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Effects of Turbidity in Fresh Waters of Alaska

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Abstract.—Turbidity results from the scattering of light in water by organic and inorganic particles; however, high turbidities usually are caused by suspended inorganic particles, particularly sediment. For several Alaskan lakes, we found that the depth to which 1% of subsurface light penetrated had a strong inverse correlation with sediment-induced turbidity. We also developed a model that describes the decrease in primary production in shallow interior Alaskan streams caused by sediment-induced turbidity. Euphotic volume in lakes correlated strongly with production of juvenile sockeye salmon (*Oncorhynchus nerka*). We also observed reduced abundance of zooplankton, macroinvertebrates, and Arctic grayling (*Thymallus arcticus*) in naturally and artificially turbid aquatic systems. Turbidity measurements correlated less consistently with measures of suspended sediment concentration (total nonfilterable residue), but provided an adequate estimator for use as a water quality standard to protect aquatic habitats.

Glacial meltwater naturally contributes enormous amounts of fine suspended sediment and consequent turbidity to major drainages in Alaska, while placer mining, timber harvest, and road construction are the principal sources of human-induced turbidity to otherwise naturally clear-water habitats. Turbidity has been described as a major water quality characteristic affecting freshwater fish communities (Judy et al. 1984). In fact, the nationwide survey of fishery biologists by Judy et al. indicated that turbidity was the most predominant adverse water quality characteristic, affecting approximately 34% of the streams in the United States and constituting a "major concern" in almost 17% of them. Sediment pollution, particularly turbidity, is the most prevalent form of pollution in Alaskan waters. Although there is a considerable amount of published and unpublished literature describing individual effects of sediment-induced turbidity on aquatic systems, we have found no substantial evaluation of this information that is suitable for management purposes.

In this paper, we report findings from previously unrelated investigations and integrate them into a review of the literature to describe the effects of turbidity on coldwater systems in Alaska and to describe relationships between suspended sediment concentration (total nonfilterable residue) and resulting turbidity. Information on significant effects of turbidity on freshwater habitats can be helpful in designing fish-stocking programs, water quality standards to protect fish habitat, and other applications where the quality of water is important to fish. In a companion paper (Lloyd 1987, this issue), this information is used to evaluate existing water quality standards applied in Alaska.

Methods

Lakes.—Several studies were performed to evaluate the rearing capacity of lakes for sockeye salmon (*Oncorhynchus nerka*) and to optimize returns from stocking programs. Detailed methods were previously reported by Koenings et al. (1983), Koenings and McDaniel (1983), and Kyle (1983). Briefly, each lake was sampled concurrently at two or three stations, and several lakes were sampled once every 3 weeks over the course of the open-water season. Light penetration (photosynthetically active radiation) was measured at several

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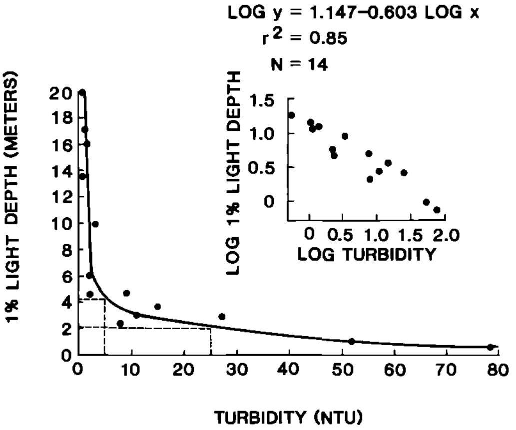

FIGURE 1.—Compensation (1% light) depth versus turbidity for several Alaskan lakes; NTU is nephelometric turbidity unit.

depths at each station with a Protomatic submersible photometer. Compensation depths were defined as the depth to which 1% of subsurface light penetrated. Turbidity was measured with an HF Instruments model DRT-150 nephelometer. We estimated algal standing crop by chlorophyll-*a* analysis, using a low-strength acid addition modification (Reimann 1978) of the fluorometric procedures outlined by Strickland and Parsons (1972). Total phosphorous was analyzed by the molybdate blue–ascorbic acid method of Murphy and Riley (1962) as modified by Eisenreich et al. (1975) after persulfate digestion. Zooplankton were collected in duplicate vertical tows from bottom to surface with 0.5-m-diameter, 153-mm-mesh, conical zooplankton nets. Abundance and biomass of outmigrating sockeye salmon smolt were estimated by using smolt fences, calibrated traps or other quantifiable means.

Streams.—Studies also were conducted to identify the effects of placer mining on streams in interior Alaska. Detailed methods, reported elsewhere (LaPerriere et al. 1983; Van Nieuwenhuyse 1983; Simmons 1984; Bjerklie and LaPerriere 1985; LaPerriere et al. 1985; Wagener and LaPerriere 1985; Van Nieuwenhuyse and LaPerriere 1986) are briefly summarized here. Light penetration was measured with LI-COR quantum sensors and integrating quantum photometers and turbidity was measured with a Hach "Portalab" nephelometric turbidimeter. Algal productivity was estimated by standard single-station diel oxygen curve methods (Odum 1956; APHA et al. 1980). Benthic macroinvertebrates were sampled with an Ellis-Ruter portable invertebrate box sampler with 350-mm mesh. Fish were sampled with 3.2- and 6.4-mm-mesh beach seines.

Relationships between turbidity and suspended sediment concentration were developed to determine if turbidity criteria can provide reasonable approximations to water quality criteria based on suspended sediment concentration. Data were provided by the U.S. Geological Survey, the Alaska Department of Fish and Game, and the Alaska Department of Environmental Conservation. Logarithmic transformation was used in regression analyses following published convention (Duchrow and Everhart 1971; Kunkle and Comer 1971; Ritter and Brown 1971; Beschta 1980) and to correct for heteroscedasticity (Zar 1984).

Turbid Lakes

Light Penetration

The depth to which 1% of available subsurface light penetrates, used to estimate algal compensation depth, showed a strong inverse relationship ($r^2 = 0.85$) with recorded turbidity levels in nephelometric turbidity units (NTU) in the 14 lakes measured. The following equation resulted:

$$\log_{10}Z_{0.01} = 1.147 - 0.603\log_{10}T \qquad (1)$$

$Z_{0.01}$ = 1% light depth (m);
T = turbidity (NTU).

In glacially turbid Tustumena Lake, the 1% light depth was about 1 m in summer at natural turbidities of 52 NTU. By contrast, the 1% light depths in clear Hidden, Cooper, and Leisure lakes exceeded 16 m at natural turbidities of less than 2 NTUs. The 1% light depth decreased sharply between turbidities of 2 and 10 NTUs (Figure 1). Small increases in turbidity greatly reduce the productive volume of lakes (Edmundson and Koenings 1985a). From Figure 1, a 5-NTU increase in turbidity of a naturally clear lake may reduce the productive euphotic volume by about 80%.

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

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

N_t = extinction coefficient (m^{-1});
T = turbidity (NTU).

The depth to which 1% of available surface or immediately subsurface light penetrates can be

TABLE 1.—Effect of turbidity on light extinction and compensation depth in an Alaskan lake.[a]

Turbidity (NTU[b])	Extinction coefficient[c] (m^{-1})	Compensation depth[d] (m)
5.5	0.26[e]	17.71
15	0.87	5.29
25	1.51	3.05
35	2.15	2.14
50	3.11	1.48

[a] Calculated from data presented by R&M Consultants (1982) for Eklutna Lake.

[b] Nephelometric turbidity units.

[c] Derived from equation (2).

[d] Depth of 1% light penetration, derived from Lambert's equation (Reid and Wood 1976; Vanous et al. 1982) $I_d = I_0 e^{-kd}$; I = light intensity; $I_d/I_0 = 0.01$ = compensation point of 1% light level; $k = N_t$ = total extinction coefficient (m^{-1}); d = depth (m).

[e] Equation (2) does not apply to turbidity less than 15 NTUs, but R&M Consultants (1982) also presented an extinction coefficient of 0.26 m^{-1} for a turbidity of 5.5 NTUs based on light transmissivity information at low turbidities in Eklutna Lake.

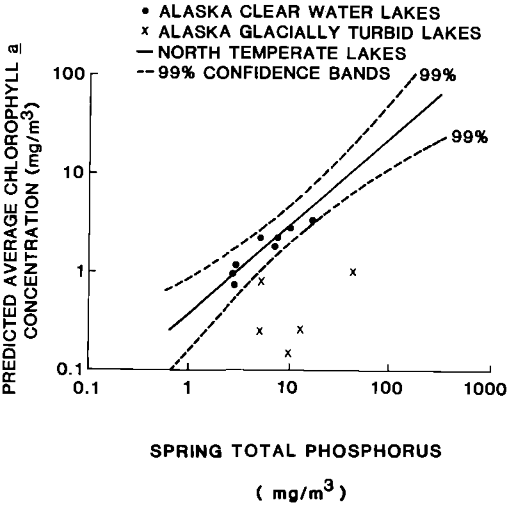

FIGURE 2.—Conformance of clear-water and glacially turbid lakes in Alaska to a general relation (Vollenweider 1976) between phytoplankton standing crop and phosphorus availability in north temperate lakes.

calculated for Eklutna Lake, using equation (2) to calculate light-extinction coefficients corresponding to specific turbidity levels and then using these extinction coefficients in Lambert's equation for transmission of electromagnetic radiation through a medium (Reid and Wood 1976; Vanous et al. 1982). The correspondence between 1% light depths and turbidity in Eklutna Lake (Table 1) is similar to the empirical data plotted in Figure 1. The 1% light depth decreases markedly at turbidities just above 5 NTUs and less so at turbidities of 25 NTUs or more. (The correspondence of compensation depth with turbidity for these data sets is not exact due to the additional light extinction caused by natural color in several of the other lakes but which is not present in Eklutna Lake.)

Similar findings in Lake Superior (Swenson 1978) indicated that the depth of the 1% light level was reduced from about 16.5 m in clear water to an average of 2.5 m at turbidities of 10–12 formazin turbidity units (FTU). Studies in North Carolina showed that each unit (NTU) increase in turbidity caused a 0.06 unit (m^{-1}) increase in light-extinction coefficient (Reed et al. 1983)—results very similar to those shown in Table 1. Strong and similar relationships between turbidity and both 1% light depth and extinction coefficients were also observed in South Africa (Walmsley et al. 1980; Grobler et al. 1983). In Arkansas, investigators have related turbidity and suspended sediment concentration to light-extinction coefficients (Stefan et al. 1983). Strong relationships between turbidity and several different measures of light extinction and scattering were also observed in Australia (Kirk 1980).

Algal Abundance and Primary Production

Because 1% light depth in clear-water lakes is very sensitive to small changes in turbidity, turbidity should have a demonstrable effect on primary production or lake fertility. Phosphorus is typically the nutrient that limits primary production in north temperate freshwater lakes (Dillon and Rigler 1974; Jones and Bachmann 1976; Oglesby 1977a; Schindler 1977); that is, phosphorus concentration usually controls summer phytoplankton production. Clear-water systems in Alaska conform to Vollenweider's (1976) relationship between phosphorus availability and chlorophyll-*a* concentration, in that all those yet investigated fell within the 99% confidence limits (Figure 2). However, for a given level of phosphorus loading each of the glacial systems showed significantly reduced levels of algal abundance as expressed by chlorophyll-*a* concentration. Reduced light availability caused by high turbidities apparently limits the production and abundance of phytoplankton even when sufficient nutrients are available (Edmundson and Koenings 1985a).

Similar reductions in algal abundance or primary production caused by turbidity in lakes have been described by studies of Lake Erie (Meyer and Heritage 1941; Chandler 1942), Oklahoma ponds (Claffey 1955), and a pond in North Carolina (Reed et al. 1983). Recent work performed in a large reservoir in Oklahoma (Hunter and Wilhm 1984) suggested that even low levels of turbidity (between 4 and 15 NTUs) can disrupt the expected relationship between light penetration, phosphorus, and chlorophyll *a* in clear-water systems. Similar conclusions on the effect of turbidity on phosphorus and chlorophyll-*a* relationships, or on primary production have been reached by other investigators in North America (Marzolf and Osborne 1972; Hergenrader and Hammer 1973; Canfield and Bachmann 1981; Jones and Novak 1981; Walker 1982; Hoyer and Jones 1983). Murphy (1962) concluded, by theoretical derivation, that turbidity has a dramatic negative effect on potential primary production.

Results of studies conducted in the Northwest Territories indicated that an increase of turbidity from 0 to approximately 75 FTUs decreased primary production, decreased plant species diversity with respect to number of species and total biomass, and altered plant species composition (McCart et al. 1980). Disregarding the influence of different nutrient concentrations, Goldman (1960) observed significant decreases in light penetration and primary productivity with increased turbidity in large salmon-producing lakes in southwest Alaska. As stated by Oglesby (1977a), published evidence amply indicates that turbidity reduces primary production below otherwise expected levels.

Although the photosynthetic efficiency of plants may sometimes compensate for low-light conditions, compensatory mechanisms are limited and do not maintain plant production under conditions of moderate to high turbidity. Recent work in northern Canada (Hecky 1984; Hecky and Guildford 1984) indicated that aquatic plants do not overcome extinction coefficients of about 2 m^{-1}. Inasmuch as an extinction coefficient of 2 m^{-1} corresponds to a turbidity of about 30 NTUs (Table 1), compensatory mechanisms cannot overcome turbidities above about 30 NTUs.

Zooplankton Abundance

Increased turbidity affects primary production, and the translation of energy to higher trophic levels should vary in lakes of different turbidities. Seasonal zooplankton densities in glacially turbid lakes were observed to be as little as 5% of those in clear-water lakes, as illustrated by mean densities of $<1{,}000\ m^{-3}$ in turbid Upper Trail Lake versus mean densities of $>20{,}000\ m^{-3}$ in clear-water Hidden Lake (Figure 3). Furthermore, zooplankton density decreased with decreasing 1% light depth. Reduced zooplankton abundance in turbid waters has been corroborated by studies in Oklahoma (Matthews 1984) and in the Northwest Territories (McCart et al. 1980).

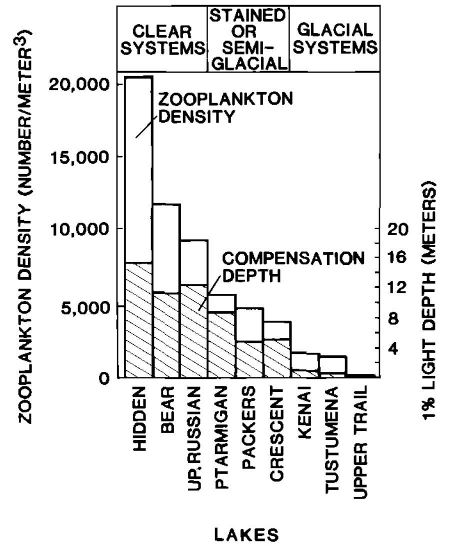

FIGURE 3.—Zooplankton density and compensation (1% light) depth for some clear-water and glacially turbid lakes in Alaska. Turbidity of these lakes ranges from approximately 0 to 52 nephelometric turbidity units or slightly above.

Of eight glacially turbid lakes that we inspected in Alaska none had populations of cladocera—in particular *Daphnia longiremis,* a group of highly favored food organisms for juvenile salmonids (Foerster 1968; Hoag 1972; Jaenicke and Kirchhofer 1976)—whereas 20 clear lakes we investigated contained these zooplankters (Edmundson and Koenings 1985b). McCabe and O'Brien (1983) observed that a turbidity of 10 NTUs resulted in significant declines in the feeding rate and food assimilation capability of *Daphnia pulex* in Kansas. Their calculations indicated that even low turbidity, caused by low suspended-sediment concentrations, reduced the reproductive potential of *Daphnia* spp. below that in clear water. Work in northern Canada (Patalas and Salki 1984) correlated reduced abundances of cladocerans, after impoundment of a large reservoir, with decreased water transparencies as well as reduced chlorophyll concentrations and lower temperatures. Earlier studies in the Northwest Territories documented reduced abundance of crustacean zooplankton with increased turbidity and suspended sediment concentration (McCart et al.

TABLE 2.—Production of juvenile sockeye salmon in relation to surface area and euphotic volume of 10 lakes in Alaska.

Lake and year	Relative turbidity	Surface area (10^6 m^2)	Euphotic volume[a] (10^6 m^3)	Mean annual smolt production (number)	Mean annual smolts per unit area (smolts/10^6 m^2)	Mean annual smolts per unit euphotic volume (smolts/10^6 m^3)
Packers 1981–1983	Clear (stained)	2.1	8.4	336,000	160,000	40,030
Falls 1982	Clear	0.95	9.5	123,000	129,473	12,950
Hugh Smith 1981–1984	Clear (stained)	2.9	14.3	200,000	69,000	14,000
Larson 1982–1983	Clear	1.8	17.9	644,000	357,778	36,000
Leisure 1983–1984	Clear	1.1	19.8	333,363	303,057	16,837
Tokun 1983–1984	Clear	1.8	25.0	438,350	243,528	17,534
Upper Russian 1978–1979	Clear	4.6	51.0	940,700	204,500	18,445
Eshamy 1982	Clear	3.7	74.8	1,351,000	361,111	18,056
Crescent 1981–1982	Semiglacial	16.2	89.0	1,236,000	76,296	13,900
Tustumena 1981–1983	Glacial	295.0	295.0	4,350,000	14,746	14,746

[a] Euphotic volume = surface area multiplied by compensation depth (depth of 1% light penetration).

1980). Carvalho (1984) also reported reduced abundance of *Daphnia gessneri* with increased turbidity in a Brazilian floodplain lake.

Fish Production

Having observed a reduction in both density and species composition of zooplankters in turbid-lake systems, we expected some definable impact on fish production. Mean annual production in populations of rearing-area-limited sockeye salmon smolt generally decreased with decreased euphotic volume (Table 2). The yield of juvenile sockeye salmon, expressed as numbers of outmigrating smolts, reflected the magnitude ($r^2 = 0.99$) of change in the euphotic volume, caused in some cases by increased turbidity (Figure 4), and the resultant decreases in primary and secondary production. Yields conformed to the equation

$$FP = 130{,}506 + 0.014(EV); \tag{3}$$

FP = fish production (number of sockeye salmon smolts);
EV = euphotic volume (10^6 m^3).

Smolt production per unit of euphotic volume ranged between approximately 13,000 and 40,000 smolts/10^6 m^3, while production of smolts per unit surface area in the same lakes ranged widely between approximately 15,000 and 360,000 smolts/10^6 m^2 (Table 2). Surface area alone does not adequately normalize smolt production because no account is taken of reduction in euphotic volume and primary production caused by increased turbidity.

Reduced fish production in turbid water has been observed elsewhere, particularly by Buck (1956), who detected smaller individual growth rates, reduced reproduction rates, and lower population sizes of fish in turbid ponds than in clear ponds in Oklahoma. A positive relationship between primary production and warmwater fish production was observed by Mills and Schiavone (1982). They proposed that the assessment of zooplankton populations and measures of primary production can be used to develop fish management strategies. They also concluded that lake productivity is directly related to algae or phytoplankton abundance and is inversely proportional to water clarity. Several other studies on lakes throughout the world have confirmed positive and predictive relationships between primary production and abundance or yield of fish (Melack 1976; McConnell et al. 1977; Oglesby 1977b; Jones and Hoyer 1982). Nelson (1958) reported a close relationship between increased rates of photosynthesis in Bare Lake on Kodiak Island, Alaska, and increased growth of juvenile sockeye salmon. Burgner et al. (1969) suggested that lakes in southwestern Alaska with high primary productivity rates may produce more salmon per unit area than lakes with lower

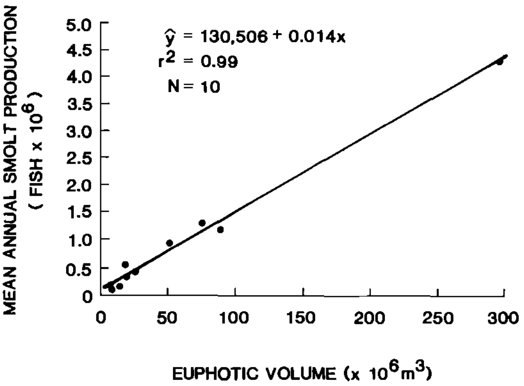

FIGURE 4.—Mean annual smolt production of juvenile sockeye salmon versus euphotic volume for several Alaskan lakes (euphotic volume equals surface area multiplied by compensation depth).

plant production. Geen and Andrew (1961) attributed increased turbidity, induced by hydroelectric diversions in a lake in British Columbia, as the cause for reduced primary and secondary production and a probable reduced capacity of the lake to produce sockeye salmon smolts. Based upon 4 years of study, Ruggles (1965) considered glacial turbidity as the predominant limitation on phytoplankton and zooplankton abundance in another lake in British Columbia, and he suggested that lower abundance of prey in the upper levels of the lake, where there was sufficient light available for feeding, limited production of juvenile sockeye salmon.

Turbid Streams

Light Penetration and Primary Production

The negative relationship between turbidity and light penetration was also quantified for streams in the Birch Creek and Chatanika River drainages of interior Alaska. Van Nieuwenhuyse (1983) found that extinction of light was directly related (r^2 = 0.99) to increased mining-induced turbidity, according to the equation

$$N_t = 1.00 + 0.024(T); \qquad (4)$$

N_t = total extinction coefficient (m^{-1});
T = turbidity (NTU).

He also used this extinction coefficient to calculate (±5%) the percentage of incident photosynthetically active radiation (surface light) that penetrated to a particular depth with the equation

$$I_Z = 10^{(2.00 - N_t Z)}; \qquad (5)$$

I_Z = percentage of incident photosynthetically active radiation (PAR) reaching any depth;
N_t = total extinction coefficient (m^{-1});
Z = depth (m).

Van Nieuwenhuyse (1983) summarized these two relationships by stating that the amount of light reaching a depth of 0.1 m ranges between 75 and 79% of that available at the surface at turbidities of 0.50–10 NTUs, from 60 to 69% at turbidities of 25–50 NTUs, and from 0.3 to 5% at turbidities of 500–1,000 NTUs. Relationships between turbidity and light penetration for interior Alaskan streams are similar to those discussed earlier for Eklutna Lake, indicating a close correspondence between turbidity and reduced light penetration in both lakes and streams (Van Nieuwenhuyse and LaPerriere 1986).

Van Nieuwenhuyse and LaPerriere (1986) also described a direct relationship (r^2 = 0.67) between gross primary productivity and light penetration in shallow streams 0–0.5 m deep, using the equation

$$P = 0.0021\ (PAR_{\bar{Z}}); \qquad (6)$$

P = gross primary productivity (kcal m^{-2} d^{-1});
$PAR_{\bar{Z}}$ = photosynthetically active radiation available at mean depth $\bar{Z}$ (kcal m^{-2} d^{-1}).

This equation provides a means for comparing primary production in streams of mean depths of up to 0.5 m for waters of varying turbidities by using equations (4) and (5). Because gross productivity is described as directly proportional to light available at depth in equation (6), any reduction in light penetration caused by turbidity above clear-water conditions could cause a corresponding decrease in plant production. Equations (4) to (6) are reduced to

$$P = \frac{10^{2-[1+0.024(T)]Z}}{10^{2-Z}}; \qquad (7)$$

P = proportion of primary production in streams of turbidity T to primary production in clear water, at depth Z;
T = turbidity (NTU);
Z = depth (m).

Equation (7) can be used to model the effect of various turbidity levels on light available at depth and consequently on production of plant material in streams (Figure 5). Calculations from these relationships indicate that a turbidity of only 5 NTUs

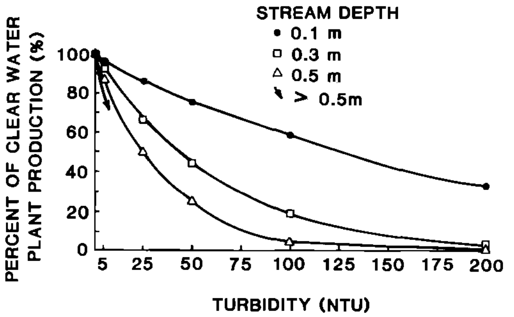

FIGURE 5.—Reduction in plant production with increased turbidity in artificially turbid streams of various depths in interior Alaska (derived from equation 7); NTU is nephelometric turbidity unit.

TABLE 3.—Spearman rank correlation (r_s) of benthic invertebrate density and biomass with turbidity and sediment concentration in paired mined and unmined watersheds in interior Alaska (analyses from Wagener and LaPerriere 1985).[a]

Invertebrate abundance	Turbidity (NTU[b])	Suspended sediment concentration (mg/L)	Settleable solids (mL/L)
Density (number/0.1 m^2)	−0.83	−0.83	−0.70
Biomass (mg/0.1 m^2)	−0.76	−0.70	−0.53

[a] Absolute values of correlation coefficient r_s > 0.58 are significant at $P < 0.05$.

[b] Nephelometric turbidity unit.

can decrease the primary productivity of shallow, clear-water streams by about 3–13%. An increase of 25 NTUs may decrease primary production by 13–50% in shallow streams. Primary production in clear streams of depths greater than 0.5 m would be reduced even further. This model is intuitively conservative because water with zero turbidity is assumed to have an extinction coefficient of 1 m^{-1} (equation 4), a greater extinction than has been measured in clear water elsewhere.

Reduction of standing crop or primary production in streams, for both algae and vascular plants, by turbidity has been corroborated by investigators in Great Britain (Swale 1964; Westlake 1966; Lund 1969; Lack and Berrie 1976), who reported turbidity and light intensity (as opposed to nutrient concentrations) as the factors most commonly limiting to primary production in streams. Stross and Stottlemeyer (1965) reported that turbidity decreased primary production per unit surface area in the Patuxent River, Maryland. Wang (1974) reported reduced algal growth with increased turbidity in Illinois rivers, and Hancock (1973) reported lower production and altered plant species composition caused by turbidity from gold mining in a stream in South Africa. Van Nieuwenhuyse (1983) concluded that, for interior Alaskan streams, the demonstrated importance of light in controlling a stream's productivity points to increased turbidity as the single most important disruption to that productivity.

Terrestrial sources of energy (which are presumably unaffected by turbidity) may be important to fish production, but their importance is often overstated (Minshall 1978), particularly in waters with little terrestrial vegetation along the banks (Vannote et al. 1980). High turnover rates of aquatic plant production and the high food quality of aquatic plants are cited as a basis for believing that aquatic food chains often are supported largely by aquatic plants (McIntire 1973; McIntire and Colby 1978; McCullough et al. 1979; Benke and Wallace 1980; Hornick et al. 1981; Lamberti and Resh 1983). Cowan and Oswood (1983) showed that the contribution of terrestrial detritus to subarctic streams in Alaska is low compared with that in temperate streams; seasonal pulses of aquatic plant production may, therefore, be crucial to the maintenance of macroinvertebrates and fish in these subarctic streams (Chapman and Demory 1963; Hornick et al. 1981; M. W. Oswood, University of Alaska, personal communication). Chapman and Knudsen (1980) and Murphy et al. (1981) concluded that even in the heavily forested watersheds of the Pacific Northwest, increased light availability to stream bottoms can translate through aquatic food webs to more salmonids.

Abundance of Macroinvertebrates

Macroinvertebrates constitute a basic component of the food supply of stream-dwelling salmonids. We observed that densities and biomass of benthic invertebrates in unmined streams were significantly higher than in mined streams and, in heavily mined watersheds, most taxa became very rare or were eliminated (Wagener and LaPerriere 1985). Although reduced invertebrate densities were thought to have resulted from habitat alteration caused by settleable solids and increased fines in bottom substrates (LaPerriere et al. 1983), Wagener and LaPerriere (1985) concluded that turbidity constituted the strongest statistical descriptor of reduced density and biomass of macroinvertebrates in those mined streams (Table 3). Similar reductions in the abundance of macroinvertebrates caused by sediment input have been ob-

TABLE 4.—Abundance of young-of-the-year Arctic grayling in paired mined and unmined watersheds in interior Alaska (data from Simmons 1984).

Creek	Year	Mean CPUE[a] (number/haul)	Mean (SD) turbidity[b] (NTU[c])	Mean (SD) settleable solids[b] (mL/L)
Twelvemile	1982	8.7		
(unmined)	1983	2.7	1.3 (1.4)	<0.1
Birch	1982	0.08		
(mined)	1983	0.09	727 (419)	0.6 (0.6)
McManus	1982	1.6		
(unmined)	1983	0.5	2.7 (6.1)	<0.1
Faith	1982	0		
(mined)	1983	0	75 (74)	<0.1

[a] Catch per unit effort (CPUE) was averaged from over 60 beach-seine hauls in each stream, July–September each year.

[b] Mean turbidity and settleable solids were averaged from over 30 samples in each stream, June–September; means not reported for 1982.

[c] Nephelometric turbidity units.

served elsewhere in interior Alaska (Weber and Post 1985) as well as in the Yukon and Northwest territories, Canada (Rosenberg and Snow 1975; Rosenberg and Wiens 1978; Mathers et al. 1981; Soroka and McKenzie-Grieve 1983; Birtwell et al. 1984).

Effects on Fish

We collected many Arctic grayling (*Thymallus arcticus*) in unmined streams but none in mined streams during our sampling, except during the presumed autumn migration of some fish through streams influenced by mining (LaPerriere et al. 1983; Simmons 1984). Although sediment input from mining included settleable solids in addition to suspended turbidity-causing sediments, distribution and abundance of young-of-the-year Arctic grayling were likely most directly influenced by turbidity in the water column (Table 4). Results of preliminary studies indicate higher mortality over 96 h of young-of-the-year Arctic grayling caged in screened enclosures in mined Birch Creek (several hundred NTUs) than in similar enclosures in clear Twelvemile Creek (J. D. LaPerriere, unpublished data). Studies in the Yukon Territory indicated that the Arctic grayling appeared to avoid turbid waters except during migration (Knapp 1975) and that the abundance of Arctic grayling was consistently lower below sources of suspended sediment than in clear-water areas upstream from these turbid discharges (Birtwell et al. 1984).

One likely effect of turbidity is a reduction in the feeding capability of Arctic grayling, because these fish feed by sight. Simmons (1984) examined the stomachs from caged Arctic grayling in mined and unmined streams and found that fish in turbid waters contained few or no aquatic insects. This observation may have been a result of reductions in the abundance of macroinvertebrates in mined streams or a reduction in the capability of the fish to find them, or both. Simmons (1984), who also observed an absence of internal fat reserves and parr-mark development in young-of-the-year Arctic grayling caged in turbid waters, attributed these effects to dietary deficiencies.

A separate study in Alaska on Arctic grayling at Toolik Lake in the Brooks Range showed that the reactive distance of feeding fish decreased with decreasing levels of available light (Schmidt and O'Brien 1982). Thus, a reduction in light penetration caused by turbidity in waters containing Arctic grayling undoubtedly hampers their ability to capture food. Direct effects of turbidity in reducing feeding rates have been observed in bluegills (*Lepomis macrochirus*) by Gardner (1981) and O'Brien (1977), and the reactive distance for bluegills was shown to be significantly reduced by turbidities between 1 and 30 Jackson turbidity units (JTU; Vinyard and O'Brien 1976).

Other preliminary studies conducted by the Alaska Department of Fish and Game (ADFG) have shown that juvenile coho salmon (*Oncorhynchus kisutch*) prefer clear water over turbid water in the Susitna River drainage (ADFG 1983b) and in the Stikine River drainage (Shaul et al. 1984), and that juvenile chinook salmon (*Oncorhynchus tshawytscha*) grow faster in clear tributaries than in the main stem of the glacially turbid Taku River (Kissner 1983). Arctic grayling prefer clear tributaries and migrate to deeper main-stem rivers primarily to spend the winter, a period when sediment and turbidity levels are significantly reduced (Tack 1980; ADFG 1983a). Arctic grayling avoid streams carrying silt produced by mining (Wojcik 1955; Warner 1957; Durtsche and Webb 1977; Meyer and Kavanaugh 1983; Weber and Post 1985). Studies conducted in the Susitna River drainage by Suchanek et al. (1984a, 1984b) indicated that adult rainbow trout (*Salmo gairdneri*) and Arctic grayling avoid turbid water above 30 NTUs and that juvenile chinook salmon use turbid waters only in the absence of object-type cover such as overhung banks and instream debris. Results of a study conducted on the Taku River by Meehan and Siniff (1962) suggested that turbidity masks differences in light between night and day and thus alters the daily pattern of downstream migration of salmon smolts. Brett and Groot (1963) suggested that turbidity may directly affect the migration of salmon through interference with visual cues.

The avoidance of turbid water by salmonid fishes has been corroborated by field studies in California (Sumner and Smith 1940) and laboratory studies in Washington (Bisson and Bilby 1982; Whitman et al. 1982). In particular, Bisson and Bilby (1982) discovered that juvenile coho salmon avoided water with turbidities of 70 NTUs and above. Again, 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). Ginetz and Larkin (1976) reported reduced predation by rainbow trout on sockeye salmon fry in turbid water of experimental streams in British Columbia; Tippets and Moyle (1978) reported altered feeding behavior of adult rainbow trout due to glacial turbidity in California; Crecco and Savoy (1984) suggested that turbidity may reduce the feeding success of larval American shad (*Alosa sapidissima*) in the Connecticut River; and Johnston and Wildish (1982) demonstrated reduced feeding of larval Atlantic herring (*Clupea harengus harengus*) in Great Britain in estuaries with suspended sediment concentrations of 20 mg/L.

Effects on Human Use

Turbidity also affects human usage. It is generally acknowledged that turbid water is less acceptable than clear water for consumption, contact recreation, and perhaps aesthetic enjoyment. Turbidity often reduces the range of opportunities available for the use of a water body (NAS and NAE 1973; USEPA 1976). An analysis of angling effort on the naturally clear Chatanika River in interior Alaska (A. H. Townsend 1983 memorandum to B. H. Baker, ADFG, on sport fishing and placer mining) indicated that a turbidity of 8–50 NTUs 40 km downstream from mine discharges coincided with, and may have contributed to, a 55% decline in sport fishing. The Chatanika River was the second most popular water body for sport fishing in interior Alaska in 1977 and 1978, but fell to seventh in 1979 when increased mining activity muddied the water. In Denali National Park and Preserve, Miller (1981) reported reduced sportfishing effort on streams made turbid by mining activities. Avoidance of turbid waters by sport fishermen and reduced angler success in turbid waters also have been described outside Alaska (Buck 1956; Tebo 1956; Bartsch 1960; Ritter and Ott 1974; Langer 1980).

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 ADFG in western, southcentral, and interior Alaska have reported specific instances where waste-water discharges from placer mines to otherwise clear streams have obstructed aerial escapement surveys for adult salmon (ADFG memoranda by D. J. Schneiderhan in 1982, L. H. Barton in 1983, and K. R. Hepler in 1983). An informal consensus of ADFG biologists is that an absolute turbidity of 4–8 NTUs may be sufficient to interfere with these aerial surveys.

Turbidity and Suspended Sediment

Although no studies conducted in Alaskan streams have identified adverse effects on aquatic habitats due to specific concentrations of suspended sediment, there have been numerous studies conducted elsewhere describing such impacts (see Lloyd 1987). Given that elevated turbidities usually are caused by suspended sediments, it would be useful to define relationships whereby turbidity could be used to estimate the more-difficult-to-measure concentration of suspended sediment.

Analysis of information from the WATSTORE data base, compiled by the U.S. Geological Survey for Alaska streams during the period 1976–1983 (May–October) and involving 235 samples from 37 stations on 34 rivers, yielded a significant correlation ($r^2 = 0.83$ for log/log transformation) between turbidity and suspended sediment concentration (Figure 6). The resulting regression equation is:

$$\log_{10}T = -0.357 + 0.858 \log_{10}SSC; \qquad (8)$$

T = turbidity (NTU);
SSC = suspended sediment concentration (mg/L).

This equation can be transformed back to

$$T = 0.44(SSC)^{0.858}. \qquad (9)$$

This relationship was developed from data dominated by a high proportion of samples from large silt-laden rivers, but diverse stream types and locations were represented. For this sample set, the regression shows that turbidity and SSC are related.

A similar relationship between turbidity and SSC ($r^2 = 0.92$, for log/log transformation) was developed by Peratrovich, Nottingham and Drage

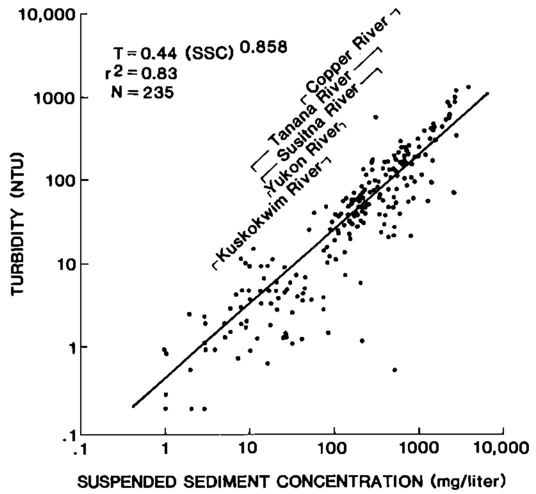

FIGURE 6.—Turbidity versus suspended sediment concentration for 34 Alaskan streams; NTU is nephelometric turbidity unit.

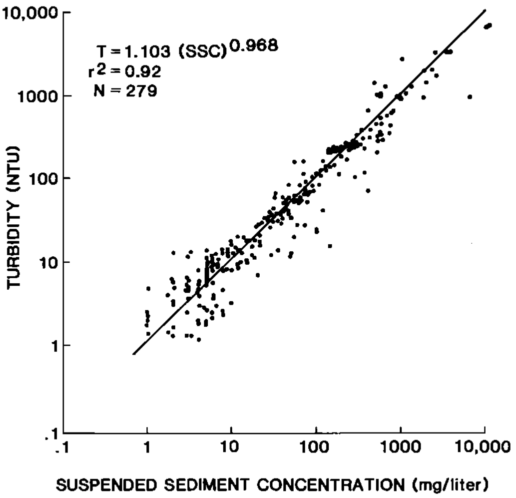

FIGURE 7.—Turbidity versus suspended sediment concentration for five interior Alaskan streams; NTU is nephelometric turbidity unit.

(1982), using data from the glacially turbid Susitna River,

$$T = 0.185(SSC)^{0.998}. \qquad (10)$$

This equation predicts slightly lower turbidities for specific SSC than does the relationship developed from the data for rivers state-wide.

Data compiled from turbid placer-mined and neighboring unmined clear streams in interior Alaska (Figure 7) also yielded a significant correlation ($r^2 = 0.92$). The resulting regression equation is:

$$\log_{10}T = 0.0425 + 0.9679 \log_{10}SSC, \text{ or} \qquad (11)$$

$$T = 1.103(SSC)^{0.968}. \qquad (12)$$

This equation predicts higher turbidities for specific SSC than equations (9) and (10).

Many investigators caution that relationships between turbidity and suspended sediment concentration are useful only for the specific drainages for which they were developed because relationships differ between drainages due to particular sediment characteristics (e.g., Duchrow and Everhart 1971; Kunkle and Comer 1971; Beschta 1980). On the other hand, several practical applications have been developed to use turbidity measurements as reasonable estimates of suspended sediment concentrations (e.g., Truhlar 1976; Schroeder et al. 1981; Earhart 1984). Calculations from equations developed for Alaskan streams (Table 5) indicate that relationships between turbidity and suspended sediment concentration vary among drainages or groups of drainages, but also that measurements of turbidity can be used to identify at least threshold levels of suspended sediment concentration for a broad range of watersheds.

Conclusions

The recent Alaskan studies summarized here illustrate the effects of turbidity in cold, freshwater habitats. Increased levels of turbidity dramatically reduce light penetration in both lakes and streams

TABLE 5.—Prediction of turbidity caused by suspended sediment concentrations in streams throughout Alaska, in the Susitna River, and in interior Alaskan streams. Values in parentheses are 95% confidence intervals.

Suspended sediment concentration (mg/L)	Estimated turbidity (NTU[a])		
	State-wide streams[b]	Susitna River[c]	Interior Alaskan streams[d]
1	0.45 (0.08–2.4)	0.20	1.1 (0.31–3.9)
10	3.2 (0.58–17)	1.8	10 (2.9–36)
20	5.8 (1.0–31)	3.7	20 (5.7–71)
25	7.0 (1.3–38)	4.6	25 (7.1–88)
50	13 (2.3–70)	9.2	49 (14–172)
80	19 (3.4–104)	15	77 (21–271)
100	23 (4.2–126)	18	95 (27–337)
400	75 (13–417)	73	364 (103–1,291)

[a] Nephelometric turbidity units.

[b] Derived from equation (9). Skewed confidence intervals are artifacts of logarithmic transformation.

[c] Derived from equation (10). Data were not available to calculate confidence intervals.

[d] Derived from equation (12).

and are associated with decreased production and abundance of plant material (primary production), decreased abundance of food organisms (secondary production), and decreased production and abundance of fish. Most notable are the dramatic changes in light penetration and subsequent primary production caused by even small (5–10 NTUs) increases in turbidity above naturally clear conditions.

There are definable relationships also between turbidity and the suspended sediment concentration of Alaskan waters that enable the use of turbidity as a reasonable estimator of suspended sediment concentration. Elevated suspended sediment concentrations have been directly related to adverse impacts on aquatic systems in studies made outside Alaska; hence, measures of turbidity can be useful in identifying not only trophic interactions resulting from reduced light penetration but also possible effects from at least threshold levels of suspended sediment concentration.

Water quality standards based upon specific turbidity levels can be developed to protect aquatic habitats from sediment pollution, and can address impacts associated with both the reduction of light penetration and the direct physical effects of suspended sediment. Specific information presented here has already been used to justify turbidity standards based on the level of protection desired (Lloyd 1987) and to predict the capacity of aquatic systems to support fish-stocking programs (Koenings and Burkett, in press).

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