similar fish acclimated to warm waters in stream cages and subjected to short exposures of concentrations up to 250,000 mg/L.

Obviously, the determination of precise concentrations of suspended sediment that cause acute mortality is difficult and results vary. In field conditions, it may be impossible to distinguish between the effects of suspended sediment and other mortality factors such as heavy metals in mined streams (LaPerriere et al. 1983; Scannell 1988), other toxicants, contaminated suspended sediment particles, and interactions of other effects that by themselves may be sublethal. Servizi and Martens (1991) observed in laboratory tests on acute lethality that smaller fish (coho salmon) were less tolerant to suspended sediment than were larger fish, and that tolerance to suspended sediment was greatest at some optimum temperature (7°C) than at lower (1°C) or higher (18°C) temperatures. In their studies of sediment from placer gold mining and its effects on Arctic grayling, Reynolds et al. (1989) used cage experiments to expose sac fry to suspended sediment in natural streams. Of the sac fry in a mined stream (turbidity >1,000 NTU) 50% died in 96 hours, whereas in an unmined stream only 13% died. Mortality in the mined stream was much higher for sac fry than for fingerlings and juveniles.

Sublethal Effects

Much more information is available on sublethal effects of suspended sediment. Most of these reports were based on laboratory experiments, wherein specific effects were observed critically and often quantified. Effects tested included (1) avoidance and distribution, (2) reduced feeding and growth, (3) respiratory impairment, (4) reduced tolerance to disease and toxicants, and (5) physiological stress (review by Lloyd 1987).

Avoidance and distribution.—Perhaps the most important sublethal effect of suspended sediment is the behavioral avoidance of turbid or silty water, resulting in long reaches or entire streams devoid of fish. Thus, the effect of avoidance may be the total preclusion of resident fish and juvenile anadromous salmonids. This factor destroys a stream as a productive fishery just as surely as if the population were killed. Many published reports have documented such effects.

Avoidance of water muddied from mining silt by spawning adult salmon was observed by Sumner and Smith (1940) in a California river. Avoidance by adult chinook salmon of a spawning stream that contained volcanic ash was reported by Whitman et al. (1982).

DeVore et al. (1980) reported on fish species and biomass in streams in the western Lake Superior region. Some contained red-clay suspended sediment with concentrations up to about 400 mg/L and some were relatively clear. The turbid, warm streams contained many warmwater species, whereas the clear streams contained few species, mostly salmonids. Total fish standing stocks in the turbid streams were about 80–100 kg/ha; in the clear streams (even though having few species) standing stocks were about the same, 50–120 kg/ha.

Birtwell et al. (1984) and Scannell (1988) concluded that Arctic grayling in Alaska streams were confined to clear water only and did not exist in streams

heavily exposed to silt from placer gold mining. In work on the Fraser River, British Columbia, Servizi and Martens (1992) observed avoidance by young coho salmon of high suspended sediment derived from gold-mining spoils; they pointed out that coho salmon may move laterally to the sides of a river to avoid high turbidity.

Much research on avoidance of silty water has been conducted in laboratory and field experiments. Juvenile coho salmon (Bisson and Bilby 1982) and young Arctic grayling (Scannell 1988) avoided high concentrations of suspended sediment (as measured by turbidity in NTU). Coho salmon avoided turbidity greater than 70 NTU, and Arctic grayling avoided turbidity greater than 20 NTU. Sigler et al. (1984) also observed that juvenile coho salmon and steelhead trout avoided turbid water in laboratory experiments. McLeay et al. (1984, 1987) observed Arctic grayling that moved in a downstream direction in laboratory streams when subjected to mining silt. Berg and Northcote (1985) observed that juvenile coho salmon exposed to short-term pulses of suspended sediment dispersed from established territories.

In experimental stream channels related to long-term studies on coho salmon in the Clearwater River, Washington, Cederholm and Reid (1987) subjected juvenile coho salmon to three levels of suspended sediment concentrations: clear water (0 mg/L); medium suspended sediment (1,000–4,000 mg/L); and high suspended sediment (4,000–12,000 mg/L). They observed that the fish preferred clear and medium conditions, suggesting that juvenile fish preferentially avoid high suspended sediment conditions in silty streams. Furthermore, they observed evidence of stress in the fish—an increased rate of opercular movement and "coughing"; sediment accumulations on gill filaments; and declines in prey capture success—at the higher suspended sediment concentrations.

In a different approach involving competition between species, Gradall and Swenson (1982) concluded that red-clay turbidity favored the creek chub over brook trout in sympatric populations in small streams. The creek chub preferred the cover provided by suspended sediment turbidity, whereas brook trout preferred clearer water.

Reduced feeding and growth.—One of the major sublethal effects of high suspended sediment is the loss of visual capability, leading to reduced feeding and depressed growth rate. Several researchers have reported decreased feeding and growth by fish in turbid conditions resulting from suspended sediment. For example, Cleary (1956) and Larimore (1975) noted that turbidity in smallmouth bass streams caused very young fry to be displaced downstream due to the loss of visual orientation. The bass left areas where they fed on the microcrustaceans so important to early fry stages.

Most research on feeding and growth, however, has been experimental. McLeay et al. (1984, 1987) reported impaired feeding ability by Arctic grayling exposed to placer mining silt; Reynolds et al. (1989) reported similar results for Arctic grayling in cage experiments in Alaska streams. Redding et al. (1987) observed little or no feeding by juvenile coho salmon and steelhead trout exposed to suspended sediment in Oregon laboratory experiments, and Berg and Northcote (1985) reported reduced feeding by juvenile coho salmon on drift (brine shrimp) in laboratory tests. In most cases, vision impairment due to suspended sediment turbidity was determined to be the factor that reduced the ability of the fish to capture prey (Sykora et al. 1972; Berg 1982).

Respiratory impairment.—Despite early speculation about gill damage by suspended sediment (Cordone and Kelley 1961; Herbert and Merkens 1961), few reports indicated gill damage and impairment of respiratory function as a source of mortality (McLeay et al. 1987; Redding et al. 1987; Reynolds et al. 1989). Whereas high suspended sediment concentrations may not be immediately fatal, thickening of the gill epithelium may cause some loss of respiratory function (Bell 1973).

Berg and Northcote (1985) reported increased gill-flaring in high turbidities due to suspended sediment; this was viewed as an attempt by fish to cleanse their gill surfaces of suspended sediment particles. Similarly, Servizi and Martens (1992) recorded an eightfold increase in "cough" frequency over controls at suspended sediment concentrations of 230 mg/L. It seems likely that fish have evolved behavioral or physiological adaptations to temporary high concentrations of suspended sediment in order to survive short-term conditions caused by natural spates and floods. Chronic high suspended sediment concentrations that are initiated by anthropogenic sources, however, may not be tolerated.

Studying the effect of Mount St. Helens volcanic ash on chinook and sockeye salmon smolts, Newcomb and Flagg (1983) reported total mortality at very high ash levels (25% ash by volume) but no mortality at less than 5% ash. Based on the appearance of the gills, they suggested that impaired oxygen exchange was the primary cause of death, but they concluded that most airborne ashfalls would not cause acute mortality.

Reduced tolerance to disease and toxicants.—Another potential sublethal effect of suspended sediment is decreased tolerance to disease and toxicants. Several investigators have commented on this possibility, although it does not appear to have been researched intensively. Redding et al. (1987) observed higher mortality in young steelhead trout exposed to a combination of suspended sediment (2.5 g/L) and the bacterial pathogen *Vibrio anguillarum* than in trout exposed to the bacterium alone. Infection in coho salmon fry by a viral kidney disease also resulted in mortality when the fish were exposed to suspended sediment. Goldes et al. (1988) suggested that observed gill lesions were the result of kaolin clay that created a favorable environment for protozoan colonization. McLeay et al. (1984, 1987) reported decreased tolerance of Arctic grayling to an experimental toxicant (pentachlorophenol) in high concentrations of suspended sediment (up to 250 g/L), compared to the toxicant alone.

It appears that suspended sediment induces stress at some raised level of concentration and that such stress tends to reduce the tolerance of fish to a number of environmental factors, including exposure to disease and toxicants. The possibility of further sediment-related problems of disease and toxicants needs more research.

Physiological stress.—Exposure to sublethal levels of suspended sediment may induce physiological stress, which in turn may reduce the ability of the fish to perform vital functions. Redding et al. (1987) reported physiological changes indicative of stress in coho salmon and steelhead trout, including elevated plasma cortisol, plasma glucose, and hematocrits; no direct mortality occurred. The authors concluded that such stress may not be severe, but it may reduce the ability of the fish to feed or resist disease. Servizi and Martens (1992) also reported elevated serum glucose in coho salmon at high suspended sediment levels. In their reviews, Hall (1984a) and Lloyd (1987) included other reports from the unpublished literature that implicated suspended sediment as a factor which induced stress, intolerance, and behavioral problems.

In a recent review, Newcombe and MacDonald (1991) pointed out that in most published studies of suspended sediment and fish, only concentrations were given; they further pointed out that the duration of exposure is essential for more complete understanding of the effects of suspended sediment. They proposed a dose–concentration duration–response model; however, the size of suspended sediment particles, a possible important factor, was not included in the model. The authors also provided a valuable set of three tables listing (1) direct mortality due to suspended sediment, including suspended sediment concentration and duration of exposure (19 papers); (2) sublethal responses (13 papers); and (3) behavioral responses (13 papers). All fish species listed were salmonids. Not all references were for inorganic or suspended sediments, but the high mortality noted in the research cited by Newcombe and MacDonald (1991) points up the need for inclusion of exposure duration. The authors also included a similar table on responses of invertebrates, discussed in a previous section.

Warmwater Fishes

Studies of either direct mortality or sublethal effects of suspended sediment on warmwater fish species are relatively few in the literature. Warmwater streams, although supporting many species, do not appear to attract research support to the same degree as do salmonid streams. Another reason may be that because warmwater streams are often muddy with silt or sand bottoms, their fish species may be perceived to have evolved tolerances to occasional high concentrations of suspended sediment. Some greater effects of deposited sediment have been reported, however, especially on reproductive success, and these are reported in a later section.

The work of Wallen (1951), cited previously, remains the most instructive about suspended sediment effects in warmwater fishes, although not all of the fishes he studied were stream inhabitants. The clogging of gills, and thus respiratory impairment, and induction of disease and parasites have been suggested as effects of suspended sediment (Trautman 1933; Pautske 1938; Wallen 1951).

Despite the observation of seemingly viable fish communities in sometimes extremely turbid and silty conditions, some warmwater species have disappeared over the long term (Larimore and Smith 1963; Smith 1971; Trautman 1981). Muncy et al. (1979), in their extensive review on suspended sediment and warmwater fish, concluded that great variation exists among these species in tolerance to suspended sediment, and that the loss of some species from an otherwise