POTENTIAL IMPACTS OF RE-SUSPENDED SEDIMENTS ASSOCIATED WITH DREDGING AND DREDGED MATERIAL PLACEMENT ON FISHES IN SAN FRANCISCO BAY, CALIFORNIA

LITERATURE REVIEW AND IDENTIFICATION OF DATA GAPS

Prepared for:

U.S. Army Corps of Engineers
San Francisco District
1455 Market Street
San Francisco, CA 94103-1398

Prepared by:

Alice A. Rich, Ph.D.
A. A. Rich and Associates
Fisheries and Ecological Consultants
150 Woodside Drive
San Anselmo, California 94960
www.aarichandassociates.com

July 20, 2010

SUMMARY

The San Francisco Bay Estuary (Bay) is a major fish passage and aquatic habitat containing a large number of fish species. Because of concerns that dredging and dredged material placement may detrimentally affect Bay fishes, this report assesses the status of knowledge on effects of re-suspended sediment on priority fishes (Chinook salmon, steelhead, North American green sturgeon, and Pacific herring). This review also discusses the potential impacts of suspended sediment, suspended solids, and turbidity from non-dredging activities (e.g., mining and logging) on fishes. Specifically, the objectives of this report are to:

- Characterize ambient suspended sediment concentrations that fishes are exposed to at dredging sites in the Bay;
- Evaluate the range of suspended sediment concentrations that occur in the Bay over relevant spatial and temporal scales (i.e. seasonally, in different embayments, and at various water depths);
- Summarize the known effects of suspended sediment on fishes with particular reference to priority Bay fishes;
- Identify data gaps to support the design of future studies on the subject; and,
- Provide a single source for accessing written and electronic material on the subject.

This literature search examined diverse historical literature reviews, peer-reviewed journal articles, books, theses/dissertations, and technical reports. Numerous experts were interviewed about the effects of suspended sediment (SS), turbidity, and dredging activities on fishes. To ascertain the state of knowledge of the effects of SS and turbidity on fishes, the following types of information were reviewed and analyzed:

- Ranges of SS concentrations in the Bay;
- Ranges of SS concentrations and turbidity levels associated with dredging activities and the factors that affect those concentrations; and,
- Responses of fishes to both dredging- and non-dredging-related SS and turbidity.

A great deal of information was found on the effects of SS and turbidity on fishes; however, few studies related those effects to dredging activities, fewer still focused on Bay fishes, and even fewer were conducted in the Bay. The studies were conducted primarily in the laboratory mostly using SS concentrations that were far above both the ambient and dredging-related SS concentrations. And, the experimental durations in the laboratory studies exceeded likely exposures found in the Bay. Consequently, to determine the effects of dredging related re-suspended sediment on fishes, a number of field- and laboratory studies are needed.

TABLE OF CONTENTS

APPENDICES

Appendix A:	Significant Contacts and Data Sources
Appendix B:	Summary, by Year, of Suspended Solids Concentrations in San Francisco Bay
Appendix C:	Summary of SS Concentrations and Turbidity Levels in Response to Dredging Activities in San Francisco Bay
Appendix D:	Summary of Review Documents on the Effects of SS and Turbidity in Fishes
Appendix E:	Summary of Studies on Mortality in Fishes Exposed to Suspended Sediment, Suspended Solids, and Turbidity in Fishes
Appendix F:	Summary of Dredging-Related Studies that Resulted in Mortality in Fishes Exposed to SS and Turbidity
Appendix G:	Summary of Studies on Mortality in Chinook Salmon, Steelhead, Rainbow Trout, Pacific and Atlantic Herring Exposed to SS
Appendix H:	Summary of Primary Stress Responses in Fishes Exposed to Suspended Sediments and Suspended Solids
Appendix I:	Summary of Secondary Stress Responses in Fishes Exposed to Suspended Sediments and Suspended Solids
Appendix J:	Summary of Dredging-Related Studies that Resulted in Secondary Stress Responses in Fishes Exposed to Suspended Sediments and Suspended Solids
Appendix K:	Summary of Studies on Secondary Stress Responses in Chinook Salmon, Steelhead, Rainbow Trout, and Pacific Herring Exposed to Suspended Sediments and Suspended Solids
Appendix L:	Summary of Studies on Tertiary Stress Responses in Fishes Exposed to Suspended Sediments, Suspended Solids, and Turbidity
Appendix M:	Summary of Dredging-Related Studies that Resulted in Tertiary Stress Responses in Fishes Exposed to Suspended Sediments, Suspended Solids, and Turbidity
Appendix N:	Summary of Studies on Tertiary Stress Responses in Chinook Salmon, Steelhead, Rainbow Trout, Pacific and Atlantic Herring, and Sturgeon Exposed to Suspended Sediments, Suspended Solids, and Turbidity

FIGURES

TABLES

INTRODUCTION

Project Background

The San Francisco Bay Estuary (Bay) comprises essential fish habitat for many migratory and resident fish species that potentially could be affected by dredging activities (i.e., dredging and dredge material placement). Levine-Fricke (2004) addressed the potential effects of dredging activities on Bay fishes and identified stakeholder concerns regarding environmental work windows (i.e. periods when dredging is allowed) in the Bay. One concern was elevated concentrations of dredging-related re-suspended sediment and potential effects on fishes. Hence, this report assesses the state of knowledge on the effects of re-suspended sediment created by dredging activities on priority Bay fishes (Table 1). This review also discusses the impact on fishes of suspended sediment/sediments, suspended solids, and turbidity from non-navigation dredging-related activities such as mining and logging.

Table 1: Priority Fish Species in San Francisco Bay

Common Name	**Species Name**
Chinook Salmon[1,2,3]	*Oncorhynchus tshawytscha*
Steelhead[4,5]	*O. mykiss*
Delta Smelt[6]	*Hypomesus transpacificus*
Green Sturgeon[7]	*Acipenser transpacificus*
Pacific Herring[8]	*Clupea harengeus pallassi*

Project Goals and Objectives

The primary objective of this review is to summarize the effects of re-suspended sediment, created by dredging activities, on Bay fishes. Specifically, the objectives of the report are to:

- Characterize the ambient suspended sediment concentrations at dredging sites in the Bay;
- Evaluate the range of suspended sediment concentration that occurs in the Bay over relevant spatial and the spatiotemporal scales (i.e., framework) for all seasons, in different embayments, and at various water depths;
- Summarize the known effects of suspended sediment on fishes with particular reference to priority Bay fishes;
- Identify data gaps to support the design of future studies on the subject; and,
- Provide a single source for accessing written and electronic material on the subject.

---

[1] Sacramento River Winter-Run: Federal-listed as Endangered, Critical Habitat Status (Federal Register, 1994a, 1993a).
[2] Central Valley Spring-Run: Federal-listed as Threatened, Critical Habitat Status (Federal Register 2005a, 1999).
[3] Fall-Run/Late-Fall-Run: Federal-listed as Species of Concern (Federal Register 2004).
[4] Central Valley Steelhead: Federal-listed as Threatened, Critical Habitat Status (Federal Register 2006a, 2005a,b).
[5] Central California Coast Steelhead: Federal-Listed as Threatened, Critical Habitat Status (Federal Register 2006a, 2005b).
[6] Delta Smelt: Federal-listed as Threatened, Critical Habitat Status (Federal Register, 1993b).
[7] North American Green Sturgeon: Federal-listed as Threatened (Federal Register, 2006b).
[8] Pacific Herring: Commercially important species and has an important role as a forage fish (Connor et al., 2005).

Fish Species

This review focuses on several priority Bay fishes (i.e., those that are Federal- or state-listed as threatened or endangered, or of commercial, recreational, or ecological importance). However, many other fishes are important as forage for predatory fishes, including Threatened and Endangered (T&E) species that reside in the Bay. To insure a broad understanding of the state of knowledge, results for other fish species and other geographic areas are also reviewed. Bay fishes were placed into four categories (Levine-Fricke, 2004):

- True estuarine (e.g., delta smelt);
- Freshwater (e.g., Sacramento squawfish);
- Marine (e.g., Pacific herring and northern anchovy); and
- Anadromous fishes (e.g., Chinook salmon, steelhead, green sturgeon).

A number of fish species use the Bay as a migratory corridor, foraging habitat, or spawning and nursery habitat. Anadromous fishes (e.g., Chinook salmon, steelhead, and green sturgeon) migrate through the Bay both as adults en route to rivers and streams in which to spawn, and as fry and juveniles emigrating from the rivers and streams to the Pacific Ocean. Pacific herring spawn at a number of sites throughout San Francisco Bay, notably from near the Richmond-San Rafael Bridge south to the Port of Redwood City (Watters et al., 2001a,b; Spratt, 1981). While dredging in the Bay may affect any of those fish species, the magnitude of the effect depends on many variables, including project site-specific environmental conditions (e.g., hydrodynamics, bathymetry) as well as the type of dredging operation (e.g., mechanical, hydraulic, knockdown).

Definitions of Terms

Many studies that examined the effects of suspended sediment on fishes used the term “suspended sediment” more or less interchangeably with the terms “suspended sediments”, “suspended solids”, “total suspended solids”, and “turbidity”. However, there is no universal relationship between the terms (Clarke and Wilber, 2008). The terms “suspended sediment”, “suspended sediments”, “total suspended sediment”, and “suspended solids” refer only to inorganic sediment (McCarthy et al., 1996). Each of these terms is reported in milligrams per liter, or mg/L, and is measured gravimetrically (measurement of dry weight of suspended solids per unit volume of water). Because suspended sediment/sediments and suspended solids have been used interchangeably throughout the years, suspended sediment, total suspended sediment, suspended solids, and total suspended solids will be referred to as “SS” in this review.

Turbidity is an optical property of water resulting from impurities (including sediment particles and organic matter) that causes light to be scattered and absorbed, rather than transmitted in straight lines through a sample (Wilber, 1970, 1983). Devices used to measure turbidity include nephelometers, Jackson candle turbidimeters, absorptimeters, and transmissometers. The nephelometer measures scattered light only; the other devices measure the effects of both absorption and scattering of light (Thackston and Palermo, 2000; McCarthy et al., 1996). Turbidity is measured in Nephelometric Turbidity Units (NTUs), or Jackson Turbidity Units (JTUs) (Witherspoon et al., 1988). However, JTUs are no longer used and cannot be directly compared to NTUs.

In the United States, due both to costs and logistical convenience, turbidity is commonly measured during regulatory requirements for compliance monitoring, using a nephelometer or optical backscatter sensor (Clarke and Wilber, 2008). To be environmentally relevant, however, the instrument must be calibrated against suspended sediment concentrations that include biologically-relevant material (Henley, 2000; Smith and Davies-Colley, 2002). For most dredging project monitoring studies, the relationship between turbidity and the biologically-relevant suspended sediment are not established (Clarke and Wilber, 2008). Thus, if one uses turbidity level instead of SS concentration without establishing a relationship between the two for each water body, it is not possible to assess the effects of suspended sediment from dredging activities on biological resources, including fishes (Clarke and Wilber, 2008).

Stress in Fish: The Basis for Assessing the Effects of SS and Turbidity on Fishes

To understand the effects of SS from dredging and other activities on fishes, it is essential that the reader understand the concept of stress in fish (Figure 1). Both direct and indirect effects of SS on fishes are caused by the fish's response to the stressor. The definition of stress in humans was originally put forth by the Canadian physician, Dr. Hans Selye (1956, 1950). His definition of stress (Selye, 1950) or the General Adaptation Syndrome (G.A.S.) as he called it, remains one of the most widely accepted and wide in scope:

"The sum of all the physiological responses by which an animal tries to maintain or re-establish a normal metabolism in the face of a physical or chemical force."

The G.A.S. involves a series of hormonal, biochemical, and physiological processes whereby an organism's responds to a stress by trying to adapt or adjust to the stressor. Until adaptation results in a change that allows the organism to function, responses to the stress continue to magnify. In extreme cases, the organism dies.

The concept of the G.A.S. was first applied to fishes in the 1970's (Mazeaud et al., 1977; Wedemeyer et al., 1990; Rich, 1983, 1979) (Figure 1). Once a stimulus (the "stressor") occurs (such as increased SS concentrations), the fish's brain responds to that stimulus by stimulating the adrenal glands and chromaffin tissue in the fish to secrete two types of hormones, the corticosteroids (e.g. blood cortisol) and the catecholamines (e.g. blood adrenalin or epinephrine), respectively. The initial secretions of these hormones into the bloodstream are considered to be the "Primary Stress Responses" of the G.A.S. These hormones, in turn, can affect every organ and function of the body via "Secondary Stress Responses". Secondary Stress Responses include changes in blood constituents, metabolism, heart rate, and osmoregulation. If those "Secondary Stress Responses" do not re-equilibrate the body so that it can function in a healthy manner, the stress responses continue to affect the organism and the Tertiary Stress Responses come into play. Examples of Tertiary Stress Responses include reduced growth, reduced disease resistance, and behavioral changes (e.g.,avoidance). As in humans, stress in fishes is cumulative. If none of the responses to the stressor result in the animal adapting and returning to homeostasis, the fish dies, maybe not immediately, but at some point in the future (Barton et al., 1986; Sigismondi and Weber, 1988; Mesa, 1994; Farrell et al., 1998).

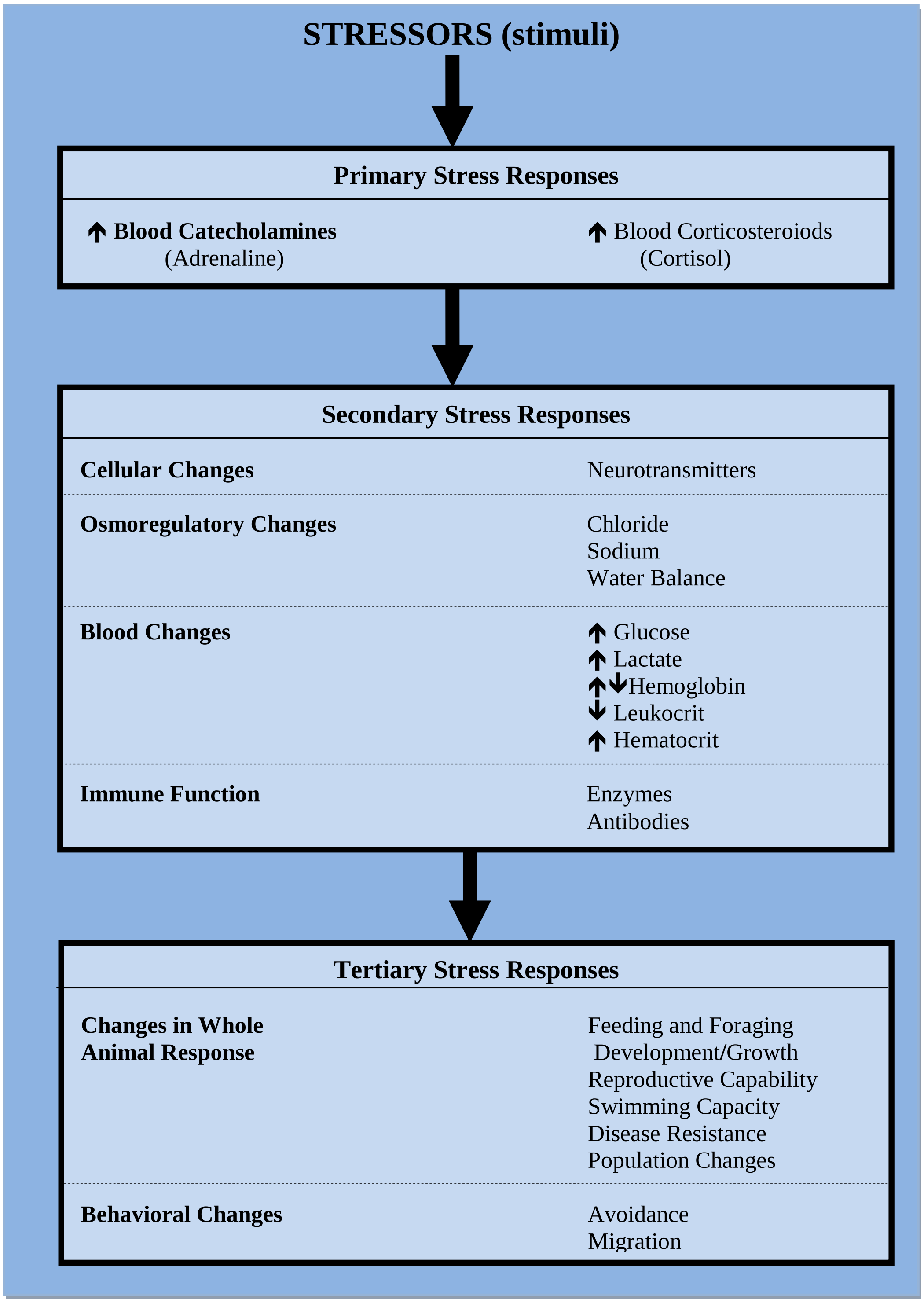

Figure 1. Responses to Stressors in Fishes.

In this review, the concept of stress in fishes provides a framework for assessing the impacts of SS caused by dredging activities. The stress, or impact, may result in direct mortality, or in sublethal impacts, such as the Primary, Secondary, or Tertiary Stress Responses associated with the G.A.S. (Figure 1).

METHODS

This report is based on existing literature reviews, peer-reviewed journal articles, books, theses/dissertations, technical reports, and interviews with knowledgeable individuals (Appendix A). Especially valuable information was obtained from Dr. Douglas Clarke at the U.S. Army Corps of Engineers (USACE) Research and Development Center in Vicksburg, Mississippi. Dr. Clarke, who has spent over 20 years working on fish issues associated with dredging activities, stated that there was a dearth of studies on the effects of re-suspended sediments from dredging activities on fishes (Clark, 2008). Although the focus of this report was on Bay fishes, relevant studies from other geographical areas were considered.

The most valuable information came from:

- Conversations with and articles received from Dr. Douglas Clarke;
- Relevant articles listed in the “Literature Cited” of the Review papers and all of the other documents reviewed for this report;
- The USACE Dredging Operations Technical Support Program (DOTS; http://el.erdc.usace.army.mil/dots);
- The USACE Dredging Literature Database called “Environmental Effects and Dredging and Disposal” (E2D2; http://el.erdc.usace.army.mil/e2d2/index.html); and,
- The University of Washington library system.

Many of the electronic database searches (e.g., Google, NTIS, Northwest and Southwest Fisheries Sciences Centers, Yahoo) were protracted because hundreds of irrelevant articles came up in those searches. For example, the Google and Yahoo searches returned over 200,000 possible references on the effects of SS and turbidity on fishes. However, only a few hundred of those were relevant to the subject at hand.

Note that this report does not include studies where it was impossible to differentiate the effects of SS or turbidity from those of other factors. For example, Carlson (1984) examined the influence of SS, dissolved solids, pH, and dissolved oxygen on coughing frequency in bluegill and brook trout. However, the study did not distinguish the contribution of SS from the other factors. Brungs and Baily (1966) studied the effects of SS concentrations on the acute toxicity of endrin, but did not differentiate the effects of SS from those of endrin. Hence, this report focuses on all studies where a cause-and-effect relationship could be linked directly to either SS or turbidity.

REVIEW AND FINDINGS

Overview

To determine the effects of SS and turbidity on priority Bay fishes, the following topics were reviewed:

- Ranges of SS concentrations in the Bay;
- Ranges of SS concentrations generated by dredging activities in the Bay; and,
- Responses of fishes to SS and turbidity in the Bay and elsewhere.

Ranges of SS Concentrations in the Bay

Monitoring Methods

The Bay comprises four embayments (Figure 2)—Suisun Bay, San Pablo Bay, Central San Francisco Bay (Central Bay), and South San Francisco Bay (South Bay). For more than 15 years, the U.S. Geological Survey (USGS), in cooperation with the San Francisco Regional Water Quality Control Board (RWQCB) and the USACE, has been studying SS in the Bay (Buchanan and Schoellhamer, 1995; USGS, 2008). The SS monitoring network is designed to capture the spatial and temporal variability of SS and three other constituents—water temperature, salinity, and water level (Buchanan and Ruhl, 2001; Schoellhamer et al., 2002). Annual reports that summarize SS concentration, or data contained in the reports, have been used by others in a wide variety of related studies. During the early and mid-1990s, stations were established in the deep channels (~7-15 m) of each major sub-embayment; subsequently, to improve spatial coverage, stations were added. Stations were discontinued when they became too difficult to service, or when the data they provided no longer were determined to be useful (Buchanan and Ganju, 2005; Schoellhamer et al., 2007).

Each year, sites within the embayments (Figure 2) are monitored for SS concentration using optical backscatter (OBS) sensors positioned at different depths at each site. The OBS sensors are periodically calibrated either in the field or in a laboratory using water samples containing the same suspended material found in the field. Biofouling of the OBS sensors has been a problem during long-term deployments. Despite the use of an antifoulant paint, anywhere from 1-84% of the data have been invalidated (Buchanan and Ganji, 2002-2005; Buchanan and Lionberger, 2006-2007, Buchanan and Ruhl, 1995, 2000-2001; Buchanan and Schoellhamer, 1995-1996, 1998-1999; Buchanan et al., 1996).

In the annual reports that summarize the SS monitoring results, the data are graphed for each of the monitoring sites and depths as SS concentration versus time. Included are calibration curves for the processed data from each site. A complete listing of the data collection methods and data analyses is available at the Bay monitoring web site http://sfbay.wr.usgs.gov/sediment/cont_monitoring. A major purpose of the web site is to make time-series data of SS and the other constituents available to scientists, resource managers, educators, and the general public. Data on that USGS web site have been reviewed, edited, and approved for release.

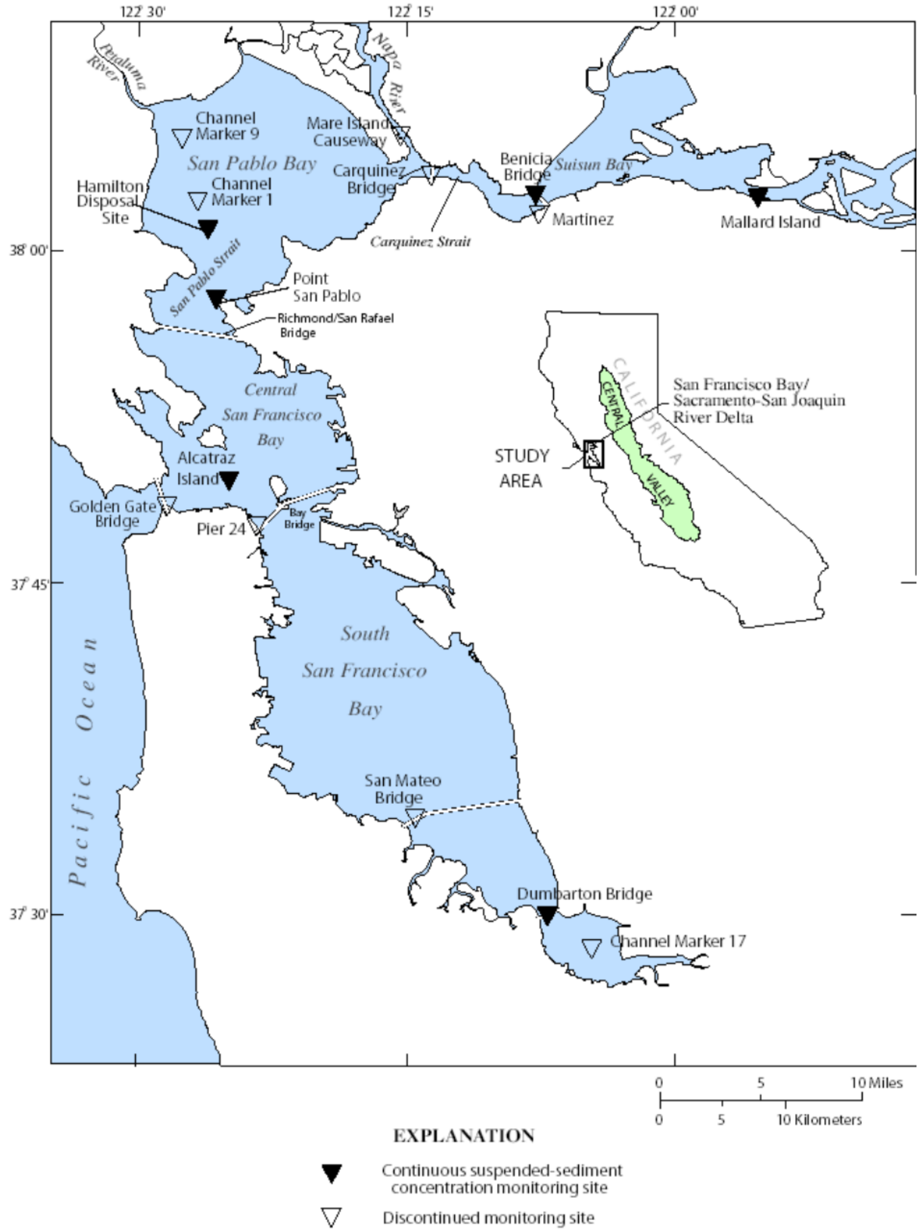

Figure 2: Suspended Solids Monitoring Sites in San Francisco Bay (Buchanan and Schoellhamer, 1999)

Summary of Results of Monitoring SS Concentrations in the Bay

Tables 2 through 5 summarize the results of SS monitoring in each of the Bay's sub-embayments starting with the 1992 water year (see Appendix B for detailed summary tables of the results of the SS monitoring data). In Suisun Bay, data have been collected at three sites starting with the 1994 water year —Suisan Bay at Mallard Island, Carquinez Strait at the Benecia Bridge, and the Martinez Marina fishing pier (Figure 2; Table 2). In San Pablo Bay, data have been collected at four sites starting with the 1998 water year —Carquinez Straight at the Carquinez Bridge, Napa River at Mare Island Causeway, Coast Guard Channel Marker 9, and Coast Guard Channel Marker 1 (Figure 2; Table 3). In Central San Francisco Bay, data have been collected at four

Table 2: Mean and Median Suspended Solids Concentrations in Suisun Bay

Monitoring Site	Latitude/Longitude	Water Years Monitored[9]	Depth	Range of Mean Concentrations (mg/L)	Range of Median Concentrations (mg/L)
Mallard Island	38°02'34"/121°55'09"	1994-2005	3.3 ft below surface	27-48	24-43
			5 ft above bottom	28-58	25-55
Martinez Marina [10]	38°01'40"/122°08'22"	1994-1996	3.3 ft below surface	47-68	42-52.4
Carquinez Strait at Benicia Bridge on Pier[7]	38°02'42"/121°07'32"	1996-1998 and 2001-2005	74 ft above bottom	29-77	21-68
			25 ft above bottom	47-141	29-123

Sources: Buchanan and Ganju, 2002-2005; Buchanan and Lionberger, 2006-2007, 2007; Buchanan and Ruhl, 2000-2001; Buchanan and Schoellhamer, 1996a,b, 1998-1999; Buchanan et al., 1996.

9 Available data through 2005.

10 The Martinez site was closed in the Spring of 1996 because the Benecia Bridge was considered to be more representative of SS concentrations in Carquinez Strait.

Table 3: Mean and Median Suspended Solids Concentrations in San Pablo Bay

Monitoring Site	Latitude/Longitude	Water Years Monitored[11]	Depth	Range of Mean Concentrations (mg/L)	Range of Median Concentrations (mg/L)
Carquinez Straight at Bridge	38°02'42"/121°07'32"	1999-2005	48 ft above bottom	31-66	21-55
			5 ft above bottom	42-290	25-216
Napa River at Mare Island Causeway	38°06'40"/122°16'25"	1999-2005	15 ft above bottom	49-80	38-61
			5 ft above bottom	109-186	82-144
Coast Guard Channel Marker [9]	38°05'42"/122°26'29"	1999-2003	2 ft above bottom	110-213	38-142
Coast Guard Channel Marker [1]	38°02'40"/122°25'57"	2004-2005	Mid-depth	38-76	27-55

Sources: Buchanan and Ganju, 2002-2005; Buchanan and Lionberger, 2006-2007; Buchanan and Ruhl, 2001

[11] Available data through 2005

Table 4: Mean and Median Suspended Solids Concentrations in Central San Francisco Bay

Monitoring Site	Latitude/Longitude	Water Years Monitored[12]	Depth	Range of Mean Concentrations (mg/L)	Range of Median Concentrations (mg/L)
San Pablo Strait at Point San Pablo	37°57'53"/122°25'42"	1992-2005	13 ft from bottom	27-112	20-79
			3 ft from bottom	37-144	28-105
San Francisco Bay at Alcatraz Island	37°49'38"/122°25'18"	2004-2005	Mid-depth	18	15-17
			Near-bottom	No Data	No Data
Golden Gate Bridge	37°49'06"/122°28'18"	1996-1997	45 ft from bottom	17-20	16-19
			5 ft from bottom	No Data	No Data
			3 ft from bottom	32-84	27-56
Pier 24	37°47'27"/122°23'05"	1992-2002	23 ft from bottom	20-43	18-38
			3 ft from bottom	32-84	27-56

Sources: Buchanan and Ganji, 2002-2005; Buchanan and Lionberger, 2000-2001; Buchanan and Ruhl, 2000-2001; Buchanan and Schoellhamer, 1995-1996, 1998-1999; Buchanan et al., 1996.

[12] Available data through 2005.

Table 5: Mean and Median Suspended Solids Concentrations in South San Francisco Bay

Monitoring Site	Latitude/Longitude	Water Years Monitored[13]	Depth	Range of Mean Concentrations (mg/L)	Range of Median Concentrations(mg/L)
San Mateo Bridge	37°35'04"/122°14'59"	1992-2005	23-29 ft from bottom	37-66	25-53
			3-8 ft from bottom	36-96	30-77
Dumbarton Bridge Pier 23	37°30'15"/122°07'10"	1992-2005	23 ft from bottom	40-122	29-106
			3-4 ft from bottom	48-257	32-213
Coast Guard Channel Marker 17	38°28'44"/122°04'38"	1992-2005	13 ft from bottom	52-200	30-135
			3 ft from bottom	61-210	35-145

Sources: Buchanan and Ganju, 2002-2005; Buchanan and Lionberger, 2006-2007; Buchanan and Ruhl, 2000-2001; Buchanan and Schoellhamer, 1995-1996,1998; Buchanan et al., 1996.

sites starting with the 1993 water year—San Pablo Strait at Point San Pablo, San Francisco Bay at Alcatraz Island, Golden Gate Bridge, and San Francisco Pier 24 (Figure 2; Table 4). In South San Francisco Bay, data have been collected at three sites starting with the 1993 water year—San Mateo Bridge, Dumbarten Bridge, and Coast Guard Channel Marker 17 (Figure 2; Table 5).

SS and Turbidity Ranges Due to Dredging Activities in the Bay

For over 100 years, large-scale dredging has taken place periodically in the Bay. Historically, the majority of that dredged sediment has been placed at three Federally-designated open-water sites—adjacent to Alcatraz Island, in San Pablo Bay, and in the Carquinez Strait—and at other sites designated for specific projects or types of material (LTMS, 1998). Currently, the USACE maintains 17 deep- and shallow-draft channels in the Bay, and private organizations maintain numerous smaller channels, marinas, and berthing areas (Connor et al., 2005). Dredging to maintain authorized channel depths occurs with varying frequency and intensity. Data from the following sites are used in this report:

- San Pablo Bay Maintenance Channel and Disposal Site;
- Carquinez Strait Disposal Site;
- Oakland Harbor Maintenance Dredging Site;
- Alcatraz Disposal Site; and,
- Port of Redwood City Knockdown Operations Site.

[13] Available data through 2005.

San Pablo Bay

San Pablo Bay Maintenance Dredging Study

An open-water site in San Pablo Bay is primarily dedicated to material dredged from the Pinole Shoal Ship Channel (Figure 3). To determine the basin-scale effects of dredging activities and natural estuarine processes, Schoellhamer (2002) compared the dredging-related SS concentration at Point San Pablo with those of natural estuarine processes. The Point San Pablo station (Figure 3) was chosen because it was the closest station to the dredged-material disposal site and had one of the longer and more complete SS data sets. Characterization of sediment re-suspension due to natural estuarine processes was based on twelve 3- to 5-week periods of mid-depth and near-bottom SS data collected at Point San Pablo every 15 minutes from 1993-1998. The data were collected during maintenance dredging in late July and August of 1993 and 1995 and in May of 1997. Ambient median SS concentrations ranged from 38.8-116 mg/L, and the SS concentration within the dredged-material disposal site ranged from 20.3-251 mg/L, depending upon dredging volume and depth (Appendix C, Table C-1).

Carquinez Strait Disposal Study

Historically, the majority of the dredged material placed at the Carquinez Strait disposal site comes from Federal maintenance dredging of the Mare Island Channel (also known as the “Suisun Bay Channel”), which extends from Martinez to Pittsburg (LTMS, 1998). The recent closure of the Mare Island Naval Shipyard has significantly reduced the need for dredging at this location because the remaining navigation interests in the area do not require a 36-foot deep channel. However, given the importance of the Carquinez Strait as a migratory corridor for several priority fish species (e.g., salmon, steelhead, and green sturgeon), SS monitoring remains important at the disposal site.

Central San Francisco Bay

Oakland Outer Harbor Maintenance Dredging Study

The Oakland Outer Harbor is seasonally occupied by salmonids, Pacific herring, and other biological resources (e.g., birds). Maintenance dredging at the Port of Oakland (Figure 4), that occurs frequently, often results in SS plumes that are visible at the water surface (MEC, 1997). Regulators have periodically voiced concerns about the spatial and temporal dynamics of the plumes. Consequently, studies were conducted in the Oakland Outer Harbor to characterize the spatial and temporal dynamics of the plumes (Clarke et al., 2006, 2005; MEC, 2003, 1997).

A study at the site showed that the SS concentration at the sediment-water interface, 100 m down-current from the disposal barge, reached 9,000 mg/L (USACE, 1976), and then decreased to background levels 25 minutes after disposal ceased. The study also showed that a highly elevated SS concentration of 20,000 mg/L could be attained at the sediment-water interface and that elevated SS could occur as far as 1,400 m down-current from the barge. However, the existence of these high concentrations rarely lasted longer than 10 minutes (USACE, 1976).

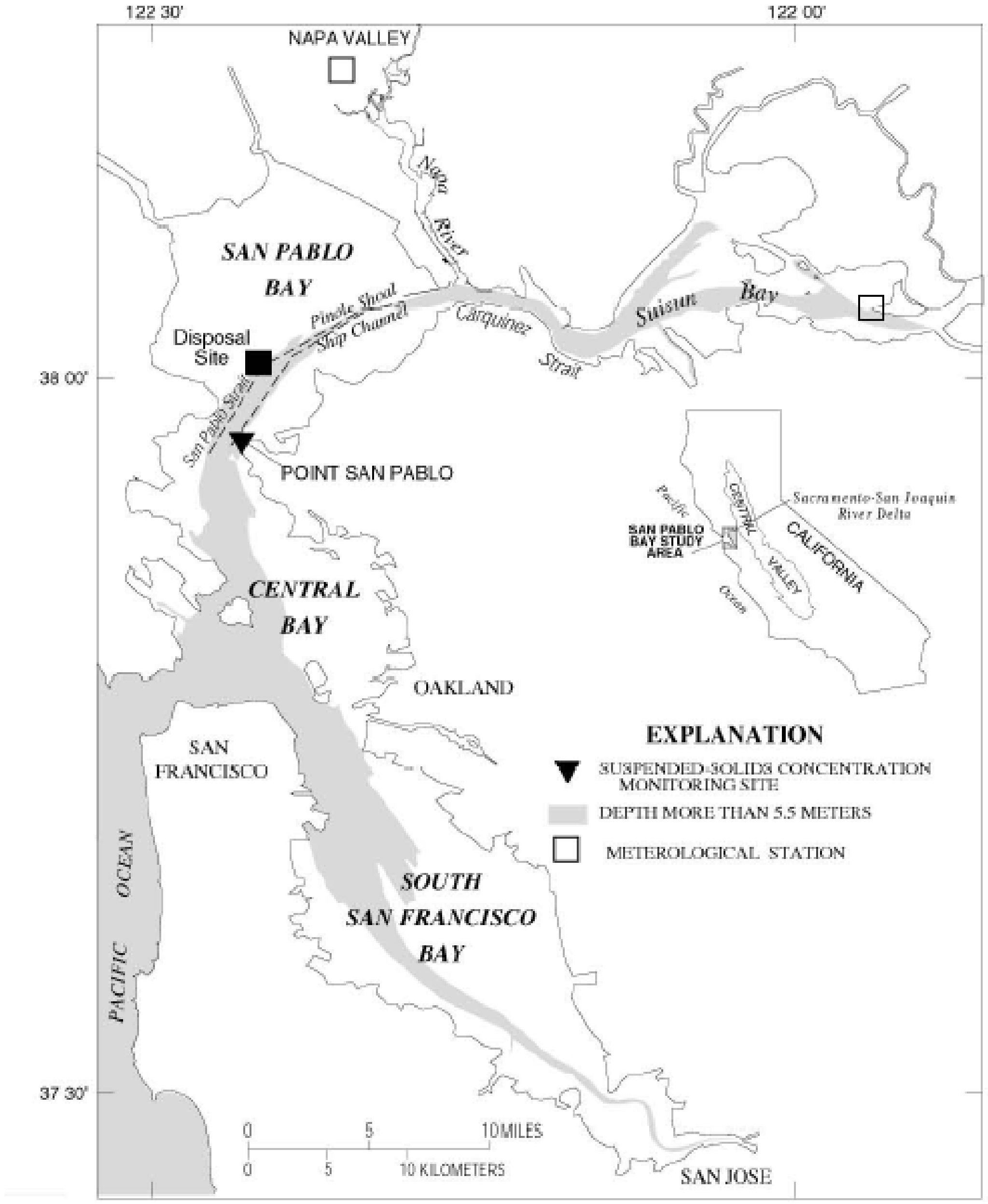

Figure 3: Pinole Shoal Ship Channel and Disposal Site in San Francisco Bay

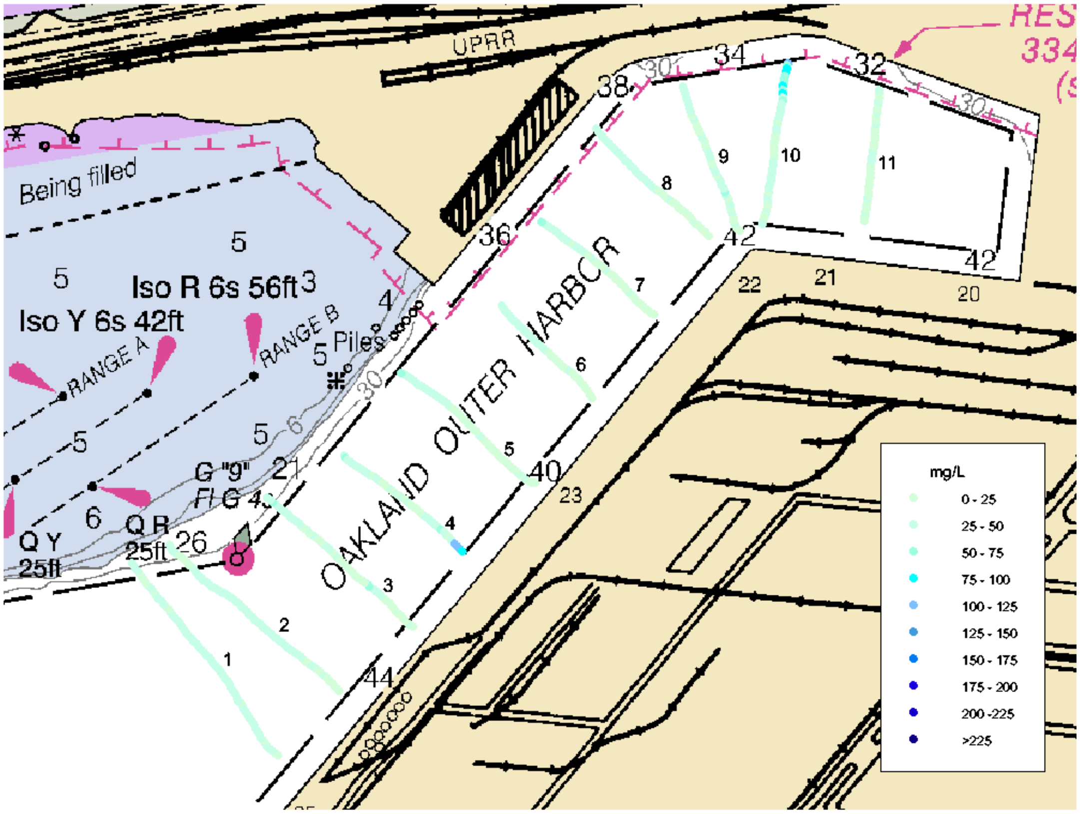

Figure 4: Oakland Outer Harbor Maintenance Dredging Study Area (courtesy of A. Martin, Weston Solutions Inc.)

The studies entailed plume characterizations during removal of maintenance sediment from the Port of Oakland's Outer Harbor complex (Clarke et al., 2006, 2005; MEC, 2003, 1997). The dredging-induced plumes resulted from mechanical dredging using a 12 cubic yard closed bucket at a channel depth between 39 and 43 ft (12 and 13 m). To characterize both ambient and dredging SS concentrations and turbidity levels, plume monitoring was conducted from a survey vessel equipped with water quality instrumentation. An acoustic Doppler current profiler (ADCP) was used to collect water current velocity and direction data, and raw acoustic backscatter data for estimation of SS concentration. To capture the spatial and temporal dynamics of the plume, the ADCP surveys were conducted during both flood and ebb tides. The studies found that ambient SS concentrations ranged from 10-15 mg/L at the surface to 25-50 mg/L at the bottom[14], and dredging-induced SS concentrations ranged from less than 25 mg/L to more than 225 mg/L (Clarke et al., 2006, 2005; MEC, 2003, 1997; Appendix C, Table C-2).

Alcatraz Disposal Site

The Alcatraz disposal site (Figure 2) is a 610 m diameter circular area located in Central Bay immediately south of Alcatraz Island (O'Connor, 1991). The Alcatraz disposal site was selected

[14] Because the dredging project began prior to the initiation of monitoring, ambient SS concentrations were estimated on the basis of data collected well outside of the area influenced by plumes, and while the dredge was inactive.

because its fast tidal currents maximized dispersion and prevented all but the coarsest or more cohesive dredged material from accumulating on the bottom at the disposal site. However, by the 1980s, a large mound had developed at the site that posed a hazard to navigation.

In the 1980s and 1990s, a number of studies in the vicinity of the Alcatraz disposal site included measurements of SS concentrations (Appendix C, Tables C-3 through C-5). The results of the various studies found that:

- Background SS concentrations ranged from 6-56 mg/L;
- SS concentrations within the disposal site ranged from 38-86 mg/L;
- SS concentrations 50-400 m down-current of the disposal ranged from 10-290 mg/L;
- SS concentrations within the disposal site returned to background concentrations within 10-20 minutes; and,
- With a few exceptions, surface waters had lower SS than bottom waters.

South San Francisco Bay

Knockdown Operations at the Port of Redwood City

One mode of maintenance dredging involves a process called “knockdown”, or “bed leveling” (Clarke et al., 2006, 2005). In many navigation channels, sediment slowly deposits within the entire channel basin; in a few, shoals can form as topographic “highs” or ridges. In the former case, conventional dredge plants are routinely used to re-establish the authorized navigable depth. In the latter case, knockdown or bed leveling, which basically consists of towing a heavy steel blade or bar over the bottom, can be used. Knockdown levels the bed by redistributing the sediment to deeper portions of the channel basins rather than physically removing it from the waterway. Knockdown is also frequently conducted during the “clean up” phase of a dredging project. Rather than remove all the high spots by keeping expensive dredge plants on site, dredging contractors have developed gear to rapidly and efficiently remove peaks and ridges. A study was designed to address regulatory concerns that knockdown operations produce sediment plumes that potentially could have negative impacts on fishes (Clarke et al., 2006).

In an effort to protect natural resources and to seek better management of dredging projects in the Bay, a study was undertaken in the Redwood Creek navigation channel (Figure 5) leading to the Port of Redwood City (Clarke et al., 2006, 2005). The objectives of the study were to: (1) describe the knockdown operation to the extent that it represented the manner in which similar operations occurred in the Bay; and, (2) characterize, in detail, the SS plumes created by the knockdown operation with respect to spatial extent, temporal variation, and total SS (TSS) concentration.

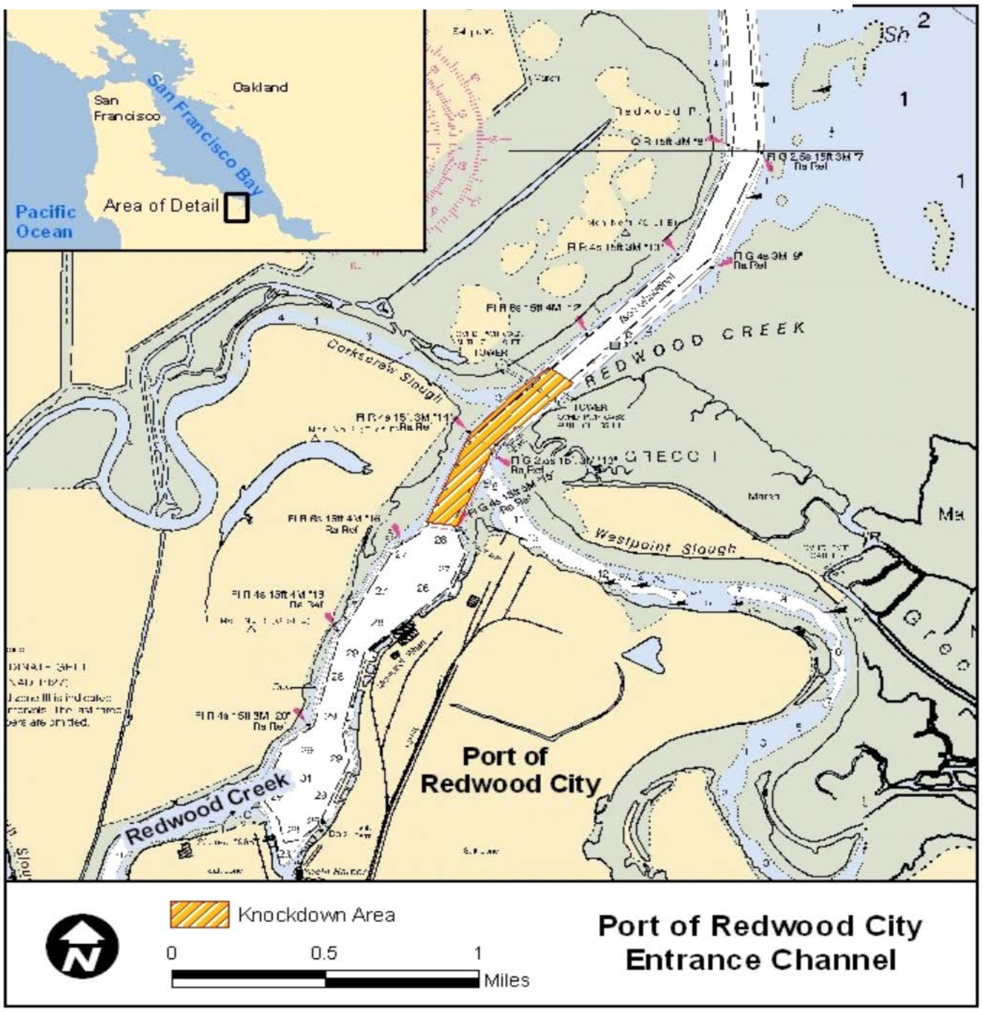

Figure 5: Redwood Creek/Port of Redwood City Knockdown Dredging Study Area (courtesy of A. Martin, Weston Solutions Inc.)

Knockdown operations at the Port of Redwood City took place north of the northern turning basin and covered an along-channel distance of ~0.8 km. Mounds up to 0.6 m above grade were scattered throughout this reach in an alignment roughly parallel with the axis of the navigation channel. An estimated 2,000 m^3 (3,000 cubic yards) of sediment were re-distributed by the knockdown operation.

ADCP surveys were conducted during both flood and ebb tides to capture the spatial and temporal dynamics of the knockdown plume. A water sampler provided real-time turbidity measurements during water sampling. The results of the study were (Appendix C, Table C-6):

- Ambient SS concentrations ranged from 10 to more than 90 mg/L and from 8 to 22 NTUs;
- During the knockdown operation, SS concentrations ranged from 25 to more than 450 mg/L, and turbidity levels ranged from 10 to more than 200 NTUs. The highest SS

concentrations were 600 mg/L, primarily directly behind the path of the towed bar and in the lower half of the water column;

- In many respects, knockdown plumes were similar to ambient conditions in Redwood Creek. Tidal circulation carried turbid slough and Bay waters into Redwood Creek, reaching 40-65 NTUs as the tide ebbed and 100-120 NTUs as the tide flooded following precipitation; these turbidities were comparable to SS concentrations as high as 150 mg/L;
- During the knockdown operation, both SS concentrations and turbidity levels decreased with time. SS concentrations generally dropped to less than 200 mg/L within five to six minutes of bar passage, and to 100 mg/L within seven to nine minutes. Residual plumes, with SS concentrations in the 50-100 mg/L range, lasted for 13 minutes or longer; and,
- SS plumes were highly variable in a temporal context, but consistent with respect to spatial dimensions.

Responses of Fishes to SS and Turbidity

Historical Overview

The response of a fish to a stressor (e.g., SS or turbidity) can be sublethal or lethal (Figure 1). Lethal effects of high SS on fishes were recorded as early as the 1880s (Jordan, 1889; Rathbun, 1889). Although the effects of SS-related sublethal stress were documented as early as the 1950s, quantification of stress responses did not begin in earnest until the 1970s. The tables in Appendix D summarize the results reported in the various review articles written during the past 120 years. The tables in Appendices E-N summarize the results of each study reviewed for this report. The tables in Appendices E-G, H, I-K, and L-N focus on mortality, Primary Stress Responses, Secondary Stress Responses, and, Tertiary Stress Responses, respectively.

The effects of SS and turbidity on fishes have been studied for over 70 years. Through the 1950s, studies focused on direct mortality. In those studies, the researchers relied heavily on circumstantial information (e.g., the observation that fish died in highly turbid creeks and rivers, or that spawning salmon avoided muddy areas). In addition, some of the earlier studies mentioned the potential effects of mining-related dredging (e.g., placer mining) on fishes. Attempts to identify safe SS threshold concentrations and turbidity levels began in the 1960s, although the criteria for those thresholds again focused on mortality. In the 1970s, there was renewed interest on the effects of SS and turbidity on fishes, and reviews appeared on the effects of dredging-related SS on fishes. During that decade under the new Forest Practices Act, there was a lot of interest on the effects of logging (e.g., sedimentation and SS) on salmon and trout. Also, there was interest in developing water quality criteria for freshwater and estuarine systems for urban-related projects. In the 1980s there were several reviews written, some of which focused on the effects of dredging-related SS on aquatic organisms.

Beginning in 1990, more studies appeared on the effects of dredging-related SS on fishes, and there was profound interest in quantifying the effects of SS on fishes. A number of models appeared in the scientific literature that incorporated both concentration and duration of exposure of SS (Newcombe and MacDonald, 1991; Newcombe and Jensen, 1996; Fiksen et al., 2002; Newcombe, 2003). Prior to those studies, researchers focused on the effects SS concentrations alone and did not recognize the importance of exposure duration.

During the past few years, there has been an increased use of models to determine the effects of dredging on fishes (Clarke and Wilber, 2000). Although modeling of potential effects of SS on fishes is a "first step" towards quantifying those effects by incorporating the concentration and duration of the stressor (i.e., the SS concentration), the models were criticized for their unreliability (Gregory et al., 1993; Clarke and Wilber, 2000). The unreliability was based on:

- The variance in the data compiled for use in the model;
- The lack of threshold durations or concentrations beyond which impacts would not occur;
- The subjectivity of the "stress index ranks";
- SS concentrations used in the models being either well below or well above levels normally found in natural systems;
- The fact that none of the ancillary variables such as water temperature, dissolved oxygen, particle size, and particle shape were incorporated into the models; and,
- The lack of field-specific data that would validate the models.

Models have also been criticized for incorporating inaccurate numbers (Wilber and Clarke, 2001). Finally, the models do not appear to have appropriately incorporated the stress adaptation syndrome (i.e., the GAS). In the models, Secondary and Tertiary Responses were used interchangeably when, in fact, it is not possible to have a Tertiary Response (e.g., reduced growth) before the Secondary Responses (e.g., metabolic changes, cellular changes, blood changes, etc.) occur (Figure 1). Newcombe and Macdonald (1993) responded to the comments made by Gregory et al. (1993) by changing their model, but did not resolve most of its inherent problems. To date, no studies have validated any of those models (Clarke and Wilber, 2000; Fiksen et al., 2002). Without cause-and-effect type studies, it is difficult to predict absolute SS thresholds that will have deleterious SS impacts in natural systems (Newcombe and Jensen, 1996; Burkhead and Jelks, 2001).

Although not as comprehensive as those summarized in the tables in Appendix D, a number of other documents have included summary reviews on the effects of SS and turbidity on fishes, including those related to:

- Dredging (Chesapeake Biological Laboratory, 1970; Sherk, 1972; Sherk et al., 1972; Windom, 1972; Sherk et al., 1974; 1975; Sherk et al., 1975a,b; Wakeman et al., 1975; Mortensen et al., 1976; Morton, 1977; Hirsch et al., 1978; Peddicord and McFarland, 1978; Peddicord et al., 1978; Allen and Hardy, 1980; Peddicord, 1980; USFWS, 1980; Priest, 1981; Pennekamp and Quaak, 1990; Reilly et al., 1992; Gray and Glysson, 2002; Anchor Environmental, 2003; Levine-Fricke, 2004; Conner et al., 2005);
- Water quality (Moore, 1932; Moore, 1937; Ellis, 1944; Doudoroff, 1957; Wilson, 1959, 1957; Cairns, 1968; Cronin, 1970; O'Connor et al., 1976, 1977; Sorenson et al., 1977; Moore, 1978; Canadian Council of Ministers of the Environment, 1984; Lloyd, 1987, 1985; Lloyd et al., 1987; Government of Canada and the Province of British Columbia, 1991; O'Connor, 1992, 1991; Edwards, 1993; Kerr, 1995; Bay, 2000; Berry et al., 2003;
- Salmonids (Servizi, 1990; Sigler, 1990; Bay, 2000; Bash et al., 2001);
- Predator-prey interactions (Ryan, 1991);
- Logging (Cederholm et al., 1981; Everest et al.,1987);
- Fish behavior (Berg, 1982, 1983);

- Reproduction in warm water fishes (Muncy et al., 1979);
- Environmental stress (Rosenthal and Alderdice, 1976);
- The Mt. St. Helens eruption (Emmett et al., 1990); and,
- Fish habitat (Reed et al., 1983).

Lethal Response

A wide variety of SS concentrations, turbidity levels, and exposure durations have been used in mortality studies (Figure 6, Tables 6 to 9, and Appendices E-G). The types of fishes and environments included:

- Salmonid adults, juveniles, smolts, larvae and eggs in freshwater;
- Non-salmonid adults, juveniles, larvae, and eggs in freshwater; and,
- Non-salmonid adults, juveniles, larvae, and eggs in marine and estuarine environments.

Eleven of the studies were related to dredging activities (four field studies and seven laboratory studies) and 45 were not related to dredging (eight field studies and 37 laboratory studies) (Figure 6; Appendices E-G). There were dredging-related studies on rainbow trout, Pacific herring, and Atlantic herring. There were five non-dredging-related studies on Chinook salmon, steelhead, rainbow trout, Pacific herring, and Atlantic herring.

Sublethal Responses - Primary Stress Responses

Three studies used Primary Stress Responses (i.e., the initial stage of the GAS) for determining the effects of SS concentrations on fishes (Table 9, Appendix H). One study focused on steelhead and coho salmon, the second on two freshwater fishes, and the third on Atlantic cod (Appendix H). None of the studies were related to dredging activities and all were conducted in laboratories. The studies found that exposure to SS elicited Primary Stress Responses by increasing circulating blood cortisol concentrations and whole body cortisol levels (Redding et al., 1987; Humborstad et al., 2006; Sutherland et al., 2008).

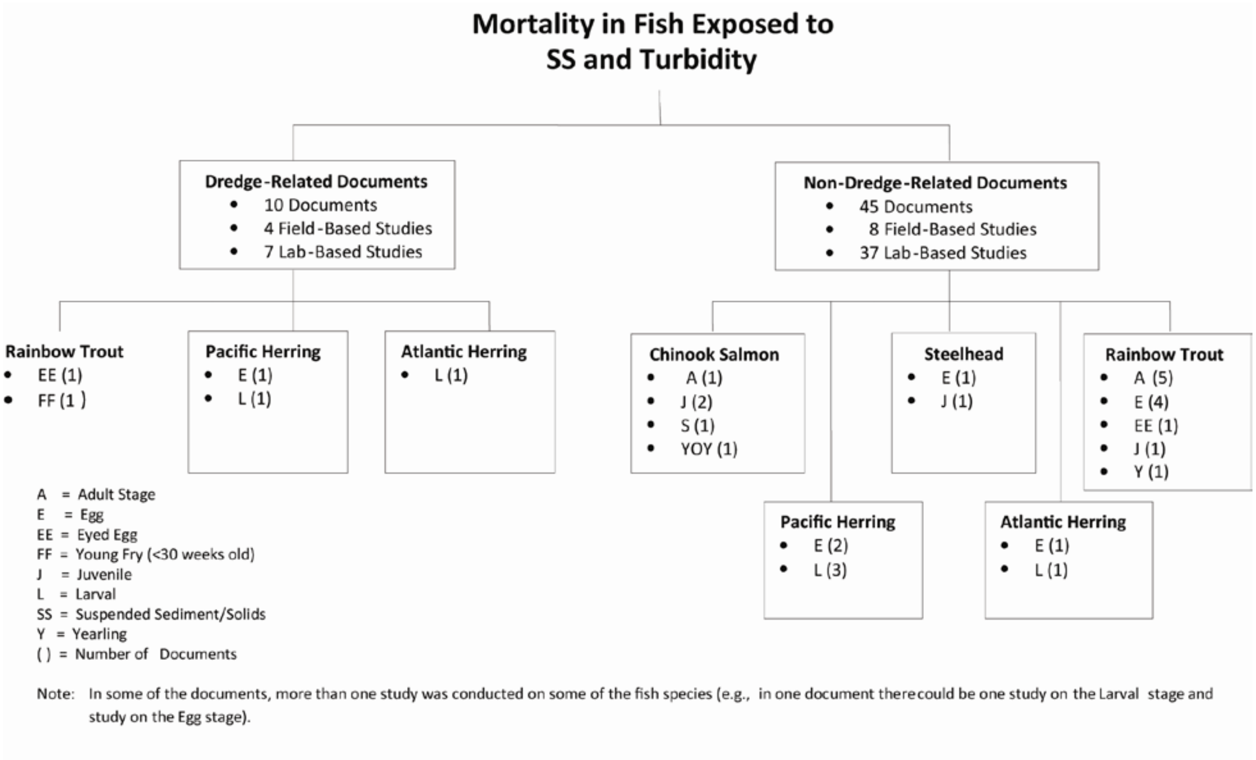

Figure 6: Depiction of the Types of Studies on Fish Mortality

Table 6: Ranges of SS Concentrations, Turbidity Levels, and Exposure Durations in Laboratory Studies that Resulted in Fish Mortality[15]

Life Stage	SS		Turbidity	
	Concentration (mg/L)	**Exposure Duration (hrs)**	**Level[16]**	**Exposure Duration (hrs)**
Freshwater Salmonids				
Egg	6.7-156	144-2,880		
Larval(EE,F*,FF,LSF,YOY)	1,700–39,400	36–1,008		
Smolt	488-28,184	96		
Juvenile(J,PS,Y)	16-100,000	0.36-672		
Adult	200-207,000	1-5,544		
Freshwater Non-Salmonids				
Egg	>100–>600	5		
Larval(YOY)	>100–>600			
Juvenile	160	1,488		
Adult	25,000-100,000	24-336		
Marine/Estuarine Non-Salmonids				
Egg	500-10,000	288-792		
Larval(L,)	100–19,000	24–792		
Juvenile	750-35,000	24-200	500-2,500	1,008
Adult	300-330,000	12-200		

15 See Appendices E-G for details of studies
16 In JTU = Jackson Turbidity Units

Table 7: Ranges of SS Concentrations, Turbidity Levels, and Exposure Durations in Field Studies that Resulted in Fish Mortality[17]

Life Stage	SS		Turbidity	
	Concentration (mg/L)	**Exposure Duration (hrs)**	**Level[18]**	**Exposure Duration (hrs)**
Freshwater Salmonids				
Egg	101-120	384-1,440		
Larval(SF)	379	24-96		
Smolt				
Juvenile(J,YOY)	4,315	0.5–57		
Adult	525	588		
Freshwater Non-Salmonids				
Egg				
Larval(YOY)				
Juvenile	160	1,488		
Adult	5-160	25-1,488		
Marine/Estuarine Non-Salmonids				
Egg				
Larval(YOY)				
Juvenile				
Adult				

[17] See Appendices E-G for details of studies.
[18] In JTU = Jackson Turbidity Unites

Table 8: Ranges of SS Concentrations and Exposure Durations that Resulted in Mortality in Chinook Salmon, Steelhead, Rainbow Trout, Pacific Herring and Atlantic Herring[19]

Life Stage	SS Concentration			
	Laboratory Studies		Field Studies	
	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Exposure Concentration (mg/L)	Exposure Duration (hrs)
		Chinook Salmon		
Larval(YOY)	29,000-33,000	96		
Smolt	488-19,364			
Juvenile	1,400-39,000	0.36-36	N/A	48-72
Adult	82,400-207,000	1-6		
		Steelhead		
Egg	37	1,388		
Juvenile			N/A	0.5
		Rainbow Trout		
Egg(E)	6.7-57	144-1,488	101-120	384-1,440
Larval(EE)	1,750*	144*		
Juvenile	270-7,433	672	4,315	57
Adult	200-160,000	24-3,240		
		Pacific Herring		
Egg*	500-10,000	288-792		
Larval(YOY)*	500-10,000	24-792		
		Atlantic Herring		
Larval(YOY)*	≤7,000-19,000	48-288	N/A	0.5

* Dredging-related study
YOY = young-of-the-year

[19] See Appendices E-G for details of studies.

Table 9: Ranges of SS Concentrations and Exposure Durations that Resulted in Primary Stress Responses[20]

Life Stage	SS	
	Concentration (mg/L)	**Exposure Duration (hours)**
	Steelhead	
Juvenile	400-2,000	12-96
	Coho Salmon	
Juvenile	400-2,000	4-48
	Freshwater Non-Salmonids	
Juvenile	50-500	48
	Marine/Estuarine Non-Salmonids	
Adult	550	120-240

Sublethal Responses - Secondary Stress Responses

Thirty-three reviewed studies used Secondary Stress Responses to address the effects of SS and turbidity on fishes (Table 10; Appendices I-K). The types of fishes and environments studied included:

- Salmonid adults, juveniles, smolts, and larvae in freshwater,
- Non-salmonid adults and larvae in freshwater, and
- Non-salmonid adults and larvae in marine and estuarine environments.

There were three dredging studies; one of which examined chum salmon. Of the other 30 studies, four were field and 26 laboratory studies (Appendices I-K) and included examinations of Chinook salmon, steelhead, rainbow trout, and Pacific herring (Figure 7; Table 11; Appendices J and K). The Secondary Stress Responses fell into two general categories: (1) physiological changes; and, (2) injury to the fish (Table 12).

Sublethal Stress Responses-Tertiary Stress Responses

Most of the studies used Tertiary Stress Responses to address the effects of SS and turbidity on fishes. In the 121 studies summarized in Appendix L, the types of fishes and environments included (Figure 8; Tables 13 and 14):

- Salmonid adults, juveniles, smolts, and larvae in freshwater;
- Non-salmonid juveniles and larvae in freshwater; and,
- Non-salmonid adults, juveniles, larvae, and eggs in marine and estuarine environments.

[20] See Appendix H for details of studies.

Table 10: Ranges of SS Concentrations and Exposure Durations that Resulted in Secondary Stress Responses in Fishes[21],*

Life Stage	Laboratory Studies		Field Studies	
	Concentration (mg/L)	**Exposure Duration (hrs)**	**Concentration (mg/L)**	**Exposure Duration (hrs)**
Freshwater Salmonids				
Egg				
Larval (YOY)	20 -100,000	0.05 – 168		
Smolt	943 – 7,447	72 - 96		
Juvenile	53.5 to > 41,000	9 - 480	N/A	1
Adult	100 – 18,000	0.25 -17,520	1,438-18,000	15-18
Freshwater Non-Salmonids				
Egg				
Larval (YOY)	500	504		
Juvenile				
Adult	3.3 – 26.7	120	144.5	720
Non-Salmonids, Marine/Estuarine				
Egg				
Larva (YOY)	790 – 4,000	3-24		
Juvenile				
Adult	305 -14,600	1 - 336		

[21] See Appendix I for details of studies.
YOY = young-of-the-year
* Note: No Secondary Stress Responses studies were found that used turbidity.

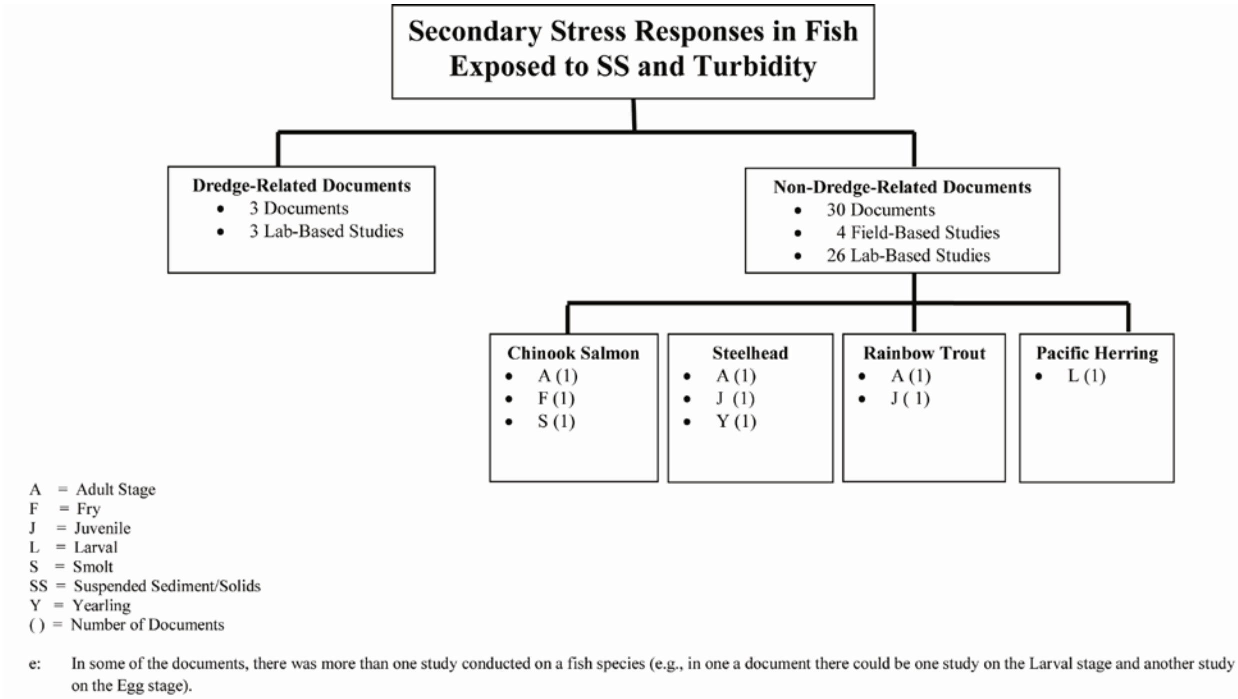

Figure 7: Depiction of the Types of Studies Conducted where Secondary Stress Responses were used as the Endpoints

Table 11: Ranges of SS Concentrations and Exposure Durations that Resulted in Secondary Stress Responses (Physiological Changes and Injury) in Chinook Salmon, Steelhead, and Pacific Herring. [22]

Life Stage	Laboratory Studies		Field Studies	
	Exposure Concentration (mg/L)	**Exposure Duration (hrs)**	**Exposure Concentration (mg/L)**	**Exposure Duration (hrs)**
Chinook Salmon				
Larval (YOY)	61-200	96		
Smolt	943	72		
Steelhead				
Juvenile	400-600	9-24		
	171-4,887	96-384		
Adult	500	3-9		
Pacific Herring				
Larval (YOY)	1,000-4,000	24		

[22] See Appendices I and J for details of studies
YOY = young-of-the-year.

Table 12: Types of Secondary Stress Responses (Physiological Changes and Injury) in Fishes Exposed to SS and Turbidity[23]

Types of Secondary Stress Responses Exhibited by Fishes Exposed to SS and Turbidity	Studies on Chinook Salmon, Steelhead, Rainbow Trout, and/or Pacific Herring
Physiological	
Decreased Body Moisture	
Decreased Fat Index	
Decreased Health Assessment Index	
Decreased Tolerance to Stress	
Decreased Hematocrit	
Increased Hematocrit	Chinook Salmon: A, Y; Steelhead: Y
Increased Plasma Glucose	
Increased Plasma Protein	
Increased Plasma Chloride	
Signs of Sublethal Stress	Steelhead: A
Injury	
Abnormal Gills and Fins	
Decreased Rate of Coughing Frequency	
Epidermis (Skin) Damage	Pacific Herring: L
Gills Clogged with Mucous	Steelhead: J
Gills Clogged with Sediment	Chinook Salmon: F
Gill Disease	Rainbow Trout: J
Gill Tissue Damage	Rainbow Trout: A, J
Increased Rate of Coughing Frequency	Rainbow Trout: A

[23] See Appendices I and J for details of studies.
A=adult; F=fry; J=juvenile; L=larval; S=smolt

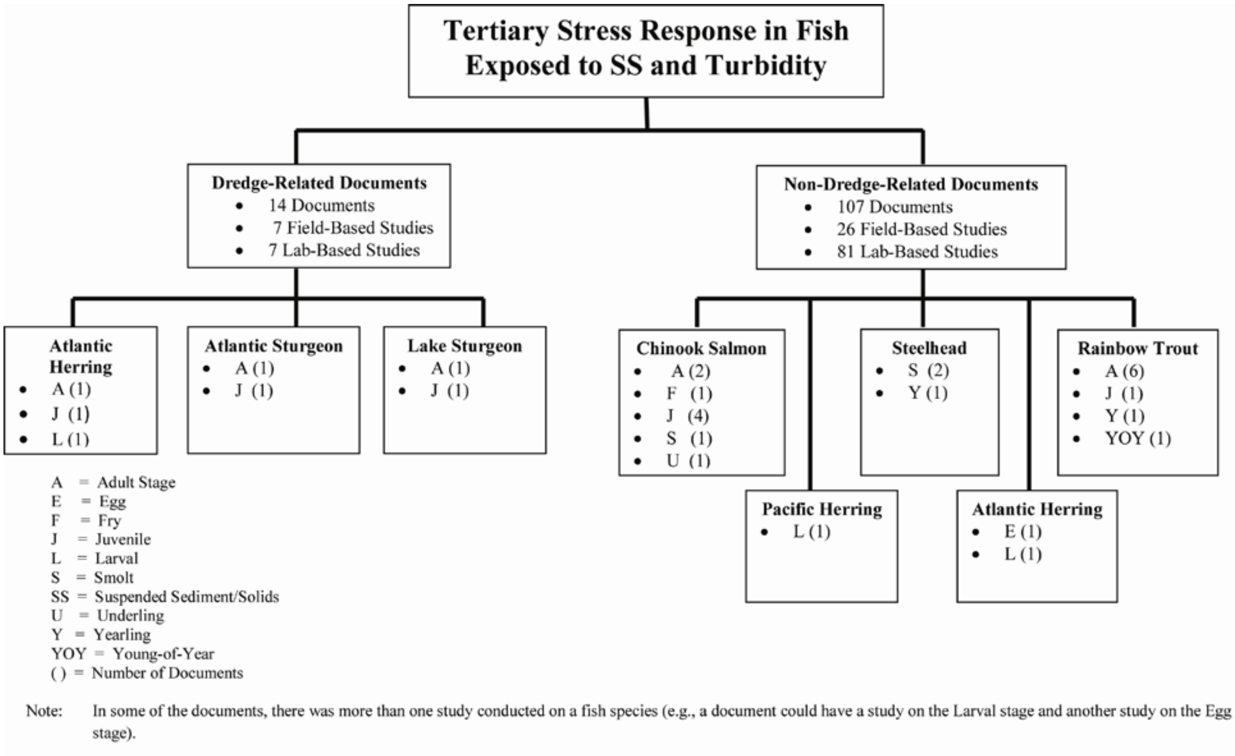

Figure 8: Depiction of the Types of Studies Conducted where Tertiary Stress Responses were Used as Endpoints

Table 13: Ranges of SS Concentrations, Turbidity Levels, and Exposure Durations that Resulted in Tertiary Stress Responses in Fishes[24]

Life Stage	SS		Turbidity	
	Concentration (mg/L)	Exposure Duration (hrs)	Level[25]	Exposure Duration (hrs)
Salmonids, Freshwater				
Egg				
Larval (YOY)	6 – 10,000	0.2 – 5,880		
Smolt	943	72		
Juvenile	25 – 6,280	0.1 – 1,008	23 - ≥ 167	0.02 - 3
Adult	4 – 18,000	0.1 - 168	0.08 - 650	0.2 - 168
Non-Salmonids, Freshwater				
Egg				
Larval (YOY)	3 - 500	408 -1488	20 -100	0.5 - 720
Juvenile			6.7 – 4,000	0.2 - 4
Adult				
Non-Salmonids, Marine/Estuarine				
Egg	100 – 1,000	24 - 168		
Larval (YOY)	2 – 8,000	0.5 - 480		
Juvenile			1 - 30	3 - 24
Adult	20 - 100	2 - 3	5 - 300	0.03 - 15

[24] See Appendix L for details of the studies.
[25] In NTU or Nephelometric Turbidity Units

Table 14: Ranges of SS Concentrations and Exposure Durations that Resulted in Tertiary Stress Responses in Chinook Salmon, Steelhead, Rainbow Trout, Pacific and Atlantic Herring, and Atlantic and Lake Sturgeon[26]

Life Stage	SS		Turbidity	
	Concentration (mg/L)	**Exposure Duration (hrs)**	**Level (NTU) [27]**	**Exposure Duration (hrs)**
		Chinook Salmon		
Larval (YOY)	6	1,440	N/A	1.75 minutes
Juvenile			~ 23	N/A
Smolt	943	72		
Adult	650	0.17	18-810	0.02-168
			27-108 [28]	N/A [28]
		Steelhead		
Juvenile	102-4,000	9-336	57 to ≥167	N/A
		Rainbow Trout		
Larval (YOY)	695-705	0-6 hour pulses over a 19-day period		
Juvenile	<10 to 10	7,920 [28]	1 to >320	3
Adult	15-18,000	0.05-960		
		Pacific Herring		
Larval	50-8,000	0.03-2		
		Atlantic Herring		
Larval	1-500	2-24	9-12	5-minute intervals
			35 -80 JTU *	0.5-1
Juvenile	2.55-55	5-minute intervals		
Adult	20	3		
		Atlantic Sturgeon and Lake Sturgeon		
Juvenile	N/A	168 hours before and after dredged material disposal		
Adult				

[26] See Appendices L-N for details of studies
[27] In NTU's or Nephelometric Turbidity Units
[28] Field-based studies
YOU = young-of-the-year
N/A = not available

Methods used to determine Secondary Stress Responses to SS in fishes included:

- Both static and flow-through bioassays;
- Blood chemistry studies;
- Studies on body moisture content;
- Examination of gills or other tissues with an electron microscope for injury;
- Studies on osmoregulatory changes (e.g., impairment of parr-smolt transformation);
- Respiratory response studies; and,
- “Coughing reflex” studies.

Fourteen studies related to dredging activities (seven field studies and eight laboratory studies) and 107 studies were not related to dredging (26 field studies and 81 laboratory studies) (Figure 9; Appendices L-N).

Of the dredging-related studies, three examined Atlantic herring and two examined sturgeon (Atlantic and lake sturgeon are of the same genus as the green sturgeon) (Figure 9; Appendix M). The non-dredging-related studies looked at Chinook salmon, steelhead, rainbow trout, Pacific herring, and Atlantic herring (Figure 9; Appendix N). Tertiary Stress Responses for the above-mentioned fishes included changes in: (1) behavior; (2) foraging and predation; (3) development and growth; (4) cumulative stress; (6) reproductive performance; and (7) populations (Table 15).

DISCUSSION AND CONCLUSIONS

Overview

This section focuses on:

- The range of SS concentrations in the Bay and the factors that affect those concentrations;
- The range of SS concentrations and turbidity levels generated by dredging activities and the factors that affect those concentrations;
- Responses of fishes to both dredging-related and non-dredging-related SS and turbidity, using the GAS as the framework for those responses;
- Gaps in our knowledge of the effects of SS and turbidity on fishes, including those related to the sensitive Bay fishes; and,
- Conclusions.

Range of SS Concentrations in the Bay and Factors that Affect those Concentrations

Within the Bay, SS concentrations range from 200 mg/L in the winter to 50 mg/L in the summer (Nichols and Pamatmat, 1988; Schoellhamer, 1996) (Table 16). Shallow areas and the adjacent channels have the highest SS concentrations (Schoellhamer, 1996). The Central Bay generally has the lowest SS concentrations; however, wind-wave action and tidal currents can elevate SS concentrations throughout the water column.

Table 15: Types of Tertiary Stress Responses Exhibited in Fishes Exposed to SS and Turbidity[29]

Types of Tertiary Stress Responses Exhibited by Fishes Exposed to SS and Turbidity	Studies on Chinook Salmon, Steelhead, Rainbow Trout, Pacific Herring, Atlantic Herring, Atlantic and Lake Sturgeon
Behavioral	
Avoidance/Attraction	Chinook Salmon–J; Steelhead–J; Rainbow Trout–A Atlantic Herring–J; Atlantic Sturgeon–A,J Lake Sturgeon–A, J
Changes in Homing Behavior	Chinook Salmon–A, F
Changes in Migration	
Loss of Fear Reaction	
Foraging and Predation	
Change in Feeding Strategy/Food Selection Preference	Rainbow Trout–J
Decreased Avoidance of Predators	
Decreased Feeding/Attack Rate/Foraging Rate	Chinook Salmon–A, J; Rainbow Trout–Pacific Herring–L; Atlantic Herring–-A
Decreased Predation/Risk of Predation	
Decreased Prey Reaction Distance	Rainbow Trout–A
Foraging and Predation	
Increased Avoidance of Predators	
Increased Feeding/Attack Rate/Foraging Rate	Chinook Salmon–A; Pacific Herring–L
Development and Growth	
Decreased Growth Rate	Chinook Salmon–U; Steelhead–J
Decreased Weight and Length	Rainbow Trout–A, YOY
Eggs/Hatching Development Slowed	
Increased Growth Rate	
Increased Weight and Length	
Eggs/Hatching Development Slowed	
Increased Growth Rate	
Cumulative Stress	
Decreased Tolerance to Stress	Chinook Salmon–S; Steelhead–Y; Rainbow Trout–A
Reproductive Performance	
Decreased Spawning Effort/No. of Eggs	
Unable to Spawn	

[29] See Appendices L and M for details of studies
A=adult; F=fry; J=juvenile; L=larval

Table 165 (cont.): Types of Tertiary Stress Responses Exhibited in Fishes Exposed to SS and Turbidity

Types of Tertiary Stress Responses Exhibited by Fishes Exposed to SS and Turbidity	Studies on Chinook Salmon, Steelhead, Rainbow Trout, Pacific Herring, Atlantic Herring, Atlantic and Lake Sturgeon
Population Changes	
Decreased Population Size	Rainbow Trout–A

Table 176: Range of Mean and Median Suspended Solids Concentrations for Each Sub-Embayment

Sub-Embayment	Water Years Monitored [30]	Range of Mean Concentrations (mg/L)	Range of Median Concentrations (mg/L)
Suisun Bay	1994-2005	27-141	24-123
Mallard Island	1994-2005	27-55	24-51.8
Martinez	1994-1996	47-56.9	42-52.4
Benecia Bridge on Pier 7	1996-1998; 2001-2005	29-141	25-123
San Pablo Bay	1999-2005	31-290	21-216
Carquinez Bridge	1998-2005	31-290	21-216
Mare Island Causeway	1999-2005	49-186	38-144
Channel Marker 9	1999-2003	110-213	38-142
Channel Marker 1	2004-2005	38-76	27-55
Central Bay	1992-2005	17-144	15-105
Point San Pablo	1992-2005	27-144	20-105
Alcatraz Island	2004-2005	18	15-17
Golden Gate Bridge	1996-1997	17-20	16-25
Pier 24	1992-2002	20-84	18-49
South Bay	1992-2005	36-257	25-213
San Mateo Bridge	1992-2005	36-95.6	25-76.9
Dumbarton Bridge	1992-2005	40-257	29-213
Channel Marker 17	1992-2005	51-210	30-145

Sources: Buchanan and Ganju, 2002-2005; Buchanan and Lionberger, 2006-2007; Buchanan and Ruhl, 2000-2001; Buchanan and Schoellhamer, 1995-1996,1998; Buchanan et al., 1996.

The variation in SS concentrations depends on many factors because each of the sub-embayments has its own mixture of the physical processes operating in the Bay—e.g., freshwater inflow, hydrology, tides, bathymetry, wind, currents and circulation, water quality, salinity, dissolved oxygen, and pH). Schoellhamer et al. (2007) and Smith (1987) found that the processes that significantly affected SS concentrations in the Bay were:

- Freshwater inflow from the Delta;
- Tides;
- Wind; and,
- Phytoplankton blooms.

The annual cycle of deposition and re-suspension begins in the winter when easily erodible sediment from the Central Valley watershed flows into the Bay (Conomos and Peterson, 1977; Goodwin and Denton, 1991; McKee et al., 2006). Much of this sediment deposits in the shallow sub-embayments, especially seaward of the Delta in north San Francisco Bay (Krone, 1979; Ruhl and Schoellhamer, 2004). Prior to that “first flush”, SS concentrations are low at the Martinez, Point San Pablo, and San Mateo Bridge stations; after that pulse, concentrations increase at all stations, most dramatically at the Point San Pablo station (Ruhl et al., 2001).

Shallow-water areas and deep channels in the Bay display significantly different responses to driving forces such as the daily tides, wind-waves, and the spring-neap cycle (Ruhl et al., 2001). Substantial sediment re-suspension occurs in shallow water, especially at low tide during windy periods. This process is especially significant during early spring when higher sustained winds generate wind waves that can readily stir up newly deposited, less consolidated sediment.

The fortnightly spring-neap tidal cycle accounts for one-half of the variance of SS in the South Bay (Schoellhamer, 2002, 1996). Maximum tidal currents, and correspondingly SS concentrations, are stronger during spring tides than during neap tides. Fluctuations in SS concentrations caused by wind and local runoff from winter storms are usually negligible in comparison to those caused by the spring-neap cycle.

A strong sea breeze, which most often occurs during spring and summer, causes wind-wave re-suspension of bottom sediment in shallow water. The ability of wind to increase SS concentrations is greatest early in the spring, when unconsolidated fine sediment can be re-suspended easily (Schoellhamer et al., 2007). Proceeding through the summer and into the fall, the fine sediment have been winnowed from the bed, and the remaining sediment become progressively less erodible (Krone, 1979; Nichols and Thompson, 1985). The result is that tidally averaged SS concentrations are greatest in spring and least in fall (Schoellhamer, 1996; Ruhl and Schoellhamer, 2004).

In addition to the physical processes, annual phytoplankton blooms affect SS concentrations in South Bay (Ruhl et al., 2001; Cloern, 1996). The annual maximum SS concentration typically occurs during the spring tide that follows the end of the spring phytoplankton bloom (Ruhl and Schoellhamer, 2001).

Ranges of SS Concentrations and Turbidity Levels Generated by Dredging Activities in the Bay and Factors that Affect those Concentrations

San Pablo Bay

San Pablo Bay Maintenance Dredging Study

The results (Figure 3; Appendix C, Table C-1) of the San Pablo Bay Maintenance Dredging Study at Point San Pablo showed that:

- Dredging volumes were not significantly correlated to SS concentrations;
- Processes other than dredging operations were significantly correlated with SS concentrations; and,
- While dredging operations might have affected SS concentrations at the dredging and disposal sites, there was no identifiable effect at the Point San Pablo station (Schoellhamer, 2002).

Hence, Schoellhamer (2002) concluded that natural physical processes, instead of maintenance dredging of the Pinole Shoal Ship Channel and disposal in San Pablo Bay, was the greatest determinant for the variability of SS concentrations at Point San Pablo. Wind-wave re-suspension had the greatest effect on SS concentrations. Median water-surface elevation was the primary factor affecting mid-depth SS concentrations. The primary factor that affected near-bottom SS concentrations was the seasonal variability in the supply of erodible sediment. In summary, natural processes control SS concentrations at Point San Pablo, even during dredging operations (Schoellhamer, 2002).

Carquinez Strait Dredged Material Disposal Site

High SS concentrations (9,000 mg/L at the sediment-water interface 100 m down-current of the disposal barge; 20,000 mg/L at the mud-water interface) were reported in the 1976 dredge study (USACE, 1976) for the Carquinez Strait dredge disposal site. Those values were several orders of magnitude higher than even the highest (290 mg/L) mean value reported for the baseline data (Table 3) collected from 1999-2005 at the Carquinez Bridge. Moreover, in the USACE (1976) study, the very high SS concentrations decreased to background levels after 25 minutes. Furthermore, the recent closure of the Mare Island Naval Shipyard has reduced significantly the need for dredging at this location. However, as suggested by Segar (1990) in an analysis of the Alcatraz disposal site, SS concentrations within the Carquinez Strait disposal-site plume could also remain high as the plume is transported beyond the SS monitoring network at the disposal site. Consequently, determining the persistence and patterns of increased SS concentrations at the Carquinez Strait Dredge Disposal Site warrants site-specific studies.

Central San Francisco Bay

Oakland Outer Harbor Maintenance Dredging Study

Routine maintenance dredging at the Port of Oakland results in SS plumes that could affect sensitive fishes that inhabit the area (e.g., salmonids, Pacific herring). The researchers for the

Oakland Outer Harbor Dredging Study (Clarke et al., 2006, 2005) concluded that (Appendix C, Table C-2):

- The surveys effectively characterized SS sediment plume structure for the maintenance bucket dredging operations in the Port of Oakland Outer Harbor navigation channel;
- The plumes were driven by relatively weak currents during both ebb and flood tidal stages;
- The fact that a closed bucket was used influenced the spatial and temporal dynamics of plumes in the study area. Few indications of surface components of plumes were detected; the major loss of sediment via re-suspension appeared limited to the lower water column;
- SS concentrations were lowest in the "dead end" area, where flows apparently allowed settlement of fine sediment;
- Plumes generated by the dredge were characterized by narrow bands of elevated concentrations that decayed within short distances from the source. SS concentrations ranged from less than 25 mg/L to more than 225 mg/L and tended to decay fairly rapidly with increasing distance from the source. SS concentrations exceeding 275 mg/L were measured only in the immediate proximity to the source and with increasing distance. Concentrations greater than 100 mg/L were observed only in relatively small pockets of water that dispersed along the bottom; and,
- Plumes tended to be entrained in bottom waters. Hence, it was concluded that fishes in the upper water column, or along the periphery of the waterway, would experience a relatively low risk of exposure, and bottom-oriented fishes would be more likely to encounter the plume, at least intermittently.

Clarke et al. (2005) also concluded that, if dredging equipment similar to that used for Oakland Outer Harbor maintenance dredging were used, it would be unlikely that transient fishes in the mid to upper portions of the water column would be exposed to SS concentrations exceeding ambient concentrations for even short durations. However, they also concluded that bottom-dwelling fishes would be more likely to encounter the plume, at least intermittently.

In conclusion, the researchers provided a cautionary note by stating that the results of their study were site-specific; i.e., plume dynamics would vary significantly throughout the Bay based on hydrodynamics, geomorphology, and numerous other factors. Hence, to determine the effects of other dredging activities in the Bay, site-specific studies were warranted.

Alcatraz Disposal Site

Studies at the Alcatraz disposal site (Gunther et al., 1990; USACE, 1976) demonstrated that, in most instances, the interval between disposal events was great enough—more than an hour or two —to allow SS concentrations at the disposal site to decrease to background levels between events (Appendix C, Tables C- 3 through C-5). However, Segar (1990) suggested that the SS concentrations within the plume could remain high as the plume was transported beyond the SS monitoring network at the disposal site. And, as disposal occurs at random times with respect to the stage of the tide, Segar (1990) also concluded that dredged materials entering the SS regime would be carried away from the disposal site by currents and would be subject to subsequent cycles of deposition and re-suspension. The Alcatraz disposal site is characterized by oscillating tidal currents with maximum speeds of about 150 cm/s that flow towards the Golden Gate on the ebb, and east towards Treasure Island on the flood. As a result, Segar (1990) concluded that, under circumstances of high disposal frequencies (e.g., up to 40 disposal events per day), it would be possible for SS concentrations in Central Bay to increase. Thus, to determine the persistence and patterns of increased SS concentrations in Central Bay during periods of high dredge disposal frequency, Gunther et al. (1990) recommended that special studies be conducted.

South Bay

Knockdown Operations at Redwood Creek/Port of Redwood City

In an effort to protect natural resources and to seek better management of dredging projects in the Bay, a study was undertaken in the Redwood Creek navigation channel that provides access to the Port of Redwood City. As a result of that study, the researchers concluded the following (Clarke et al., 2006, 2005):

- During knockdown operations, bottom-dwelling fishes could be exposed to significantly higher SS concentrations than normally occur;
- During knockdown operations, fishes occupying the upper portion of the water column would be unlikely to encounter substantially elevated SS concentrations; and,
- Assessing the degree of risk posed by knockdown operations would require knowledge of the behavior, distribution, and tolerance of organisms, including fishes that occupy the waterway.

Dredging Equipment as a Factor Affecting SS Concentrations and Turbidity Levels

The type of dredging equipment determines the spatial and temporal distribution of SS and turbidity (Barnard, 1978) and, hence, determines the effects of SS and turbidity on fishes. The two major types of dredging equipment are: (1) hydraulic dredges (e.g., cutterheads, dustpans, hoppers, hydraulic pipelines, plain suction, and sidecasters); and, (2) mechanical dredges (clamshell, dipper, and ladder dredges) (Gren, 1976). Hydraulic dredges are generally faster and create less re-suspension of sediment than mechanical dredges (Barnard, 1978). Mechanical dredges cause more sediment re-suspension when dredging occurs in fine, loose, or non-cohesive substrate (LaSalle, 1990).

In summary, data were obtained from five dredging and dredged material disposal sites in the Bay. Although the studies provided temporal and spatial characterizations of specific areas of the Bay during dredging activities, the researchers in all of the studies recommended additional site-specific studies. The rationale for those recommendations is that dredging activities in the Bay take place in a variety of geomorphologic and hydrodynamic settings using a variety of equipment and operational techniques.

Responses of Fishes to SS and Turbidity

Lethal Response

Mortality is the result of the failure of Secondary and Tertiary Stress Responses to re-adapt a fish. Mortality can occur quickly when SS concentrations are exceedingly high (e.g., when Mt.

St. Helens in Washington State erupted, within 2-3 days, all juvenile Chinook salmon died in the affected rivers (Phinney, 1982)). Mortality can also occur after a period of time, when sublethal SS concentrations completely take their toll on the immune system of the fish (Appendix E).

Within ranges found naturally in aquatic environments, high SS and turbidity levels are not usually directly lethal to fish (Wallen, 1951; Swenson and Matson, 1976; Auld and Schubel, 1978). Mortality may be due to the combination of both physiological and physical factors related to oxygen availability. Studies on a variety of fishes attributed acute mortality from high SS concentrations to reduced oxygen uptake (Newcomb and Flagg, 1983; Noggle, 1978; Neumann et al., 1981; Horkel and Pearson, 1976; Peddicord et al., 1975; O'Connor et al., 1977) because fish must keep their gills clear for oxygen exchange. Fine particles can coat the gill surfaces, which isolates them from contact with the water, thereby preventing gas exchange. Or, the larger particles can lodge in the gill lamellae and, hence, block water circulation and create a "dead" space at the site of gas exchange (Servizi and Martens, 1992; Noggle, 1978; Martens and Servizi, 1993).

Although lethal SS concentrations as low as 6.7 mg/L and 37 mg/L SS were reported for rainbow trout and steelhead eggs, respectively, and 90 mg/L for juvenile rainbow trout, most studies used extremely high (e.g., 500-207,000 mg/L) SS concentrations, particularly those in laboratories (Tables 6 and 7). Such high SS concentrations are neither representative of baseline conditions, nor comparable to conditions during dredging activities in the Bay. Baseline mean SS concentrations in the Bay ranged from 17 to 290 mg/L, depending upon the sub-embayment (Tables 2 to 5). SS concentrations, as a result of dredging activities, ranged from 20.3 to 251 mg/L (median SS concentrations) in San Pablo Bay (Appendix C, Table C-1), 25 to 125 mg/L in the Oakland Outer Harbor (Appendix C, Table C-2), 10 to 290 mg/L at the Alcatraz Disposal Site (Appendix C, Tables C-3 through C-5), and 25 to over 450 mg/L during knockdown operations in Redwood Creek/Port of Redwood City (Appendix C, Table C-6). Although a variety of factors (e.g., tide, depth, inflows, etc.) affected SS concentrations in the Bay, the ranges of both ambient and dredging-generated SS concentrations were considerably lower than those used in most of the laboratory studies on fishes (Table 6).

With regard to SS and mortality in fishes, a number of general conclusions can be drawn from the studies:

- Due to the many factors (both natural and human-induced) that can affect the outcome of any of these types of studies, the results of the numerous laboratory studies on the effects of SS on mortality should not be applied directly to any field situation;
- Although 55 studies assessed the impacts of SS and turbidity on fishes, only 12 were field studies. Ten studies focused on mortality associated with dredging-related activities, and none took place in the Bay;
- Most of the laboratory studies used extremely high (e.g., 500-207,000 mg/L) SS concentrations that were neither representative of baseline conditions (17-290 mg/L, depending upon the embayment) nor comparable to those resulting from dredging activities (10 to > 450 mg/L) in the Bay;
- Responses to SS were highly species-specific with salmonids generally more sensitive to SS and turbidity than non-salmonids;

- Bottom-dwelling fishes appeared to have more tolerance for SS than pelagic and/or filter feeders;
- Angularity, shape, and size of the SS particles were believed to be correlated with fish mortality; and,
- To determine mortality-related effects on the sensitive fish species in the Bay, focused dredging-related laboratory and field studies are needed that use concentrations that are representative of those found in the Bay with and without dredging activities.

Primary Stress Responses

Although there have been hundreds of studies on the Primary Stress Responses in fishes—particularly salmonids–exposed to a variety of stressors (Adams, 1990), only three were found that used Primary Stress Responses in fishes exposed to SS (Table 9). The primary reason for the paucity of such studies is probability the difficulty in measuring these substances in a controlled situation, let alone in a "stressed" situation such as in the field. Having a human in close proximity to a salmonid will rapidly increase its blood adrenaline levels (Rich, 1979, 1983). Hence, it is not surprising that there have been few laboratory and no field studies that used Primary Stress Responses in fishes exposed to SS and turbidity.

In most of the laboratory studies, relatively high SS concentrations (e.g., 400-2,000 mg/L) were used (Table 9). To realistically assess the Primary Stress Responses of sensitive Bay fishes exposed to SS generated by dredging activities, studies should use SS concentrations that are representative of baseline and dredging-related conditions. Due to the difficulty with measuring Primary Stress Responses in fishes, such studies would probably be limited to the laboratory.

Secondary Stress Responses

Studies on the Secondary Stress Responses in fishes (Tables 10 and 11) exposed to SS fall into the following two general categories: (1) changes in blood chemistry; and (2) injury to the body, primarily to the gills and skin (Table 12). Although there have been numerous studies on the Secondary Stress Responses in fishes exposed to SS, only a few have been conducted on the sensitive Bay fishes and all of those were laboratory based (Tables 10 to 12, Figure 7). Although Secondary Stress Response indicators are easier to measure than Primary Stress Response indicators, studies still involve obtaining blood or tissue, both more time-consuming than mortality-type studies.

SS concentrations that resulted in Secondary Stress Responses for Chinook salmon, steelhead, and Pacific herring ranged from 61 to 943, 171 to 4,887, and 1,000 to 4,000 mg/L, respectively (Table 11). Again, except for the lower ranges in SS concentrations for Chinook salmon and steelhead, most of the SS concentrations in previous studies on the priority fish species were higher than either baseline (Tables 2 to 5) or dredging conditions in the Bay (Appendix C). To realistically assess the Secondary Stress Responses of priority Bay fishes exposed to SS generated by dredging activities, it will be necessary to conduct both laboratory and field studies that use concentrations that are representative of baseline and dredging-related conditions.

Tertiary Stress Responses

If Primary and Secondary Stress Responses do not result in a fish adapting to its conditions so that it can function in a healthy manner, the stress responses continue and can affect the organism as a whole, via Tertiary Stress Responses (e.g., reduced growth, reduced disease resistance, and reduced population size (Figure 1)). Many of the reviewed studies reported numerous Tertiary Stress Responses in fishes exposed to SS and turbidity (Tables 12 to 14; Figure 8). Because Tertiary Stress Responses affect the organism as a whole, it is possible that if SS concentrations generated by dredging activities occur in close proximity to sensitive areas in the Bay (e.g., migratory pathways for salmon, steelhead, and green sturgeon, and spawning areas for Pacific herring), those concentrations could have a negative impact on the populations of those fishes. However, from the studies reviewed, it is not clear what magnitude of changes, or even how such changes, would occur in the Bay.

For some studies on the Tertiary Stress Responses in fishes exposed to SS, the results have been contradictory. Because there are so many ways that SS can affect the priority Bay fishes, it is worthwhile to summarize what is known about the Tertiary Stress Responses in fishes exposed to SS, and how those responses could affect those fishes. Tertiary Stress Responses, as a result of exposing different fish species to SS and turbidity, involved the following:

- Behavior (avoidance/attraction) responses;
- Foraging and predatory behavior;
- Development and growth;
- Cumulative stress;
- Reproductive performance; and,
- Populations.

Behavioral (Avoidance/Attraction) Responses

SS and turbidity can play a significant role in the distribution of fishes (Blaber and Blaber, 1980). In addition to behavioral avoidance and attraction responses, fish may abandon spawning habitat, change depths in the water column, and alter swimming behavior. Other than the fact that avoidance and attraction occur, and that duration of exposure is important, little is known about what triggers the avoidance or attraction to elevated SS concentrations in fishes. Several fish species actively choose turbid water over clear water during their early life stages (Blaber and Blaber, 1980; Cyrus and Blabber, 1987a; De Graff et al., 1999; Emmet et al., 2004). Studies have demonstrated that, to reach spawning areas, salmonids moved through areas that contained high SS concentrations (137-395 mg/L) (Ward, 1938). It is believed that avoidance responses are learned and that one conditioning stimulus involves vision (Messieh et al., 1981). Nightingale and Simenstad (2001) postulated that the primary determinant of whether or not avoidance occurred was due to the spatial and temporal overlap between the area of elevated SS concentrations, the occurrence of fish, and the options available to the fish relative to carrying out the critical functions of their present life-history stage.

Avoidance of areas that contain elevated SS concentrations could affect migratory and reproductive behavior of sensitive Bay fishes. Sumner and Smith (1939) and Smith (1940) found that Chinook salmon avoided the muddy waters in the Yuba River and entered a clean tributary. These fish also chose a clear streak in a muddy river for spawning rather than using more turbid areas nearby. Home-water preference was disrupted in migrating Chinook salmon at turbidity levels of 350 NTU, lasting 10-minutes (Whitman et al., 1982). Juvenile steelhead avoided turbid water above a level of 167 NTUs (Sigler et al., 1984). In a laboratory study on the effects of the Mt. St. Helens eruption in Washington State, Brannon et al. (1981) found that adult Chinook salmon avoided ash-laden (146-373 mg/L) water. Although SS concentrations in that study were subject to considerable temporal and spatial variations, it was concluded that migratory behavior of adult salmon could be altered at sublethal SS concentrations and that there could be a significant amount of straying. In a dredging-related laboratory study, juvenile herring avoided SS concentrations above 2.5 mg/L (Messieh et al., 1981). In another laboratory study, juvenile herring avoided water that had turbidity levels of 9 to 12 NTUs (Johnston and Wildish, 1981). Extrapolating these results to Pacific herring is difficult in that both studies involved exposures to SS concentrations well below expected ambient concentrations. In a dredging-related field study, juvenile and adult Atlantic sturgeon avoided water in the vicinity of a dredged material disposal site (Hatin et al., 2007). Hence, as these fishes avoided SS concentrations that were similar to those resulting from dredging activities in the Bay (Appendix C, it is reasonable to assume that both migratory (Chinook salmon, steelhead, and green sturgeon) and reproductive behavior (Pacific herring) could be altered in the Bay.

Complicating the interpretation or prediction of behavioral responses to SS and turbidity by fishes is the fact that fishes can be attracted to turbid waters. Juveniles of many marine and anadromous fish species seem to prefer rivers and estuaries with high concentrations of SS (Blaber and Blaber, 1980; Levy and Northcote, 1982; Gregory and Levings, 1998). These species actively chose turbid (10-80 NTU) over clear areas (Cyrus and Blaber, 1987a,b,c). Their attraction to turbid waters has been related to feeding and predation strategies (see discussion on *Foraging and Predatory Behavior*, below). It was concluded that fishes chose turbid areas because of the following: (1) the fish were adapted to the habitat; (2) suitable food sources were in those areas; and, (3) the turbidity was beneficial to the fishes (e.g., as a refuge from predation).

Foraging and Predatory Behavior

It is known that SS and turbidity affect the feeding strategies of fishes. Although elevated SS concentrations and turbidity levels generated by dredging-related activities could affect predator-prey interactions for priority Bay fishes, the details of those effects are unclear. In adult Chinook salmon and larval Pacific herring, both decreased and increased foraging rates occurred as a result of SS and turbidity (Table 15). Such contradictory results were found with other fish species exposed to SS and turbidity (Table 15). The reasons for the apparent contradictions are complex and not fully understood. Interpreting the effects of SS and turbidity on fishes is complicated by a number of factors, including the following:

- Visibility of prey;
- Type of environment fish are residing in;
- Whether or not turbidity provides protective cover; and,
- Type of feeding behavior (e.g., piscivorous versus planktivorous; drift-feeder versus bottom-feeder) and size of fish.

Depending upon the life stage and the species of fish, SS and turbidity can have both positive and negative effects on both predators and prey. Following is a discussion of the factors listed above that affect the feeding strategies and, hence, the seemingly contradictory responses of fishes to SS and turbidity.

Many fish species depend on vision in their search for prey (Guthrie, 1986). The characteristics of the prey, such as size, pigmentation, and motion also play important roles for predatory fishes depend primarily on predacious vision to capture prey (Confer et al., 1978; O'Brien, 1987; O'Keefe et al., 1998). In most instances, visual detection range is manifested in behavior (Utne-Palm, 1999). A common measure of visual range is the reaction distance (RD), which is the distance at which a fish reacts to an object in its environment. The probability of prey detection is proportional to RD (Confer and Blades, 1975). A number of factors affect RD, including turbidity; usually turbidity is inversely proportion to the RD (Utne,1997), although fish larvae may actually have enhanced detection capabilities when turbidity accentuates the visual contrast of certain prey items.

Fishes inhabiting different types of environments have different visual capabilities. For example, studies demonstrated that fishes adapted to highly turbid habitats responded less to increased turbidity than those used to less turbid habitats (Bonner and Wilde, 2002). For example, due to the early development of retinal (eye) receptors, juvenile walleye were able to consume large quantities of food in turbid waters (Vandenbyllaardt et al., 1991).

Many of the most productive aquatic ecosystems in the world are characterized by turbid water (Abrahams and Kattenfeld, 1997). Researchers demonstrated that the impact of predation risk was reduced in such estuaries. These ecosystems are believed to provide a protective cover, thus enabling fish to evade detection or capture. This protective cover hypothesis has been referred to as the "turbidity as cover" hypothesis (Gradall and Swenson, 1982; Gregory and Levings, 1998; Gregory, 1993). The results of both laboratory and field studies suggest that juvenile fish engage in activities in turbid conditions that would be risky in clear water, including increasing their feeding activity (Gregory and Northcote, 1993; Gregory, 1994), reducing their cover-seeking behavior (Gradall and Swenson, 1982; Gregory, 1993), and increasing the use of high-risk open-water habitat (Miner and Stein, 1988). Thus, when the higher feeding rates of juvenile Chinook salmon occurred at turbidity levels of 35-160 NTUs (Appendix N, Table N-1), this outcome was believed to be linked to the fish perceiving that there was decreased predatory risk (Gregory, 1993). The researcher speculated that the increased foraging activity was due to the salmon behaving in a riskier manner.

Piscivorous (e.g., salmonids) and planktivorous (e.g., herring) fishes differ in their responses to SS and turbidity, mainly because of the different size of prey they consume (De Robertis et al., 2003). In clear water and under high light intensity, piscivorous fishes are able to detect their fish prey from a greater distance than planktivorous fish can detect their smaller-sized planktonic prey (Breck, 1993; Utne, 1997; Vogel and Beauchamp, 1999). An increase in SS or turbidity could be more beneficial for planktivorous fish because their encounter rates with piscivorous predators are reduced more than their encounter rates with their planktonic prey (De Robertis et al., 2003). This is similar to fog, which has little effect on short-range vision, but can greatly diminish the visibility of objects at a distance (Lythgoe, 1979, 1968).

Ritchie (1972) suggested that turbidity reduced the ability of fish to locate prey but also decreased predation pressure. The decreased feeding capabilities of larger planktivorous fishes in turbid conditions (Vinyard and O'Brien, 1976; Gardner, 1981) are a function of the limitation of visual field. Thus, in turbid conditions, if larvae are able to maintain high feeding rates, their advantage increases. Blaber and Blaber (1980) suggested that turbidity was the most important factor that affected juvenile fish abundance in estuaries, with highest fish abundance occurring during highest turbidity levels; moreover, where a gradient of turbidity existed, fish abundance was highest in the most turbid waters.

The elevated SS concentrations and turbidity levels generated by dredging activities could affect predator-prey interactions for priority Bay fishes. However, due to the numerous factors that affect an individual fish's response to SS and turbidity, it is not clear how those concentrations would affect, either negatively or positively, predator-prey interactions in the Bay.

Development and Growth

Foraging and predatory behavior are inextricably linked to early development and growth of fishes and can influence survival. Thus, if increased SS concentrations from dredging activities affect feeding strategies of sensitive Bay fishes, development and growth could also be altered. And, the effects of SS and turbidity on development and growth can be contradictory. Both laboratory and field studies demonstrated that elevated SS concentrations and turbidity levels reduced growth rate, weight, and length in fishes (Table 15). In juvenile Chinook salmon, growth rate was reduced at a concentration of only 6 mg/L (Appendix N, Table N-1). In juvenile steelhead, growth rate decreased beginning at 102 mg/L (Appendix N, Table N-2). By contrast, turbidity can also decrease the costly anti-predator behavior of prey fish (Lehtiniemi et al., 2005) and increase energy gain for growth. Larval Pacific herring lowered their activity levels in turbid water due to reduced predation risk and increased better growth rate (Fiksen et al., 2002).

In summary, although no dredging-related development and growth studies were found, studies on the effects of SS on fishes demonstrated that the SS concentrations generated by dredging activities in the Bay could have either a negative or positive impact on the development and growth of priority Bay fishes.

Cumulative Response to Multiple Stressors and Tolerance to Stress

SS or turbidity, together with other stressors, can produce cumulative stress responses in fishes (Barton et al., 1986). Although all studies reviewed herein that demonstrated cumulative stress responses were conducted in the laboratory, many potential factors (e.g., escaping predators, contaminants, etc.) in the Bay could influence effects of dredging-related SS on fishes. A few studies were found that demonstrated the effects of subjecting fish to SS plus another stressor. For example, adult Arctic grayling were less tolerant of a second stressor (water temperature or the chemical pentachlorophenol) at a SS concentration of 300 mg/L (12 hours exposure duration) (McLeay et al. 1984), and disease resistance decreased at a SS concentration of 100 mg/L (and 1008 hours exposure duration) (McLeay et al,, 1987; Appendix L, Table L-33). Chinook salmon during the parr-smolt transformation experienced reduced tolerance to stress as a result of first being exposed for three days to a SS concentration of 943 mg/L (Stober et al., 1982). Note that exposures at comparably high SS concentrations would be very unlikely to persist for three days for most dredging projects. Steelhead experienced reduced disease resistance after being exposed to SS concentrations between 2,000 – 4,000 mg/L (Redding et al., 1987; Appendix L, Table L-33). SS concentrations this high would only occur within very short distances from dredging sources and for relatively short durations at placement sites. Hence, priority Bay fishes can be expected to be exposed to multiple stressors in addition to SS such that cumulative stress responses on fish populations should be considered.

Reproductive Responses

Although no studies could be found that explored the reproductive responses of priority species to elevated SS or turbidity, SS concentrations that ranged from 100 to over 600 mg/L resulted in delays in spawning, decreased spawning effort, and increased mortality of eggs and larvae in other fish species (Appendix L, Table L-34). In many cases these responses were exhibited by fishes adapted to clear-water stream spawning habitats quite distinct from typical San Francisco Bay habitats. However, the fact that spawning could be compromised by sufficiently increased SS concentrations should be considered in evaluating dredging project site-specific conditions when in proximity to priority Bay fish habitats.

Changes in Fish Populations

When Secondary Stress Responses do not result in re-adapting fish so that they can easily tolerate altered conditions, the population can ultimately suffer. In the natural world, population changes that result from increased SS concentrations are usually observed after some catastrophic event (e.g., the Mt. St. Helens eruption, or huge amounts of silt emptying into a river system as a result of the collapse of a hillside). However, over time, if a species is subjected to one or more stressors, the population can decline. Although few studies were found that explored fish population changes as a result of SS and turbidity and no dredging-related studies were found, it is conceivable that chronically-elevated SS concentrations can contribute to the decrease in fish populations. Populations decreased in both field and laboratory studies at SS concentrations as low as 18 mg/L in brown trout (Peters, 1967), to 18,000 mg/L in rainbow and brown trout (Bergstedt and Bergersen, 1997) (Appendix L, Tables L-35 and L-36).

Gaps in Knowledge

This review of the effects of re-suspended sediment on the sensitive Bay fishes summarizes useful information and identifies many important data gaps (Tables 17 and 18). Clearly, to adequately assess potential impacts of dredging-related SS on priority Bay fishes, there is a need for more research. To assess how dredging-related SS concentrations affect fishes requires the following types of information (Clarke and Wilber, 2000):

- Knowledge of SS and turbidity thresholds that cause negative impacts onto a given fish species for key life history stages;
- Reliable estimates of spatial and temporal dynamics associated with dredging-induced SS plumes; and,
- Knowledge of the probability that SS concentrations generated by a dredging-induced SS plume would exceed the sublethal or lethal effects thresholds for an exposed fish.

Table 187: Life Stages of Priority Bay Fishes for which there have been SS and Turbidity Studies

Species Group	**SS (in mg/L)**		**Turbidity (in NTU or JTU)***	
	Field	Lab	Field	Lab
		Chinook Salmon		
Egg				
Larval (YOY, U F, EE)		1, 3, 4		
Smolt		1, 3, 4		
Juvenile (Y,J)	1	1		4
Adult		1, 3, 4	4	4
		Steelhead		
Egg	1**	1, 1**		
Larval (YOY, EE, F,FF)		**4**, 1DRBT**		
Juvenile (Y,JF)	1, 1**, 3	**1, 2, 3, 3**, 4**		**4, 4****
Adult	4**	**1**, 3, 3**, 4****		
		Pacific Herring		
Egg		1, 1D		
Larval (YOY)		1, 1D, 3, 4		
Juvenile				
Adult				

*NTU = Nephelometric Turbidity Units; JTU = Jackson Turbidity Units
1 = Studies using mortality as the endpoint.
1** = Studies on rainbow trout using mortality as the endpoint.
2 = Studies using Primary Stress Responses as endpoints.
2** = Studies on rainbow trout using Primary Stress Responses as endpoints.
3 = Studies using Secondary Stress Responses as endpoints.
3** = Studies on rainbow trout using Secondary Stress Responses as endpoints.
4 = Studies using Tertiary Stress Responses as endpoints.
4** = Studies on rainbow trout using Tertiary Stress Responses as endpoints.
1D = Dredge-related mortality study.
1DRBT = Dredge-related mortality study using rainbow trout.

Table 18: Life Stages of Fishes Related (i.e., same genus) to the Priority Bay Fishes where there have been SS and Turbidity Studies

Species Group	**SS (in mg/L)**		**Turbidity (in NTU or JTU)***	
	Field	Lab	Field	Lab
Coho Salmon				
Egg	1			
Larval (YOY)		1, 3, 4		
Smolt		1		
Juvenile (Y,J)		1,2,3,4		
Adult				
Sockeye Salmon				
Egg		3		
Larval (YOY, EE, F,FF)		3		
Juvenile (Y,JF)		3		
Smolt		3		
Adult		1,3		
Chum Salmon				
Egg		1		
Larval (YOY)				
Smolt				
Juvenile		1D,3D,4D		
Adult				
Pink Salmon				
Egg				
Larval (YOY)		3		
Smolt				
Juvenile		4D		
Adult				

Table 18 (cont.): Life Stages of Fishes Related (i.e., same genus) to the Priority Sensitive Bay Fishes where there have been SS and Turbidity Studies

Species Group	SS (in mg/L)		Turbidity (in NTU or JTU)*	
	Field	Lab	Field	Lab
Atlantic Herring				
Egg		1,1D,4		
Larval (YOY)		4D		
Juvenile		4D		
Adult		4D		
Atlantic Sturgeon				
Egg				
Larval				
Juvenile	4D			
Adult	4D			
Lake Sturgeon				
Egg				
Larval				
Juvenile		4D		
Adult		4D		

*NTU = Nephelometric Turbidity Units; JTU = Jackson Turbidity Units
1 = Studies using mortality as the endpoint.
2 = Studies using Primary Stress Responses as endpoints.
3 = Studies using Secondary Stress Responses as endpoints.
4 = Studies using Tertiary Stress Responses as endpoints.

Information on SS and Turbidity Response Thresholds for Priority Bay Fishes

Due to many data gaps, it is not possible to quantitatively define response thresholds for SS concentrations for any of the priority Bay fishes. Studies on the effects of SS and turbidity were found only on Chinook salmon, steelhead, and Pacific herring. None of those studies were associated with dredging-related activities nor occurred in the Bay, and only some of the life stages were represented. Laboratory studies demonstrated that the priority Bay fishes may respond to relatively low SS concentrations and turbidity levels. Salmonid eggs sustained fairly high mortality rates (40-72%) at low SS concentrations (6.7-37 mg/L; 1488-1152 hours exposure; Appendix E, Table E-3) (Slaney et al., 1977a,b). In addition, various sublethal effects occurred in salmonids at SS concentrations as low as 3.5 mg/L. In field studies on Arctic grayling, avoidance occurred at 3.5 mg/L for 168 hours exposure (Appendix L, Table L-1) (Suchanek et al., 1984a,b). Reduced feeding efficiency in salmon occurred at 25 mg/L and 4 hours exposure (Appendix L, Table L-12) (Philips, 1971), and at 16 mg/L for 24 hours exposure (Appendix L, Table L-12) (Townsend, 1983; Ott, 1984). Sublethal effects occurred at low SS concentrations in herring, as well. Avoidance occurred at SS concentrations, beginning at 9 mg/L (5 minutes exposure, Appendix L, Table L-5), and decreased feeding occurred at ≥ 3 mg/L (2 hours exposure, Appendix L, Table L-23) in dredging-related studies on juvenile Atlantic herring (Messieh et al., 1981).

In summary, although evidence suggests that at least some priority Bay fishes could respond negatively to relatively low SS concentrations, identifying actual SS response thresholds for those fishes currently is not possible due to the following data/informational gaps:

- Lack of information on lethal and sublethal effect thresholds for SS concentrations;
- Lack of dredging-related studies on priority Bay fishes; and,
- Reliable estimates of spatial and temporal dynamics of Temporal Dynamics Associated dredging-induced SS plumes.

Both the ongoing agency-sponsored long-term monitoring program on SS concentrations throughout the Bay, and project-specific monitoring studies on the effects of dredging activities on SS and turbidity in the Bay have provided invaluable information and should be expanded to include other prevalent dredging activities. However, future project-specific SS monitoring studies should be conducted within the framework of relevant site-specific SS threshold studies on priority species in the Bay. By comparing SS concentrations associated with specific dredging activities with SS concentration thresholds it would be possible to assess the impacts of dredging-related re-suspended sediment on those fishes.

The Probability that the SS Concentrations from a Dredge-Related SS Plume would Exceed a Sublethal or Lethal Threshold for Exposed Fishes

To assess the probability that the SS concentrations from a dredging-related SS plume would exceed a SS concentration threshold for any of the priority Bay fishes requires the following information:

- Knowledge of how frequently the fishes encounter the dredging-related SS plume; and,
- Threshold SS concentrations for the relevant life stages of the fishes in question.

Although ongoing salmonid tagging studies in the Bay (USACE, 2007) provide some information about migratory pathways and the presence of anadromous fish species in the Bay, the following types of dredging-related studies would provide additional needed information:

- Field studies on migration routes and timing in the Bay for Chinook salmon, steelhead, and green sturgeon, especially for those areas where dredging activities occur;
- Field studies on how the priority fish species in the Bay respond to dredging-generated SS plumes;
- Field studies on Pacific herring in the Bay, focusing on their spawning activities, especially in those areas where dredging activities occur; and,
- Laboratory and field studies to determine safe SS concentration/duration exposure limits for the relevant life stages of each priority species. Such studies could include appropriately validated simulation modeling applications.

Many previous studies could provide the framework to facilitate the design of the different studies that are needed.   For example:

- SS-related studies on migratory behavior of fishes;
- Studies that established sublethal or lethal thresholds for SS concentrations in fishes;
- SS-related studies on reproductive behavior; and,
- SS-related studies on how fish respond to dredging-generated plumes.

Conclusions

Available studies and conversations with experts on the effects of suspended sediment on sensitive fish species in the Bay lead to the following conclusions:

- Factors that significantly affect SS concentrations in the Bay include freshwater inflow from the Delta, tidal cycles, wind, and phytoplankton blooms;
- Ambient SS concentrations in the Bay range from 200 mg/L in the winter to 50 mg/L in the summer with the lowest SS concentrations in the Central Bay and the highest in shallow areas and adjacent channels;
- Natural processes control SS concentrations at Point San Pablo even during dredging operations;
- Of the many studies on the effects of SS and turbidity on fishes, only a few were related to dredging activities and even fewer focused on Bay fishes;
- Due to the lack of relevant information throughout the Bay, it is not possible to assess the extent to which priority fish species would encounter dredging-related SS plumes;
- SS concentrations at the dredging sites for which SS data were reviewed decreased to background levels within 25 minutes;
- As dredging-plume dynamics vary significantly throughout the Bay, determining the effects of specific dredging activities requires site-specific studies;
- The type of dredging equipment determines the spatial and temporal distribution of SS and turbidity and, hence, determines the potential effects on fishes;
- If dredging equipment similar to that used for Oakland Outer Harbor maintenance dredging were used, fishes in the upper water column or along the periphery of that waterway would experience a relatively low risk of exposure and bottom-oriented fishes would be more likely to encounter the plume;
- To determine the effects of SS and turbidity on fishes, both concentration and duration of exposure must be included;
- The results of laboratory studies on the effects of SS on fishes should not be directly applied to any field situation;
- The degree of response to SS concentrations by fishes was related to angularity, shape and size of the SS particles;
- Responses to SS were highly species-specific, with salmonids generally more sensitive to SS and turbidity than non-salmonids;
- Bottom-dwelling fishes appeared to tolerate higher SS concentrations than pelagic and/or filter feeders;
- SS concentrations generated by dredging activities in the Bay could have impacts (either negative of positive) on the priority fish species in the Bay;

- It is not possible to establish safe SS concentration/exposure duration limits for priority Bay fishes because of a lack of relevant information and dredging-related studies;
- To determine the effects of re-suspended sediment associated with dredging activities, a number of focused field-and laboratory studies are needed; and,
- If models are used to predict the effects of re-suspended SS associated with dredging activities, validation of the modeling results must be included as part of the study design.

REFERENCES

Abrahams, M. and M. K. Kattenfeld. 1997. The role of turbidity as a constraint on predator-prey interactions in aquatic environments. *Behavioral Ecology and Sociobiology* **40**, 169-174.

Adams, S. M. 1990. *Biological Indicators of Stress in Fish*. American Fisheries Symposium 8, Bethesda, Maryland.

Alabaster, J.S. and R. Lloyd. 1980. Finely divided solids. Pages 1-20 *in* Water Quality Criteria for Freshwater Fish. Butterworth, London.

Allen, K.O. and J. W. Hardy. 1980. Impacts of navigational dredging on fish and wildlife: a literature review. U.S. Fish and Wildlife Services. FWS/OBS-80/07. 81 pages. September 1980.

Anchor Environmental LLC. 2003. Literature review of effects of resuspended sediment due to dredging operations. 87 pp. + Appendices. June. Prepared for Los Angeles Contaminated Sediment Task Force.

Auld, A.H. and J. R. Schubel. 1978. Effects of suspended sediment on fish eggs and larvae: a laboratory assessment. *Estuarine and Coastal Marine Science* **6**, 153-164.

Baker, C. F. 2003. Effect of adult pheromones on the avoidance of suspended sediment by migratory banded kokopu juveniles. *Journal of Fish Biology* **62**, 386-394.

Barnard, W. D. 1978. Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operations. Technical Report DS-78-13. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Barrett, J.C., Grossman, G. D. and J. Rosenfeld. 1992. Turbidity-induced changes in reactive distance of rainbow trout. *Transactions of the American Fisheries Society* **121**, 437-443.

Barton, B. A., C. B. Schreck and L. G. Fowler. 1988. Fasting and diet content affect stress-induced changes in plasma glucose and cortical in juvenile Chinook salmon. *Progressive Fish Culturist* **50**, 16-22.

Barton, B. A., C. B. Schreck, and L. A. Sigismondi. 1986. Multiple acute disturbances evoke cumulative physiological stress responses in juvenile Chinook salmon. *Transactions of the American Fisheries Society* **115**, 245-251.

Bash, J., C. Berman and S. Bolton. 2001. Effects of turbidity and suspended solids on salmonids. Final Research Report. Research Project T1803, Task 42. University of Washington, Center for Coastside Studies. Prepared for the Washington State Transportation Commission and U.S. Department of Transportation. 80 pp.

Bay, B. S. 2000. Quantitative assessment of suspended sediment concentration on coho salmon in Freshwater Creek. A Senior Project presented to the Department of Environmental Resources Engineering, Humboldt State University in partial fulfillment of the requirement for the degree of Bachelor of Science. Humboldt State University. Fall, 2000. 83 pages.

Benfield, M.C. and T. J. Minello. 1996. Relative effects of turbidity and light intensity on reactive distance and feeding of an estuarine fish. *Environmental Biology of Fishes* **46**, 211-216.

Berg, L. 1983. Effects of short-term exposure to suspended sediment on the behavior of juvenile coho salmon. M.S. Thesis, University of British Columbia, Vancouver, Canada.

Berg, L. 1982. The effect of exposure to short-term pulses of suspended sediment on the behavior of juvenile salmonids. Pages 177-196 *in* G. Hartman (ed). Proceedings of the Carnation Creek workshop, a 1- year review. Department of Fisheries and Oceans, Nanimo, B.C., Canada.

Berg, L. and T. G. Northcote. 1985. Changes in territorial, gill-flaring and feeding behavior in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. *Canadian Journal of Fisheries and Aquatic Sciences* **42**, 1410-1417.

Bergstedt, L. C. and E. P. Bergersen. 1997. Health and movements of fish in response to sediment sluicing in the Wind River, Wyoming. *Canadian Journal of Aquatic Science* **54**, 312-319.

Berry, W., N. Rubinstein, and B. Melzian. 2003. The biological effects of suspended and bedded sediment (SABS) in aquatic systems: a review. Internal Report to US EPA, Office of Research and Development, National Health and Environmental Effects Laboratory, Narragansett, RI. August 20, 2003.

Birtwell, I.K., G. F. Hartman, B. Anderson, D. J. McLeay, and J. G. Malick. 1984. A brief investigation of Arctic grayling (*Thymallus arcticus*) and aquatic vertebrates in the Minto Creek Drainage, Mayo, Yukon Territory: an area subjected to placer mining. *Canadian Technical Report of Fisheries and Aquatic Sciences* No**. 1287**.

Bisson, P. A. & R. E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. *North American Journal of Fisheries Management* **4**, 371-374.

Blaber, S.J.M. and T. G. Blaber. 1980. Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of Fisheries Biology* **17**, 143-162.

Boehlert, G.W. 1984. Abrasive effects of Mount Saint Helens ash upon epidermis of yolk sac larvae of Pacific herring (*Clupea harengus pallassi*). *Marine Environmental Research* **12**, 113-126.

Boehlert, G. W. and J. B. Morgan. 1985. Turbidity enhances feeding abilities of larval Pacific herring, *Clupea harengus pallasi. Hydrobiologia* **123**, 161-170.

Boehlert, G. W., J. B. Morgan, and M. M. Yoklavich. 1983. Effects of volcanic ash and estuarine sediment on the early life history stages of Pacific herring (*Clupea harengus pallassi*). Prepared for the Bureau of Reclamation, Washington D.C. Mt. St. Helens Research and Development Program. Final Completion Report. October 1983.

Boehmer, R., A. Westnest, and D. Cook. 1975. Effects of suspended marine sediment on selected commercially-valuable fish and shellfish of Massachusetts. Proceedings of the 7th Annual Offshore Technology Conference, Dallas, Texas. Paper Number OTC 2161.

Bonner, T.H. & Wilde, G.R. 2002. Effects of turbidity on prey consumption by prairie stream fishes. *Transactions of the American Fisheries Society* **131,** 1203-1208.

Borgström, R., A. Brabrand, and J. T. Solheim. 1992. Effects of siltation on resource utilization and dynamics of alloptric brown trout, *Salmo trutta*, in a reservoir. *Environmental Biology of Fishes* **34**, 247-1992.

Boubée, J. A. T., T. L. Dean, D. W. West, and R. F. G. Barrier. 1997. Avoidance of suspended sediment by the juvenile migratory stage of six New Zealand native fish species. *New Zealand Journal of Marine and Freshwater Research* **31**, 61-69.

Brannon, E.L., Whitman, R.P. and Quinn, T.P. 1981. Report on the influence of suspended volcanic ash on the homing behavior of adult Chinook salmon (*Oncorhynchus tshawytscha*). Final Report to Washington State University, Washington Water Research Center, Pulman, WA.

Breck, J. E. 1993. Foraging theory and piscivorous fish: are forage fish just big zooplankton? *Transactions of the American Fisheries Society* **122**, 902-911.

Breitburg, D. L. 1988. Effects of turbidity on prey consumption by striped bass larvae. *Transactions of the American Fisheries Society* **117**, 72-77.

Bristow, B. T. and R. C. Summerfelt. 1994. Performance of larval walleye cultured intensively in clear and turbid water. *Journal of the World Aquaculture Society* **25**, 454-464.

Brungs, W. A. and G. W. Bailey. 1966. Influence of suspended solids on the acute toxicity of endrin to fathead minnow. Pages 4-12 in *Proceedings of the 21st Purdue Industrial Waste Conference.* Purdue University, Lafayette, Indiana.

Bruton, M. N. 1985. The effects of suspensoids on fish. *Hydrobiologia* **125**: 221-241.

Buchanan, P. A. 2008. U.S.G.S., Sacramento, California. Provided Figure 2, via email, to the author, September 2008.

Buchanan, P.A. and N. K. Ganju. 2005. Summary of suspended-solids concentration data, San Francisco Bay, California, water year 2003. U.S.G.S. Open File Report Data Series 113.

Buchanan, P.A. and N. K. Ganju. 2004. Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 2002. U.S.G.S. Open File Report No. 04-1219.

Buchanan, P.A. and N. K. Ganju. 2003. Summary of suspended-sediment concentration data, San Francisco Bay, California, Water Year 2001. U.S.G.S. Open File Report No. 03-312.

Buchanan, P.A. and N. K. Ganju. 2002. Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 2000. U.S.G.S. Open File Report No. 02-146.

Buchanan, P.A. and M. A. Lionberger. 2007. Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 2005. U.S.G.S. Open File Report Data Series 282.

Buchanan, P.A. and M. A. Lionberger. 2006. Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 2004. U.S.G.S. Open File Report Data Series 226.

Buchanan, P.S. and C. S. Ruhl. 2001. Summary of suspended-sediment concentration data, San Francisco Bay, California, Water Year 1999. U.S.G.S. Open File Report 01-100.

Buchanan, P. S. and C. A. Ruhl. 2000. Summary of suspended-solids concentration data in San Francisco Bay, California, Water Year 1998. U.S.G.S. Open File Report 00-88. Sacramento, California.

Buchanan, P.A. and D. H. Schoellhamer. 1999. Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 1997. U.S.G.S. Open File Report No. 99-189.

Buchanan, P.S. and D. H. Schoellhamer. 1998. Summary of suspended solids concentration data, San Francisco Bay, California, Water Year 1996. U.S.G.S. Open File Report No. 98-175.

Buchanan, P.S. and D. H. Schoellhamer. 1996a. Summary of suspended solids concentration data San Francisco Bay, California, Water Year 1995. U.S.G.S. Open File Report No. 96-591.

Buchanan, P.S. and D. H. Schoellhamer. 1996b. Summary of suspended solids concentration data, San Francisco Bay, California, Water Years 1992 and 1993. U.S.G.S. Open File Report No. 94-543.

Buchanan, P.S., D. H. Schoellhamer, and R. G. Shepline. 1996. Summary of suspended solids concentration data, San Francisco Bay, California, Water Year 1994. U.S.G.S. Open File Report No. 95-776.

Buck, D. H. 1956. Effects of turbidity on fish and fishing. Pages 249-261 i*n* Transactions of the Twenty-First North American Wildlife Conference.

Burczynski, J. 1991. Hydroacoustic survey of fish distribution and reaction to dredge disposal activities in San Francisco Bay. Final Report. BioSonics, Inc., Seattle, Washington. February 21, 1991. 19 pp + Appendices.

Burkhead, N. N. and H. L. Jelks. 2001. Effects of suspended sediment on the reproductive success of the tricolor shiner, a crevice-spawning minnow. *Transactions of the American Fisheries Society* **130**, 959-968.

Cairns, J., Jr. 1968. Suspended solids standards for the protection of aquatic organisms. Second Purdue Industrial Waste Conference. Purdue University Engineering Bulletin **129**, 16-27.

Campbell, H.J. 1954. The effect of siltation from gold dredging on the survival of rainbow trout and eyed eggs in Powder River, Oregon. *Bulletin of the Oregon State Game Commission*, Portland, Oregon.

Canadian Council of Ministers of the Environment. 1984. Canadian water quality guidelines, chapter 3: Freshwaters and aquatic life. Task Force on Water Quality Guidelines, Environment Canada, Ottawa, Ontario.

Carlson, R. W. 1984. The influence of pH, dissolved oxygen, suspended solids or dissolved solids upon ventilator and cough frequencies in the bluegill *Lepomis macrochirus* and brook trout *Salvelinus fontinalis*. *Environmental Pollution, Series A,* **34**, 149-169.

Cederholm, C.J., Reid, L.M. Reid & Salo, E.O. 1981. Cumulative effects of logging and road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington. Pages 38-74 in Salmon-spawning Gravel: a Renewable Resource in the Pacific Northwest. Washington State University, Washington Water Resource Center, Pullman, Washington. Report 39.

Chesapeake Biological Laboratory. 1970. Ross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Final Report to the U.S. Bureau of Sport Fisheries and Wildlife (Contract 14-16-0005-2096). Reference Number. 70-3.

Chesney, E.J. Jr. 1989. Estimating the food requirements of striped bass larvae *Morone saxatilis*: effects of light, turbidity and turbulence. *Marine Ecological Progress Series* **53**, 191-200.

Chiasson, A.G. 1993a. The effects of suspended sediment on rainbow smelt (O*smerus mordax*). *Canadian Journal of Zoology* **71**, 2419-2424.

Chiasson, A.G. 1993b. The effects of suspended sediment on ninespine stickleback, *Pungitius pungitius* and golden shiner, *Notemigonus crysoleucas*, in a current of varying velocity. *Environmental Biology of Fishes* **37**, 283-295.

Clarke, D. G. 2008. US Army Engineer Research and Development Center Dredging Operations Technical Support Program, Vicksburg, Mississippi. Email and phone communications to author.

Clarke, D. G. and D. Wilber. 2008. Compliance monitoring of dredging-induced turbidity: defective designs and potential solutions. Pages 129-142 *in* WEDA Proceedings XXVIII Technical Conference and 39th Texas A & M Dredging Seminar. June 8-11, 2008. St. Louis, Missouri.

Clarke, D. G. and D. H Wilber. 2000. Assessment of potential impacts of dredging operations due to sediment resuspension. DOER Tech. Notes Collection (ERDC TN-DOER-E9). U.S. Army Corps Engineer Research and Development Center, Vicksburg, MS. May 2000. 14 pages.

Clarke, D., A. Martin, C. Dickerson and D. Moore. 2006. Suspended sediment plumes associated with knockdown operations at the Port of Redwood City, California. Pages 277-296 *in* Western Dredging Association Proceedings XXVI, Technical Conference and 38th Texas A and M Dredging Seminar, June 25-28, San Diego, California.

Clarke, D., A. Martin, C. Dickerson and D. Moore. 2005. Suspended sediment plumes associated with mechanical dredging at the Port of Oakland, California. Pages 187-201 *in* Western Dredging Association Proceedings XXV, Technical Conference and 37th Texas A and M Dredging Seminar, June 19-22, 2005, New Orleans, Louisiana.

Clarke, D., Reine, K.J. Dickerson, C. and Garman, G. 2002. Distribution of fishes in the vicinity of dredging operations in the James River, Virginia. *Proceedings of the Third Specialty Conference on Dredging and Dredged Material Disposal*, May 5-8, 2002, Orlando, Florida. Published by the American Society of Civil Engineers.

Cloern, J. E. 1996. Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California. *Review Geophysical* **34**, 127-168.

Colby, D. and D. Hoss. 2004. "Larval Fish Feeding Responses to Variable Suspended Sediment and Planktonic Prey Concentrations," DOER-E16, U.S. Army Engineer Research and Development Center, Vicksburg, MS. ERDC TN-DOER-E16. September 2004. 10 pages.

Confer, J. L., and P. I. Blades. 1975. Omnivorous zooplankton and plantivorous fish. *Limnology and Oceanography* **20**, 571-579.

Confer, J. L., G. L. Howick, M. H. Corzette, S. L. Kramer, S. Fitzgibbons, and I. Landesberg. 1978. Visual predation by planktivores. *Oikos* **31**, 27-37.

Connor, M., J. Hunt and C. Werme. 2005. Potential impacts of dredging on Pacific herring in San Francisco Bay. White Paper. Final. Prepared for the U.S. Army Corps of Engineers, South Pacific Division by the. San Francisco Estuary Institute. 94 pages.

Conomos, T. J. and D. H. Peterson. 1977. Suspended-particle transport and circulation in San Francisco Bay, an overview. Pages 82-97 *in* Estuarine Processes, v. 2. Academic Press, New York.

Cordone, A. & Kelley, D.W. 1961. The influence of inorganic sediment on aquatic life of streams. *California Fish and Game*, **47**, 189-228.

Cronin, L. E. 1970. "Summary, conclusions and recommendations," (ed. E. Cronin.)., Gross physical and biological effects of overboard spoil disposal in Upper Chesapeake Bay. Report. Number 3. University Maryland, Natural Res. Institute. Page 1-6.

Crouse, M.R., Callahan, C.A., Malueg, K. W. & Dominguez, S.E.. 1981. Effects of fine sediment on Life of juvenile coho salmon in laboratory streams. *Transactions of the American Fisheries Society* **110**, 281-286.

Crowl, T.A. 1989. Effects of crayfish size, orientation, and movement on the reactive distance of largemouth bass foraging in clear and turbid water. *Hydrobiologia* **183**,133-140.

Cyrus, D. P. & Blaber, S. J. 1992. Turbidity and salinity in a tropical northern Australia estuary and their influence on fish distribution. *Estuarine, Coastal and Shelf Science* **35,** 545-563.

Cyrus, D. P. & Blaber, S.J. 1987a The influence of turbidity on juvenile marine fishes in estuaries. Part 1. Field studies at Lake St. Lucia South Africa on the Southeastern coast of Africa. *Journal of Experimental Marine Biology and Ecology* **109**, 53-70.

Cyrus, D. P. and S. J. M. Blaber. 1987b The influence of turbidity on juvenile marine fishes in estuaries. Part 2. Laboratory studies, comparison with field data and conclusions. *Journal of Experimental Marine Biology and Ecology* **109,** 71-91.

Cyrus, D. P. & Blaber, S. J. 1987c The influence of turbidity on juvenile marine fishes in the estuaries if Natal, South Africa. *Continental Shelf Research Journal* **7**, 1411-1416.

Dadswell, M.J., Melvin, G.D. and Williams, P.J. 1983. Effect of turbidity on the temporal and spatial utilization of the inner Bay of Fundy by American shad (*Alosa sapidissima*) (Pisces: Clupeidae) and its relationship to local fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **40** (suppl. 1), 322-330.

De Graaf, G. J., A. F. Born, A. M. K. Uddin, and S. Huda. 1999. Larval fish movement in the River Lohajang, Tangail, Bangladesh. *Fisheries Management and Ecology* **6**, 109-120.

De Robertis, A., C. H. Ryer, A. Veloza, and R. D. Brodeur. 2003. Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences* **60**, 1517-1526.

Doan, K. H. 1941. Relation of sauger catch to turbidity. *Ohio Journal of Science* **41**, 449-452.

Doeg, T. J. and J. D. Koehn. 1994. Effects of draining and silting a small weir on downstream fish and macroinvertebrates. *Regulated Rivers Research & Management* **9**, 263-277.

Dörgeloh, W. G. 1995. Fish distribution in relation to turbidity gradients in a man-made lake, Sterkfontein Dam (South Africa). *Water South Africa* **21**, 95-99.

Doudoroff, P. 1957. Suspended solids (turbidity). Pages 416-417 *in* M. E. Brown (ed), The Physiology of Fishes, Volume 2, Academic Press, New York, New York. 526 pp.

Dovel, W. L. 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay, Project E, fish and eggs and larvae. Pages 42-49 *in* NRI Special Report No. 3, Chesapeake Biological Laboratory, Solomon, Maryland, to the Bureau of Sport fisheries and Wildlife, U. S. Department of the Interior.

Eccles, D.H. 1986. Diet of the cyprinid fish *Barbus aeneus* (Burchell) in the P.K. le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. *South African Journal of Zoology*. **21**, 257-263.

Edwards, C.J. 1993. A review of aquatic impact associated with turbidity. Pages 109-112 *in* Proceedings of a Technical Workshop on Sediment, February 3-7, 1992, Corvallis, Oregon. Terrene Institute, Washington, D.C.

EIFAC (European Inland Fisheries Advisory Commission). 1965. Water quality criteria for European freshwater fish: report on finely divided solids and inland technical fisheries (EIFAC).

Ellis, M.M. 1944. Water purity standards for fresh-water fishes. *U.S. Fish and Wildlife Service Special Scientific Report* **2**, 18 pp.

Ellis, M. M. 1936. Erosion silt as a factor in aquatic environments. *Ecology* **17**, 29-42.

Emmett, R. L., R. D. Brodeur, and P. M. Orton. 2004. The vertical distribution of juvenile salmon (*Oncorhynchus* spp.) and associated fishes in the Columbia River plume. *Fisheries Oceanography* **13**, 392-402.

Emmett, R. L., G. T. McCabe, Jr., and W. D Muir. 1990. Effects of the 1980 Mt. St. Helens eruption on Columbia River estuarine fishes: implications for dredging in Northwest estuaries. Pages 74-91 *in* Simenstad, C. A. (ed). Effects of dredging on anadromous Pacific Coast fishes. Workshop Proc., Seattle, September 8-9. 1988. 160 pp. Washington Sea Grant Program, University of Washington, Seattle, Washington.

Erman, D. and F. K. Ligon. 1988. Effects of discharge fluctuation and the addition of fine sediment on stream fish and macroinvertebrates below a water-filtration facility. *Environmental Management* **12**, 85-97.

Everest, F. H., R. L. Beschta, J. C. Scrivener, K.V. Koski, J.R. Sedell, and C. J.Cederholm.. Fine sediment and salmonid production: a paradox. Pages 98-142 *in* Streamside Management: Forestry and fishery Interactions, Institute of Forest Research, University of Washington, Seattle, Washington.

Farrell, A. P., A. K. Gamperl and I. K. Birtwell. 1998. Prolonged swimming, recovery and repeat swimming performance of mature sockeye salmon *Oncorhynchus nerka* exposed to moderate hypoxia and pentachlorophenol. *Journal of Experimental Biology* **201**, 2183-2193.

Federal Register. 2006a. Endangered and Threatened Species: Final Listing Determinations for 10 Distinct Population Segments of West Coast Steelhead; Final Rule. **71**, 834-862.

Federal Register. 2006b. Endangered and Threatened Wildlife and Plants: Threatened status for Southern Distinct Population Segment of North American Green Sturgeon. Final Rule. **71**, 17757-17766

Federal Register. 2005a. Endangered and Threatened Species; Final listing for 16 ESUs of West Coast Salmon, and Final 4(d) Protective Regulations for Threatened Salmonid ESUs. 7**0**, 3716-37204.

Federal Register. 2005b. Endangered and Threatened Species; Designation of Critical Habitat for Seven Evolutionary Significant Units of Pacific Salmon and Steelhead in California; Final Rule. **70**, 52488-52627.

Federal Register. 2004. Endangered and Threatened Species; Establishment of Species of Concern List, Addition of Species to Species of Concern List, Description of Factors for Identifying Species of Concern, and Revision of Candidate Species List under the Endangered Species Act. **69**, 19975-19979.

Federal Register. 1999. Endangered and Threatened Species; Threatened Status for two Chinook salmon Evolutionary Significant Units (ESUs) in California; Final Rule **64,** 50394-50415

Federal Register. 1994a. Endangered and Threatened Species; Status of Sacramento River Winter-Run Chinook Salmon **59**, 440-450.

Federal Register. 1994b. Endangered and Threatened Wildlife and Plants; Final Critical Habitat Determination for the Delta Smelt. 59, 852-862.

Federal Register. 1993a. Designated Critical Habitat: Sacramento River Winter-Run Chinook Salmon. **58**, 33212-35219.

Federal Register. 1993b. Endangered and Threatened Wildlife Species; Determination Threatened Status for Delta Smelt; Final Rule: March 5, 1993.

Fiksen, Ø. D. L. Aksnes, M. H. Flyum, and J. Giske. 2002. The influence of turbidity on Life and survival of fish larvae: a numerical analysis. *Hydrobiologia* **484**, 49-59.

Gadomski, D. M. and M. J. Parsley. 2005. Effects of turbidity, light level, and cover on predation of white sturgeon larvae by prickly sculpin. *Transactions of the American Fisheries Society* **134**, 369-374.

Gardner, M.B. 1981. Effects of turbidity on feeding rates and selectivity of bluegills. *Transactions of the American Fisheries Society* **110**, 446-450.

Gibson, A.M. 1933. Construction and operation of a tidal model of the Severn Estuary, His Majesty's Stationary Office, London, England (cited in Newcombe and Jensen, 1996).

Goldes , S.A. 1983. Histological and ultrastructural effects of the inert clay kaolin on the gills of rainbow trout (*Salmo gairdneri* Richardson). M.S. Thesis, University of Guelph, Guelph, Ontario, CA.

Goldes, S.A., H.W. Ferguson, P.Y. Daoust, and R.D. Moccia. 1986. Phagocytosis of the inert suspended clay kaolin by the gills of rainbow trout, *Salmo gaidneri* Richardson. *Journal of Fish Diseases* **9**, 147-151.

Goodwin, P. and R. A. Denton. 1991. Seasonal influences on the sediment transport characteristics of the Sacramento River. Proceedings of the Institute of Civil Engineers 91 (part 2), 163-297.

Government of Canada and the Province of British Columbia. 1991. Environmental effects of dredging. Pages 60-61 in Navigation, Dredging and environment in the Fraser River estuary, navigation and dredging workgroup report, Fraser River Estuary Management Program, Vancouver, B.C.

Gradall, K. S. and W. A. Swenson. 1982. Responses of brook trout and creek chubs to turbidity. *Transactions of the American Fisheries Society* **111**, 392-395.

Granqvist, M. and J. Mattila. 2004. The effects of turbidity and light intensity on the consumption of mysids of juvenile perch (*Perca fluviatilis* L.). *Hydrologia* **514,** 93-101.

Gray, J. R. and G. D. Glysson. 2002. "Synopsis of outcomes from the federal interagency workshop on turbidity and other sediment surrogates." http://water.usgs.gov/osw/techniques/turbidity_blacksburg.pdf

Grecay, P. A. and T. E. Targett. 1996. Effects of turbidity, light level and prey concentration on feeding of juvenile weakfish *Cynoscion regalis*. *Marine Ecology Progress Services* **131**, 11-16.

Gregory, R. 1994. The influence of ontogeny, perceived risk of predation and visual ability on the foraging behavior of juvenile Chinook salmon. Pages 271-284 *in* D.J. Stouder, K. L. Fresh, and R. J. Feller, editors. Theory and application in fish feeding ecology. Belle W. Baruch Library in Marine Science 18.

Gregory, R. S. 1993. Effect of turbidity on the predator avoidance behavior of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Science* **50**, 241-246.

Gregory, R. S. and C. D. Levings. 1998. Turbidity reduces predation on migration juvenile Pacific salmon. *Transactions of the American Fisheries Society* **127**, 275-285.

Gregory, R. S. and T. G. Northcote. 1993. Surface, planktonic, and benthic foraging by juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in turbid laboratory conditions. *Canadian Journal of Fisheries and Aquatic Science* **50**, 233-240.

Gregory, R.S., J.A. Servizi, and D.W. Martens. 1993. Comment: utility of the stress index for predicting suspended sediment effects. *North American Journal of Fisheries Management* **13**, 868-873.

Gren, G. G. 1976. Hydraulic dredges, including boosters. Pages 115-124 in P. A. Krenkel, J. Harrison, and J. C. Burdick III, editors. Proceedings of the specialty Conference on Dredging and its Environmental Effects. American Society of Civil Engineers, New York, New York.

Griffin, L. E. 1938. Experiments on the tolerance of young trout and salmon for suspended sediment in water. Pages 28-31 *in* Placer mining on the Rogue River, Oregon, in its relation to the fish and fishing in that stream.. Oregon Department of Geology and Mineral Industries. Bull 10, Appendix B.

Gunther, A., J. Davis, J. O'Connor, D. Phillips, K. Kramer, B. Richardson, and P. Williams. 1990. *Status and Trends Report on Dredging and Waterway Modification in the San Francisco Estuary.* Report to the San Francisco Estuary Project, Oakland, California. 250 pp.

Guthrie, D. M. 1986. Role of vision in fish behavior. In *The behavior of Teleost Fishes* (Pitcher, T. J., ed), pp 75-113. London: Croom Helm.

Hamilton, J.D. 1961. The effect of sand-pit washings on a stream fauna. *Internationale Vereinigung für theoretische und angewandte Limnologie Verhandlugen* **14**, 435-439.

Hatin, D., S. Lachance, and D. Fournier. 2007. Effect of dredged sediment deposition on use by Atlantic sturgeon and lake sturgeon at an open-water disposal site in the St. Lawrence Estuarine Transition Zone. *American Fisheries Society Symposium* **56**, 235-255.

Hayes, J.W., and M. J. Rutledge. 1991. Relationship between turbidity and fish diets in Lakes Waahi and Whangape, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **25**, 297-304.

Hayes, J.W., M.J. Rutledge, B.L. Chisnall, and F.J. Ward. 1992. Effects of elevated turbidity on shallow lake fish communities. *Environmental Biology of Fishes* **36**, 149-168.

Hecht, T. and C. D. van der Lingen. 1992. Turbidity-induced changes in feeding strategies of fish in estuaries. *South African Journal of Zoology* **27**(3), 95-107.

Herbert, D.W. 1980. Cited in Newcombe and Jensen, 1996. Personal Communication to J. Alabaster and R. Lloyd.

Herbert, D.W.M., J.S. Alabaster, M.C. Dart, and R. Lloyd. 1961. The effect of china-clay wastes on trout streams. *International Journal of Air and Water Pollution* **5**, 56-74.

Herbert, D. W. and C. Merkens. 1961. The effect of suspended mineral solids on the survival of trout. *International Journal of Air and Water Pollution*. **5**, 46-55.

Herbert, D.W.M. and J.M. Richards. 1963. The Life and survival of fish in some suspensions of solids of industrial origin. *International Journal of Air and Water Pollution*. **7**, 297-302

Herbert, D.W.M and A. C. Wakeford. 1962. The effect of calcium sulphate on the survival of rainbow trout. *Water Waste Treatment Yearly* **8**, 608-609.

Hesse, L.W. and B.A. Newcombe. 1982. Effects of flushing Spencer Hydro on water quality, fish, and insect fauna in the Niobrara River, Nebraska. *North American Journal of Fisheries Management* **2**, 45-52.

Hirsch, N.D., L. H. DiSalvo, and R. Peddicord. 1978. Effects of dredging and disposal on aquatic organisms. Synthesis of Research Result, Dredging Materials Research Progress Technical Report. DS-78-5. 41 pp. Waterways Experimental Station, Vicksburg, Mississippi. August.

Horkel, J.D. and W.D. Pearson. 1976. Effects of turbidity on ventilation rates and oxygen consumption of green sunfish, *Lepomis cyanellus*). *Transactions of the American Fisheries Society* **105**, 107-113.

Horppila, J., A. Liljendahl-Nurminen, and T. Malinen. 2004. Effects of clay turbidity and light on the predator-prey interaction between smelts and chaoborids. *Canadian Journal of Aquatic Science* **61**, 1862-1870

Hughes, G.M. 1975. Coughing in the rainbow trout (*Salmo gairdneri*) and the influence of pollutants. *Revue Suisse de Zoologie* **82**, 47-64.

Humborstad, O-Børre, T. Jørgensen, and S. Grotmol. 2006. Exposure of cod *Gadus morhua* to resuspended sediment: an experimental study of the impact of bottom trawling. *Marine Ecology Progress Series* **309**, 247-254.

Johnson, J.E. and R.T. Hines. 1999. Effect of suspended sediment on vulnerability of young razorback suckers to predation. *Transactions of the American Fisheries Society* **128**, 648-655.

Johnston, D. and D. J. Wildish. 1982. Effect of suspended sediment on feeding by larval herring (*Clupea harengus harengus* L.). *Bulletin of Environmental Contamination and Toxicology* **29**, 261-267.

Johnston, D. and D. J. Wildish. 1981. Avoidance of dredge spoil by herring (*Clupea harengus harengus* L.). *Bulletin of Environmental Contamination and Toxicology*. **26**, 307-314.

Jordan, D. S. 1889. Report of explorations in Colorado and Utah during the summer of 1889, with an account of the fishes found in each of the river basins examined. *U.S. Fisheries Commission Bulletin*. **9**, 1-40.

Kerr, S. J. 1995. Silt turbidity and suspended sediment in the aquatic environment: an annotated bibliography and literature review. Ontario Ministry of Natural Resources, Southern Region Science & Technology Transfer Unit Technical Report TR-008. 277 pages.

Kiørboe, T., E. Frantsen, C. Jensen and G. Sorensen. 1980. Effects of suspended sediment on development and hatching of herring (*Clupea harengus*) eggs. *Estuarine, Coastal, and Shelf Science* **13**, 107-111.

Kroger, R. L. and J. F. Guthrie. 1972. Effect of predators on juvenile menhaden in clear and turbid estuaries. *Marine Fisheries Review* **34**, 78-80.

Krone, R. B. 1979. Sedimentation in the San Francisco Bay system. Pages 347-385 *in* Conomis, T. J. (Ed), San Francisco Bay. The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Lake, R.G., and S.G. Hinch. 1999. Acute effects of suspended sediment angularity on juvenile coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Science* **56**, 862-867.

Langer, O.E. 1980. Effects of sedimentation on salmonid stream life. Environment Canada, Environmental Protection Service, unpublished report, North Vancouver, British Columbia.

LaSalle, M. W. 1990. Physical and chemical alterations associated with dredging: an overview. Pages 1-12 in Simenstad, C. A. (ed). Effects of dredging on anadromous Pacific Coast fishes. Workshop Proceedings, Seattle, September 8-9. 160 pp. Washington Sea Grant Program, University of Washington, Seattle, Washington.

Lawrence, M. and E. Scherer. 1974. Behavioral responses of whitefish and rainbow trout to drilling fluids. *Canada Fisheries and Marine Service Technical Report* **502**.

LeGore, R.S. and D.M. DesVoigne. 1973. Absence of acute effects on threespine sticklebacks (*Gasterosteus aculeatus*) and coho salmon (*Oncorhynchus kisutch*) exposed to resuspended harbor sediment contaminants. *Journal Fisheries Research Board of Canada* **30**, 1240-1242.

Lehtiniemi, M. J. Engstrom-Ost, and M. Viitasalo. 2005. Turbidity decreases anti-predator behavior in pike larvae, *Esox lucius*. *Environmental Biology of Fishes* **73**, 1-8.

Levine-Fricke. 2004. Framework for assessment of potential effects of dredging on sensitive fish species in San Francisco Bay. Prepared for the U.S. Army Corps of Engineers, San Francisco. Final Report. August 5, 2004. 105 pages + Appendices.

Liepolt, R. 1961. Biologische Auswirkung der Entschlammung eines Hochgebirgsstausees in einem alpinen Fliessgewasser. *Wass. U. Abwass* **3**, 110-113.

Lloyd, D. S. 1987. Turbidity as a water quality standard for salmonid habitats in Alaska. *North American Journal of Fisheries Management* **7**, 34-45.

Lloyd, D. S. 1985. Turbidity in freshwater habitats of Alaska: a review of published and unpublished literature relevant to the use of turbidity as a water quality standard. Alaska Department of Fish and Game, Habitat Division, Report 85, Part 1, Juneau, Alaska

Lloyd, D.S., J.P. Koenings, and J.D. LaPerriere. 1987. Effects of turbidity in fresh waters of Alaska. *North American Journal of Fisheries Management* **7**, 18-33.

LTMS. 1998. Long-term Management Strategy for Bay Area Dredged Material Final Environmental Impact Statement/Environmental Impact Report. LTMS, San Francisco.

Lythgoe, J. N. 1979. The Ecology of Vision. Oxford University Press, Oxford.

Lythgoe, J. N. 1968. Visual pigments and visual range underwater. *Vision Research* **8**, 997-1012.

Martens, D. W. and J. A. Servizi. 1993. Suspended sediment particles inside gills and spleens of juvenile Pacific salmon (*Oncorhynchus* spp.*). Canadian Journal of Fisheries and Aquatic Science* **50**, 586-590.

Matthews, W. J. 1984. Influence of turbid inflows on vertical distribution of larval shad and freshwater drum. *Transactions of the American Fisheries Society* **113**, 192-198.

Mazeud, M. M., F. Mazeaud, and E.M. Donaldson. 1977. Primary and secondary effects of stress in fish: some new data with a general review. *Transactions of the American Fisheries Society*. **106**, 201-212.

Mazur, M. M. and D. A. Beauchamp. 2003. A comparison of visual prey detection among species of piscivorous salmonids: effects of light and low turbidities. *Environmental Biology of Fishes* **67**, 397-405.

McCarthy, J.C., T. E. Pyle, and G. M. Griffin. 1996. Light transmissivity, suspended sediment, and the legal definition of turbidity. *Estuarine and Coastal Marine Science* **2**, 291-299.

McFarland, V. A. and R. K. Peddicord. 1980. Lethality of a suspended clay to a diverse selection of marine and estuarine macrofauna. *Archives of Environmental Contamination and Toxicology* **9**, 733-741.

McKee, L., N. K. Ganju, and D. H. Schoellhamer. 2006. Estimates of suspended sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California. *Journal of Hydrology* **323**, 335-352.

McLeay, D.J., I.K. Birtwell, G.F. Hartman, and G.L. Ennis. 1987. Responses of Arctic grayling (*Thymallus arcticus*) to acute and prolonged exposure to Yukon placer mining sediment. *Canadian Journal of Fisheries and Aquatic Science* **44**, 658-673.

McLeay, D.J., G.L. Ennis, I.K. Birtwell, and G.F. Hartman. 1984. Effects on Arctic grayling (*Thymallus acticus*) of prolonged exposure to Yukon placer mining sediment: a laboratory study. *Canadian Technical Report of Fisheries and Aquatic Sciences* No. 1241. 96 pages.

MEC. 2003. Port of Oakland outer harbor maintenance dredging operations: spatial characterization of suspended sediment plumes during dredging operations through acoustic monitoring. Final report. Prepared for U.S. Army Corps of Engineers, San Francisco District.

MEC. 1997. An investigation into the turbidity plume associated with the dredge activities in the Port of Oakland Estuary. Prepared for the Port of Oakland. September 1997. 30 pages

MEC. 1990. Results of the Larkspur Landing Dredge Disposal Monitoring Program. Report to Golden Gate Bridge District. November, 1990. 50 pp.

Menzel, B.W., J.B. Barnum, and L.M Antosch. 1984. Ecological alterations of Iowa prairie-agricultural streams. *Iowa State Journal of Research* **59**, 5-30.

Mesa, M. G. 1994. Effects of multiple acute stressors on the predator avoidance ability and physiology of juvenile Chinook salmon. *Transactions of the American Fisheries Society* **123**, 786-793.

Messieh, S. N., D. J. Wildish, and R. H. Peterson. 1981. Possible impact from dredging and spoil disposal on the Miramich Bay herring fishery. *Canadian Technical Report on Fisheries and Aquatic Sciences* **1008**, 33 pages. April.

Minello, T.J., R. J. Zimmerman, and E.X.Martinez. 1987. Fish predation on juvenile brown shrimp, *Penaes aztecus* Ives: effects of turbidity and substratum on predation rates. *Fisheries Bulletin* **85**, 59-70.

Miner, J.G and R.A. Stein. 1996. Detection of predators and habitat choice by small bluegills: effects of turbidity and alternative prey. *Transactions of the American Fisheries Society* **125**, 97-103.

Miner, J.G and R.A. Stein. 1993. Interactive influence of turbidity and light on larval bluegill (*Lepomis macrochirus*) foraging. *Canadian Journal of Fisheries and Aquatic Science* **50**, 781-788.

Miner, J.G and R.A. Stein. 1988. Suspended sediment affect bluegill habitat choice: apparent risk declines but predation increases. *Bulletin of the Ecological Society of America* **69**, 233-234.

Monteleone, D. M. and E. D. Houde. 1992. Vulnerability of striped bass Morone saxatilis Waldbaum eggs and larvae to predation by white perch *Morone americana* . *Journal of Experimental Marine Biology and Ecology* **158**, 93-104.

Moore, E. 1937. The effect of silting on the productivity of waters. Pages 658-661 *in* Transactions of the Second North American Wildlife Conference.

Moore, E. 1932. Stream pollution as its affects fish life. *Sewage Works Journal* **4,** 59-165.

Moore, P.E. 1978. Inorganic particulate suspensions in the sea and their effects on marine animals. *Oceanography and Marine Biology Annual Review* **15**, 225-363

Morgan, J. D. and C. D. Levings. 1989. Effects of suspended sediment on eggs and larvae of lingcod (*ophiodon elongates*), Pacific herring (*Clupea harengus pallassi*), and surf smelt (*Hypomesus pretiosus*). *Canadian Technical Report of Fisheries and Aquatic Sciences* **1729.**

Morgan, R. P., II, V. J. Rasin, Jr., and L. A. Noe. 1983. Sediment effects on eggs and larvae of striped bass and white perch. *Transactions of the American Fisheries Society* **112**, 220-224.

Morgan, R.P, II, J.V. Raisin, Jr., and L.A. Noe. 1973. Effects of suspended sediment on the development of eggs and larvae of striped bass and white perch, Appendix 11. Final Report to U.S. Army Corps of Engineers, Contract DACW61-71-C0062, Philadelphia, Pennsylvania.

Mortensen, D.G., B.P. Snyder, and E.O. Salo. 1976. An analysis of the literature on the effects of dredging on juvenile salmonids. Prepared for the Department of the Navy, FRI-UW-7605, Bremerton, Washington. March 15, 1976. 37 pp.

Morton, J. W. 1977. Ecological effects of dredging and dredge spoil disposal: a literature view. U.S. Dept. Interior, Fish and Wildlife Service Tech. Paper Number 94, Washington, D.C. 33 pages.

Muncy, R. J., G. J. Atchison, R. V. Bulkley, B.W. Menzel, L. G. Perry, and R.C. Summerfelt. 1979. Effects of suspended solids and sediment on reproduction and early life of warmwater fishes: a review. Corvallis Environmental Research Laboratory, U.S. EPA, Corvallis, Oregon. EPA-600/3-79-042. April 1979. 100 pages.

Neumann, D. A., J. M. O'Oonnor, J. A. Sherk, and K. V. Wood. 1982. Respiratory response of striped bass (*Morone saxatilis*) to suspended solids. *Estuaries* **5**, 29-39.

Neumann, D. A., J. M. O'Oonnor, and J. A. Sherk Jr. 1981. Oxygen consumption of white perch (M*orone americana*) striped bass (*M. saxatilis*) and spot (*Leiostomus xanthurus*). *Comparative Biochemistry and Physiology* **69A**, 467-478.

Neumann, D. A., J. M. O'Oonnor, J. A. Sherk, and K. V. Wood. 1975. Respiratory and hematological responses of oyster toadfish (*Opsanus tau*) to suspended solids. *Transactions of the American Fisheries Society* **104**, 775-781.

Newcomb, T.W. and T.A. Flagg. 1983. Some effects of Mt. St. Helens volcanic ash on juvenile salmon smolts. *Marine Fisheries Review* **45**, 8-12.

Newcombe, C.P. 2003. Impact assessment model for clear water fishes exposed to excessively cloudy water. *Journal of the American Water Resources Association* **39**, 529-544.

Newcombe, C. P. and J. O.T. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis of quantitative assessment of risk and impact. *North American Journal of Fisheries Management* **16**, 693-727.

Newcombe, C. P. and D. D. MacDonald. 1993. Utility of the stress index for predicting suspended sediment effects: response to comment. *North American Journal of Fisheries Management* **13**, 873-876.

Newcombe, C. P. and D. D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management* **11**, 72-82.

Newcombe, C.P., B. Shepherd, G. Hoyer, and M Ladd. 1995. Documentation of a fish kill (juvenile rainbow trout: *Oncorhynchus mykiss*) in Bellevue Creek (near Mission, Kelowna, British Columbia, Canada), caused by silty water discharge. British Columbia Ministry of Environment, Land and Parks Habitat and Protection Branch, Habitat Protection Occasional Report, Victoria, B.C.

Nichols, F. H. and M. M. Pamatmat. 1988. The Ecology of the Soft-Bottom Benthos of San Francisco: A Community Profile. Prepared for the U. S. Department of the Interior, Fish and Wildlife Service. Biological Report 85 (7.23). 73 pages.

Nichols, F. H. and J. K. Thompson. 1985. Time scales of change in the San Francisco Bay benthos. *Hydrobiologia* **192,** 121-138.

Nightingale, B. and C. Simenstad. 2001. Dredging activities: marine issues. White Paper. Prepared for Washington Department of Fish and Wildlife, Washington Department of Ecology, Washington Department of Transportation. 11 9 pages + Appendices. July 13.

Noggle, C. C. 1978. Behavioral, physiological and lethal effects of suspended sediment on juvenile salmonids. M.S. Thesis. University of Washington, Seattle. August 31, 1978. 87 pp.

O'Brien, D. P. 1987. Description of escape response of krill (Crustacea: Euphausiacea), with particular reference to swarming behavior and the size and proximity of the predator. *Journal of Crustacean Biology* **7**, 449-457.

O'Connor, J. M. 1992. Evaluation of and design for studies of sediment related bioaccumulation and effects in San Francisco Bay. Prelimin. Draft Report to Long-term Management Strategy In-Bay Studies Group. 31 pp. San Francisco Bay-Delta Aquatic Habitat. Institute, Richmond, California. September 6.

O'Connor, J. M. 1991. Evaluation of turbidity and turbidity-related effects on the biota of the San Francisco Bay-Delta Estuary. 84 pp. San Francisco Estuary Institute, Richmond, California. Report submitted to the U.S. Army Corps of Engineers, San Francisco District. April 3, 1991.

O'Connor, J.M., D. A. Neumann, and J. A. Sherk, Jr. 1977. Sublethal effects of suspended sediments on estuarine fish. Natural Resources Institute, University of Maryland, Maryland. Prepared for U.S. Army Corps of Engineers, Coastal Engineering Research Center, Virginia. Technical Report No. 77-3. February, 1977.

O'Connor, J.M., D. A. Neumann, and J. A. Sherk, Jr. 1976. Lethal effects of suspended sediment on estuarine fish. Natural Resources Institute, University of Maryland, Maryland. Prepared for U.S. Army Corps of Engineers, Coastal Engineering Research Center, Virginia. Technical Report.

Ogden Beeman and Associates, Inc. 1989. Letter Report to the United States Army Corps of Engineers, San Francisco District on sampling at Alcatraz Dredge Spoil Disposal Site in 1989.

Ogden Beeman and Associates, Inc. 1988. Letter Report to the United States Army Corps of Engineers, San Francisco District on sampling at Alcatraz Dredge Spoil Disposal Site in 1988.

O'Keefe, T. C., M. C. Brewer, and S. I. Dodson. 1998. Swimming behavior of Daphnia: its role in determining predation risk. *Journal of Plankton Research* **20**, 973-984.

Ott, A. 1984. Personal communication. Alaska Department of Fish and Game, Fairbanks. From Newcombe and Jensen, 1996, cited as personal communication in Lloyd, 1985.

Pautzke, C.F. 1938. Studies on the effect of coal washings on steelhead and cutthroat trout. *Transactions of the American Fisheries Society* **67**, 232-233

Peddicord, R.K. 1980. Direct effects of suspended sediments on aquatic organisms. Pages 501-536 (Chapter 25) *in* R. A. Baker (ed.), Contaminants and sediments, Volume 1: fate and transport, case studies, Ann Arbor Science, Ann Arbor, Michigan.

Peddicord, R.K. and V. A. McFarland. 1978. Effects of suspended dredged material on aquatic animals. Technical Report D-78-29. U.S. Army Engineer Waterways Experiment Station. July 1978. Final Report. 109 pages.

Peddicord, R.K., V. A. McFarland, D.P. Belfiori, and T. E. Byrd. 1975. Effects of suspended solids on San Francisco Bay organisms. Appendix G in Dredge Disposal Study, U.S. Army Corps of Engineers, San Francisco, California. 158 pages.

Pekcan-Hekim, Z. 2007. Effects of turbidity on feeding and distribution of fish. Academic Dissertation, Department of Biological and Environmental Sciences, University of Helsinki, Finland. June 2007. 39 pages.

Pennekamp, J.G.S. and M.P. Quaak. 1990. Impact on the environment of turbidity caused by dredging. *Terra et Aqua* **42**, April, 1990.

Peters, J. C. 1967. Effects on a trout stream of sediment from agricultural practices. *Journal of Wildlife Management* **31**, 805-812

Phillips, R.W. 1971. Effects of sediment on the gravel environment and fish production. Pages 64-74 *in* J.T. Kruger and J.D. Hall (eds.), Forest Land Uses and Stream Environments. *Continuing Education Publication*, Oregon State University, Corvallis, Oregon.

Phinney, D. E. 1982. General overview of the immediate and longer-term effects of Mount St. Helens on the salmon resources. Pages 294-299 *in* Proceedings from the conference Mt. St. Helens: effects on water resources, October 7-8, 1981. Jantzen Beach, Oregon.

Priest, W.I. 1981. The effects of dredging on water quality and estuarine organisms: a literature review. *Special Report in Applied Marine Science and Ocean Engineering*, No. 247, Virginia Institute of Marina Science, Gloucester Point, VA, 24-266.

Rathbun, R. 1889. Report upon the inquiry respecting food fishes and the fishing-grounds. *U.S. Commission of Fish and Fisheries, Annual Report* **17**, 97-171.

Redding, J. M., C. B. Schreck, and F. H. Everest. 1987. Physiological effects on coho salmon and steelhead of exposure to suspended solids. *Transactions of the American Fisheries Society* **116**, 737-744.

Redding, J.M. and C.B. Schreck. 1982. Mount. Saint Helens ash causes sublethal stress responses in steelhead trout. Pages 300-307 *in* Proceedings from the conference Mt. St. Helens: effects on water resources, October 7-8, 1981. Jantzen Beach, Oregon.

Reed, J.P., J.M. Miller, D.F.Pench, and B.Schaich. 1983. The effects of low level turbidity on fish and their habitat. *Water Resources Research Institute Report* 83-190. University of North Carolina, Chapel Hill, North Carolina. 40 pages.

Reid, S. M., M. G. Fox, and T. H. Whillans. 1999. Influence of turbidity on piscivory in largemouth bass (*Micropterus salmoides*). *Canadian Journal of Fisheries and Aquatic Science* **56**, 1362-1369.

Reilly, F.J., J.U. Clarke, V.A. McFarland, C.H. Lutz, and A.S. Jarvis. 1992. Review and analysis of the literature regarding potential impacts of dredged material disposal in central San Francisco Bay on fisheries and contaminant bioavailability. Miscellaneous Paper EL-92. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. . 99 pages.

Reynolds, J. B., R. C. Simmons, and A. R. Burkholder. 1989. Effects of placer mining discharge on health and food of Arctic grayling. *Water Resources Bulletin, American Water Resources Association,* June, 625-635.

Rich, A. A. 1983. Smolting: circulating catecholamine and thyroxine levels in coho salmon (*Oncorhynchus kisutch*). Ph.D. Dissertation, University of Washington, Seattle. 97 pages.

Rich, A. A. 1979. The use of stress to quantitate the survival potential of three strains of trout. M. S. Thesis, University of Washington, Seattle. 65 page.

Richardson, J., D. K. Rowe, and J. P. Smith. 2001. Effects of turbidity on the migration of juvenile banded kokopu (*Galaxias fasciatus*) in a natural stream. *New Zealand Journal of Marine and Freshwater Research* **35**, 191-196.

Rieger, P. W. and R. C. Summerfelt. 1997. The influence of turbidity on larval walleye behavior and development in tank culture. *Aquaculture* **159**, 19-32.

Ritchie, C. 1972. Sediment, fish, and fish habitat. *Journal of Soil and Water Conservation* **27**, 124-125.

Rogers, B.A. 1969. Tolerance levels of four species of estuarine fishes to suspended mineral solids. Master's Thesis. University of Rhode Island, Kingston.

Rosenthal, H. and F. Alderdice, 1976. Sublethal effects of environmental stressors, natural and pollution, on marine fish eggs and larve. *Journal of the Fisheries Resources Board of Canada* **33**, 2047-2065.

Rowe, D. K. and T. L. Dean. 1998. Effects of turbidity on the feeding ability of the juvenile migrant stage of six New Zealand freshwater fish species. *New Zealand Journal of Marine and Freshwater Research* **32**, 21-29.

Rowe, D. K. and A. Taumoepeau. 2004. Decline of common smelt (*Retropinna retropinna*) in turbid, eutrophic lakes in the North Island of New Zealand. *Hydrobiologia* **523,** 149-158.

Rowe, D. K., T. L. Dean, E. Williams, and J. Smith. 2003a Effects of turbidity on the ability of juvenile rainbow trout *Oncorhynchus mykiss*, to feed on limnet and benthic prey in laboratory tanks. *New Zealand Journal of Marine and Freshwater Research* **37**, 45-52.

Rowe, D. K., E. Graynoth, G. James, M. Taylor, and L. Hawke. 2003b. Influence of turbidity and fluctuating water levels on the abundance and depth distribution of small, benthic fish in New Zealand alpine lakes. *Ecology of Freshwater Fish* **12**, 216-227.

Rowe, D. K., J. Smith, and E. Williams. 2002. Effects of turbidity on the feeding ability of adult, riverine smelt (*Retropinna retropinna*) and inanga (*Galaxias maculates*) *New Zealand Journal of Marine and Freshwater Research* **36,** 143-150.

Rowe, D., M. Hicks, and J. Richardson. 2000. Reduced abundance of banded kokopu (*Galaxias fasciatus*) and other native fish in turbid rivers of North Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research* **34**, 547-558.

Ruhl, C. A. and D. H. Schhoellhamer. 2004. Spatial and temporal variability of suspended sediment concentrations in a shallow estuarine environment: *San Francisco Estuary and Watershed Science* **2**, Article 1. http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art1.

Ruhl, C. A., D. H. Schoellhamer, R. P. Stumpf, and C. L. Lindsay. 2001. Combined use of remote sensing and continuous monitoring to analyze the variability of suspended-sediment concentrations in San Francisco Bay, California. *Estuarine, Coastal, and Shelf Science* **53**, 801-812.

Ryan, P. A. 1991. Environmental effects of sediment on New Zealand streams: a review. *New Zealand Journal of Marine and Freshwater Research* **25**, 207-221.

SAIC. 1987a. Alcatraz Disposal Site Survey. Phase 1. San Rafael Clamshell/Scow Operation. Technical Report. Report of Science Applications International Corporation. Newport, Rhode Island to the San Francisco District, U.S. Army Corps of Engineers, San Francisco, California.

SAIC. 1987b. Alcatraz Disposal Site Survey. Phase 2. Richmond Channel Hopper Dredge Operation. Technical Report. Report of Science Applications International Corporation. Newport, Rhode Island to the San Francisco District, U.S. Army Corps of Engineers, San Francisco, California

Savino, J.F., M.A. Blouin, B.M. Davis, P.L. Hudson, T.N. Todd, and G.W. Fleischer. 1994. Effects of pulsed turbidity and vessel traffic on lake herring eggs and larvae. *Journal of Great Lakes Research* **20**, 366-376.

Scannell, P.A. 1988. Effects of elevated sediment levels from placer mining on survival and behavior of immature Arctic grayling. M.S. Thesis, University of Alaska, Fairbanks. 93 pages.

Schoellhamer, D. H. 2008. U.S.G.S., Sacramento, California. Provided Figure 3 and data in Appendix C, Table C-1, to author via email, October 2008.

Schoellhamer, D. H. 2002. Comparison of the basin-scale effect of dredging operations and natural estuarine processes on suspended sediment concentration. *Estuaries* **25**, 488-495.

Schoellhamer, D. H. 1996. Factors affecting suspended-solids concentrations in South San Francisco Bay, California. *Journal of Geophysical Research* **101**, 12087-12095.

Schoellhamer, D. H., T. E. Mumley, and J. E. Leatherbarrow. 2007. Suspended sediment and sediment-associated contaminants in San Francisco Bay. *Environmental Research* **105**, 119-131.

Schoellhamer, D. H., P. A. Buchanan, and N. K. Ganju. 2002. Ten years of continuous suspended-sediment concentration monitoring in San Francisco Bay and Delta. *In* Proceedings of the Federal Interagency Workshop on Turbidity and other Sediment Surrogates, April 30-May 2, 2002, Reno Nevada. J. R. Gray and G. D. Glysson, Editors.

Schubel, J.R. and J.C.S. Wang. 1973. The effects of suspended sediment on the hatching success of *Perca flavescens* (white perch), *Morone saxatillis* (striped bass) and *Alosa pseudohaengus* (alewife) eggs. Chesapeake Bay Institute, John Hopkins University Special Report 30, Reference 73-3, Baltimore, MD

Schubel, J.R., A. H. Auld, and G.M. Schmidt. 1973. Effects of suspended sediment on the development and hatching success of yellow perch and striped bass eggs. Pages 689-694 *in* Procedures of the 27th Annual Conference of Southeastern Association of Game and Fish Commissions.

Scullion, J. and R.W. Edwards. 1980. The effects of pollutants from the coal industry on fish fauna of a small river in the South Wales coalfield. *Environmental Pollution Series A* **21**, 141-153.

Segar, D. A. 1990. Turbidity and suspended sediments at the Alcatraz, California, dumpsite. Pages 92-100 *in* Simenstad, C. A. (ed). Effects of dredging on anadromous Pacific Coast fishes. Workshop Proceedings., Seattle, September 8-9. 1988. 160 pp. Washington Sea Grant Program, University of Washington, Seattle, WA.

Selye, H. 1956. *The Stress of Life*. McGraw Hill. N.Y., N.Y. 324 pp.

Selye, H. 1950. Stress and the general adaptation syndrome. *British Medical Journal* **1**, 138-192.

Servizi, J. A. 1990. Sublethal Effects of dredged sediments on juvenile salmon. Pages 57-73 in Simenstad, C. A. (ed). Effects of dredging on anadromous Pacific Coast fishes. Workshop Proceedings., Seattle, September 8-9. 1988. 160 pp. Washington Sea Grant Program, University of Washington, Seattle, Washington.

Servizi, J.A. and R.W. Gordon. 1990. Acute lethal toxicity of ammonia and suspended sediment mixtures to chinook salmon (*Oncorhynchus tshawytscha*). *Bulletin of Environmental Contamination and Toxicology* **44**, 650-656.

Servizi, J.A. and D.W. Martens. 1992. Sublethal responses of coho salmon (On*corhynchus kisutch*) to suspended sediments. *Canadian Journal of Fisheries and Aquatic Science* **49**, 1389-1395

Servizi, J.A. and D.W. Martens. 1991. Effect of temperature, season, and fish size on acute lethality of suspended sediments to coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Science* **48**, 493-497

Servizi, J.A. and D.W. Martens. 1987. Some effects of suspended Fraser River sediments on sockeye salmon (*Oncorhynchus nerka*). Pages 254-264 *in* H.D. Smith, L. Margolis, and C.C. Wood (ed) Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. *Canadian Special Publication. Fish and Aquatic Science*.

Shaw, P.A. and J.A. Maga. 1943. The effect of mining silt on yield of fry from salmon spawning beds. Calif. Fish Game **29**, 29-41.

Shaw, E.A. and J.S. Richardson. 2001. Direct and indirect effects of sediment pulse duration on stream invertebrate assemblages and rainbow trout (*Onchorhynchus mykiss*) growth and survival. Canadian Journal of Fisheries and Aquatic Science **58**, 2213-2221.

Sherk, J.A. 1972. Current status of knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay (incomplete). Chesapeake Science 13, Supplement: Biota of the Chesapeake Bay. December 1972, Pages S137-S144.

Sherk, J.A. 1971. The effects of suspended and deposited sediments on estuarine organisms: Literature summary and research needs. Natural Resources Institute, University of Maryland, Chesapeake Biological Laboratory, Maryland. Contribution No. 443, February 1971.

Sherk, J. A. and L. E. Cronin. 1970 The effects of suspended and deposited sediments on estuarine organisms: an annotated bibliography of selected references. University Maryland Natural Resources Institute, Chesapeake Biological Laboratory, Solomons, Maryland. N.R.I. Reference No. 70-19.. April 1970.

Sherk, J.A., J.M. O'Connor, and D. A. Neumann. 1975a. Effects of suspended and deposited sediments on estuarine environments. Pages 541-558 in L.E. Cronin, editor, Estuarine Research, Volume II Academic Press, N.Y.

Sherk, J.A., J.M. O'Connor, and D. A. Neumann. 1975b. Effects of suspended and deposited sediments on estuarine environments. *Estuarine Research* **2**, 541-559.

Sherk, J.A., J.M. O'Connor, D. A. Neumann, R. D. Prince, and K.V. Wood. 1974. Effects of suspended and deposited sediments on estuarine environments. Phase II. University of Maryland Natural Resource Institute, Reference 74-10, Solomons. Pages 541-558 in L.E. Cronin, editor, *Estuarine Research* **2**. Academic Press.

Sherk, J.A., J.M. O'Connor, and D. A. Neumann,. 1972. Effects of suspended and deposited sediments on estuarine environments. Phase II. University of Maryland Natural Resource Institute, Reference 79-9E, Solomons.

Shingles, A., D. J. McKenzie, G. Claireaux, and P. Domenici. 2005. Reflex cardioventilatory responses to hypoxia in the flathead gray mullet (*Mugil cephalus*) and their behavioral modulation by perceived threat of predation and water turbidity. *Physiological and Biochemical Zoology* **78**, 744-755.

Sigismondi, L. A. and L J. Weber. 1988. Changes in avoidance response time of juvenile chinook salmon exposed to multiple acute handling stresses. *Transactions of the American Fisheries Society* **117**, 196-201.

Sigler, J. W. 1990. Effects of chronic turbidity on anadromous salmonids: recent studies and assessment techniques perspective. Pages 26-37 *in* Simenstad, C. A. (ed) Effects of dredging on anadromous Pacific Coast fishes. Workshop Proc., Seattle, September 8-9. 1988. 160 pp. Washington Sea Grant Program, Univ. Washington, Seattle, WA.

Sigler, J. W., T. C. Bjornn, and F. H. Everest. 1984. Effects of chronic turbidity on density and growthof steelhead and coho salmon. *Transactions of the American Fisheries Society* **113**, 142-150.

Simmons, R.C. 1982. Effects of placer mining on Arctic grayling of interior Alaska. M.S. Thesis, University of Alaska, Fairbanks.

Sissenwine, M.P. and S.G. Saila. 1974. Rhode Island sound dredge spoil disposal and trends in the floating trap fishery. *Transactions of the American Fisheries Society* **103**, 498-506.

Slaney, P.A., T.G. Halsey, and H.A. Smith. 1977a. Some effects of forest harvesting on salmonid rearing habitat in two streams in the central interior of British Columbia. British Columbia Ministry of Recreation and Conservation, Fish and Wildlife Branch, Fisheries Management Report 71, Victoria, B.C.

Slaney, P.A., T.G. Halsey, A.F. Tautz. 1977b. Effects of forest harvesting practices on spawning habitat in two streams in Centennial Creek watershed, British Columbia. British Columbia Ministry of Recreation and Conservation, Fish and Wildlife Branch, Fisheries Management Report 73, Victoria, B.C.

Slanina, K. Beitrag zür Wirkung mineralischer Suspensionen auf Fische. *Wasser und Abwasser* **1962**,186-194.

Smith, D. G. and R. J. Davies-Colley. 2002. If visual water clarity is the issue, then why not measure it? Poster Paper presented at the National Water Quality Monitoring Council Annual Conference, Madison, Wisconsin. May, 2002.

Smith, D. W. 1978. Tolerance of juvenile chum salmon (*Oncorhyncus keta*) to suspended sediments. M.S. Thesis, University of Washington. 124 pages.

Smith, L. H. 1987. A review of circulation and mixing studies of San Francisco Bay, California: U.S. Geological Survey Circular 1015, 38 p.

Smith, O.R. 1940. Placer mining silt and its relation to the salmon and trout on the Pacific coast. *Transactions of the American Fisheries Society* **69**, 225-230.

Sorensen, D.L., M. M. McCarthy, E.J. Micclebrooks, and D. B. Porcella. 1977. Suspended and dissolved solids effects on freshwater biota: a review. U.S. Environmental Protection Agency EPA-600/3-77-042. April 1977. Washington, D.C. 64 pages.

Spratt, J. D. 1981. Status of the Pacific herring, *Clupea harengus pallasii*, resource in California 1972-1980. State of California, Department of Fish and Game. Fish Bulletin 171.

Stern, E.M. and W.B. Stickle. 1978. Effects of turbidity and suspended material in aquatic environments: a literature review. Technical Report D-78-21. Prepared for Office, Chief of Engineers, U.S. Army. June 1978. 118 pages.

Stober, Q.J., B.D. Ross, C.L. Melby, P.A. Dinnel, T. Jagielo, and E.O. Salo. 1981. Effects of suspended volcanic sediment on coho and Chinook salmon in the Toutle and Cowlitz rivers. Pages 308-344 *in* Proceedings from the conference Mt. St. Helens: effects on water resources, October 7-8, 1981. Jantzen Beach, Oregon. Fisheries Institute Publication FRI-UW-8124. November 1981. 147 pages with Appendices.

Suchanek, P.M., R.P. Marshall, S.S. Hale, and D.C. Schmidt. 1984a. Juvenile salmon rearing suitability criteria. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, 1984 Report 2, Part 3, Anchorage, AK.

Suchanek, P.M., R.L. Sundet, and M.N. Wenger. 1984b. Resident fish habitat studies. Alaska Department of Fish and Game, Susitna Hydro Aquatic Studies, 1984 Report 2, Part 6, Anchorage, AK.

Sumner, F. H. and O. R. Smith. 1939. A biological study of the effect of mining debris dams and hydraulic mining on fish life in the Yuba and American Rivers in California. Submitted to the U.S. District Engineer's Office, Sacramento, California. Stanford University, California. 51 pages.

Sutherland, A. B. and J. L. Meyer. 2007. Effects of increased suspended sediment on growth rate and gill condition of two southern Appalachian minnows. *Environmental Biology of Fish* **80**, 389-403.

Sutherland, A. B., J. Maki, and V.Vaughan. 2008. Effects of suspended sediment on whole-body cortisol stress response of two southern Appalachian minnows, *Erimonax monachus* and *Cyprinella galactura*. *Copeia* **1**, 234-244.

Sweka, J. A. and K. J. Hartman. 2001. Effects of turbidity on prey consumption and growth in brook trout and implications for bioenergetics modeling. *Canadian Journal of Fisheries and Aquatic Sciences* **58**, 386-393.

Swenson, W.A. 1978. Influence of turbidity on fish abundance in Western Lake Superior. U.S. Environmental Protection Agency, National Environmental Research Center, Ecological Research Series EPA 600/3-78-067. 83 pages.

Swenson, W. A. and M. L. Matson. 1976. Influence of turbidity on survival, growthLife, and distribution of larval lake herring (*Coregonus artedii*). *Transactions of the American Fisheries Society* **105**, 541-545.

Sykora, J.L., E.J. Smith, and M. Synak.1972. Effect of lime-neutralized iron hydroxide suspensions on juvenile brook trout (*Salvelinus fontinalis* Mitchill). *Water Research* **6**, 935-950.

Thackston, E.L., and M.R. Palermo. 2000. Improved methods of correlating turbidity and suspended solids for monitoring. DOER Technical Notes Collection (ERDC TN DOER-E8), U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. April 2000. 12 pages.

Thomas, A. E. 1975. Migration of Chinook salmon fry from simulated incubation channels in relation to water temperature, flow and turbidity. *Progressive Fish Culturist* **37**, 219-223.

Townsend, A. H. 1983. Sport-fishing-placer mining: Chatanika River, memorandum to Director B. Baker, Habitat Division, Alaska Department of Fish and Game, February 2, 1983, Juneau (cited by Lloyd, 1985).

Turnpenny, A.W.H. and R. Williams. Effects of sedimentation on the gravels of an industrial river system. *Journal of Fish Biology* **17**, 681-693.

USACE (U. S. Army Corps of Engineers). 2007. Juvenile salmonid outmigration and distribution in the San Francisco Estuary: Draft Annual Report. San Francisco District, September 2007. 52 pages + Appendices.

USACE (U.S. Army Corps of Engineers). 1976. Dredge Disposal Study, San Francisco Bay and Estuary. U.S. Army Corps of Engineers, San Francisco District, San Francisco.

USFWS (U.S. Fish and Wildlife Service). 1980. Impacts of navigational dredging on fish and wildlife: a literature review. FWS/OBS-80/07. 81 pages.

USFWS (U.S. Fish and Wildlife Service). 1970. Effects on fish resources of dredging and spoil disposal in San Francisco and San Pablo Bays, California. Un-numbered Spec. Report. November 1970. Washington, D.C.

U.S.G.S. 2008. http://sfbay.wr.usgs.gov/sediment/cont_monitoring/background.html

Utne, A. C. 1997. The effects of turbidity and illumination on the reaction distance and search time of the marine planktivore *Gobiusculus flavescens. Journal of Fish Biology* **50,** 926-938.

Utne-Palm, A. C. 2004. Effects of larvae ontogeny, turbidity, and turbulence on prey attack rate and swimming activity of Atlantic herring larvae. *Journal of Experimental Marine Biology and Ecology* **310**, 147-161.

Utne-Palm, A. C. 1999. The effect of prey mobility, prey contrast, turbidity, and spectral composition on the reaction distance of *Gobiusculus flavescens* to its planktonic prey. *Journal of Fish Biology* **54**, 1244-1258.

Vandenbyllaardt, L., F.J. Ward, C.R. Braekevelt, and D.B. McIntyre. 1991. Relationships between turbidity, piscivory, and development of the retina in juvenile Walleyes. *Transactions of the American Fisheries Society* **120**, 82-390.

Vinyard, G. L. and W. J. O'Brien. 1976. Effects of light and turbidity on the reactive distance of bluegill (*Lepomis macrochirus*). *Journal of the Fisheries Research Board of Canada* **33**, 2845-2849.

Vinyard, G.L. and A. C. Yuan. 1996. Effects of turbidity on feeding rates of Lahontancutthroat trout (*Oncorhynchus clarki henshawi*) and Lahontan redside shiner (*Richardsonius egregious*). *Great Basin Naturalist* **56**, 157-161.

Vogel, J. L. and D. A. Beauchamp. 1999. Effects of light, prey size, and turbidity on reaction distances of lake trout (*Salvelinus namaycush*) to salmonid prey. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 1293-1297.

Wakeman, T., R. Peddicord, and J. Suster. 1975. Effects of suspended solids associated with dredging operations in estuarine organisms. Pages 431-436 *in* D. M. Bolle, ed., Proceedings of Ocean 75, San Diego, California.

Wallen, I.E. 1951. The direct effect of turbidity on fishes. *Bulletin of Oklahoma Agriculture and Mechanical College*, *Biological Series 2*, **48**, 1-27.

Ward, H.B. 1938. Placer mining in the Rogue River, Oregon, in its relation to the fish and fishing in that stream. *Bulletin of the Oregon Department of Geology* **10**, 31 pp.

Watters, D. L., H.M. Brown, E.J. Larson, F. J. Griffin, K. T. Oda, and G.N. Cherr. 2001a. Use of the San Francisco Bay Estuary for spawning by Pacific herring, *Clupea pallasi:* 1973 to present. Pages 101 *in* : Anon., San Francisco Estuary: achievements, trends and the future. 5th Biennial State of the Estuary Conference, Palace of Fine Arts, San Francisco, October 9-11, 2001. Abstract.

Watters, D.J, K. T. Oda, and J. Mello. 2001b. Pacific Herring. California Department of Fish and Game: California's Living Marine Resources, A Status Report. Pages 456-459. December 2001.

Wedemeyer, G. A., B.A. Barton, and D. J. McLeay. 1990. Chapter 14 Stress and Acclimation. Pages 451-489 *in* Methods for Fish Biology, C.B. Schreck and P.B. Moyle (editors).

Whitman, R.P., T. P. Quinn, and E. L. Brannon. 1981. Influence of suspended volcanic ash on homing behavior of adult Chinook salmon. *Transactions of the American Fisheries Society* **111**, 63-69.

Wilbur, C.G. 1983. Turbidity in the aquatic environment: an environmental factor in fresh and oceanic waters. Charles C. Thomas, Springfield, Illinois 133 pages

Wilber, C.G. 1970. "Turbidity" pages 1151-1165 *in* O. Kinne (ed) Marine Ecology Volume 1. Wiley Interscience, NY.

Wilber, D. H. and D. G. Clarke. 2001. Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. *North American Journal of Fisheries Management* **21**, 855-875.

Wildish, D. J. and J. Power. 1985. Avoidance of suspended sediments by smelt as determined by a new "single fish" behavioral bioassay. *Bulletin of Environmental Contamination and Toxicology* **34**, 770-774.

Wilson, J. N. 1959. Effects of erosion, silt, and other inert materials on aquatic life. Pages 269-271 *in* Biological problems in water pollution. U.S. Department of Health, Education and Welfare. Robert A. Taft Sanitary Engineering Center.

Wilson, J. N. 1957. Effects of turbidity and silt on aquatic life. Pages 235-239 *in* Biological problems in water pollution. U.S. Dept. Health, Education and Welfare. Robert A. Taft Sanitary Engineering Center.

Windom, H. L. 1972. Environmental aspects of dredging in estuaries. *Journal of Waterways,* Harbors and Coastal Engineering Division. ASCE **98,** 475-487.

Winzler and Kelly. 1985. Oceanographic Investigation at the Alcatraz Disposal Site, San Francisco Bay, California. Report prepared by Winzler and Kelly, Consulting Engineers, for the U.S. Army Corps of Engineers, San Francisco District, San Francisco, California.

Witherspoon, N., M. Strand, J. Holloway, Jr., B. Price, D. Brown, and R. Miller. 1988. Experimentally measuring MTF's associated with imaging through turbid water. *SPIE* **925**, 365-370.

APPENDIX A

SUMMARY, BY YEAR, OF SUSPENDED SOLIDS CONCENTRATIONS IN SAN FRANCISCO BAY

Sources: Buchanan and Ganju, 2002-2005; Buchanan and Lionberger, 2006; Buchanan and Ruhl, 2000-2001; Buchanan and Schoelhamer, 1995-1996; 1998-1999; Buchanan et al., 1996

Table A-1. Summary, by Year, of Suspended Solids Concentrations (mg/L), Mallard Island, Suisun Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	No Data				
1994	3.3 ft below surface	44.5	42.1	34.0	52.4
	5 ft above bottom	54.3	51.8	38.9	65.6
1995	3.3 ft below surface	43	32	27	41
	5 ft above bottom	41	33	27	43
1996	3.3 ft below surface	42	39	33	47
	5 ft above bottom	55	49	36	68
1997	3.3 ft below surface	48	40	28	60
	5 ft above bottom	54	44	28	69
1998	3.3 ft below surface	46	43	37	52
	5 ft above bottom	47	41	29	59
1999	3.3 ft below surface	42	39	31	49
	5 ft above bottom	46	38	23	58
2000	3.3 ft below surface	37	34	27	45
	5 ft above bottom	48	44	32	57
2001	3.3 ft below surface	41	37	27	51
	5 ft above bottom	52	46	33	68
2002	3.3 ft below surface	36	34	29	41
	5 ft above bottom	58	55	43	70
2003	3.3 ft below surface	38	33	28	42
	5 ft above bottom	48	41	31	56
2004	3.3 ft below surface	34	31	24	41
	5 ft above bottom	39	36	29	46
2005	3.3 ft below surface	27	24	20	30
	5 ft above bottom	28	25	21	31

Table A-2. Summary, by Year, of Suspended Solids Concentrations (mg/L), Martinez, Suisun Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	No Data				
1994	3.3 ft below surface	56.9	52.4	41.9	66.4
1995	3.3 ft below surface	68	52	37	77
1996[1]	3.3 ft below surface	47	42	29	60
1997-2005	No Data				

[1] Data collected October 1995 through January 19, 1996 because Benecia Bridge was considered to be more representative of SS concentrations in Carquinez Strait.

Table A-3. Summary, by Year, of Suspended Solids Concentrations (mg/L), Benecia Bridge on Pier 7, Suisun Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1995	No Data				
1996[2]	74' above bottom	60	55	45	72
	25' above bottom	130	120	86	170
1997	74' above bottom	77	64	48	94
	25' above bottom	137	123	78	173
1998	74' above bottom	73	68	53	86
	25' above bottom	141	104	61	170
1999-2000	No Data				
2001	74' above bottom	35	25	18	43
	25' above bottom	47	29	29	96
2002	74' above bottom	29	21	13	37
	25' above bottom	70	54	33	93
2003	74' above bottom	40	29	17	52
	25' above bottom	86	74	46	112
2004	74' above bottom	46	37	25	59
	25' above bottom	96	85	53	127
2005	74' above bottom	37	31	23	46
	25' above bottom	67	61	44	82

[2] Data collected May 14 through September 30, 1996.

Table A-4. Summary, by Year, of Suspended Solids Concentrations (mg/L), Carquinez Bridge, San Pablo Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1997	No Data				
1998	48' above bottom	71	55	41	94
	5' above bottom	290	216	136	386
1999	48' above bottom	66	46	22	78
	5' above bottom	203	151	52	297
2000	48' above bottom	56	37	37	37
	5' above bottom	85	34	34	112
2001	48' above bottom	37	28	28	96
	5' above bottom	42	25	25	89
2002	48' above bottom	39	27	19	48
	5' above bottom	54	39	25	69
2003	48' above bottom	31	21	13	38
	5' above bottom	81	59	29	107
2004	48' above bottom	49	41	28	62
	5' above bottom	77	65	42	95
2005	48' above bottom	42	30	19	52
	5' above bottom	66	50	31	84

Table A-5. Summary, by Year, of Suspended Solids Concentrations (mg/L), Napa River at Mare Island Causeway, San Pablo Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1998	No Data				
1999	15’ above bottom	80	61	39	101
	5’ above bottom	186	144	89	235
2000	15’ above bottom	76	57	39	94
	5’ above bottom	180	136	85	224
2001	15’ above bottom	49	38	25	63
	5’ above bottom	117	100	65	150
2002	15’ above bottom	53	42	27	67
	5’ above bottom	126	94	53	169
2003	15’ above bottom	70	53	29	89
	5’ above bottom	114	86	52	147
2004	15’ above bottom	69	53	33	90
	5’ above bottom	121	99	64	158
2005	15’ above bottom	55	42	27	70
	5’ above bottom	109	82	51	141

Table A-6. Summary, by Year, of Suspended Solids Concentrations (mg/L), Channel Marker 9, San Pablo Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1998	No Data				
1999	2 ft from bottom	213	142	81	263
2000	2 ft from bottom	203	110	25	280
2001	2 ft from bottom	167	38	38	214
2002	2 ft from bottom	110	69	39	132
2003	2 ft from bottom	132	63	32	160
2004-2005	No Data				

Table A-7. Summary, by Year, of Suspended Solids Concentrations (mg/L), Channel Marker 1, San Pablo Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-2003	No Data				
2004	Mid-depth	76	55	34	94
2005	Mid-depth	38	27	17	47

Table A-8. **Summary, by Year, of Suspended Solids Concentrations (mg/L), Point San Pablo, Central San Francisco Bay.**

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	13 ft from bottom	87.9	70.4	37.3	114
	3 ft from bottom	90.9	65.3	31.5	121
1994	13 ft from bottom	98.5	78.8	45.2	128
	3 ft from bottom	96.3	77.2	45.4	126
1995	13 ft from bottom	58	45	30	68
	3 ft from bottom	91	66	42	110
1996	13 ft from bottom	65	50	31	81
	3 ft from bottom	90	74	56	100
1997	13 ft from bottom	112	77	49	132
	3 ft from bottom	144	105	72	170
1998	13 ft from bottom	83	67	40	104
	3 ft from bottom	110	81	50	138
1999	13 ft from bottom	48	40	28	59
	3 ft from bottom	81	62	40	99
2000	13 ft from bottom	43	40	24	54
	3 ft from bottom	59	47	33	72
2001	13 ft from bottom	41	35	22	54
	3 ft from bottom	59	51	36	72
2002	13 ft from bottom	32	27	21	37
	3 ft from bottom	46	39	29	55
2003	13 ft from bottom	27	20	14	31
	3 ft from bottom	62	44	30	74
2004	13 ft from bottom	46	36	23	58
	3 ft from bottom	61	49	33	76
2005	13 ft from bottom	32	25	17	40
	3 ft from bottom	37	28	20	44

Table A-9. Summary, by Year, of Suspended Solids Concentrations (mg/L), Alcatraz Island,Central San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-2003	No Data				
2004	Mid-Depth	18	17	15	20
2005	Mid-Depth	18	15	12	21

Table A-10. Summary, by Year, of Suspended Solids Concentrations (mg/L), Golden Gate Bridge, Central San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1995	No Data				
1996	45 ft above the bottom	20	19	14	25
1997	45 ft above the bottom	17	16	13	21
1998-2005	No Data				

Table A-11. Summary, by Year, of Suspended Solids Concentrations (mg/L), Pier 24, Central San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	23 ft above bottom	29.0	24.4	15.3	37.4
	3 ft above bottom	36.0	32.5	17.7	48.8
1994	23 ft above bottom	42.7	38.4	25.8	54.6
	3 ft above bottom	45.4	40.0	26.2	60.2
1995	23 ft above bottom	41	36	20	53
	3 ft above bottom	84	56	30	110
1996	23 ft above bottom	29	23	12	40
	3 ft above bottom	53	49	32	68
1997	23 ft above bottom	28	27	19	34
	3 ft above bottom	47	36	24	55
1998	23 ft above bottom	28	26	14	36
	3 ft above bottom	38	30	24	41
1999	23 ft above bottom	25	22	18	29
	3 ft above bottom	33	28	22	38
2000	23 ft above bottom	23	21	19	24
	3 ft above bottom	32	28	23	36
2001	23 ft above bottom	24	23	20	26
	3 ft above bottom	37	36	29	43
2002	23 ft above bottom	20	18	15	22
	3 ft above bottom	32	27	20	39
2003-2005	No Data				

Table A-12. Summary, by Year, of Suspended Solids Concentrations (mg/L), San Mateo Bridge, South San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	23 ft above bottom	65.7	53.4	34.8	82.4
	3 ft above bottom	95.2	76.9	45.8	119
1994	23 ft above bottom	62.6	51.7	38.3	73.0
	3 ft above bottom	95.6	75.7	53.1	118
1995	23 ft above bottom	44	35	27	48
	3 ft above bottom	47	40	30	53
1996	29 ft above bottom	40	25	11	46
	8 ft above bottom	47	41	20	66
1997	29 ft above bottom	58	45	26	75
	8 ft above bottom	59	47	31	71
1998	29 ft above bottom	44	35	22	53
	8 ft above bottom	36	30	18	46
1999	29 ft above bottom	60	47	30	73
2000	29 ft above bottom	42	29	17	45
	8 ft above bottom	42	31	23	50
2001	29 ft above bottom	37	31	19	46
	8 ft above bottom	40	34	21	50
2002	29 ft above bottom	54	47	34	65
	8 ft above bottom	75	67	43	96
2003	29 ft above bottom	44	36	27	50
	8 ft above bottom	51	40	28	62
2004	29 ft above bottom	41	37	27	49
	8 ft above bottom	40	33	24	48
2005	29 ft above bottom	47	43	35	57
	8 ft above bottom	45	38	28	53

Table A-13. Summary, by Year, of Suspended Solids Concentrations (mg/L), Dumbarton Bridge, South San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	23 ft above bottom	72.9	64.1	48.8	86.7
	3 ft above bottom	93.6	82.2	56.7	118
1994	23 ft above bottom	96.9	85.7	63.0	118
	3 ft above bottom	133	112	68.0	173
1995	23 ft above bottom	98	63	42	110
	3 ft above bottom	140	98	65	150
1996	23 ft above bottom	120	89	45	170
	4 ft above bottom	170	140	78	230
1997	23 ft above bottom	122	106	79	143
	4 ft above bottom	177	133	82	212
1998	23 ft above bottom	92	67	39	113
	4 ft above bottom	257	213	131	323
1999	23 ft above bottom	95	76	52	117
	4 ft above bottom	150	127	80	190
2000	23 ft above bottom	69	58	44	82
	4 ft above bottom	112	97	67	139
2001	23 ft above bottom	40	29	21	42
	4 ft above bottom	58	42	26	68
2002	23 ft above bottom	70	57	41	85
	4 ft above bottom	98	76	53	120
2003	23 ft above bottom	56	45	31	64
	4 ft above bottom	76	59	36	91
2004	23 ft above bottom	44	35	26	52
	4 ft above bottom	48	35	25	54
2005	23 ft above bottom	48	43	23	62
	4 ft above bottom	43	32	24	51

Table A-14. Summary, by Year, of Suspended Solids Concentrations (mg/L), Channel Marker 17, South San Francisco Bay.

Water Year	Depth	Mean	Median	Lower Quartile	Upper Quartile
1992-1993	13 ft above bottom	121	88.6	52.8	153
	3 ft above bottom	170	108	67.1	197
1994	13 ft above bottom	166	135	76.1	222
	3 ft above bottom	204	145	82.9	256
1995	13 ft above bottom	120	92	57	160
	3 ft above bottom	190	130	65	240
1996	13 ft above bottom	110	71	35	160
	3 ft above bottom	200	130	61	260
1997	13 ft above bottom	168	119	65	223
	3 ft above bottom	207	125	53	269
1998	13 ft above bottom	200	122	65	257
	3 ft above bottom	210	140	76	274
1999	13 ft above bottom	132	96	56	170
	3 ft above bottom	171	112	64	215
2000	13 ft above bottom	110	85	53	138
	3 ft above bottom	143	98	58	172
2001	13 ft above bottom	62	39	23	74
	3 ft above bottom	87	55	33	105
2002	13 ft above bottom	80	61	35	103
	3 ft above bottom	88	64	35	112
2003	13 ft above bottom	72	53	29	91
	3 ft above bottom	83	55	31	102
2004	13 ft above bottom	52	30	17	61
	3 ft above bottom	61	35	21	69
2005	13 ft above bottom	51	40	31	57
	3 ft above bottom	56	36	25	65

APPENDIX B

SUMMARY OF SS CONCENTRATIONS AND TURBIDITY LEVELS IN RESPONSE TO DREDGING ACTIVITIES IN SAN FRANCISCO BAY

Table B-1. Comparison of Mid-Depth and Near-Bottom SS Concentrations with Dredging Volume at Point San Pablo, San Pablo Bay.

Dredge or No Dredge	Dredging Volume (m^3 X 1000)	Median Mid-Depth SS (mg/L)	Median Near-Bottom SS (mg/L)
No Dredging	0	65.5-87.7	38.8-116
Dredging	90,000	92	51.8
	196,000	251	84.5
	286,000	20.3	67.8

Source: Schoellhamer, 2008.

Table B-2. **Results of SS Concentrations during Mechanical Dredging Operations at the Port of Oakland, Central San Francisco Bay.**

Projection Distance (m)	**Depth (m)**	**SS Concentrations (mg/L) [3]**	**Conditions Under Which Data Were Collected**
350	2-15	25 - 125	Vertical profile of SS concentrations on transect 1 during an ebbing tide survey. (SS concentrations estimated from Figure 4 from Clarke et al., 2006a.)
275	2-13	25 - 125	Vertical profile of SS concentrations on Transect 3 during an ebbing tide survey during dredging. (SS concentrations estimated from Figure 6 from Clarke et al., 2006a.)
240	2-13	25 - 125	Vertical profile of SS concentrations on Transect 4 during an ebbing tide survey during dredging. (SS concentrations estimated from Figure 7 from Clarke et al., 2006a.)
230	2-13	25 - 125	Vertical profile of SS concentrations on Transect 6 during an ebbing tide survey during dredging. (SS concentrations estimated from Figure 8 from Clarke et al., 2006a.)
130	2-13	25 - 175	Vertical profile of SS concentrations on Transect 8 during an ebbing tide survey during dredging. (SS concentrations estimated from Figure 9 from Clarke et al., 2006a.)
275	2-13	25 - 125	Vertical profile of SS concentrations on Transect 11 during an ebbing tide survey during dredging. (SS concentrations estimated from Figure 10 from Clarke et al., 2006a.)

Table B-2 (cont.). **Results of SS Concentrations during Mechanical Dredging Operations at the Port of Oakland, Central San Francisco Bay.**

Projection Distance (m)	Depth (m)	SS Concentrations (mg/L) [3]	Conditions Under Which Data Were Collected
250	2-13	25 - 125	Vertical profile of SS concentrations on transect 3 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 12 from Clarke et al., 2006a.)
160	2-13	25 - 225	Vertical profile of SS concentrations on Transect 5 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 13 from Clarke et al., 2006a.)
250	2-13	25 - 125	Vertical profile of SS concentrations on Transect 6 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 14 from Clarke et al., 2006a.)
230	2-13	25 - 125	Vertical profile of SS concentrations on Transect 8 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 15 from Clarke et al., 2006a.)
230	2-12	25 - 125	Vertical profile of SS concentrations on Transect 10 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 16 from Clarke et al., 2006a.)
250	2-14	25 - 125	Vertical profile of SS concentrations on Transect 2 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 18 from Clarke et al., 2006a.)

[1] SS concentrations were estimated from figures that depicted time series records generated from a program that interpreted the output from the Acoustic Doppler Current Profiler (Clarke et al., 2006a, 2005a).

Table B-2 (cont.). **Results of SS Concentrations during Mechanical Dredging Operations at the Port of Oakland, Central San Francisco Bay.**

Projection Distance (m)	Depth (m)	SS Concentrations (mg/L) [3]	Conditions Under Which Data Were Collected
240	2-14	25 - 125	Vertical profile of SS concentrations on transect 3 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 19 from Clarke et al., 2006a.)
150	2-14	25 - > 225	Vertical profile of SS concentrations on Transect 4 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 20 from Clarke et al., 2006a.)
130	2-14	25 - >225	Vertical profile of SS concentrations on Transect 5 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 21 from Clarke et al., 2006a.)
115	2-14	25 - 125	Vertical profile of SS concentrations on Transect 6 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 22 from Clarke et al., 2006a.)
205	2-14	25 - 125	Vertical profile of SS concentrations on Transect 8 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 23 from Clarke et al., 2006a.)
260	2-14	25 - 100	Vertical profile of SS concentrations on Transect 12 during a flooding tide survey during dredging. (SS concentrations estimated from Figure 34 from Clarke et al., 2006a.)

Table B-3. SS Concentrations in the Vicinity of the Alcatraz Disposal Site, Central Bay.

Monitoring Site	Date	Depth or General Location	Duration of Monitoring	SS Concentration (mg/L)	Reference
Alcatraz Disposal Site	July 1985	4,7,11 m below surface	12 hours	9-56; mean = 19.3l; greatest at 11 m; least at 4 m	Winzler and Kelly, 1985
	Summer 1986			9-17	SAIC, 1987a,b
	April 1988 through August 1989	3 m		6	MEC, 1990
		6.1 m		14	
		9.15 m		22	
		Bottom		14	

Table B-4. **SS Concentrations in the Vicinity of the Alcatraz Disposal Site, Central Bay, Before, during and after Dredge Disposal Activities.**

Monitoring Site	Date	General Location	Depth (m)	SS Concentration (mg/L)	Comments	Reference
Alcatraz Disposal Site		50 m down current from disposal operation	1	60	Surface waters had less SS than bottom waters; maximum SS concentrations occurred in bottom waters close to disposal site SS returned to background concentrations thoughout the water column 1-15 minutes after disposal	Gunther et al., 1990
			5	50		
			9	290		
		100 m down current from disposal operation	1	40		
			5	50		
			9	100		
		400 m down current from disposal site	1	30		
			5	10		
			9	40		

Table 4 (cont.). **SS Concentrations in the Vicinity of the Alcatraz Disposal Site, Central Bay, before, during and after Dredge Disposal Activities.**

Monitoring Site	Date	General Location	Depth (m)	SS Concentration (mg/L)	Comments	Reference
Alcatraz Disposal Site	May 1, 1990	Background	Near the disposal site	6-22	Influence of descending material from the dredging activities could be seen to a depth of 13 m	MEC, 1990
	May, 1990	Outside influence of disposal event	3.1	12		
			9	18		
			Bottom	38		
		Within the disposal plume	6.5	86		
			9	38		
			12	44		
	1987	Tracked SS plume from 11 disposal events on six different days	Background SS Concentrations	9-17	SS data estimated from acoustic backscattering data Plume moved with tidal currents; at slack water there was little lateral movement of plume Within 1-15 minutes, plume had dissipated except for one instance where SS plume of 80 mg/L persisted for 20 minutes after disposal	SAIC, 1987a, 1987b
			Lower water column	44-165		

Table B-5. Turbidity Levels in the Vicinity of the Alcatraz Disposal Site, Central Bay, before, Before, during, and after Dredge Disposal Activities.

Monitoring Site	Date	Specific Date	Depth (m)	Turbidity Levels (NTU)	Reference
Alcatraz Disposal Site	Spring 1988 through August 1989	August 3, 1989	0.3 m below surface, 6 m (mid-depth), and 0,3 m from the bottom	9.3 at center of site 8,4-12 at perimeters	Ogden Beeman Associates, 1988, 1989
		June 15, 1989		94 at one site	
		July 20, 1989		15 at all stations	
		September, 1989		2.5-3	

Table B-6. Results of Turbidity Levels during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.

Date	Time	Depth (m)	Turbidity Levels (NTU)[2]	Conditions Under Which Data Were Collected
10/26/04	8 am – 5 pm	3.0	10-20	Ambient turbidity conditions at the northernmost moored buoy. (Turbidities estimated from Figure 6 from Clarke et al., 2006b.)
		6.2	<1 – 18	
		9.0	<1 - 20	
10/26/04	8 am – 5 p.m	1.5	11-58	Time series of turbidity at the bay-side moored buoy during knockdown operations. (Turbidity estimated from Figure 7 from Clarke et al., 2006b.)
		6.0	11-75	
		8.0	18-90	

Table B-6 (cont.). **Results of Turbidity Levels during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Date	Time	Depth (m)	Turbidity Levels (NTU)[2]	Conditions Under Which Data Were Collected
10/27/04	1:30 pm – 4 pm	1.5	20-60	Knockdown plume turbidity at bay-side buoy during an ebbing tide. (Turbidities estimated from Figure 8 from Clarke et al., 2006b.)
		6.0	20-80	
		8.25	20 - >200	
10/27/04	4 pm – 5 p.m	0.5	20-30	Time series record turbidity as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge. (Turbidities estimated from Figure 9 from Clarke et al., 2006b.)
		2.0	15-30	
		3.5	13-50	
		5.0	10-70	
		6.5	10 - > 100	

Table B-6 (cont.). **Results of Turbidity Levels during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Date	Time	Depth (m)	Turbidity Levels (NTU) [2]	Conditions Under Which Data Were Collected
10/28/04	9 am – 10 am	1.5	10-40	Time series recorded turbidity as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge. (Turbidities estimated from Figure 10 from Clarke et al., 2006b.)
		3.0	10-40	
		6.0	20-70	
		7.5	20 - >250	

[2] NTU levels were estimated from figures that depicted time series records generated from a program that interpreted the output from the Acoustic Doppler Current Profiler (Clarke et al., 2006b, 2005b)

Table B-6 (cont.). **Results of SS Concentrations during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Distance (m)	Depth (m)	SS Concentrations (mg/L) [3]	Conditions Under Which Data Were Collected
1,000	1-11	10 - 70	Vertical profile of ambient SS concentrations across Redwood Creek during an ebbing tide. (SS concentrations estimated from Figure 12 from Clarke et al., 2006b.)
1,050	1-11	10 - 80	Vertical profile of ambient SS concentrations across Redwood Creek during a flooding tide. (SS concentrations estimated from Figure 13 from Clarke et al., 2006b.)
1,200	1-12	25 - >225	Parallel course on ebbing tide, 50 m directly behind the barge at slack water. (SS concentrations estimated from Figure 14 from Clarke et al., 2006b.)

Table B-6 (cont.). **Results of SS Concentrations during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Distance (m)	Depth (m)	SS Concentrations (mg/L)[3]	Conditions Under Which Data Were Collected
325	1-11	50 - > 450	Parallel course on flooding tide, 55 m directly behind the barge. (SS concentrations estimated from Figure 15 from Clarke et al., 2006b.)
400	1-11	50 - > 450	Parallel course in flooding tide, 80 m directly behind the barge. (SS concentrations estimated from Figure 16 from Clarke et al., 2006b.)
925	1-11	25 - >225	Zigzag course on ebbing tide, 60 m behind the barge. (SS concentrations estimated from Figure 17 from Clarke et al., 2006b.)

Table B-6 (cont.). **Results of SS Concentrations during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Distance (m)	Depth (m)	SS Concentrations (mg/L)[3]	Conditions Under Which Data Were Collected
625	1-11	25 - > 225	Zigzag course on ebbing tide, 70 m behind the barge. (SS concentrations estimated from Figure 18 from Clarke et al., 2006b.)
1,175	1-12	25 - > 225	Zigzag course on ebbing tide, 90 m behind the barge. (SS concentrations estimated from Figure 19 from Clarke et al., 2006b.)
575	1-11	50 - > 450	Zigzag course on flooding tide, 45 m behind the barge. (SS concentrations estimated from Figure 20 from Clarke et al., 2006b.)

Table B-6 (cont.). **Results of SS Concentrations during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Distance (m)	**Depth (m)**	**SS Concentrations (mg/L)[3]**	**Conditions Under Which Data Were Collected**
1,075	1-10	50 - > 450	Zigzag course on flooding tide, 65 m behind the barge. (SS concentrations estimated from Figure 21 from Clarke et al., 2006b.)
90	1-12	25 - > 225	Perpendicular course on ebbing tide, barge passes 60 m beyond transect. (SS concentrations estimated from Figure 22 from Clarke et al., 2006b.)
135	1-11	25 - > 225	Perpendicular course on ebbing tide, barge 200 m from transect. (SS concentrations estimated from Figure 23 from Clarke et al., 2006b.)

Table B-6 (cont.). **Results of SS Concentrations during Knockdown Operations in Redwood Creek/Port of Redwood City, South San Francisco Bay.**

Distance (m)	Depth (m)	SS Concentrations (mg/L)[3]	Conditions Under Which Data Were Collected
125	1-11	25 - > 225	Perpendicular course on ebbing tide, barge 235 m from transect. (SS concentrations estimated from Figure 24 from Clarke et al., 2006b.)
125	1-12	25 - > 225	Perpendicular course on ebbing tide, barge 300 m from transect. (SS concentrations estimated from Figure 25 from Clarke et al., 2006b.)
120	1-11	25 - 125	Perpendicular course on ebbing tide, barge approaching. (SS concentrations estimated from Figure 26 from Clarke et al., 2006b.)

Table B-6 (cont.). **Results of SS Concentrations During Knockdown Operations in Redwood Creek/Port of Redwood City.**

Distance (m)	Depth (m)	SS Concentrations (mg/L)[3]	Conditions Under Which Data Were Collected
110	1-11	25 - > 225	Perpendicular course on ebbing tide, barge approaching. (SS concentrations estimated from Figure 27 from Clarke et al., 2006b.)
110	1-11	25 - > 225	Perpendicular course on ebbing tide, barge approaching. (SS concentrations estimated from Figure 28 from Clarke et al., 2006b.)

APPENDIX C

SUMMARY OF REVIEW DOCUMENTS ON THE EFFECTS OF SS AND TURBIDITY IN FISHES

Table C-1. Summary of Review Documents on the Effects of SS and Turbidity on Fishes.

Reference	Comments
Jordan, 1889; Rathbun, 1889	● Loss of trout accompanied by high turbidity and silt loads from mining and agriculture.
Ellis, 1936; Doan, 1941; Wilson, 1957, 1959	● Summarized prior studies that demonstrated SS-related smothering of aquatic organisms and impairment of fish spawning.
Cordone and Kelley, 1961	● Acknowledged that turbidity and silt were major problems to fishery resources. ● Lack of information made it impossible to determine the specific effects of SS and turbidity on fishes. ● Brought up concept of "sublethal" effects, although did not use the term"sublethal".
EIFAC, 1965	● Acknowledged that turbidity and silt were major problems to fishery resources. ● Lack of information made it impossible to determine the specific effects of SS and turbidity on fishes. ● Brought up concept of "sublethal" effects, although did not use the term"sublethal". ● No evidence that SS concentrations < 25 mg/L would harm fish. ● Good or moderate fisheries could be maintained in waters containing 25-80 mg/L. ● Waters containing 80-400 mg/L were unlikely to support good freshwater fisheries. ● Poor fisheries likely in waters containing > 400 mg/L.
Mortensen et al., 1976	● Documented the effects of dredging on fishes. ● Dredging and dredge disposal operations created higher SS concentrations than normally found. ● Stated that since the 1930's most studies had dealt with SS-tolerant fish species and, hence, EIFAC (1965). conclusions were based on fishes that were more tolerant to SS than juvenile salmonids.

Table C-1 (cont.). Summary of Review Documents on the Effects of SS and Turbidity on Fishes.

Reference	Comments
Morton, 1977	● Objective was to identify alternative dredge spoil methods. ● Impacts of dredging activities on fishes was complicated by the difficulty in observing and sampling fishes. ● Fish less likely to suffer from the effects of dredging activities because fish avoided unsuitable areas. ● To determine location of fishes in the area of dredging activities, surveys were needed.
Everhart and Duchrow, 1970	● Concluded that SS concentrations of 20,000 mg/L or greater were harmful to fishes.
Sherke and Cronin, 1970; Sherk, 1971	● Determination of SS thresholds was difficult because of the differing sensitive of life stage of different fish species, as well as the highly variable nature of natural SS concentrations. ● Identical SS concentrations could be composed of greatly differing numbers, sizes, and shapes of particles and, hence, when attempting to apply laboratory results to the field, that should be taken into account. ● Values of turbidity measured in NTU's or JTU's might be satisfactory from a water quality perspective, but irrelevant from the standpoint of effects on fishes. ● Laboratory studies should always complement field studies because there is high variability inherent in natural systems.
Stern and Stickle, 1978	● Laboratory studies, without field studies, could not be used to determine effects of SS on fishes in the field. ● When attempting to determine effects of SS on fishes, sublethal effects should be considered. ● Natural factors would also affect the results in the field. ● Wide variety of fish species could tolerate very high SS concentrations. ● High SS concentrations and turbidity levels caused from natural processes frequently had more impact on fishes than SS from dredging activities. ● Could not use the results of laboratory-based mortality studies to establish safe SS concentrations because, to do so would ignore significant sublethal effects.

Table C-1 (cont.). **Summary of Review Documents on the Effects of SS and Turbidity on Fishes.**

Reference	Comments
Muncy et al., 1979	● Focused on effects of SS on reproduction and early life of warmwater fishes. ● Variations of year-class strength of economically-important fishes had not been correlated with SS concentrations. ● Substantial evidence existed that SS affected reproduction in some fishes. ● Larval stage of warmwater fishes were less tolerant of SS than adult or egg stages.
Bruton, 1985	● Focused on effects of SS on fishes in Southern Hemisphere. ● Discussed mortality, breeding behavior, reduced feeding efficiency, reduced growth rates, reduced population size, interference with respiration, and reduced habitat diversity.
Servizi, 1990; Sigler, 1990; Gregory, 1990	● Focused on the effects of dredging-related SS and turbidity on fishes ● Discussed sublethal effects of dredged sediments, including SS and turbidity on juvenile salmonids. ● Discussed effects of chronic turbidity on anadromous salmonids. ● Discussed the effects of turbidity on foraging and predation risk on juvenile Chinook salmon.
Lloyd, 1987, 1985; Lloyd et al., 1987	● Review of Alaskan salmonids. ● Moderately high protection provided if turbidity increased 25 NTU's above ambient turbidity. ● High protection provided if turbidity increased 5 NTU's above ambient turbidity.

Table C-1 (cont.). Summary of Review Documents on the Effects of SS and Turbidity on Fishes.

Reference	Comments
Reilly et al., 1992	● Reviewed literature on potential impacts of dredged disposal material on fishery resources in central San Francisco Bay. ● Discussed effects on spawning success of herring. ● Discussed effects of SS on larval starry founder because SS could affect their feeding source during migration. ● Discussed distribution of SS associated with dredging activities. ● Discussed need for more research to address potential impacts of dredge disposal at the Alcatraz Island Disposal Site on fishes.
Kerr, 1995	● Reviewed effects of SS on fishes and other aquatic organisms. ● Reviewed sources of SS, physical and chemical processes, impacts of silt and SS, techniques used to reduce SS and turbidity, and SS water quality standards.
Newcombe and MacDonald, 1991 Gregory et al., 1993 Sweeten et al., 2003	● Characterized effects of SS on freshwater fishes by using model approach. ● Importance of exposure duration, as well as SS concentrations. ● Importance of identifying SS safe thresholds for salmonids and other fishes.
Newcombe and Jensen, 1996	● Characterized effects of SS on estuarine fishes by using model approach developed by Newcombe and MacDonald (1991).
Fiksen et al., 2002	● Used models developed by Newcombe and MacDonald (1991) to predict influence of turbidity on growth and survival of fish larvae.

Table C-1 (cont.). **Summary of Review Documents on the Effects of SS and Turbidity on Fishes.**

Reference	Comments
Wilbur and Clarke, 2001	• Used models developed by Newcombe and MacDonald (1991), and corrected some of the data, to predict influence of turbidity on growth and survival of fish larvae.
Bash et al., 2001	• Discussed the inconsistent correlation between turbidity and SS. • Discussed the need for reliable method for determining SS. • Discussed the need for incorporating other types of studies/data (e.g., life stages, physiology, behavior, habitat, and background data). • Discussed water quality standards for the state of Washington.
Anchor Environmental, 2003	• Discussed avoidance behavior • Discussed changes in feeding behavior • Discussed changes in spawning habitat and effects on eggs. • Discussed reduced larval growth and abnormal larval development. • Discussed fish injuries. • Discussed changes in ambient water chemistry. • Concluded that it was only possible to correlate SS with turbidity under controlled site-specific conditions.

APPENDIX D

SUMMARY OF STUDIES ON MORTALITY IN FISHES EXPOSED TO SUSPENDED SEDIMENTS, SUSPENDED SOLIDS, AND TURBIDITY IN FISHES

Legend

[1] A=adult; E=egg; EE= eyed egg; F*=swim-up fry; FF=young fry (<30 weeks old); J=juvenile; L=larval; PS=pre-smolt; S=smolt; SF=sac fry; Y=approximately yearling; YOY=young-of-the-year.

[2] Particle sizes of suspended sediment (SS): FSS = fine (15-74 um); MFSS = medium to fine (75-149); MCSS = medium to coarse (150-290); and, CSS = coarse 9180-740 um). BS=Bay Sediment; CS = calcium sulfate; CWS = coal washery solids; DE diatomaceous earth; DM = drilling mud (nontoxic); FE = fuller's earth; IA = incinerator ash; KS = Kingston silt; MC = montmorillonite clay; NS = natural sediment; PS= patuxent silt; SI = silt; VA = volcanic ash; WF = wood fibers.

N/A = Not Available

Table D-1. **Summary of Studies on Mortality of Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	A	39,300 (VA)	24	No mortality (<5-100 um; Median <15 um)	Laboratory	Newcomb and Flagg, 1983
		82,400 (VA)	6	Mortality rate 60% (<5-100 um)		
		207,000 (VA)	1	Mortality rate 100% (<5-100 um)		
Salmon, Sockeye (*O. nerka*)		39,300 (VA)	24	No mortality (<5-100 um; median <5 um)		
		82,400 (VA)	6	Mortality rate 60% (<5-100 um; median, <15 um)		
Salmon, Pacific (*O.* spp.)		525	588	No mortality (other end points not investigated)		Griffin, 1938
Trout, Rainbow (*O. mykiss*)		200 (WF)	24	Test fish began to die on first day		Herbert and Richards, 1963
		270	3,240	Survival rate reduced		
		810 (DE, KC)	504	Some fish died		Herbert and Merkens, 1961

Table D-1. (Cont.) **Summary of Studies on Mortality of Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Rainbow (*O. mykiss*)	A	4,250 (CS)	588	Mortality rate 50%	Laboratory	Herbert and Wakeford, 1962
		49,838 (DM)	96	Mortality rate 50%		Lawrence and Scherer, 1974
		160,000	24	Mortality rate 100%		Herbert, personal communication listed in Alabaster and Lloyd, 1980
Whitefish, Lake (*Coregonus clupeaormis*)		10,000 (SI)	24	Fish died; silt clogged gills		Langer, 1980
		16,613 (DM)	96	Mortality rate 50%		Lawrence and Scherer, 1974

Table D-2. Summary of Studies on Mortality in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*O. tshawytscha*)	J	Unknown (VA)	24-72 hours following Mt. St. Helens eruption	100% mortality	Field: Mt. St. Helens eruption	Phinney, 1982
		1,400 (VA)	0.36	Mortality rate 50%	Laboratory	Newcomb and Flagg, 1983
		9,400 (VA)	36			
		39,400 (VA)		Mortality rate 90%		
	S	488 (VA)	96	Mortality rate 50%		Stober et al., 1981
		11,000 (VA)				
		19,364 (VA)				
Salmon, Chum (*O. keta*)	J	28,000 (NS)			Dredge-related (placer mining), laboratory	Smith, 1940
		55,000 (NS)				
Salmon, Coho (*O. kisutch*)		1,200			Laboratory	Noggle, 1978
		8,000				
		35,000				
		8,000		Mortality rate 1%		Servizi and Martens, 1991
	YOY	22,700		Mortality rate 50%		

Table D-2. (cont.) **Summary of Studies on Mortality in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Coho (*O. kisutch*)	F*	8,100	96	Mortality rate 50%	Laboratory	Noggle, 1978
	PS	18,672 (VA)				Stober et al., 1981
	S	1,217 (VA)				
		28,184 (VA)				
		8,200 (VA)				
		17,560 (VA)				
	J	100,000 (VA)		Mortality observed when fish were exposed to angular and round silicate sediments		Lake and Hinch, 1999
Salmon, Sockeye (*O. nerka*)	YOY	2,100 (MFSS)		No mortality		Servizi and Martens, 1987
		9,000				
		13,900 (FSS)		Mortality rate 10%		
	J	1,400 (VA)	36	Mortality rate 50%		Newcomb and Flagg, 1983
		9,400 (VA)				

Table D-2. (cont.) **Summary of Studies on Mortality in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Sockeye (*O. nerka*)	YOY	1,700 – 17,560 (CSS, MCSS, MFSS, FSS)	96	Mortality rate 50%	Laboratory	Servizi and Martens, 1987
		13,000 (MFSS, FSS)		Mortality rate 90%		
		23,900 (MFSS, FSS)				
		39,400 (VA)	36	Mortality rate 90%		Newcomb and Flagg, 1983
Grayling, Arctic (*Thymallus arcticus*)	J	14-2,301 (NS)	96	No significant difference compared to control fish	Dredge-related (placer mining), field (caged fish in rivers)	Scannell, 1988
	YOY	>3,000	24-216	Mortality rate 0%		Reynolds et al., 1989
		<1,000 (FSS)	1,108	Mortality rate 5-13%	Laboratory	McLeay et al., 1987
Trout, Rainbow (*O. mykiss*)	FF	1,750 (NS)	480	Mortality rate 57% (controls 5%)	Dredging-related (mining), laboratory	Campbell, 1954
	Y	90 (DE, KC)	456	Mortality rates 0-20%	Laboratory	Herbert and Merkens, 1961
				Mortality rates 0-15%		
		270 (KC)		Mortality rates 10-35%		
		810 (DE)		Mortality rates 35-85%		

Table D-2. (cont). **Summary of Studies on Mortality in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Steelhead (*O. mykiss*)	J	N/A (CWS)	0.5	100% mortality	Field, fish held in cages in river downstream of coal washing	Pautzke, 1938
Trout, Rainbow (*O. mykiss*)	Y	810 (KC)	456	Mortality rates 5-80%	Laboratory	Herbert and Merkens, 1961
		270 (DE)		Mortality rates 25-80%		
		7,433 (CS)	672	Mortality rate 40%		
		4,250		Mortality rate 50%		
		2,120		Mortality rate 100%		
	J	4,315	57	Mortality rate ≈ 100%	Field (fish kill)	Newcombe et al., 1995
Salmon, Chinook (*O. tshawytscha*)	YOY	29,000-33,000	96	Mortality rate 50%	Laboratory	Servizi and Gordon, 1990
Salmon, Pacific (*O.* spp.)	J	300-750 that were increased to 2,300 – 76,500 for short periods each day	504-672	No mortality		Griffin, 1938

Table D-3. Summary of Studies on Mortality of Salmonid Eggs and Larvae (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	**Life Stage [1]**	**Exposure Concentration (mg/L) [2]**	**Exposure Duration (hrs)**	**Fish Response**	**Type of Study (e.g., lab, field, dredge-related, etc.)**	**Reference**
Salmon, Chum (*Oncorhynchus keta*)	E	97 (SI)	2,808	Mortality rate 77% (controls 6%)	Laboratory	Langer, 1980
Salmon, Coho (*O. kisutch*)		157	1,728	Mortality rate 100% (controls 16.2%)	Field	Shaw and Maga, 1943
Steelhead (*O. mykiss*)		37	1,488	Hatching success 42% (controls 63%)	Laboratory	Slaney et al., 1977b
Trout, Rainbow (*O. mykiss*)	EE	1,750 (NS)	144	Mortality rate greater than controls (16%)	Dredging-related (mining), laboratory	Campbell, 1954
	E	6.7	1,152	Mortality rate 40%	Laboratory	Slaney et al., 1977b
		57	1,488	Mortality rate 47% (controls 38.6%)		
		120	384	Mortality rates 60-70% (controls 38.6%)	Field, eggs and larvae placed in boxes in stream	Erman and Ligon, 1988
		20.8	1,152	Mortality rate 72%	Laboratory	Slaney et al., 1977a
		46.6		Mortality rate 100%		Slaney et al., 1977b
		101	1,440	Mortality rate 98% (controls 14.6%)	Field	Turnpenny and Williams, 1980

Table D-3 (cont). **Summary of Studies on Mortality of Salmonid Eggs and Larvae (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	SF	379 (mean) (NS)	24	15% mortality compared to 6% mortality for control fish	Dredge-related (placer mining), field (caged fish in rivers)	Reynolds et al., 1989
			48	26% mortality compared to 14% mortality for control fish		
			72	41% mortality compared to 15% mortality for control fish		
			96	47% mortality compared to 13% mortality for control fish		
	E	14-2,301 (NS)	1 week	No significant difference with control fish	Dredge-related (placer mining), egg boxes in rivers	Scannell, 1988

Table D-4. Summary of Studies on Mortality of Adult and Juvenile Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Various Fish Species	A and J	160 (NS)	N/A	No mortality, compared to controls (19-23 mg/L)	Dredge-related, field	Liepolt, 1961
Various Fish Species	A	620	48	Fish kill downstream of sediment source	Field	Hesse and Newcomb, 1982
Carp, Common (*Cyprinus carpio*)		25,000 (MC)	336	Some mortality	Laboratory	Wallen, 1951
Goldfish (*Carassius auratus*)			24			
Fish, Warmwater		100,000 (MC)		Some fish died; most survived		
		22	8,760	Fish population destroyed	Field	Menzel et al., 1984

Table D-4 (cont.). **Summary of Studies on Mortality of Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Shiner, Tricolor (*Cyprinella trichroistra*)	E and L	>100 to >600	5	Egg and larval mortality increased as SS concentrations increased	Laboratory	Burkhead and Jelks, 2001
Catfish, Channel (*Ictalurus punctatus*)	A and J	N/A Fish were 200-400 yards from dredge disposal site (NS)	1,488	16% mortality, compared to 0% for control	Dredge-related study, field (mortality of fish determined caged fish before and after dredging) *	Ritchie, 1972
Hogchoker (*Trinectes maculates*)				43% mortality, compared to 50% mortality for control		
Bass, Striped (*Morone saxatilis*)				67% mortality; no control		
Perch, White (*M. americana*)				75% mortality, compared to 29% for control		
Bluegill (*Lepomis macrochirus*)	A	0-50	25	Beginning at > 5 mg/L mortality increased	Field	Miner and Stein, 1988

* Note: No caged fish were placed in non-spoil area.

Table D-5. Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Anchovy, Bay (*Anchoa mitchilli*)	A	2,310 (FE)	24	Mortality rate 10%	Laboratory	Sherk et al., 1975a, b, 1974
		4,710 (FE)		Mortality rate 50%		
		9,600 (FE)		Mortality rate 90%		
Cunner or Conner (*Tautogolabrus adspersus*)		28,000		Mortality rate 50%		Rogers, 1969
		133,000	12			
		100,000	24			
		72,000	48			
Flounder, Winter (*Pseudopleuronectes americanus*)		20,000	24	No mortalities		Boehmer et al., 1975
		6,800				
		1,200				
		20,000	96			
		6,800				
		1,200				
		45,000	24	Mortality rate 40%		
		45,000	96	Mortality rate 60%		

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Flounder, Yellowtail (*Pleuronectes ferrugineus*)	A	6,000	24	No mortalities	Laboratory	Boehmer et al., 1975
		1,200	96			
		22,000	24	Mortality rate 40%		
		32,000		Mortality rate 100%		
			96			
Hake, Red (*Urophysis chuss*) and Hake, White (*U. tenius*)		3,000	24	No mortalities		
		1,200				
		3,000	96			
		1,200				
		15,000	24	Mortality rate 40%		
			96	Mortality rate 60%		
		33,000	24	Mortality rate 100%		
			96			

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response [2]	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Killifish, Striped (*Fundulus majalis*)	A	23,770 (FE)	24	Mortality rate 10%	Laboratory	Sherk et al.,1975a,b, 1974
		38,190 (FE)		Mortality rate 50%		
		61,360 (FE)		Mortality rate 90%		
		97,200 (PS)		Mortality rate 10%		
		128,200 (PS)		Mortality rate 50%		
		169,300 (PS)		Mortality rate 90%		
Menhaden, Atlantic (*Scomber scombrusi*)	J	1,540 (FE)		Mortality rate 10%		
		2,470 (FE)		Mortality rate 50%		
		3,960 (FE)		Mortality rate 90%		
		6,800		No mortalities		Boehmer et al., 1975
		1,200				
		6,800	96			
		1,200				
		35,000	24	Mortality rate 100%		
		20,000	96			

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) and Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Minnow, Sheepshead (*Cyprinodon variegates*)	A	200,000	24	Mortality rate 10% (15°C)	Laboratory	Rogers, 1969
		300,000		Mortality rate 30% (10°C)		
		100,000		Mortality rate 90% (19°C)		
Mummichog (*Fundulus heteroclitus*)		24,470 (FE)		Mortality rate 10%		Sherk et al, 1975a,b, 1974
		39,000 (FE)		Mortality rate 50%		
		62,170 (FE)		Mortality rate 90%		
		35,860 (FE)	48	Mortality rate 10%		
		45,160 (FE)		Mortality rate 50%		
		56,890 (FE)		Mortality rate 90%		
		39,000 (FE)	24	Mortality rate 50% (15ºC)		
		300,000 (FE)		No mortality (15ºC)		
		24,470 (FE)		Mortality rate 10%		
		62,170 (FE)		Mortality rate 90%		

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Perch, White (*Morone americana*)	A	9,970 (NS)	24	Mortality rate 10%	Laboratory	Sherk et al., 1975a, b, 1974
		19,800 (NS)		Mortality rate 50%		
		39,400 (NS)		Mortality rate 90%		
		3,050 (FE)		Mortality rate 10%		
		9,850 (FE)		Mortality rate 50%		
		31,810 (FE)		Mortality rate 90%		
		670 (FE)	48	Mortality rate (10%)		
		2,960 (FE)		Mortality rate 50%		
		13,060 (FE)		Mortality rate 90%		
Perch, Shiner (*Cymatogaster aggregata*)		1,000	96	Mortality rate 10%		McFarland and Peddicord, 1980
		3,600		Mortality rate 20%		
		6,000		Mortality rate 50%		

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Rasbora, Harlequin (*Trigonostigma heteromorpha*)	A	6,000	168	No mortality	Laboratory	Alabaster and Lloyd, 1980
Silverside, Atlantic (*Menidia menidia*)		580 (FE)	24	Mortality rate 10%		Sherk et al., 1975a,b,1974
		2,500 (FE)		Mortality rate 50%		
		10,000 (FE)		Mortality rate 90%		
		20,000		No mortalities		Boehmer et al., 1975
		6,800				
		1,200	96			
		20,000		Mortality 100%		
		6,800				
		35,000	24			
			96			

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Cod (*Gadus morhua*)	A	550	24 -240	No mortality	Laboratory related to bottom trawling	Humborstad et al., 2006
Spot (*Leiostomus xanthurus*)		1,270	96		Laboratory	Sherk et al., 1975a,b, 1974
		14,680	168			
		1,140 (FE)	48	Mortality rate 10%		
		13,090 (FE)	24			
		68,750 (PS)				
		1,890 (FE)	48	Mortality rate 50%		
		20,340 (FE)	24			
		88,000 (PS)				
		3,170 (FE)	48	Mortality rate 90%		
		112,630 (PS)	24			
		31,620				

Table D-5. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Conditions Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Stickleback, Fourspine (*Apeltes quadracus*)	A	100 (IA)	24	Mortality rate <1%	Laboratory	Rogers, 1969
		10,000 (KS)		No mortality (10-12°C)		
		300 (IA)		Mortality rate ~ 50%		
		18,000		Mortality rate 50% (15-16°C)		
		50,000 (KS)		Mortality rate 50%		
		53,000		Mortality rate 50% (10-12°C)		
		330,000		Mortality rate 50% (9-9.5°C)		
		500		Mortality rate 100%		
		200,000 (KS)		Mortality rate 95%		
Stickleback, Threespine (*Gasterosteus aculeatus*)		28,000	96	No mortality in test designed to identify lethal threshold		LeGore and DesVoigne, 1973

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Perch, White (*Morone Americana*)	J	0-15	0.25	No change in mortality of prey	Laboratory	Monteleone and Houde, 1992
		750 (FE)	24	Mortality rate 100%		Sherk et al., 1975a,b,1974
Bluefish (*Pomatomus saltator*)		800				
Menhaden, Atlantic (*Scomber scombrusi*)						
Perch, Shiner (*Cymatogaster aggregata*)	A and J	14,000-89,000	240	Mortality rate 100%	Dredge-related, laboratory	Peddicord et al., 1975
			26	All died except 1 fish at 14,000 mg/L		
		3,000	200	Mortality rate 50%		
		600-6,000	70	Mortality rate 20%		
		<1,000	240	Mortality rate 10%		
Sole, English (*Parophrys vetulus*)		<70,000		No mortality		
		117,000		Mortality rate 80%		

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Anchovy, Bay (*Anchoa mitchilli*)	J	2,310 (FE)	24	Mortality rate 10%	Laboratory	O'Connor et al., 1976
		365 (FE)				
		4,710 (FE)		Mortality rate 50%		
		673 (FE)				
		9,600 (FE)		Mortality rate 90%		
		982 (FE)				
Silverside, Atlantic (Menidia menidia)		570 (FE)		Mortality rate 10%		
		2.400 (FE)		Mortality rate 50%		
		380 (FE)				
		10,000 (FE)		Mortality rate 90%		
		1,000 (FE)				
Perch, White (*Morone Americana*)		3,050 FE)		Mortality rate 10%		
		484 (FE)				
		9,850 (FE)		Mortality rate 50%		
		9,930 (FE)				

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Perch, White (*Morone Americana*)	J	3,181 (FE)	24	Mortality rate 90%	Laboratory	O'Connor et al., 1976
		1,503 (FE)				
		32,070 (FE)	12	Mortality rate 10%		
		41,000 (FE)		Mortality rate 50%		
		52,410 (FE)		Mortality rate 90%		
		7,910 (FE)	20	Mortality rate 10%		
		14,990 (FE)		Mortality rate 50%		
		28,380 (FE)		Mortality rate 90%		
		670 (FE)	48	Mortality rate 10%		
		2,960 (FE)		Mortality rate 50%		
		13,060 (FE)		Mortality rate 90%		
		9,970 (NS)	24	Mortality rate 10%		
		3,050 (FE)				
		19,800 (NS)		Mortality rate 50%		
		9,850 (FE)				
		39,400 (NS)		Mortality rate 90%		
		31,810 (FE)				

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Spot (*Leiostomus xanthurus*)	J	27,560 (FE)	12	Mortality rate 10%	Laboratory	O'Connor et al., 1976
		42,360(FE)		Mortality rate 50%		
		65,120 (FE)		Mortality rate 90%		
		21,070 (FE)	18	Mortality rate 10%		
		33,060 (FE)		Mortality rate 50%		
		51,870 (FE)		Mortality rate 90%		
		13,080 (FE)	24	Mortality rate 10%		
		11,170 (FE)				
		28,380 (FE)		Mortality rate 90%		
		20,340 (FE)		Mortality rate 50%		
		31,620 (FE)		Mortality rate 90%		
		15,100(FE)				
		1,130 (FE)	48	Mortality rate 10%		
		1,900 (FE)		Mortality rate 50%		
		3,170 (FE)		Mortality rate 90%		

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Killifish, Striped (*Fundulus majalis*))	J	27,770 (FE)	24	Mortality rate 10%	Laboratory	O'Connor et al., 1976
		1,376 (FE)				
		38,180(FE)		Mortality rate 50%		
		1,582 (FE)				
		61,360 (FE)		Mortality rate 90%		
		1,788 (FE)				
		97,100 (NS)		Mortality rate 10%		
		23,770 (FE)				
		128,200 (NS)		Mortality rate 50%		
		38,180 (FE)				
		169,300 (NS)		Mortality rate 90%		
		61,360 (FE)				
Croaker (*Micropogon undulatis*)		11,400 (FE)		Mortality rate 100%		
Weakfish (*Cynoscion regalis*)		6,800 (FE)				
Bluefish (*Pomatomus saltatrix*)		800 (FE)				

Table D-5 (cont). **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Mummichog (*Fundulus heteroclitus*)	J	24,470 (FE)	24	Mortality rate 10%	Laboratory	O'Connor et al., 1976
		1,389 (FE)				
		39,000(FE)		Mortality rate 50%		
		1,581 (FE)				
		62,170 (FE)		Mortality rate 90%		
		1,794 (FE)				
Menhaden, Atlantic (*Scomber scombrusi*))		1,200 (FE)		Mortality rate 100%		
		800 (FE)				
Bass, Striped (*Morone saxatilis*)		16,000 (FE)				

Table D-6. **Summary of Studies on Mortality of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Turbidity.**

Fish Species	Life Stage [1]	Turbidity Level (JTU) [2,*]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Rockfish, Brown (*Sebastes auriculatus*)	A and J	500-2,500 (BS)	1,008	No mortality	Dredge-related (hopper and clam shell dredging), in San Francisco and San Pablo Bays, laboratory	USFWS, 1970
Bass, Striped (*Morone saxatilis*)				Mortality was 7-11% , as increased JTU's		
Seaperch, Rubberlip (*Rhacochilus toxotes*)				Mortality was 16-47% , as increased JTU's		
Tomcod, Pacific (*Microgadus proximus*)				Mortality was 5-40% , as increased JTU's		
Perch, Shiner (*Cymatogaster aggregata*)				Mortality was 34-58% , as increased JTU's		
Perch, White (*Morone Americana*)				Mortality was 30-92% , as increased JTU's		

* JTU = Jackson Turbidity Units

Table D-7. **Summary of Studies on Mortality of Non-Salmonid Eggs and Larvae (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Pacific (*Clupea harengus pallasi*)	E	500-10,000 (NS)	432-792 hours to hatching	Decreased hatchability with increased SS concentration	Dredge-related, laboratory	Morgan and Levings, 1989
	L			Decreased survival with increased SS concentration		
	E vs L			Larval stage was more sensitive to SS than egg stage		
Smelt, Surf (*Hypomesus pretiosus*)	E			Decreased hatchability with increased SS concentration		
				Decreased survival with increased SS concentration		
	E vs L			Larval stage was more sensitive to SS than egg stage		
Lingcod (*Ophiodon elongates*)	E			No change in hatchability with increased SS concentration		
	L			No change in survival with increased Ss concentration		

Table D-7. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Eggs and Larvae (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Pacific (*Clupea harengus pallasi*)	E	500-8,000 (VA and NS)	288	Increased mortality with increased SS concentrations SS more lethal than VA	Laboratory	Boehlert et al., 1983
Bass, Striped (*Morone saxatilis*)	L	500	72	Mortality rate 42% (controls 17%)		Auld and Schubel, 1978
		1,000	68	Mortality rate 35% (controls 16%)		
		2,800 (NS)	48	Mortality rate 50%		Sherk et al., 1975a,b, 1974
		4,850 (NS)	24			
	E	1,000		Did not affect hatching success		Schubel et al., 1973
		≤500				
	L	485		Mortality rate 50%		Morgan et al., 1973
		1,200 (BC)	240	Mortality rate 10%	Dredge-related (San Francisco Bay), laboratory	Wakeman et al., 1975
Herring, Atlantic (*Clupea harengus harengus*)		19,000 (NS)	48	Mortality rate 100%	Dredge-related, laboratory	Messieh et al., 1981
		≤7,000 (NS)	216-288 (to hatching)	No effect on hatching success		

Table D-7. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Eggs and Larvae (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Atlantic (*Clupea harengus harengus*)	E	5-300 mg/L continuously	240	No effect on hatching success	Laboratory	Kiørboe et al., 1981
		500 mg/L pulses				
Perch, White (*Morone americana*)	E	1,000	96	No effect		Auld and Schubel, 1978
	L		168	Reduced hatching success		
		3,730 (NS)	24	Mortality rate 50%		Sherk et al., 1975a,b, 1974
		1,550	48	Mortality rate 50%		Morgan et al., 1973
		373	24			
		280	48			
Perch, Yellow (*Perca flavescens*)	L	500	96	Mortality rate 37% (controls 7%)		Auld and Schubel, 1978
		1,000		Mortality rate 38% (controls 7%)		
	E	≤500	24	Did not affect hatching success		Schubel et al., 1973
		1,000				
		500		Mortality rate 36% (controls 4%)		

Table D-7. (Cont.) **Summary of Studies on Mortality of Non-Salmonid Eggs and Larvae (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Shad, American (*Alosa sapidissima*)	L	100	96	Mortality rate 18% (controls 7%)	Laboratory	Auld and Schubel, 1978
		500		Mortality rate 36% (controls 4%)		
		1,000		Mortality rate 34% (controls 5%)		
Herring, Lake (*Coregonus artedi*)	E and L	20 mg/L three times per day	288	No significant effect on egg hatching success		Savino et al., 1994
		20 mg/L one time per day				
		2 mg/L one time per day				

APPENDIX E

SUMMARY OF DREDGE-RELATED STUDIES THAT RESULTED IN MORTALITY IN FISHES EXPOSED TO SS AND TURBIDITY

Legend

[1] A=adult; E=egg; EE= eyed egg; FF=young fry (<30 weeks old); J=juvenile; L=larval; U=underyearling; YOY young-of-the-year.

[2] Particle sizes of suspended sediment (SS): BS = Bay sediment; NS = natural sediment.

[3] JTU = Jackson Turbidity Units

Table E-1. Summary of Dredge-Related Studies that Resulted in Mortality in Salmonids (Freshwater) Exposed to SS.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Salmon, Chum (*Oncorhynchu keta*)	J	15.8-54.9	96	Mortality rate 50%	Dredge-related, laboratory	Smith, 1978
		28,000 – 55,000 (NS)			Dredge-related (placer mining), laboratory studies	Smith, 1939
Trout, Rainbow (*O. kisutch*)	FF	1,750 (NS)	480	Mortality rate 57% (Controls 5%)	Dredge-related (placer mining), laboratory studies	Campbell, 1954
	EE		144	Mortality rate greater than controls (16%)		
Grayling, Arctic (*Thymallus arcticus*)	J	14-2,301 (NS)	96	No significant difference compared to control fish	Dredge-related (placer mining), field cages fish in rivers) studies	Scannell, 1988
	YOY	>3,000	24-216	Mortality rate 0%		Reynolds et al., 1989
	SF	379 (mean) (NS)	24	15% mortality compared to 6% mortality for control fish		
		48		26% mortality compared to 14% mortality for control fish		
		72		41% mortality compared to 15% mortality for control fish		
		96		47% mortality compared to 13% mortality for control fish		
	E	14-2,301 (NS)	1 week	No significant mortality	Dredge-related (placer mining), field (egg boxes in rivers) studies	Scannell, 1988

Table E-2. Summary of Dredge-Related Studies that Resulted in Mortality in Pacific Herring and Atlantic Herring Exposed to SS and Turbidity.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (JTU) [3]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Herring, Pacific (*Clupea harengus palassi*)	L	500-10,000 (NS)		432-792	Decreased hatchability with increased SS concentration	Dredge-related, laboratory studies	Morgan and Levings, 1989
	L vs E				Larval stage was more sensitive to SS than egg stage		
	E				Decreased survival with increased SS concentration		
Herring, Atlantic (*Clupea harengus harengus*)	L		19,000	48	No living larvae observed	Dredge-related, laboratory studies	Messieh et al., 1981

Table E-3. Summary of Dredge-Related Studies that Resulted in Mortality in Non-Salmonids (Freshwater) Exposed to SS.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Various Fish Species	A and J	160 (NS)	N/A	No mortality, compared to controls (19-23 mg/L)	Dredge-related, field	Liepolt, 1961
Catfish, Channel (*Ictalurus punctatus*)		N/A Fish were 200-400 yards from dredge disposal site (NS)	1,488	16% mortality, compared to 9% for controls	Dredge-related; field (mortality of fish determined in caged fish in the rivers before and after dredging) studies *	Ritchie, 1970
Hogchoker (*Trinectes maculates*)				43% mortality compared to 50% mortality for controls		
Bass, Striped (*Morone saxatilis*)				67% mortality, no controls		
Perch, White (*M. Americana*)				75% mortality compared to 29% for controls		

* Note: No caged fish were placed in non-spoil areas.

Table E-4. Summary of Dredge-Related Studies that Resulted in Mortality in Non-Salmonids (Marine and Estuarine Environments) Exposed to SS and Turbidity.

Fish Species	Life Stage [1]	Exposure Concentration	Turbidity Level (JTU) [2,3]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Bass, Striped (*Morone saxatilis*)	L		1,200	240	Mortality rate 10%	Dredge-related, laboratory (San Francisco Bay) studies	Wakeman et al., 1975
Rockfish, Brown (*Sebastes auriculatus*)	A and J		500-2500 (BS)	1,008	No mortality	Dredge-related (hopper and clam shell), field studies (San Francisco Bay)	USFWS, 1970
Seaperch, Rubberlip (*Rhacochilus toxotes*)					Mortality was 70-11% as JTU's increased		
Tomcod, Pacific (*Microgadus proximus*)					Mortality was 16-47% as JTU's increased		
Perch, Shiner (*Cymatogaster aggregata*)					Mortality was 5-40% as JTU's increased		
Perch, White (*M. americana*)					Mortality was 34-58% as JTU's increased		
Smelt, Surf (*Hypomesus pretiosus*)	E	500-10,000 (NS)		432-792 hours to hatching	Decreased hatchability and survival with increased SS concentration	Dredge-related, laboratory studies	Morgan and Levings, 1989
	L vs E				Larval stage was more sensitive to SS than egg stage		

Table E-4 (cont.). **Summary of Dredge-Related Studies that Resulted in Mortality in Non-Salmonids (Marine and Estuarine Environments) Exposed to SS and Turbidity.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (JTU) [2,3]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Lingcod (*Ophiodon elongates*)	E	500-10,000 (NS)		432-792 hours to hatching	No change in hatchability or survival with increased SS concentration	Dredge-related, laboratory studies	Morgan and Levings, 1989
	L vs E				No change in survival		
Perch, Shiner (Cymatogaster aggregate)	A and J	14,000-89,000		240	Mortality rate 100%	Dredge-related, laboratory	Peddicord et al., 1975
				26	All died except 1 fish at 14,000 mg/L		
		3,000		200	Mortality rate 50%		
		600-6,000		70	Mortality rate 20%		
		<1,000		240	Mortality rate 10%		
Sole, English (*Parophrys vetulus*)		<70,000			No mortality		
		117,000			Mortality rate 80%		

APPENDIX F

SUMMARY OF STUDIES ON MORTALITY IN CHINOOK SALMON, STEELHEAD, RAINBOW TROUT, AND PACIFIC AND ATLANTIC HERRING EXPOSED TO SS *

Legend

[1] A=adult; J=juvenile; L=larval; S=smolt; SF=sac fry; YOY=young-of-the-year

[2] Particle sizes of suspended sediment (SS): CSS = coarse 9180-740 um). CS = calcium sulfate; DE diatomaceous earth; DM = drilling mud (nontoxic); KC = kaolin clay; NS = natural sediment; VA = volcanic ash; WF = wood fibers.

* No mortality studies were found that used turbidity on the fish species mentioned in this Appendix.

Table F-1. Summary of Studies on Mortality of Chinook Salmon (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
A	39,300 (VA)	24	No mortality, <5-100 um; median <15 um)	Laboratory	Newcomb and Flagg, 1983
	82,400 (VA)	6	Mortality rate 60% , <5 -100 um)		
	207,000 (VA)	1	Mortality rate 100%, <5 -100 um)		
J	N/A (VA)	48-72 hours following Mt. St. Helens eruption	100% mortality	Field: Mt. St. Helens eruption	Phinney, 1982
	1,400	0.36	Mortality rate 50%	Laboratory	Newcomb and Flagg, 1983
	9,400 (VA)	36			
	39,400 (VA)		Mortality rate 90%		
S	488	96	Mortality rate 50%		Stober et al., 1981
	11,000				
	19,364				
YOY	29,000-33,000				Servizi and Gordon, 1990

Table F-2. Summary of Studies on Mortality of Steelhead (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
J	N/A	0.5	Mortality rate 100%	Field, fish held in cages in river downstream of coal washing	Pautzke, 1938
E	37	1,388	Hatching success 42% (controls were 63%)	Laboratory	Slaney et al., 1977b

Table F-3. Summary of Studies on Mortality of Rainbow Trout (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
A	200 (WF)	24	Fish began to die on first day	Laboratory	Herbert and Richards, 1963
	270	3,240	Survival rate reduced		
	810 (DE, KC)	504	Some fish died		Herbert and Merkens, 1961
	4,250 (CS)	588	Mortality rate 50%		Herbert and Wakeford, 1962
	49,838 (DM)	96	Mortality rate 50%		Lawrence and Scherer, 1974
	160,000	24	Mortality rate 100%		Alabaster and Lloyd, 1980
J	4,315 (CSS)	57	Mortality rate ~100	Field (fish kill)	Newcombe et al., 1995
Y	270 (DE)	456	Mortality rate 25-80%	Laboratory	Herbert and Merkens, 1961
	90 (DE, KC)		Mortality rates 0-20%		
			Mortality rates 0-15%		
	810 (KC)		Mortality rate 5-80%		
	810 (DE)		Mortality rates 35-85%		
	2,120	672	Mortality rate 100%		
	4,250		Mortality rate 50%		

Table F-3 (cont.). **Summary of Studies on Mortality of Rainbow Trout (Freshwater) Exposed to Suspended Sediments/Solids.**

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Y	7,433 (CS)	672	Mortality rate 40%	Laboratory	Herbert and Merkens, 1961
E	6.7	1,152	Mortality rate 40%		Slaney et al., 1977b
	20.8		Mortality rate 72%		Slaney et al., 1977a
	46.6	1,152	Mortality rate 47% (control 38.6%)	Laboratory	Slaney et al., 1977b
	57	1,488	Mortality rate 100%		
	101	1,440	Mortality rate 98% (controls 14.6%)	Field	Turnpenny and William, 1980
	120	384	Mortality rates 60-70% (controls 38.6%)	Field, eggs and larvae placed in boxes in stream	Erman and Ligon, 1988
EE	1,750 (NS)	144	Mortality rate greater than controls	Dredge-related (placer mining), laboratory	Campbell, 1954
FF		480	Mortality rate 57% (controls 5%)		

Table F-4. Summary of Studies on Mortality of Pacific and Atlantic Herring Exposed to Suspended Sediments/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Pacific (*Clupea harengus pallasi*)	E vs L	500-10,000 (NS)	432-792 hours to hatching	Larval stage was more sensitive to SS than egg stage	Dredge-related, laboratory	Morgan and Levings, 1989
	E			Decreased hatchability with increased SS concentrations		
		500-800 (VA)	288	Increased mortality with increased SS concentrations	Laboratory	Boehlert et al., 1983
	L	500 mg/L static; 8,000 mg/L continuous	24	Decreased survival with increased SS concentrations	Dredge-related, laboratory	Morgan and Levings, 1989
				No significant effect on larval mortality or hatching	Laboratory	Boehlert, 1984
		4,000		No effect on survival		Boehlert et al., 1983
Herring, Atlantic (*Clupea harengus harengus*)		≤7,000	216-288 hours to hatch	No effect on hatching success		Messieh et al., 1981
		19,000	48	Mortality rate 100%	Dredge-related, laboratory	
	E	5-300 mg/L continuous; 500 mg/L pulses	240	No effect on survival or hatchery success	Laboratory	Kiørboe et al., 1981

A.A. RICH AND ASSOCIATES

APPENDIX G

SUMMARY OF PRIMARY STRESS RESPONSES IN FISHES EXPOSED TO SUSPENDED SEDIMENTS AND SUSPENDED SOLIDS *

Legend

[1] A=adult; Y=approximately yearling; YOY=young-of-the-year

* Note: No Primary Stress Response studies were found that used turbidity.

Table G-1. Summary of Primary Stress Responses in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related	Reference
Salmon, Coho (*Oncorhynchus kisutch*)	Y	2,000	4	Increased blood cortisol concentrations	Laboratory	Redding et al., 1987
		4,000	24			
			48			
		400	4			
		600	24			
Steelhead (*O. mykiss*)		1,700-2,000	12			
			24			
			48			
			96			
		400-600	48			

Table G-2. Summary of Primary Stress Responses in Juvenile Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids Concentrations.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related	Reference
Shiner, Whitetail (*Cyprinella galactura*)	YOY	50-500	48	Whole-body cortisol concentration increased as SS concentrations increased	Laboratory	Sutherland et al., 2008
Chub, Spotfin (*Erimonax monachus*)						

Table G-3. Summary of Primary Stress Responses in Non-Salmonids in Marine and Estuarine Conditions Exposed to Suspended Sediment/Solids Concentrations.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related	Reference
Cod, Atlantic (*Gadus morhua*)	A	550	24	No change in blood cortisol concentrations	Laboratory	Humborstad et al., 2006
			120-240	Increased blood cortisol concentrations		

A.A. RICH AND ASSOCIATES

APPENDIX H

SUMMARY OF SECONDARY STRESS RESPONSES IN FISHES EXPOSED TO SUSPENDED SEDIMENTS AND SUSPENDED SOLIDS *

Legend

[1] A=adult; F=fry; J=juvenile; L=larval; S=smolt; U=underyearling; Y=approximately yearling; YOY=young-of-the-year

[2] Particle sizes of suspended sediment (SS): FE = fuller's earth; NS = natural sediment; VA = volcanic ash.

N/A = not available

* Note: No Secondary Stress Response studies were found that used turbidity.

Table H-1. Summary of Secondary Stress Responses (Physiological) in Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Sockeye (*Oncorhynchus nerka*)	A	500	96	Plasma glucose levels increased 39%	Laboratory	Servizi and Martens, 1987
		1,500		Plasma glucose levels increased 150%		
Steelhead (*O. mykiss*)		500 (VA)	3	Signs of sublethal stress		Redding and Schreck, 1982
			9	Blood glucose increased; hematocrit increased		

Table H-1 (cont.). **Summary of Secondary Stress Responses (Physiological) in Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Whitefish, Mountain (*Prosopium williamsoni*)	A	1,438-18,000	15-18	Hematocrit, plasma protein, fat index, and Health Assessment Index decreased	Field (electrofishing)	Bergstedt and Bergersen, 1997

Table H-2. **Summary of Secondary Stress Responses (Physiological) in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Coho (*Oncorhynchus kisutch*)	J	40,000	96	Leucocrit increased when fish exposed to "angular" and "round" silicate sediments	Laboratory	Lake and Hinch, 1999
		>41,000		Hematocrit increased when fish exposed to "angular" and "round" silicate sediments		
	Y	2,000-4,000	9	Hematocrit increased		Redding et al., 1987
			24			
		400-600	9			
			24			
Salmon, Sockeye (*O. nerka*))	J	14,407	96	Impaired parr-smolt Transformation (osmoregulatory impairment		Servizi and Martens, 1987
	S	1,261		Body moisture content reduced		
		7,447		Plasma chloride levels increased slightly		

Table H-2 (cont.). Summary of Secondary Stress Responses (Physiological) in Juvenile Salmonids (Freshwater) Exposed to Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*O. tshawytscha*)	S	943 (VA)	72	Tolerance to stress reduced	Laboratory	Stober et al., 1981
Salmon, Coho (*O. kisutch*)	U	530	96	Blood glucose levels increased		Servizi and Martens, 1992
	J	53.5	12	Increased physiological stress		Berg and Northcote, 1985
Steelhead (*O. mykiss*)	Y	400-600	9	Hematocrit increased		Redding et al., 1987
		2,000	24			
		4,000	9			
			24			
Salmon, Chum (*O. keta*)	J	150-200	96	No change in blood glucose levels, compared to controls (SS = <35 mg/L)	Dredge-related, laboratory	Smith, 1978

Table H-3. **Summary of Secondary Stress Responses (Injury) in Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	A	650 (VA)	168	No histological signs of damage to olfactory epithelium	Laboratory	Brannon et al., 1982
Trout		270	312	Gill tissue damage		Herbert and Merkens, 1961
Trout, Rainbow (*O. mykiss*)		100 (FSS)	0.25	Rate of coughing increased		Hughes, 1975
		250 (FSS)				
		810	504	Gills of surviving fish had thickened epithelium		Herbert and Merkens, 1961
		17,500	168	Gills of surviving fish had thickened and perforated epithelium		Slanina, 1962
Trout, Brown (*Salmo trutta*)		1,040 (VFSS)	17,520	Gill lamellae thickened		Herbert et al., 1961
		1,210 (VFSS)		Some gill lamellae fused		
Whitefish, Mountain (*Prosopium williamsoni*)		1,438 – 18,000	15-18	Abnormal gills and fins		Bergstedt and Bergersen 1997

Table H-4. **Summary of Secondary Stress Responses (Injury) in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)[2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	YOY	1,250 (NS)	48	Moderate damage to gill tissue	Laboratory	Simmons, 1982
		1,388 (NS)	96	Hyperplasia and hypertrophy of gill tissue		
		2,810 (NS)	144	Mucous accumulated in gill lamellae and fish displayed signs of poor condition		
	U	100,000	168	No changes in gill histology (not an end point)		McLeay et al., 1983
Salmon, Sockeye (*O. nerka*))	U	3,143	96	Hypertrophy and necrosis of gill tissue (FSS)		Servizi and Martens, 1987
		17,560				
		23,790				
		1,465		Hypertrophy and necrosis of gill tissue (CSS)		
		2,688		Hypertrophy and necrosis of gill tissue (MCSS)		
		9,851				
		9,850		Gill hyperplasia, hypertrophy, separation, necrosis (MFSS)		

Table H-4 (cont). **Summary of Secondary Stress Responses (Injury) in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Coho (*O. kisutch*)	J	1,547	96	Gill damage	Laboratory	Noggle, 1978
Steelhead (*O. mykiss*)	J	N/A	1	Gills clogged with mucous	Field, fish held in cages downstream of coal washing	Pautzke, 1937
Salmon, Coho (O. *kisutch*)	F	16,000-41,000	96	Gills clogged with sediment particles	Laboratory	Martens and Servizi, 1993
Salmon, Pink (*O. gorbuscha*)		4,000- 21,000				
		1,600		No sediment particles in the gills		
Salmon, Sockeye (*O. nerka*)		5,000		Gills clogged with sediment particles		
Salmon, Chinook (*O. tshawytscha*)		61-200				
Trout, Rainbow (*O. mykiss*)	J	4,887	384	Hyperplasia of gill tissue and parasitic infection of gill tissue		Goldes, 1983, Goldes et al., 1986
		171	96	Particles penetrated gills		

Table H-4 (cont). **Summary of Secondary Stress Responses (Injury) in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chum (*O. keta*)	J	N/A (NS)	240-480	Tail fin rot	Dredge-related, laboratory	Smith, 1978
Salmon, Coho (*O. kisutch*)	U	20	0.05	Cough frequency not increased	Laboratory	Servizi and Martens, 1992
		240	24	Coughing frequency increased more than 5-fold		
		2,460	0.05	Coughing behavior manifested within minutes Fatigue of the cough reflex		

Table H-5. Summary of Secondary Stress Responses (Physiological) in Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bluegill (*Lepomis cyanellus*)	A	144.5	720	Fish unable to reproduce	Field (farm ponds, hatchery, reservoir, seined fish)	Buck, 1956
Bass, Largemouth (*Lepomis salmoides*)						
Sunfish, Redear (*Lepomis microlophus*)						
Green Sunfish (*Lepomis cyanellus*)		3.3-26.7	120	50-70% increased gill ventilation and oxygen consumption rates at > 13.3 mg/L	Laboratory	Horkel and Pearson, 1976

Table H-6. Summary of Secondary Stress Responses (Physiological) in Non-Salmonids (Marine and Estuary) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bass, Striped (*Morone saxatilis*)	YOY	790-1,320	3	Swimming performance decreased as SS concentrations increased Depressed oxygen consumption as SS concentrations increased	Laboratory	Neumann et al., 1982
	A	1,500 (FE)	336	Plasma osmolality increased		Sherk et al., 1975a,b, 1974
Hogchoker (*Trinectes maculates*)		1,240 (FE)	120	Hematocrit increased		
Killifish, Striped (*Fundulus majalis*)		960 (FE)				
Mummichog (*Fundulus heteroclitus*)		1,620 (FE)	96			
Perch, White (*M. Americana*)		650 (FE)	120			

Table H-6 (cont.). **Summary of Secondary Stress Responses (Physiological) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Hogchoker (*Trinectes maculates*)	A	1,240	24	Energy utilization increased	Laboratory	Sherk et al., 1975a,b,1974
			120	Erythrocyte and hematocrit increased		
Killifish, Striped (*Fundulus majalis*)		960		Hematocrit increased		
Perch, White (*Morone americana*)		650		Hematocrit, erythrocytes, and hemoglobin increased		Neumann et al., 1975
Toadfish, Oyster (*Opsanus tau*)		3,360	1	Oxygen consumption more variable in pre-stressed fish		
		14,600	72	Fish initially largely unaffected, but developed ill effects later		
		11,090				

Table H-6 (cont.). **Summary of Secondary Stress Responses (Physiological) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Hogchoker (*Trinectes maculates*)	Probably A and J	12,400 (FE)	120	Increased RBC's and hematocrit, decreased liver glycogen, no change in hemoglobin	Dredge-related, laboratory	O'Connor et al., 1977
Killifish, Striped (*Fundulus majalis*)		960 (FE)	120	Increased hematocrit, but no changes in RBC's or hemoglobin		
Perch, White (*Morone americana*)		12,400 (FE)	120	Increased RBC's and hematocrit , no change in hemoglobin		
		2,000 (NS)	96	No changes in RBC's, hematocrit or hemoglobin		
			144	Significant increases in RBC's, hematocrit, and hemoglobin		
			336	No changes in RBC's, hematocrit, and hemoglobin		

RBC's = red blood cells

Table H-6 (cont.). **Summary of Secondary Stress Responses (Physiological) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Spot	Probably A and J	16,960 (NS)	24	No change in RBC's, hematocrit or hemoglobin	Dredge-related, laboratory	O'Connor et al., 1977
			72			
			168			
		12,700 (FE)	120			
Bass, Striped (*Morone saxatilis*)		1,500 (FE)	336	Increased hematocrit, no changes in RBC's or hemoglobin		
		1,500 (NS)	144	No changes in RBC's, hematocrit or hemoglobin		
		6,000 (NS)				
		1,310	1	Oxygen consumption decreased		
		1,330				
Mummichog		16,000	96	Increased hematocrit, no change in RBC's or hemoglobin		
			168			
			288			
Toadfish (*Opsanus tau*)		24.600 (NS)	72	No change in RBC's, hematocrit or hemoglobin		

RBC's = red blood cells

Table H-7. Summary of Secondary Stress Responses (Injury) in Non-Salmonid Juveniles (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Shiner, Whitetail (*Cyprinella galactura*)	YOY	0-100	504	No significant gill injury	Laboratory	Sutherland and Meyer, 2007
		500		Significant gill injury		
Chub, Spotfin (*Erimonax monachus*)		0-100		No significant gill injury		
		500		Significant gill injury		
Menhaden, Gulf (*Brevoortia patronus*)	A and J	Turbid versus Clear	N/A	Injuries, such as missing fins, flesh wounds	Field, netted fish	Kroger and Guthrie, 1972
Sea Trout, Spotted (*Cynoscion nebulosus*)						
Blue Runner (*Caranx crysos*)						

Table H-8. Summary of Secondary Stress Responses (Injury) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related)	Reference
Perch, White (*Morone americana*)	A	305 (FE)	120	Gill tissue may have been damaged	Laboratory	Sherk et al., 1975a, b, 1974
		650 (FE)		Histological damage to gill tissue		
	Probably A and J	650 (FE)		Gill damage		O'Connor et al., 1977
Cod (*Gadus morhua*)	A	550	24-240	Gill hypertrophy and hyperglasia		Humborstad et al., 2006

Table H-9. **Summary of Secondary Stress Responses (Injury) in Non-Salmonid Eggs and Larvae (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Pacific (*Clupea harengus palassi*)	L	1,000	24	Mechanical damage to epidermis	Laboratory	Boehlert, 1984
		4,000		Epidermis punctured		

APPENDIX I

SUMMARY OF DREDGE-RELATED STUDIES THAT RESULTED IN SECONDARY STRESS RESPONSES IN FISHES EXPOSED TO SUSPENDED SEDIMENTS AND SUSPENDED SOLIDS *

Legend

[1] J=juvenile

* Note: No dredge-related Secondary Stress Response studies were found that used turbidity

Table H-1. Summary of Dredge-Related Studies that Resulted in Secondary Stress Responses (Physiological and Injury) in Salmonids Exposed to Sediments/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chum (*O. keta*)	J	150-200	96	No change in blood glucose levels, compared to controls (SS = <35 mg/L)	Dredge-related, laboratory	Smith, 1978
		N/A (NS)	240-480	Tail fin rot		

Table I-2. **Summary of Dredge-Related Studies that Resulted in Secondary Stress Responses (Physiological and Injury) in Non-Salmonids (Marine and Estuarine Environments) Exposed to Sediments/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Spot	Probably A and J	16,960 (NS)	24	No change in RBC's, hematocrit or hemoglobin	Dredge-related, laboratory	O'Connor et al., 1977
			72			
			168			
		12,700 (FE)	120			
Bass, Striped (*Morone saxatilis*)		1,500 (FE)	336	Increased hematocrit, no changes in RBC's or hemoglobin		
		1,500 (NS)	144	No changes in RBC's, hematocrit or hemoglobin		
		6,000 (NS)				
		1,310	1	Oxygen consumption decreased		
		1,330				
Mummichog		16,000	96	Increased hematocrit, no change in RBC's or hemoglobin		
			168			
			288			
Toadfish (*Opsanus tau*)		24.600 (NS)	72	No change in RBC's, hematocrit or hemoglobin		

RBC's = red blood cells

APPENDIX J

SUMMARY OF STUDIES ON SECONDARY STRESS RESPONSES IN CHINOOK SALMON, STEELHEAD, RAINBOW TROUT, AND PACIFIC HERRING EXPOSED TO SUSPENDED SEDIMENTS AND SUSPENDED SOLIDS *

Legend

[1] A=adult; F=fry; J=juvenile; L=larval; S=smolt; U=underyearling; Y=approximately yearling; YOY=young-of-the-year

[2] Particle sizes of suspended sediment (SS): FSS = fine (15-74 um); VA = volcanic ash.

* No secondary Stress Response studies were found that used turbidity.

Table J-1. Summary of Studies on Secondary Stress Responses in Chinook Salmon (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
A	650 (VA)	168	No histological signs of damage to olfactory epithelium	Laboratory	Brannon et al., 1981
J	61-200	96	Gills clogged with sediment particles		Martens and Servizi, 1993

Table J-2. Summary of Studies on Secondary Stress Responses in Steelhead (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
A	500 (VA)	3	Signs of sublethal stress	Laboratory	Redding and Schreck, 1982
		9	Blood glucose and hematocrit increased		
J	N/A	1	Gills clogged with mucous	Field, fish held in cages downstream of coal washing	Pautzke, 1037
Y	400-600	9	Hematocrit increased	Laboratory	Redding et al., 1987
		24			
	2,000	9			
	4,000	24			

Table J-3. Summary of Studies on Secondary Stress Responses in Rainbow Trout (Freshwater) Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
A	100 (FSS)	025	Rate of coughing increased	Laboratory	Hughes, 1975
	250 (FSS)				
	810	504	Gills developed thickened epithelium		Herbert and Merkens, 1961
	17,500	168	Gills developed thickened epithelium and were perforated		Slanina, 1962
J	171	96	Particles penetrated gills		Goldes, 1983; Goldes et al., 1986
	4,887	384	Hyperplasia of gill tissue and parasitic infection of gill tissue		

Table J-4. Summary of Studies on Secondary Stress Responses in Pacific Herring Exposed to Suspended Sediments/Solids.

Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
L	1000	24	Mechanical damage to epidermis	Laboratory	Boehlert, 1984
	4,000		Epidermis punctured		

APPENDIX K

SUMMARY OF STUDIES ON TERTIARY STRESS RESPONSES IN FISHES EXPOSED TO SUSPENDED SEDIMENT, SUSPENDED SOLIDS, AND TURBIDITY

Legend

[1] A=adult; E=egg; F=fry; FF=young fry (<30 weeks old); J=juvenile; L=larval; S=smolt; U=underyearling; Y=approximately yearling; YOY=young-of-the-year

[2] Particle sizes of suspended sediment (SS): FSS = fine (15-74 um); LNFH = lime-neutralized ferric hydroxide; MFSS = medium to fine (75-149); BS=Bay Sediment; FE = fuller's earth; NS = natural sediment; VA = volcanic ash.

[3] NTU= Nephelometric Turbidity Units

NA = Not available.

Table K-1. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	A	650 (VA)	10 minutes exposure, then fish released	Number of returning adults not significantly different from controls	Laboratory, artificial stream	Brannon et al., 1982
		146-373, mean 337 (VA)		Decreased number of salmon that chose volcanic ash-laden "home water" (i.e., avoidance)	Laboratory, Y-maze study	
Salmon (*O.* spp)		210 (NS)	24	Abandoned traditional spawning habitat	Dredge-related (sand pits), field	Hamilton, 1961
Trout, Brown (*Salmo trutta*)		N/A Used a secchi disk and did not relate depth of clarity to any turbidity level	July during 1984 and 1985 when siltation became a problem	Changes from feeding off the bottom (where food sources were before siltation) to feeding at surface or mid-water where food sources were	Field, CPUE *	Borgström et al., 1992
Grayling, Arctic (*Thymallus arcticus*)		100	0.10	Avoidance behavior	Field	Suchanek et al., 1984a,b
Trout, Lake (*Salvelinus namaycush*)		3.5	168		Laboratory	Swenson, 1978
Trout, Brook (*S. fontinalis*)		45	168	Fish less dependent on cover, more active		Gradall and Swenson, 1982

* CPUE = catch-per-unit-effort

Table K-1 (cont.). **Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Rainbow (*O. mykiss*)	J	<10 ≥ 10	7,920, sampled monthly	Inhabited clear areas (i.e., < 10 mg/L)	Field (reservoir)	Dörgeloh, 1995
		66	1	Avoidance behavior manifested part of the time	Laboratory	Lawrence and Scherer, 1974
		665		Attraction		
Whitefish, Mountain (*Prosopium williamsoni*)		0.60		Swimming behavior changed		

* CPUE = catch-per-unit-effort

Table K-2. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	U	20 (NS)	24	Fish avoided parts of the stream	Dredge-related (placer mining), field	Birtwell et al., 1984
		100	756	Fish moved out of test channel	Laboratory	McLeay et al., 1987
		300		Fish displaced from their habitat		
		300 (FSS)	1	Avoidance behavior		
		1,000 (FSS)				
		10,000	96	Fish swam away from turbid water towards water surface		
	J	86	0.42	78% of fish avoided water	Field	Scannell, 1988
Salmon, Coho (*Oncorhynchus kisutch*)		88	0.08		Laboratory	Bisson and Bilby, 1982
		54	0.02	Alarm reaction		Berg, 1983
		6,000	1	Avoidance behavior		Noggle, 1978
	U	3,000	48			
		300	0.17	Avoidance behavior within minutes		Servizi and Martens, 1993

Table K-3. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Juvenile Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	J	≈23	N/A	Swam to deeper water as response to presence of predators (fish, birds)	Laboratory	Gregory, 1993
Trout, Steelhead (*O. mykiss*)		57-77		Fish remained in turbid water	Laboratory stream	Sigler et al., 1984
		≥167		Fish left turbid water		

Table K-4. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction in Non-Salmonids (Freshwater) Exposed to SS and Turbidity.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-(related, etc.)	Reference
Stickleback, Ninespine (Pungitius pungitius)	A		0-150 JTU*	0.3	No change	Laboratory	Chiasson, 1993b
Bullie, common (*Gobiomorphus cotidianus*)	J and A		N/A	720	Less abundant in more turbid lakes than in clear ones	Field (minnow trapping), CPUE**	Rowe et al., 2003a
Koaro (*Galaxias brevipinnis*)					More abundant in more turbid lakes than clear ones		
Bluegill (*Lepomis macrochirus*)	A		0-50	25	At 20-50 NTU used open-water habitat but at lower turbidity remained inshore	Laboratory	Miner and Stein, 1988
	YOY		1-100	1	Moved from shallow water at 3 NTU to deep water at >10 NTU		Miner and Stein, 1996
Yellowfish, Smallmouth (*Barbus aeneus*)	A		*	2	Adversely affected by increased turbidity	Field (reservoir), nets, trawl	Eccles, 1986
			<10	7,920, sampled monthly	Stayed in clear habitat	Field (reservoir)	Dörgeloh, 1995
			>10		Inhabited turbid (i.e., > 10NTU) areas		
Mudfish, Orange River (*Labeo capensis*)			<10		Stayed in clear habitat		
			>10		Inhabited turbid (i.e., > 10NTU) areas		
			>10		Inhabited clear (i.e., <10 NTU) areas)		

Table K-4 (cont.). **Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction in Non-Salmonids (Freshwater) Exposed to SS and Turbidity.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-(related, etc.)	Reference
Carp, Moggel (*Labeo umbratus*)	A		<10		Stayed in clear habitat	Field (reservoir)	Dörgeloh, 1995
			>10		Inhabited clear (i.e., <10 NTU) areas)		
Cattfish, African (*Clarias gariepinus*)			<10		Stayed in clear habitat		
			>10		Inhabited clear (i.e., <10 NTU) areas		
Sucker, Razorback (Xyrauchen texanus)	J	250		0.16	Avoidance	Laboratory	Johnson and Hines, 1999
		2,000					

* JTU = Jackson Turbidity Unites
** CPUE = catch-per-unit-effort

Table K-5. **Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Smelt, Rainbow (*Osmerus mordax*)	A	10-40 (NS)	24-48	Increased activity (alarm reaction) at SS concentrations ≥ 10 mg/l	Dredge-related, laboratory	Chiasson, 1993a
		≥ 21.8	1	Avoidance	Laboratory	Wildish and Power, 1985
Herring, Atlantic (*Clupea harengus harengus*)	J	9-12 (NS)	5-minute intervals		Dredge-related, laboratory	Johnston and Wildish, 1981
		2.5-55.3 (NS)		Avoidance beginning at > 9 mg/L	Dredge-related, laboratory	Messieh et al., 1981
Sturgeon, Atlantic (*Acipenser oxyrinchus*)	A and J	N/A	168, before and after dredge disposal	3-7 fold decrease in CPUE *	Dredging-related, field (gillnets)	Hatin et al., 2007
Sturgeon, Lake (*A. fulvescens*)				No change in CPUE *		
Shad, American (Alosa sapidissima)		**	0.25	Change in preferred swimming depth; swam to shallow turbid areas	Field (estuary), drift gillnets	Dadswell et al., 1983

* CPUE = Catch-Per-Unit Effort
** Used a secchi disk to measure visibility

Table K-5 (cont.). **Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Adult, Juvenile, Larval, and Egg Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Fishes in the James River, Virginia: Blue Catfish, White Perch, Spot, Atlantic Menhaden, Striped Bass, Atlantic Croaker, Gizzard Shad, Weakfish	Probably J and A	N/A (NS)	< 24	No avoidance or attraction to the dredge plume	Dredge-related, field, using hydroacoustics, both idle and active dredge	Clarke et al., 2002
Fishes in San Francisco Bay		N/A (BS)	48-72	Avoided dredge disposal area	Dredge-related, using field hydroacoustic studies	Burczynski, 1991
Tropical estuary fishes - Northern Australia	A&J	N/A	2.5 years	Attracted to turbid areas of estuary	Field (estuary)	Cyrus and Blaber, 1992
African estuarine fishes – Anchovy (*Thryssa vitrirotris*), Sole (*Solea bleekeri*)	J		N/A		Laboratory studies, field studies (estuary)	Cyrus and Blaber, 1987a,b,c
Herring, Lake (*Coregonus artedi*)	L	10 (NS)	3 24	Depth preference changed	Dredge-related, laboratory studies	Johnston and Wildlish, 1982
Variety (20 species) Of estuarine fish species	L and E	N/A (NS)	March through November	Indication that fish moved into freshwater away from dredging activities, but another author stated that too many problems with the study to conclude anything	Dredge-related, field (Chesapeake Bay Estuary, plankton tow nets used to collect larvae and eggs	Dovel, 1970

Table K-6. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) Responses in Non-Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g,. lab, field, dredging-related, etc.)	Reference
Walleye (*Sander vitreus*)	L	30-40	17 days post-hatch	Avoided sides of the tank in laboratory, compared to those in clear water which gravitated towards sides of tank	Laboratory	Rieger and Summerfelt, 1997
Kokopu (*Galaxias fasciatus*)	J	25	10 minutes	77% avoidance response		Baker, 2003
Inanga (*Galaxias maculates*)		420	20 minutes	50% avoidance response		Boubée et al., 1997
Banded kokopu (*Galaxias fasciatus*)		17 and 25		50% avoidance response		
Koaro (*Galaxias brevipinnis*)		70		50% avoidance response		
Longfinned elvers (*Anguilla dieffenbachia*)		1100		No avoidance response		
Shortfinned elvers (*Anguilla australis*)		1100		No avoidance response		
Redfinned Bully (*Gobiomorphus huttoni*)		1100		No avoidance response		
Shiner, Golden (*Notemigonus crysoleucas*)	A	0-150*	0.3	Alarm reaction at turbidities ≥ 75 JTU's		Chiasson, 1993b

* JTU = Jackson Turbidity Units

Table K-7. Summary of Tertiary Stress Responses (Behavior: Avoidance/Attraction) in Non-Salmonids (Marine and Estuarine) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration	Fish Response	Types of Study (i.e., lab, field, dredging, etc.)	Reference
Kingfish, Yellowtail (*Alepes dyedaba*)	A and J	N/A	1 year with monthly seine nets	Juveniles occurred only in turbid water during summer; adults occurred in low turbid areas	Field study, beach seining, CPUE *	Blaber and Blaber, 1980
Garfish, Snubnose (*Arrhamphus sclerolepis*)						
Trevally, Giant (*Caranx ignobilis*)						
Trevally, Bigeye (*Caranx sexfasciatus*)						
Silverbelly, Common (*Gerres ovatus*)						
Garfish, River (*Hyporhamphus regularis*)						
Mullet, Flat-Tail (*Liza argentea*)						
Mullet, Dussumieri's (*L. dussumieri*)						
Mullet, Silver (*Mugil georgii*)						
Trumpeter, Eastern Striped (*Pelates quadrilineatus*)						
Bluefish (*Pomatomus saltator*)						
Hardyhead (*Pranesus ogilbyi*)						

* CPUE = Catch-per-unit effort

Table K-7 (cont.). **Summary of Tertiary Stress Responses (Habitat Preference) in Non-Salmonids (Marine Estuarine) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration	Fish Response	Types of Study (i.e., lab, field, dredging, etc.)	Reference
Herring, Southern (*Acanthopagrus australis*)	A and J	N/A	1 year with monthly with seine nets	Both adults and juveniles occurred in turbid areas	Field, beach seining	Blaber and Blaber, 1980
Threadfish, Australian (*Polydactylus multiradiatus*)						
Anchovy, Gulf of Carpenteria (*Stolephorus carpenteriae*)						
Anchovy, Hamilton's (*Thryssa hamiltoni*)						
Longtom, Stout (*Tylosurus macleayanus*)						
Silverbelly, Glined (*Gerres oyena*)				Both adults and juveniles restricted to low turbidity areas		
Garfish, Flatsided (*Hemiramphus robustus*)						
Halfbeak, Dussumier's (*Hyporhamphus dussumiera*)						
Seabream, Goldlined (*Rhabdosargus sarba*)						

Table K-8. Summary of Tertiary Stress Responses (Behavior: Loss of Fear Reaction) in Fishes (Marine and Estuarine) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Mullet, Flathead Gray (*Mugil cephalus*)	A	300	15 hrs	Decreased fear response and performed ASR * under protective shelter	Laboratory	Shingles et al., 2005

* ASR = Aquatic surface respiration (please see text for discussion)

Table K-9. Summary of Tertiary Stress Responses (Behavior: Migration) in Adult Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	A	350	0.17	Home water preference displayed	Laboratory	Whitman et al., 1982
		650	168	Homing behavior normal but fewer test fish returned		

Table K-10. Summary of Tertiary Stress Responses (Behavior: Migration) in Larval Salmonids (Freshwater) Exposed to Suspended Sediment/Solids Concentrations.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Chinook (*Oncorhynchus tshawytscha*)	F	* (NS)	1.75 months	Increased rate of fry emigration	Laboratory, using river water	Thomas, 1975

***** SS composed of 2% gravel (>1.1 mm in diameter), 74% sand (0.04-1.1 mm), 21% silt (0.0005-0.04 mm), and 3% clay (< 0.0005 mm).

Table K-11. Summary of Tertiary Stress Responses (Behavior: Migration) in Non-Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Kokopu (*Galaxias fasciatus*)	A	<25	0.03	100 % of fish migrated	Field	Richardson et al., 2001
		25-50		40% of fish migrated		
		50-75		0 % of the fish migrated upstream		

Table K-12. Summary of Tertiary Stress Responses (Foraging and Predation) of Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	A	100	1,008	Decreased feeding rate	Laboratory	McLeay et al., 1984
Salmon (*Oncorhynchus* spp.)		25	4	Feeding activity reduced		Phillips, 1971
		16.5	24	Feeding activity apparently reduced		Townsend, 1983; Ott, 1984
Salmon, Atlantic (*Salmo salar*)		2,500	24	Increased risk of predation		Gibson, 1933

Table K-13. Summary of Tertiary Stress Responses (Foraging and Predation) of Adult Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Trout, Lake (*Salvelinus namaycush*)	A	0.09-7.4	1	Reaction distance decreased as turbidity increased, but not affected by prey size	Laboratory	Vogel and Beauchamp, 1999
Trout, Brook (*S. fontinalis*)		10-40	168	No effect on mean daily consumption		Sweka and Hartman, 2001
				Switched feeding strategy from drift feeding to active searching		
Trout, Lahontan (*Salmo clarki henshawi*)		3.5-25	2	Feeding rates decreased with increased NTU levels At ≥ 20 NTU's, not prey-size selective		Vinyard and Yuan, 1996
Trout, Rainbow (*Oncorhynchus mykiss*)		15	72-96	Reduced reactive distance to prey	Laboratory (artificial stream channel)	Barrett et al., 1992
		30				
		1.5	0.5-1	13% reduction in reactive distance to prey	Laboratory	Mazur and Beauchamp, 2003
		0.08		No change in reactive distance to prey		
		0.55				
Trout, Cutthroat (*O. clarki Utah*)		1.5		17% reduction in reactive distance to prey		
		0.08		No change in reactive distance to prey		
		0.55				

Table K-13 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) of Adult Salmonids (Freshwater) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Char, Lake (*S. namaycush*)	A	1.5	0.5-1	17% reduction in reactive distance to prey	Laboratory	Mazur and Beauchamp, 2003
		0.08		No change in reactive distance to prey		
		0.55				

Table K-14. Summary of Tertiary Stress Responses (Foraging and Predation) of Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	YOY	100	1	Catch rate reduced (unfamiliar prey)	Laboratory	McLeay et al., 1987
		300				
		1,000				
		3,810	144	Amount of food intake severely limited		Simmons, 1982
		1,000	1,008	Fish had frequent mis-strikes and responded slowly to prey		McLeay et al., 1987
		300		Rate of feeding reduced		
		1,000	840			
		1,000	1,008	Fish failed to consume prey		
		300	840	Serious impairment of feeding behavior		
		100		Fish responded less rapidly to drifting food		
	J	1,340 – 6,280 (NS)	144	Reduced food intake and variety of food organisms eaten	Field, caged fish	Reynolds et al., 1989

Table K-14 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) of Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Salmon, Coho (*Oncorhynchus kisutch*)	J	25	1	Feeding rate decreased	Laboratory	Noggle, 1978
		100		Feeding rate decreased to 55% of maximum		
		250		Feeding rate decreased to 10% of maximum		
		300		Feeding ceased		

Table K-15. Summary of Tertiary Stress Responses (Foraging and Predation) of Juvenile Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Rainbow (*Oncorhynchus mykiss*)	J	0-160	3	Selected large-sized prey and rejected small prey as turbidities increased No change in feeding rates	Laboratory	Rowe et al., 2003a
		>160 and less than 320		Reduced feeding rates and reduced selection of large prey		
		>320		No prey selectivity preference		
Salmon, Chinook (*O. tshwytscha*)		27 - 108	NA	Reduction of predation in turbid waters	Field, various nets, using a boat	Gregory and Levings, 1998
		35 - 150	<2	Increased foraging rate compared to control, <1 NTU	Laboratory	Gregory and Northcote, 1993
		18-150	0.02-0.2	Increased foraging rate, compared to < 18 NTU's		Gregory, 1994
		370-810		Decreased foraging rates, compared to < 150 NTU's		

Table K-16. Summary of Tertiary Stress Responses (Foraging and Predation) of Non-Salmonid Adults and Juveniles (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bluegill (*Lepomis macrochirus*)	A	1-100	720	Decreased reactive distance with increased SS concentrations	Farm ponds, hatchery, reservoir, seined fish	Buck, 1956
		423	0.05	Rate of feeding reduced	Laboratory, plastic wading pools	Gardner, 1981
		15	1	Reduced capacity to locate prey	Laboratory	Vinyard and O'Brien, 1976
Smelt (*Osmerus perlanus*)		28	2	Decreased prey-capture rate, compared to control		Horppila et al., 2004
Sculpin, Prickly (*Cottus asper*)		60-360	<1	Decreased predation occurred compared to 20 NTU and 0 NTU		Gadomsky and Parsley, 2005
Bullies (*Gobiomorphus cotidianus*)	A and J	10	N/A	Decreased food consumption, compared to 5 mg/L	Field, captured from 2 lakes using beach seines, preserved fish, and then analyzed stomach contents	Hayes and Rutledge, 1991
Common Smelt (*Retropinna retropinna*)						
Mosquitofish (*Gambusia affinis*)						
15 fish species, of which 8 were indigenous and 7 were non-native		20-40		No difference in CPUE, compared to "clear" lake with 5 mg/L SS	Field, 18-hour gill nets, beach and purse seines	Hayes et al., 1992
Smelt, Rainbow (*Osmerus mordax*)	A	3.5	168	Increased vulnerability to predation	Laboratory	Swenson, 1978

Table K-17. Summary of Tertiary Stress Responses (Foraging and Predation) Responses in Non-Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Walleye (*Sander vitreus*)	L	20-50	504-720	Began feeding sooner than those in clear water	Laboratory	Bristow and Summerfelt, 1994
Bass, Largemouth (*Micropterus salmoides*)	A	17 - 19	N/A	No change in reactive distance to capturing prey		Crowl, 1989
	J	18-37	1	No change in number of prey eaten, compared to 1 NTU	Field and Laboratory	Reid et al., 1999
		70		Decrease number of prey, compared to 1 NTU		
Chub, Peppered (*Macrhybopsis tetranema*)		4,000	0.2	Prey consumption decreased 21% compared to controls	Laboratory	Bonner and Wilde, 2002
Chub, Flathead (*Platygobio gracilis*)				Prey consumption decreased 26% compared to controls		
Shiner, Arkansas River (*Notropis girardi*)				Prey consumption decreased 59% compared to controls		
Shiner, Emerald (*N. atherinoides*)				Prey consumption decreased 84% compared to controls		
Shiner, Red (*Cyprinella lutrensis*)				Prey consumption decreased 89% compared to controls		
Shiner, Sand (*N. stramineus*)				Prey consumption decreased 73% compared to controls		

Table K-17 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) Responses in Non-Salmonid Adults (Freshwater) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Perch (*Perca fluviatilis*)	A	5-50	0.5-2	Decreased eating of prey, compared to clear water	Laboratory	Pekcan-Hekim, 2007
Bream, White (*Abramis björkna*)		5-500	0.5-2	No change in eating of prey, compared to clear water		
Smelt (*Osmerus perlanus*)		20 -50	2	Decreased prey-capture rate, compared to controls		Horppila et al. 2004
Inanga (*Galaxias maculates*)		10-160	0.5	No difference in feeding, compared to those in water containing 2 NTU		Rowe et al., 2002
Smelt, Riverine or Common (*Retropinna retropinna*)						
Minnow, Fathead (*Pimephales promelas*)		13	288	Decreased avoidance of dangerous (i.e., contained predatory fish) feeding area		Abrahams and Kattenfeld, 1997
Shiner, Lahontan Redside (*Richardsonius egregious*)		4-35	2	At ≥ 20 NTU's, consumed more and larger prey		Vinyard and Yuan, 1996

Table K-17 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) Responses in Non-Salmonid Adults (Freshwater) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Walleye	J 85 mm long	100	1	Inhibits feeding	Laboratory	Vandenbyllaardt et al., 1991
		161				
		121	4	No food inhibition		
	J < 85 mm long	100	1			
		161				
		121	4			
	J < 75 mm long	100	1	Inhibits feeding		
		161				
		121	4			
	J 85 mm long	23	1	Feeding rate decreased at ≥ 100 NTU's		
		42				
		100				
		161				
		6.8	4	No change in feeding rate		
		14				
		121				
	J < 75 mm long	23	1	Feeding rate decreased at ≥ 100 NTU's		
		42				
		100				
		161				
		6.8	4	No change in feeding rate		
		14				
		121				

Table K-17 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) Responses in Non-Salmonid Adults (Freshwater) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Minnow, Fathead (*Pimephales promelas*)	A	13	288	Decreased avoidance of dangerous (i.e., predatory fish) feeding area	Laboratory	Abrahams and Kattenfeld, 1997
Shiner, Lahontan Redside (*Richardsonius egregious*)		3.5-25	2	At ≥ 20 NTU's, consumed more and larger prey		Vinyard and Yuan, 1996

Table K-18. Summary of Tertiary Stress Responses (Foraging and Predation) Responses in Non-Salmonid Juveniles and Larvae (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bluegill (*Lepomis macrochirus*)	YOY	1-100	1	Decreased reactive distance with increasing turbidity	Laboratory	Miner and Stein, 1996
	L	30-40	2	Compared to 10-20 NTU's, reduced food consumption (although consumed larger prey) when light intensity low		Miner and Stein, 1993
Banded Kokopu (*Galaxias fasciatus*)	J	10-640	3	Significant decrease in feeding at ≥20 NTU		Rowe and Deane, 1998
Inanga (*Galaxias maculates*)				Significant decrease in feeding beginning at ≥320 NTU		
Common Smelt (*Retropinna retropinna*)				No change in feeding		
Koaro (*Galaxias brevipinnis*)						
Common Bully (*Gobiomorphus cotidianus*)						
Redbanded Bully (*Gobiomorphus huttoni*)						

Table K-19. Summary of Tertiary Stress Responses (Foraging and Predation) Responses of Non-Salmonid Adults (Marine and Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Herring, Atlantic (*Clupea harengus harengus*)	A	20	3	Reduced feeding rate	Dredge-related, laboratory*	Johnston and Wildish, 1982
Croaker, Atlantic (*Micropogonius undulates*)		100	2		Laboratory	Minello et al, 1987

*Authors cautioned that their results were inconclusive

Table K-20. Summary of Tertiary Stress Responses (Foraging and Predation) in Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Killifish, Striped (*Fundulus majalis*)	A	100	2	Reduced predation rate	Laboratory	Benfield and Minello, 1996
Sablefish (*Anoplopoma fimbria*)		5-10	0.5	Decreased pursuit of prey		De Robertis et al., 2003
Weakfish (*Cynoscion regalis*)	J	0.95-11	24 hours, repeated for 4 days	No effect on prey consumption, except under total darkness		Grecay and Targett, 1996
Goby (*Gobiusculus flavescens*)	A	15-50 JTU *	0.5-1	Increasing turbidity resulted in reduced feeding reaction distances		Utne-Palm, 1999
		0-111 JTU *	0.17	RD ** decreased at > 20 JTU		Utne, 1997
Perch (*Perca fluviatilis*)	J	1-30	3	No change in consumption of food		Granqvist and Mattila, 2004
Herring, Atlantic (*Clupea harengus harengus*)	L	35 JTU *	0.5-1	Increased feeding attack rate		Utne-Palm, 2004
		80 JTU *		Decreased feeding attack rate		

* JTU = Jackson Turbidity Units = 1 JTU defined as 1 mg diatomaceous earth per liter of water (Witherspoon et al., 1988).
****** RD = Reaction Distance

Table K-20 (cont.). **Summary of Tertiary Stress Responses (Foraging and Predation) in Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Turbidity.**

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Skipjack (*Elops machnata*)	A	1-28	0.05	Decreased reactive distance as turbidity increased Decreased feeding rate as turbidity increased No effect on size selection of prey	Laboratory	Hecht and van der Lingen, 1992
		68-91	N/A	Feeding intensity lower than in "clear" (2-9 NTU) lake Higher percent of fish had food in stomachs, compared to "clear" lake	Field, sampled with gill nets overnight	
Spotted Grunter (*Pomadasys commersonnii*)				Feeding intensity higher than in "clear" (2-9 NTU) lake Lower percent of fish had food in stomachs, compared to "clear" lake		
Silverside (*Atherina breviceps*)				Feeding intensity higher than in "clear" (2-9 NTU) lake Higher percent of fish had food in stomachs, compared to "clear" lake		

Table K-21. Summary of Tertiary Stress Responses (Foraging and Predation) of Non-Salmonid Larvae (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bass, Striped (*Morone saxatilis*)	L	200- 500	0.42	Feeding rate reduced 40%, compared to 0 or 75 mg/L	Laboratory	Breitburg, 1988
Bass, Largemouth (*Micropterus salmoides*)		150	25	Decreased foraging ability		Chesney, 1989

Table K-22. Summary of Tertiary Stress Responses (Foraging and Predation) of Non-Salmonid Juveniles and Larvae (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response [1,2]	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Walleye (*Sander vitreus*)	L	20-50	504-720	Began feeding sooner than those in clear water	Laboratory	Bristow and Summerfelt, 1994
Bass, Largemouth (*Micropterus salmoides*)	J	18- 37	1	No change in number of prey eaten, compared to 1 NTU	Field and laboratory	Reid et al., 1999
		70	1	Decrease number of prey, compared to 1 NTU		

Table K-23. Summary of Tertiary Stress Responses (Foraging and Predation) of Non-Salmonid Larvae (Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Herring, Lake (*Coregonus artedi*)	L	20 (3 times/day)	480	Feeding rates not affected	Laboratory	Rowe and Taumoepeau, 2004
		20 (1 time/day)				
		2 (1 time/day)				
Herring, Pacific (*Clupea harengus pallasii*)		500	2	Increased feeding, compared to 0 mg/L	Laboratory, water connected to estuary	Boehlert and Morgan, 1985
		1,000-8,000		Decreased feeding as SS increased		
Herring, Atlantic (*Clupea harengus harengus*)		1-6	2	Decreased feeding at ≥ 3 mg/L	Dredge-related, laboratory	Messieh et al., 1981
Pinfish (*Lagodon rhomboids*)		20-20,000	0.5	SS concentration had no effect on foraging	Dredge-related, laboratory	Colby and Hoss, 2004
Spot (*Leiostomus xanthurus*)				SS concentration had no effect on foraging		
Flounder (*Paralichthys spp*)				Fed at low SS concentrations only		
Croaker, Atlantic (*Micropogonias undulates*)				SS concentration had effect on foraging		
Menhaden, Atlantic (*Brevoortia tyrannus*)				Fed at low SS concentrations only		

Table K-24. Summary of Tertiary Stress Responses (Growth and Development) of Adult Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (days)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	A	100	42	Reduced Growth	Laboratory	McLeay et al, 1984

Table K-25. Summary of Tertiary Stress Responses (Growth and Development) of Adult Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Exposure Concentration (NTU) [3]	Exposure Duration (days)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Brook (*Salvelinus fontinalis*)	A	38	168	62% decrease in specific growth rate, compared to clear (i.e., 1 NTU) water	Laboratory	Sweka and Hartman, 2001

Table K-26. Summary of Tertiary Stress Responses (Growth and Development) of Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Rainbow (*Oncorhynch mykiss*)	YOY	695-705	0-6 hour pulses over a 19-day period	Length and weight decreased over time and decreased with increased pulse duration	Laboratory	Shaw and Richardson, 2001
Salmon, Coho (*O. kisutch*)	J	*	2,880	Growth rate decreased as sediment increased	Laboratory streams	Crouse et al., 1981
Grayling, Arctic (*Thymallus arcticus*)	U	100	1,008	Growth rate reduced	Laboratory	McLeay et al., 1984
		300		Weight gain reduced		
		1,000		Weight gain reduced by 33%		
Salmon, Chinook (*O. tshawytscha*)		6 (LNFH)	1,440	Growth rate reduced		
Salmon, Coho (*O. kisutch*)	J	102 (FC, BC)	336		Laboratory streams	Sigler et al., 1984
Steelhead (*O. mykiss*)						
Salmon, Chum (*O. keta*)		N/A (NS)	240	Weight increased as SS concentrations increased	Dredge-related, laboratory	Smith, 1978
			488			
Trout, Brook (*Savelinus fontinalis*)	FF	24 (FC, BC)	5,208	Growth rate reduced	Laboratory	Sykora et al, 1972
		50 (FC, BC)	1,848			
		120	5,880			
		12 (LNFH)				
		100 (LNFH)	1,176	Test fish weighed 16% of controls		

* Placed substrate from <1 mm to <250 mm into laboratory stream; no SS concentrations calculated

Table K-26 (cont). **Summary of Tertiary Stress Responses (Growth and Development) of Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout, Rainbow (*Oncorhynchus mykiss*)	Y	50 (WF)	6,720	Growth rate reduced as SS concentrations increased	Laboratory	Herbert and Richards, 1963
		100 (WF)				
		200 (WF)				
		50 (CSW)	5,544			
		100 (CSW)				
		200 (CSW)	6,720			

Table K-27. Summary of Tertiary Stress Responses (Growth and Development) of Adult Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bass, Largemouth (*Micropterus salmoides*)	A	62.5	720	Weight gain reduced ≈50%	Farm ponds, hatchery, reservoir, seined fish	Buck, 1956
		144.5		Growth retarded		
Bluegill (*Lepomis macrochirus*)		62.5		Weight gain reduced ≈50%		
Sunfish, Redear (*Lepomis microlophus*)				Weight gain reduced ≈50% compared to controls		
		144.5		Growth retarded		

Table K-28. Summary of Tertiary Stress Responses (Growth and Development) of Juvenile Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[2]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Shiner, Whitetail (*Cyprinella galactura*)	YOY	0-100	504	No change in Specific Growth Rate	Laboratory	Sutherland and Meyer, 2007
		500		Specific Growth Rate reduced significantly		
Chub, Spotfin (*Erimonax monachus*)		0-100		No change in Specific Growth Rate		
		500		Specific Growth Rate reduced significantly		

Table K-29. Summary of Tertiary Stress Responses (Growth and Development) of Larval Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Bass, Largemouth (*Micropterus salmoides*)	L	150	600	Reduced weight	Laboratory	Chesney, 1989
Walleye (*Sander vitreus*)		30-40	408 hours post-hatch	Faster growth rates, compared to those in clear water		Rieger and Summerfelt, 1997
Herring, Lake (*Coregonus artedii*)		3-28	1,448	No change in growth rate		Swenson and Matson, 1976

Table K-30. Summary of Tertiary Stress Responses (Growth and Development) of Larval Non-Salmonids (Freshwater) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Walleye (*Sander vitreus*)	L	20-40	504-720	Increased length and weight compared to those in clear water	Laboratory	Bristow and Summerfelt, 1994

Table K-31. Summary of Tertiary Stress Responses (Development and Growth) of Non-Salmonid Adults and Juveniles (Marine and Estuarine) Exposed to Turbidity.

Fish Species	Life Stage[1]	Turbidity Level (JTU) [2,*]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Rockfish, Brown (*Sebastes auriculatus*)	A and J	500-2,500 (BS)	1,008	No change in weight	Dredge-related, laboratory (from San Francisco and San Pablo Bays)	USFWS, 1970
Bass, Striped (*Morone saxatilis*)				10-23% decreased weight, as increased JTU's		
Seaperch, Rubberlip (*Rhacochilus toxotes*)				16-34% decreased weight, as increased JTU's		
Tomcod, Pacific (*Microgadus proximus*)				18-23% decreased weight, as increased JTU's		
Perch, Shiner (*Cymatogaster aggregata*)				14% decreased weight , as increased JTU's		
Perch, White (*Morone americana*)				15-25% decreased weight as JTU's increased		

* JTU = Jackson Turbidity Units

Table K-32. Summary of Tertiary Stress Responses (Growth and Development) of Non-Salmonid Eggs (Marine and Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Bass, Striped (*Morone saxatilis*)	E	800	24	Development rate slowed significantly	Laboratory	Morgan et al., 1983
Perch, White (*M. americana*)				Egg development slowed significantly		
Bass, Striped (*Morone saxatilis*)		100		Hatching delayed		Schubel and Wang, 1973
		1,000	168	Reduced hatching success		Auld and Schubel, 1978
Herring, Atlantic (*Clupea harengus harengus*)		300 500	24	Egg development not impaired	Laboratory, collected gonads in the field	Kiørboe et al., 1981
Perch, White (*M. americana*)		100		Hatching delayed	Laboratory	Schubel and Wang, 1973

Table K-33. Summary of Tertiary Stress Responses (Cumulative Stress) in Adult and Juvenile Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Grayling, Arctic (*Thymallus arcticus*)	A	100	1,008	Decreased resistance to environmental stress	Laboratory	McLeay et al., 1984
	U	300	12	Reduced ability to tolerate high temperatures		
			1,008	Fish less tolerant of Pentachlorophenol		McLeay et al., 1987
Salmon, Chinook (*Oncorynchus tshawytscha*)	S	943 (VA)	72	Tolerance to stress reduced		Stober, et al., 1982
Steelhead (*O. mykiss*)	Y	2,000-4,000	9	Reduced disease resistance		Redding et al., 1987
			24			

Table K-34. Summary of Tertiary Stress Responses (Reproductive Performance) in Adult Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Shiner, Tricolor (*Cyprinella trichroistia*)	A	>100 to >600	720	Spawning effort and number of eggs laid decreased as SS concentration increased. Increasing SS concentrations delayed timing of spawning	Laboratory	Burkhead and Jelks, 2001
Bluegill (*Lepomis macrochirus*)		144		Fish unable to spawn and population declined	Farm ponds, hatchery, reservoir, seined fish	Buck, 1956
Bass, Largemouth (*Micropterus salmoides*)						
Sunfish, Redear (*Lepomis microlophus*)						

Table K-35. Summary of Tertiary Stress Responses (Population Changes) in Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Trout	A	300	720	Decrease in population size	Field	Peters, 1967
Trout, Brown (*Salmo trutta*)		18				
		100		Decrease in population size	Field, electrofishing	Scullion and Edwards, 1980
		1,040 – 7,470	8,760	Fish numbers one- seventh of expected size	Laboratory	Herbert et al., 1961
		1,438-18,000	3 months	CPUE* was lower	Field (electrofishing)	Bergstedt and Bergersen, 1997
Trout, Rainbow (*Oncorhynchus mykiss*)		3,500	1,488	Catastrophic reduction in population size	Laboratory	Herbert and Merkens, 1961
		1,438-18,000	3 months	CPUE* was lower	Field (electrofishing)	Bergstedt and Bergersen, 1997

* CPUE = catch-per-unit effort

Table K-36. **Summary of Tertiary Stress Responses (Population Changes) in Non-Salmonids (Freshwater) Exposed to Suspended Sediment.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Sauger (*Stizostedion canadense*)	A	25-50	April through May for three consecutive years	Significant increase in sauger population	Field (Lake Erie)	Doan, 1941
Banded Kokopu (*Galaxias fasciatus*)		120 mg/L less than 20% of the time, compared with the control (>120 mg/L more than 10% of the time)	N/A	Mean occurrence reduced by 89% *	Laboratory	Rowe et al., 2000 **
Riverine Smelt (*Retropinna retropinna*)				Mean occurrence reduced by 33% *		
Inanga (*Galaxias maculates)*				Mean occurrence reduced by 54%		
Koaro (*Galaxias brevipinnis*)				Mean occurrence increased by 30%		
Longfinned eel (*Anguilla dieffenbachia*)				Mean occurrence reduced by 4%		
Shortfinned eel (*Anguilla australis*)				Mean occurrence reduced by 29%		
Torrentfish (*Cheimarrichthys fosteri*)				Mean occurrence increased by 4%		

* Significant

** This study focused on 8 turbid and 7 clear rivers in New Zealand. Data on the frequency of occurrence (i.e., "Fish Response" column in the table) of the native species were obtained from the New Zealand Freshwater Fish Database (McDowall and Richardson, 1983).

Table K-36 (cont.). **Summary of Tertiary Stress Responses (Population Changes) in Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Bluegilled Bully (*Gobiomorphus hubbsi*)	A	120 mg/L less than 20% of the time, compared with the control (>120 mg/L more than 10% of the time)	N/A	Mean occurrence increased by 16%	Laboratory	Rowe et al., 2000 **
Redfinned Bully (*Gobiomorphus huttoni*)				Mean occurrence reduced by 81%		
Common Bully (*Gobiomorphus cotidianus*)				Mean occurrence increased by 48%		
River Blackfish (*Gadopsis marmoratus*)	A and J	< 4,610	240-336	93% reduction in population ***, compared to previous surveys; previous surveys conducted in much less turbid water	Field (electrofishing)	Doeg and Koehn, 1994
Drum, Freshwater (*Aphodinotus grunniens*)	L	N/A	2-3 minute tows; 2 week gill nets	Distributed throughout water column instead of near bottom	Field	Matthews, 1984
Shad Species (*Dorosoma* spp)				Concentrated at surface water		

Table K-36 (cont.). **Summary of Tertiary Stress Responses (Population Changes) in Non-Salmonids (Freshwater) Exposed to Suspended Sediment/Solids.**

Fish Species	Life Stage[1]	Exposure Concentration (mg/L)	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Koaru (*Balaxias brevipinnis*)	A and J		N/A	5-20 times more abundance in turbid lakes	Field	Rowe et al., 2003b
Bully, Common (*Gobiomorphus cotidianus*)				70-90% decrease in turbid lakes		

* Significant

** This study focused on 8 turbid and 7 clear rivers in New Zealand. Data on the frequency of occurrence (i.e., "Fish Response" column in the table) of the native species were obtained from the New Zealand Freshwater Fish Database (McDowall and Richardson, 1983).

*** Survey conducted after a small weir was cleaned out and the turbid water with high SS concentrations was allowed to flow down river. Fish were collected 10-14 days after water from cleaned weir was allowed to flow downstream. For comparison, previous surveys were conducted under less turbid conditions.

Table K-37. Summary of Tertiary Stress Responses (Population Changes) in Non-Salmonids (Marine and Estuarine) Exposed to Suspended Sediment/Solids.

Fish Species	Life Stage[1]	Exposure Concentration (mg/L) [2]	Exposure Duration	Fish Response	Type of Study (e.g., lab, field, dredging-related, etc.)	Reference
Scup (*Stenotomus chrysops*)	A and J	N/A (NS)	2.75 years	Decline in population, but may not be due to dredging	Dredge-related, field (float traps)	Sissenwine and Saila, 1974
Bluefish (*Pomatomus saltatrix*)				No effect On population		
Cod, Atlantic (*Gadus morhua*)						
Mackeral, Atlantic (*Scomber scombrus*)						
Flounder, summer (*Paralichthys dentatus*)						
Henhaden, Atlantic (*Brevoortia tyrannus*)						
Bass, Striped (*Morone saxatilis*)						
Demersal (bottom-dwelling) fish species	A and J	N/A (BS)	12-18 months	Reduced number of fish and species composition near Mare Island and Pt. San Pablo); could not determine changes in other areas of the Bays	Dredge-related (hopper and clam shell dredging), field (San Francisco and San Pablo Bays)	USFWS, 1970

APPENDIX L

SUMMARY OF DREDGE-RELATED STUDIES THAT RESULTED IN TERTIARY STRESS RESPONSES IN FISHES EXPOSED TO SUSPENDED SEDIMENTS, SUSPENDED SOLIDS, AND TURBIDITY

Legend

[1] A=adult; E=egg; EE= eyed egg; FF=young fry (<30 weeks old); J=juvenile; L=larval; U=underyearling; YOY young-of-the-year.

[2] Particle sizes of suspended sediment (SS): BS = Bay sediment; NS = natural sediment;

[3] JTU = Jackson Turbidity Units

Table L-1. **Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Behavior, Growth and Development) from Salmonids Exposed to SS.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Salmon, Chum (*Oncorhynchus keta*)	J	N/A (NS)	240 488	Weight increased as SS concentrations increased	Dredge-related, laboratory	Smith, 1978
Trout, Sea (*Salmo trutta*)	A	210 (NS)	24	Fish abandoned traditional spawning habitat	Dredge-related, field studies (sand pits)	Hamilton, 1961
Salmon species (*Oncorhynchus* spp.)						
Grayling, Arctic (*Thymallus articus*)	U	20 (NS)		Fish avoided parts of the stream	Dredge-related (placer mining), field studies	Birtwell et al., 1984
Salmon (*O.* spp)	A	210 (NS)		Abandoned traditional spawning habitat	Dredge-related (sand pits), field	Hamilton, 1961

Table L-2. Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Behavior, Foraging, and Predation) from Pacific Herring and Atlantic Herring Exposed to SS.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Herring, Atlantic (*Clupea harengus*)	J	9-12 (NS)	5-minute intervals	Avoidance	Dredge-related, laboratory studies	Johnston and Wildish, 1981
		2.5-55.3 (NS)		Avoidance beginning at >9 mg/L		Messieh et al., 1981
	A	20	3	Reduced feeding rate *		Johnston and Wildish, 1982
	L	1-6	2	Decreased feeding at ≥ 3 mg/l		Messieh et al., 1981

* Authors cautioned that their results were inconclusive.

Table L-3. Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Population Changes) from Atlantic and Lake Sturgeon Exposed to SS.

Fish Species	Life Stage [1]	Exposure Concentration (mg/L)	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Sturgeon, Atlantic (*Acipenser oxyrinchus*)	A and J	N/A	168 (7 days) before and after dredge disposal	3-7 fold decrease in CPUE *	Dredge-related, field (gillnets)	Hatin et al., 2007
Sturgeon, Lake (*A. fulvescens*)				No change in CPUE *		

* CPUE = catch-per-unit effort.

Table L-4. **Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Behavior, Foraging and Predation, and Population Changes) from Non-Salmonids (Marine and Estuarine Environments) Exposed to SS.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Demersal (bottom-dwelling) fish species	A and J	N/A (BS)	12-18 months	Reduced number of fish and species composition near Mare Island and Pt. San Pablo; could not determine changes in other areas of the Bay	Dredge-related (hopper and clam shell dredging) field (in San Francisco Bay)	USFWS, 1970
Smelt, Rainbow (Osmerus mordax)	A	10-40 (NS)	24-48	Increased activity (alarm reaction) as SS concentration ≥10 mg/L	Dredge-related, laboratory	Chiasson, 1993a
Pinfish (*Lagodon rhomboids*) *	L	20-20,000	0.5	SS concentration had no effect on foraging		Colby and Hoss, 2004
Spot (*Leistomus xanthurus*) *						
Flounder (*Paralichthys* spp.)				Fed at low SS concentration only		
Menhaden, Atlantic (*Brevoortia tyrannus*)						
Croaker, Atlantic (*Micropogonias undulates*)				SS concentration had effect on foraging		

Table L-4 (cont.). **Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Behavior, Foraging and Predation, and Population Changes) from Non-Salmonids (Marine and Estuarine Environments) Exposed to SS.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Scup (*Stenotomus chrysops*)	A and J	N/A (NS)	2.75 years	Decline in population, but may not be due to dredging	Dredge-related, field (float traps) studies	Sissenwine and Saila, 1974
Bluefish (*Pomatomus saltatrix*)				No effect on population		
Cod, Atlantic (*Gadus morhua*)						
Mackerel, Atlantic (*Scomber scombrus*)						
Flounder, summer (*Paralichthys dentatus*)						
Menhaden, Atlantic (*Brevoortia tyrannus*)						
Bass, Striped (*Morone saxatilis*)						

Table L-4 (cont.). **Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Behavior, Foraging and Predation, and Population Changes) from Non-Salmonids (Marine and Estuarine Environments) Exposed to SS.**

Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Fishes in James River, Virginia: blue catfish, white perch, spot, Atlantic menhaden, striped bass, Atlantic Croaker, Gizzard shad, weakfish	Probably A and J	N/A (NS)	<24	No avoidance or attraction to the dredge plume	Dredge-related, field, using hydroacoutics, both idle and active dredge	Clarke et al., 2002
Fishes in San Francisco Bay		N/A (BS)	48-72	Avoided dredge disposal area	Dredge-related, using field hydroacoustic studies	Burczynski, 1991
Variety (20 species) of estuarine fishes	E and L	N/A (NS)	March through November	Indication that fish moved into freshwater away from dredging and dredge disposal areas, but author stated that too many problems with the study to conclude anything.	Dredging-related (Chesapeake Bay Estuary), field (plankton tow nets)	Dovel, 1970
Herring, Lake (*Coregonis artedii*)	L	10 (NS)	3	Depth preference changed	Dredge-related, laboratory	Johnston and Wildish, 1982
		16 (NS)	24			

Table L-5. Summary of Dredge-Related Studies that Resulted in Tertiary Stress Responses (Growth and Development) in Non-Salmonids (Marine and Estuarine Environments) Exposed to Turbidity.

Fish Species	Life Stage [1]	Turbidity Level (JTU) [2,3]	Exposure Duration (hours)	Fish Response	Type of Dredging Study (e.g., field or laboratory or both)	Reference
Rockfish, Brown (*Sebastes auriculatus*)	A and J	500-2,500 (BS)	1,008	No change in weight	Dredge-related (from San Francisco Bay and San Pablo Bay), laboratory	USFWS, 1970
Bass, Striped (*Morone saxatilis*)				10-23% decreased weight as increased JTU's		
Seperch, Rubberlip (*Rhacochilus toxotes*)				16-34% decreased weight as increased JTU's		
Tomcod, Pacific (*Mirogadus proximus*)				18-23% decreased weight as increased JTU's		
Perch, Shiner (*Cymatogaster aggregata*)				14% decreased weight as increased JTU's		
Perch, White (*Morone americana*)				15-25% decreased weight as increased JTU's		

APPENDIX M

SUMMARY OF STUDIES ON TERTIARY STRESS RESPONSES IN CHINOOK SALMON, STEELHEAD, RAINBOW TROUT, PACIFIC AND ATLANTIC HERRING, AND STURGEON EXPOSED TO SUSPENDED SEDIMENTS, SUSPENDED SOLIDS AND TURBIDITY

Legend

[1] A=adult; F=fry; F=fry; J=juvenile; L=larval; S=smolt; U=underyearling; Y=approximately yearling; YOY=young-of-the-year

[2] Particle sizes of suspended sediment (SS): LNFH = lime-neutralized ferric hydroxide; NS = natural sediment; VA = volcanic ash.

[3] NTU=Nephelometric Turbidity Units

Table M-1. Summary of Studies on Tertiary Stress Responses in Chinook Salmon (Freshwater) Exposed to Suspended Sediment/Solids and Turbidity.

Type of Response	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [2,3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Behavior (Avoidance/Attraction)	A	650 (VA)		10 minute exposure, then fish released	Number of returning adults not significantly different from control fish	Laboratory, artificial stream	Brannon et al., 1982
	J		~23	N/A	Avoidance: swam into deeper water in response to presence of predators (fish, birds)	Laboratory	Gregory, 1993
Behavior (Migration)	A		350	0.17	Home water preference		Whitman et al., 1982
			650	168	Homing behavior normal, but fewer test fish returned		
	F	*		1.75 months	Increased rate of fry emigration		Thomas, 1975
Foraging and Predation	A		27-108	N/A	Decreased predation as turbidity increased	Field, using various nets, using a boat	Gregory and Levings, 1998
			35-150	<2	Increased foraging rate, compared to < 1 NTU's	Laboratory	Gregory and Northcote, 1993
			18-150	0.02-.2	Increased foraging rate compare to <18 NTU's		Gregory, 1993
			370-810		Decreased foraging rate, compared to <150 NTU's		
Growth and Development	U	6 (LNFH)		1,440	Growth rate reduced		McLeay et al., 1984
Cumulative Stress	S	943 (VA)		72	Tolerance to stress reduced		Stober et al., 1981

* SS composed of 2% gravel (>1.1 mm in diameter), 74% sand (0.04-1.1 mm), 21% silt (o.ooo5-0.04 mm), and 3% clay (<0.0005 mm).

Table M-2. Summary of Studies on Tertiary Stress Responses in Steelhead (Freshwater) Exposed to Suspended Sediments/Solids and Turbidity.

	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [2,3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Behavior (Avoidance/Attraction)	J		57-77	N/A	Attraction: fish remained in turbid water	Laboratory streams	Sigler et al., 1984
			≥167		Avoidance: fish left turbid water		
Growth and Development		102		336	Growth rate reduced		
Cumulative Stress	Y	2,000-4,000		9	Reduced disease resistance	Laboratory	Redding et al., 1987
				24			

Table M-3. Summary of Studies on Tertiary Stress Responses in Rainbow Trout (Freshwater) Exposed to Suspended Sediments/Solids and Turbidity.

	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [2,3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Behavior (Avoidance/Attraction)	J	<10		7,920, sampled monthly	Inhabited clear areas (i.e., < 10 mg/L)	Field (reservoir)	Dörgeloh, 1995)
		≥ 10					
Foraging and Predation	A	15		72-96	Reduced reactive distance to prey	Laboratory (artificial stream channel)	Barrett et al., 1992
		30					
	J		1-160	3	Change in prey size selection with increased turbidity	Laboratory	Rowe et al., 2003a
			>160 to < 320		Reduced feeding rate and reduced selection of larger prey		
			>320		No selection of prey		

* CPUE = Catch-per-unit effort

Table M-3 (cont.). **Summary of Studies on Tertiary Stress Responses in Rainbow Trout (Freshwater) Exposed to Suspended Sediments/Solids and Turbidity.**

	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [2,3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Growth and Development	A	50		960	Rate of weight gain reduced	Laboratory	Herbert and Richards, 1963
	YOY	695-705		0-6 hour pulses over a 19-day period	Length and weight decreased over time and decreased with increased pulse duration		Shaw and Richards, 2001
Population Changes	A	3,500		1,488	Catastrophic reduction in population size		Herbert and Merkens, 1961
		1,438-18,000		0.05	CPUE*	Field (electrofishing)	Bergstedt and Bergersen, 1997

* CPUE = Catch-per-unit effort

Table M-4. Summary of Studies on Tertiary Stress Responses in Pacific Herring Exposed to Suspended Sediments/Solids and Turbidity.

	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Foraging and Predation	L	50		0.03	Increased feeding, compared to 0 mg/L	Laboratory, water connected to estuary	Boehlert and Morgan, 1985
		1,000-8,000		2	Decreased feeding as SS concentrations increased		

Table M-5. Summary of Studies on Tertiary Stress Responses in Atlantic Herring Exposed to Suspended Sediments/Solids and Turbidity.

	Life Stage [1]	Exposure Concentration (mg/L) [2]	Turbidity Level (NTU) [2,3]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Avoidance/Attraction	J	2.5-55 (NS)		5-minute intervals	Avoidance, beginning at >9 mg/L	Dredge-related, laboratory	Messieh et al., 1981
		9-12 (NS)		5 minute intervals	Avoidance of water from spawning site		Johnston and Wildish, 1981
Foraging and Predation	A	20		3	Reduced feeding rate *		Johnston and Wildish, 1982
	L		35 JTU **	0.5-1	Increased feeding attack rate	Laboratory	Utne-Palme, 2004
			80 JTU **		Decreased feeding attack rate		
		1-6		2	Decreased feeding at ≥ 3 mg/L	Dredge-related, laboratory	Messieh et al., 1981
Growth and Development		300		24	Egg development not impaired	Laboratory, collected gonads in the field	Kiørboe et al., 1981
		500					

* Authors cautioned that their results were inconclusive.

** JTU = Jackson Turbidity Units

Table M-6. **Summary of Studies on Tertiary Stress Responses in Atlantic and Lake Sturgeon Exposed to Suspended Sediments/Solids and Turbidity.**

	Fish Species	Life Stage [1]	Exposure Concentration (mg/L) [2]	Exposure Duration (hrs)	Fish Response	Type of Study (e.g., lab, field, dredge-related, etc.)	Reference
Avoidance/ Attraction	Sturgeon, Atlantic (*Acipenser oxyrinchus*)	A and J	N/A (NS)	168 hours, before and after dredge disposal	3.7 fold decrease in CPUE *	Dredge-related, field studies (gillnets)	Hatin et al., 2007
	Sturgeon, Lake (*A. fulvescens*)				No change in CPUE *		

* CPUE = Catch-per-unit-effort