gravel bed of waters utilized by anadromous or resident fish for spawning may not be increased more than 5% by weight over natural condition (as shown from grain size accumulation graph). In no case may the 0.1 mm to 4.0 mm fine sediment range in the gravel bed of waters utilized by anadromous or resident fish for spawning exceed a maximum of 30% by weight (as shown from grain size accumulation graph). (See note 3 and 4). In all other surface waters no sediment loads (suspended or deposited) which can cause adverse effects on aquatic animal or plant life, their reproduction or habitat. [18 AAC 70.020(b)(1)(c)(7)]

How could this sediment standard be improved? By definition, turbidity and suspended sediment concentration are closely intertwined. While there have not been extensive investigations of the lethal and sublethal effects of suspended sediments on fish in Alaska to determine acceptable levels of SSC, or the development of precise regression equations of SSC versus turbidity for each drainage of concern, information summarized in this report indicates that a statewide turbidity standard can be used to address the effects of turbidity as an optical property of water and also as an indicator of suspended sediment concentration. The effects of sedimentation onto lake and stream bottoms could then be addressed by a separate, enforceable settleable solids standard.

Whether or not such changes are made to the sediment standard, there is still a need to establish or reaffirm those levels of turbidity, and consequently SSC, which are appropriate as standards for regulating human activity. What, then, are acceptable levels of human-induced turbidity in freshwater aquatic habitats that support fish and wildlife?

Light Penetration and Productivity

To protect aquatic habitats, an acceptable turbidity standard must: 1) prevent a loss of aquatic productivity and 2) cause no lethal or chronic, sublethal effects to fish and wildlife. The studies summarized in this report indicate that even small increases in turbidity may dramatically reduce primary plant production in lakes and streams, which apparently translates to a reduced production and abundance of fish. With reference to the current standard for the propogation of fish and wildlife, a 5 NTU increase of turbidity in a clear-water lake can reduce the productive volume of that lake by approximately 75 percent; a 25 NTU increase in a clear-water stream only 1.5 feet deep may reduce primary plant production by approximately 50 percent. Alaska's standard for protection of fish and wildlife is above the 10 JTU criteria previously recommended by the Federal Water Pollution Control Administration (FWPCA 1968). A comparison of turbidity standards used in Alaska and other western and northern states (Table 9) indicates that Alaska currently allows liberal increases over natural conditions.

The current drinking water standard of 5 NTU over ambient levels in shallow clear-water lakes and streams may also induce a reduction of primary plant production, however not to the extent the 25 NTU over ambient standard would induce in streams. For comparison, a 5 NTU increase of turbidity in a clear-water stream may reduce primary production by 3 to 13 percent or more, depending on stream depth. Additional arguments can be applied to a 5 NTU standard: that absolute turbidities of 4-8 NTU and above preclude the efficient management of fisheries in Alaska because aerial observers cannot see into the streams and estimate returns of adult salmon, and that absolute turbidities of 8 NTU and greater have been shown to reduce sportfishing activity in fish-bearing waters in Alaska. The current Interagency Placer Mining Guidelines (State of Alaska 1984) use turbidity of 3 NTU or less as a criterion for establishing "high priority" streams. Application of a 5 NTU above ambient standard would bring total turbidities in these streams to 8 NTU, the level at which recreational fishing may decline and at or above the level at which efficiency of aerial surveys is affected.

So, in light of the information produced by recent studies in Alaska and elsewhere, it appears that the turbidity standard for the propagation of fish and wildlife should be more restrictive, perhaps at the level currently used for drinking water, if aquatic productivity is to be maintained.

TABLE 9. NUMERICAL TURBIDITY STANDARDS FOR PROTECTION OF FISH AND WILDLIFE IN ALASKA AND OTHER WESTERN AND NORTHERN STATES (ADEC, 1978; API, 1980)

STATE	TURBIDITY* (NTU or JTU)
Alaska	25 above natural in streams 5 above natural in lakes
California	20% above natural, not to exceed 10 above natural
Idaho	5 above natural
Minnesota	10
Montana	10 (5 above natural)+
Oregon	10% above natural
Vermont	10 (cold-water)
Washington	25 above natural (5 & 10 above natural)++
Wyoming	10 above natural

* NTU and JTU are roughly equivalent.

\+ Montana places the more stringent limit on waters containing salmonid fishes.

++ API (1980) reports different values in Washington, for excellent and good classes of water.

Suspended Sediment

Regarding appropriate limitations to suspended sediment concentrations, there is evidence (non-Alaskan) that high concentrations prove lethal to fish, and additional information that lower levels of SSC and turbidity cause chronic, sublethal effects such as loss of sight-feeding capabilities, reduced growth, increased stress, interference with environmental cues necessary for orientation in fish migrations, transport of heavy metals and other pollutants, and other potentially adverse effects to the quality of aquatic habitats. Several organizations have made recommendations for appropriate suspended sediment concentrations in fish-bearing waters. Using our statewide equation (Equation 8) relating turbidity to suspended sediment concentration, we can translate these recommendations into approximate turbidity criteria (Table 10).

Recommendations for a "moderate" level of protection (up to 100 mg per liter) translate into turbidity values up to 23 NTU. This is very close to the current Alaska standard of 25 NTU above natural conditions for protection of fish and wildlife.

Recommendations for a "high" level of protection (0-25 mg per liter) translate into turbidity values ranging from 0 to 7 NTU, closely approximating Alaska's drinking water standard of 5 NTU above natural conditions. Application of the present drinking water standard, 5 NTU above natural conditions, to waters statewide would conform to a consensus view of a "high" level of protection from suspended sediments.

Using our equation for interior Alaska streams (Equation 11), "moderate" and "high" levels of protection from suspended sediment translate into higher turbidities (95 and 25 NTU, respectively) (see Table 10), but these turbidities would not offer protection from light extinction and reduced production of plants, fish food, and fish as discussed earlier.

Conclusion

The conclusion of this report is that turbidity is a reasonable water quality standard for use on a statewide basis. Although turbidity is not a direct measure of either light penetration (Phinney 1959, Austin 1974) or of suspended sediment concentration (Pickering 1976), it is shown to be a very useful indicator of these characteristics (Gibbs 1974, Ritter and Ott 1974). Use of a turbidity standard in the regulation of water quality is justified much in the same way that

TABLE 10. RECOMMENDED LEVELS OF SUSPENDED SEDIMENT CONCENTRATION FOR THE PROTECTION OF FISH HABITAT AND TRANSLATION TO TURBIDITY VALUES

CITATION	CITED LEVEL OF PROTECTION FROM SUSPENDED SEDIMENT	CITED RECOMMENDED SUSPENDED SEDIMENT CONCENTRATION (mg/l) LIMITATION	TRANSLATED* MAXIMUM TURBIDITY LEVEL STATE-WIDE (NTU)	TRANSLATED** MAXIMUM TURBIDITY LEVEL INTERIOR ALASKA (NTU)
EIFAC, 1964;	High	0 - 25	7	25
Alabaster, 1972	Moderate	26 - 80	19	77
NAS, 1973	High	0 - 25	7	25
	Moderate	26 - 80	19	77
Alabaster and	High	0 - 25	7	25
Lloyd, 1980	Moderate	26 - 80	19	77
Newport and	High	0 - 25	7	25
Moyer, 1974	Moderate	26 - 100	23	95
Wilber, 1969; 1983	High	0 - 30	8	30
	Moderate	30 - 85	20	81
Hill, 1974	High	0 - 10	3	10
DFO, 1983	High	0	0	0
	Moderate	1 - 100	23	95

* Derived from a state-wide equation for Alaska streams developed in this report from U.S. Geological Survey water analyses May - October, 1976 - 1983 (see Equation 8):

$$T = 0.44(SSC)^{0.858}$$

where

T = Turbidity (NTU)
SSC = Suspended sediment concentration (mg/liter)

** Derived from an equation for interior Alaska streams developed in this report from data compiled by Post (1984) and Toland (1984), for summer 1983-1984 (see Equation 11):

$$T = 1.103(SSC)^{0.968}$$

Equation 13, from R&M Consultants (1982a), was not used due to concerns outlined in the text, and because the equation describes a set of data which includes only four values of SSC equal to or less than 100 mg per liter and none less than 25 mg per liter.

fecal coliform bacteria are widely used as a water quality standard indicating the presence and concentration of other harmful bacteria (LaPerriere 1983).

Increased turbidity accounts for demonstrable decreases in aquatic productivity, in the presence and abundance of fish, in the human use of fish-bearing waters, and in the efficiency of certain fishery management techniques. Turbidity is also directly related to concentrations of suspended sediments, which can cause demonstrable lethal and sublethal impacts to fish. Based upon current information, continued application of the present State Water Quality Standard for the propagation of fish and wildlife (25 NTU above natural conditions in streams, 5 NTU in lakes) can be expected to provide a moderate level of protection to clear-water aquatic habitats. A higher level of protection would require a more restrictive standard, similar to the one currently applied to drinking water (5 NTU above natural conditions in streams and lakes).

LIMITATIONS, FURTHER STUDY, AND ALTERNATIVE STANDARDS

The information presented in this report justifies a general statewide water quality standard based on turbidity. Such a statewide turbidity standard can be established from consistent physical relationships, derived from studies on lakes and streams in Alaska and elsewhere, between turbidity and light penetration, and resulting effects on aquatic primary productivity. Furthermore, a statewide turbidity standard can be established based upon observed effects of turbidity on, or associations with, secondary production, distribution and abundance of fish, recreational use of streams, and fishery management practices. Also, a statewide turbidity standard can be used to provide protection from direct effects of suspended sediment on aquatic life including fish.

However, it may be desirable at some point, if sufficient data allow, to further justify or modify statewide turbidity standards. In order to take a more detailed look at the effect of turbidity on freshwater habitats in Alaska we need to identify the limitations of existing information and develop plans for further study. On another tack, it may be desirable in the future to create alternative standards to turbidity, perhaps based more directly on measures of light extinction and sediment loading.

Limitations to Existing Information

It is apparent that even though current information from Alaska and elsewhere supports the need for regulating land use with fairly strict turbidity standards, there is detailed information for only a small sample of aquatic habitats in the state. With regard to primary production, assumptions made about the importance of primary production in interior Alaska streams may not be completely applicable to heavily forested watersheds in southeast Alaska, which likely rely more upon organic material derived from terrestrial sources (see Chapman and Demory 1963, Chapman 1966). In addition, there has been little work performed to identify the capacity of compensatory mechanisms to increase photosynthetic efficiency under low-light or turbid conditions (see Van Nieuwenhuyse 1983, Anderson 1984), the effect of organic staining of water on turbidity and suspended sediment concentration, or the influence of increased or depressed nutrient concentrations caused by the same sediments that decrease light availability (see Tilzer et al. 1976, Jackson and Hecky 1980).

Regarding any relationship between turbidity and sediment loading, the current information is understandably tentative. First, it is well recognized that the amount of turbidity produced per unit of suspended sediment concentration depends upon sediment particle size, shape or angularity, and refractive index, and that relationships will change, based upon hydrologic or hydraulic conditions such as increasing flows versus decreasing flows (rising limb versus falling limb of the hydrograph), spring versus fall seasonal flows, and interactions with sediment reservoirs in the streambed, as well as the geologic composition of the sediment source (see Duchrow and Everhart 1971, Beschta 1980, Milhous 1982).

Second, as illustrated in a recent study on placer-mined streams by the Alaska Department of Environmental Conservation (Toland 1984), the relationship between turbidity and SSC can change along a downstream gradient from a sediment (discharge) source. Specifically, Toland (1984) found that within the first fifteen miles downstream from placer mine discharges on the Chatanika River each mg per liter of SSC produced less than one NTU of turbidity but that below fifteen miles each mg per liter of SSC produced more than one NTU of turbidity (within the range of 10-150 units for each of NTU and mg/liter). This follows the intuitive notion that larger particles, which generally produce less turbidity per unit concentration than smaller particles, will gradually settle out, thus shifting the turbidity versus SSC relationship to a higher NTU per unit SSC at distances downstream.

Third, an instantaneous, or even continuous, measurement of turbidity may contain suspended sediment and some settleable solids, depending on the amount of settling that takes place before the sample is taken (see Duchrow and Everhart 1971). Moreover, it is often difficult to distinguish adverse impacts to aquatic habitats caused by suspended as opposed to settleable material. This confusion is illustrated by our citation of Langer (1980) who reported reduced survival of chum salmon eggs, presumably caused by sediment material deposited onto the eggs, with increased concentrations of suspended sediment measured in mg per liter. However, as we mentioned earlier, Cooper (1965) describes a mechanism whereby suspended sediment may be incorporated into the streambed, not only through settling but through filtration during intragravel flow.

Fourth, depending on geomorphic, hydrologic, and hydraulic factors, different streams are able to accommodate different levels of sediment input and may naturally support different biotic communities. Also, different species and even different life stages within species are susceptible to adverse effects from varying levels of sediment and to sediments of different sizes. In this paper we have reported that cold-water salmonids are generally more susceptible to acute and chronic effects of sediment than many species of warm-water non-salmonid fishes. However, even among salmonids some species may be more sensitive than others, and the eggs and juvenile stages of these species are apparently much more sensitive than adults.

Topics for Further Study

To address the limitations outlined above, topics warranting study include the relationships of specific levels of turbidity and sediment loading with the following factors in the various types of aquatic habitats in Alaska:

Light Penetration
Primary Productivity
Compensatory Mechanisms in Photosynthetic Efficiency
Aquatic Plant Species Composition
Abundance and Species Composition of Benthic
  Invertebrates
Abundance and Species Composition of Fish

Other topics for study may include the dependence of particular aquatic habitats on aquatic versus terrestrial sources of production, the threshold level of adverse effects of turbidity and sediment on benthic invertebrates, similar thresholds for fish in their various life stages, as well as the association of toxic concentrations of trace metals with levels of turbidity.

Regarding the use of turbidity to estimate suspended sediment concentration, it may be necessary to establish detailed relationships for specific drainage types, account for variability caused by temporal factors such as fluctuating flows and erosion rates, and consider the change in those relationships downstream from a point source of sediment. Recently, data have been collected in selected drainages near Fairbanks that may allow the development of these detailed types of relationships (see EPA 1984, KRE 1984, Post 1984, Toland 1984). A particular gap in data available from Alaska and elsewhere is the extent downstream from a source of sediment, such as a placer mine, that the various impacts exist, what mechanisms act to modify these effects, and how long it takes a system to recover.

In view of the potential to develop alternative standards, an important topic for consideration and study should be possible tiering or grading of turbidity standards dependent upon ambient water quality conditions and the level of protection desired for a particular body of water. A grading approach could allow a certain percentage increase in turbidity above ambient levels rather than an absolute increase; a tiered approach could allow different increases for different ranges of ambient turbidity. These approaches must recognize, however, the effects of turbidity on light penetration particularly at low ambient levels of turbidity and the direct effects of suspended sediment concentration at higher ambient levels of turbidity.

Suggestions for Possible Alternative Standards

Several authors have suggested the need for standards other than simple turbidity levels to control pollution from sediments. Wilson (1957) proposed that turbidity standards be based on a percentage increase above normal low-flow conditions. Tarzwell (1957) recommended that turbidity standards be altered to state that some percentage of incident light at the surface be allowed to reach a specified depth, standardized to a time between 11:00 a.m. and 1:00 p.m. The National Academy of Sciences (NAS 1973) recommended that the depth of light penetration not be decreased by more than 10 percent, and that suspended sediment concentrations be limited to specific values, as outlined for the NAS in Table 10.

Cairns (1968) recognized the value of more flexible approaches but suggested that truly responsive regulations should be developed on a drainage-by-drainage basis and should change with streamflow and other temporal characteristics. A significant problem with this approach, however, is that implementation and enforcement of such standards would require an enormous baseline study and almost continuous surveillance and monitoring. There is a question as to whether such an approach is feasible in Alaska.

The U.S. Environmental Protection Agency (EPA 1976) recommended a joint standard for turbidity and solids:

> Freshwater fish and other aquatic life: Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life.

This standard suffers from several deficiencies. First, the standard does not address any impacts associated with sediment deposited on the bottom, even though it mentions settleable solids. Second, in relation to the water column, the standard does not address specific levels of suspended sediment concentration and places a severe burden on regulatory agencies to define a "seasonally established norm" for the compensation point. Finally, as emphasized by the American Fisheries

Society (AFS)(Thurston et al. 1979), compensation point is of little value in streams, particularly where the water is so clear and shallow that light naturally penetrates all the way to the bottom. The AFS (Thurston et al. 1979) recommends that separate solids standards (mg/liter) and turbidity standards (NTU) be developed, designed to facilitate ease of measurement.

Any alternative standards to turbidity should account for both major aspects of turbidity: light extinction and suspended sediment concentration. Direct measurement of both of these parameters is possible and may be conducted in a feasible manner, however it should be recognized that the measure of turbidity was developed to make such measurements easier. Light penetration can be measured with portable photometers and extinction coefficients calculated with simple graphs or equations; sediment concentration can be sampled in the field and measured gravimetrically in a laboratory.

The development of any alternative standards will require considerable research and justification. It is premature to judge in this paper whether such alternatives will or will not provide more effective regulatory tools than the current turbidity standards can offer us today, particularly if we consider that turbidity standards can be tiered or graded, if necessary, to ambient water quality conditions and the level of protection desired for a body of water.

GLOSSARY

Chlorophyll - green pigment that facilitates photosynthesis in plants. Measurement of chlorophyll concentration is used as an indication of abundance and production of plant material in water.

Compensation depth - the depth within a body of water at which light intensity is just sufficient to promote photosynthesis equal to respiratory, or metabolic, requirements of phytoplankton populations. Usually considered the depth to which one percent of available surface light penetrates into a body of water. Net production of plant material occurs above this depth.

Euphotic volume - the volume of water above the compensation depth. Equals surface area multiplied by compensation depth.

FTU - formazin turbidity unit. Roughly equivalent to NTU.

JTU - Jackson turbidity unit. Roughly equivalent to NTU.

LC_{50} - the concentration of a material that proves lethal to fifty percent of a sample of organisms being tested. Usually modified by a specified length of time, such as a 96-hour LC_{50}.

Macroinvertebrates - those invertebrate animals (without backbones) that are not microscopic. In streams, usually consist of aquatic insects on the stream bottom.

Macrophytes - large plants, often rooted in sediment, that grow from the bottom of a body of water.

Mixing zone - a zone of mixing or dilution within a body of water, adjacent to a wastewater discharge, within which receiving water may exceed water quality standards.

mg per liter - milligrams per liter. Used to describe a weight-to-volume concentration of a solid material in a fluid.

Nephelometer - an instrument that transmits a beam of light through a sample of water and records the amount of that light scattered by that sample to an angle of approximately 90° from the original light path.

NTU - nephelometric turbidity unit. A unit of light scattering in a sample of water measured by a nephelometer, standardized against the scattering of light caused by a suspension of formazin in water.

Periphyton - small, often single-celled, plants that are attached to rocks and other substrates on the bottom of a body of water.

Phytoplankton - small, often single-celled, plants that are suspended in a body of water.

ppm - parts per million. Used to describe a weight-to-weight concentration of one material in another. Roughly equivalent to mg per liter when considering concentration of a solid in water.

Primary production - the amount of tissue or energy assimilated through photosynthesis by plants.

Reactive distance - the distance between a fish and its prey within which a positive feeding response occurs.

Secondary production - the amount of tissue or energy assimilated by consumers of plants. Usage in this paper generally refers to production of zooplankton (small floating animals) and macroinvertebrates (aquatic insects).

Settleable solids - solid material in water that settles to the bottom. Usually standardized to the volume of solid material within a one-liter sample of water that settles to the bottom of an Imhoff Cone within one hour.

SSC - abbreviation for suspended sediment concentration. Usually expressed in units of milligrams of sediment per liter of water (mg per liter, mg/liter), sometimes expressed as parts per million (ppm).

Stained - refers to color imparted to water, usually by natural organic (dissolved) material.

Suspended sediment - solid material in water that remains suspended, does not settle, often times due to low specific gravity and/or water turbulence. Usually measured as total nonfiltrable residue, meaning material that will not pass through a standard-sized filter. Generally does not include dissolved material.

Turbidity - an optical property of water wherein light is scattered or absorbed rather than transmitted in a straight line. Caused by suspended material such as clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms. In common usage, refers to a muddy condition of water. Historically expressed as ppm, but more recently reported in FTU, JTU or NTU.

Zooplankton - small animals, such as copepods and Cladocerans, that are suspended in a body of water.

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