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Biological Effects of Suspended Sediments: A Review of Suspended Sediment Impacts on Fish and Shellfish with Relation to Dredging Activities in Estuaries

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Abstract.—Objective assessment of the effects of increased concentrations of suspended sediment caused by human activities, such as navigation dredging, on estuarine fish and shellfish requires an integration of findings from biological and engineering studies. Knowledge is needed of (1) the suspended sediment characteristics typical of both ambient and dredging-induced conditions, (2) the biological responses of aquatic organisms to these suspended sediment dosages, and (3) the likelihood that organisms of interest will encounter suspended sediment plumes. This paper synthesizes the results of studies that report biological responses to known suspended sediment concentrations and exposure durations and relates these findings to suspended sediment conditions associated with dredging projects. Biological responses of taxonomic groups and life history stages are graphed as a function of concentration and exposure duration. The quality and taxonomic breadth of studies on which resource managers must rely when evaluating potential impacts from activities that resuspend sediments, such as dredging projects, are addressed. Review of the pertinent literature indicates that few data exist concerning biological responses of fish and shellfish to suspended sediment dosages commonly associated with dredging projects. Much of the available data come from bioassays that measured acute responses and required high concentrations of suspended sediments to induce the measured response, usually mortality. Although anadromous salmonids have received much attention, little is known of behavioral responses of many estuarine fishes to suspended sediment plumes. Likewise, the effects of intermittent exposures at periodicities that simulate the effects of tidal flushing or the conduct of many dredge operations have not been addressed.

Many human activities in or near aquatic habitats resuspend bottom sediments and create turbid conditions that differ in scope, timing, duration, and intensity from the resuspension events induced by storms, freshets, or tidal flows. Dredging of navigation channels is one such source of bottom disturbance. Although impacts on benthic communities as a consequence of dredging have been documented in numerous studies (e.g., Kaplan et al. 1973; Van Dolah et al. 1984; Clarke et al. 1993), other categories of impact remain largely unquantified. Among the latter are effects of resuspended sediments on fish and shellfish.

Suspended sediments can elicit a variety of responses from aquatic biota, primarily because many attributes of the physical environment are affected. For example, increased light attenuation caused by turbidity reduces visibility, shortens the depth of the photic zone, and can alter the vertical stratification of heat in the water column (Moore 1978). Not all of these effects are necessarily detrimental to aquatic organisms; for example, many fish thrive in turbid estuarine environments (Blaber and Blaber 1980; Cyrus and Blaber 1992), presumably benefiting from a reduced risk of predation. Under laboratory conditions, several species actively prefer turbid over clear water conditions (Gradall and Swenson 1982; Cyrus and Blaber 1987), presumably using turbid conditions to facilitate feeding and avoidance behaviors. Alternatively, physical impacts from increased concentrations of suspended sediment can be detrimental, for example, resulting in egg abrasion, reduced bivalve pumping rates, and direct mortality.

The literature concerning impacts of suspended sediment on aquatic fauna has been reviewed periodically (e.g., Morton 1977; Priest 1981; Kerr 1995); until recently, however, there has been little attempt to characterize environmental impacts with models that can be easily used by resource managers (Newcombe and MacDonald 1991). Historically, the effects of suspended sediment on fish

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were viewed as a function of concentration. That is, most experimental studies used concentration alone as the variable of interest; exposure durations were not varied and in many cases were not reported (Sherk and Cronin 1970; LaSalle et al. 1991). More recently, exposure duration has been recognized as another important factor. For instance, concentration alone correlated poorly with the responses of salmonid fishes to suspended sediments, whereas dosage (measured as mg h L^{-1}) was more strongly associated with fish responses (Newcombe and MacDonald 1991). Simplified models that predict the impacts of suspended sediment dosages on freshwater fishes have been developed (Newcombe and MacDonald 1991; Gregory et al. 1993; MacDonald and Newcombe 1993) and recently expanded to include estuarine fishes (Newcombe and Jensen 1996). The estuarine model, however, was developed using some concentration data that were incorrectly converted from the original study, which greatly compromises its general application. We have modified the approach of Newcombe and Jensen (1996) to provide a composite empirical view of the effects of suspended sediment on estuarine fish and shellfish; we also further examine the salmonid responses.

Methods

Newcombe and Jensen (1996) recognized the utility of ''look-up tables,'' which can be used in the field or as an easy reference when estimating biological responses to suspended sediments. Their literature review synthesized dose–response studies for which data triplets were available, yielding a matrix of predicted biological responses. The data triplet variables were (1) suspended sediment concentration, (2) duration of exposure, and (3) severity of ill effect for fishes. We too used these data triplets, synthesized from the reviewed literature, to depict the biological responses of salmonids, estuarine fish, and shellfish to various dosages of suspended sediment. We present graphs illustrating biological responses as a function of suspended sediment dosages along with hatched boxes depicting the probable range of suspended sediment dosages associated with dredging projects. The upper limits of the concentration axis of the hatched boxes represent extreme conditions—conditions that have been observed but are not typical—of navigation dredging impacts. These graphs combine data from available studies that report suspended sediment concentrations, exposure durations, and a description of organisms' responses by taxonomic group and life history stage. Response categories include the following effects: none, behavioral, sublethal, and lethal (measured as percentage mortality). The behavioral category includes those responses recognized by Newcombe and Jensen (1996): alarm reaction, abandonment of cover, and avoidance response. The sublethal category includes all of the sublethal effects recognized by Newcombe and Jensen (1996): short-term reduction in feeding rates or success, minor physiological stress such as increased coughing or respiration rates, moderate physiological stress, moderate habitat degradation, impaired homing, and indications of major physiological stress such as long-term reduction in feeding rate or success. The following effects, which were classified as paralethal by Newcombe and Jensen (1996), were also included in the sublethal category: reduced growth rate, delayed hatching, and reduced fish density. By excluding the paralethal response category, we assume a distinction between lethal responses and sublethal and behavioral responses. The nature of all biological responses depicted in this study for fish and shellfish are listed in Table A.1. Data for salmonid fish responses were taken from Table A.1 of Newcombe and Jensen (1996).

Descriptive accounts of fish and shellfish responses to various conditions are given in cases where studies did not report suspended sediment concentrations or exposure durations or where optical measures of turbidity (nephelometric turbidity units [NTUs] or Jackson turbidity units [JTUs]) were reported rather than gravimetric measures of suspended sediments (mg/L). Hypothetical impacts related to dissolved oxygen depletion and the release of contaminants have been summarized by LaSalle (1990) and are not addressed here. The habitat types simulated in experimental tests for nonsalmonid freshwater fishes are noted in Table 1.

Various kinds of particulate matter, including silt, Fuller's earth, kaolin clay, incinerator residue, charcoal, silica, and volcanic ash, have been used to test fish and shellfish responses to suspended sediments. In studies testing natural sediments in addition to other sediment types, only the results of the natural sediment tests were used in this review. Sediment types are noted in Tables A.1–5. Because Sherk et al. (1974) tested a broad range of species with Fuller's earth, both those results and those elicited by natural sediments are included in this review.

Results

Salmonid and Selected Freshwater Fishes

Behavioral responses.—Behavioral responses to suspended sediments have been extensively stud-

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TABLE 1.—Life history stages and habitats of estuarine and nonsalmonid freshwater fishes for which concentration and duration data are available from studies that test biological responses to suspended sediments. Responses to natural sediments were used where available. Cases where the life history stage occurs in freshwater are noted by fw.

Habitat	Eggs	Larvae	Juveniles	Adults
Pelagic	Blueblack herring	Pacific herring	Bluefish	White perch
	Alosa aestivalis (fw)	*Clupea pallasi*	*Pomatomus saltatrix*	
	Alewife	American shad (fw)	Atlantic menhaden	Bay anchovy
	Alosa pseudoharengus (fw)		*Brevoortia tyrannus*	*Anchoa mitchilli*
	Yellow perch	Striped bass (fw)	White perch	Sheepshead minnow
	Perca flavescens (fw)			*Cyprinodon variegatus*
	Striped bass	Yellow perch (fw)		Four spine stickleback
	Morone saxatilis (fw)			*Apeltes quadracus*
				Mummichog
				Fundulus heteroclitus
				Striped bass
				Atlantic silverside
				Menidia menidia
				Shiner perch
				Cymatogaster aggregata
Epibenthic feeders				Spot
				Leiostomus xanthurus
				Cunner
				Tautogolabrus adspersus
Demersal eggs or bottom dwellers	Atlantic herring	White perch (fw)		Striped killifish
	Clupea harengus			*Fundulus majalis*
	American shad			Oyster toadfish
	Alosa sapidissima (fw)			*Opsanus tau*
	White perch			Hogchoker
	Morone americana (fw)			*Trinectes maculatus*

ied for salmonid fishes, which have been measured for subtle reactions that may be early precursors to physiological stress and mortality, such as cough reflexes, swimming activity, gill flaring, and territoriality. Short-term pulses of suspended sediments (sharp increases within an hour) disrupt the feeding behavior and dominance hierarchies of juvenile coho salmon *Oncorhynchus kisutch* and elicit alarm reactions that may cause fish to relocate downstream to undisturbed areas (Berg and Northcote 1985). Increased swimming behavior, interpreted as an alarm reaction, occurred when rainbow smelt *Osmerus mordax* were exposed in a laboratory setting to suspended sediment concentrations of 10 mg/L or more (Chiasson 1993). Alarm reactions disrupt schooling behavior, a concern raised in association with dredging operations in Miramichi estuary, New Brunswick (Wildish and Power 1985).

The influence of turbidity on foraging success or vulnerability to predation is not easily summarized by any generality. Many studies have demonstrated detrimental effects of suspended sediments on the foraging rates of fish (reviewed in Bruton 1985). Conversely, under turbid conditions, the reaction distances to planktonic prey of juvenile chinook salmon *Oncorhynchus tshawytscha* (Gregory and Northcote 1993), bluegill *Lepomis macrochirus* (Vinyard and O'Brien 1976), and rainbow trout *O. mykiss* (Confer et al. 1978; Barrett et al. 1992) decrease as a log-linear function of increasing turbidity. Reaction distance is measured as either the maximum distance at which visual predators can detect their prey (Vinyard and O'Brien 1976) or the maximum distance at which they will pursue their prey (Ware 1972). Reduced visual acuity of fishes in turbid water may result from either shading by particulate matter or the scattering of light by suspended particles, as has been demonstrated with estuarine fishes (Benfield and Minello 1996). However, turbid conditions may also enhance the visual contrast of prey items and thus increase overall feeding rates, as was demonstrated for larval Pacific herring *Clupea pallasi* (Boehlert and Morgan 1985). Alternatively, increased turbidity may reduce the risk of predation while foraging and result in increased foraging rates, as was observed for juvenile chinook salmon (Gregory and Northcote 1993). Turbidity alone as a source of cover for juvenile salmonids is ineffective protection from at least one predator, the cutthroat trout *Oncorhynchus clarki* (Gregory and Levings 1996). Turbidity also reduces the avoidance response of juvenile chinook salmon to bird and fish predator models (Gregory 1993) and induces a surfacing response in juvenile coho salm-

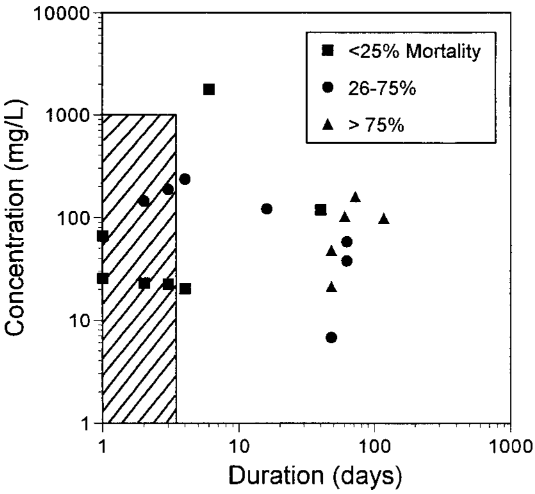

FIGURE 1.—Responses of salmonid and freshwater fish eggs and larvae to suspended sediment concentrations at the given durations of exposure. Data in this figure and Figure 2 came from Table A.1 of Newcombe and Jensen (1996). Lethal response categories are as follows: solid squares (25%), solid circles (26–75%), and solid triangles (>75%). The hatched box (concentration < 1,000 mg/L, duration < 3.5 d) depicts the range of dredging-related suspended conditions most likely to be encountered by stationary eggs.

on, which potentially increases their vulnerability to predation (Servizi 1990; Servizi and Martens 1992).

Sublethal and lethal effects.—The effects of suspended sediments on five species of salmon and trout eggs and larvae (Table A.1 of Newcombe and Jensen 1996) have been tested for durations ranging from 1 to 117 d at concentrations generally less than 200 mg/L (Figure 1). Although spawning behavior and the influence of environmental factors are species specific, several generalizations can be made concerning environmental impacts on spawning success. Salmonid fish eggs incubate in nests on bottom habitat, such as gravel, for 1 to 5 months, the periods depending on several factors, including water temperature (Hassler 1987). Because sedimentation can reduce egg survival (Erman and Lignon 1988; Pauley et al. 1988), suspended sediment dosages in bottom habitats near spawning grounds are a concern near dredging projects. The greatest mortality rates (>75%) were elicited by suspended sediment dosages exceeding those typically generated by hydraulic cutterhead dredges (see Human Activities section for a review of dredge advance rates).

The biological responses of juvenile salmonids to suspended sediment dosages have been relatively well studied, yielding more than 100 data points from which to construct a summary graph (Figure 2a). Under most scenarios, fishes and other motile organisms encounter localized suspended sediment plumes for exposures of minutes to hours, unless the organism is attracted to the plume and follows its location. ''Most probable'' suspended sediment dosages relevant to dredging projects, therefore, are delineated on the figures that depict fish responses by a box that ranges up to 1,000 mg/L for an exposure of up to 1 d (Figure 2a). For juvenile salmonids, the 1-d exposure du-

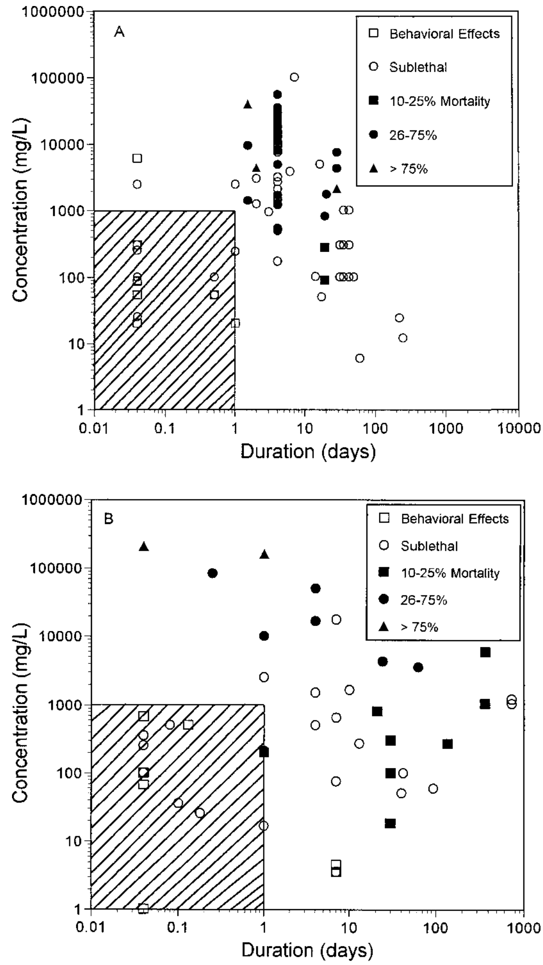

FIGURE 2.—Responses of **(A)** juvenile and **(B)** adult salmonid and freshwater fish to suspended sediments. Behavioral effects are depicted by open squares and sublethal effects by open circles; lethal response categories are the same as in Figure 1. The hatched box (<1,000 mg/L, <1 d) depicts a range of dredging-related suspended sediment conditions that may be experienced by salmonids, based on average rates of out-migration.

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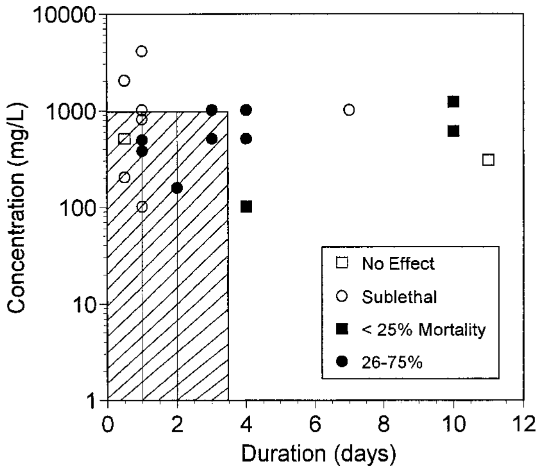

FIGURE 3.—Responses to suspended sediments of nonsalmonid and estuarine fish eggs and larvae. The longest probable exposure duration (3.5 d) corresponds to species with demersal adhesive eggs, whereas shorter durations are expected for demersal semibuoyant and pelagic egg forms. Data for this graph are given in Table A.1.

ration is estimated on the basis of an average rate of out-migration. An additional consideration is the location of the dredging operation in relation to species-specific behavior. For example, exposures would be lengthened in areas where out-migrants meander while making osmoregulatory adjustments in transition from fresh to salt water. For juvenile salmonids, biological responses within the estimated relevant dosage range are limited to behavioral effects and some sublethal responses, such as reduced feeding (Table A.1 of Newcombe and Jensen 1996). Similar results are apparent for adult salmonids and rainbow smelt (Figure 2b). Adult salmonid fish movements are generally based on diel patterns, for example, meandering during daylight hours and progressing upstream at night. Thus, exposure would probably still be less than 1 d. The behavioral responses of adult salmonids for suspended sediment dosages under dredging-related conditions include altered swimming behavior, with fish either attracted to or avoiding plumes of turbid water (Table A.1 of Newcombe and Jensen 1996).

Nonsalmonid Estuarine Fishes

The eggs and larvae of nonsalmonid estuarine fishes exhibit some of the most sensitive responses to suspended sediment exposures of all the taxa and life history stages for which data are available (Figure 3). Probable exposure durations vary for this taxonomic grouping because of the diversity of egg forms. For example, the demersal adhesive eggs of American shad may be exposed to a passing suspended sediment plume for as long as 3.5 d (see Human Activities section for review of dredge advance rates), whereas demersal semibuoyant eggs (e.g., striped bass) and pelagic eggs (e.g., bay anchovy) would probably experience shorter exposure durations. Hatching is delayed for striped bass and white perch eggs exposed to sediment concentrations of 800 and 100 mg/L, respectively for 1 d (Table A.1). These species release eggs in freshwater habitats. Atlantic herring was the only coastal egg-releasing species for which data were found (Table 1); its egg development was not impaired by suspended sediment dosages of 300 and 500 mg/L for 1 d. Mortality occurred at moderate suspended sediment dosages for the larval stages of fishes that occur in freshwater and brackish habitats at this life history stage (Table A.1; Table 1). The larvae of striped bass, American shad, yellow perch, and white perch exhibited increased mortality when exposed to suspended sediment dosages less than or equal to 500 mg/L for 4 d (3 d for striped bass). Pacific herring, which has an estuarine larval form, experienced inhibited feeding at a suspended sediment dosage of 2,000 mg/L for 1 d (Boehlert and Morgan 1985).

Behavioral responses.—Behavioral responses to suspended sediment impacts have been studied in several estuarine fish species. Because many of these studies addressed fish responses to various optical properties of the water, the investigators used turbidity to quantify suspended sediment levels and did not report concentrations. Because turbidity is influenced by many factors—not only sediment concentration but also particle size and hydraulic conditions (Bruton 1985; Lloyd 1987)—conversions of turbidity measures into units of concentration can be unreliable (although see Buchanan and Schoellhamer 1996; Schoellhamer 1996a). Therefore, the results of these behavioral studies are summarized but are not included in the graphs.

Foraging patterns and success are commonly studied behavioral responses of estuarine fishes to suspended sediments. Turbid water reduced feeding in adult Atlantic croaker *Micropogonias undulatus* and pinfish *Lagodon rhomboides* (Minello et al. 1987). Feeding rates of the silverside *Atherina breviceps* were also markedly reduced at high turbidity conditions (120 NTU), presumably because of a decrease in the reactive distance of the fish to their planktonic prey, which can occur at

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turbidities as low as 28 NTU (Hecht and Van der Lingen 1992). Feeding responses under turbid conditions might also be affected by prey behavior. When the prey assemblage was composed primarily of copepods, larval striped bass had lower feeding rates at suspended sediment concentrations of 200 and 500 mg/L but showed no change in feeding success when the prey item was the less elusive cladoceran prey, *Daphnia pulex* (Breitburg 1988).

If persistent, a decreased feeding success among juvenile fish may have serious consequences, influencing survival, year-class strength, recruitment, and overall condition. Measures of these effects, however, did not differ for estuarine fishes collected from turbid and relatively clear water conditions in South Africa (Hecht and Van der Lingen 1992). Feeding strategies may change in turbid waters, as suggested by differences in the stomach contents of the visual predator skipjack *Elops machnata* collected in different turbidity conditions (Hecht and Van der Lingen 1992). Juvenile weakfish *Cynoscion regalis* feed effectively under various turbidity conditions (Grecay and Targett 1996), but their ability to capture prey at low irradiance levels depends on the density of the prey (Connaughton et al. 1994; Grecay and Targett 1996). In contrast, gulf killifish *Fundulus grandis* are less effective at feeding in turbid water but feed readily in clear water at an equivalent reduced illumination; this suggests they are visually limited by the scattering of light rather than light attenuation (Benfield and Minello 1996).

Sublethal responses.—Sherk et al. (1974, 1975) have conducted the most extensive bioassays of suspended sediment impacts on estuarine fishes. They assessed the sublethal effects of Fuller's earth suspensions by measuring blood cell counts, hemoglobin concentrations, blood ionic composition, carbohydrate utilization, and gill histology. Common sublethal responses were increases in red cell counts, hematocrit, and hemoglobin concentrations in the peripheral blood, all of which are consistent with the responses of fish deprived of oxygen (O'Connor et al. 1976). At high concentrations, fine particles coated the fishes' respiratory epithelia, which cut off gas exchange with the water. Larger sediment particles were trapped by the gill lamellae and blocked the passage of water, leading to asphyxiation. The lowest observed concentration–duration combination eliciting a sublethal response in white perch was 650 mg/L for 5 d, which increased blood hematocrit (Sherk et al. 1974). The longest duration for which respons-

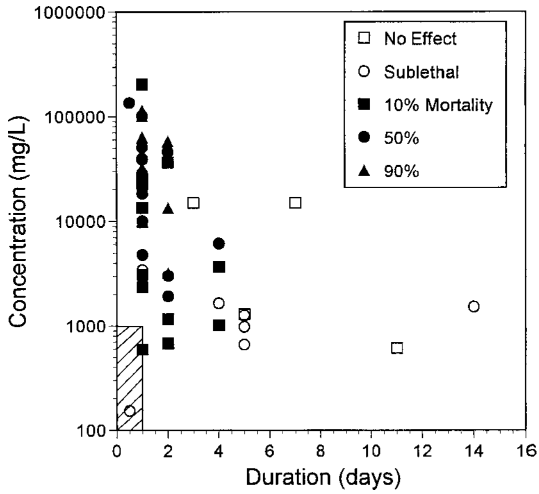

FIGURE 4.—Responses of nonsalmonid and estuarine fish to suspended sediments. Data for this graph are given in Table A.2.

es to suspended sediments were available for estuarine fish was 14 d, which at a concentration of 1,500 mg/L increased the hematocrit in striped bass (Table A.2; Figure 4).

Lethal responses.—Sherk et al. (1974, 1975) used Fuller's earth to generate mortality curves (LC10, LC50, LC90) for six species: white perch, spot, Atlantic silversides, bay anchovies, mummichogs, and striped killifish. Other species were also tested for suspended sediment tolerances, but concentration-dependent mortality curves were not determined for them. From the results of these tests, fish were classified as either tolerant (24-h LC10 $>$ 10,000 mg/L), sensitive (1,000 $<$ 24-h LC10 $<$ 10,000) mg/L, or highly sensitive (24-h LC10 $<$ 1,000 mg/L) to suspensions of Fuller's earth. Tolerant species were the mummichog, striped killifish, spot, oyster toadfish, hogchoker, and cusk eel *Rissola marginata,* all of which are commonly found near the sediment–water interface, where suspended sediment concentrations tend to be higher. White perch, bay anchovy, juvenile Atlantic menhaden, striped bass, Atlantic croaker, and weakfish were classified as sensitive species. This grouping of fish did not share a particular habitat preference. Highly sensitive species included Atlantic silversides, juvenile bluefish, and age-0 white perch.

Several estuarine fish studies evaluated the concentrations of suspended sediments needed to induce mortality for 1- or 2-d exposures (Figure 4; Table A.2). Atlantic silversides and white perch were among the estuarine fish with the most sen-

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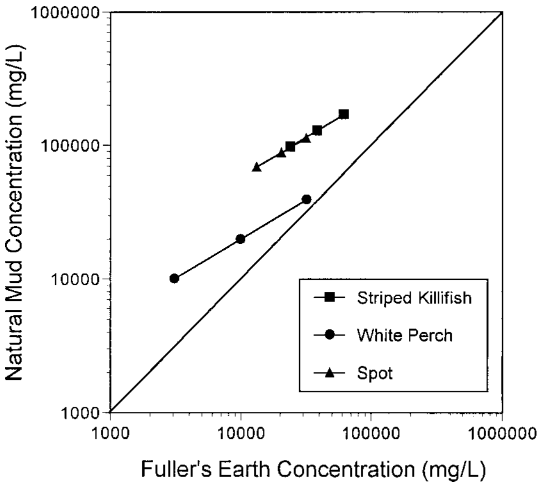

FIGURE 5.—The concentrations of Fuller's earth and natural mud at which 10%, 50%, and 90% mortality occurred in striped killifish (closed squares), white perch (closed circles), and spot (closed triangles) after a 1-d exposure are shown by the three respective symbols per species. The diagonal line depicts equal concentrations of the sediment types.

sitive lethal responses to suspended sediment exposures, exhibiting 10% mortality at sediment concentrations less than 1,000 mg/L for durations of 1 and 2 d, respectively. The lethal effects of natural muds were tested for white perch, killifish, and spot; in general, for equivalent exposure durations, higher concentrations of natural muds were required to elicit the same extent of mortality observed when Fuller's earth was used (Figure 5).

Shellfish

Bivalve eggs and larvae.—The effects of suspended sediments on bivalve egg survival have been investigated for the eastern oyster *Crassostrea virginica* (Davis 1960) and northern quahog *Mercenaria mercenaria* (Davis and Hidu 1969). Although the durations of exposure to various suspended sediment concentrations were not given in these studies, the results can be placed in context with potential exposures, given that the egg stages last only several hours for oysters (Cake 1983) and about 12 h for quahogs (Mulholland 1984). The investigators measured the percentage of eggs that developed to the straight-hinged larval stage. Negative impacts to oyster egg development occurred at a silt concentration of 188 mg/L, compared with 1,000 mg/L for quahog eggs.

Bivalve larval development may take several days to weeks, depending on the species and environmental conditions. Any factor that slows the

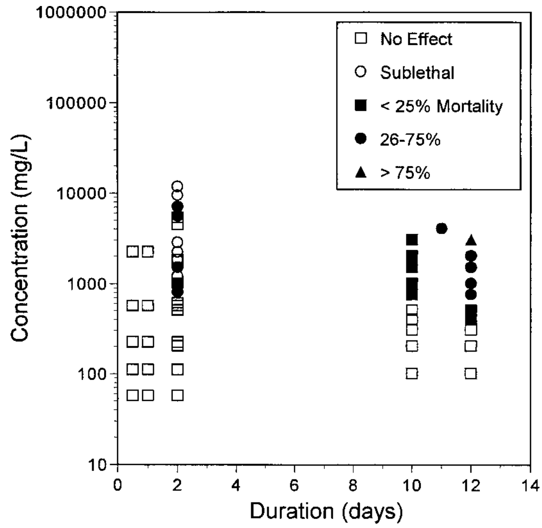

FIGURE 6.—Responses of larval bivalves to suspended sediment concentrations at the given exposure durations.

rate of larval development may detrimentally affect recruitment to the adult population. Because factors controlling larval survival, such as predation, are a function of the time spent in the plankton, prolonged developmental periods may reduce survival. Temperature, food concentration, salinity, turbidity, and oxygen content have been documented to affect eastern oyster larval development (reviewed in Dekshenieks et al. 1993). Larval development continued normally at suspended sediment concentrations less than 750 mg/L for quahogs and Pacific oysters *C. gigas*, whereas greater concentrations consistently had lethal effects at durations of 10 and 12 d, respectively (Figure 6; Table A.3). Eastern oyster larvae exhibited mortality when exposed to 400 mg/L for 12 d (Davis and Hidu 1969).

The effect of suspended sediments on larval development is not necessarily negative. At concentrations less than 100 mg/L, larval growth rates of northern quahog are enhanced (Davis 1960; Huntington and Miller 1989). Suspended sediment concentrations as much as 500 mg/L increase eastern oyster larval growth rate (Davis and Hidu 1969). Quahog larvae selectively ingest algae suspended with inorganic particulates at low concentrations. Larval growth decreased at sediment concentrations of 400 mg/L for quahogs (Davis 1960) and 750 mg/L for oysters (Davis and Hidu 1969). However, the larval concentrations used by Davis (1960) were 100-fold greater than typical field

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concentrations, and the algal ratios were unspecified (Huntington and Miller 1989).

Adult bivalves.—Primary mechanisms used by bivalves to deal with high concentrations of suspended sediment include reducing their net pumping rates (Foster-Smith 1976) and rejecting excess filtered material as pseudofeces (Robinson et al. 1984; Turner and Miller 1991; Hawkins et al. 1996). When suspended sediment concentrations exceed the threshold at which bivalves can effectively filter material, the available food is diluted (Widdows et al. 1979). The responses of suspension-feeding bivalves to relatively low concentrations of suspended sediment are varied. Blue mussels *Mytilus edulis* (Kiorboe et al. 1981b), surf clams *Spisula subtruncata* (Mohlenberg and Kiorboe 1981), and eastern oysters (Urban and Langdon 1984) exhibit increased growth rates in high algal concentrations after the addition of silt. Northern quahogs, however, decrease their algal ingestion with increasing sediment loads (Bricelj and Malouf 1984), resulting in no difference in their growth rates in comparison with quahogs exposed to an algal diet alone (Bricelj et al. 1984). The presence of suspended clay (20 mg/L) interferes with the ability of juvenile eastern oysters to ingest algae preferentially but does not reduce the overall amount of algae ingested (Urban and Kirchman 1992). The summer growth of European oysters *Ostrea edulis* in the field was enhanced at low concentrations of sediment resuspension and inhibited as sediment deposition increased (Grant et al. 1990). Suspensions of sediment chlorophyll in low concentrations may act as a food supplement, enhancing growth, but at higher concentrations may dilute planktonic food resources and suppress food ingestion.

Although adult bivalves are silt-tolerant organisms (Sherk 1972), their survival in naturally silty areas does not necessarily indicate they are unaffected by high concentrations of suspended sediment. Northern quahogs (Pratt and Campbell 1956) and eastern oysters (Kirby 1994) exposed to sediments of high silt-clay content exhibit reduced growth and less survival, respectively. Suspended sediment concentrations required to elicit mortality were extremely high (Figure 7), beyond the upper limits of concentrations reported for most estuarine systems under natural conditions and greater than typical concentrations associated with dredging activities. Sublethal effects, such as reduced pumping rates and growth, were evident for adult bivalves at concentrations that may be seen under natural conditions, albeit for a short duration, for example, during a storm (Schubel 1971; Turner and Miller 1991).

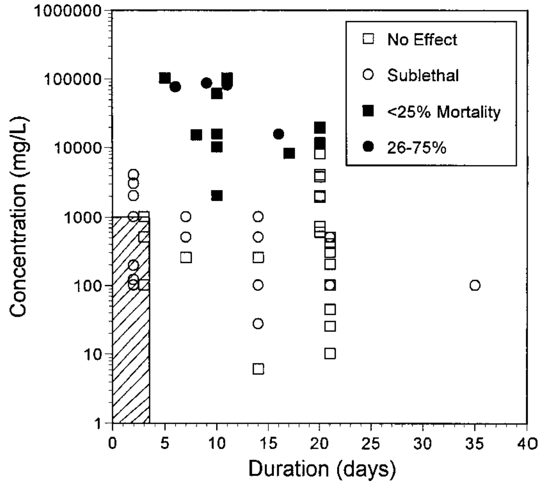

FIGURE 7.—Responses of adult bivalves to suspended sediment concentrations at the given exposure durations.

Softshell clams *Mya arenaria* exposed to 100–200 mg/L suspended sediments demonstrate a progression of sublethal effects associated with relatively low concentration exposures. The softshell clams first exhibit reduced gape width and partial retraction of their siphons and mantles over the first 7 d of exposure, a decreased response to mechanical stimuli by 15 d, and excessive protrusion of their siphons by day 30 (Grant and Thorpe 1991). In laboratory studies, lethal concentrations for adult bivalves exposed for less than 3 weeks were in the realm of fluid mud, that is, around 10,000 mg/L (Figure 7; Table A.4). Data on responses to long-term exposures were not available.

In situ experiments have been conducted with juvenile northern quahogs in which juveniles transplanted to a variety of conditions grew slower at sites with more exposure to muddy suspensions; if raised approximately 30 cm above the bottom, however, growth was improved (Rhoads and Young 1970). A similar study was conducted with eastern oysters; however, the methods and experimental design of both the oyster and the clam studies have been criticized (Moore 1978). Oyster mortality and low yield (reduced weight/bushel) were seen in caged oysters held for 90 d near dredged material disposal sites in the Wright River Estuary, South Carolina (Wirth et al. 1996). These negative effects, however, may be attributable to arsenic contamination of the dredged material in combination with low salinity, high turbidity, and low dissolved oxygen.

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TABLE 2.—Life history stages and habitats of shellfish that have been tested for biological responses to suspended sediment dosages.

Habitat	Eggs	Larvae	Juveniles	Adults
Pelagic	Eastern oyster	Eastern oyster		Mysid shrimp *Mysidopsis bahia*
	Northern quahog	Pacific oyster Northern quahog		
Benthic and mobile			Kuruma shrimp *Penaeus japonicus* Dungeness crab *Concer magister*	Spot-tailed sand shrimp *Crangon nigromaeulata* Black-tailed sand shrimp *Crangon nigrocauda* Grass shrimp *Paleomon macrodactylus* Dungeness crab
Demersal eggs or sessile organisms			Coast mussel *Mytilus californianus*	Coast mussel
			Blue mussel Northern quahog	Blue mussel Eastern oyster Softshell clam Northern quahog Surf clam Bay scallop *Agropecten irradians*

Crustaceans.—The suspended sediment tolerances of crustaceans have not been the focus of many laboratory studies (Table A.5; Table 2). Most studies record the concentration of suspended sediments required to induce mortality. In experiments shorter than 2 weeks, nearly all mortality was elicited by concentrations of suspended sediments exceeding 10,000 mg/L (Figure 8). Nonetheless, the majority of these mortality levels were less than 25%, even at very high concentrations. None of the crustaceans tested exhibited detrimental responses at dosages within the realm of suspended sediment conditions associated with dredging projects.

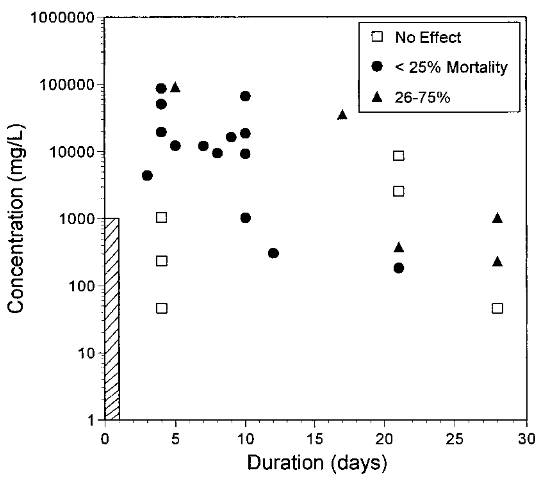

FIGURE 8.—Responses of adult and juvenile crustaceans to suspended sediment concentrations at the given exposure durations.

The turbid water of estuaries may provide refuge from predation for juvenile shrimp, which are heavily preyed upon by estuarine fishes. Brown *Peneaus aztecus* and white *P. setiferus* shrimp are common over a wide range of turbidities, whereas pink shrimp *P. duorarum* are most abundant in areas with low turbidity. Juvenile penaeid shrimp burrow in sandy sediments during the day and emerge at night to forage. In experimental aquaria, predation by Atlantic croaker and pinfish on juvenile shrimp was reduced in turbid water, whereas the predation efficiency of the southern flounder *Paralichthys lethostigma*, an ambush predator, was increased (Minello et al. 1987).

Increased Environmental Suspended Sediment Conditions

Natural causes.—Predicting the potential impact of disturbances, such as dredging projects, on fish and shellfish requires an understanding of the suspended sediment conditions that occur under both natural and dredging-related conditions. Several natural processes create high concentrations of suspended solids in the marine environment, such as plankton blooms, bioturbation, soil erosion, and the resuspension of sediments by waves and currents (Moore 1978). Unfortunately, very few data are available concerning increased concentrations of suspended sediment in estuaries under natural conditions. Especially lacking are reports that give the durations at which high concentrations were sustained during natural events such as storms or high runoff. Excessively high concentrations of suspended sediment reported under natural conditions include 570 mg/L in Indian River Bay, Delaware (Huntington and Miller 1989); 600 mg/L in Chesapeake Bay (Brownlee et al. 1988); 3,000 mg/L in the Bay of Fundy (Grant and Thorpe 1991); and 10,000 mg/L in False Bay, Washington (Miller and Sternberg 1988), and in Chesapeake Bay during a hurricane (Moore 1978).

In a study of surface sediment plumes analyzed with remote sensing data, the largest plume in a 25-year dataset along coastal California was 10 km long and 25 m wide, with concentration peaks between 70 and 100 mg/L (Mertes et al. 1998). This plume was created by the combined outflow of two rivers after 25 cm of rainfall in the previous month. In the San Francisco Bay area, a network of sites has been established at which suspended sediment concentrations are obtained from turbidity measures taken every 15 min (Buchanan and Schoellhamer 1996; Schoellhamer 1996a). after two storms in 1995, near-surface and near-bottom concentrations peaked around 250 and 300 mg/L, respectively. Tidal influences on suspended sediment concentrations were apparent, with peak concentrations occurring during the slack periods after the ebb tides. Because tidal influence caused a 100–200 mg/L fluctuation in suspended sediment concentrations, peak concentrations were sustained for less than 12 h before recurring at somewhat reduced values after the next ebb tide. Increased concentrations of suspended sediment lasted nearly 5 d after both storms, and suspended sediment concentrations returned to background values in approximately 1 month.

Human activities.—Dredging-induced suspended sediment conditions are generally better documented than other activities, such as trawling and large vessel traffic, which have more frequent, if not as acute, impacts on the estuarine environment. Concentrations of resuspended sediments vary among dredge and sediment types and the environmental conditions at the time of dredging (McLellan et al. 1989; Herbich and Brahme 1991; Hayes et al. 2000). Although extrapolations of suspended sediment conditions between dredging projects are variable in their reliability (Johnson and Pachure 1999), generalities can be made concerning the relative impacts of different types of dredging and the concentrations of suspended sediments associated with each. In general, mechanical dredges (e.g., bucket or clamshell) increase suspended sediment concentrations more than hydraulic (hopper and cutterhead) methods, unless the hydraulically pumped sediments are allowed to overflow. Mechanical dredges generate suspended sediments through the impact and withdrawal of the bucket from the bottom, washing of material out of the bucket as it moves through the water column and above the water's surface, and loss of water when loaded onto the barge (LaSalle 1990). Mechanical dredges are commonly used for small projects near docks and piers or where rocky deposits are present (Morton 1977) and are easier to use at greater depths than are hydraulic methods. A suspended sediment plume at its maximum concentration (1,100 mg/L) may extend as far as 1,000 m along the bottom for a clamshell dredge (LaSalle 1990).

Many factors, such as weather and hydrodynamic conditions, sediment type, and dredge operator skill, interact to affect the progress of a dredging operation. The advance rate of a dredge, however, can be estimated from historical records. Based on the average advance rates for clamshell dredging projects (12–18 m/h) recorded by the Mobile District of the U.S. Army Corps of Engineers, a 1,000 m suspended sediment plume would take approximately 2.3–3.5 d to pass a stationary point. The actual suspended sediment exposure to the plume experienced by sessile organisms may be highly variable, depending on the hydrodynamics of the area near the dredging site. Tidal flushing may alleviate exposures to the plume for periods of hours as described above for the San Francisco Bay area study. Alternatively, a fluff zone may be established, in which the settling of particles is inhibited as the concentrations of suspended sediment in the lower water column increase. This fluff zone may continue to exist within the confines of the channel for a few weeks after the termination of the dredging project (Wakeman et al. 1975).

Hydraulic dredging mixes large volumes of water with sediments to form a slurry that either is pumped through a pipeline to an upland location or into a hopper bin or is sidecast away from the dredging site (Morton 1977). The rate of the cutterhead rotation, the vertical thickness of the dredge cut, and the swing rate of the dredge all affect the turbidity levels created by the dredging project (LaSalle 1990). Cutterhead dredging is the most common method of maintenance dredging used by the U.S. Army Corps of Engineers (Morton 1977). Maximum concentrations generally remain less than 500 mg/L, and bottom suspended sediment plumes are usually limited to within 500

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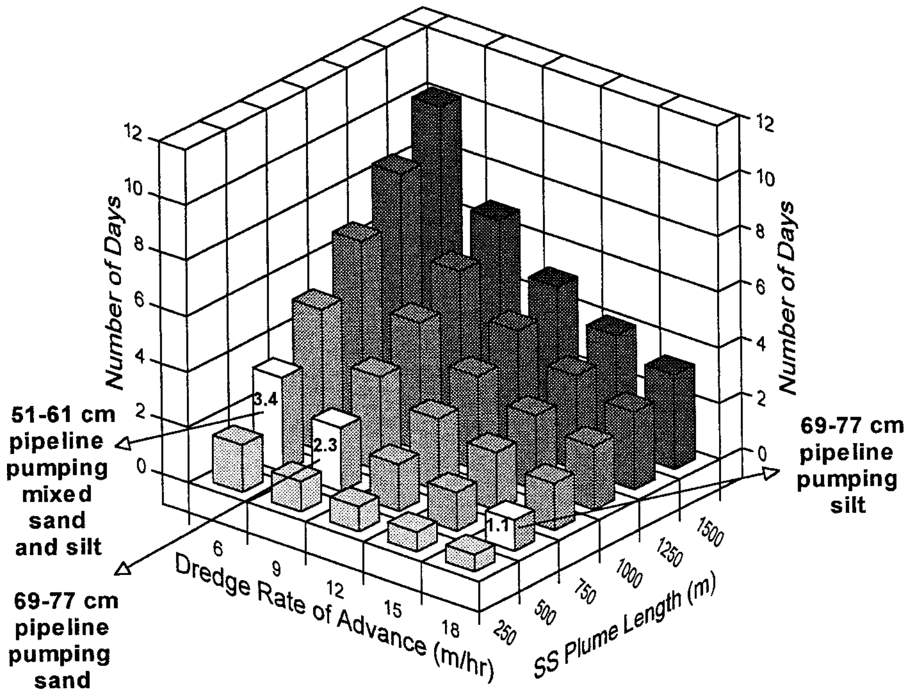

FIGURE 9.—Range of exposure durations that may be experienced by sessile organisms when a suspended sediment plume passes them in association with a hypothetical hydraulic cutterhead dredging project. The white bars depict estimated exposure durations based on selected pipeline diameters and in situ sediment types.

m of the dredge (LaSalle 1990; Hayes et al. 2000). Advance rates for cutterhead dredges vary by pipeline size and sediment type but range from approximately 6 m/h for 51.2–61.4-cmdiameter pipelines dredging sands to 18 m/h for 69.1–76.8-cm-diameter pipelines dredging silty material (C. Dyess, Mobile District Corps of Engineers Office, personal communication). Exposure to suspended sediment plumes generated by cutterhead dredging for sessile benthic organisms may last from approximately 1 to 3.5 d, depending on the project conditions and a variety of other factors (Figure 9). This range in exposure duration represents one way of estimating relevant biotic exposures. Different advance rates of other dredge types and site-specific conditions will alter these duration estimates.

Hopper dredges, self-contained vessels resembling barges, can maintain speeds of 12.6 km/h while dredging (Morton 1977). Bottom turbidity associated with hopper dredges is caused by the dragheads pulled through bottom sediments. Surface turbidity may be substantial if the hoppers overflow during loading, a practice that increases the sediment content in the hopper bins (LaSalle 1990). Suspended sediment plumes may extend as far as 1,200 m along the bottom at concentrations as great as 800 mg/L. Concentrations at the surface depend on whether overflow is occurring.

Putting the increased suspended sediment conditions caused by dredging into the context of how storms and other bottom disturbances, such as trawling and large vessel traffic, affect suspended sediment levels remains somewhat elusive, given the few data available for each disturbance type. Bohlen et al. (1979) estimate that major storms displace sediments in the Thames River estuary in Connecticut by nearly an order of magnitude more than that of dredging projects. Such storms, which may occur one to three times each year, are much more frequent than dredging, which typically recurs once every 10 years. Sediment resuspension caused by dredging, however, is restricted to a much smaller region than that affected by storms; therefore, the concentration gradients and response options of motile organisms are different.

The effects on benthic habitats of trawling, a fishing method in which a weighted net that scrapes the sediment surface is towed behind a boat, have been studied in the Middle Atlantic Bight region (Messieh et al. 1991). Pulling the trawl doors over the bottom stirs up sediments and

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detritus, which causes fish to swim toward the suspended sediment-plume and congregate at the net mouth, thus increasing catches. Trawling over the northwest Atlantic Continental Shelf is extensive, creating suspended sediment clouds that can extend as high as 10 m above the bottom (Churchill 1989). Although trawling primarily over sand in this area is unlikely to elicit acute negative biological responses, chronic sublethal effects may influence fish feeding and reproductive behaviors and thus ultimately affect community structure (Messieh et al. 1991). In regions such as the Gulf of Mexico, where the bottom may have a high silt and clay content, turbidity plumes caused by trawling are more likely to reach higher concentrations. Shrimp trawlers operating in Corpus Christi Bay, Texas, increased the suspended sediment concentrations to between 100 and 550 mg/L at 2 m above the bottom and 100 m astern of the trawls (Schubel et al. 1978).

Large vessel traffic in a dredged ship channel in Hillsborough Bay, Florida, can generate solitary long waves that increase the concentrations of suspended sediment to five times that of background, reaching 250 mg/L (Schoellhamer 1996b), and these sediments can stay in suspension as long as 8 h. Schoellhamer (1996b) estimates that sediment resuspension by vessel-generated long waves is an order of magnitude greater than natural sediment resuspension during winter storms.

Discussion

Assimilating biological and engineering information to objectively evaluate the potential impacts of suspended sediments on fish and shellfish is a challenge. In the case of potential dredging impacts, variations in the project-specific conditions of a dredge plant, in situ sediment characteristics, local hydrodynamics, and distributions of organisms in space and time all interact to affect the suspended sediment dosage the local biota experience. For motile organisms, such as fish, exposure durations to suspended sediment plumes are probably minutes to hours, unless individuals follow the plume or are confined to an area with restricted circulation. Suspended sediment dosages for juvenile and adult fishes (depicted by hatched boxes in Figures 2 and 4 in this study), therefore, have exposure durations extending up to 1 d. Data points falling within the hatched boxes indicate known responses to dosages relevant to dredging impacts. For organisms or life history stages that are nonmotile, for example, salmonid eggs and adult bivalves (Figures 1 and 7), the projected maximum exposure durations extend up to 3.5 d, based on estimates of dredge advance rates. Nonsalmonid estuarine fish eggs and larvae (Figure 3) exhibit more diverse forms, that is, demersal adhesive, semibuoyant, and pelagic, thus expanding the range of potential exposure durations up to 3.5 d for demersal adhesive forms. The other forms are likely to experience shorter exposure durations.

Few relevant data are available for biological responses of adult estuarine fishes (Figure 4) to suspended sediments within the range of concentration and exposure durations associated with navigation dredging projects. Existing data (Figure 4) clearly show a high degree of species variability in response, reports of ‘‘no effect’’ were made at concentrations as great as 14,000 mg/L for durations of 3 d and more (oyster toadfish and spot) and mortality was observed at a concentration/duration combination of 580 mg/L for 1 d (Atlantic silversides). Several studies have examined behavioral responses of salmonid fishes to suspended sediments at exposures of a few hours at concentrations relevant to dredging impacts for both juveniles and adults of several species (Figure 2). Responses of nonsalmonid, estuarine fishes are not as well established; most data are derived from bioassay-type tests that measure endpoints (usually mortality) reached at high concentrations and under conditions that do not reflect what organisms are likely to encounter in the field. Such studies measured dose–response relationships under laboratory conditions, where organisms were subjected to continuous exposure. The effects of intermittent exposures to increased concentrations of suspended sediment, which simulate conditions in many areas that are subject to tidal flushing, or are typical of hopper dredging operations (i.e., dredging is discontinued during transit to and from a placement site), are not addressed in the literature. For both salmonid and estuarine fishes, the egg and larval stages were more sensitive to suspended sediment impacts than were the older life history stages. Although our depiction of the exposure–concentration regime is based on case studies of dredging conditions, site- and operation-specific information should be used to predict dosages on a case-by-case basis.

A recent attempt to model estuarine fish responses as a function of both suspended sediment concentration and exposure duration (Newcombe and Jensen 1996), although correctly aimed at producing a useful resource management tool, included erroneous data; hence, the model output for estuarine nonsalmonids is misleading. Concentra-

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tions (listed for group 5 in Table A.1 of Newcombe and Jensen 1996) are too low by a factor of 10 because of a conversion error for all adult estuarine fish mortality effects taken from Sherk et al. (1975). These data account for 29 of the 66 total cases listed in the table and more than 50% of the cases used in the estuarine fish regression model. Thus, lethal effects are predicted for adult estuarine fish at very low dosages of suspended sediment. For example, paralethal responses are predicted for exposure to a concentration of 148 mg/L for 7 h, and lethal responses are predicted for all concentrations greater than 55 mg/L for exposures of 1 d or more. The projected responses of adult estuarine fishes to low concentrations are much more severe than those projected for juvenile and adult salmonids at the same dosages of suspended sediment. A revised model that incorporates the correct data from Sherk et al. (1975) projects less severe effects (severity of ill effects scores reduced by one) at these dosages (C. P. Newcombe, personal communication). The estuarine fish model, however, is still restricted to providing predictive response scores for only 15 dosages of suspended sediment; the rest of the model output falls beyond the confidence limits of reliable predictions (C. P. Newcombe, personal communication). In contrast, the model outputs for juvenile and adult salmonid fishes yielded 97 and 50 predictive response scores, respectively (Newcombe and Jensen 1996), which reflects the paucity of relevant empirical data for estuarine fishes.

The concept of consolidating study results for predictive purposes advanced by Newcombe and Jensen (1996), and the recognition that estuarine organisms need to be included in these modeling efforts, are valuable contributions to estuarine resource management. Results of our study indicate much less is known about estuarine fish responses to suspended sediment dosages within the range associated with dredging projects than is known about salmonid responses to relevant conditions. Concern that increased turbidity caused by human activities may adversely affect salmonid resources has led to research resulting in the body of knowledge summarized in Figures 1 and 2. Although human activities affecting the concentrations of suspended sediment in the estuarine environment also have a long history, no similar relevant body of research exists for estuarine species but is needed for effective resource management.

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Appendix: Responses to Suspended Sediment

TABLE A.1.—Responses of estuarine fish eggs (E) and larvae (L) to suspended sediment concentration and exposure duration combinations. Sediment types, when known, are indicated as follows: ns = natural sediment, s = silt, k = kaolin, ac = attapulgite clay, b = bentonite, and fe = Fullers earth. The table is adapted in part from Newcombe and Jensen (1996).

Species	Life stage	Concentration (mg/L)	Duration (d)	Effect	Source
Striped bass	E	800	1	Development slowed	Morgan et al. 1983 (ns)
	E	1,000	7	Reduced hatching success	Auld and Schubel 1978 (ns)
	L	1,000	3	Increased mortality	
	L	500	3	Increased mortality	
	L	485	1	50% mortality	Morgan et al. 1973
	L	200	<1	Reduced feeding rate	Breitburg 1988 (k)
	L	500	<1	Reduced feeding rate	
	L	1,200	10	10% mortality	Wakeman et al. 1975 (b)
Atlantic herring	E	300	11	Normal egg development	Kiorboe et al. 1981 b (ns)
	E	500	<1	Normal egg development	
Pacific herring	L	2,000	<1	Reduced feeding rate	Boehlert and Morgan 1985
	L	1,000	1	Damage to epidermis	Boehlert 1984 (ns)
	L	4,000	1	Epidermis punctured	
White perch	E	100	1	Hatching delayed	Schubel and Wang 1973
	E	1,000	7	Reduced hatching success	Auld and Schubel 1978
	L	155	2	50% mortality	Morgan et al. 1973
	L	373	1	50% mortality	
Yellow perch	L	500	4	30% mortality	Auld and Schubel 1978
	E	1,000	4	No effect	
American shad	L	100	4	13% mortality	Auld and Schubel 1978
		500	4	32% mortality	
		1,000	4	29% mortality	
	E	1,000	4	No effect	
Blueback herring	E	1,000	4	No effect	Auld and Schubel 1978
Alewife	E	1,000	4	No effect	Auld and Schubel 1978

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TABLE A.2.—Responses of juvenile and adult estuarine fish to known suspended sediment concentrations for given durations. All data pertain to adult fish unless otherwise noted. See Table A.1 for abbreviations of sediment types.

Species	Concentration (mg/L)	Duration (d)	Effect	Source
Bluefish (juveniles)	800	1	100% mortality	Sherk et al. 1974 (fe)
Atlantic menhaden (juveniles)	800	1	100% mortality	
White perch (juveniles)	750	1	100% mortality	
Bay anchovy	2,310	1	10% mortality	Sherk et al. 1975 (fe)
	4,710	1	50% mortality	
	9,600	1	90% mortality	Sherk et al. 1974 (fe)
Striped bass	1,500	14	Hematocrit increased	
	600	11	No effect	
Hogchoker	1,240	5	Hematocrit increased	
Striped killifish	960	5	Hematocrit increased	
	23,770	1	10% mortality	
	38,190	1	50% mortality	
	61,360	1	90% mortality	
Mummichog	24,470	1	10% mortality	
	39,000	1	50% mortality	
	62,170	1	90% mortality	
	35,860	2	10% mortality	
	45,160	2	50% mortality	
	56,890	2	90% mortality	
	1,620	4	Hematocrit increased	
White perch	650	5	Hematocrit increased	Sherk et al. 1975 (fe)
	3,050	1	10% mortality	
	9,850	1	50% mortality	Sherk et al. 1974 (fe)
	31,810	1	90% mortality	
	670	2	10% mortality	
	2,960	2	50% mortality	
	13,060	2	90% mortality	
Atlantic silverside	580	1	10% mortality	
	2,500	1	50% mortality	
	10,000	1	90% mortality	
Spot	13,090	1	10% mortality	
	20,340	1	50% mortality	
	31,620	1	90% mortality	
	1,140	2	10% mortality	
	1,890	2	50% mortality	
	3,170	2	90% mortality	
	1,270	5	No effect	
Striped killifish	97,200	1	10% mortality	Sherk et al. 1975 (s)
	128,200	1	50% mortality	
	169,300	1	90% mortality	Sherk et al. 1974 (ns)
White perch	9,970	1	10% morality	
	19,800	1	50% mortality	
	39,400	1	90% mortality	
Spot	68,750	1	10% mortality	
	88,000	1	50% mortality	
	112,630	1	90% mortality	
	14,680	7	No effect	
Cunner	28,000	1	50% mortality	Rogers 1969 (s)
	133,000	<1	50% mortality	
	100,000	1	50% mortality	
Sheepshead minnow	200,000	1	10% mortality	
	300,000	1	30% mortality	
Fourspine stickleback	18,000	1	50% mortality	Rogers 1969 (s)
	200,000	1	95% mortality	
Oyster toadfish	3,360	1	O_2 consumption variable	Neumann et al. 1975 (ns)
	14,600	3	No effect	
Shiner perch	1,000	4	10% mortality	McFarland and Peddicord 1980
	3,600	4	20% mortality	
	6,000	4	50% mortality	

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TABLE A.3.—Responses of larval bivalves to known suspended sediment concentrations for given durations. See Table A.1 for abbreviations of sediment types. When more than one sediment type was used in the experiments, results for silt or natural sediments are reported.

Species	Concentration (mg/L)	Duration (d)	Effect	Source
Eastern oyster	100	12	No effect	Davis and Hidu 1969 (s)
	200	12	No effect	
	300	12	No effect	
	400	12	10% mortality	
	500	12	18% mortality	
	750	12	Reduced growth	
	750	12	30% mortality	
	1,000	12	40% mortality	
	1,500	12	58% mortality	
	2,000	12	75% mortality	
	3,000	12	99% mortality	
Pacific oyster	200	2	No effect	Cardwell et al. 1976 (ns)
	500	2	No effect	
	600	2	No effect	
	1,000	2	No effect	
	1,800	2	No effect	
	4,400	2	No effect	
	5,300	2	No effect	
	1,200	2	Abnormal shell development	
	1,800	2	Abnormal shell development	
	2,800	2	Abnormal shell development	
	9,400	2	Abnormal shell development	
	11,700	2	Abnormal shell development	
	800	2	50% mortality	
	1,000	2	50% mortality	
	1,500	2	50% mortality	
	5,510	2	50% mortality	
	7,000	2	50% mortality	
Northern quahog	100	10	No effect	Davis and Hidu 1969 (s)
	200	10	No effect	
	300	10	No effect	
	400	10	No effect	
	500	10	No effect	
	750	10	10% mortality	
	1,000	10	10% mortality	
	1,500	10	10% mortality	
	2,000	10	10% mortality	
	3,000	10	15% mortality	
	4,000	11	30% mortality	
	56	0.5	No effect	Huntington and Miller 1989
	110	0.5	No effect	
	220	0.5	No effect	
	560	0.5	No effect	
	2,200	0.5	No effect	
	56	1	No effect	
	110	1	No effect	
	220	1	No effect	
	560	1	No effect	
	2,200	1	No effect	
	56	2	No effect	
	110	2	No effect	
	220	2	No effect	
	560	2	No effect	
	2,200	2	Reduced growth	

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TABLE A.4.—Responses of adult bivalves to known suspended sediment concentration for given durations. See Table A.1 for abbreviations of sediment types. When more than one sediment type was used in the experiments, results for silt or natural sediments are reported.

Species	Concentration (mg/L)	Duration (d)	Effect	Source
Eastern oyster	100	21	No effect	Mackin 1961 (ns)
	200	21	No effect	
	300	21	No effect	
	400	21	No effect	
	500	21	No effect	
	590	20	No effect	
	710	20	No effect	
	1,000	2	Reduced pumping	Loosanoff 1962 (ns)
	2,000	2	Reduced pumping	
	3,000	2	Reduced pumping	
	4,000	2	Reduced pumping	
Softshell clam	100	21	O_2 consumption down	Grant and Thorpe 1991 (ns)
	100	14	NH_4 excretion up	
	100	35	Reduced growth	
Northern quahog	6	14	No effect	Murphy 1985
	27	14	Reduced growth	
	100	2	Reduced growth	Turner and Miller 1991 (ns)
	120	2	Reduced growth	
	193	2	Reduced growth	
(Juveniles)	10	21	No effect	Bricelj et al. 1984 (ns)
	25	21	No effect	
	44	21	Reduced growth	
Coast mussels	1,900	20	No effect	Peddicord 1980 (ns)
	3,700	20	No effect	
	8,100	17	10% mortality	
(Juveniles)	11,600	20	10% mortality	
	19,500	20	10% mortality	
	15,500	10	10% mortality	
	15,500	16	20–40% mortality	
(Adults)	75,000	6	20–40% mortality	McFarland and Peddicord 1980 (k)
	10,000	10	20–40% mortality	
	85,000	9	50% mortality	
	80,000	11	50% mortality	
Blue mussel	2,000	20	No effect	Peddicord 1976 (k)
	4,000	20	No effect	
	8,000	20	No effect	
	11,000	20	No effect	
	19,000	20	No effect	
	15,000	8	0–20% mortality	
(Juveniles)	100,000	5	10% mortality	McFarland and Peddicord 1980 (k)
(Adults)	100,000	11	10% mortality	
	60,000	10	10% mortality	Wakeman et al. 1975 (b)
	10,000	10	10% mortality	
	2,000	10	10% mortality	
Surf clam	100	3	No effect	Robinson et al. 1984 (ac)
	500	3	No effect	
	1,000	3	No effect	
	100	21	No effect	
	500	21	Reduced growth	
Bay scallop	250	7	No effect	Moore 1978 (k)
	250	14	No effect	
	500	7	Higher respiration	
	500	14	Higher respiration	
	1,000	7	Higher respiration	
	1,000	14	Higher respiration	

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TABLE A.5.—Responses of Crustacea to known suspended sediment concentrations for given durations. See Table A.1 for abbreviations of sediment types. When more than one sediment type was used in the experiments, results for silt or natural sediments are reported.

Species	Concen-tration (mg/L)	Duration (d)	Effect	Source
Spot-tailed sand shrimp	16,000	8	10% mortality	McFarland and Peddicord 1980 (k)
	50,000	8	50% mortality	
Grass shrimp	24,000	10	10% mortality	
	77,000	8	20% mortality	
Dungeness crab	9,200	8	5% mortality	Peddicord and McFarland 1976 (ns)
	11,700	7	20% mortality	
(Juveniles)	15,900	9	15% mortality[a]	
	18,900	4	20% mortality	
(Adults)	10,000	8	10% mortality	McFarland and Peddicord 1980 (k)
	32,000	8	50% mortality	
Kuruma shrimp	180	21	10% mortality	Lin et al. 1992 (ns)
(Juveniles)	370	21	32% mortality	
Black-tailed sand shrimp	2,500	21	No effect	Peddicord 1980 (ns)
	8,400	21	No effect	
	11,900	5	10% mortality	
	4,300	3	5% mortality	
	9,000	10	10% mortality	Wakeman et al. 1975 (b)
	1,000	10	10% mortality	
Mysid shrimp	45	28	No effect	Nimmo et al. 1982 (ns)
	230	28	40% mortality	
	1,020	28	60–80% mortality	
	45	4	No effect	
	230	4	No effect	
	1,020	4	No effect	

[a] Molt related.

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