US Army Corps of Engineers

Literature Review
(for studies conducted prior to 2008): Fish Behavior in Response to Dredging & Dredged Material Placement Activities
(Contract No. W912P7-07-P-0079)

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Notice to Reviewer

This literature review on fish behavior in response to dredging and dredge material placement activities was conducted in 2007 and 2008. Therefore, only those studies that were performed or published prior to 2007/2008 are included in this document.

CONTENTS

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LIST OF TABLES

1.0 SUMMARY

Dredging and dredged material placement activities may result in exposure of fish to various stimuli that may result in positive, negative, or neutral behavioral responses. Information regarding behavioral responses of fish to specific dredging and related activities in the San Francisco Bay is being requested by the U.S. Army Corps of Engineers, San Francisco District (USACE), members of the San Francisco Bay Long Term Management Strategy (LTMS) forum, and state and federal resource/regulatory agencies (1) to better evaluate the potential affects of dredging and dredged material placement activities to in-bay fisheries, and (2) to support the preparation of Biological Assessments for Endangered Species Act (ESA) consultations. The objectives of this literature review are (1) to conduct a comprehensive review of fish behavioral responses to dredging, dredged material placement, and other maritime activities, and (2) to provide the USACE and the SF Bay LTMS agencies with an understanding of the availability of knowledge regarding fish behavioral responses, especially for those fish species in San Francisco Bay.

Information presented in this paper was gathered from a broad range of sources including electronic databases and local university libraries. This literature review is focused on behavioral effects of fish to dredging and dredged material placement, but also includes effects relative to other aquatic actions, including knockdown operations. Data gathered during the search phase were summarized and in a series of tables by fish type (i.e., anadromous species, bay resident species, bay non-resident species, and surrogate species), and then, by dredge-induced stimulus (i.e., turbidity, suspended sediment levels, entrainment, and noise).

Major findings of this document indicate that the available literature regarding specific effects to fish behavior from dredging activities is generally confined to turbidity and suspended sediments, with little available information on effects of other aspects of dredging. Most of the available information comes from laboratory studies, and far less *in situ* research has been performed. In particular, there are gaps in species-specific knowledge relative to the effects to fish behavior resulting from dredging activities. While it appears that pelagic fish species

(especially salmonids) generally exhibit avoidance response to dredging activities and sediment plumes, other species, especially epibenthic species and sedentary species (e.g., gobies), may show a more neutral response to dredging activities. Further, there is little research regarding dredging effects on anadromous fish behavior in San Francisco Bay. Some species are thought to prefer, or at least have evolved to accommodate, elevated suspended sediment levels (e.g., sturgeon and striped bass). However, there are no stochastic data available that confirm avoidance, attraction, or even neutral responses to dredging activities.

Specific findings suggest that:

- Juvenile salmonid migration behavior is disrupted (through avoidance response) when encountering dredging activity or sediment plumes,
- Juvenile salmonid migration behavior generally returns to normal (i.e., assumes prior distribution patterns) soon after encountering a dredge or dredge plume,
- Fish tend to exhibit avoidance behavior for about two to three hours after dredged material placement and fish community densities generally return to pre-disposal levels after about three hours,
- Juvenile salmonid avoidance response behavior to elevated suspended sediment levels may be initiated in the range of 22 to 100 NTUs, and may be at least partially mediated by irritation of gill tissues from suspended sediment particles,
- Ambient turbidity levels are important when considering effects of increased turbidity, since some species (e.g., striped bass, white sturgeon, and green sturgeon) have evolved to tolerate naturally high turbidity levels,
- Typical maximum suspended sediment levels resulting from mechanical dredging operations in San Francisco are around 250 mg/L, in the range of preferred turbidity levels for Pacific herring feeding behavior,
- Initial adverse affects to the benthic macroinvertebrate community are almost universally observed from dredging or dredged material placement, followed by substantial variances in recovery time and resultant community structure,

- Demersal fish species (e.g., Pacific staghorn sculpin, Pacific sand lance, Pacific sanddab, and juvenile sturgeon) are more vulnerable to being entrained during dredging activities than are pelagic species, and anadromous salmonids exhibit avoidance behavior to increased velocities associated with hydraulic and suction type dredge activities, and
- Noise generated from pile driving activities is generally within the range to elicit avoidance by juvenile salmonids.

2.0 INTRODUCTION

Dredging and dredged material placement activities may result in exposure of fish to various stimuli that may result in positive, negative, or neutral behavioral responses. Behavioral responses of fish to specific dredging and related activities in the San Francisco Bay area are of concern to the U.S. Army Corps of Engineers, San Francisco District (USACE), members of the San Francisco Bay Long Term Management Strategy (LTMS) forum, and to state and federal resource/regulatory agencies, (1) to better evaluate the potential affects of dredging and dredged material placement activities to in-bay fisheries, and (2) to support the preparation of Biological Assessments for Endangered Species Act (ESA) sections 7 and 10 consultations. Species- and life stage-specific behavioral responses to changes in environmental conditions (e.g., turbidity, water quality, physical structure, sediment and water column contaminant loads, and noise levels) should be well understood for an accurate assessment of the potential for maritime project-related effects to aquatic communities.

Several literature reviews have been conducted in recent years regarding the effects of dredging on biological resources. Two well-known reviews (Nightingale and Simenstad [2001] and Wilber and Clarke [2001]) indicate the general lack of specific information relative to the effects on fishes, in particular, from dredge-induced stimuli. In fact, both reviews indicate the need for additional research on lethal and sublethal effects to fish. A more recent literature review by Anchor Environmental (2003) was conducted as part of an assessment of dredging effects in the Los Angeles Harbor and provides a similar conclusion. Numerous studies have been conducted in the San Francisco Bay and Delta by the various agencies of the Interagency Ecological

Program (IEP) for the San Francisco Estuary, regarding fish response to changes in environmental conditions including delta outflow, sediment loading, and other physical and biological parameters. The studies conducted by IEP provide a basis for further investigations relative to behavioral responses of fish to specific dredging and dredge material placement activities (e.g., dredging, knockdown operations, pile driving, and other maritime activities).

This document summarizes current information obtained through a comprehensive literature review process. The process described in the *Framework for Assessment of Potential Effects of Dredging on Sensitive Fish Species in San Francisco Bay* (Lebednik 2004) (i.e., Framework Document) was used as a model for this document. Information was obtained through a review of available scientific literature, monitoring data from dredging and other maritime projects, and local and regional sources. This document includes a review of behavioral responses to dredge-induced stimuli, such as increased turbidity, suspended sediment, entrainment, noise, and other physical characteristics associated with dredge and dredged material placement activities. Areas of uncertainty, data gaps, and limitations of available research have also been identified.

2.1 Objectives

The objectives of this project are (1) to conduct a comprehensive review of fish behavioral responses to dredging, dredged material placement, and other maritime activities, and (2) to provide the USACE and the SF Bay LTMS forum with a synthesis of existing knowledge regarding fish behavioral responses, especially for those species occurring in San Francisco Bay, when considering dredging permit management.

3.0 METHODOLOGY

The literature search focused primarily on behavioral effects of fish to dredging and dredged material placement, as well as knockdown (i.e., bed leveling) operations. However, information was also obtained on other types of maritime activities that are similar to dredging operations that could also elicit behavioral responses of fish. For example, increased turbidity due to mining, land use changes and ground disturbance activities that result in episodic sediment inputs following rain events, and even naturally-occurring conditions (i.e., wind or storm induced) may result in fish behavioral responses that are similar to those associated with dredge-related stimuli.

Behavioral responses (e.g., avoidance, attraction, or neutral response) to a particular stimulus may change with varying environmental conditions and by species and life stage. In general, the majority of behavioral effects are associated with the re-suspension of sediments and the resulting physical and chemical alterations within the water column (Germano and Cary 2005). For this reason, a broad-based assessment of the effects of sediment (including sediment chemistry) and turbidity on fish behavior is included in this document. For example, Sigler (1984) determined that even low levels of turbidity may affect fish foraging ability, migration habits, and predator-prey relationships; while higher turbidity levels may produce more serious sublethal or lethal effects. Other investigators such as Hanson and Walton (1990) have noted the importance of ambient turbidity levels when considering effects of increased turbidity, since some species (in this case, striped bass) have evolved to tolerate naturally high turbidity levels.

Data regarding the behavioral effects of dredging activities on fish behavior were gathered from a variety of sources including electronic databases and local university libraries. Electronic databases were searched using a combination of keywords and phrases appropriate to the topic of this paper. A variety of internet search engines (e.g., Google, GoogleScholar, Yahoo, Endnote connection files and import filters, such as Animal Behavior and Applied Animal Behavior Science, and Endnote international connection files) were used to acquire literature. Information gathered from other electronic databases included existing literature reviews, peer-reviewed journal articles, books, symposia and conference proceedings, technical reports, and theses/dissertations. In addition to the internet, searches were also conducted using library databases at Sacramento State University, Long Beach State University, and the University of California, Davis.

All potential sources of information obtained through the literature search were initially reviewed and summarized. To evaluate the applicability of each article to the scope of this project, literature summaries were then reviewed by the author. Information obtained during the search and deemed to be suitable by the author was then summarized by fish type in a series of tables (i.e., anadromous species, bay resident species, bay non-resident species, and surrogate species), and then, by dredging-induced stimulus (i.e., turbidity, suspended sediments, entrainment, and noise). Anadromous fish species include all migratory salmonids, sturgeons, American shad, and striped bass. Bay resident species include those fishes that spend their entire life history in San Francisco Bay. Non-resident fish species include fish that may reside in San Francisco Bay during a specific life stage, but not their entire life history (e.g. Pacific herring). Surrogate species are those fishes that do not occur in San Francisco Bay, but are similar to other resident or non-resident fish species that do occur in San Francisco Bay. However, due to differences in ecological characteristics and life-history requirements, making direct comparisons between these species would not likely be appropriate. However, this information may be useful in indicating potential responses of fish in a generalized manner.

4.0 RESULTS

Available literature indicates that specific maritime activities and mechanisms can have the ability to influence fish behavior. Direct and cumulative assessments of dredging activity effects have been conducted at the Port of Los Angeles/Port of Long Beach (POLA/POLB) Channel Deepening Project, including channel deepening (i.e., change in habitat type), turbidity caused by dredging activity, suspension of contaminants from sediments during dredging and dredged material placement, and construction of submerged fill or landfill associated with dredged material placement. The most significant effect of the project was the loss of habitat resulting from the placement of fill in shallow water at the Outer Harbor dredge material placement sites. Further, water quality was locally degraded as a result of construction of the placement sites, which required mitigation. Although direct behavioral responses were not measured, it was apparent that fish species that had previously inhabited the shallow water habitat at the placement sites were no longer present, at least in the same population densities or species assemblage. However in summary, the observed ‘avoidance’ response of fish to dredging activities at the site appeared to be localized to the specific area of construction and dredge material placement.

Other types of information reviewed as part of this literature search are presented in a National Oceanographic and Atmospheric Administration (NOAA) Fisheries document prepared to assist agency personnel in reviewing proposed projects that may result in adverse affects to Essential Fish Habitat (EFH), per EFH provisions under the Magnuson-Stevens Act (Hanson et al. 2003). Potential environmental effects of dredging on EFH, include direct removal/burial of organisms, turbidity/siltation effects (including light attenuation), contaminant release and uptake (including nutrients, metals, and organics), release of oxygen consuming substances, entrainment, noise disturbances, and alteration to hydrodynamic regimes and physical habitat. The document further describes effects of dredged material placement as impacting or destroying benthic communities, affecting adjacent habitats, creating turbidity plumes, and introducing contaminants, and/or nutrients. However, no stochastic information describing actual behavioral responses of fish are presented.

One of the important outcomes of the current literature search was the identification of data gaps and other types of missing nformation that are necessary to better understand and evaluate impacts associated with dredging activities. Based on the results of this literature review, there was an overall paucity of studies that describe direct behavioral responses of fish to dredging activities. The preponderance of behavioral effects studies conducted in association with dredging activities was related to physiological responses to dredge-induced stimuli. Since inferences of behavioral responses can be drawn from physiological responses, this document includes both direct behavioral responses and physiological responses to dredge and dredge material placement actions. The findings of this document are provided below by stimulus category and fish type.

4.1 Turbidity

Turbidity is a measure of the degree to which water loses its transparency due to the presence of suspended particulates and the scattering and absorption of light. Size, angularity, and composition of dissolved and suspended matter all affect the degree to which light is scattered and absorbed in water. Turbidity is not only a measure of the amount of sediments suspended in the water at any one time but a product of volume, background water conditions, and sediment type (Thackston and Palermo 2000). Through the process of reflection, refraction, and absorption, this suspension of solids in the water column scatters light wavelengths and reduces light available to underwater environments (Nightingale and Simenstad 2001, McCarthy et al. 1974).

Turbidity measurements are often reported in Nephelometric Turbidity Units (NTUs), which are units of turbidity measured from a calibrated nephelometer. The nephelometer measures the level of light scatter in a water sample resulting from a focused beam of light. An alternative (and somewhat less accurate) method for reporting turbidity is the Jackson Turbidity Unit (JTU), which is a measure of light beam attenuation through a calibrated column of water.

Turbidity related effects on fish behavior are often confounded by the existence of additional variables, including clean vs. contaminated sediments, chemical constituents within the sediment, sediment type, and fish species affected. Behavioral responses of fishes to increased levels of turbidity have been studied in both *in situ* and under laboratory conditions, using silt, clay, sand, and volcanic ash (Whitman et al. 1982, Newcombe and Flagg 1983, Brannon et.al. 1981, Redding et al. (1987). Some of the documented effects of turbidity on fish behavior include avoidance, disorientation, decreased reaction time, increased or decreased predation, increased or decreased feeding activity, and physical injury and mortality (Abrahams and Kattenfield 1996, Bash et al. 2001, Beer et al. 2003, Berggren and Filardo 1993, Brannon 1978, Crouse et al. 1981, Ginetz and Larkin 1976, Henley et al. 2000). However, many fish species (especially estuarine species) have been documented to prefer higher levels of turbidity for cover from predators and for feeding strategies (Wilbur and Clarke 2001). According to Boehlert and Morgan (1985) increased turbidity may enhance feeding rates of Pacific herring through resultant visual contrast of prey items. Additionally, Gregory and Northcote (1993) found that increased foraging rates for juvenile Chinook salmon were attributed to the increase in cover provided by increased turbidity.

Increased turbidity may result from other activities related to dredging, especially knockdown operations. Published studies on the effects of knockdown operations on fish behavior are lacking. However, Clarke et al. (2008) provided detailed characterizations of suspended sediment plumes resulting from knockdown operations for the Port of Redwood City and found that suspended sediment plumes were highly variable over time and displayed predictable spatial patterns. In general, higher density suspended sediment plumes were observed directly behind the knockdown bar and in the lower half of the water column. It appears that effects to aquatic organisms would be limited to those in the lower water column, and with the limited duration of plume events, would result in avoidance behavior by fishes similar to that observed for dredge plumes. Further, only those organisms directly displaced by the knockdown bar would be at elevated risk of mortality.

Since dredging does not generally occur continuously over a 24-hour period and daily tidal changes affect the spatial extent of sediment plumes, turbidity results provided in the following sections for specific groups of fishes does not represent chronic exposure to resuspended sediments (greater than 96 hrs). However, chronic effects can occur in association with naturally-occurring, generally climatic events.

Turbidity-related effects on behavioral responses of various fish species are provided below and presented in Table 1a for anadromous species, Table 1b for bay resident species, Table 1c for bay non-resident species, and Table 1d for surrogate species.

4.1.1 Turbidity – Anadromous Species

The effects of increased turbidity on the behavior of anadromous fish are dependent on the species and habitat type; although in general, alterations to feeding activity and predatory responses are the most commonly observed reactions (see Table 1a). In San Francisco Bay, typical turbidity values range between 10 and 180 NTUs.

Gregory and Northcote (1993) tested juvenile Chinook salmon within a range of 1 to 810 NTUs and found that feeding rates were greatest at levels between 35 and 150 NTUs. Gregory and Levings (1996 and 1998) provided evidence of increased cover with increased turbidity, suggesting that reduced rates of encounters rather than reduced rates of attacks or captures is the mediated-response. Gregory (1993) also found that juvenile Chinook salmon had reduced predator-avoidance recovery time after exposure to turbid water.

Conversely, Madej et al. (2007) found that juvenile steelhead and juvenile coho salmon had reduced feeding activity and prey capture rates at relatively low turbidity levels of 25 to 45 NTUs. DeYoung (2007) also found that juvenile steelhead had reduced reactive distance with increasing turbidity from 17 to 63 NTUs, although growth rates were not significantly different at the higher turbidity levels. In addition, Barrett (1992) found that predatory reactive distance was reduced by 52 to 62 percent for juvenile Coho salmon at turbidity levels between 20 and 30 NTUs, and Bisson and Bilby (1982) documented juvenile Coho salmon avoidance response at turbidity levels of 70 NTUs.

4.1.2 Turbidity – Resident, Non-Resident, and Surrogate Species

Resident Fish Species. Turbidity experiments were conducted as early as 1969 on several San Francisco Bay fish species as part of an assessment of dredging effects by the United States Department of the Interior, Fish and Wildlife Service (1970) (see Table 1b). During these experiments, shiner perch, rubberlip sea perch, white seaperch, striped bass, Pacific tomcod, and brown rockfish were subjected to turbidity levels of 500, 1500, and 2,500 JTUs in controlled laboratory conditions. Experimental turbidity levels were selected based on the expected initial turbidity levels at the time of dredged material placement. With the exception of brown rockfish and striped bass which generally survived in all experiments, results of this study indicated that most of the fish experienced weight loss and increased mortality in the highest turbidity levels (1,500 and 2,500 JTUs)., White seaperch and shiner perch performed relatively poorly over all experiments (including 500 JTUs), exhibiting high mortality. Pacific tomcod and rubberlip seaperch also exhibited moderate lethal and sublethal effects, especially during experiments at

1,500 and 2,500 JTUs. However, these laboratory experiments were conducted up to 210 days at these elevated turbidity levels, which would not occur *in situ*. Background turbidity levels in San Francisco Bay at the time of the experiments ranged from 3 to 190 JTUs. Further, turbidity values in San Francisco Bay rarely exceed 200 JTUs. For this reason, these results must be considered to be extreme worst case.

In situ sampling was also conducted for this project. Monthly trawling was initiated two months prior to the dredging and dredged material placement activities, and continued over the course of one year. In general, results indicated that fish abundance was not significantly different between pre- and post dredging. At several trawling sites, there were no significant effects on the benthic community or demersal fish populations; while at other sites, there were temporary reductions in the benthic community and demersal fish populations.

<u>Surrogate Fish Species.</u> Similar to the findings noted for steelhead, adult resident rainbow trout elicited a 20 percent reduction in reactive distance at 15 NTUs, and a 52 percent reduction in reactive distance along with a decline in feeding behavior at 30 NTUs (Barrett 1992) (Table 1d). Artic grayling showed decreased reactive distance with increasing turbidity, and eventual mortality at 727 NTUs (Lloyd et al. 1987). Shaw and Richardson (2001) documented reduced growth rates for juvenile rainbow trout at a turbidity level of 23 NTUs. Clarke and Wibur (2000) documented reduced feeding rates for Cape silverside at 120 NTUs; and bluegill showed reduced feeding activity at 200 NTUs, with no affect on prey size selectivity (Gardner 1981). Conversely, walleye exhibited higher growth rates and more uniform swimming behavior at 30 to 40 NTUs than in clear water conditions (Rieger and Summerfelt 1997).

Cyrus and Blaber (1987) performed turbidity preference studies on 10 estuarine species in the Lake St. Lucia estuary (southeastern Africa). Results of these studies indicated that turbidity is the single most important factor (relative to other environmental factors) affecting fish distribution patterns. Their most important finding (and germane to the current literature review) showed that turbidity concentrations required to cause mortality are far above the highest documented naturally-occurring turbidity conditions, and that both sublethal and lethal effects of extremely high turbidities are largely due to lack of oxygen resulting from fouled gills.

Reactive distance and feeding were also reduced with increased turbidity (15 to 30 NTUs) for brook trout, rainbow trout, and cutthroat trout (Barrett 1992, DeYoung 2007, Sweka and Hartman 2001). In addition, cutthroat trout displayed reduced cover seeking activities in response to increased turbidity. Robertis et al. (2003) found that chum salmon feeding and predation were both reduced at higher turbidity levels (up to 40 NTUs). Utne-Palm (2004) reported that prey attack rates of Atlantic herring increased at 35 JTUs, and began to decrease at 80 JTUs. Kuruma prawn showed reduced feeding activity and fouled gill lamellae at turbidity levels over 20 NTUs; and water fleas (*Daphnia pulex*) had decreased filtration and assimilation efficiencies at 60 NTUs when compared with clear water conditions (McCabe and O'Brien 1983).

4.2 Suspended Sediments

Since turbidity effects on fish may be different than that of suspended sediments, effects of suspended sediments are treated separately. Turbidity is often used as a surrogate for suspended sediments, but is more accurately, an optical measure of suspended sediments. As a result, variability in the linear relationship between suspended sediment levels and turbidity indicates that it would be difficult or impossible to derive an overall correlation between turbidity and suspended sediment levels (Anchor Environmental 2003). Anchor Environmental (2002) reported that mechanical dredging in San Francisco Bay typically resulted in suspended sediment levels of 90 mg/L (mid range) and 200 mg/L (maximum) based on measurements obtained 160 feet from actual dredging operations.

The effects of suspended sediments on various fish species are provided below and presented in Table 1a for anadromous species, Table 1b for bay resident species), Table 1c for bay non-resident species, and Table 1d for surrogate species.

4.2.1 Suspended Sediments – Anadromous Species

One of the key studies regarding direct behavioral responses of anadromous salmonids to dredging activities was conducted by Carlson et al. (2001) in the Columbia River. During hydroacoustic observations of dredging operations (see Table 1a), Carlson documented several behavioral responses in the downstream movement of juvenile/smolt salmon that encountered the dredge and the dredge plume. These responses were (1) fish that were oriented along the deep-channel margin moved inshore when encountering the dredge; (2) most fish passing inshore moved offshore when encountering the dredge plume; and (3) fish assumed normal distribution patterns within a short time of encountering both dredge activity and the dredge plume.

Servizi (1990) reviewed juvenile salmonid (steelhead and Coho salmon) responses to suspended sediment loads by examining histological, immunological, physiological, and behavioral responses. Biochemical stress indicators were found to be highly sensitive to suspended sediment exposure, especially for chronic (rather than acute) exposures. Feeding and avoidance responses were also highly sensitive to suspended sediment exposure. Servizi reports that behavioral responses to suspended sediments are typically initiated in the range of 22 to 100 NTUs, and indicate that such avoidance behavior may be due at least partially to irritation of gill tissues. Both Servizi (1990) and McLeay et al. (1983) describe surfacing response behavior of smolt salmonids (sockeye salmon and arctic grayling, respectively) at higher suspended sediment levels, suggesting the fish were attempting avoidance behavior and were seeking the lower suspended sediment levels that typically occur near the surface.

Sigler et al. (1984) examined steelhead and coho juvenile/fry behavior following exposure to various levels of suspended sediments. Fish were found to emigrate from experimental channels with higher suspended sediment loads (100 to 300 NTUs). Additionally, when fish were retained in the experimental channels, growth rates were significantly higher in the clear water channels (less than 25 NTUs) relative to the treated channels.

Servizi and Martens (1991) examined underyearling sockeye, Chinook, and coho salmon tolerance to Fraser River sediments. Juveniles of these three species were exposed for 96-hrs, (LC50 [lethal concentration at which 50 percent mortality of test organisms is observed]) to concentrations of 17.6 g/L and 31 g/L, respectively; and Chinook salmon were found to be most tolerant, followed by coho and sockeye salmon. LC50 values varied with life stage: 8,100 mg/L for the swim-up fry, 22,700 mg/L for underyearlings, and 18,672 mg/L for juveniles (pre-smolt).

Servizi and Martens (1992) also exposed underyearling coho salmon to sublethal concentrations of Fraser River suspended sediment in lab experiments and noted that cough frequency increased when exposed for 24-hrs to a suspended sediment load of 0.24 g/L, and blood sugar levels increased during a 96-hr exposure period. When the sediment load increased to 6.78 g/L., the cough frequency increased after only 1-hr of exposure. Additionally, the tolerance of underyearling juvenile Coho salmon (0.5 g in weight) to suspended sediment was 35 percent lower than larger fish. Relationships also exist between temperature and tolerance to suspended sediments, involving several factors such as cough reflex (to clear gills of sediments), oxygen transfer, oxygen saturation levels, metabolic rates and ‘work’ capacity; all of which decrease with declining water temperature.

Lake and Hinch (1999) exposed coho salmon to various suspended sediment concentrations for a period of 96-hrs, and found that concentrations of suspended sediments at levels over 40 g/L resulted in gill damage, but mortalities did not occur until concentrations reached about 100 g/L.

Juvenile Chinook salmon exposed for 48-hrs to a sediment concentration of 30,000 mg/L were less likely to seek protective cover and react to change in light conditions (Korstrom and Birtwell 2006). Results of this study concluded that a brief exposure to high sediment concentrations in the wild would elicit overt behavioral changes that may increase susceptibility to predation from avian and aquatic predators.

The affects of suspended sediments on feeding rates of juvenile Chinook salmon were examined by Gregory (1988). Results showed that intermediate turbidities (100 mg/L) resulted in higher feeding rates than were apparent in clear water, or in water with the highest level treatment (800 mg/L).

In the lower Columbia River system, the Mt. Saint Helens eruption on 18 May 1980 created volcanic ash (VA) flows in numerous tributary systems. The affects of the VA on anadromous salmonids were subsequently evaluated to assist with management decisions. Whitman et al. (1982), Newcombe and Flagg (1983), and Brannon et.al. (1981) examined the affects of VA on Chinook salmon adults and found no histological signs to olfactory epithelium at a concentration of 650 mg/L for 168-hr exposures. Newcombe and Flagg (1983) exposed Chinook salmon juveniles, smolts, and adults to various VA concentrations and found no mortality in adult Chinook salmon when exposed to a concentration of 39,300 mg/L for 24-hrs. Increasing the exposure concentration to 82,400 mg/L for 6 hours resulted in a 60 percent mortality rate, and 100 percent mortality was reached at a concentration of 207,000 mg/L for 1-hr. Juvenile Chinook salmon, exposed for 36-hrs to 1,400 mg/L and 9,400 mg/L VA concentrations, resulted in 50 percent mortality rates; while a 36-hr exposure to a VA suspended sediment concentration of 39,400 mg/L resulted in 90 percent mortality.

Whitman et al. (1982) studied the affects of VA on homing behavior of adult Chinook salmon and observed a disruption in home preference in treated conditions compared to controls, although numbers of returning fish were similar between test and control fish. In addition, Chinook salmon were also found to stray to non-natal rivers when water quality in their natal stream is degraded.

Redding et al. (1987) exposed yearling coho salmon and steelhead to three types of suspended solids (VA, topsoil, and kaolin clay) in the lab and examined physiological affects. Results were similar in all three treatments; although a potential affect on feeding frequency was noted during treatment with VA, compared to the topsoil and clay replicates, when surface feeding did not occur. In another study, steelhead yearlings were subjected to long-term exposure to two topsoil sediment concentrations (high - 1.7 to 2.7 g/L, and low - 0.5 g/L) for up to six days. Blood tests conducted at regular intervals revealed that chronic exposure to suspended sediments of up to 4 g/L may initially be stressful to fish. Mortalities only occurred during the disease challenge phase of the experiment where 25 percent of the treated animals died after exposure to a pathogen. Survivors of the topsoil experiments were also found to be more susceptible to exposure to the pathogen. In general, steelhead exposed to suspended sediment showed signs of sublethal stress with elevated levels of plasma cortisol and reduced feeding. Coho salmon showed similar results with increased plasma cortisol levels and reduced feeding. Martens and Servizi (1993) found that suspended sediment particles were present in gill lamellae when salmon (Coho, Chinook, pink, and sockeye) were chronically exposed to river sediment concentrations.

Auld and Schubel (1978) examined effects of natural Chesapeake Bay sediments on early life stages of fish and found that American shad larvae, when exposed to suspended sediment concentrations of 100 mg/L for 96-hrs, experienced 18 percent mortality; and exposure to concentrations of 500 mg/L and 1,000 mg/L for 96-hrs resulted in mortality rates of 36 and 34 percent, respectively. They also determined that sediment concentrations greater than 500 mg/L reduced survival of striped bass and yellow perch larvae exposed for 48- to 96-hrs. American shad were even less tolerant with higher mortalities at lower suspended sediment concentrations (100 mg/L).

Striped bass exposed to a suspended sediment concentration of 1,500 mg/L for 336 hrs had increased haematocrits and plasma osmolality (Newcombe and Jensen, 1996). Breitberg (1988) exposed striped bass to various suspended sediment treatments and found 40 percent fewer prey consumed by striped bass in concentrations ranging from 200 to 500 mg/L, when compared with 0 or 75 mg/L concentrations. Morgan et al. (1983) examined effects of sediment exposure on striped bass and white perch eggs and larvae and found that hatchings of striped bass eggs were not affected by concentrations ranging from 20 to 2,300 mg/L, but development slowed at concentrations above 1,300 mg/L. Striped bass larvae exposed (24-hr) to sediment concentrations from 1,626 to 5,380 mg/L, resulted in 20 to 31 percent mortality, while 48-hr exposures resulted in 23 to 49 percent mortalities.

4.2.2 Suspended Sediments – Resident, Non-Resident, and Surrogate Species

Resident Fish Species. Inland silverside exposed to 58 mg/L, 250 mg/L, and 1,000 mg/L of suspended sediment for a 24-hr period experienced 10, 50, and 90 percent mortality, respectively (Newcombe and Jensen 1996) (see Table 1b); although threespine stickleback exposed to 28,000 mg/L suspended sediment concentrations resulted in no mortality. Data obtained by Newcombe and Jensen (1996) indicate that fish are able to avoid high concentrations of suspended sediments; however, indirect effects of extreme suspended sediment events on invertebrate populations (fish food) and primary production can be substantial.

Non-Resident Fish Species. Several researchers have studied the effects of suspended sediment on Pacific and Atlantic herring, including San Francisco Bay stocks (Conner et al. 2005, Ogle 2005) (see Table 1c). Juvenile Atlantic herring were observed to elicit avoidance response behavior to suspended sediment concentrations at a threshold of 9 to 12 mg/L (Ogle 2005). However, Boehlert and Morgan (1985) found that maximum feeding rates occurred at 500 to 1,000 mg/L concentrations, well above the typical concentrations observed for mechanical dredging operations in San Francisco Bay (Ogle 2005). A gradual decrease in feeding rates was observed at concentrations of 2,000-8,000 mg/L (Boehlert and Morgan 1985). A 24-hr exposure to 1,000 mg/L of suspended sediment caused mechanical damage to the epidermis of Pacific herring larvae, while 4,000 mg/L caused epidermal punctures and abrasion of micro-ridges on scales (Newcombe and Jensen 1996).

Surrogate Fish Species. Clarke and Wilber (2000) provided an overview of the behavioral effects of suspended sediments on fish (all of which are surrogate species in this document) in an ERDC technical Memorandum entitled "*Assessment of potential impact of dredging operations due to sediment suspension*." In the document, potential behavioral and physiological effects caused by the presence of suspended sediment particles and associated debris are described. Behavioral effects may include alarm reaction, altered schooling behavior, cover abandonment, and avoidance or attraction depending on the type of sediments and sediment concentration. The authors suggest that such behavioral effects may be caused by changes in light penetration/scattering. Physiological effects may include changes in respiration rate, choking, coughing, abrasion and puncturing of structures (gills, epidermis), reduced feeding, reduced water filtration rates, smothering, delayed or reduced hatching of eggs, reduced larval growth/development, abnormal larval development, and reduced responses to physical stimuli. Extreme levels of suspended sediments can result in increased mortality and/or decreased growth and reproduction (Nightingale and Simenstad 2001, Benfield and Minello 1996, Lloyd 1987).

The behavioral affects of suspended sediments on several Atlantic coast fish species were investigated by Sherk, O'Connor, and Newman (1976) and Sherk et al. (1974) who developed sediment tolerances using fuller's earth (a standardized bioassay medium) for several estuarine fish species. Fish species classified as highly sensitive (24-hr LC_{10} < 1,000 mg/L) included Atlantic silversides, juvenile bluefish, and young-of-the-year white perch (see Table 1d). Sensitive species (24-hr LC_{10} > 1,000 mg/L and < 10,000 mg/L) included bay anchovy, juvenile menhaden, striped bass, weakfish, and Atlantic croaker. Tolerant species (24-hr LC_{10} > 10,000 mg/L) included mummichog, striped killifish, spot, toadfish, hogchoker, and cusk eel. Colby and Hoss (2004) found that a 48-hr exposure to 19,000 mg/L of suspended sediment resulted in 100 percent mortality to Atlantic herring larvae, while avoidance and reduced feeding was observed at 1.0 to 6.0 mg/L suspsended sediment (Messieh et al. 1981). Atlantic herring eggs exposed to constant concentrations of 5 to 300 mg/L suspended sediment and short-term exposure to 500 mg/L suspended sediment elicited no adverse response (Kiorboe et al. 1981).

Rainbow smelt adults were more susceptible to predation at suspended sediment concentrations of 3.5 mg/L than in clear water (Newcombe and Jensen 1996). Johnson and Hines (1999) reported that razorback sucker adults were less susceptible to predation at 2,000 mg/L than at 0 mg/L, although they typically avoided levels of 2,000 mg/L suspended sediment. Sockeye salmon smolts showed possible altered osmoregulatory capacity when exposed to 14,400 mg/L of suspended sediment for 96-hrs, and juvenile sockeye salmon showed hypertrophy and necrosis of gill tissue under the same exposure regime (Newcombe and Jensen 1996, Servizi 1990). Juvenile sockeye salmon and juvenile pink salmon exposed to 200 mg/L suspended sediment for 96-hrs had particles present in gill lamellae and spleen (Martens and Servizi 1993).

Servizi (1990) found that juvenile sockeye and pink salmon exposed to 11,400 mg/L suspended sediment exhibited 28 percent mortality with survivors showing a 36 percent reduction in salinity tolerance. However, at 5,800 mg/L no mortality or reduction in salinity tolerance was observed. Atlantic salmon adults and juveniles showed increased risk of predation at 2,500 mg/L of suspended sediment (Newcombe and Jensen 1996), and juveniles showed decreased feeding behavior and predator avoidance behavior at concentrations of 260 to 460 mg/L suspended sediment, with increased feeding behavior and decreased predator avoidance at 20 to 180 mg/L (Robertson et al. 2007).

As suspended sediment concentrations increased from 2 to 35 mg/L, cutthroat trout adults showed decreased feeding behavior and cover-seeking responses. Artic grayling showed impaired feeding and reduced growth when exposed to 100 mg/L suspended sediment for 84 days (Phua 2005). Atlantic cod avoided sediment plumes of 39,713 mg/L (Phua, no date). Newcombe and Jensen (1996) reported various LC values for 24-hr exposures to suspended sediments for striped killifish, including an LC_{10} value of 9,720 mg/L, an LC_{50} value of 12,820 mg/L, and an LC_{90} of 16,930 mg/L. Newcombe and Jensen (1996) found that 50 percent mortality rates for fourspine stickleback exposed for 24 hours were dependent on suspended sediment type and water temperature. Fifty percent mortality rates ranged from 300 mg/L for incinerator ash (temperature was not specified) to 333,000 mg/L for Kingston silt at 9-9.5 ° C.

Newcombe and Jensen (1996) summarized a number of studies on the affects of suspended sediment on centrarchids. Green sunfish exposed for 1-hr to 9,600 mg/L of suspended sediment showed an increased rate of ventilation. Bluegill, redear sunfish, and largemouth bass had decreased growth rates and reproductive failure when exposed for 720 hours to 144.5 mg/L of suspended sediment, while similar exposure to 62.5 mg/L of suspended sediment caused a 50 percent reduction in weight gain for bluegill and largemouth bass, and a five percent reduction in weight gain for redear sunfish. Bluegill exposed to suspended sediment concentrations of 423 mg/L for three minutes showed reduced feeding rates, while exposure to 15 mg/L for 1-hr had a reduced capacity for locating prey.

4.2.3 Effects of Dredging and Dredged Material Placement to Benthic Macroinvertebrates (BMIs)

Several studies are available on the affects of sediment placement or deposits on benthic macroinvertebrate (BMI) communities, important both as a direct indicator of local aquatic health, but also as an indication of indirect effects to fish. A full review of dredging effects to the benthic community was not included in the scope for this project; however, the results of some representative studies are presented to give the reader a sense of the relatively similar results found throughout the literature. As expected (and documented in numerous additional studies not presented in the current document), the initial adverse affects from dredging or dredged material placement on BMI communities include burial and initial depression of abundance and community structure, with variances noted in recovery time and resultant community structure (Anchor Environmental 2003, Angonesi et al. 2006, Berry et al. 2003, Cooper et al. 2007, Diaz 1994, Dolmer et al. 2001, Essink 1999, Guerra et al. 2007, Hanson et al. 2003, Harvey et al. 1998, Hill et al. 1999, Haynes and Makarewicz 1982, Hauton et al. 2003, Jones 1986, Leatham et al. 1973, Lin et al. 1992, Newell et al. 1999, Ohimain et al. 2005, Rosenberg 1977, Sheridan 2004, Smith et al. 2006, Wilbur et al. 2007, and Wilbur et al. 2008).

Recovery time is influenced by a number of factors including BMI community structure, relative disturbance level, water depth, sediment placement depth, and tidal or current velocities. Recovery times reported in the literature for BMIs showed considerable variation. Wilber et al. (2007) reported an initial reduction in the BMI community resulting from a burial depth of 2 to 10 cm and recovery times ranging from 3 to 24 months compared to the reference site. Simonini et al. (2007) reported initial defaunation of dredged areas, with recovery times in the range of 12 to 30 months. Angonesi et al. (2006) reported that species composition and richness remained virtually identical at pre and post disposal sites. Diaz (1994) reported an initial reduction in the BMI community after burial by 10 to 50 cm of disposed dredge material, followed by recovery within three months. Harvey et al. (1998) reported that BMI communities were substantially altered after deposition of 1,500 m^3 of sediment, and that recovery of a community structure similar to undisturbed areas required over two years. Haynes and Makarewicz (1982) reported that BMI abundance and species composition were greater at reference sites than at dredged sites. Hirsch et al. (1978) reported that a dredge disturbed BMI community initially showed recovery by opportunistic species and full recovery with species composition similar to undredged sites within one year. Jones (1986) reported that BMI abundance recovered faster than species richness at dredged sites, with full recovery taking several months.

Hard-shell clams had reduced growth rates at suspended sediment concentrations above 40 mg/L (Bricelj et al. 1984), while soft-shell clams had damaged siphons, decreased oxygen consumption, feeding inhibition, and decreased responsiveness when exposed to 100 to 200 mg/L of suspended sediment (Grant and Thorpe 1991). Long-term exposure to suspended sediment concentrations of 1,020 mg/L resulted in numerical but not statistically significant reductions to mysid shrimp populations (Nimmo et al. 1975). Kiorboe et al. (1981) reported increased growth rates of bay mussel when exposed to increased sediment levels.

4.3 Entrainment

Reine and Clarke (1998) defined entrainment by hydraulic dredges as the direct uptake of aquatic organisms by the suction field. Benthic organisms are particularly vulnerable to entrainment by dredges, due primarily to their sedentary habits. Similarly, demersal and epibenthic organisms are also vulnerable to entrainment by dredging activities. Other traits such as swimming speed, reaction time, and flight response can also affect the rate at which a species is entrained. Entrainment rates are usually described as the number of organisms entrained per cubic yard of sediment dredged (fish/y^3). Entrainment rates have also been described for vessel propellers and man-made structures (i.e., water diversions).

The effects of entrainment on fish may not be considered technically as a behavioral response; sessile fish species and young life stages of fish in general may not elicit a successful avoidance response. However, as fish grow and mature, and swimming or darting speeds improve, there is a definite avoidance behavior associated with potential entrainment from hydraulic dredging. Affects of entrainment rates associated with dredging activities for various fish species are provided below and presented in Table 1a for anadromous species, Table 1b for bay resident species), Table 1c for bay non-resident species, and Table 1d for surrogate species.

4.3.1 Entrainment – Anadromous Species

Limited information is available regarding entrainment of anadromous fishes along the Pacific coast. Entrainment sampling conducted by Taplin and Hanson (2006) in the Sacramento and San Joaquin River estuary produced very few fall-run Chinook salmon (a total of eight fish). Additionally, only one striped bass was entrained during the study period. Entrainment rates for this study were considered to overestimate the vulnerability of juvenile salmon based on the placement of the dredge head during sampling. Between 2006 and 2008, entrainment sampling was conducted during dredging activities associated with the Port of Sonoma Marina, located at the mouth of the Petaluma River. During this study, Woodbury and Swedberg (2008) found that no salmon, steelhead, or sturgeon were entrained. During the first year of the study some juvenile striped bass were entrained, but none were found during the second year of the study. Larson and Moehl (1990) concluded that it is unlikely that anadromous fish are entrained by hopper dredging in estuarine channels, or at large river mouths such as the Columbia River. Buell (1992) found that white sturgeon were entrained by dredging at a rate of 0.015 fish/y^3, although this occurred in an area known as the “sturgeon hole”, with greater than average sturgeon densities. According to McCabe (1997), juvenile white sturgeon are susceptible to entrainment due to their small size, limited swimming ability, and orientation towards bottom habitats.

Hanson (2001) found that 0.05% of marked juvenile salmonids were entrained at an unscreened water diversion in the Sacramento River and were not entrained at a rate equivalent to the amount of water being diverted. Suction dredging impacts have been documented on Chinook salmon redds (Harvey and Lisle 1999) and benthic habitat and biota (Prussian et al. 1999). Studies conducted in the Frasier River identified eulachon and pink salmon (up to 858 entrained per day) as the dominant species entrained (Larson and Moehl 1990). However, these studies were conducted in restricted waterways during outmigration periods. Similar studies in Grays Harbor found only one chum salmon entrained and no eulachon.

4.3.2 Entrainment – Resident, Non-Resident, and Surrogate Species

Resident Fish Species. Demersal and epibenthic fish are likely to have the highest rates of entrainment based on their life history strategies of residing or burrowing into bottom substrates. Entrainment studies conducted on a dredge in the Sacramento and San Joaquin river estuary (i.e., Delta) found low entrainment rates of one to two individuals for yellowfin goby, Pacific staghorn sculpin, starry flounder, and threespine stickleback (Taplin and Hanson 2006). Longfin smelt, bay pipefish, topsmelt, northern anchovy, and Sacramento splittail were only occasionally entrained. All of these species were found in small numbers in relation to the amount of dredged material (Taplin and Hanson 2006, Woodbury per comm.). Sampling conducted during dredging activities at the Port of Sonoma Marina resulted in relatively high numbers of non-native gobies (mostly yellowfin goby) and a few individuals of Pacific staghorn sculpin, prickly sculpin, starry flounder, and three-spine stickleback (Woodbury per comm.).

Non-Resident Fish Species. McGraw and Armstrong (1990) determined from trawl sampling conducted simultaneously with dredging operations in Grey's Harbor, Washington, that most fish species were able to avoid dredging activities. However, demersal fish species such as Pacific staghorn sculpin, Pacific sand lance, and Pacific sanddab were more vulnerable to entrainment than other species (Larson and Moehl 1990, McGraw and Armstrong 1990). At the mouth of the Columbia River, Pacific sand lances were entrained at the highest frequency (0.341 fish/y^3), likely due to their infaunal habit. In comparison, entrainment rates for all other fish species ranged from <0.001-0.009 fish/y^3 (Larson and Moehl 1990).

Entrainment of Dungeness crab has been widely studied in Grays Harbor and the Columbia River. Nightingale and Simenstad (2001) determined that Dungeness crab entrainment was a function of the type of dredge used. Factors influencing entrainment were bottom depth, hopper dredge speed or cutterhead rates of advance, flow field velocities at the drag or cutterhead, the volume of dredged material, and the direction of dredging in relation to tidal flow. Mechanical dredges were found to have both the lowest average entrainment and mortality rates. Average entrainment rates for mechanical dredges were found to be 0.012 crabs/y^3 with a mortality rate of 10% (Reine and Clarke 1998). Pipeline dredge entrainment rates ranged from 0.0017-0.243 crabs/y^3 with 100% mortality and hopper dredge entrainment rates ranged from 0.040-0.592 crabs/y^3 with mortality ranging from 5 to 86 percent (Reine and Clarke 1998).

Surrogate Fish Species. Guetreter et al. (2003) conducted a study of entrainment mortality through the propellers of hydraulic dredge towboats and found that 0.53 shovelnose sturgeon per kilometer were killed following the tow boat. Mortality for this study was correlated to swim speed of shovelnose sturgeon. Total fish mortality (including sturgeon) was estimated at 3.72 fish/km.

4.4 Noise

Underwater noise can influence both fish behavior and physiology. Awareness of sounds in the environment allows fish to interact socially, avoid predators, and locate prey (Myrberg 1990). Popper and Carlson (1998) reported that sonic, infrasonic, and ultrasonic sounds may potentially be used to control fish behavior; however, most research has provided conflicting results on the sustainability and longevity of altering fish behavior. Effects of noise on various fish species are provided below and presented in Table 1a for anadromous species, Table 1b for bay resident species, Table 1c for bay non-resident species, and Table 1d for surrogate species.

4.4.1 Noise – Anadromous Species

Studies involving the effect of noise on anadromous Pacific coast fishes are primarily related to pile driving activities. Based on the known range of salmonid hearing, sounds generated during pile driving activities are likely heard by fish within a radius of 600 meters from the source (Feist 1991). Feist (1991) determined that sounds generated during pile driving activities influenced both fish behavior and distribution of schooling salmonids in the vicinity of the site. On non-pile driving days the number of schooling salmonids drastically increased as compared to pile driving days. Necropsy results of Chinook salmon exposed to concrete pile driving found no gross or microscopic physiological affects (Marty (2004). A study by Vagle (2003) discovered that juvenile Chinook salmon and chum salmon became disoriented after exposure to sounds ranging between 40 and 50kPa, and that mortality occurred with sounds in the range of 150kPa. Juvenile Chinook salmon displayed both flight and avoidance responses to sounds in the 10Hz range (Knudsen et al. 1997). Vanderwalker (1967) found juvenile steelhead displayed an awareness reaction to sound, with the greatest response at levels between 35 and 170Hz. After continuous exposure, juvenile steelhead showed no signs of habituation to the sound. Noise guiding systems have been studied at energy facilities in the Pacific Northwest as a means of guiding salmonids away from turbines. Noise in the range of 300-400Hz at 160dB was determined to be ineffective at deterring salmonids away from turbines.

Several studies have been conducted on the effects of noise on Atlantic salmon and its ability to control their behavior. Hawkins and Johnstone (1978) determined that noise in the 30-300Hz at 6-40dB elicited bradycardia. Between 0 and 200Hz, a spontaneous awareness reaction was elicited with bradycardia more pronounced at the lower frequencies (Knudsen et al. 1992). A similar study showed that Atlantic salmon displayed a flight and avoidance response at 10Hz, with no response at 150Hz (Knudsen et al. 1994).

The intensity and duration of noise varies between pile driving and dredging activities (Dickerson et al. 2001). Pile driving results in bursts of intense noise for short durations while dredging activities create sustained noise over longer periods of time. Further research is needed to understand the effect dredging noise has on anadromous fishes (Nightingale and Simenstad 2001).

4.4.2 Noise – Resident, Non-Resident, and Surrogate Species

<u>Non-Resident Fish.</u> Effects of noise on Pacific coast fishes have been documented by several investigators (Baldwin 1954, Greene 2001). Schwarz and Greer (1984) found that Pacific

herring exposed to noise levels in the range of 0 to 3kHz at 90 to 100dB showed avoidance responses with little habituation. Mortality was documented in juvenile Pacific herring at noise levels of 150kPa (Vagel 2003). In a study of northern anchovy and shiner perch, Marty (2004) found no physical damage to either species as a result of concrete pile driving activities.

Surrogate Fish. Exposure to noise has been shown to cause physiological damage to all life stages of fish. Noise levels between 10-1000Hz at 0-20dB reduced egg viability and larval growth rates of sheepshead minnows (Banner and Hyatt 1973). Damage to hair cells, ciliary bundles, and ear cells has been documented in Atlantic cod, pink snapper, and oscar exposed to noise ranging from 0 to 1000Hz from 0 to 180dB (Hastings 1995, Hastings et al. 1996, McCauley et al. 2003).

The hearing threshold for rainbow trout was documented by Abbott (1973) to be between 25 and 600Hz at 5 to 40dB, with the greatest sensitivity between 100 and 200Hz. Knudsen et al. (1997) found that juvenile rainbow trout exposed to 10Hz noise displayed initial flight response followed by an avoidance response. Rainbow trout demonstrated stress responses and increased cortisol levels when exposed to vibrations for five days (Hastings and Popper 2005). Cutthroat trout showed some response to noise in the range of 0 to 650Hz at 0 to 40dB (Henderson 1998).

5.0 DISCUSSION/CONCLUSIONS

This literature review summarizes current literature and other available information pertaining to dredging activities and the resulting effects on fish behavior and associated physiological responses including feeding success, foraging rates, reaction distances, and schooling characteristics, especially as they relate to turbidity. However, variability in responses associated with individual species and geographic location to turbidity and other dredge-induced stimuli are relatively common in the literature. Nightingale and Simenstad (2001) concluded that the primary risks associated with dredging were factors of the spatial and temporal overlap between the area of turbidity, the degree of elevated turbidity, the occurrence of specific fish species and life-stages, and options available to the fish relative to the relevant life-stage present.

Consequently, a single turbidity standard is not available for the protection of all fish species and life-stages.

Many of the cited responses for fish feeding and reaction distance were obtained from laboratory experiments. Further, many of the cited responses involved fish species inhabiting relatively clear freshwater habitats, and cannot be directly compared with studies environments where ambient turbidity levels are generally high. This is especially true for San Francisco Bay, where ambient turbidity levels are affected by upstream sediment input, sediment input during storm events from altered landscapes due to various landuse patterns, and wind-induced wave action.

Major findings of this document indicate that the available literature regarding specific effects to fish behavior from dredging activities is generally confined to turbidity and suspended sediments, with little available information on effects of other aspects of dredging. Most of the available information comes from laboratory studies, and far less *in situ* research has been performed. In particular, there are gaps in species-specific knowledge relative to the effects to fish behavior resulting from dredging activities. While it appears that pelagic fish species (especially salmonids) generally exhibit avoidance response to dredging activities and sediment plumes, other species, especially epibenthic species and sedentary species (e.g., gobies), may show a more neutral response to dredging activities. Further, there is little research regarding dredging effects on anadromous fish behavior in San Francisco Bay. Some species are thought to prefer, or at least have evolved to accommodate, elevated suspended sediment levels (e.g., sturgeon and striped bass). However, there are no stochastic data available that confirm avoidance, attraction, or even neutral responses to dredging activities.

Specific findings suggest that:

- Juvenile salmonid migration behavior is disrupted (through avoidance response) when encountering dredging activity or sediment plumes,
- Juvenile salmonid migration behavior generally returns to normal (i.e., assumes prior distribution patterns) soon after encountering a dredge or dredge plume,

- Fish tend to exhibit avoidance behavior for about two to three hours after dredged material placement and fish community densities generally return to pre-disposal levels after about three hours,
- Juvenile salmonid avoidance response behavior to elevated suspended sediments may be initiated in the range of 22 to 100 NTUs, and may be at least partially mediated by irritation of gill tissues from suspended sediment particles,
- Ambient turbidity levels are important when considering effects of increased turbidity, since some species (e.g., striped bass, white sturgeon, and green sturgeon) have evolved to tolerate naturally high turbidity levels,
- Typical maximum suspended sediment levels resulting from mechanical dredging operations in San Francisco are around 250 mg/L, in the range of preferred turbidity levels for Pacific herring feeding behavior,
- Initial adverse affects to the benthic macroinvertebrate community are almost universally observed from dredging or dredged material placement, followed by substantial variances in recovery time and resultant community structure,
- Demersal fish species (e.g., Pacific staghorn sculpin, Pacific sand lance, Pacific sanddab, and juvenile sturgeon) are more vulnerable to being entrained during dredging activities than are pelagic species, and anadromous salmonids exhibit avoidance behavior to increased velocities associated with hydraulic and suction type dredge activities, and
- Noise generated from pile driving activities is generally within the range to elicit avoidance by juvenile salmonids.

5.1 Data Gaps and Identified Research Needs

Literature regarding specific effects of dredging activities on fish behavior is generally confined to turbidity and suspended sediment issues, with very limited information on the effects of other aspects of dredging activities. In particular, substantial data gaps exist relative to species-specific information relative to the direct effects of dredging activities on fish behavior. Most of the available data has been obtained through laboratory studies, with very limited information available from *in situ* research. Past studies, such as those performed by the U.S. Dept. of the

Interior, Fish and Wildlife Service (1970) indicate the difficulty in performing affects assessments *in situ* using net and trawl methodologies. However, more recent technological advances, such as hydroacoustic sonar gear and hydroacoustic fish tags and receivers, are currently being utilized to evaluate fish behavioral affects. Recent studies associated with dredge entrainment and pile driving noise in San Francisco Bay, provide some of the most current information available. The LTMS-funded San Francisco Bay salmonid and green sturgeon tagging studies (initiated in 2007, in progress) along with similar riverine work being conducted by University of California, Davis investigators are providing important information regarding the distribution and timing of salmonid smolts in the Sacramento River and San Francisco Bay. Similar studies are being performed by ERDC on the east coast (studies documented herein by Clarke and Clarke et al.). Much of this type of work has also been summarized and addressed in the San Francisco Estuary Project (www.sfestuary.com). As more of this research is conducted, it is anticipated to evolve into more site-specific, species-specific, and activity-specific behavioral affects study planning and implementation (especially by the LTMS program). These types of research efforts are necessary, especially with regards to native resident and native anadromous species in San Francisco Bay. Additional information needs include the following:

- More research on the effects of turbidity and suspended sediments on anadromous fish species, in-bay resident species, and non-resident species of San Francisco Bay is necessary. Recent literature does indicate that many fish species are able to avoid suspended sediment plumes associated with typical dredging, knockdown, and dredged material placement operations with minimal risk to individual or population level health (Burczynski 1991). However, those species with infaunal or sessile life stages (e.g., Pacific herring eggs) are more vulnerable to eliciting sublethal to lethal effects, depending on site-specific and dredge project-specific considerations. Additional quantitative studies on species-specific (and life-stage specific) fish distribution in the immediate area of dredging, dredged material placement, and associated sediment plumes that integrate state-of-the-art hydroacoustic techniques and local knowledge of fish habitats, with well planned survey tactics are recommended.

- Considerable research has been conducted worldwide on the affects of turbidity and suspended sediments on aquatic communities, often with conflicting results. Quantitative models for assessing impacts resulting from dredging activities are currently being developed to help understand the variability of these findings. Models developed by Newcombe and MacDonald (1991), Newcombe and Jensen (1996), and more recent efforts (i.e., ERDC) have attempted to quantify affects of a variety of suspended sediment on fishes and other aquatic biota. This type of research is critical, especially in conjunction with traditional *in situ* research and monitoring and local modeling efforts. Follow-up monitoring is generally recommended prior to, during, and following the results of modeling activities, especially to ground truth site-specific actions (dredging or dredged material placement).
- The effects of dredging activities on specific behavioral responses of special-status fish species, particularly on green sturgeon and delta smelt (and on many other species of concern, including Pacific lamprey) are only surmised through largely anecdotal sources, and specific data is generally lacking. The local LTMS efforts currently being conducted to describe salmonid and sturgeon distribution and in-bay residency relative to hydroacoustic tagging and monitoring, should be considered as preliminary, and should continue to be funded. New methods and important ideas for further research are often the result of on-going research (Ehrenberg and Steig 2003). Additionally, the current tagging studies as well as innovative study designs should be applied to actual dredging and dredged material placement activities.
- Available information indicates that many of the fish species that reside either permanently or intermittently in San Francisco Bay have evolved to cope with elevated turbidity; even adapting life history strategies around increased turbidity (e.g., cover for protection, improved predator – prey relationships). Striped bass have been shown to improve their predatory foraging success in elevated turbidities. Both white and green sturgeon may be attracted to higher turbidities, as evidenced by increased habitat-based abundance along channel edges and shallow ‘flats’ during high tidal exchanges and when turbidity levels are elevated above otherwise ambient conditions. Stochastic information

is not available to assess whether dredging activities may result in a similar attraction response of sturgeon, or other species, to increased turbidity.

- Recent local research regarding entrainment effects on anadromous and resident species has been conducted during dredging activities, including sand mining and marina channel dredging during appropriate environmental work windows that result in relatively low impacts to these species.
- Non-native fish species appear to be the primary fishes affected in these studies; however juvenile sturgeon may be vulnerable to entrainment, depending on the specific project area. More of this type of monitoring, especially outside the environmental work windows, would help to define potential effects to anadromous and other special-status species.
- Although the affects of noise (especially related to pile driving) on some fish species (including pelagic species such as Delta smelt) in San Francisco Bay, have been relatively well documented, additional research is still needed.
- Research should also be focused on other issues where information is lacking, such as effects of dredging vessel movement and placement (and operations) on local aquatic community conditions, and propeller damage to surface dwelling fish.
- Research is also lacking on effects of dredging and dredged material placement to specific habitats in San Francisco Bay, including shallow water and channel habitats, and seagrass (i.e., eelgrass) habitat and associated fish communities (Erftemeijer and Lewis III 2006). Limited research has been conducted in eelgrass beds adjacent to ferry terminal and ferry approach routes in San Francisco Bay, and in embayments elsewhere; however, more detailed research on both the vegetative and fish community, as well as effects to avian populations is needed.

5.2 Potential Modeling Approaches for Affects Determination

In the last twenty years, several tools have been developed to examine or predict the possible effects of suspended sediments on aquatic biota. Newcombe and MacDonald (1991) examined more than 70 papers on effects of suspended sediments on freshwater and marine fishes and other organisms and compiled a database of suspended sediment effects. Their model evaluated suspended sediment concentrations and durations of exposure and found that the concentration was a poor indicator of mediated effects. In contrast, other investigators found that regression analysis on the product of sediment concentration and duration of exposure is a better indicator of potential effects. The authors developed an index of pollution intensity (stress index) as a convenient tool for predicting effects from a known intensity of pollution. The stress index is defined as the natural log of the product of concentration times the duration of the pollution event. Barry and Rees (2008) used simulated datasets for testing the performance of diversity indices as response indicators to organic enrichment. Bayer et al. (2008) provide a regulatory framework for dredging effects indicators in the United Kingdom, for review and potential use as a possible model for other nations. Auld et al. (1998) provide a population dynamics model to assess risks of hydraulic entrainment by dredges.

Newcombe and Jensen (1996) examined 80 published reports on fish responses to suspended sediment in streams and estuaries to determine severity of adverse effects, a metric that examines exposure, dose and response. They defined the metric on a 15-point scale with superimposed decision categories. These categories range from no effect through behavioral and sub-lethal effects to lethal effects. This study also provided best available estimates of the beginning of sub-lethal and lethal effects from suspended sediments. This model is supported by the hypothesis that susceptible individuals are affected by sediment doses (concentration x exposure duration) lower than the population responses can be detected.

Ault et al. (1998), in a Technical Note, provide a description of a population dynamics model (FISHFATE) to assess the environmental risks of hydraulic entrainment (of fish) by dredges. This technical note comments on the general lack of research available on the effects of dredging and related activities on aquatic resources. However, the existence of a relatively large database and body of literature on the effects of power plant entrainment and impingement on fishes is not mentioned in this document. The FISHFATE model attempts to use this database as a basis for the current model, suggesting that the approach may be transferable to modeling the affects of

USACE dredging operations on fish resources, provided sufficient quantities of quality biological, physical, and operational data are available.

5.3 Synopsis

The objectives of this literature review were (1) to conduct a comprehensive review of fish behavioral responses to dredging, dredged material placement, and other maritime activities, and (2) to provide the USACE and the SF Bay LTMS agencies with an understanding of the availability of knowledge regarding fish behavioral responses. This document concludes that considerable research has been conducted on the physical aspects of increased turbidity and suspended sediment levels resulting from dredging and dredged material disposal. There has also been considerable research conducted on the biological aspects and biological responses to increased turbidity and suspended sediment levels; however, that the majority of these studies has been conducted in laboratory settings. Although this type of research may be useful and provides insights regarding potential behavioral effects on fishes, it is also often difficult to relate these research results to conditions in San Francisco Bay. Most in-bay habitats (and surface sediments) are in a constant state of flux due to past (e.g., Sierran gold mining) and present (e.g., in–bay and upstream landuse practices, industrial and POTW discharges) anthropomorphic practices. Generally speaking, many habitats in San Francisco Bay are highly variable and confounding factors such as local toxic hot spots, geographical effects, tidal flows, variable currents obscure otherwise obtainable results.

Based on available literature, fish (especially pelagic species) often exhibit avoidance behavior when encountering dredge activities and sediment plumes. However, research at the species level is largely absent. As a result, additional local research on the affects of dredging to specific fish species and life-stages, similar to the studies currently being conducted (and funded by LTMS) is needed, especially for:

- Pacific herring, regarding effects to spawning and egg incubation success,
- Green sturgeon in-bay distribution and residency (especially the juvenile life stage), and

- Chinook salmon and steelhead in-bay distribution and residency.

Future research efforts should be designed to build on the results of more recent studies. More intensive and *in situ* research is necessary to fully understand dredging effects. Research should be focused in the immediate vicinity of dredging projects, dredged material placement projects, and also in similar habitats where neither dredging nor placement is occurring, so that dredging effects can be isolated from other, often naturally-occurring events.

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LIST OF TABLES

Table 1a. Behavioral Affects on Anadromous Fishes from Suspended Sediment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	0-108				Reduced piscivory with increasing turbidity	Gregory and Levings. 1998
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	0-250				Reduced reaction distance with increasing turbidity	Gregory and Northcote. 1993
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	0-810				Reduced feeding activity at lowest and highest turbidity levels, optimum feeding between 35-150 NTU	Gregory and Northcote. 1993
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	0-250				reduced reaction distance with increasing turbidity	Gregory. 1988
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile	0-45				Decreased feeding activity with increasing turbidity, decrease in prey capture with increased turbidity	Madej et.al. 2007
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile	70		N/A		Avoidance response	Bisson and Bilby. 1982
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile	0-45				Decreased feeding activity with increasing turbidity, decrease in prey capture with increased turbidity	Madej et.al. 2007
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile	20-30				Reduced reactive distance by 52%-	Barrett. 1992
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	23				Turbid waters reduced magnitude and postexposure recovery time after predator exposure	Gregory. 1993
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	0.5 - 87				Turbid waters reduce rate of encounter rather than rate of attack or capture	Gregory and Levings. 1996
Acipenseridae	*Acipenser transmontanus*	white sturgeon	Adult						
Clupeidae	*Alosa sapidissima*	American shad	Larvae		100	96		Mortality rate 18%, control 5%	Auld and Schubel. 1978, Newcombe and Jensen. 1996
Clupeidae	*Alosa sapidissima*	American shad	Larvae		500	96		Mortality rate 36%, control 4%	Auld and Schubel. 1978, Newcombe and Jensen. 1996
Clupeidae	*Alosa sapidissima*	American shad	Larvae		1,000	96		Mortality rate 34%, control 5%	Auld and Schubel. 1978, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus spp.*	salmon	Smolt/Juvenile		N/A	N/A		Fish orienting to the channel margin move inshore when encounting the dredge	Carlson, et.al. 2001
Salmonidae	*Oncorhynchus spp.*	salmon	Smolt/Juvenile		N/A	N/A		Most fish passing inshore moved offshore when encountering plume	Carlson, et.al. 2001
Salmonidae	*Oncorhynchus spp.*	salmon	Smolt/Juvenile		N/A	N/A		Fish were observed to assume their prior distribution trends within a short time after encountering both the dredging activity and the plume	Carlson, et.al. 2001
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		650	168		No histological signs of damage to olfactory epithelium	Brannon et.al., 1981, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		350	0.17		Disrupt home water preference	Whitman et.al.. 1982, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		650	168		Homing behavior normal, fewer test fish returned	Whitman et.al.. 1982, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		39,300	24	None: Vocanic ash		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		82,400	6	60% mortality rate		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Adult		207,000	1	100% mortality rate		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996

Table 1a. Behavioral Affects on Anadromous Fishes from Suspended Sediment Associated with Dredging Activities (Continued).

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		1400	36	50% mortality rate		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		9400	36	50% mortality rate		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		50-100			increased feeding rates	Gregory. 1988
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		30,000	48		Decreased ability to seek protective cover and reduced swimming speed	Korstrom and Birtwell. 2006
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		39,400	36	90% mortality rate with volcanic ash		Newcombe and Flagg. 1983, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		0-200	96		Particles in gill lamellae and spleen	Martens and Servizi. 1993
Salmonidae	*Oncorhynchus mykiss*	steelhead	Adult		500	3		Volcanic ash: signs of sublethal stress	Redding et. al. 1987, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus mykiss*	steelhead	Adult		500	9		Blood cell count and chemistry change	Redding et. al. 1987, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile		102	336		Growth rate reduced	Sigler et.al. 1984; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile		2,500	48		reduced tolerance to infection	Servizi. 1990
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile		2,000-3,000	168-192		plasma sodium levels same as control group	Servizi. 1990
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile		2,000-3,000	168-192		plasma cortisol levels elevated, reduced feeding	Redding et. al. 1987
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		2,000-3,000	168-192		plasma cortisol levels elevated, reduced feeding	Redding et. al. 1987
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		2,000-3,000	168-192		plasma sodium levels same as control group	Servizi. 1990
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		53.5	0.02		Alarm reaction	Berg. 1982, Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		20	0.05		cough frequency not increased	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		53.5	12		Change in territorial behavior	Berg and Northcote. 1985; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		6,000	1		Avoidance behavior	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		300	0.17		Avoidance behavior in minutes	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		25	1		feeding rate decreased	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		100	1		feeding rate decreased to 55 % of max	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		250	1		feeding rate decreased to 10 % of max	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		300	1		Feeding ceased	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		2,460	0.05		coughing behavior within minutes	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		53.5	12		Increased physiological stress	Berg and Northcote. 1985; Newcombe and Jensen. 1996

Table 1a. Behavioral Affects on Anadromous Fishes from Suspended Sediment Associated with Dredging Activities (Continued).

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		2,460	1		Cough frequency greatly increased	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		240	24		Cough frequency increased more than 5-fold	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		530	96		Blood glucose level increase	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		1,547	96		Gill damage	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		2,460	24		Fatigue of cough reflex	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		3,000	48		High level sublethal stress, avoidance	Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		102	336		reduced growth rate (clays: fire, bentonite)	Sigler et.al. 1984; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		8,000	96			Servizi and Martens. 1992; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (U)		22,700	96	50% mortality		Servizi and Martens. 1991; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Fry: swim up		8,100	96	50% mortality		Servizi and Martens. 1991; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile (presmolt)		18,672	96	50% mortality		Servizi and Martens. 1991; Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		40,000	96		Gill damage	Lake and Hinch. 1999
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		0-41,000	96		Particles in gill lamellae	Martens and Servizi. 1993
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile		0-200	96		particles in gill lamellae and spleen	Martens and Servizi. 1993
Moronidae	*Morone saxatilis*	striped bass	Adult		1,500	336		Haematocrit increased (FE)	Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Adult		1,500	336		Plasma osmolality increased (FE)	Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Adult/Juvenile						
Moronidae	*Morone saxatilis*	striped bass	Juvenile						
Moronidae	*Morone saxatilis*	striped bass	Larvae		200	0.42		40% reduced feeding rate	Breitberg. 1988
Moronidae	*Morone saxatilis*	striped bass	Larvae		1,000	68		35% mortality rate, control 16%	Auld and Schubel. 1978, Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Larvae		500	72		42% mortality rate, control 17%	Auld and Schubel. 1978, Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Larvae		485	24		50% mortality rate	Morgan II, et.al.. 1983; Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Egg		800	24	Development rate slowed significantly		Morgan II, et.al.. 1983; Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Egg		100	24		hatching delayed	Newcombe and Jensen. 1996
Moronidae	*Morone saxatilis*	striped bass	Egg		1,000	168		Reduced hatching success	Auld and Schubel. 1978, Newcombe and Jensen. 1996

Table 1a. Behavioral Affects on Anadromous Fishes from Suspended Sediment Associated with Dredging Activities (Continued).

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Adult		28,000	96		No mortality: test lethal threshold	Newcombe and Jensen. 1996
Sediment Load									
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile					Immunosuppression associated with contaminated estuaries	Arkoosh et. al..1998b
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		unknown			Increased mortality from Vibrio anguillarum at contaminated estuary containing HCBD, PCBs, and CHWSE	Arkoosh et.al. 2001
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile		unknown			Increased mortality from *Vibrio anguillarum* at contaminated estuary, immunosuppression retained after removal from contaminants	Arkoosh et. al..1998a

Table 1b. Behavioral Affects on Resident Fishes from Suspended Sediment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Atherinopsidae	*Menidia beryllina*	inland silverside	Adult		58	24	Mortality rate 10% (FE)		Newcombe and Jensen. 1996
Atherinopsidae	*Menidia beryllina*	inland silverside	Adult		250	24	Mortality rate 50% (FE)		Newcombe and Jensen. 1996
Atherinopsidae	*Menidia beryllina*	inland silverside	Adult		1,000	24	Mortality rate 90% (FE)		Newcombe and Jensen. 1996
Pleuronectidae		flounder	Larvae		100-10,000			Reduced feeding activity	Colby and Hoss. 2004

Table 1c. Behavioral Affects on Non-Resident Fishes from Suspended Sediment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Clupeidae	*Clupea harengeus*	Pacific herring	Adult		9-12			Avoidance of suspended sediment	Ogle. 2005
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		19000	48	100% Mortality		Messieh et. al. 1981
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		2000	2		Reduced feeding rate	Newcombe and Jensen. 1996
Clupeidae	*Clupea harengus pallasi*	Pacific herring	Larvae		1000	24		Mechanical damage to epidermis	Newcombe and Jensen. 1996
Clupeidae	*Clupea harengus pallasi*	Pacific herring	Larvae		4000	24		Epidermis punctured; microridges less distinct	Newcombe and Jensen. 1996
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		500-1,000 mg/L	Constant		Increased feeding	Boehlert and Morgan. 1985
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		2000	24		Reduced feeding	Colby and Hoss. 2004
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		0-1,000	2		Increased feeding activity with increaing turbidity	Boehlert and Morgan. 1985
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		1,000-8,000	2		Decreased feeding activity with increased turbidity	Boehlert and Morgan. 1985
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		1.0-6.0			Avoidance and reduced feeding activity	Messieh et. al. 1981
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		500		Increased mortality with contaminated sediment		Ogle. 2005
Clupeidae	*Clupea harengeus*	Pacific herring	Larvae		2,000		None	None, treatment with sewage sludge not sediment	Ogle. 2005

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Salmonidae	*Oncorhynchus keta*	chum	Juvenile	0-40				Reduced feeding at highest turbidity level, significant interaction between light and turbidity, reduced predation at higher levels of turbidity	Robertis et. al. 2003
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Adult	15				Reduced reactive distance 20%	Barrett. 1992
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Adult	30				Reduce reactive distance 55%, Decline in feeding behavior	Barrett. 1992
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Adult	>30				Avoidance response to turbidity	Lloyd et. al. 1987
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Juvenile	23		0-6		Reduced growth rate with increased turbidity over time	Shaw and Richardson. 2001
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Juvenile	17-63				Reduced reactive distance with increasing turbidity	DeYoung. 2007
Salmonidae	*Oncorhynchus mykiss*	rainbow trout						All the rainbow trout responses to hexavalent chromium exposure were sensitive behavioral indicators of sublethal exposure. Sensitivity parameter responses could be arranged in the following sequence: latent period of detection response = locomotor activity>gill ventilation frequency>coughing rate	Svecevicius 2009
Salmonidae	*Thymallus arcticus*	arctic grayling	Adult	1-727			Mortality associated with high turbidity	Avoidance of areas with high turbidity (75-727 NTU), decreased reactive distance with increased turbidity	Lloyd et. al. 1987
Atherinidae	*Atherina breviceps*	Cape silverside	Adult	120				Reduced feeding rate	Clarke and Wilber. 2000
Moronidae	*Morone americana*	white perch	Adult	0-138				Avoided strobe lights at high turbidity	McIninch and Hocutt.
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult	0-200				Reduced feeding activity with increasing turbidity	Gardner. 1981
Centrarchidae	*Lepomis macrochirus*	bluegill		0-200				No effect on size selectivity patterns of prey	Gardner. 1981
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult	0-30 (JTU)				Decreased reactive distance with increased turbidity	Vinyard and O'Brien. 1976
Percidae	*Stizostedion vitreum*	walleye	Larvae	30-40				Constant distribution and swimming speed, increased growth rate	Rieger and Summerfelt. 1997
Sciaenidae	*Leiostomus xanthurus*	spot	Adult	0-138				Avoided strobe lights at high turbidity	McIninch and Hocutt. 1987
Clupeidae	*Clupea harengeus*	Atlantic herring	Adult		9-22 mg/L			Avoidance of plume	Phua et al. 2005
Clupeidae	*Clupea harengeus*	Atlantic herring	Larvae		19000	48	100% Mortality		Colby and Hoss. 2004
Clupeidae	*Clupea harengeus*	Atlantic herring	Eggs		5-300 mg/L	Constant		No effect on embryonic development	Kiorboe et. al. 1981
Clupeidae	*Clupea harengeus*	Atlantic herring	Eggs		500	Short-term		No effect on embryonic development	Kiorboe et. al. 1981
Clupeidae	*Clupea harengeus*	Atlantic herring	Eggs		0-7,000	Constant		No effect on hatching success	Messieh et. al. 1981
Clupeidae	*Alosa aestivalis*	blueback herring	Adult						
Engraulididae	*Anchoa mitchilli*	bay anchovy	Adult		231	24		Mortality rate 10% (FE)	
Engraulididae	*Anchoa mitchilli*	bay anchovy	Adult		471	24		Mortality rate 50% (FE)	
Engraulididae	*Anchoa mitchilli*	bay anchovy	Adult		960	24		Mortality rate 90%	
Catostomidae	*Xyrauchen texanus*	razorback sucker	Adult		0-2,000			Avoidance of high turbidity	Johnson and Hines,. 1999
Catostomidae	*Xyrauchen texanus*	razorback sucker	Adult		0-2,000			Reduced predation in high turbidity	Johnson and Hines,. 1999
Osmeridae	*Osmerus mordax*	rainbow smelt	Adult		3.5	168		Increased vulnerability to predation	Newcombe and Jensen. 1996
Salmonidae	*Oncorhynchus nerka*	sockeye salmon	Smolt		14400	96		Possible altered osmoregulatory capacity	
Salmonidae	*Oncorhynchus nerka*	sockeye salmon	Juvenile			96		Hypertrophy and necrosis of gill tissue	Servizi. 1990
Salmonidae	*Oncorhynchus nerka*	sockeye salmon	Juvenile		0-200	96		Particles present in gill lamellae and spleen	Martens and Servizi. 1993
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Juvenile		11400		28% mortality	36% reduction in salinity tolerance	Servizi. 1990
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Juvenile		5800		No mortality	No change in salinity tolerance	Servizi. 1990
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Juvenile		0-21,000	96		Particles in gill lamellae	Martens and Servizi. 1993
Salmonidae	*Salmo salar*	Atlantic salmon	Adult		2,500	24		Increased risk of predation	Newcombe and Jensen. 1996
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile		2500	24		increased predation risk	Newcombe and Jensen. 1996
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile		20-180			Icreased feeding and decreased predator avoidance behavior	Robertson et. al. 2007
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile		260-460			Decreased feeding and predator avoidance behavior	Robertson et. al. 2007

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities (Continued

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Salmonidae	*Salmo salar*	Atlantic salmon	Adult					Study showed that the majority of released tagged fish (approx. 70%) used the North Fork, suggesting that natural fish populations avoid tributaries with high metal	Goldstein et.al. 1998
Salmonidae	*Salmo salar*	Atlantic salmon	Adult					Migration delays due to natural and manmade barriers, as well as other potential migration delay-causing effects, including but not limited to water quality impacts.	Thorstad et.al. 2007
Salmonidae	*Salvelinus fontinalis*	brook trout	Adult					Predatory reactive distance decreased with increased turbidity	Sweka and Hartman. 2001
Salmonidae	*Oncorhynchus clarki*	cutthroat trout	Adult		35	2		Decreased feeding, cover seek response	Newcombe and Jensen. 1996
Salmonidae	*Thymallus arcticus*	arctic grayling	Adult		100	1,008		Impaired feeding and reduced growth	Newcombe and Jensen. 1996
Gadidae	*Gadus morhua*	Atlantic cod	Adult		39713			Avoidance of plume	Phua et al, XXXX.
Fundulidae	*Fundulus majalis*	striped killifish	Adult		960	120		Haematocrit increased	
Fundulidae	*Fundulus majalis*	striped killifish	Adult		3277	24		Mortality rate 10% (FE)	Newcombe and Jensen. 1996
Fundulidae	*Fundulus majalis*	striped killifish	Adult		9720	24		Mortality rate 10%	Newcombe and Jensen. 1996
Fundulidae	*Fundulus majalis*	striped killifish	Adult		3819	24		Mortality rate 50%	Newcombe and Jensen. 1996
Fundulidae	*Fundulus majalis*	striped killifish	Adult		12820	24		Mortality rate 50%	Newcombe and Jensen. 1996
Fundulidae	*Fundulus majalis*	striped killifish	Adult		16930	24		Mortality rate 90%	Newcombe and Jensen. 1996
Fundulidae	*Fundulus majalis*	striped killifish	Adult		6136	24		Mortality rate 90%	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		28000	96		No mortality: test lethal threshold	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		100	24		Mortality rate <1% (Incinerator Ash)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		10000	24		No mortality (Kinston silt: 10-12°C)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		300	24		Mortality rate ~ 50% (IA)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		18000	24		Mortality rate 50% (15-16 °C)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		50000	24		Mortality rate ~ 50% (Kingston silt)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		53000	24		Mortality rate ~ 50% (10-12 °C)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		330000	24		Mortality rate ~ 50% (9-9.5 °C)	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		500	24		Mortality rate 100%	Newcombe and Jensen. 1996
Gasterosteidae	*Apeltes quadracus*	stickleback (fourspine)	Adult		200000	24			Newcombe and Jensen. 1996
Centrarchidae	*Lepomis cyanellus*	green sunfish	Adult		9600	1		Rate of ventilation increased	Newcombe and Jensen. 1996
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult		423	0.05		Feeding rate reduced	Newcombe and Jensen. 1996
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult		15	1		Reduced capacity for prey location	Newcombe and Jensen. 1996
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult		144.5	720		Growth retarded	Newcombe and Jensen. 1996
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult		62.5	720		Weight gain reduced ~50%	Newcombe and Jensen. 1996
Centrarchidae	*Lepomis macrochirus*	bluegill	Adult		144.5	720		Reproduction failure	Newcombe and Jensen. 1996

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities (Continued

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
Centrarchidae	*Lepomis microlophus*	redear sunfish	Adult		62.5	720		Reduced weight gain~5-% compared to controls	
Centrarchidae	*Lepomis microlophus*	redear sunfish	Adult		144.5	720		Growth retarded	
Centrarchidae	*Lepomis microlophus*	redear sunfish	Adult		144.5	720		Reproduction failure	
Centrarchidae	*Micropterus salmoides*	largemouth Bass	Adult		62.5	720		Weight gain reduced- 50%	Newcombe and Jensen. 1996
Centrarchidae	*Micropterus salmoides*	largemouth Bass	Adult		144.5	720		Growth retarded	Newcombe and Jensen. 1996
Centrarchidae	*Micropterus salmoides*	largemouth Bass	Adult		144.5	720		Reproduction failure	Newcombe and Jensen. 1996
Mugilidae	*Mullus barbatus*	Red Mullet	Adult					Results indicate a biological impact to organisms near the disposal site mainly related to organic chemicals such as PAH. Red mullet appears to be a useful sentinel species for biomarker approach to monitor impact caused by dredged materials.	Regoli et.al. 2002
Cyprinidae	*Dionda dichroma*	Crevice-Spawning Minnow	All					Observations included significantly more eggs than larvae in tanks that had increased suspended sediment – suggesting that an effect on the crevice spawning white-tail shiner included delayed spawning. Although, whitetail shiner spawning success was only considered moderately affected.	Sutherland 2006
		fish	All	0-80				No direct correlation between turbidity and preference of areas, but turbidity influences distribution patterns among species	Cyrus and Blaber. 1987
		fish	All					Acoustic survey documented fish abandoning dredge disposal area during operations and returning 2-3 hours after disposal ceased	Burczynski. 1991
		fish	All					Behavioral toxicity tests used with metals. Examination of metal behavior toxicity tests compared to standard laboratory analysis and an assessment of potential ecological significance of observed behavioral changes (e.g., locomotion, avoidance, feeding, cough rate, and predator avoidance)	Atchison et.al. 1986
		fish	All					High suspensoid loads may influence fish breeding success, egg and larval survival, population structure and size, food availability, and feeding efficiency.Sustained high suspensoid loads reduce the photic zone, blanket the benthos, and reduce fish feeding efficiency	Brunton 1985
		fish	All					Dredged materials in the Central Bay have been shown to affect the movement of fish schools. A supportive study showed striped bass forage species near the Alcatraz disposal site moved away from the site following a disposal event. Evidence suggests that repeated disposal events at the same site can keep fish away from an area – conceivably, this would affect angler success in a given area.	San Francisco Bay Institute, San Francisco Bay Estuary Project. 2004

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities (Continued

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
INVERTEBRATES									
Veneridae	*Mercenaria mercenaria*	hard clams	Juvenile		10-44			Normal growth between 10-40, reduced growth above 40	Bricelj et. al. 1984
Myacidae	*Mya arenaria*	soft-shell clam	Adult		100-200	0-360		Damage to siphons, decreased oxygen consumption, inhibited feeding, decreased responsiveness	Grant and Thorpe. 1991
Solenidae	Solen marginatus	Razor clams	All					Fate of burrowing megafauna (primarily razor clams, otter sheel, and burrowing heart urchin) following commercial dredging for the target species – razor clams. Poor survivability of most burrowing megafauna following a single dredging activity. Reburial capacity of burrowing megafauna	Hauton et.al. 2003
Mytilidea	*Mytilus edulis L*	common mussel	Adult					Dredging changed community structure by reducing the density of polychaetes.	Dolmer et.al. 2 2001
Mytilidea	*Mytilus edulis*	common mussel	Adult					50% increased growth in suspended	Kiorboe et. al. 1981
Mysidae	*Mysidopsis bahia*	opossum shrimp	All		1,00 mg/L			Reduction in planktonic or nektonic organisms	Nimmo et. al. 1975
Parvoviridae	*Penaeus japonicus*	Kuruma prawn	Juvenile	0-80			10-100%	Reduced feeding activity, contaminated gill lamellae above 20 NTU	
Daphniidae	*Daphnia pulex*	water flea	Adult	0-60				Reduced filtering rate and assimilation efficiencies with increasing turbidity	McCabe and O'Brien. 1983
		Invertebrates	All					Effects of long-term scallop dredging activitiesStudies in heavily and lightly dredged areas showed increased polychaete mollusk ratios, loss of fragile species, and increase in the predominance of scavenger predators	Hill et.al. 1999
		Invertebrates	All					Effects of dredging in estuaries included: Reduction of light penetration by increased turbidity; altered tidal exchange; mixing and circulation; reduction of nutrient outflow from marshes and swamps; increased saltwater intrusion; creation of environ. susceptible to low dissolved oxygen levels; siltation (coral, oysters, and barnacles particularly	Johnston 1981
		Invertebrates	All					Epifaunal scavenger species were observed attracted to the site following jet dredging for razor clams.The majority of the infaunal community was largely unaffected by the jet dredging activities – although large bivalves notably affected by the activities (10-28% observed damaged in samples)	Tuck et.al. 1999
		Invertebrates (Benthic)	All					Differences in benthic infauna community structure between placement and reference areas: the placement areas returned to pre-placement levels one-year after placement.	Wilber et.al. 2008
		Invertebrates (Benthic)	All					Two years following completion of mining activities – found lower abundance, biomass, and diversity in sand mined pit than in adjacent areas (macrofaunal activities were less than 32% similar inside the pit to those communities outside the pit).	Palmer et.al. 2008

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities (Continued

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
		Invertebrates (Benthic)	All					Compares successional sequences and recovery rates in euhaline and polyhaline systems. Following dredge disposal in relatively unstressed marine environments, the bentos communities generally takes one to four years to recover, while in more naturally stressed areas, recovery takes about nine months	Bolam and Rees 2003
		Invertebrates (Benthic)	All					Results indicated that the degree of natural disturbance plays an important role in influencing epifaunal community structure following cessation of dredging activities.	Smith et.al. 2006
		Invertebrates (Benthic)	All					Within highly dredged areas, the data may suggest that the "colonization community" may go through a transitional period before eventually reaching equilibrium.	Cooper et.al. 2007
		Invertebrates (Benthic)	All					Mud disposal from dredging - settling and resuspension – weather/tide effect on settling rates.	Wolanski et.al. 1992
		Invertebrates (Benthic)	All					Periphyton served as good indicators for analyzing potential eutrophic effects of wastewater discharge on peripyton communities occurring on artificial substrata. Wastewater stimulated periphyton growth and overall production	Cosgrove et.al. 2004
		Invertebrates (Benthic)	All					Model to understand if purposefully resuspended sediments (for keeping a lock dredged) is functioning to allow sediment to be transported out to sea by ebb tides or not. Study indicates that the methodology effectively removes sediment	Bai et.al. 2002
		Invertebrates (Benthic)	All					General discussion how dredging activities can impact coastal environments and the biological communities through dispersion of sediments that increase turbidity, pollutant release, other water quality impacts	Windom and Stickney 1976
		Invertebrates (Benthic)	All	23		0-6		Reduction in benthic abundance and richness over time, reduction in drift richness and increase in drift abundance over time	Shaw and Richardson. 2001
		Invertebrates (Benthic)	All					There was no evidence that dredge disposal had a detrimental impact on benthic	Wilber and Clarke 1998
		Invertebrates (Benthic)	All					Simulated data sets - Demonstrated how data on macrobenthic species numbers and abundance, after an organic enrichment event, can be simulated using the Emperical Pearson-Rosenberg Model	Barry and Rees 2008
		Invertebrates (Benthic)	All					Initial reduction in BMI community from burial depth of 2-10 cm, returned to reference levels in 3-24 months with different species composition	Wilber et.al. 2007.
		Invertebrates (Benthic)	All					Initial defaunation of dredged areas, benthic community recovery between 12-30 months	Simonini et.al. 2007
		Invertebrates (Benthic)	All					Species composition and richness remained virtually identical at pre and post disposal	Angonesi et.al. 2006
		Invertebrates (Benthic)	All					Initial reduction in BMI community after burial by 10 - 50 cm, followed by a recovery in 3 months, species composition relatively the same	Diaz. 1994

Table 1d. Behavioral Effects on Surrogate Fish Species from Suspended Sediment Associated with Dredging Activities (Continued

Family	Scientific Name	Common Name	Life Stage	Turbidity (NTU)	Suspended Sediment Concentration (mg/L)	Duration in Hrs	Lethal Effects	Response to Suspended Sediment	Reference ID
		Invertebrates (Benthic)	All					BMI community change substantially after deposition of sediment (1,500 m^3)	Harvey et.al. 1998
		Invertebrates (Benthic)	All					BMI abundance greater at reference sites as opposed to dredged sites	Haynes and Makarewicz. 1982
		Invertebrates (Benthic)	All					BMI community changed resulting from dredging, initial recovery by oppurtunistic species, full recovery within one year	Hirsch et.al. 1978
		Invertebrates (Benthic)	All					BMI community changed in abundance and richness at dredge and disposal sites, recovery time not known (191,000 m^3)	Leathem et.al. 1973
		Invertebrates (Benthic)	All					BMI community changed in abundance and richness at dredged sites, recovery of abundance occurred faster than richness, full recovery within months (14,500 m^3)	Jones. 1986
		Seagrass						Alterations in habitat characteristics and use by fishery and forage oraganisms were detectable at dredge disposal sites. Mean seagrass coverage of dredge material observed reached 48% after 3 years.	Sheridan 2004

Table 2a. Behavioral Effects on Anadromous Fishes from Entrainment Associated with Dredging Activities

Family	Scientific Name	Common Name	Life Stage	Entrainment Rate	Lethal Effects	Response to Entrainment	Reference ID
Acipenseridae	*Acipenser transmontanus*	white sturgeon	Adult	0.015 fish/y^3 for pipeline dredge			Buell. 1992
Salmonidae	*Oncorhynchus spp.*	salmon	Smolt/Juvenile	0.05 mean for entrainment at unscreened water diversion. Entrainment rate not in direct proportion to volume of water diverted.			Hanson. 2001
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	8 fish during sampling period		minor physical damage	Taplin and Hanson. 2006
Moronidae	*Morone saxatilis*	striped bass	Adult/Juvenile	1 fish entrained during sampling		minor physical damage	Taplin and Hanson. 2006
Moronidae	*Morone saxatilis*	striped bass	Juvenile	entrained in study numbers unknown			Woodbury and Swedberg. 2008
Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Adult	entrained in study numbers unknown			Woodbury and Swedberg. 2008
Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Adult	1 fish entrained during sampling		minor physical damage	Taplin and Hanson. 2006
Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Adult	0.004 fish/y^3 for pipeline dredge			Reine and Clarke. 1998

Table 2b. Behavioral Effects on Resident Fishes from Entrainment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Entrainment Rate	Lethal Effects	Response to Entrainment	Reference ID
Osmeridae	*Spirinchus thaleichthys*	longfin smelt	Juvenile	entrained in study numbers unknown			Woodbury and Swedberg. 2008
Osmeridae		smelt	Adult/Juvenile	0.009 fish/y^3 for hopper dredge			Reine and Clarke. 1998
Atherinopsidae	*Atherinops affinis*	topsmelt	Adult/Juvenile	<15 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Syngnathidae	*Syngnathus leptorhynchus*	bay pipefish	Adult/Juvenile	0.006 fish/y^3 for hopper dredge			Reine and Clarke. 1998
Syngnathidae	*Syngnathus leptorhynchus*	bay pipefish	Adult/Juvenile	<15 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Cottidae	*Leptocottus armatus*	Pacific Staghorn sculpin	Adult/Juvenile	0.003-0.092 fish/cy for hopper dredge			Reine and Clarke. 1998
Cottidae	*Leptocottus armatus*	Pacific Staghorn sculpin	Adult/Juvenile	0.001-0.037 fish/y^3 for pipeline dredge			Reine and Clarke. 1998
Cottidae	*Leptocottus armatus*	Pacific Staghorn sculpin	Adult/Juvenile	<15 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Cottidae	*Leptocottus armatus*	Pacific Staghorn sculpin	Adult/Juvenile	1 fish entrained during sampling		minor physical damage	Taplin and Hanson. 2006
Cottidae	*Cottus asper*	Prickly Sculpin	Adult/Juvenile	<15 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Embiotocidae		surfperch	Adult/Juvenile	0.001 fish/y^3 for hopper dredge			Reine and Clarke. 1998
Embiotocidae	*Cymatogaster aggregata*	shiner perch	Adult				
Gobiidae	*Acanthogobius flavimanus*	yellowfin goby	Adult/Juvenile	~1265 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Gobiidae	*Acanthogobius flavimanus*	yellowfin goby	Adult/Juvenile	2 fish during sampling		minor physical damage	Taplin and Hanson. 2006
Plueronectidae	*Platichthys stellatus*	starry flounder	Adult/Juvenile	0.001-0.002 fish/y^3 for hopper dredge			Reine and Clarke. 1998
Plueronectidae	*Platichthys stellatus*	starry flounder	Adult/Juvenile	<15 in 50,000 cubic yards of material			Woodbury and Swedberg. 2008
Plueronectidae	*Platichthys stellatus*	starry flounder	Adult/Juvenile	1 fish entrained during sampling		minor physical damage	Taplin and Hanson. 2006
Pleuronectidae	*Pleuronectes vetulus*	english sole	Adult/Juvenile	0.006-0.035 fish/cy for hopper dredge			Reine and Clarke. 1998
Pleuronectidae	*Pleuronectes vetulus*	english sole	Adult/Juvenile	0.001-0.003 fish/y^3 for pipeline dredge			Reine and Clarke. 1998
Pleuronectidae		flounder	Larvae				
Pleuronectidae	*Citharichthys sordidus*	speckled sanddab	Adult/Juvenile	0.003 fish/y^3 for hopper dredge			Reine and Clarke. 1998
Cancridae	*Cancer magister*	Dungeness crab	Adult/Larvae	0.040-0.592 crabs/y^3 mean for hopper dredge studies	5%-86% Mortality Depending on size class		Reine and Clarke. 1998
Cancridae	*Cancer magister*	Dungeness crab	Adult/Larvae	0.0017-0.243 crabs/y^3 mean for pipeline dredge	100% Mortality for all size classes		Reine and Clarke. 1998
Cancridae	*Cancer magister*	Dungeness crab	Adult/Larvae	0.012 crabs/cy for clamshell dredge	10% Mortality for all size classes		Reine and Clarke. 1998
Crangonidae	*Crangon* sp.	shrimp	Adult	0.063-3.38 shrimp/y^3 mean for hopper dredge studies			Reine and Clarke. 1998
Crangonidae	*Crangon* sp.	shrimp	Adult	0.001-3.404 shrimp/y^3 for pipeline dredge			Reine and Clarke. 1998

Table 2c. Behavioral Effects on Non-Resident Fishes from Entrainment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Entrainment Rate	Lethal Effects	Response to Entrainment	Reference ID
Engraulidae	*Engraulis mordax*	northern anchovy	Adult/Juvenile	0.018 fish/y^3 for Hopper dredge			Reine and Clarke. 1998
Engraulidae	*Engraulis mordax*	northern anchovy	Adult/Juvenile	2 fish during sampling		minor damage to fish	Taplin and Hanson. 2006
Cyprinidae	*Pogonichthys macrolepidotus*	Sacramento splittail	Adult/Juvenile	20 fish during sampling		minor damage to fish	Taplin and Hanson. 2006

Table 2d. Behavioral Effects on Surrogate Fish Species from Entrainment Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Entrainment Rate	Lethal Effects	Response to Entrainment	Reference ID
Acipenseridae	*Scaphirhynchus platorynchus*	shovelnose sturgeon	Adult	0.53 kills/km by entrainment in river tow boat			Gutreuter et.al. 2003
Acipenseridae	*Scaphirhynchus albus*	pallid sturgeon	Juvenile			Based on swimming endurance likely to be entrained by dredge drawing 15-20 ft/sec	Hoover et.al. 2005
Acipenseridae	*Acipenser fulvescens*	lake sturgeon	Juvenile			Based on swimming endurance not likely to be entrained by dredge drawing 15-20 ft/sec	Hoover et.al. 2005
Engraulididae	*Anchoa mitchilli*	bay anchovy	Adult	0.001-0.008 fish/y^3 for hopper dredge			Reine and Clarke. 1998

Table 3a. Behavioral Effects on Anadromous Fishes from Noise Associated with Dredging Activities

Family	Scientific Name	Common Name	Life Stage	Sound Level or Pressure	Lethal Effects	Response to Noise	Reference ID
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	10Hz		Initial flight response followed by avoidance response	Knudsen et al. 1997
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	300-400 Hz, 0-160 dB		Ineffective in causing fish to avoid turbines	Ploskey et. al. 2000
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	150kPa	Mortality		Vagle. 2003
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	44kPa		Disorientation following exposure	Vagle. 2003
Salmonidae	*Oncorhynchus tshawytscha*	Chinook	Juvenile	unknown		Pile driving had no gross or microscopic effect of fish	Marty. 2004
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile	20-200Hz, 0-30 Db		Awareness reaction to sound, highest response to 35-170 Hz, no habituation to sound	Vanderwalker. 1967
Salmonidae	*Oncorhynchus mykiss*	steelhead	Juvenile	300-400 Hz, 0-160 dB		Ineffective in causing fish to avoid turbines	Ploskey et. al. 2000
Salmonidae	*Oncorhynchus kisutch*	Coho	Juvenile	300-400 Hz, 0-160 dB		Ineffective in causing fish to avoid turbines	Ploskey et. al. 2000

Table 3b. Behavorial Effects on Resident Fishes from Noise Associate with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Sound Level or Pressure	Lethal Effects	Response to Noise	Reference ID
Embiotocidae	*Cymatogaster aggregata*	shiner perch	Adult	Unknown		Pile driving had no effect on gross or microscopic fish features	Marty. 2004

Table 3c. Behavioral Effects on Non-Resident Fishes from Noise Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Sound Level or Pressure	Lethal Effects	Response to Noise	Reference ID
Clupeidae	*Clupea harengeus*	Pacific herring	Adult	0-3 kHz, 90-100 dB		Avoidance away from sound source with less habituation	Schwarz and Greer. 1984
Clupeidae	*Clupea harengus pallasi*	Pacific herring	Juvenile	150kPa	Mortality		Vagle. 2003
Engraulidae	*Engraulis mordax*	northern anchovy	Adult/Juvenile	unknown		Pile driving had no effect on gross or microscopic features of fish	Marty. 2004

Table 3d. Behavioral Effects on Surrogate Fish Species from Noise Associated with Dredging Activities.

Family	Scientific Name	Common Name	Life Stage	Sound Level or Pressure	Lethal Effects	Response to Noise	Reference ID
Salmonidae	*Oncorhynchus keta*	chum	Juvenile	150kPa	Mortality		Vagle. 2003
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Adult	25-600Hz, -5 to 40dB		Hearing threshold within this range, most sensitive between 100-200Hz	Abbott. 1973
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Juvenile	10Hz		Initial flight response followed by avoidance response	Knudsen et.al. 1997
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Juvenile	Unknown		Observed stress after 1-5 days of vibrations, increased serum cortisol levels	Hastings and Popper. 2005
		fish	All	25-50Hz at 20 dB		Some attraction to sounds by predatory fish	Richard. 1968
Clupeidae	*Alosa aestivalis*	blueback herring	Adult	120-130kHz at 190dB		Avoidance	Popper and Carlson. 1998
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Juvenile	200-500Hz, 90-110db		Impact on distribution and behavior, schooling away from pile driving in protected areas	Feist and Miyyamoto. 1992
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon	Juvenile				
Salmonidae	*Salmo salar*	Atlantic salmon	Adult				
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile	30-300Hz, -6 to 40 dB		Hearing range that elicited bradycardia	Hawkins and Johnstone. 1978
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile	0-200Hz		Spontaneous awareness reaction, Bradycardia more pronounced at lower frequencies	Knudsen et.al. 1992
Salmonidae	*Salmo salar*	Atlantic salmon	Juvenile	10Hz and 150Hz		At 10 Hz Immediate and active swimming away from source, at 150 Hz no response from fish	Knudsen et.al. 1994
Salmonidae	*Oncorhynchus keta*	chum	Juvenile	200-500Hz, 90-110db		Impact on distribution and behavior, schooling away from pile driving in protected areas	Feist and Miyyamoto. 1992
Salmonidae	*Oncorhynchus kisutch*	silver	Juvenile	10-8,000 cps		Awareness reaction without avoidance	Moore and Newman. 1956
Salmonidae	*Salvelinus fontinalis*	brook trout	Adult				
Salmonidae	*Oncorhynchus clarki*	cutthroat trout	Adult	0-650 Hz, -40 to 0 dB		Show some response within these thresholds	Henderson. 1998
Salmonidae	*Thymallus arcticus*	arctic grayling	Adult				
Gadidae	*Gadus morhua*	Atlantic cod	Adult	50-400 Hz, 180 dB		Destroyed ciliary bundles	Hastings, 1995
Cyprinodontidae	*Cyprinodon variegatus*	sheepshead minnow	Egg/Larvae	10-1000 Hz, 0-20dB	Reduced egg viability	Reduced growth rate in larvae	Banner and Hyatt. 1973
Capsalidae	*Pagrus auratus*	pink snapper	Adult	0-1,000 Hz, 100-170 dB		Holes and blistering in ear sensory cells, fish poosibly would have swam away if possible	McCauley et.al. 2003
Cichlidae	*Astronotus ocellatus*	oscar	Adult	300Hz, 180 dB		Damage to utricle/lagena of ear	Hastings et al. 1996