TOOLS FOR ASSESSING AND MONITORING FISH BEHAVIOR CAUSED BY DREDGING ACTIVITIES

FINAL REPORT

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EXECUTIVE SUMMARY

A variety of fish species inhabit the San Francisco Bay Estuary (Bay) and there is concern that dredging activities (dredging and placement of dredged material) could have adverse impacts on the behavior of those fishes. This report reviews the status of knowledge of the methods and tools used to assess the behavioral responses of fishes to dredging activities and how those methods and tools could be used in the Bay.

The objectives of the report are to provide:

- A discussion of methods and tools used to design studies, analyze and interpret data, and perform QA/QC that address the behavioral effects of dredging activities on fishes;
- A discussion of the equipment used to measure environmental changes caused by dredging activities that could be used in studies of fish responses to dredging;
- Several hypothetical research scenarios for measuring the behavioral responses of fish to various types of dredging activities;
- Gaps in knowledge to direct the design of specific studies; and,
- A single source for accessing written and electronic material on the subject at hand.

To achieve those objectives, a variety of sources were used and the following topics were reviewed:

- Methods and tools used to determine behavioral responses of fishes exposed to suspended sediments/solids related to dredging activities;
- Methods and tools used to determine behavioral responses of fishes to noise (sound) related to dredging and other vessel-related activities;
- Methods and tools used to study behavioral responses of fishes to entrainment related to dredging activities;
- Methods and tools used to study fish presence, distribution, and population abundance related to dredging activities; and,
- Types of equipment used to measure environmental changes caused by dredging activities that could be used in studies of fishes' responses to those changes.

Analysis of information led to the following conclusions:

- Provided that the suspended sediment concentrations used were similar to those generated by dredging activities in the Bay, the methods and tools used in the laboratory-based avoidance and attraction studies would provide a useful approach for Bay studies;
- The methods and tools used to determine suspended sediment-induced changes in swimming performance, foraging, and predation behavior caused by dredging activities were problematic and, hence, any future studies proposed for the Bay should initially include a pilot study;
- No studies were found on either ESA-listed fishes or fishes of commercial importance with regard to behavioral responses to dredging-caused suspended sediment;

- No studies were found on the behavioral responses of fishes to dredging-produced noise. However, the methods and tools used in studies on behavioral responses of fishes to the noise of fishing vessels and gear could be used to help design dredge-related noise/behavior studies; and,
- Modeling the results of swimming performance for a given fish (i.e., ESA-listed and commercially important fish species), as a function of water velocity, could be used as a preliminary assessment of entrainment risk to different types of dredgers.

Of the five study approaches that focused on presence, distribution, and population abundance, the most promising appeared to be those that used a combination of biotelemetry, or fish sampling and hydroacoustics.

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INTRODUCTION

Project Background

A variety of fish species inhabit the San Francisco Bay Estuary (Bay), all of which can be adversely affected by dredging activities (dredging and dredged material placement). Levine-Fricke (2004) addressed the potential effects of dredging activities on fishes in the Bay, identifying stakeholder concerns, regarding environmental work windows. One concern was the potential adverse effects of dredging activities on fish behavior. This report reviews the status of knowledge of the methods and tools used to assess the dredging-caused behavioral changes of fishes in the Bay. However, because there have been so few studies that specifically addressed the behavioral changes of dredging activities on fishes anywhere, this review includes non-dredge-related studies (e.g., studies on the behavioral responses of fishes to the noise generated by fishing vessels and gear) that may produce the same behavioral responses by fishes as those produced by dredging activities. The term, "behavior" in this report is a general term that includes topics such as avoidance/attraction, migration, habitat preference, foraging and predation, fish distribution, and population abundance.

Project Goal and Objectives

The goal of this review is to summarize the methods and tools used to assess and monitor behavioral responses of fishes to dredging activities. Specifically, the objectives of the report are to provide:

- A discussion of methods and tools used to design studies, analyze and interpret data, and perform QA/QC that address the behavioral effects of dredging activities on fishes;
- A discussion of the equipment used to measure environmental changes caused by dredging activities that could be used in studies of fish responses to dredging activities;
- Several hypothetical research scenarios for measuring the behavioral responses of fish to various types of dredging activities;
- Gaps in knowledge to direct the design of specific studies; and,
- A single source for accessing written and electronic material on the subject at hand.

Stress in Fish: The Basis for Assessing the Behavioral Effects of Dredging Activities on Fishes

To discuss the methods and tools used to determine the behavioral effects of dredging activities on fishes, it is essential to understand the concept of stress in fish (Figure 1). The behavioral effects of dredging activities 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 (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."

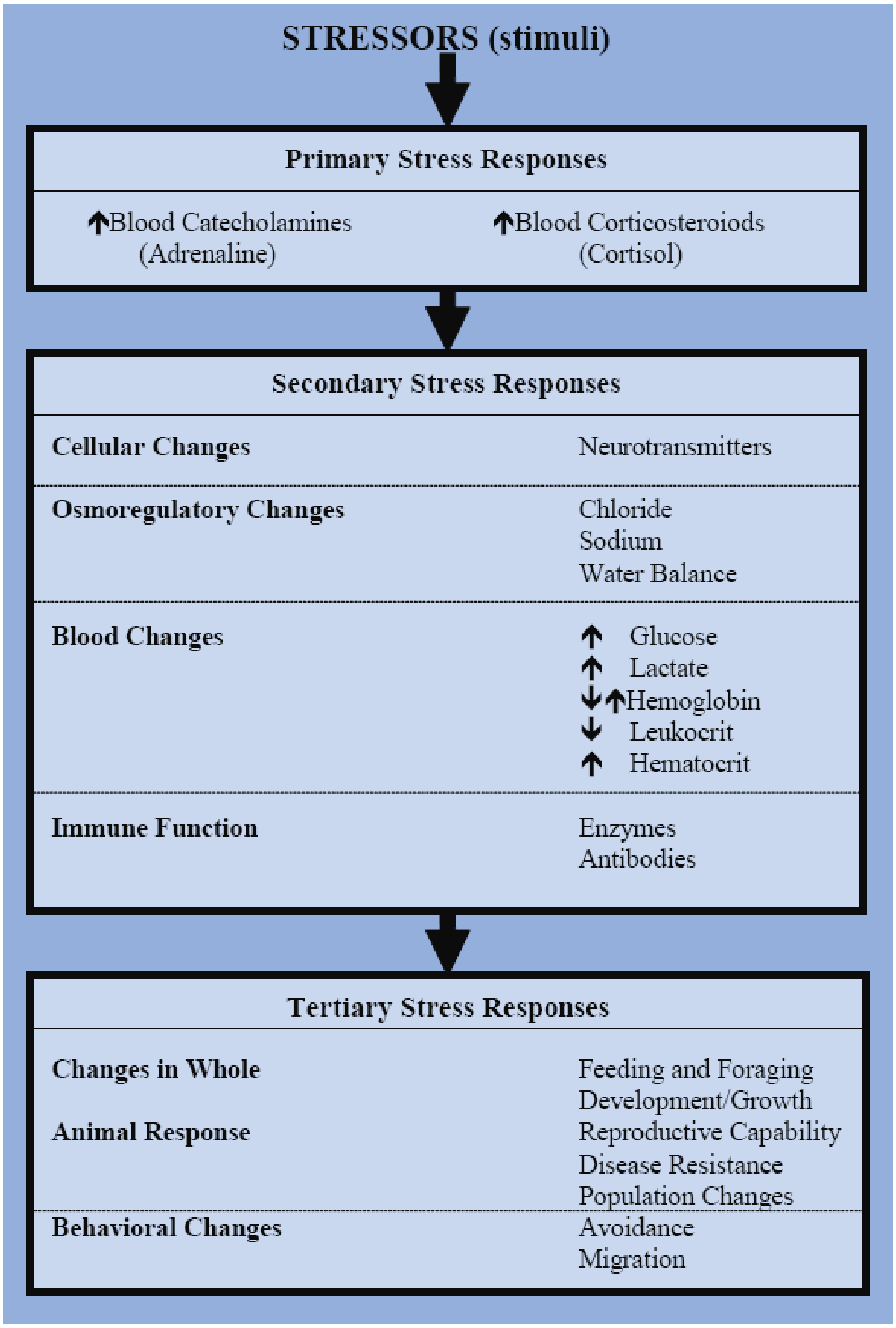

Figure 1: GAS Responses to Stressors in Fishes

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).

This report focuses on the methods and tools used to determine behavioral responses of fishes to dredging activities. The stressors discussed in this report are: (1) suspended sediments; (2) noise (sound); and, (3) entrainment. Each of these stressors is directly or indirectly related to dredging activities. And, each of the stressors can, ultimately, affect fish presence, distribution, and population abundance.

METHODS

This report draws on a broad range of existing literature reviews, peer-reviewed journal articles, books, theses/dissertations, and technical reports. In addition, the author contacted numerous individuals who were knowledgeable about the behavioral effects of dredging activities on fishes (Table 1). Information was initially obtained from Dr. Douglas Clarke (Clarke, 2007) at the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi. Dr. Clarke has spent over 20 years working on fish issues associated with dredging activities. He stated that there was a dearth of studies on the behavioral effects of dredging activities on fishes. Furthermore, the objectives of many of those studies were not to study behavioral responses on fishes, per se, but to determine the presence or absence of fishes in an affected area. Thus, determining the behavioral responses of fishes to dredging activities is still in its "embryonic stage"

In addition to the contact information listed in Appendix A, information was obtained from relevant articles listed in the *Literature Cited* sections of all of the articles obtained throughout the process. Although the focus of this document was on fishes within the Bay, work from other geographical areas was also documented and discussed.

The most efficient document searching came from the following:

- 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);
- 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 article titles came up in those searches.

This report focuses on all studies where a cause-and-effect type response could be determined from the methods and tools described in each of the studies reviewed. Consequently, the report does not include all of the studies reviewed. For example, the two studies on placer mining involved direct observation, but there were no specific details on how the studies were conducted (Hamilton, 1961; Birtwell et al., 1984). Other studies did not differentiate between other factors (e.g. pollutants) and suspended sediments; hence, it was not possible to determine the behavioral responses of suspended sediment on fishes.   And some studies (MES, 2003; Veshchev, 1982) were not included because there was insufficient detail about the methods and tools used

The information reviewed in this report covered over 25 years of studies. With the exception of some recent studies using hydroacoustics and ultrasonic tagging, manufacturer names were not provided. The equipment used in most, if not all, of the older studies, has been refined and updated.

Finally, this document contains a wide range of biological and acoustic terms that are defined in Appendix B.

REVIEW AND FINDINGS

Overview

Fish respond behaviorally to the following perturbations created by dredging activities:

- Suspended sediment plumes;
- Noise (sound); and,
- Entrainment.

The behavioral responses to these environmental perturbations (e.g., avoidance/ attraction/alarm reactions, changes in migration, habitat preference, and foraging and predatory behavior) can result in changes in fish presence, distribution and abundance (Sullivan et al., 2003; Figure 2).

To that end, in this report the following topics were reviewed:

- Methods and tools used to study behavioral responses of fishes to suspended sediments/solids related to dredging activities;
- Methods and tools used to study behavioral responses of fishes to noise (sound) related to dredging activities, and other vessel-related activities;
- Methods and tools used to study behavioral responses of fishes to entrainment related to dredging activities;
- Methods and tools used to study fish presence, distribution, and population abundance related to dredging activities; and,
- Types of equipment used to measure environmental changes caused by dredging activities that could be used in studies of fishes' responses to those changes.

The lack of standardization in methodologies and the limited number of studies related to dredge-related fish behavior, presence, distribution and population abundance studies necessitates summarizing each of the types of studies that have been undertaken. Although it appears that most future studies will focus on a combination of biotelemetry, hydroacoustics, and fish sampling surveys, there have only been a few of those studies, to date, and each of them used somewhat different methodologies.

With the exception of the USACE (2007) juvenile salmonid migration study, none of the documents reviewed, nor the scientists spoken to, used the terms quality assurance/quality control (QA/QC). In documents that were published in peer-reviewed journals, it is assumed that standard operating procedures were followed for that journal and that those would include a thorough review of the methods and the analyses of the data. Hence, no further QA/QC details will be provided for the studies published in peer-reviewed journals.

Both the ERDC and USGS have their own QA/QC procedures. The ERDC team that works on the various fish-related studies is small and handles all of the data acquisition, post-processing and analysis phases (Clarke, 2008). They develop and use standard field and laboratory operating procedures for the various tasks. They have equipment operating procedures for using and calibrating instruments, laboratory operating procedures for analytical work, etc. The Columbia River Research Laboratory of the USGS implements and uses a variety of QA/QC procedures (Parsley, 2007). Under their general research protocols, they develop and use standard field and laboratory operating procedures for various tasks. They have equipment operating procedures for calibrating and using instruments, laboratory operating procedures for analytical work, etc. The USGS requires internal peer and policy review of all documents for public dissemination. For each project, the USGS maintains official files, including investigator signature and initial sheets, agreements, products, etc. The USGS uses standard operating procedures for capturing fish, surgical procedures, telemetry tag validation, backing up data and archiving electronic biotelemetry data, etc. (Parsley, 2007). In a few of the studies discussed, additional information was provided that identified specific QA/QC procedures.

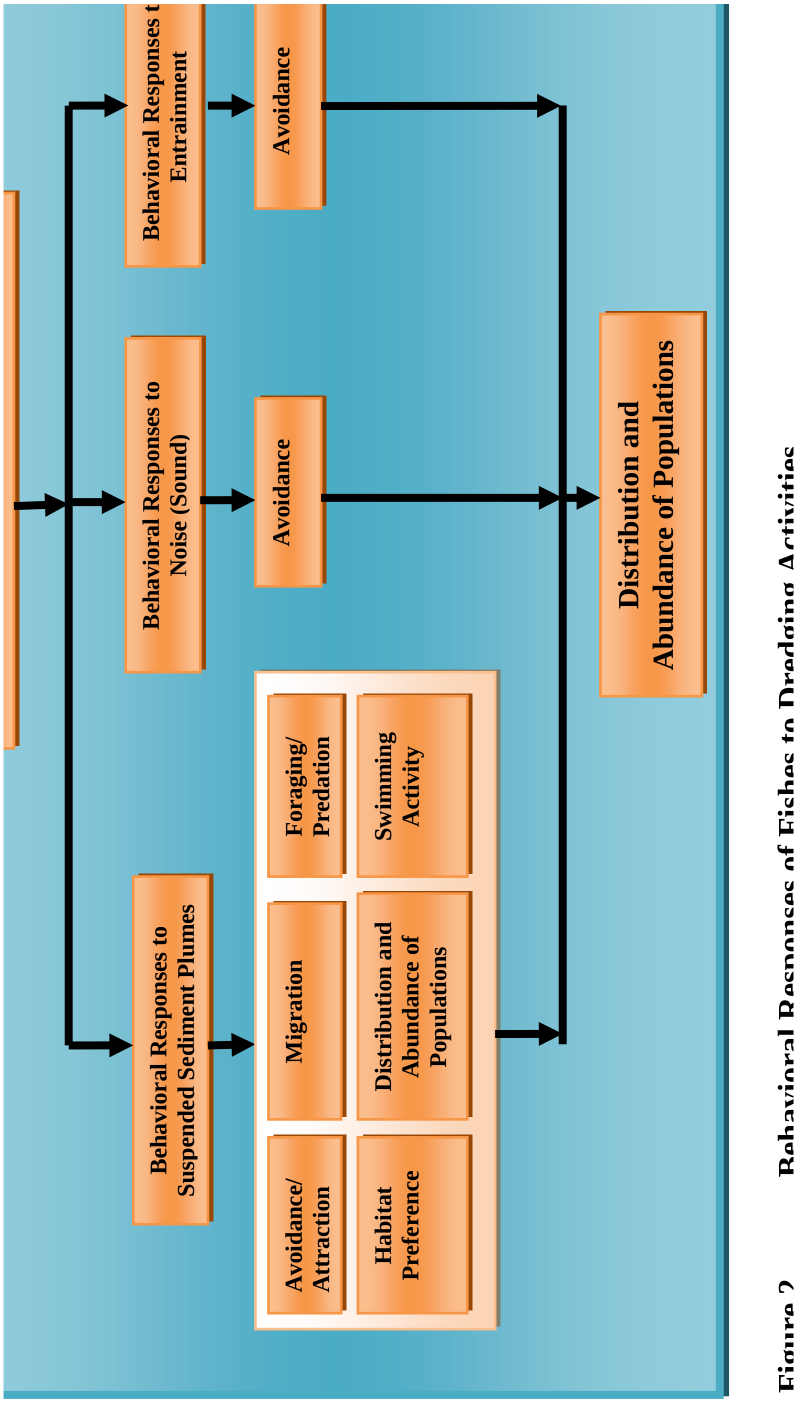

Figure 2: Behavioral Responses of Fishes to Dredging Activities

Methods And Tools Used To Determine Behavioral Responses Of Fishes Exposed To Suspended Sediments/Solids Related To Dredging Activities

Overview

Studies on the behavioral responses of fishes to suspended sediments, that were reviewed by Rich (2010) included:

- Avoidance and attraction;
- Swimming performance;
- Foraging and predation;
- Migration patterns;
- Habitat preference; and,
- Fish distribution and abundance of populations.

The first three types of studies have been conducted in connection with dredging activities. Of those types of studies, four focused on the behavioral responses of fishes to suspended sediment concentrations related to dredging activities. Of those four, three focused on fish avoidance and attraction to suspended sediments related to a large dredging project in New Brunswick, Canada. In the fourth, researchers studied swimming behavior in response to dredge-related suspended sediments. Studies on fish avoidance and attraction, as a result of dredge-related suspended sediment concentrations, were conducted in laboratories and in the field. Studies on swimming activity, foraging, and predation were conducted only in the laboratory. The methods and tools used in each of the studies are discussed next.

Fish Avoidance and Attraction Studies

Overview

To assess the behavioral avoidance or attraction of fishes to suspended sediments, laboratory-based studies were conducted in relation to a large dredging project in the Miramichi Estuary, New Brunswick, Canada (Johnston and Wildish, 1981; Messieh et al., 1981; Wildish and Power, 1985). The studies were conducted on juvenile Atlantic herring (*Clupea harengus harengus*) and rainbow smelt (*Osmerus mordax*). The results demonstrated that juvenile herring and rainbow smelt avoided suspended sediments, implying that dredged-material disposal could result in low catches near the dredged-material disposal site.

Fishes

Fish were obtained by trawling and acclimated in large holding tanks with seawater at appropriate water temperatures until the fish were feeding satisfactorily on brine shrimp. Ten individual fish were used for each experiment. The fish were randomly selected from the holding tank, placed into the experimental apparatus, and allowed to acclimate for either 15 minutes (rainbow smelt) or 45 minutes (Atlantic herring).

Experimental Apparatus and Experimental Protocol

The laboratory apparatus consisted of a trough that had two interconnecting areas (side A and side B) forming a figure-of-eight maze. A door (gate), that allowed fish passage, but limited water exchange between the sides, connected the two halves of the maze. Each of the two areas was supplied with flow-through seawater.

Each experiment consisted of a Control Test and a Treatment Test. The control period of the test was defined as the total time spent by the fish in side A or side B that it required to traverse the gate for a specified number of times. The control period set the observation time required for the treatment period. Sham treatments were made to determine the effect of the experimental operation on behavior. The test variable was the time, in seconds, spent in one side of the area during the control period, compared to the time spent in the treated side during the treatment period. The temporal criterion used was the time taken to traverse the gate either 10 or 30 times. This method tended to reduce the individual variability between fish in background swimming activity. A record was kept of the number of times the fish passed through the gate and the accumulative time spent in side A or side B.

Five control tests were conducted. Each control test consisted of 13 observations at 5-minute intervals and sham procedures involving an initial injection of seawater followed by injections of seawater in either side A or side B at 5-minute intervals.

To determine avoidance or preference (attraction) responses, the following fluids were injected in the side that the fish preferred during the control period: (1) sediment slurry from the dredging area; or, (2) seawater. Then, the observation time was chosen for the treated fish, based on the observation time for the control fish. The treated side, A or B, was chosen from a table of random numbers. One minute before the test, either the sediment slurry or the seawater was injected by syringe into the selected area. To maintain a constant suspended sediment concentration, additional slurry was added every five minutes throughout the treatment period. Seawater samples were taken at 5-minute intervals from the maze throughout the test period. Concentrations of suspended sediments were determined using a spectrophotometer. The results from the spectrophotometer were used to determine the suspended sediments concentrations that the fish avoided. Flow rates and water temperatures were also recorded during the experiments.

Data Analyses

To determine whether or not the proportion of fish in side A or side B in the control period was significantly different from that in the treatment period in each experiment, a Student's t-test was made.

Quality Assurance and Quality Control

In terms of QA/QC, in addition to including both control and sham procedures, the researchers avoided bias from the fish's learning processes. Learning is a temporal process and the arbitrary choice of a time period, as used in the experiments, might have biased the results obtained and helped yield an apparatus-specific threshold avoidance result because visual cues could be used as conditioning stimuli. To test that hypothesis, the researchers tested whether or not a fish that had not previously been in the maze, relied on vision for swimming. The fish were exposed to normal white light conditions, and the time it took to make 30 passages through the gate was recorded. Then, for the control fish, the only change made in the experimental protocol was to replace the white with red light, and the fish were observed again. The result demonstrated that there was no learned behavior. In addition, two (Johnston and Wildish, 1981; Wildish and Power, 1985) of the three studies were in peer-reviewed published journals. Hence, it is assumed that standard protocols were followed for those studies.

Fish Studies on Swimming Behavior

Overview

In the presence of suspended sediment, fish often behave by increased swimming activity (as in “frenetic” and, hence, decreased swimming performance) and by reacting in a frightened or alarmed manner. To determine swimming behavioral responses of rainbow smelt to dredge-related suspended sediment, the fish were evaluated at four concentrations of suspended sediment in a laboratory apparatus that permitted the smelt to select different water velocities in a current gradient (Chiasson, 1993). The effects of both single and multiple exposures were examined. As dredging operations occurred over a period of days, the effects of repeated exposure of smelt to suspended sediment were investigated. It was hypothesized that if suspended sediments resulted in impaired swimming performance due to stress, fish distribution would shift to areas of lower current velocity. Alternatively, if suspended sediments did not impair swimming performance, but was a source of stress, smelt would increase their locomotory activity, presumably in an attempt to leave the area. The results demonstrated increased swimming activity and an alarm reaction.

Sediment/Suspended Sediment

Grab samples of sediment were collected in the same areas as the fish and filtered prior to use. Suspended sediment was measured with a turbidimeter. Suspended sediment concentrations in the testing apparatus were determined optically. Suspended sediment was added as a slurry to the water in the testing apparatus. To avoid sediment buildup on the bottom, the trough was cleaned between trials. Suspended sediment concentration was always checked before each fish was tested and, if necessary, adjusted prior to the trial.

Fishes

Fish were captured during one day of fishing by commercial fishermen in the Miramichi River Estuary, New Brunswick, Canada. Fish were transported to holding tanks and allowed to acclimate for two weeks during which they were treated with tetracycline as a preventative measure against illness. Frozen brine shrimp and freeze-dried krill were fed to the fish on a daily *ad libitum* basis. At the time of each experiment, fish were selected by “blindly” passing a fish net through an initial school of about 270 fish. Fish were exposed, one at a time, to each treatment. Fish were left to acclimate for 15 minutes prior to each test; a number of test trials indicated that fish displayed less erratic swimming behavior after 15 minutes.

Experimental Apparatus and Protocol

The experimental design apparatus consisted of a V-shaped trough constructed of plywood treated with several coats of non-toxic paint. To create areas of different current velocity, but without differences in depth, a fan-shaped design was used. Seawater was pumped from a catch-box at the foot of the apparatus, circulated through a chiller, and then emptied into a head-box. To increase the diffusion of inflowing water, the head-box was equipped with a smaller insert lined with layers of mosquito screen. To produce a more even dispersion of water, small straws were placed at the outflow of the head-box. Current velocities in the testing area were determined using a Marsh-McBirney portable water-velocity meter. The trough was divided into four zones based on the measured mean current. Velocities were checked throughout the experiments. To record the position of the fish in the apparatus, a grid-work of strings suspended over the water and an electric event recorder were used.

Two types of tests were conducted: (1) single exposure; and, (2) repeated exposure. For the single exposure experiments, 24 fish were tested, with six fish evaluated in each test. In the repeated exposure experiments, 18 fish were used, with six fish in each of three groups. In the single exposure experiments, suspended sediment concentrations of 0 (control), 10, 20, and 40 mg/L were tested. All trials lasted 30 minutes. In the repeated exposure experiments, the control group was exposed, and exposed again at 24 and 48 hours, to water containing no added suspended sediments. A second group of fish was exposed to 10 mg/L suspended sediment concentration at 24 and 48 hours. A third group was exposed to 10 mg/L of suspended sediment at 0, and then again at 72 hours, following the previous protocol.

Data Analyses

To examine the data, a two-way non-parametric ANOVA was used; variances were not homogeneous. Where tests gave significant results, differences among medians were determined, using non-parametric multiple comparison procedures.

Studies on Changes in Foraging And Predation Behavior in Fishes

Overview

Three studies were found that assessed the changes in foraging and predation behavior caused by suspended sediments produced during dredging activities. Two of the studies looked at larval Atlantic herring (Johnston and Wildish, 1982; Messieh et al., 1981); the third study looked at several larval marine fish species (Colby and Hoss, 2004). The studies on herring demonstrated that suspended sediment concentrations of 20 mg/L that could be produced during dredging activities, reduced feeding rate. The study on the larval marine fishes demonstrated that the impact of suspended sediment concentrations on larval fish foraging varied with fish species.

Larval Atlantic Herring Feeding Behavior Studies

Overview

In addition to the behavioral avoidance and attraction studies in connection with the large dredging project in the Miramichi Estuary, New Bunswick, Canada, the researchers examined the behavioral responses to feeding in larval Atlantic herring.

Fish

Atlantic herring larvae were obtained from hatched eggs. Eggs were collected from one female and milt collected from two males near the area where dredging activities occurred. Eggs were stripped into plastic buckets, after which the milt from the males was added. To permit mixing, a few milliliters (ml) were added to the bucket and the bucket swirled gently. To allow the eggs, which had now become adhesive, to coat the sides and bottom of the buckets in a single layer, the bucket was the half-filled with seawater and swirled again. The water was drained from the bucket and filled again with fresh seawater. The bucket of eggs was aerated and kept at 5 °C for 19 hours during transportation to the laboratory. At the laboratory, the eggs were allowed to reach 12 °F (Messieh et al., 1981) or 9.5 °C (Johnston and Wildish, 1982), under aeration in a constant-temperature room. To prevent buildup of excretory products, the water was changed every 2-3 days. Hatching occurred within 10-14 days.

After the eggs hatched, the larvae were reared in conical tanks aerated from the bottom. The larvae were supplied with locally caught zooplankton collected daily in a 64 mm mesh net. The larvae were kept in a 10°C constant temperature room with a 16-hour light/8 hour dark photoperiod. As soon as possible, the larvae were encouraged to take newly-hatched brine shrimp nauplii.

Experimental Apparatus and Protocol

Treatment tanks received a measured magnitude of sediment/suspended sediments (10 and 20 mg dry weight of sediment in the study by Johnston and Wildish, 1982; 1-6 mg/L in the study by Messieh et al., 1981) from the dredge area. Control tanks received no sediment/suspended sediments. Larvae that had begun feeding were transferred from the rearing tanks to smaller conical tanks. Ten (Messieh et al., 1981) or three (Johnston and Wildish, 1982) larvae were added to the filtered seawater in each tank and left to acclimate, without feeding, for an 18-hour period. Each experiment started by adding four brine shrimp/ml to each tank. Observations were made for either 2 hours (Messieh et al., 1981) or 3 hours (Johnston and Wildlish, 1982). At the completion of each experiment, the total length of each fish was measured and the larvae placed in buffered formalin for later dissection. The gut of each fish was later dissected under a binocular microscope and the number of brine shrimp consumed per larvae was counted.

Data Analyses

To determine if the differences in the proportion of fish feeding in the control and treatment tests were significantly different, the data were analyzed, using the Student's t-test. In addition, the number of brine shrimp consumed per herring larva was regressed against larval length.

Studies on Feeding Behavior of Some Marine and Estuarine Larval and Juvenile Fishes

Overview

Colby and Hoss (2004) conducted a study to understand feeding behavior of larval and juvenile fishes in connection with dredging plumes. As a basis for the study, they quoted Wilber and Clarke (2001) by stating that there was little empirical information concerning how suspended sediments influenced the behavior of estuarine and marine fishes under conditions typically encountered during dredging operations.

Experimentally exposing fish to controlled turbidities requires methods that compensate for the tendency of suspended sediment particles to flocculate and settle out of suspension. Thus, it is difficult to maintain a specified suspended sediment concentration for the duration of a test interval. Maintaining uniform prey densities is also a challenge because many planktonic organisms exhibit strong phototaxis. Hence, in a static system, prey may aggregate with respect to the existing light gradient, thereby influencing the ability of predatory fish to feed upon them. A testing apparatus was designed to address these issues. The main conclusion of the study was that suspended sediment concentrations affect estuarine fish foraging success differently for different species.

Suspended Sediments

To form a slurry before each test, four total suspended sediment concentrations (20, 200, 2,000, and 20,000 mg/l) were created by blending the appropriate weight of pre-wetted kaolin clay with aerated and filtered seawater.

Fishes

Fishes used in the experiment included spot (*Leiostomus xanthurus*), pinfish (*Lagodon rhomboids*), Atlantic croaker (*Micropogonias undulates*), Atlantic menhaden (*Brevoortia tyrannus*), and flounder (*Paralichthys* sp). Larval and juvenile fishes were collected on flooding tides using a mesh net with an opening and live-box attached to its terminal end. Fishes were held in flow-through tanks and were fed freshly hatched brine shrimp.

Experimental Apparatus and Protocol

To deal with the problems discussed in the Overview, a clear acrylic “wheel”, partitioned into six chambers, was designed that held seawater, sediment, fish and brine shrimp nauplii. Each chamber had two access ports with expandable plugs for filling and draining the chamber. To maintain the sediment in suspension, and to continuously alter the direction of light during each test, the wheel was slowly rotated on its vertical axis on a motorized base.

For each test, a suspended sediment slurry and prey were randomly assigned to the 12 chambers of the two wheels. Each wheel chamber was partially filled with filtered seawater while the wheel was in a horizontal orientation. The assigned suspended sediment slurries were then poured into the chambers followed by the prey. Each chamber was filled with filtered water. In one randomly-selected chamber from each apparatus, dissolved oxygen, temperature, and salinity were measured.

A fish that had been held without food for 24 hours was introduced into the chamber. The access ports were plugged and the two wheels were placed in a vertical orientation on top of a motorized roller system powered by a variable-speed motor. To re-suspend any settled silt-clay, the wheels were set in motion for one minute, and then slowed down for a 30-minute feeding period. At the end of the feeding period, both wheels were removed from the motorized roller, the contents of each chamber strained through a dip net, the fish recovered and processed for gut-content analyses.

Freshly-hatched brine shrimp nauplii were used as prey in all of the experiments during the first phase of the study. Three levels of brine shrimp concentrations were used. To see if fish reacted differently to prey they would be more likely encounter in nature, natural plankton assemblages were used in subsequent experiments. Marine plankton were collected just prior to introduction into the test apparatus.

Data Analyses

To estimate the probabilities that a fish would feed under different levels of turbidity and food concentrations, logistic regression models were applied to the data for each species and prey type. The parameter estimates for the models also provided a convenient means for making comparisons between species, concerning the relative importance of turbidity and prey concentrations in determining feeding success. The logistic regression models were fit to the logarithms of the sediment and prey concentrations.

Methods and Tools Used to Determine Behavioral Responses of Fishes to Noise (Sound) from Dredging and other Vessel-Related Activities

Overview

In the latter half of the 20th century researchers began to conduct studies that demonstrated that anthropogenic (human-generated) sound could affect animals, including fishes (Hastings and Popper, 2005). Studies demonstrated increased concentrations of blood corticosteroids (Primary Stress Responses) and glucose (Secondary Stress Responses) (Smith et al., 2004) in fishes exposed to anthropogenic sound. Hence, anthropogenic sound can affect fish behavior at the Tertiary Stress Response level (Figure 1).

Although not the most frequently-cited concern, noise-related disturbance has been cited as justification for environmental windows for Federal navigation dredging projects in both marine and freshwater systems (Reine et al., 1998). Clarke et al. (2002a) and Dickerson et al. (2001) hypothesized that noise emitted from dredging activities could block or delay fish migration through navigable waterways. In addition, Hastings and Popper (2005) raised concerns on the potential behavioral impacts of anthropogenic sound on communication within and between fish species. While we know a lot about the types of noise produced by dredging activities, we do not know much about the behavioral responses of fishes to those types of noise. Despite advances in sound research on fishes, little is known about the behavioral responses of Pacific coastal fishes to anthropogenic sound (Hastings and Popper, 2005). Nothing is known about the behavioral responses of noise generated by dredging activities (Clarke, 2008, 2007).

Because no studies could be found on the behavioral responses of fishes to noise related to dredging activities, studies on the behavioral responses of fishes to noise generated by fishing vessels and gear are discussed. It is assumed that some of the behavioral responses of fishes to the noise from the fishing vessels and gear would be similar to those from dredging activities.

Determining behavioral responses of fishes to noise generated by dredging activities requires the following types of information:

- Intensity of sound produced by the dredging activity of interest; and,
- Sound frequency thresholds for each fish species of interest,

The methods and tools used for each of these types of studies are discussed next, followed by those used to study behavioral responses of fishes to noise generated by fishing vessels and gear.

Studies that Characterize Underwater Sounds Produced by Different Types of Dredging Activities

Overview

Field studies by Clarke et al. (2002a) and Dickerson et al. (2001) characterized underwater sounds produced by three common dredge types (bucket, hydraulic cutterhead, and hopper). Sources of underwater noise generated by dredging activities include both continuous (e.g., propellers, pumps, and generators) and repetitive sounds (e.g., the dredge bucket striking the channel bottom). Bucket dredges have a repetitive sequence of sounds generated by winches, bucket impact with the substrate, closing and opening of the bucket, and sounds associated with dumping of material into the barge. Cutterhead dredges have relatively continuous sounds made by the cutterhead rotating through the substrate. Hopper dredges produce a combination of sounds from the engine and propeller, that are similar to those from large commercial vessels, and sounds of the draghead moving in contact with the substrate. The intensity, periodicity, and spectra of emitted sounds differ greatly among dredge types. Hence, different intensitys of sound are produced by mechanical bucket or clamshell, hydraulic cutterhead, and hydraulic hopper dredges.

The studies found that cutterhead dredging operations were relatively quiet compared to other sound sources in aquatic environments. Hopper dredges produced somewhat more intense sounds, similar to those generated by vessel of comparable size. Bucket dredging sounds represent a more complex spectrum of sounds, very different than either cutterhead or hopper dredges. Unfortunately, without fundamental studies on biological responses to characteristic dredging sounds, interpreting underwater sound data may be futile. Dredging-sound data must be integrated with knowledge of aquatic organisms' auditory thresholds and behavioral responses to acoustic stimuli.

Field Equipment and Protocol

The underwater acoustic monitoring of bucket (mechanical or clamshell), cutterhead, and hopper dredging operations occurred on vessels in Alaska, Mississippi, and Alabama, respectively. The sounds of the dredging activities were recorded with a low-noise hydrophone with a built-in preamplifier. The preamplifier was connected to a hydrophone audio amplifier through a deck cable. The hydrophone audio amplifier was used to amplify the source levels for both bucket and cutterhead dredging sessions before the audio data were recorded on a Digital audio tape (DAT) recorder. All hydrophone source audio data were recorded on the left audio track of the DAT recorder, while simultaneous field notes were narrated and recorded on the right audio track. The hydrophone audio data were input into an analog-to-digital converter, digitized, and stored on a laptop computer. To display a real-time audio spectrum, an audio analysis software was used.

The system was powered by two 12V DC deep-cycle marine batteries that were connected to a pure sine-wave inverter. The inverter provided a 120V AC power source to an uninterruptible power supply. The power supply powered the DAT recorder, the laptop computer, and a variable voltage DC power supply that was used to provide 24 V DC power to the hydrophone audio amplifier. By using the two 12V DC batteries as the only power source, the entire system could be operated with the listening vessel completely shut down to a "quiet" mode. This eliminated any noise that would be introduced by the engine or generator operating on the research vessel.

To record depth, water temperature, and salinity data, a HydroLab water quality surveyor was suspended 1 meter (m) above the hydrophone. The resulting data were used for calculating sound speeds.

Recording sounds for the three dredge types differed. All bucket dredging recording sessions were conducted aboard a steel hull launch. Due to extremely high tidal amplitudes and flow velocities in Cook Inlet, it was determined that monitoring the acoustic levels from a fixed or anchored position was not possible. Instead, a "drift" transect approach was used in which a vessel was maneuvered to a predetermined distance from the sound source and then completely shut down and allowed to drift with the current during each recording session. This approach minimized the flow conditions present at the hydrophone, thereby reducing drag imposed on the hydrophones. A similar sampling protocol was employed to record sounds from the cutterhead dredge. It involved multiple recording sessions at increasing distances from the dredge plant. To record sounds of hopper dredging operations, the listening vessel was held in a stationary position a short distance to the side of the track of the advancing dredge, and the position was maintained as the hopper dredged continued past that location.

At the start and end of each recording session, the distance to the dredge sound source was measured. At close ranges the distance was determined with a laser range finder and the distance recorded in meters. When the distance was further than the maximum usable distance for the laser range (approximately 500 m), ranges were estimated using radar units and recorded in nautical miles. In addition to the distance notes narrated on the DAT tape, positional information including latitude and longitude was recorded at the beginning and end of each drift session with differential GPS.

Data Analyses

Each recording session was digitized from the DAT tape using an analog-to-digital converter and stored in computer files. Each of the files was reviewed and the contents of each file summarized. Initial sessions were used only to determine appropriate gain settings for the hydrophone audio channel (left) on the DAT and not for audio analysis purposes. Twelve additional sessions were conducted to monitor the bucket dredging operations. Because cutterhead sounds are continuous, several-minute intervals were recorded at selected distances. Durations of the hopper-dredge sessions were determined as the dredge began and ended an individual pass within the navigation channel. Each pass involved: (1) turning on the draghead pumps; (2) lowering the dragheads to the bottom while underway; (3) dredging along a zigzag track in the channel; (4) raising the dragheads; and, (5) turning the vessel. Then the process was repeated in the opposite direction.

Studies on Sound Thresholds in Fishes

Overview

The ears of fishes are located in the cranial cavity and the auditory organs consist of three fluid-filled otolith organs (utricle, saccule, and lagena), each containing a dense calcified matrix (the otolith) overlying a sensory epithelium containing hair cells (Popper and Fay, 1993). The sensory hair cells are part of the sensory epithelium, and their cilia contact the otolith. Any relative motion (i.e., a sound field impinging upon a fish) between the epithelium and the otolith will result in bending, or shearing, of the cilia. This bending results in a change in the receptor potential of the cell. The change in the receptor potential of the cell, in turn, excites neurons of the eighth cranial nerve which innervates each sensory hair cell (Popper and Fay, 1993).

The hearing ability of fishes ranges from infrasound (Sand and Karlsen, 1986) to above one kilohertz (kHz) (Hawkins, 1993). Generally, fish hear sounds at frequencies between 100 and 2,000 Hz and the most sensitive bandwidth varies from species to species. Some fish have hearing thresholds as low as 50 decibels (dB) *re: 1ĖPa*, while others have their hearing thresholds as high as 150 dB *re:1ĖPa*.

It is generally agreed that fish are either "hearing specialists" (e.g., Pacific herring, American shad) or "hearing generalists" (e.g., salmon, steelhead) (Popper and Fay, 1993). Hearing specialists have adaptations that enhance their bandwidth and sensitivity (i.e., lower their hearing threshold). For example, in the Pacific and Atlantic herring, there is a connection between the swim bladder and inner ear (Popper et al., 2003). In contrast, hearing generalists do not have evolved mechanisms that enhance hearing. As a result, hearing specialists detect sound pressure with greater sensitivity (as low as 50 dB *re: 1ĖPa*) and in a wider bandwidth (up to 3 kHz) than hearing generalists, such as a salmon or steelhead.

Fishes can discriminate between sounds of different amplitude and frequency, determine direction and distance to the sound source (Popper et al., 2003), and distinguish between sounds with complex patterns in temporal structure (Popper et al., 2003). Fishes can also identify one sound amongst several (e.g., background noise). These higher hearing capabilities are far more important to a fish than just detection of sound because, for example, a fish must discriminate between the sounds of a predator versus those of a prey.

Sound travels as a wave whose amplitude is related to the intensity of acoustic energy it carries, or how loud the sound will appear to be (Popper and Fay, 1993). The amplitude of any sound can be measured in terms of the two parameters sound pressure or particle motion (Chapman and Sand, 1974). Sound propagating through any medium consists of both pressure fluctuations and particle motion (Popper and Fay, 1993). Particle motion can be expressed in terms of particle displacement, velocity, or acceleration. Particle motions have been classified as those occurring in the "near field" or in the "far field". Far-field particle motions can be predicted from sound-pressure measurements alone, whereas predicting near-field particle motions requires measurements of both particle motion and sound pressure (Popper and Fay, 1993).

To determine how well fishes hear, researchers use a set of hearing curves, or audiograms (Popper and Fay, 1993). Hearing thresholds in fishes (and other vertebrates) can be found by using either behavioral-hearing or physiological tests. The results of such tests are presented as an audiogram that plots sound-pressure threshold (in dB) as a function of frequency (in Hz). Sound-pressure thresholds have been reported as root-mean-square (RMS), peak, peak-to-peak (p-p), or with no designation. Each fish species has a different auditory system and a different audiogram (Popper and Fay, 1993).

The following three approaches have been used to obtain fish audiograms:

- Behavioral;
- Microphonics; and,
- Measuring the auditory brain-stem response (ABR).

Because of the complexity of the processes necessary to obtain the audiograms (i.e., fish species, experimental apparatus, field methods, etc.), only a summary is provided for each approach. More details of these studies, as well as those in numerous other studies on the hearing thresholds of fishes, are given in the *Literature Cited* section of Popper and Fay (1993).

Behavioral Approaches

To obtain fish audiograms using behavioral methods requires that a fish be trained to react in a specified and measurable way (e.g., avoidance conditioning, heart-rate response, or food seeking). The four behavior-type studies summarized below determined sound thresholds for several fish species.

To define auditory thresholds for carp (*Cyprinus carpio*), Popper (1972) used avoidance conditioning. The fish were trained to cross a barrier in the middle of a tank whenever a pure tone was presented through a loudspeaker mounted in the air near the test tank. To reduce ambient noise, the experimental tank was placed in an acoustic chamber. Using one fix per trial, a total of six fish were used in the experiments. When a fish failed to cross the barrier during the stimulus, it was concluded that the fish had not heard the sound, and thresholds were determined at the 50% level.

Offutt (1974) used heart-rate conditioning to determine hearing thresholds in the Atlantic cod (*Gadus morhua*). Fish were held in a nylon mesh net, positioned lengthwise in a wooden framework inside a tubular tank. The test tank and all test equipment were housed in an underground concrete room, and the pure-tone stimulus sounds were generated by a speaker built into the wall of the chamber. Electrocardiograms were obtained using an electrode inserted into the pericardial cavity of the fish. A reduction in the heart rate indicated that the fish had heard the signal and sound thresholds were determined (Dixon,1965).

Chapman and Sand (1974) conducted a field study of hearing thresholds in two species of flatfish (*Pleuronectes platessa* and *Limanda limanda*) in a loch in Scotland. A PVC frame was located between the water surface and the seabed. To administer an electric shock to the fish's tail, stainless steel electrodes were built into the cage. The potentials generated by the fish's cardiac muscles were recorded, using a subcutaneous electrode. The conditioning stimulus was a pure-tone pulse presented to the fish for 10 seconds, paired with a 6 to 12 volt (DC) electric pulse administered to the fish from shore. The cardiac potential from the fish was amplified and recorded using a storage oscilloscope. A hydrophone, positioned below the head of the fish, recorded the sound pressure of the stimulus tone. The sound was presented to the fish through two sound projectors. To condition the fish, the electric shock was administered after presentation of the stimulus sounds. Conditioning using this methodology was repeated until the fish showed an alteration in heart rate after onset of sound but before the shock. Full conditioning was considered to have occurred when five consecutive trials had yielded positive responses.

Yan and Popper (1992) defined the auditory sensitivity of a cichlid (*Astronotus ocellatus*) using a non-invasive reward-based methodology. The experiment involved using an automatic feeding device to train three cichlids to respond to an acoustic cue. A clear plastic tube delivered food pellets to the fish. To allow the fish to receive visual, as well as acoustic, cues to a feeding event, the feeding tube was clear. Two paddles were suspended from a platform and sent response signals to a computer that controlled food delivery if the correct sequence of paddles were pressed during acoustic stimulation. The experiments were conducted in a soundproof chamber and the stimulus tones were presented to the fish using an underwater speaker. The fish were trained to peck one paddle and then to peck the other paddle, if they detected the stimulus sound. A correct response resulted in the fish obtaining food. Once trained, thresholds were determined from the sound level at which 50% of the trials resulted in a correct response.

Microphonics Approach

A number of researchers have studied sound thresholds in fishes by measuring microphonic potentials (Enger and Anderson, 1967). The microphonic potential is an evoked potential elicited by hair bundle deflections and recorded with extracellular electrodes placed near the apical portion of a group of hair cells. In fishes, microphonic potentials can be measured from hair cells in the inner ear or the lateral line.

To measure microphonic potentials from the Atlantic cod and the sculpin (*Cottus scorpious*) in the open sea, Enger and Anderson (1967) implanted electrodes by drilling small holes in the cranium close to the saccular nerve. A silver wire was inserted into the hole and sealed using dental cement. The stimulator was a tone burst from an underwater sound projector driven by an oscillator and amplifier.

Fay and Popper (1974) recorded microphonic potentials from the ear of a goldfish (*Carassius auratus*) in a situation where sound pressure and particle displacement could be independently varied. When two transducers positioned facing each other are operated in phase, the water between them is compressed, creating a sound field dominated by pressure and minimal particle displacement. When the transducers are operated out of phase, one compresses the water while the other pulls it, creating a field dominated by particle displacement with minimal sound pressure. Also tested were fish with the swim bladder present and then again, after removal of the swim bladder. The fish were tested in a PVC cylinder located in a soundproof acoustic chamber. A water bag containing the fish was suspended in the middle of the cylinder; air speakers were positioned above and below the bag containing the fish. An amplifier and function generator were used to generate the sound presented to the fish.

Popper and Fay (1974) recorded potentials from the saccule of the African mouthbreeders (*Tilapia macrocephala*) with submerged glass-insulated tungsten electrodes. The fish were exposed to both acoustic and vibrational stimulation in a soundproof acoustic chamber for sound reception both with the swim bladder filled with air and with water. The test tank was a PVC cylinder mostly filled with water. The floor of the cylinder was made from rubber that was supported by a plastic grating. A loudspeaker was suspended facing upwards below the test tank in an airtight extension of the cylinder. The sound-pressure level required to evoke 1 ĖV RMS Auditory Evoked Potential (AEP), was determined using a hydrophone positioned adjacent to the fish's ear.

Auditory Brain Stem Response (ABR) Approach

The Auditory Brain Stem Response (ABR) audiometric method to generate audiograms has been used on a variety of fishes (Kenyon et al., 1998; Casper et al., 2003; Akamatsu et al., 2003). In all cases, the experiments were conducted in a soundproof booth into which anaesthetized fish (4-8 fish in all, depending upon the study and species) were clamped in place with a net mesh that was positioned so that the top of the head was above the water surface. Two electrodes were pressed against the exposed cranium above the medulla with the reference electrode positioned opposite the recording electrode. Sound was generated by a loudspeaker suspended above the water surface with one speaker used to generate frequencies below 3 kHz and a second speak used to generate frequencies above 3 kHz. The Sound Pressure Level (SPL) was recorded using a hydrophone placed near the ear of the fish. The tones and clicks were presented at various pressure levels to obtain thresholds, which were identified by visual inspection of the averaged ABR traces when superimposed over the first run.

Studies to Determine the Behavioral Responses of Fishes to Noise Generated by Fishing Vessels and Gear

Overview

Population estimates of commercially important fish in Europe are based on hydroacoustic and trawl surveys. The accuracy of the fish population estimates depends on a number of assumptions, most of which have been demonstrated to be invalid (Vabø et al., 2002; Handegard, 2007; Handegard et al., 2003, 2005; Bez et al., 2007). In fact, the behavioral responses of fish to vessel noise have been cited as the causes of significant errors when assessing the abundance of fish stocks (Handegard and Ona, 2001). As a result, in an effort to provide more accurate population estimates of commercially important fish species, the Europeans, particularly the Norwegians, have conducted studies on the behavioral responses of fishes to fishing vessels and gear, including those related to sound (Engås et al., 1998, 1995; Ona and Godø, 1990; Olsen et al., 1983; Erickson, 1979). Behavioral responses of fishes to sound produced by fishing vessels and gear included:

- Avoidance (change from loose schooling or random orientation in shoals to dense schooling, slow diving, diagonal swimming , or swimming away from the noise of the vessel;
- Alarm reaction (rapid polarization and burst swimming); and,
- Increased swimming speed.

Fishes' behavioral responses to fishing vessels and gear are complicated and, hence, difficult to determine. The levels of radiated noise from the vessels are such that many fishes are capable of detecting them at great distances (Buerkle, 1977; Chapman and Hawkins, 1969). Evidence suggests that there is a large difference between the distance at which fishes detect sounds and the distance at which they react to it (Mitson, 1993). However, it is not understood which specific characteristics of the sound are necessary to make fishes not only detect but also react to the sound. Finally, researchers often had a difficult time interpreting the results of the behavioral studies because of inadequate types of equipment used and/or assumptions that could not be validated. The methods and tools used in studies on behavioral responses of fishes to noise produced by fishing vessels and gear included:

- Biotelemetry with sound-detection equipment;
- Playback of selected sounds (using sound recording equipment) to fish that were enclosed in net pens; and,
- Hydroacoustic surveys.

Behavioral Responses of Cod Using Biotelemetry and Sound Detection Equipment

Overview

Because sound generated by a trawler falls within the hearing range of fishes, they may hear sounds from an approaching vessel and react at a long distance (Buerkle, 1977). Tracking individual acoustically-tagged fish with sonar or hydrophones is an approach to a better understanding of the behavior of individual fish to the pre-vessel zone. To determine the behavioral responses of Atlantic cod to vessel-related sound, individual free-swimming cod were acoustically-tagged close to the bottom and tracked in the pre-vessel zone during trawling in a sheltered marine area outside Bergen, Norway (Engås et al., 1998). To determine whether or not sound, and not sight, triggered the behavioral responses of the fish, the surveys were conducted under different light conditions.

The researchers concluded that:

- Vessel-related sound triggered the behavioral response in the cod;
- The sound intensity from the vessel had its highest intensity well within the range where cod have their highest hearing sensitivity; and,
- There were indicators of a lower level of sensory awareness during reduced light levels.

Survey Equipment and Protocol

To determine the behavioral responses of the Atlantic cod to vessel-related sound, a biotelemetry system (VEMCO) was used. It consisted of two components:

- Ultrasonic tags ingested by the fish; and,
- A stationary positioning system to track the acoustically-tagged cod.

The stationary positioning system had a fixed array of three hydrophone buoys with radio transmission to a base station (a stationary vessel). The hydrophone buoys were anchored to the sea bed in a triangular configuration.

To measure sound level and frequency spectrum of the trawling (shrimp) vessel during fishing operations, the researchers used a hydrophone suspended in the water. The sound measurements were made from a stationary vessel anchored in the investigation area with its engine turned off. The sound was amplified and logged on a digital tape recorder. The equipment was calibrated before and after the measurements. To calculate the horizontal distance between the vessel and the trawl doors, a transmitter was mounted on the starboard trawl door.

During the 20 days before the arrival of the trawler, the researchers studied the natural behavior of the cod to a baited longline. The trawl was set with the codend at a specific distance from the tagged fish. The vessel headed at a constant speed towards the center of the triangle of hydrophones. Trawling was conducted every day, at different light conditions. Nine trawl hauls were performed during the experiment and sound was recorded when the vessel was free-running. Before and after the sound level and frequency measurements, the ambient sound level was recorded on a digital tape recorder. The equipment was calibrated before and after the measurements.

Fish

Ten days before the shrimp trawler arrived in the study area, three cod were tagged, *in situ*, close to the sea bed with acoustic transmitters; the cod were allowed to voluntarily ingest the transmitters wrapped in mackerel bait. Each transmitter gave horizontal (two-dimensional) position fixes (x and y coordinates). To identify and estimate the length of the tagged fish, an underwater camera was mounted in a frame.

Data Analyses

Behavioral reactions to the trawling vessel were defined as attempts by the fish to move to an area with lower sound intensity. The behavior of the fish had to satisfy the following criteria: (1) before the trawl entered the study area, the fish must have shown consistency in movement by swimming in one direction for at least 30 minutes; and, (2) reaction to the approaching vessel was defined when the fish changed either its swimming direction or speed, based on ANOVA and Duncan's multiple range tests. If these criteria could not be satisfied, the case was characterized as no reaction. To calculate the distance between the vessel and the fish, x-y positions of the vessel were back-calculated to the same time as the position of the fish. In all cases, it was assumed that the fish were close to the bottom.

Behavioral Responses of Penned Herring and Cod to Tape-Recorded Sounds from a Fishing Vessel

Overview

To determine characteristics of vessel sound that could arouse avoidance reactions in Atlantic cod and Atlantic herring, researchers studied the behavioral responses of penned fish to playback of original, filtered, and time-smoothed recordings from a factory bottom trawler (Engås et al., 1995). The behavioral responses included avoidance, alarm, or no response. Avoidance reactions of both cod and herring were observed during playback of the original 60-300 Hz and 300-3,000 Hz spectra, but hardly any avoidance reaction to the 20-60 Hz spectrum. The cod responded longer to the original sound than to the time-smoothed sound. The researchers concluded that the main determinant for triggering avoidance reactions in the cod and herring was vessel sound level within the most sensitive frequency region, although other sound characteristics appeared to be important.

Fishes

For the study, two groups of cod (18 and 16 fish) and one group of herring (18 fish) were caught with traps and a near-surface purse seine, respectively, and placed without food in a net pen for four and seven days, respectively. An underwater loudspeaker was positioned outside the nearest net wall at a distance beyond the near field of the lowest frequency transmitted). The ambient noise level and the playback of the sound recordings were measured with a hydrophone placed inside the net pen. The behavior of the fishes was observed with an underwater camera mounted in a corner of the net pen. During daylight of every second day, both species were presented with 3-4 paired randomly-selected original and smoothed sequences of the same spectrum for 130 seconds, separated by a rest of at least 20 minutes.

Experimental Equipment and Protocol

The experiments were carried out during spring in a sheltered area near Bergen, Norway. Sound energy generated by an operating bottom trawler under normal throttle (rpm, pitch and speed settings) was recorded using two hydrophones. The sound recordings started when the hydrophones were about 200 m in front of the vessel and stopped when they were about 200 m astern of it. This gave sound recordings of about 130 seconds in duration.

Four categories of vessel sound were edited and used for playback experiments:

- The original sound recordings of the vessel noise;
- The original sound recording split up into three frequency bands based on the audiogram established for cod;

- The amplitude of the original recordings time-smoothed and, through a series of amplifications, provided the same maximum sound level as that of the original sound; and,
- The three bands (above), but time-smoothed.

Avoidance responses of cod and herring were observed at the higher (60-300 Hz and 300-3000 Hz) spectra, but not to the lower (20-60 Hz) spectrum. It was concluded that: (1) the main determinant for triggering avoidance reactions was vessel sound level within the most sensitive frequency for the fish; and, (2) other sound characteristics (e.g., temporal structure) seemed to be important.

Data Analyses

Video recordings of the fish behavior in the pen were analyzed in 10 second intervals. The behavior was classified by three criteria: group pattern (shoal, school); vertical swimming (downward, horizontal, or upward); and, tail beat frequency (i.e., number of tail beats per 10 second interval). Three types of responses were noted:

- No response (no systematic change in behavior during playback sequence);
- Avoidance response (change from loose schooling or random orientation in shoals to dense schooling, slow diving, or diagonal swimming close to the bottom of the pen); and,
- Alarm response (rapid polarization and burst speed swimming to the bottom of the pen).

The start and duration of the overall responses to the playbacks were measured.

Behavioral Responses of Pacific Herring to Tape-Recorded Sounds of Fishing Vessels

Overview

Fluctuations in Pacific herring (*C. h. pallasi*) biomass stimulated interest in the possibility that the fish were avoiding underwater noises generated by operating fishing vessels. Consequently, Schwarz and Greer (1984) studied the behavioral responses of the herring to a variety of underwater sounds, including those generated by fishing vessels. Avoidance responses were elicited by sounds of large vessels (i.e., loud sounds) approaching at constant speeds and by smaller vessels (i.e., softer sounds), but only when on accelerated approach (Appendix D). Captive herring showed no response to playbacks of these sounds.

Fish

All the fish came from a single stock of about 500 adult herring that were captured by seine net in Stuart Channel, B.C. and transported in a partially-submerged enclosure to the Pacific Biological Station fish farm in Departure Bay. The fish were held in the pen from January through April.

Experimental Equipment and Protocol

The recording equipment consisted of a DC-powered cassette tape recorder and hydrophone with matching preamplifier. All field recordings were made from a small, unpowered seiner with the hydrophone lowered to 25-30 m, the depth at which herring schools were observed to travel during the day.

Sounds made by fishing vessels and several items of gear, as well as various background sounds, were recorded at traditional Pacific herring spawning grounds just before the opening of the herring roe fishery. Background sounds included: (1) rain on the water surface; (2) cries of several species of gulls floating on the water; and, (3) barks of swimming steller's sea lions (*Eumetropias jubatus*). To determine the behavioral responses of the herring, selected recordings were played back to the herring in the net pens.

Sounds from the following fishing vessels and gear were recorded from a quiet anchored ship 0.2 km away: (1) various types of seiners; (2) a troller; and, (3) a gill netter. Recordings of sounds from the moving fishing vessels always included departure from, as well as approach to, the hydrophone. The distance of each vessel from the hydrophone was determined by radar at the start of the recording and at three-minute intervals thereafter. A recording of a hull-mounted echo sounder and background noise were added to the sound recording that was played to the herring.

Data Analyses

Reactions to sound were of three types: Avoid; Alarm; and, Startle. The duration (in seconds) of the responses Avoid and Alarm was the measure used to quantify the effect of a sound on the fish. Each group of herring served as its own control. To monitor the sounds as they were projected to the fish, an observer wearing earphones sat quietly by the net pen.

Recordings of electronic sounds comprised 11 combinations of three variables: amplitude; frequency; and, temporal pattern. Each variable was manipulated in one of three ways (the Triad) to create three types of sounds: continuous tone; regular pulses; or, irregular pulses. Recorded sounds were analyzed using a spectrum analyzer and an oscilloscope. Only sounds recorded in net pens or in the field were subjected to spectrographic analysis.

Responses were evaluated using nonparametric statistics and two measures of effectiveness: the number of groups responding to a given treatment; and, the percent of responding groups habituating to that treatment.

For the electronic sounds, a two-way ANOVA was used to determine whether one member of a pair was more effective than another, with duration of the first and fifth responses as the test measure. Habituation was also investigated. The criterion used for habituation to a triad was a response of shorter duration to the fifth repetition of that triad than to the first one.

Using Hydroacoustics to Study the Behavioral Responses of Marine Fishes to Trawling Noise

Overview

Cod and other demersal fishes are sensitive to low-frequency noise (Hawkins, 1993; Sand and Karlsen, 1986). They can discriminate and localize engine and propeller noise above background noise at distances greater than 2 (km) (Ona and Godø, 1990). Ona and Godø (1990) used a stationary echo sounder on board a launch to study the behavioral responses of demersal fishes to the noise associated with a fishing trawler near Bergen, Norway. The study found that a significant number of fish at depths from the surface down to 200 m began to respond (avoidance) before the vessel arrived. At greater depths, such pre-vessel avoidance response was not significant.

Experimental Equipment and Protocol

The experimental equipment mounted on the launch included two portable echo sounder systems, a portable tape recorder and a hull-mounted transducer. To compare fish responses under different noise conditions, a purse seiner/trawler was first operated without the net, but at "trawling speed", and then at "surveying speed". For the trawling experiments, two trawlers were used. Both nets had been used to sample cod and haddock in the northeast Arctic. During periods of observation, the engine in the launch was turned off.

Data Analyses

Based on the observations during the study, four zones were defined:

- Pre-vessel avoidance zone (the volume in front of the hull-mounted vessel transducer);
- Propeller noise and warp avoidance zone (volume between the acoustic axis of the vessel's transducer and the trawl doors);
- Herding zone (the sweep volume from the trawl doors to the trawl); and,
- Mesh selection zone (the part of the trawl where the fish that have entered are subjected to mesh selection).

To evaluate the significance of pre-vessel avoidance, a statistical analysis of the data was undertaken. Pre-vessel avoidance was interpreted as a systematically lower acoustic abundance during the process of trawling, compared with the abundance when surveying at full speed in the area adjacent to the trawl station.

Methods and Tools Used To Determine Behavioral Responses Of Fishes To Entrainment Related To Dredging Activities

Overview

Entrainment is defined as the direct uptake of aquatic organisms by the suction field generated at the draghead or cutterhead of a hydraulic dredge (Reine and Clarke, 1998). During the dredging process, the primary type of behavior is the fishes' ability or inability to swim away to avoid becoming entrained.

Hydraulic entrainment of fishes has been a concern linked to dredging operations in the United States and elsewhere for several decades. In the Bay, dredging effects associated with entrainment were rated a high priority for herring larvae and juvenile Chinook salmon, steelhead, and herring (Levine-Fricke, 2004). Yet few studies have been conducted on fish entrainment during dredging operations. Two studies are:

- Laboratory-based swimming behavioral study on lake and pallid sturgeon and paddlefish (Hoover et al., 2005); and,
- Field-based fisheries hydroacoustics and trawling study (Reine et al., 2001).

The laboratory-based swimming performance study demonstrated that the paddlefish were very unlikely to be entrained because of a failure to orient against a flow field and, swimming behavior varied relative to the size and species of fish. The results of the field-based hydroacoustic and trawling study did not demonstrate that dredging operations resulted in hydraulic entrainment and mortality.

Swimming Performance Studies

Overview

Paddlefish and sturgeon collectively constitute one of the most imperiled groups of fishes in North America (Hoover et al., 2005). Recently, agencies have expressed concern that inland dredging could have a negative impact on populations of these species by entraining juveniles; small young-of-year fish (<200 cm) are believed to be especially susceptible. The entrainment of juvenile paddlefish and sturgeon is not detected during normal dredging operations because dredging activities are not monitored and because the remains of these largely cartilaginous fishes may be unrecognizable. Hoover et al. (2005) conducted a study that used swimming performance as an indicator of risk in the paddlefish (*Polyodon spathula*), pallid sturgeon (*Scaphirhynchus albus*) and lake sturgeon (*Acipenser fulvescens*).

The purpose of the study was to determine the potential risk of entrainment of the paddlefish and the two species of sturgeon from dredging operations. To that end, the researchers estimated potential risk of entrainment by designing models that used swimming performance as a function of water velocity. To measure swimming behavior in the fish, the researchers used simplified flow models and modeled the results of each fish's reaction to both rheotaxis and endurance, in addition to noting other behavioral responses. Rheotaxis was defined as the response or reaction of an organism, such as a fish, to the stimulus of a current (Tweeny and Hughes, 1967). Endurance was defined as the time that a fish could continue to move or maintain its position during the swimming trial. Behavior was defined as any overt actions of a fish in direct response to a stimulus. In the study, swimming and station-holding behaviors were categories. Two notable results came out of the study: ranges of sustained, prolonged, and burst speeds were substantially different among the fish species; and, paddlefish were unlikely to be entrained because of a failure to orient against a flow field.

Fishes

Juvenile fishes were obtained from fish hatcheries and housed in closed-system tanks with re-circulating water as weak (<5 cm/s) directional flows. Daily cycles approximated 12 hours of light and 12 hours of darkness. Fish were fed two to four times daily and were not fasted prior to testing. To avoid “training effects”, new individuals were used for each experiment.

Experimental Equipment and Protocol

The experimental apparatus consisted of a swim chamber, and the procedure followed a protocol from a previous study on pallid sturgeon. A motor-driven propeller generated the flow, and a rheostat on the motor water controlled velocity. Collimators (flow filters) at the upstream end of the swim chamber removed turbulence so flow through the working section of the tunnel was straight and uniform (rectilinear). The rear portion of the chamber was covered with a removal cap of fine mesh screen. A constant water temperature was used in all trials for each species.

During testing, three components of swimming performance and recovery were evaluated:

- Rheotaxis;
- Endurance; and,
- Station-holding behavior (i.e., the method used by the fish to maintain its position in flowing water).

The same experimental protocol was used in each experiment. Each “test fish” was placed in the working section of the swim chamber and allowed to acclimate for 15-30 minutes at low flow (5-10 cm/s). At the end of the acclimation period, water velocity was increased to the test velocity over a two- to three-second interval, and timing began. Test velocities ranged from 30 to 90 cm/s. If the fish failed to exhibit rheotaxis, it was allowed a one- to two-minute rest before the flow returned to the test velocity. If, after multiple attempts, the fish still did not exhibit rheotaxis, it was considered a non-swimmer and excluded from further testing and subsequent analysis.

With a fish oriented into the flow, the test continued for 200 minutes, or until the fish could no longer maintain position. During the trial, swimming behaviors of the sturgeon were identified and the duration of each behavior was timed separately (when trials were of long duration and individual behavioral prolonged). Any fish that could no longer maintain position, and was swept back against the screen, was gently stimulated by fanning the water against the screen using a broad wooden probe. If the fish was unable to dislodge itself from the screen the test was ended and time noted.

At the conclusion of each trial, water temperature was recorded and the fish was removed from the swim chamber and placed in a plastic bag or an enamel pan of water. Lengths and weights were recorded, and the fish observed for injuries, changes in behavior or mortality.

Data Analyses

Rheotaxis was described as the percentage of fish tested at specific water velocities that successfully oriented into the flowing water. So that species could be compared, ranges of water velocities were used because not all species were tested at all water velocities.

Swimming speeds were classified by endurance for a given water velocity as follows:

- Sustained Speeds: > 200 minutes endurance. Sustained swimming depends on aerobic metabolism but does not result in muscular fatigue. It is used in migration, foraging, and routine activities;
- Prolonged Speeds: 30 second to 200 minute endurance. Prolonged swimming uses both aerobic and anaerobic metabolism and results in fatigue;
- Burst Speeds: <30 second endurance. Burst swimming depends upon anaerobic metabolism; it quickly depletes short-term energy reserves. It is used in prey capture and predator avoidance; and,
- Escape Speeds: velocity at which predicted endurance was one minute or less (i.e., the upper limits of prolonged swimming and the entire range of burst swimming).

Predictive models of swimming performance were developed using regression analysis with water velocity as the independent (predictor) variable and endurance as the dependent (response) variable. Fish exhibiting sustained speeds and those that were non-swimmers were excluded from model development. Curvilinear and linear models were developed simultaneously. The model with the greatest predictive ability was used to represent data for that species.

Swimming and station-holding behaviors were categorized and quantified. Classification of behavior was based both on previous studies and on novel observations in this study. Following each trial, the duration of each behavior was estimated and the mean time at each velocity was calculated.

Studies that Used Fisheries Hydroacoustics in Conjunction with Fish Sampling

Overview

Reine et al. (2001) designed a study to characterize movements of fishes at spatial and temporal scales appropriate for detection of interactions between fishes and the presence of a dredge. The objective was to determine fish entrainment associated with a dredging project. The study was not designed to quantify actual absolute entrainment rates; rather, it was designed to determine probabilities of entrainment by examining several factors associated with the dredging project. As a “by-product” of the study, some fish behavioral changes were noted. Due to logistical problems with using screens to collect and quantify entrained fishes, fisheries hydroacoustic surveys were used in conjunction with otter trawl surveys. These methods enabled the researchers to characterize movements of fishes at various spatial and temporal scales in the vicinity of dredging activities.

Fish distributions were examined in the vicinity of a hydraulic pipeline dredging operation in the outlet of the St. Joseph River into Lake Michigan, Michigan. The researchers were interested in the directional component of fish distributions from the dredge. By knowing the directional component of changes in fish distributions with distance from the dredge, they could determine whether or not fish were attracted to, or avoided, the dredge operation. In theory, an attraction response, particularly for bottom-oriented fishes, could increase the fishes' susceptibility to entrainment. Likewise, an avoidance response could affect access of fish to either lake or river waters. The authors discussed the relative risk of entrainment of fishes by dredging activities; bottom-dwelling fishes were more likely to be susceptible to entrainment. The results indicated that there was little evidence that the dredging operations resulted in hydraulic entrainment and mortality.

Survey Equipment and Protocol

The hydroacoustic surveys used a dual-beam echo sounder with transducer, signal processor, interface box, and data logging equipment. For the spatial coordinates of hydroacoustic targets to be related to the dredging location, a differential Global Positional System (GPS) was linked to the surface unit. The transducer was a dual-beam piezoelectric type with both a narrow and wide-beam mode. The digitized echo returns were processed by a standard laptop microcomputer for display, storage, and analysis. The transducer was attached in a vertical, downward-sensing orientation to a hydrodynamically-balanced towfish that was deployed from the survey vessel. To avoid noise effects from the vessel's wake, the towfish was positioned just below the water surface and towed from the side of the vessel. Tow speeds were maintained at 2.5 knots.

Year one was a pilot study, and year two was the full study. Two mobile hydroacoustic survey designs were employed: wide area; and, spatially intensive. Wide-area surveys, which were designed to examine large-scale spatial distributions of fishes in both the dredging site and adjacent nearshore lake and river waters, consisted of 16 harbor and five lake surveys. Spatially-intensive surveys were focused at the dredging site, using the cutterhead position at the time of the survey as a benchmark. This design gathered data on small-scale distribution patterns in proximity to the dredge. To obtain 360 degree spatial coverage, each survey used radial transects.

To examine diurnal shifts in the distribution of the targeted fish, both the wide-area and spatially intensive hydroacoustic surveys were conducted during day and night. The surveys were run during times when the dredge was active, and when the dredge was either absent or present but not in operation.

To provide target species identification and two "ground" target length estimates from acoustic target-strength data, conventional trawling techniques were used. A standard otter trawl with a mesh liner was deployed from the same vessel used for the hydroacoustics surveys. A total of four surveys were made in two consecutive years. In the first year, trawl surveys were conducted during the first and last weeks of May. In the second year, one survey was taken during early April and a second during early May. Surface, mid-depth, and bottom trawling was conducted at three inshore and eight offshore stations. In an effort to standardize the catch-per-unit effort, the nets were towed for approximately five minutes.

To calibrate the echo-sounding equipment used in the fishery resources surveys, water quality data were collected. Hydrographic data were obtained using a Hydrolab® unit to record depth, temperature, and dissolved oxygen. A total of 10 profiles were recorded from one offshore and one onshore station the first year. The subsequent year, a total of 18 profiles were taken at a single inshore and four offshore stations. Profiles of the water column were taken in 2-m depth increments from bottom to surface.

Data Analyses

Data from both wide area and intensive surveys were collected for the entire water column and subjected to echo integration and single target analysis. Echo integration is necessary at high fish densities because echoes from multiple fishes can overlap, which prevents the fish from being individually counted. To examine changes in distributions through the water column using echo integration, vertical distributions of fish density or biomass can be plotted. Echo integration analysis was performed with visual-analyzer software that outputs ASCII files containing individual target data, including target strength (in dB), depth, date, time, and latitude/longitude.

The researchers carried out single-target analysis with a software package developed by the USACE ERDC. That package provides trackline information with bottom depth output in a GIS-ready format, visual echogram files in standard Microsoft Windows BMP format, volume calculations, and enhanced single-target analysis. Individual target-fish lengths were estimated by a modified version of an equation reported by Love (1971), based on dorsal aspect target length. To produce spatial displays of the data, output files are entered into GIS.

To identify fish targets with various size ranges, acoustic target strength data were compared with observed otter trawl catch data. Densities of detected fish targets reported for both echo integration and single target analysis were normalized to 100 cubic meters of sampled water volume for comparison. For spatial analysis, transects were divided into 30-m segments. Individual horizontal segments were vertically partitioned into surface, mid-water and bottom zones. Fish densities, estimated by echo integration and single target analyses, were plotted in the following three ways: (1) dredge-present and dredge-absent; (2) dredge-active and dredge-inactive; and, (3) daytime and nighttime dredging operations.

Methods and Tools Used To Determine Fish Presence, Distribution and Population Abundance In Response To Dredge-Related Activities

Overview

Field studies that measured presence, distribution and population abundance of fishes during dredging activities fell into five general categories:

- Studies that used biotelemetry;
- Studies that used fisheries hydroacoustics in conjunction with fish sampling;
- Studies that used fish sampling in conjunction with biotelemetry and external Peterson tags;
- Studies that used fish sampling and external spaghetti tags; and,

- Studies that used fish sampling alone.

The methods and tools used in the above-listed study provided four types information:

- Individual fish movements, including emigration, dispersal, and localized movement, both in the vicinity of, and outside of areas in which dredging activities occurred;
- Whether or not dredging activities affected fishes;
- The types of habitat that fishes resided in relative to dredging activities; and,
- The presence or absence of fishes in the vicinity of dredging activities and dredged-material disposal areas.

The studies that used biotelemetry in conjunction with hydroacoustics or hydroacoustics combined with fish sampling provided the most detailed and quantitative types of information. Neither the use of hydroacoustics alone nor fish sampling alone were reliable to quantify behavioral responses of fishes to dredging activities, nor to assess the impacts of dredging activities on fish presence, distribution, or abundance.

Studies that Used Biotelemetry

Overview

Two studies used biotelemetry, establishing biotelemetry arrays and implanting ultrasonic tags in fish:

- White sturgeon maintenance dredging study on the Columbia River (Parsley and Popoff, 2004); and,
- Juvenile salmonid outmigration and distribution study in the Bay (USACE, 2007).

In the white sturgeon study, the fish exhibited a variety of movements. The results of the Bay salmonid studies were preliminary in nature, but demonstrated that a substantial proportion of the salmonids used at least one dredged-material placement site.

White Sturgeon Maintenance Dredging Study on the Columbia River

Overview

The USGS Columbia River Research Laboratory in Cook, Washington, studied how channel-maintenance dredging activities might influence the behavior of white sturgeon (*A. transmontanus*) in the lower Columbia River (Parsley and Popoff, 2004). Two objectives were addressed in their study:

- To determine if site fidelity of home ranges of juvenile and adult sturgeon were restricted to areas that might be affected by dredged material disposal in flow lanes; and,
- To monitor sturgeon behavior in flow-lane disposal areas as dredged materials were added.

To that end, the USGS implanted ultrasonic tags in some of the sturgeon and conducted surveys using acoustic telemetry systems containing:

- An acoustic positioning system; and,
- Acoustic data loggers.

The results provided information on individual fish movements, including emigration, dispersal, and localized movement. Hence, the study provided a way to monitor fish behavior in and out of dredging disposal areas. From the results of the study, the researchers concluded that dredging activities did not result in behavioral avoidance or attraction by the white sturgeon.

Fish

To capture sturgeon for implanting ultrasonic tags baited setlines were used. Fishing effort occurred within (<100 m outside), or adjacent to, the triangle formed by the three VEMCO radio-acoustic positioning system (VRAP) buoys. Setlining occurred as needed. Most setlines were set overnight, but soak times varied between 8 and 20 hours in duration.

Six adult and 27 juvenile white sturgeon were surgically implanted with VEMCO ultrasonic tags. After measuring fork length and total length, individual fish were placed ventral side up in a foam-lined, V-shaped trough. An incision was made with a surgical scalpel along the mid-ventral line about 50-70 mm anterior to the insertion of the pelvic fins while a small pump attached to a hose moved river water gently over the gills. Forceps were used to spread the muscles apart and insert the transmitter into the abdominal cavity. Incisions were closed by four or five interrupted sutures with 2-0 or 4-0 coated PDS II. Fish were released near the capture site.

Survey Equipment and Protocol

To collect data on fish movements and depths over time, two independent telemetry systems (VEMCO) were used: a VRAP, and an acoustic data logging receiver system. The VRAP provided detailed information on fish movements within a localized area. The acoustic data loggers (located primarily upstream and downstream of the VRAP), provided information about direction of fish that left the center of the study area and gave a longer record of depths used by the fish.

The VRAP comprised three moored buoys, each with a hydrophone, an acoustic receiver, a radio modem and a shore-based processing center composed of a base station and a computer. Acoustic signals from the fish that carried ultrasonic transmitters were received at each buoy and then transmitted to the base station. The VRAP system software calculated the *x* and *y* coordinates of the transmitter relative to the center of the triangular buoy array with hyperbolic equations and times of arrival of acoustic signals at each hydrophone. Real-world geographic coordinates of each buoy position were checked repeatedly with GPS receivers operating the Precise Positioning Service.[1] Vendor-provided software transformed the VRAP derived *x* and *y*

[1] Precise Positioning Service (PPS) is available to the military and certain Federal civilian agencies. This service differs from the Standard Positioning Service available to civilian users. The GPS receiver, which incorporated the Wide Area SPS Enhancement (WAGE) system, can achieve less than 4 m error in horizontal positioning

coordinates to real-world geographic coordinates through use of a geo-referenced raster image. The spatial coordinates were used for display and analysis within a GIS.

Each buoy, that was independently moored, was powered by an internal 12-volt battery with voltages continuously displayed on the base station computer. A fourth buoy was rotated into the array when the voltage of a functioning buoy dropped below 11 volts even though experience had shown that buoys were able to function at voltages greater than 9.5 volts.

Positioning of the acoustic transmitters relied on synchronized clocks among system components. The base station updated the clocks of the buoys and received stored acoustic data from the buoys. The base station obtained real-world time from the computer system. Analyses comparing fish positions with dredge positions also required synchronization of the clocks. To improve data integration, an external clock that used time available in GPS signals was installed on the computer. Highly accurate time is available in GPS signals, and GPS is used by ships, including the dredges operated in the lower Columbia River.

To accurately calculate the position of a transmitter and to calculate buoy separation distances, the speed of sound in water was needed. To directly measure this parameter, the researchers used a Smart CTSV manufactured by Applied Microsystems Limited of Canada. The sound velocity measurement was rounded to the nearest whole number and input into the project settings of the VRAP software.

To provide additional information about fish that moved beyond the range of the acoustic positioning system, seven submersible acoustic receivers (VEMCO VR2) were placed around the acoustic positioning system. The VR2 receivers are single-channel omni-directional units that record the time and date, and identify each fish fitted with an ultrasonic transmitter that swims within the range of the unit. In addition, they can record the depth of the fish if the transmitter has depth-sensing capabilities. Each receiver consists of an identification detector, data logging memory, and a battery contained in a submersible case. Each receiver was suspended below the water surface with the hydrophone oriented downward.[2] An internal lithium battery allowed the receivers to operate autonomously for up to eight months. The information was stored in flash memory until downloaded onto a computer.

Two types of individually indentified coded ultrasonic tags were used in this study: pingers that conveyed identification information only; and biotelemetry transmitters that also conveyed the pressure (converted to depth) that the tag was exposed to. The standard pinger tags were smaller than the pressure tags, and therefore were used in smaller fish. VEMCO pingers and pressure tags were used on the larger fish.

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autonomously in real-time without the need for broadcast variable or post-processing. To indicate the quality of the data, the WAGE also provides position error estimates.

[2] After deployment of the receivers, commercial fishermen immediately voiced concern that the moorings were interfering with their traditional gill net drifts. The USGS removed the data loggers from the river during commercial fishing but left the positioning array. This action had the potential to reduce the information collected on movements away from the positioning array. However, it was deemed a reasonable compromise against potential loss of gear that might have occurred had the USGS not removed the data loggers.

To determine short-term behavioral responses during dredging operations, data on fish movements were collected before, during, and after two pipeline dredging and one hopper dredged-material disposal operations. To investigate shifts in focal areas during the short period before and during dredging operations, spatial analyses of density plots were also conducted with the GIS program, ArcView.

Data Analyses

The acoustic data received from the buoys were automatically stored on the base-station computer. Vendor-supplied software was used to generate ASCII files of all fish position data, as well as depth and buoy calibrations. After a series of steps where the data were "filtered" to validate the data, the resulting ASII files were imported into a spreadsheet for further formatting. Column headings were added, geographic coordinates were converted to decimal degrees, and the spreadsheets were converted into an Access® database. Data analyses followed further filtering of the data. Acoustic tag data (i.e., date, time, tag code, and depth, if the tag was a sensor tag) downloaded from the VR2 receivers also were placed into an Access® database, but no additional processing was done on these data.

Analyses of fish-movement data during the dredge-disposal operation differed somewhat from analyses of movements during pipeline operations because hopper-dredge operations were distinct instead of continuous. For the hopper dredge, attraction or avoidance was evaluated for the entire cycle (24 hours). White sturgeon movement and depth were compared among three 24-hour blocks of time - before, during, and after the dredge-disposal cycle. When there was a significant difference in the ANOVA, a least-squares-mean procedure was used to locate those differences. A repeated-measures analysis was used to compare fish movement and depths among 20 minutes before and after disposal. To see if there was an attraction, avoidance, or no change in distance from the disposal area, a Mann-Whitney test was used to compare the distances from individual fish locations to the disposal site for the 20 minute period before and after disposal.

The analyses of fish behavior before, during, and after pipeline dredging operations were complicated by the inactive periods during the dredging operations. Attraction or avoidance by dredging operations was determined by investigating fish movements during the first 24 hours of dredging activities. A repeated-measures ANOVA (with individual fish as the repeated variable) was used to test for difference in movement and depths of individual sturgeon among periods of equal time before and after dredging. Movement and depth variances were heterogeneous, so a mixed model was used.

Habitats associated with fish locations were identified by frequency analysis. Relative importance of habitats was further ascertained by calculating the density of fish locations per unit of each habitat description. Plots of the density of fish locations within habitat categories provided an assessment of important habitat.

Juvenile Salmonid Outmigration Study in the Bay

Overview

Environmental work windows (June through November in most areas) have been established for the placement of dredged material in the Bay (USACE et al., 2001). These work windows were based on geography and time of year when Chinook salmon and steelhead were believed to be absent. The current work windows resulted from a programmatic consultation based on scientific and commercial data gathered at the time the windows were established. During the environmental work windows, dredging operations in the Bay can occur without having to conduct ESA Consultations with NOAA Fisheries. If dredging activities are proposed during non-window months, consultation with NOAA Fisheries is required.

To provide more recent site-specific quantitative information on relevant work windows for dredging, in 2007 the Corps completed the first year (a pilot study) of a proposed three-year study on emigration behavior of juvenile Central Valley late-fall-run Chinook salmon and Central Valley steelhead in the Bay (USACE, 2007). The three main objectives of the study were:

- Establish transit times through the Bay;
- Measure residence times in areas of interest; and,
- Identify trends in migratory pathway.

The laboratory and field methods, data interpretation, and some data analysis techniques were adopted from a CALFED-funded study design (USACE, 2007). The objective of the pilot study was to determine the suitability of equipment, logistics, and feasibility of addressing certain study questions. The study demonstrated that the logistics and collaboration would yield results in support of information needs, and a substantial proportion of the populations of both species used at least one dredged-material placement site.

Fishes

Juvenile Chinook salmon and steelhead from the USFWS Coleman National Fish Hatchery were used for this study. It is assumed that the fish were proceeding through the parr-smolt transformation during the time of the study. The fish were held in an outdoor cement raceway at the hatchery and separated by species with a mesh net. The fish were then transferred by an aerated fish-transport truck to the CABA Putah Creek Lab Facility in Davis, California. To acclimate the fish to the cooler lab water, local well water from the lab facility was poured into the tank of the transport truck. The fish were then netted out of the truck and transferred to four outdoor holding tanks that were filled with fresh well water. The water in the tanks mixed continuously. To prevent fish from leaping towards the outlet of the faucet and falling out of the tank, the tanks were covered with a round net. The fish were held in the tanks for seven days prior to the first week of surgery.

Prior to surgery, the fish were held in a cooler with local well water and anaesthetized. Each fish was tagged following CALFED's procedure (USACE, 2007). Each week for five weeks, beginning in January, ten individuals of each species were implanted with an acoustic transmitter tag. Each fish was removed from the anaesthetic solution when it lost equilibrium. The fish's weight, fork length and the condition of its scales, fins, and eyes were recorded. A digital picture of the fish alongside of its individual identification number was taken. The fish was placed ventral-size up on a surgery cradle. Using a submersible pump, water containing anaesthetic passed through tubing from a container through a pipette inserted into the fish's mouth, and flushed over the fish's gills. An incision was made, and the salmonid was surgically implanted with VEMCO ultrasonic tag.

Each individually-coded cylindrical ultrasonic tag was inserted into the peritoneal cavity of the fish. The tag was positioned so that it was lying just under the incision. The incision was closed with two simple interrupted sutures using Extra Nylon Cable Sutures. To recover from the surgery, the fish was then placed into a tank. After a five-day holding period, the implanted tags were checked for proper function using a VEMCO VR100 manual tracking receiver. The fish were then released into the Sacramento at Rio Vista, California. As a precaution against release predation, untagged Chinook salmon and steelhead were also released with the tagged fish.

Survey Equipment and Protocol

A biotelemetry system was used to collect data on juvenile salmonid emigration down the Sacramento-San Joaquin System and through the Bay. The essential components of the system were:

- Ultrasonic tags that had been implanted in the salmonids; and,
- An acoustic data logging receiver system ("monitors")[3] that recorded the passage of juvenile salmonids by detecting the ultrasonic signals.

The acoustic data receivers tracked the passage of juvenile salmonids by detecting an ultrasonic signal propagated by the ultrasonic internal tags on the fish. VEMCO V2 submersible receivers ("monitors") were used, similar to those described previously for the Columbia River white sturgeon studies. The V2 receivers were placed in a variety of locations in the Bay. Some of the receivers were placed with overlapping ranges ("curtain arrays") at "choke points" in the estuary. The data from these receivers provided information on transit times from one array to the next, and total transit time from the release site near Rio Vista to the Golden Gate Bridge (last array).

Data Analyses

The data from each of the receivers were transferred to a PC in the field with a magnetic probe. A single Windows-based PC was used to download all of the receivers. The data forms and unprocessed data were managed by researchers at the NOAA Fisheries Southwest Fisheries Science Center in Santa Cruz, California. Those researchers created and maintained the shared SQP Microsoft Access database, which is organized into tables that summarize all the unprocessed data and data from the submitted data forms. The data tables allow the user to conduct queries for specific data.

[3] In the USACE (2007) study, the VR2 receivers are called "monitors". VEMCO refers to the VR2's as receivers. In the white sturgeon study conducted on the Columbia River that is discussed earlier in the report, the researchers referred to the VR2's as receivers. For consistency sake, in this review, the VR2's are referred to as receivers.

Quality Assurance and Quality Control

The Corps is actively collaborating with UC Davis and NOAA Fisheries to formalize and finalize QA/QC procedures (USACE, 2007):

- Receivers will be checked upon installation and soon before fish release;
- All ultrasonic tags will be checked for proper operation and transmittal of ID number before implantation;
- Initial data collection will be done using protocols established by the UC Davis group
- Full data auditing will occur on a percentage of fish to be determined, based on the total quantity of data obtained, but is expected to be at least 5% of the individuals; and,
- Since it is expected that results and conclusions of this study will be published in the peer-reviewed technical literature, data handling, data analysis, and conclusions will conform to contemporary scientific standards.

Studies that Used Fisheries Hydroacoustics in Conjunction with Fish Sampling

Overview

There were four studies to determine presence, distribution, and abundance of fish populations using hydroacoustic surveys in conjunction with fish sampling related to dredging activities:

- Alcatraz Island Disposal Site (San Francisco Bay) fisheries hydroacoustic and trawling study;
- St. Joseph River (Michigan) fisheries hydroacoustic and trawling study;
- James River (Virginia) fisheries hydroacoustic and gill net study; and,
- St. Lawrence River Estuary (Quebec, Canada) fisheries hydroacoustic and trawling study.

Of the four studies, the oldest survey—Alcatraz Island—was the least informative, due primarily to the lack of an appropriate study design. The more recent studies used more sophisticated methods and detailed analyses.

Alcatraz Island Dredged-Material Disposal Site Fisheries Hydroacoustics and Trawling Study

Overview

One USACE dredged-material disposal site is located in San Francisco Bay south of Alcatraz Island. In the early 1990’s, the Department of Fish and Game requested an analysis of potential impacts from the disposal of high sulfide sediments on fish populations. Although the fish disappeared for two to three hours after dredged-material disposal, the reason for the fish disappearance was not known. In response, Burczynski (1991) conducted a study whose objectives were to determine: (1) the feasibility of using hydroacoustic methods to monitor the distributions of fish and other aquatic organisms in the Alcatraz island dredged-material disposal area before, during, and after disposal activities; and, (2) if high sulfide levels could be implicated in fish avoidance behavior in the vicinity of the Alcatraz Island dredged-material disposal site.

Study Area

The study area , located approximately 1,000 m south of Alcatraz Island in 11 m of water, was divided into two sections, one east and one west of an underwater mound. During the study, dredged-material disposal was of west of the mound. The dredged-material plume moved eastward with the current during flood tide.

Survey Equipment and Protocol

The study used a combination of hydroacoustics and midwater trawling surveys. The hydrocoustic data-collection system consisted of a dual-beam echo sounder, a dual-beam transducer, a chart recorder, a tape-recorder interface, a digital tape recorder, and dual-channel oscilloscope. Bottom information, fish traces, and dredged-material disposal were displayed in real-time on the oscilloscope and the chart recorder. Survey data were recorded on digital tape and later analyzed in the laboratory. The system was installed on a survey vessel, with the tow fin deployed from a davit on the starboard side near mid-ship. The fishing depth was approximately one meter.

Survey operations were conducted for three consecutive days from 7 a.m. to 4 p.m. The first two days were used for trials of different transect patterns; the third day was used to conduct a survey with an optimum survey pattern. Data were collected along a transect cruising in a westward direction during flood tide. Survey operations proceeded as follows. Hydroacoustic transects and mid-water trawls were conducted before, and hydroacoustic transects were conducted after, the dredged-material disposal. A trawl sample was attempted after dredged-material disposal but was abandoned due to technical problems. The survey vessel cruised in a westward direction at approximately six knots during hydroacoustic transects and three knots during the trawl sampling. No QA/QC measures were discussed in the report.

Data Analyses

The analysis was based on data from echo integration and dual-beam techniques and the results from the trawl surveys. The echo signals were processed with an echo signal processor (ESP) that produces computer files for later analysis. The ESP can also produce graphic presentations of the data in the form of color echograms and distributions of fish density or fish size. Data analysis included comparing relative fish sizes and estimating fish distribution, by estimating fish target strengths and densities. To examine changes in distributions throughout the water column, vertical distributions of fish density and biomass were plotted. The data provided characteristic patterns of traces that indicated the difference between fish and dredge materials.

St. Joseph River Fisheries Hydroacoustics and Trawl Study

The methods and tools used for the St. Joseph River fisheries hydroacoustic study (Reine et al., 2001) were discussed previously in the section on behavioral responses of fishes to entrainment generated by dredging activities (pages 28-30).

James River, Virginia, Fisheries Hydroacoustics and Gill Net Study

Overview

Researchers wanted to know whether or not dredging operations would pose significant risks to local fish populations on the James River in Virginia (Clarke et al., 2002b). To that end, they conducted a study that used a combination of hydroacoustics and gill net surveys to determine whether or not fish distributions changed during periods of hydraulic cutterhead dredge operations, compared to those when the dredge was inactive. Fish abundance and spatial and temporal distribution patterns were examined in proximity to the dredge operations in a selected reach of the river. The results indicated that the presence of an active dredging operation did not shift fish distributions in a detectable manner. However, the researchers concluded that the absence of a pronounced attraction or avoidance response could have been due to a number of factors other than dredging activities.

Survey Equipment and Protocol

The hydroacoustics survey equipment was discussed previous for the St. Joseph River fish entrainment hydroacoustics studies (pages 28-29). Two hydroacoustic survey designs were employed: (1) wide-area; and, (2) spatially intensive. The wide-area surveys were designed to determine whether or not fishes occurred in the following areas:

- In the deeper waters of the river, including the excavation channel;
- Over shoals bordering the channel; and,
- In certain vertical segments of the water column.

Three wide-area surveys were conducted: two during ebb, and one during flood tide. Those surveys consisted of nine transects that extended laterally across the river. To examine both horizontal and vertical distribution of fishes over as large an area as possible within a single tidal cycle, the surveys were conducted in roughly a zigzag pattern.

To examine distribution patterns at spatial scales appropriate for the presence of a dredge, pipeline discharge, or suspended sediment plume, spatially intensive surveys were conducted. Using either the dredge or the discharge pipe as a focal point, radial transects were established at intervals covering a complete 360 degree area encircling the dredge or discharge. Radial transects were assigned to “zones”, denoting whether or not their location was up- or down-river, or lateral to the focal point. Intensive surveys in the vicinity of an active dredge were conducted during flood tide; at the pipeline discharge site, intensive surveys were conducted during both flood and ebb tides.

To provide site-specific data on fish distribution and populations, panel-separated, horizontal, anchored, variable-mesh gill nets were used. Sampling occurred at 11 stations along established geo-referenced transects during daylight hours and, to the extent possible, at slack tide. To reduce mortality in the catch, the gill nets were deployed for short (<1 hour) soak periods. The surveys were conducted during dredge operations.

An acoustic Doppler current profiler (ADCP) was deployed to characterize flood and ebb current structure and velocity during the hydroacoustic surveys. ADCP surveys can characterize both the structure of flow fields, which provide insights into observed fish distribution patterns, and suspended sediment concentration gradients. Fish target positions can be related to the current, as well as to turbidity gradients, because both the fishery hydroacoustics and ADCP data are "tagged" with differential GPS coordinates. Measurements recorded were vessel direction and speed, current velocity in three-dimensions at selected collection data ranges, bottom depth, and surface-water temperature.

Data Analyses

The methods used for data acquisition were the same as those described previously for the St. Joseph River fish entrainment hydroacoustic studies (pages 28-29). Fish target densities were estimated by echo integration techniques as described by Thorne (1983). Acoustic data were compared with catches of fishes in gill nets deployed at the study site. Estimates of individual target fish length were calculated by a data analysis software program, based on an equation for dorsal aspect target strength (Love, 1971). To filter out noise, a minimum target-strength-detection threshold was set at a decibel level equivalent to an estimated fish length of 4 cm.

Densities of detected fish targets were normalized to 100 cubic meters of sample water for comparison. All transects were divided into 30-m segments for spatial analysis. Individual horizontal segments were vertically partitioned into three depth increments, as follows:

- Surface;
- Mid-water; and,
- Bottom stratum. An ANOVA statistical analysis was used to detect significant differences in fish densities (fish/100 m^3) between zones (e.g., upstream, downstream, or lateral to the dredge position) or segments (30-m increments) for both active and idle dredges.

St. Lawrence River Fisheries Hydroacoustics and Trawling Study

Overview

The St. Lawrence River, Quebec, Canada is a major waterway that has been modified considerably over time due to commercial navigation. The estuarine transition zone (Winkler et al., 2003) of the St. Lawrence system is a part of an estuary known for its importance to several anadromous fish species, including the Atlantic sturgeon (*Acipenser oxyrinchus*) and the lake sturgeon. Both of these species are under consideration for designation as "endangered" or "vulnerable" species by the Quebec Provincial Government. To ensure ship access to the navigational channel, ferry wharves and marinas, maintenance dredging is required annually. A potential threat to these sturgeon species is the annual disposal of dredged sediments in the St. Lawrence Estuary near Quebec City, Quebec, Canada (Hatin et al., 2007b).

Dredged material was disposed of in different locations, notably upstream of an area of concentration of young-of-the-year and juvenile Atlantic sturgeon in the estuarine transition zone. Given the importance of these juvenile nursery areas, McQuinn and Nellis (2007) conducted a study to:

- Determine the short-term and cumulative impacts of the dredged disposal material on abundance, distribution, and movements of the sturgeon species downstream of the disposal area; and,
- Investigate the usefulness of acoustic surveys for assessing sturgeon density and distribution.

The researchers employed a two-phase adaptive protocol using both acoustic and catch-trawl data. Although the results were somewhat subjective and, therefore, considered to be experimental, the results indicated that the spatial distribution of demersal fishes was dependent on substrate, as the fishes avoided areas of dredged sediment disposal and association with sand dunes.

Survey Equipment and Protocol

The hydroacoustic data-collection system consisted of an echo sounder coupled with a split-beam transducer and a data acquisition system Simrad et al., 1998). The system was installed on a survey vessel with the transducer on an acoustic platform suspended by two chain links over the starboard side.

The experimental protocol involved using acoustic data collected along transects and catch data collected from trawling stations chosen on the basis of the acoustic densities. The result was to produce two discrete density estimates: (1) one from the results of the acoustic data; and, (2) one from the results of the trawl data. To avoid biases in detection ability due to diurnal differences in the vertical distribution of demersal fishes, the surveys were conducted during the daytime.

To measure distribution and abundance of fishes, the studies were conducted within five strata before and after dredged-material disposal. The strata were defined to cover a range of habitats where sturgeon had been observed during preliminary fishing and telemetry studies. One stratum was assumed to be most disturbed; it encompassed the dredged-material disposal zone. The other four strata were used as control sites.

Each integrated hdyroacoustic survey within each stratum was conducted according to a two-phase adaptive protocol. This protocol involved using acoustic data collected along transects and catch data collected from trawling stations to produce two discrete estimates. For the hydroacoustic survey, the research vessel ran parallel transects aligned perpendicular to the river flow with a 1.5 km spacing.

The trawling gear was specially built for the study area. The trawl survey stations were chosen on the basis of hydroacoustic densities. From the initial hydroacoustic surveys, the acoustic area backscattering coefficient of all fish echoes along all transects was broken down into 100-m intervals, or “bin” estimates that defined a series of potential trawl stations. The bin values were sorted in ascending order and divided into three proportionally equal-sized density classes, or ‘substrata” (low, medium, and high), based on the cumulative probability distribution of the square root of the bin estimate. For trawling, up to three bin locations were randomly selected from each density substratum for trawling. A standard trawl set was designed to cover 1.5 km, towed perpendicular to a hydroacoustic transect, intersecting it at the randomly selected bin locations. Trawling speed was maintained in the direction of the current. This protocol allowed for a random-stratified abundance estimate (i.e., stratified on the hydroacoustic population density), from the trawl catches as well as a systematic abundance estimate from the hydroacoustic transects.

Data Analyses

To differentiate between sturgeon and other bottom-dwelling fishes, acoustic backscatter data were visually scrutinized using an acoustic data analysis software. Echoes within 1 m of the bottom were classified as demersal fish if the amplitude of at least two consecutive pulses constituting the echo decreased before detection of the bottom signal. Echoes were ignored when demarcation from the bottom was ambiguous.

Raw sample backscatter and phase-angle data were filtered and stored on disk, along with GPS and platform motion data in a standard hydroacoustic data format used previously by the researchers. The acoustic estimates were integrated for all echoes classified as demersal fish at intervals of 100 m along each transect. The mean fish density was calculated for each stratum by averaging the integrated backscatter per transect.

The trawl catches were identified to species and length was recorded for all fish. All fish were sampled for length-frequency distribution. Individual weights were estimated from length-weight relationships. To estimate the catch weight and relative abundance for each species, the sums of the individual weights were used. Abundance and variance estimates were calculated from the mean catch, weighted by the swept area of the trawl and the proportional area of each of the three density substrata.

Although all fish species were sampled acoustically and by trawling, only the demersal species were analyzed. Student's t-tests were used to determine significant differences between the estimated survey mean densities before and after dredged-material disposal.

Quality Assurance and Quality Control

With regard to QA/QC procedures, in addition to conforming to the procedures for the peer-reviewed journal that the paper was published in, the following were noted in the study:

- Without having a way to stabilize the vessel, the ability to detect demersal fishes on the echograms was much reduced. Hence, platform pitch and roll on the vessel with the transducer was kept to within ± 5 ° as much as possible, monitored in real time, and stored in the acoustic data file;
- To avoid bottom signals in echo integration, in the data analysis, care was taken to delineate fish echoes closer to the bottom; and,
- In the data analysis, echoes were ignored when demarcation from the bottom was ambiguous.

Studies that Used Fish Sampling in Conjunction with Biotelemetry and External Peterson Tags

Overview

A study that used fish sampling on conjunction with both telemetry and fish tagging was conducted on adult shortnose (*A. brevirostrum*) and juvenile Atlantic sturgeon (*A. oxyrhinchus*) in an dredged area (Lower Cape Fear River, North Carolina) (Moser and Ross, 1995). These two sturgeon species historically supported valuable commercial fisheries in North Carolina. The results provided information on the relative abundance, seasonal occurrence, habitat use (in both routinely dredged and undisturbed areas), and movements of the sturgeon. The study comprised:

- Gill nets and trammel nets;
- Biotelemetry; and,
- External Peterson tags.

To address presence, distribution, and population abundance of two species of sturgeon, the sturgeon were tracked during dredging operations. The results provided information on the relative abundance, seasonal occurrence, habitat use, and movements of the sturgeon in areas that were routinely dredged and in undisturbed areas. Both species occupied regularly-dredged areas and were present during dredging operations.

Survey Equipment and Protocol

To sample fish, two sizes of monofilament gill nets and a trammel net were used. Gill nets were set in three areas. Samples were taken weekly for six months and every two weeks during the rest of the year. In each sampling week, the nets were deployed for three days and two nights and checked daily. When water temperature exceeded 28 °C, to reduce fish mortality, the nets were checked twice daily. Surface and bottom salinity and temperature were recorded at each set on each sampling day. Weights and lengths (fork and total) of all sturgeon caught were recorded. CPUE was defined as the number of fish caught in one 50 m net fished for 24 hours (a "net day"). Both species of sturgeon were tagged externally with Peterson disc tags through the dorsal caudal fin, and sturgeons in excellent condition were selected for sonic tagging.

The biotelemetry system consisted of: (1) high-power telemetry transmitters; (2) portable digital readout receiver; and, (3) a directional hydrophone. The fish were divided up into large (>80 cm total length) and small (< 80 cm total length) and different-sized transmitters were fit on the two size groups; the larger transmitters had an 18-month battery life and the smaller-sized transmitters had a seven-month battery life. The transmitters were usually attached externally. To minimize handling stress, sturgeons were surgically implanted only when water temperature was less than 28 °C. To identify the fish, all transmitters were uniquely coded by frequency and pulse interval. The sonically-tagged fish were released at the site of capture and tracked continuously for at least six hours after release. Transmitter signals were located by a portable digital-readout receiver and a directional hydrophone. During periods of continuous tracking, fish positions were determined by a combination of triangulation and signal strength at least every 15 minutes. Current velocity was measured with a Marsh-McBirney meter at least every

30 minutes during continuous tracking. Surface and bottom water temperatures and salinities were recorded frequently. After the release date, sonically-tagged fish were relocated during daily surveys with portable receivers or whenever the fish passed one of the three remote receiver stations. The remote receivers, operated around the clock, provided a record of diel activity. Depth, water temperature, and salinity were recorded at each location.

Data Analyses

Data analysis included:

- Determining whether or not the sturgeon exhibited diel activity pattern by comparing the frequency of passage events in sonically-tagged fish during six 4-hour time periods, using the X^2 Test. To assess individual variation and ensure a minimum expected frequency of four in each time period, only fish that passed the monitors at least 24 different times were included in this test;

- Documenting depth distribution of sonically-tagged juvenile sturgeon by comparing depths at daily relocations to available depths, using X^2 analysis. The mapped area was divided into depth zones and the proportional area of each depth zone was determined by the map-weighing method (White and Garrott, 1990); and,
- Calculating mean bottom temperature, salinity, and CPUE.

Studies that Used Fish Sampling and External Spaghetti Tags

Overview

The importance of the St. Lawrence River System to the Atlantic and lake sturgeon, and the potential threat of annual dredging to these species, was discussed previously. In a second-dredge-related sturgeon study on the St. Lawrence River Estuary, Hatin et al. (2007a) tested whether or not dredging disposal affected presence, distribution, and population abundance of Atlantic and lake sturgeon. The researchers used gill nets to sample fish, used external spaghetti tags to identify the fish, and compared catch-per-unit effort before and after dredging events. The study sampling design was a before-and-after approach that included affected and control stations. The results suggested that the Atlantic sturgeon avoided the dredged-material disposal site and the lake sturgeon did not.

Survey Equipment and Protocol

Each station was sampled using the following two connected gill nets:

- A monofilament experimental net comprised of eight long panels with stretched mesh of varying sizes; and,
- A multifilament net with stretched mesh.

Sampling took place at four stations, using gill nets for four 24-hour periods before, and four 24-hour periods after sediment disposal operations. To avoid possible confounding effects caused by different environmental variables on sturgeon distribution, depth, salinity, current velocity, and water temperatures were also recorded.

The gill nets were set in the direction of the current at the beginning of the ebbing tide and hauled the following day during slack tide; the fishing effort was approximately 24 hours. Captured fish were identified and counted by mesh size. Total length was measured on each individual and fork length was also measured on Atlantic and lake sturgeon. Weight was determined on a subsample of sturgeon (198 Atlantic and 63 lake sturgeon). Weights of other Atlantic sturgeon captured were estimated using the length-weight relationship reported by Hatin et al. (2007a) for fish less than or equal to 60 cm total length and by Trencia et al (2002) for fish > 60 cm total length. Weights of lake sturgeon were estimated with a relationship computed for another study (Hatin et al., 2007a).

To identify fish, the sturgeons were tagged with a spaghetti tag at the base of the dorsal fin, at either the anterior or posterior extremity, depending on fish size. For age determination, a cross section of the first pectoral fin ray was collected on live fish, and the entire first pectoral fin ray was removed on dead fish. Fin rays were collected on 98 Atlantic sturgeon and 41 lake sturgeon. Age was determined by two independent readers.

Data Analyses

CPUE values were computed by species, station, period (before and after sediment disposal), and year. One unit of fishing effort corresponded to the total of the two nets set per station for 24 hours. To compare mean CPUE for each species for a given year in the study area, a paired t-test was used. To compare total length and weight between years for both species, a *mixed effects* ANOVA model was used with stations and dates within the year considered as random factors. For each year, statistical comparisons of CPUE were conducted, using a log-linear model with stations and period considered as fixed factors, and dates within period considered as random factors. In addition, to compare mean CPUE between the affected station and the control station, and also CPUE between control stations for each year, a *posteriori contrast* analysis was used. Statistical analyses were performed, using SAS software (SAS Institute, Inc.).

Studies that Used Fish Sampling Alone

Overview

Historically, the shortnose sturgeon was relatively common in the Delaware River in Pennsylvania and New Jersey (Brundage and Meadows, 1982). However, in 1967, it was listed as endangered throughout its range (Federal Register, 1967) under the endangered Species Preservation Act of 1966 (a predecessor of the ESA of 1973). The Delaware River between Trenton, NJ, and Philadelphia, PA, is periodically modified and/or affected by maintenance dredging. Maintenance dredging includes periodically removing accumulated natural and man-induced sediment from the river channel, and depositing those sediments on shore in diked spoil areas.

To determine the population status and biology of shortnose sturgeon, and to assess the impacts of maintenance dredging on this endangered species, a study was conducted in the Delaware River between Trenton and Philadelphia (Hastings, 1983). Due to the preference for channel areas by larval and juvenile sturgeon, it was concluded that dredging operations could severely affect this part of the sturgeon population, either by direct injury or by increased turbidity and/or silting by dredging activities.

Survey Equipment and Protocol

To determine the presence of fishes, two stations were identified within about six kilometers of the Delaware River. Small-mesh gill nets and two otter trawls were used to sample juvenile sturgeon in the vicinity of five dredging sites.

Each standard gill net sampling effort involved setting three nets at each station: (1) one station was 0.8 km upstream of the dredge site; (2) one station was 0.8 km downstream of the dredge site; and, (3) the third station was at the dredge site. Each net was anchored and weighted to the bottom so that it would fish parallel to the current in shallow and mid-depth, and on the bottom. The set time ranged from three to eight hours.

One ten-minute otter trawl haul was sampled in the channel. Otter trawls were made in the direction of the current with sufficient warp depth to length ratio to ensure fishing on the bottom. Each standard trawl sampling effort involved two 10-minute trawl hauls at each gill net station, one in the channel, and one at an intermediate depth. Sampling was initiated in the middle of the year and continued through the end of the year, with gill net and trawl samples taken monthly at each site. A total of 439 separate fish collections were made.

Data Analyses

Data analysis included:

- Tabulating sampling effort by stations, including approximate sampling time, sampling date, sampling depth, length of gill net set, net depth, and species collected;
- Tabulating distribution and abundance of Age 0+ juveniles, and larvae;
- Estimating correlations between age estimates and size ranges;
- Calculating monthly CPUE;
- Tabulating reproductive activity, by date;
- Calculating mean (± standard deviation) monthly weight and length distributions;
- Calculating relative abundance of each species as a function of gear type (i.e., gill nets, otter trawl); and
- Tabulating water quality data

Equipment That Could Be Used In Studies Of Fish Responses To Dredging-Related Environmental Impacts

Overview

Both abiotic and biotic monitoring studies have been used to measure environmental changes caused by dredging activities. Dredging-related monitoring studies include:

- Suspended sediment plumes from dredging activities;
- Water-quality sampling;
- Bottom-sediment sampling;
- Noise characterization of dredging activities;
- Plankton sampling; and,
- Benthic-organism sampling.

Following is a summary of how each of those monitoring studies could be integrated with studies of behavioral responses of fishes to dredging activities. Few studies are available on the behavioral responses of fishes to re-suspended sediments from dredging activities. To determine such responses the Bay, it is crucial to know the range of suspended sediment concentrations in the area of study. Behavioral responses of fishes to suspended sediments depend upon the size, shape, angularity of the suspended sediment particles. Hence, to determine behavioral responses of fishes to dredging activities in the Bay, it would be useful to know the types of sediment that would be re-suspended as a result of dredging activities.

To a large extent, the behavioral responses of fishes to dredging activities depend on the levels of various water-quality parameters—e.g., water temperature, dissolved oxygen, suspended sediments. Hence, to determine behavioral responses of fishes to dredging activities in the Bay, water quality sampling needs to be included in the studies.

Behavioral responses of fishes to noise generated by dredging activities depend on the intensity of the noise; consequently, characterizing the noise from dredging activities would be an integral part of future studies on noise effects on fishes. Fishes' behavioral response to noise that is generated by dredging activities was discussed previously in detail (pages 13-25).

Only two studies were found that assessed the changes in foraging and predation behavior as a result of dredge-related suspended sediment. The design of both laboratory- and field-based foraging and predation behavior studies should include studies on the types of food that the fish are feeding on. Hence, it would be useful to include plankton and benthic organism sampling in the design of such studies. In addition, small fishes are more prone to becoming entrained than larger fish. Plankton sampling would provide information on the relative abundance of larval fishes in the vicinity of dredging activities.

Characterizing Suspended Sediment Plumes from Dredging Activities

Field-based studies that characterize suspended sediment plumes from dredging activities use the following types of equipment to monitor suspended sediment concentrations:

- A dredger;
- A survey vessel;
- Differential GPS;
- Acoustic Doppler Current Profiler (ADCP);
- Water quality sampler;
- Turbidimeter;
- Water quality instrumentation package ;
- A software package that will calibrate the ADCP data; and,
- Aerial photography and satellite imagery

Plume monitoring is conducted on a survey vessel equipped with a differential GPS to provide navigation and position data that are integrated during post-processing. The ADCP is used to collect current velocity, direction, and acoustic backscatter data. Water samples are collected at known locations and are analyzed gravimetrically. The suspended sediment samples represent the concentration gradient prevailing at the study site and are used to "ground truth" the acoustic data. In recent years, researchers have used a Rosette Water Sampler that consisted of nine remotely triggered Niskin bottles. Integrated with the Rosette Water Sampler was an instrumentation package (Seabird Electronics) that continuously recorded depth, salinity, water temperature, conductivity, and transmissivity. Conversion of acoustic backscatter data to estimates of total suspended sediment concentrations is accomplished by application of a calibration procedure (e.g., the Seaview Method, developed by Land and Bray, 2000) (Clarke et al., 2006, 2005, MEC, 2003, 1997; Reine et al., 2002). Finally, aerial photography and satellite imagery have both been used to document the appearance of turbidity plumes related to dredging activities (Goodwin and Michaelis, 1984).

Models also have been developed to simulate environmental effects of suspended sediment plumes from dredging activities. The SSFATE, SSDOSE, and FISHFATE models, respectively, simulate sediment re-suspension and transport/dispersion, calculate exposure of aquatic organisms to sediment plumes, and estimate the population dynamics consequences of hydraulic entrainment (Ault et al., 1998; Swanson et al., 2000; Johnson et al., 2000). SSFATE is a flexible model built on a GIS platform that simulates the fate of sediment re-suspended by hopper, cutterhead, and bucket dredges. The user customizes the model to accommodate best available knowledge of the dredging operation, *in situ* sediment characteristics, and local bathymetry and flow fields. Output includes particle-tracking plume animation in tidal and non-tidal situations and time series plots of suspended sediment concentration at any location in the model domain. The SSDOSE model can calculate the hypothetical exposure of various organisms (e.g., sessile bottom invertebrates, passively drifting plankton, and adult fishes). The FISHFATE model can place estimated rates of mortality due to hydraulic entrainment into context with other sources of mortality acting upon a given stock, and predict the short and long-term consequences of multiple dredging project scenarios. Each model is capable of examining alternative dredging practices and providing insights into risk minimization.

Monitoring Suspended Sediment Concentrations

For more than 15 years, the USGS, in cooperation with the San Francisco Regional Water Quality Control Board (RWQCB) and the USACE, has been studying sediment suspension in the Bay (USGS, 2008). Their suspended sediment network is designed to capture the spatial and temporal variability of suspended sediments, water temperature, salinity, and water level. Some of these monitoring studies were related to dredging activities in the Bay (Schoellhamer, 2002; USACE, 1976; Clarke et al., 2006, 2005; MEC, 1997, 2003; O'Connor, 1991). The following equipment is used to monitor suspended sediments in the Bay:

- Optical backscatter sensors;
- PVC pipe carriages;
- Specific conductance monitors;
- Thermistors;
- Water-stage recorder;
- Electronic data logger;
- Water sampler;
- Conductivity meter; and,
- Water temperature probe.

The optical backscatter (OBS) sensors are used to monitor concentrations of suspended solids. The OBS sensors are positioned in the water column with PVC pipe carriages that are coated with an antifoulant paint to impede biological growth. The salinity stations are equipped with specific conductance monitors and thermisters. The specific conductance sensor is a heavy-duty probe that is designed for caustic slurries. The thermister measures the voltage drop to the sensor resistance. The water-stage recorder is equipped with an incremental encoder attached to a float. All data are stored in an electronic data logger. The water sampler is lowered to the depth of the sensor and triggered while the sensor is operating. Water samples are placed in a cooler and chilled for future analyses. Conductance samples are analyzed in the field using a conductivity meter. The temperature probe is checked using a thermister during site visits.

Water Quality Sampling

To monitor water quality related to dredging activities, the following types of equipment have been used:

- Survey vessels;
- Water quality samplers;
- Water bottles;
- Water quality meters;
- Depth measuring device or depth sensor; and,
- Secchi disks.

Usually, when obtaining samples for water-quality measurements or using water-quality meters in the vicinity of dredging activities, a vessel is required to access the area and take the measurements. In addition to the more sophisticated Rosette Water Sampler discussed previously, water bottles are often used to collect water samples for later analyses. Following dredging requirements by state and federal agencies, water samples are collected to determine, suspended sediment concentrations, dissolved oxygen concentrations, water temperatures, heavy metals and other pollutants (MEC, 1990a; USACE, 1976; Clarke et al., 2006, 2005; MEC, 1997, 2003; O'Connor, 1991). In connection with such studies, portable water quality meters (e.g., dissolved oxygen meter, pH meter, conductivity meter; turbidimeter, etc.) are often used that can provide on-site readings (MEC, 1990a; Goodwin and Michaelis, 1984; Bennett and Shrier, 1987, 1986). If water samples are to be taken at a specific depth, a measuring device is required. And to provide an idea of water transparency, Secchi-disk readings may be taken at different depths.

Bottom-Sediment Sampling

Benthic, or bottom, sediment samples are often obtained in connection with dredging activities, to determine either the type of substrate or to use for subsequent analyses of potentially toxic constituents (e.g., heavy metals, PCB's, sulfides, etc) (MEC, 1990a, b, 1997, 2003). To obtain benthic sediment samples for studies related to dredging activities, either a grab sample is taken using a grab sampler (e.g., Van Veen grab sampler) or a core is taken using a core sampler.

Plankton Sampling

Plankton tows, using fine mesh plankton nets towed by a vessel, may be used to determine identity and number of plankton in connection with dredging activities (MEC, 1990a, b; Bennett and Shrier, 1986, 1987). In one study (MEC, 1990a), plankton sampling was conducted to assess the potential of entrained benthic species present in the overflow waters from the barge.

Benthic-Organism Sampling

Benthic grab samples are often taken for enumeration and identification of benthic organisms (MEC, 1990a,b). Often they are taken to determine grain-size analysis, as well.

DISCUSSION

Overview

A variety of methods and tools have been used in studies to determine behavioral responses of fishes to dredging activities. The methods and tools used in the studies reviewed previously are discussed in more detail next.

Methods and Tools Used to Determine Behavioral Responses of Fishes to Suspended Sediments/Solids Produced by Dredging Activities

Overview

Of the six types of studies found that addressed behavioral responses of fishes to suspended sediments, only three (avoidance and attraction, swimming behavior, foraging and predation) were related to dredging activities. From the results of the latter studies, the following conclusions were made:

- The methods and tools for the laboratory-based fish avoidance and attraction studies provided a useful approach for determining behavioral responses of fishes to dredging-caused suspended sediments;
- Laboratory-based studies should be validated in the field, whenever possible;
- No studies could be found on either the ESA-listed fishes or fishes of commercial importance with regard to behavioral responses to dredging-caused suspended sediments;
- The methods and tools used to determine suspended sediment-induced changes in swimming performance, foraging, and predation in response to dredging activities, were problematic and, hence, future studies should initially include a pilot study; and,
- It is important that appropriate QA/QC measures be used in all studies.

Fish Studies on Avoidance and Attraction

During dredging operations, bottom sediments are mechanically disturbed and re-suspended (Morton, 1977); different operations produce different magnitudes of suspended sediments (LaSalle, 1990). From the three types of studies that focused on the avoidance and attraction of fishes to suspended sediments caused by dredging activities, the following conclusions were made:

- Provided the suspended sediment concentrations used were similar to those generated by dredging activities, the methods and tools used in the dredge-related laboratory-based avoidance-and-attraction studies provided a useful approach to determine fishes' behavioral responses (e.g., avoidance thresholds) to suspended sediments. This information may be useful in determining whether or not the fish are potentially capable of avoiding re-suspended sediments from dredging activities (Wildish and Power, 1985). It should be noted, however, that the researchers for the three studies (Johnston and Wildish, 1981; Messieh et al., 1981; Wildish and Power, 1985) recommended field-validation studies;
- No studies were found on either the ESA-listed fishes or fishes of commercial importance, with regard to behavioral responses to dredging-caused suspended sediments;
- Extrapolating laboratory results directly to field conditions is not recommended because: (a) thresholds are experiment-specific; (b) learning by the fish is involved; and, (c) the presence of suspended sediments under field conditions could introduce subtle changes that would not be present in the laboratory (Wildish and Power, 1985; Messieh et al., 1981);
- As no field-related behavioral studies were found, such studies are recommended, but should be conducted in tandem with laboratory-based studies; and,
- The degree to which fish responded behaviorally to re-suspended sediments was dependent upon particle type, size, and shape, as well as operations during the dredging process (Gregory and Northcote, 1993; Clarke and Wilber, 2000). Hence, studies on the behavioral effects of dredging-caused suspended sediments should take into account such factors.

Table 1. Summary of Methods and Tools Used to Assess and Monitor Behavioral Responses of Fishes to Dredging Activities.

Objective	Methods and Tools	References
Determine fish avoidance and attraction in response to suspended sediments produced by dredging activities.	Laboratory-based studies after catching fish by trawler. Laboratory equipment: figure-of-eight maze.	Johnson and Wildish, 1982; Messieh et al., 1981; Wildish and Power, 1985
Determine fish swimming behavior in response to suspended sediments produced by dredging activities.	Laboratory-based swimming performance studies: V-shaped trough (plywood); portable water velocity meter; and, electric event recorder.	Chiasson, 1993
Determine fish behavioral changes in foraging and predation in response to suspended sediments produced by dredging activities.	Laboratory-based studies using laboratory-hatched fish eggs and reared fish larvae. Laboratory-based studies using fish collected during flooding tides, using mesh nets with live box attached. Laboratory studies using a 12-chambered wheel apparatus.	Colby and Hoss, 2004; Johnston and Wildish, 1982; Messieh et al., 1981
Determine behavioral responses of fish to noise.	Field-based studies: fishing trawler; hydrophone; ultrasonic tags; digital tape recorder (stationary and portable); stationary system with hydrophone buoys; real-time sound analyzer; sound equipment calibrator; underwater loudspeaker; underwater TV video camera; amplifier; hull-mounted echo sounder; portable echo sounder; and, hull-mounted transducer.	Engås et al., 1995; Hawkins, 1973; O)no and Gødo, 1990; Sand and Karlson, 1986; Schwarz and Greer, 1984
Characterize sounds produced by different types of dredging activities.	Field-based studies: dredgers; sound recording and amplifying equipment; and, a HydroLab Water Quality Surveyor.	Clarke et al., 2002a; Dickerson et al., 2001

Objective	Methods and Tools	References
Determine the effects of dredging activities on abundance, distribution, and movements of fishes in the vicinity, upstream, or downstream of dredging activities	Field-based studies, using biotelemetry and hydroacoustics combined with fish sampling (e.g., trawling, gill netting, trammel netting).	Burczynski, 1991; Clarke et al., 2002a; Hastings, 1983; Hatin et al., 2007b; McQuinn and Nellis, 2007; Moser and Ross, 1995; Parsely and Popoff, 2004; Reine et al., 2001; USACE, ___
Determine sound thresholds in fishes.	Laboratory-based studies (Behavioral Approach, Microphonic Potential Approach, or ABR Approach) and train fish (suspended in cylinder) to respond: acoustic chamber; electrical stimulator; electrocardiogram; loudspeaker; hydrophone; electrodes implanted in fish cranium; and, transducers.	Akamatsu et al., 2003; Casper et al., 2003; Chapman and Sand, 1974; Enger and Anderson, 1967; Fay and Popper, 1995, 1974; Kenyon et al., 1998; Ladich and Yan 2001; Lugli et al., 2003; Popper, 1972; Yan, 2001; Yan and Popper, 1992.
Determine potential risk of fish entrainment by dredging activities	Field-based studies, using biotelemetry with sound detection and recording equipment. Field-based studies, using tape-recorded sounds, hydrophone, and underwater video camera. Field-based studies, using hydroacoustics combined with dredgers producing the sound.	Hoover et al., 2005; Reine et al., 2001.
.	Laboratory-based studies using swimming performance tests. Field-based studies, using hydroacoustics with fish sampling (e.g., trawling).	

In summary, the results of the three studies reviewed on this topic demonstrated that laboratory-based studies can provide useful information on the behavioral avoidance or attraction by fishes to dredging-caused suspended sediment. However, whenever possible, laboratory-based studies should be validated by field-based studies.

Studies on Swimming Performance

The laboratory-based swimming behavioral study provided information on the suspended sediment concentrations at which the rainbow smelt responded (an "alarm" reaction) (Chiasson, 1993). However, there were some problems with the experimental apparatus. The physical confines of a swimming trough made it difficult to separate a general increase in swimming activity brought about by an alarm reaction, a loss of orientation, or a search activity, from a non-random attempt to move away from an area containing a high concentration of suspended sediment. It was concluded that swimming behavior studies could provide useful information on other fish species exposed to dredging-caused suspended sediments, but that laboratory-based studies should not be the sole method for assessing swimming behavior responses to suspended sediments (Chiasson, 1993).

Fish Studies on Changes in Foraging and Predation Behavior

The different approaches used to determine dredging-related behavioral changes in foraging and predation of fishes provided different types of information. The experimental apparatus used in larval Atlantic herring studies (Johnston and Wildish, 1982; Messieh et al., 1981) limited examination to one species and one concentration at a time. The study on the larval marine fishes (Colby and Hoss, 2004) enabled more than one concentration to be evaluated simultaneously. From the results of the studies that focused on dredging-caused changes in foraging and predation behavior, the following conclusions were made:

- Due to problems with the experimental apparatus and protocol, the results of the foraging and predation behavior studies were inconclusive;
- In the larval herring study, there were a limited number of larvae used, due to logistical difficulties in obtaining larvae and availability of natural zooplankton as food; and,
- In the study on larval marine fishes, it was not evident whether or not reduced visual acuity or physical contact with suspended particles (which can clog gill tissues) was responsible for reduced feeding rates. Therefore, the approach used by Colby and Hoss (2004) was not recommended (Clarke, 2008).

In summary, if a study approach, such as that used for the feeding behavior studies on Atlantic herring, were used on Bay fishes, it would be important to conduct an initial pilot study.

Methods and Tools Used to Determine Behavioral Responses of Fishes to Noise (Sound) Caused by Dredging and Other Vessel-Related Activities

Overview

Determining behavioral responses of fishes to noise generated by dredging activities requires two types of information:

- Intensity of sound produced by the dredging activities of interest; and,
- Sound frequency threshold for each fish species of interest.

Two documents were found that focused on the intensity of sound produced by three dredging operations (bucket, cutterhead, and hopper dredging). With regard to sound frequency thresholds in fishes, there were three approaches for such studies: (1) behavioral; (2) micophonics; and, (3) auditory brain stem response.

One of the sound-related activities that occur during dredging activities is the noise generated by the dredging vessel. No studies were found on the behavioral responses of fishes to dredging-caused noise. Thus, studies on the behavioral responses of fishes to noise generated by fishing vessels and gear were discussed.

Studies that Characterized Underwater Sounds Produced by Different Types of Dredging Activities

The results of the underwater sound produced by different dredging operations were considered to be a first step towards providing a database of dredge sounds (Clarke et al., 2002a). The data presented a small set of examples of sounds associated with three major categories of dredge plants. Based on the methods and tools used to characterize underwater sounds produced by different types of dredging activities, the researchers concluded the following.

- Future studies need to assess the characteristics of a range of dredge plants sizes (e.g., 10-inch versus 36-inch cutterhead plants) and operation features (e.g., barge dumping sounds at open water disposal sites, and sounds associated with barge tenders, tugs, and other support vessels).
- When estimating the noise level that may be introduced into the water from bucket dredging, the following may be important:
    - Sediment type;
    - Size of bucket (if bucket dredging);
    - State of repair of the various types of equipment;
    - Hydrodynamic conditions, notably prevailing suspended sediment loads and water conditions; and,
    - Skill of the dredge-plant operator.
- Maintenance of equipment related to dredging activities is extremely important. Poorly maintained or repaired winches, power plants, and propellers are major contributing factors to underwater noise.

- Any studies that characterize underwater sounds from dredging operations must be integrated with knowledge of fishes' auditory thresholds and responses to acoustic stimuli.

In summary, the two documents that characterized underwater sounds from the three types of dredging activities provided the beginning of a "sound database" for dredging activities. Studies to determine the behavioral responses of fishes to dredging-produced noise should characterize the underwater sounds of the dredging activities in question.

Studies on Sound Thresholds in Fishes

The methods and tools used to measure sound thresholds in fishes differ a great deal, and each approach has its advantages and disadvantages. The techniques used to identify hearing thresholds require varying degrees of time, technical and surgical expertise, or the use of behavioral studies to gain statistically-sound data.

Based on the results of the studies to determine sound thresholds in fishes, the researchers concluded the following.

- The advantage of the reward- or shock-based behavioral conditioning methodology is that invasive procedures are not required and the stimulus can be relatively simple. In practice, however, the behavioral studies are very time consuming and only effective with species that are easy to train.

- Results can be obtained more readily from studies that used microphonic potentials than from behavioral studies. However, in the former, preparation can often be complex and require invasive surgery to implant the electrodes directly into the nerve. The electrode is thus restricted to a specific end organ or region of the macula, and the evoked potential does not necessarily represent the whole auditory pathway (Kenyon et al., 1998).
- The ABR technique of measuring hearing thresholds is non-invasive, but has only been used in far-field studies (Kenyon et al., 1998). It is useful in studies where behavioral methods cannot be applied.

There was little information on the hearing capabilities of either ESA-listed or commercially important fishes in the Bay. However, because the auditory system is similar in all salmonids, it is possible that existing information on other salmonids could be used to determine sound frequency thresholds for Chinook steelhead or steelhead. In addition, some information exists on Pacific herring hearing thresholds and there have been hearing studies on various flatfish species, although not ones that inhabit the Bay.

Studies to Determine the Behavioral Responses of Fishes to the Noise Generated by Fishing Vessels and Gear

Three general approaches were used to determine the behavioral responses of fishes to noise generated by fishing vessels and gear:

- Biotelemetry with sound-detection equipment;

- Playback of tape-recorded sounds; and,
- Hydroacoustic surveys.

The objective of the studies was to increase knowledge about how fish respond to fishing vessels and gear so that the precision with which fish stocks are assessed could be improved. The studies provided a good basis on which to design studies to determine the behavioral response of fishes to noise generated by dredging activities. However, the researchers often had a difficult time interpreting their results because of inadequate types of equipment used or assumptions that could not be validated. Thus, due to the inherent problems experienced in sound studies related to vessels, studies on the behavioral responses of fishes to noise from dredging activities should be carefully designed with the assistance of those who have experience with sound-related fish behavioral studies.

Methods and Tools Used to Determine Behavioral Responses of Fishes to Entrainment Caused by Dredging Activities

Overview

Two approaches were used to determine the behavioral responses of fishes to dredging caused entrainment:

- Laboratory-based swimming behavioral study (Hoover et al., 2005); and,
- Field-based fisheries hydroacoustics and trawling study (Reine et al., 2001).

The two approaches provided very different types of information. The swimming-performance studies provided assessments of entrainment risk using a modeling approach. The field-based hydroacoustics and trawling study provided information in the field about the fishes' proximity to dredging operations.

Swimming Performance Studies

In the sturgeon and paddlefish study, swimming performance models were used to predict whether or not the fish would become entrained as a result of dredging activities (Hoover et al., 2005). The swimming performance entrainment risk study was based on modeling the results of swimming performance as a function of water velocity. As a preliminary assessment of entrainment risk to different types of dredgers, such an approach could be used on other fish species (Figure 3). Intake water-velocity data are available for simulations of flow fields created

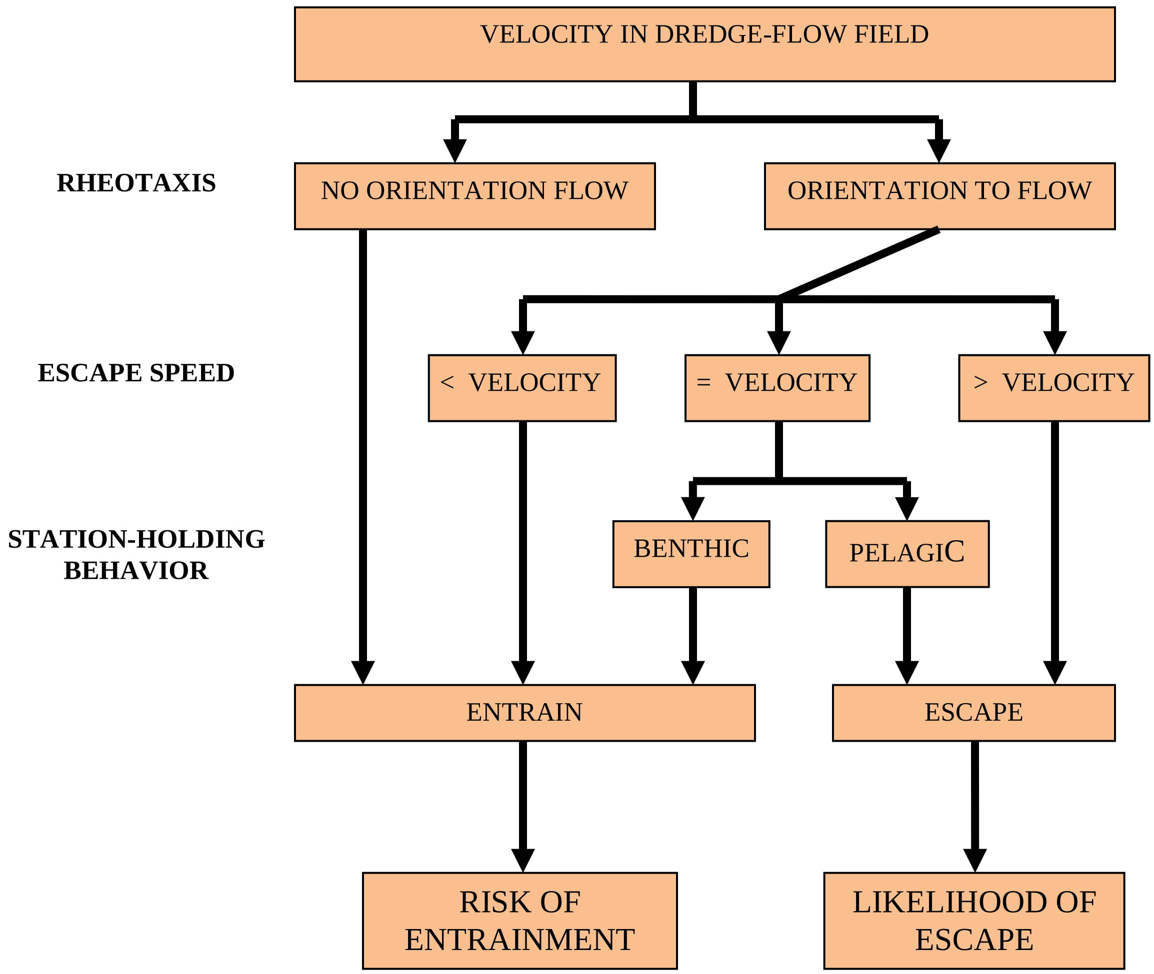

Figure 3: Conceptual Model for Assessing Risk of Entrainment by Dredge, Based on Swimming Performance of Fishes.

by different types of hydraulic dredges (http://el.erdc.usace.army.mil/dots/doer/flowfields/dtb350. html). Water velocity can be determined, based on swimming performance data for a test fish. Hence, a simple assessment of entrainment risk could be estimated for a given water velocity based on swimming performance data for the fish in question.

For example, paddlefish were strongly rheotactic and very unlikely to be entrained because of failure to orient against a flow field. Their escape speed was approximately 50 cm/s, but because they are pelagic free-swimming fish, and not stationary on the bottom, risk of entrainment is low (Table 3). By contrast, pallid sturgeon frequently failed to exhibit rheotaxis and so that species would likely be entrained. They are benthic station-holders, and their escape speeds are low, placing them at higher risk of entrainment.

Thus, as a "first cut", such risk estimates could be used to identify fish species and size classes that could be susceptible to entrainment. However, the authors cautioned that the total risk of entrainment is a cumulative value associated with behavioral, physiological, and demographic data. In addition to swimming-performance data, a risk analysis would require information on responses of the fish to dredging-induced perturbations such as noise and turbidity, and localized abundance and distribution at the dredging location. The researchers concluded that continued behavioral studies on a variety of important fish species, along with increased monitoring of the populations, would improve predictions of risk associated with dredge entrainment.

Table 2: Evaluation of Entrainment Risk at 50 cm/sec in Paddlefish, Lake Sturgeon, and Pallid Sturgeon.

Species	Rheotaxis: Percent of Non-Swimmers	Escape Speed: Minimum Cm/S	Swimming Behavior: Percent of Time Benthic	Relative Risk
Paddlefish	7.7	48.4	0	Lowest
Lake Sturgeon	9.1	66,8	98.7	Low
Pallid Sturgeon (> 11.5 cm)	26.7	51.5	73.2	High
Pallid Sturgeon (≤ 11.5 cm)	26.1	51.7	81.8	Highest

Source: Hoover et al., 2005.

The relationship between fish behavior and dredging-caused entrainment is complex. Thus, the design of studies to determine behavioral responses of fishes to entrainment in the Bay might include studies such as those conducted on the sturgeon and paddlefish (Hoover et al., 2005), but should also include field studies that include rigorous sampling of fish populations.

Fisheries Hydroacoustics in Conjunction with Fish Sampling

The use of hydroacoustic surveys in conjunction with fish sampling provided the following types of information (Reine et al., 2001):

- Distribution (i.e., bottom, mid-water, surface) of fishes in the water column;

- Distribution of fishes by size (length) in both the dredging site and nearshore lake and river waters;
- Distribution of fishes in proximity to the dredge site; and,
- Identification and size (length) of fish species.

Combining the results of hydroacoustic surveys with those of fish sampling provides a study approach for assessing: (1) the relative entrainment risk; (2) the distribution of fishes in the vicinity of dredging activities; and, (3) the identification and size (length) of the fish in the area. However, this approach would not be useful if one wanted to determine the entrainment risk of a specific species. For that, biotelemetry, including ultrasonic tagging, should be considered.

Methods and Tools Used to Determine Fish Presence, Distribution, and Population Abundance in Response to Dredging Activities

Overview

The following five approaches were used to study presence, distribution, and fish-population abundance related to dredging activities:

- Studies that used biotelemetry;
- Studies that used hydroacoustics in conjunction with fish sampling;
- Studies that used fish sampling in conjunction with biotelemetry and external Peterson tags;
- Studies that used fish sampling and external spaghetti tags; and,
- Studies that used fish sampling alone.

Each approach has its advantages and disadvantages. Of the various types of approaches used, the most promising appeared to be those that used a combination of biotelemetry and hydroacoustics or hydroacoustics and fish sampling.

Studies that Used Biotelemetry

Of the two studies that used biotelemetry, the white sturgeon study (Parsley and Popoff, 2004) provided a great deal more information and statistical analyses that allowed for cause-and-effect-conclusions than did the Bay salmonid emigration study (USACE, 2007). The lack of cause-and-effect-conclusions from the Bay salmonid studies (USACE, 2007) was to be expected, because the first year of the three-year juvenile salmonid outmigration and distribution study was a pilot study; further refinements are anticipated from the results of the data for that first year.

Study design is a key component to assess fish presence, distribution, and abundance relative to dredging activities. The study design used by Parsley and Popoff (2004) on white sturgeon provided information that could be used to assess potential behavioral effects of dredging activities on that species. The approach of a long-term deployment of the two types of acoustic telemetry systems met spatial and temporal data requirements for the two objectives of the study.

Such a study was shown to be useful for determining:

- Behavioral responses of fish over time;
- Habitats that the fish occupy;
- How the fish reacted around dredging operations; and,
- Movements during daytime versus nighttime.

Studies that Used Hydroacoustic Surveys in Conjunction with Fish Sampling

In the Alcatraz Island Disposal site hydroacoustic and trawling study (Burczynski, 1991), the results were inconclusive, due to poor study design and incomplete information. Although the fish disappeared for two to three hours after the dredged-material disposal, the reason for their disappearance was not known because no follow-up studies were conducted. It was not demonstrated that sulfides were responsible for the fish disappearance. The fish disappearance could have been due to suspended sediments, water quality, or other physical factors (e.g., noise) that caused the fish to leave the area. To produce better quantitative results and meaningful statistical data, the following additional focused studies were suggested by the author of the report:

- Follow the same survey transects with and against the current before, during and after dredged-material disposal, start monitoring immediately after discharge and repeat transects until fish traces appear again;
- Monitor underwater currents and direction of movement of dredge plume;
- Use high frequency (i.e., 420 kHz) for monitoring dredge plume, and lower frequency (i.e., 120 kHz) for monitoring fish; a dual frequency system would provide better quantitative results; and,
- Measure absolute density of dredge plume.

In conclusion, to determine the cause for fish disappearance in the vicinity of the dredged-material disposal site, a considerable amount of information would be required that was not included in the Burczynski (1991) study.

The discussion of the St. Joseph River fisheries hydroacoustic and trawling study (Reine et al., 2001) was provided in the section on behavioral responses of fish to entrainment (pages 28-30).

The approach used in the James River fisheries hydroacoustic and gill net study (Clarke et al., 2002b) was not comprehensive enough to determine why there were no behavioral responses (i.e., avoidance or attraction) to the dredging activities. The authors stated that the absence of a pronounced attraction or avoidance response could also be interpreted in at least the following three ways:

- The particular fish assemblage in the James River consisted of fishes tolerant to varying estuarine conditions and, therefore, they might not have been responsive to sensory cues associated with the dredging or disposal operations;
- Underwater sounds emitted by the hydraulic cutterhead dredge were of a very low intensity and, hence, the fish may not have respond to it; or,

- Background suspended sediment concentrations ranged widely (40 mg/l at slack tide to over 200 mg/l during flood and ebb flows). Hence, the fishes may not have perceived dredging-induced plumes.

Hence, determining the effects of dredging activities on fish presence, distribution, and abundance required more than the use of the type of hydroacoustic surveys and fish sampling conducted in the study. Types of information that would have been useful include: (1) baseline data on the fish assemblage in the James River; (2) separate studies on behavioral responses of the fishes to noise generated by the dredging activities; and, (3) separate studies on the effects of background suspended sediment concentrations on the fishes.

In the St. Lawrence River hydroacoustic and trawling study (McQuinn and Nellis, 2007), the researchers concluded that, because they did not have all of the necessary information, their application of hydroacoustic surveying to assess sturgeon behavior was subjective. To quantify their results, the researchers stated that the following types of information were necessary, but lacking in the study:

- The relationship between species-species target strength and length; and,
- The effect of vertical distribution of fishes on fish detectability.

Target strength-to-length relationships are used to convert the acoustic energy backscatter to fish biomass. Such information can be determined from the following: (1) *in situ* measurements; (2) cage experiments; and, (3) modeling. Furthermore, acoustic detection can be influenced by variations in the distance between the fish and the bottom. Insufficient data were collected during the study to estimate those relationships. Finally, considering some of the very large individual sturgeon in their study, the researchers stated that their assumption that the fish targets represented a point source may not have been fulfilled. This would have prevented the unbiased estimation of *in situ* target strength. In fact, since the target strength and acoustic detectability may vary over time and affect estimate precision, they considered their approach to be experimental. If such a study were to be repeated, all required types of information would have to be collected.

However, even given those drawbacks, the researchers still concluded that:

- The combined acoustic-trawl method could be an effective way to examine sturgeon density and distribution;
- The acoustic results provided the basis for the stratified design of the trawl survey; and,
- The combined acoustic-trawl method could be an important tool for examining how demersal fishes respond to change in habitat as a response to dredging activities.

Studies that Used Fish Sampling in Conjunction with Biotelemetry and External Peterson Tags

The researchers that used fish sampling in conjunction with biotelemetry and external Peterson tags to determine presence, distribution, and abundance of sturgeon in the vicinity of dredging operations in the Lower Cape Fear River (North Carolina) obtained the following types of information (Moser and Ross, 1995):

- Specific areas that the fish inhabited;
- Whether or not the fish were present during dredging operations;
- CPUE in different areas;
- Tracking of specifically-tagged fish;
- Depth distribution of the fish; and,
- Gross travel rates (km/day).

However, there were some problems with the tags. For example, most of the external transmitter tags fell off the fish within three months.

Studies that Used Fish Sampling and External Spaghetti Tags

The researchers that used fish sampling in conjunction with external spaghetti tag tags to determine presence, distribution, and abundance of sturgeon in the vicinity of dredging obtained the following information (Hatin et al., 2007b):

- Relative abundance (CPUE) in the four sampling stations before and after dredging disposal operations; and,
- The suggestion that the Atlantic sturgeon avoided the dredged-material disposal area and the lake sturgeon did not.

However, there were some problems with the sampling method. The gill net sampling was ineffective because many fish were too small to be captured. The results of other studies that used hydroacoustics and biotelemetry provided additional information upon which to base their conclusions.

Studies that Used Fish Sampling Alone

The shortnose sturgeon study on the Delaware River in Pennsylvania and New Jersey provided information on the number of sturgeon (as well as other fish species) upstream and downstream of the dredge sites and within the dredge site (Hastings, 1983). However, the author concluded that, due to the lack of data, the decreased number of sturgeon downstream of the dredge site was not necessarily due to dredging activity. It could just as well have been random or correlated with natural movements of the population. To determine the effects of dredging on the sturgeon, the following additional studies were recommended: (1) sampling before and after dredging in specific areas where sturgeon were known to congregate; (2) detailed sampling for several weeks; and, (3) use of several types of gear to assess the effects on presence, distribution, and abundance of the sturgeon. Hence, a much more comprehensive sampling approach was recommended.

Advantages and Disadvantages of Methods and Tools Used to Assess Behavioral Responses of Fishes to Dredging Activities

Each of the study approaches on the behavioral responses of fishes to dredging activities has advantages and disadvantages. In addition to general advantages and disadvantages associated with specific approaches (e.g., laboratory versus field, biotelemetry versus hydroacoustics, etc.), each study had its own set of benefits and problems. A list of advantages and disadvantages is provided in Appendix G. The list is both generic for specific approaches (e.g., hydroacoustic surveys do not harm the fish it monitors) and, in some cases, reflects specific problems associated with a particular study that had been conducted. Approaches that combined different types of methods and tools provided the more useful data from the standpoint of being able to determine the behavioral responses of fishes to dredging activities.

Hypothetical Research Scenarios for Measuring Behavioral Responses of Fishes To Various Types of Dredging Activities

Overview

Dredging activities associated with behavioral responses were rated a high priority for all species, including juvenile and adult Pacific herring in the Levine-Fricke (2004) report. In that report, behavioral responses included such topics as re-suspended sediment plumes, avoidance, migration, distribution, noise, and feeding. Of those topics, the following were the types of information that were considered to be high priority for future studies:

- Anadromous salmonid avoidance or blockage during migration that could be caused by dredging activities;
- Potential adverse effects on anadromous salmonid feeding behavior and increased predation success as a result of increased suspended sediment concentrations caused by dredging activities;
- Potential adverse effects on delta smelt feeding behavior and increased predation success, as a result of suspended sediment concentrations associated with dredging activities;
- Potential adverse effects on Pacific herring spawning behavior as a result of suspended sediment concentrations associated with dredging activities;
- Potential adverse effects on delta smelt spawning behavior as a result of suspended concentrations associated with dredging activities;
- Potential adverse behavioral responses of anadromous salmonids and Pacific herring to noise generated by dredging activities; and,
- Behavioral responses by juvenile salmonids and larval and juvenile herring to entrainment associated with dredging activities

Based on the various types of issues identified as high priority, the following three hypothetical research designs are offered as examples of the types of studies that could be undertaken to address some key issues:

- Studies to assess the behavioral responses of juvenile Chinook salmon to suspended sediments related to dredging activities in the Bay;
- Studies to characterize the underwater noise generated by bucket dredging operations in the Bay; and,
- Studies to estimate the potential risk of entrainment of juvenile Chinook salmon from dredging operations in the Bay.

Of the three hypothetical study designs, the first and third are laboratory-based and the other is field-based.

For each of the hypothetical studies, data collection, handling, and analyses would conform to contemporary scientific standards. The following would be included in the QA/QC procedures:

- Written detailed study design, including specific QA/QC procedures, approved by the USACE;
- Standard field operating procedures;
- Standard operating procedures for calibrating and using instruments;
- Back-up stored copies of all data (both electronic and paper) collected. Data would be backed up on a predetermined schedule;
- Depending upon the time of year and the length of time for the studies, either monthly or quarterly status reports would be provided to the USACE;
- Internal (i.e., the USACE) review of draft manuscripts; and,
- Peer review of approved (by the USACE) draft manuscript by three external reviewers knowledgeable about the subject at hand.

Studies to Assess the Behavioral Responses of Juvenile Chinook Salmon to Suspended Sediments Related to Dredging Activities

Overview

One of the primary concerns expressed by NOAA Fisheries included anadromous salmonid avoidance of dredging locations that could result in altering migration to desirable routes or blocking migration. It is believed that blockage is likely to occur only in restricted locations where dredging activities could substantially occupy the migration route, such as narrow channels or the mouths of tributaries (Levine-Fricke, 2004). Behavioral responses of anadromous salmonids could come from either re-suspended sediment plumes or noise associated with dredging activities. The hypothetical study below summarizes a laboratory-based study to assess the behavioral response of juvenile Chinook salmon to suspended sediments related to dredging activities. The design of the study is similar to that described earlier (pages 6-12) (Messieh et al., 1981; Wildish and Power, 1985; Johnston and Wildish, 1981).

Fish

Juvenile Chinook salmon would be obtained at a hatchery and transported to the laboratory. In the laboratory, the fish would be acclimated and fed in holding tanks prior to the experiments. Twenty-four hours before each test, food would be withheld. For each experiment, ten salmon would be placed in the experimental apparatus and observations made.

Suspended Sediments

Grab samples of sediment would be collected from an area of maintenance dredging in the Bay. Before each experiment, separate slurries (or suspension media) of pre-determined concentrations of suspended sediments would be created with water from the fish tank. The slurries would consist of a control concentration (0 mg/L of suspended sediments) and a series of experimental concentrations. The experimental suspended sediment concentrations would represent ranges of concentrations typical of the suspended sediment plumes generated by dredging activities. For each test, a slurry concentration would be injected (by syringe) into the figure-of-eight maze (described below). For control experiments, the same procedure would be followed with an injection of the water the fish had been residing in.

Experimental Apparatus

The laboratory apparatus would be similar to the one described previously (pages 6-12) for similar studies on herring (Johnston and Wildish, 1981; Wildish and Power, 1985; Messieh et al., 1981). The apparatus would consist of a trough that had two interconnecting areas that form a figure-of-eight maze. Each half of the apparatus would be joined by an aperture that would allow fish passage to all parts of the maze but would minimize water mixing. Water would flow into each half of the maze and water temperature would be kept at a constant, pre-determined temperature.

Experimental Protocol

Each experiment would consist of a Control test and a Treatment test. The protocol for each test would be similar to the protocol described previously for the herring studies (pages 10-11). Duplicate Control Tests and Treatment Tests would be made for each concentration.

Data Analyses

To determine whether or not the proportion of fish in side A or side B in the control period was significantly different from that in the treatment period, a Student's t-test would be made.

Studies to Characterize the Underwater Noise (Sound) Generated By Bucket Dredging Operations in the Bay

Overview

One type of information required to determine behavioral responses of fishes to noise generated by dredging activities is the noise intensity produced by the dredging activity. Following is a hypothetical study design to characterize the noise produced by bucket dredging operations in the Bay. It is based on the study design discussed previously (pages 13-15) on characterizing underwater sounds of different dredging activities.

Experimental Equipment

To characterize sounds produced by bucket dredging operations, the following types of equipment would be required:

- Bucket dredger;
- Field recording equipment;
- Sound data analysis equipment; and,
- Some type of equipment for collecting depth, water temperature, and salinity data.

The sounds of the bucket dredging activities would be recorded with a hydrophone with a built-in preamplifier. The preamplifier would be connected to a hydrophone audio amplifier. The hydrophone audio amplifier would be used to amplify the source levels for the bucket dredging sessions before the audio data were recorded on a Digital Audio Tape (DAT) recorder. The hydrophone audio data would be input into an analog-to-digital converter, digitized, and stored on a laptop computer. In addition, field notes would be narrated and recorded on the DAT recorder.

To power the system, 12V DC marine batteries would be connected to a power inverter would provide an AC power source to an uninterrupted power supply. The power supply would, in turn, power the DAT recorder, the laptop computer, and the hydrophone audio amplifier.

To calculate the speed of sound, a water-quality meter would be used to record depth, water temperature, and salinity data.

Field Recording

To monitor sounds from bucket dredging operations, sound data would be collected from a fixed, or anchored, position, a short distance from the bucket dredging operations. The number of sound recording sessions, and the timing of the study (i.e., months of year), would be determined prior to the studies, based on discussion with those (e.g., Dr. Doug Clarke of ERDC) familiar with such studies[4]. Sound recordings would be made of both bucket dredging operations and ambient noise. Ambient noise would be recorded at the dredging site with the dredger shut down into as quiet a mode as possible.

Sound Data Analysis Procedure

Each dredge sound recording session would be digitized from the DAT recorder and stored on a laptop computer. To display a real-time audio spectrum, audio-analysis software would be used. Each sound file would be reviewed and the contents summarized. The results of the sound data from the bucket dredging operations would be provided in graphs and tables.

Studies to Estimate The Potential Risk Of Entrainment Of Juvenile Chinook Salmon From Dredging Operations

Overview

Due to their poor swimming abilities, juvenile salmonids may not be able to avoid entrainment during dredging operations. A field-based study to determine the behavioral responses of a juvenile fish species to entrainment associated with dredging activities would be difficult to design and implement. The field-based entrainment-related study by Reine et al. (2001) discussed previously (pages 28-30) used hydroacoustics in conjunction with fish sampling. However, the study was designed to determine the probability of entrainment of a variety of fish species. Hence, the design of a laboratory-based study on juvenile Chinook salmon, such as the swimming performance study described earlier (pages 26-28) for sturgeon and paddlefish (Hoover et al., 2005) is recommended.

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[4] As an example, 19 sound recording sessions of bucket dredging operations were conducted in the study that characterized bucket dredging sounds in Cook Inlet, Alaska (Dickerson et al., 2001).

Fish

Juvenile Chinook salmon would be obtained from a hatchery and transported to the laboratory. At the laboratory, the fish would be acclimated and fed in holding tanks prior to the experiments. Twenty-four hours before each test, food would be withheld. Individual salmon would be tested only once. The number of juvenile Chinook salmon to be tested would be determined prior to the studies[5].

Experimental Apparatus

The experimental apparatus would consist of a swim chamber similar to that used by Brett (1964). Water temperatures would be controlled in all tests.

Experimental Protocol

During each test, the following components of swimming performance and recovery would be evaluated: (1) rheotaxis; (2) endurance; and, (3) station-hold behavior. Each test fish would be placed in the working section of the swim chamber and allowed to acclimate at a pre-determined low velocity[6]. At the end of the acclimation period, water velocity would be increased to a pre-determined test velocity. If a fish failed to exhibit rheotaxis, it would be allowed time to rest before flow was again increased to the test velocity. If, after multiple attempts, the salmon did not exhibit rheotaxis, it would be excluded from the study.

With fish oriented into the flow, the tests would continue for a pre-determined amount of time, or until the fish could no longer maintain position. During the test, swimming behaviors of the juvenile salmon would be identified and the duration of each behavior timed separately. If a fish could not maintain position, the test would be ended and the time noted. At the end of each trial, water temperature would be recorded and the salmon removed from the swim chamber. Length and weight would be recorded, and the fish observed for injuries, mortality, or changes in behavior.

Assessment of Entrainment Risk

Predictive models of swimming performance would be developed, using regression analyses with water velocity as the independent variable and endurance as the dependent variable. Curvilinear and linear models would also be developed. Swimming and station-holding behavior would be categorized and quantified. Duration of each behavior would be estimated following each trial and the mean time for each velocity would be calculated. As a preliminary assessment of entrainment by juvenile Chinook salmon, swimming performance models would be used to predict whether or not the juvenile salmon would become entrained as a result of different types of dredging activities. The swimming performance risk would be based on modeling the results of swimming performance of the juvenile Chinook salmon, as a function of water velocity (Figure 3) (Hoover et al., 2005).

[5] 42-48 sturgeon and paddlefish were used in a previous study (Hoover et al., 2005).
[6] Water velocity would be dependent upon the size of the fish.

Gaps in Our Knowledge

Despite the numerous studies that have been conducted on the effects of dredging activities on fishes, few have focused on those related to fish behavior. A detailed summary of information gaps is provided in Appendix H. Following is a summary of information gaps, with regard to behavioral responses of fishes to dredging activities:

- No studies were found that focused on the behavioral responses of Bay-related ESA-listed fish species to suspended sediments related to dredging activities;
- With the exception of one Pacific herring study, there were no studies that focused on the behavioral responses of Bay-related commercial fish species to suspended sediments related to dredging activities;
- No studies were found that focused on the behavioral responses of any fish species to migration, habitat preference, or fish distribution and abundance related to suspended sediments associated with dredging activities;
- No studies were found that focused on the characterization of noise generated by dredging activities;
- No studies were found that focused on the behavioral responses of fishes to noise related to dredging activities;
- No studies were found that focused on the behavioral responses of Bay-related ESA-listed fish species to entrainment by dredging activities; and,
- With regard to fish presence, distribution and population abundance in response to dredging activities, there was a lack of scientifically-rigorous studies that focused on dredge-related Bay-related fishes.

CONCLUSIONS

Based on the results of information that was reviewed for this report, the following conclusions were made, with regard to the methods and tools used for assessing and monitoring fish behavior in relation to dredging activities.

- Behavioral Responses of Fish to Suspended Sediments Related to Dredging Activities.
    - Provided that suspended sediment concentrations were similar to those generated by dredging activities in the Bay, the methods and tools used in the laboratory-based avoidance and attraction studies would provide a useful approach for Bay studies. The information may be useful in determining whether or not a fish species is potentially capable of avoiding re-suspended sediment from dredging activities; however, field validation studies are recommended.
    - The methods and tools used to determine suspended sediment-induced changes in swimming performance, foraging, and predation behavior in response to dredging activities were problematic and, hence, any future studies proposed for the Bay should initially include a pilot study.
    - Only a few studies examined the behavioral responses of fishes to suspended sediments related to dredging activities.
    - No studies were found on either ESA-listed fishes or fishes of commercial importance with regard to behavioral responses to dredging-caused suspended sediment.

- Behavioral Responses of Fish to Dredging-Caused Noise.
  - No studies were found on the behavioral responses of fishes to dredging-caused noise. However, the methods and tools used in studies that determined the behavioral responses of fishes to the noise related to fishing vessels and gear could be used to help design studies on the impact of dredging-caused noise on fishes' behavior. Due to the inherent problems experienced with such studies, the studies should be carefully designed with the assistance of researchers who have experience with sound-related fish behavior studies.
  - To determine the behavioral responses of fishes to noise generated by dredging activities, it is necessary to characterize the underwater sounds produced by those activities. Hence, future studies in the Bay should include a sound-characterization component.
  - To determine the behavioral responses of fishes to noise generated by dredging activities, it is necessary to determine the sound frequency threshold for each species of interest. Little information was found on the hearing capabilities of either the ESA-listed or commercially important fishes in the Bay. However, because the auditory system in salmonids is similar, it is possible that existing information on other salmonids could be used to determine sound frequency thresholds on Chinook salmon and steelhead. In addition, some information exists on Pacific herring thresholds, and there have been hearing studies on various flatfish species, although not the ones that inhabit the Bay.
- Behavioral Responses of Fishes to Entrainment Related to Dredging Activities.
  - Modeling the results of swimming performance for a given fish (i.e., ESA-listed and commercially important fish species), as a function of water velocity, could be used as a preliminary assessment of entrainment risk to different types of dredging activities.
  - Hydroacoustics in conjunction with fish sampling can provide a study approach for assessing the entrainment risk to fishes in the vicinity of a dredger. However, such a method would not be useful to determine the entrainment risk for a specific species. For that, biotelemetry, using ultrasonic tags, would be helpful.
- Fish Presence, Distribution, and Population Abundance in Relation to Dredging Activities:
  - Of the five study approaches reviewed, the studies that used biotelemetry in combination with hydroacoustics or hydroacoustic with fish sampling provided the most detailed and quantitative types of information. Neither the use of hydroacoustics alone, nor fish sampling alone, were reliable, in quantifying behavioral responses of fishes to dredging activities, nor for assessing the impacts of dredging activities on fish presence, distribution and/or abundance.

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APPENDIX A

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Table A-2. Sources of Information – Electronic Databases.

Organization	Internet Address
Google searches using "dredging noise fishes", "fish behavior dredging", fish behavior entrainment", "fish behavior noise", "fish behavior sediment fishes", "fish behavior suspended sediments" fish behavior suspended solids fishes", "fish behavior turbidity fishes", "sound thresholds fish.	http://www.google.com
International Association of Dredging Companies	http://www.iadc-dredging.com/index.php?option=com_content&task=view&id=120&Itemid=288
International Council for the Exploration of the Sea	http://www.ices.dk/iceswork/wgdetail.asp?wg=WGFTFB
Biosonics, Inc.	http://www.biosonicsinc.com/resources/document_library.html
National Technical Information Center	http://www.NTIS.gov
NOAA-NMFS Northwest Fisheries Science Center	http://www.nwfsc.noaa..gov
NOAA-NMFS Southwest Fisheries Science Center	http://www.swfs.noaa.gov
San Francisco Estuary Project	http://www.sfei.org
State of Washington Water Resource Center	http://www.swwrc.wsu.edu/reports.asp/
University of Washington Library System	http://uworld.lib.washington.edu

Table A-2 (cont.). Sources of Information – Electronic Databases.

Organization	Internet Address
U.S. Army Corps of Engineers Dredging Operations Technical Support (DOT) Program	http://el.erdc.usace.army.mil/dots
U.S. Army Corps of Engineers Environmental Effects and Dredging and Disposal (E2D2) Database	http://el.usace.army.mil/e2d2/index.html
Western Dredging Association Proceedings for Conferences	http://www.weda.org
Western Fisheries Research Center	http://www.wfrc.usgs.gov/
World Dredging Congress	http://www.woda.org
Yahoo searches using "dredging noise fishes", "fish behavior dredging", fish behavior entrainment", "fish behavior noise", "fish behavior sediment fishes", "fish behavior suspended sediments" fish behavior suspended solids fishes", "fish behavior turbidity fishes", "sound thresholds fish".	http://www.yahoo.com

APPENDIX B

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Ambient Noise (Sound): Normal background noise in the environment, which has no distinguishable sources.

Amplitude: The maximum deviation between the sound pressure and the ambient pressure.

Audiogram: An audiogram is a standard way of representing hearing thresholds. Audiograms depict frequency in hertz (Hz) on the horizontal axis, most commonly on a logarithmic scale and sound threshold in decibels (dB) on the vertical axis on a linear scale.

Auditory Brainstem Response (ABR): A physiological method to determine hearing bandwidth and sensitivity of animals without training (e.g., Casper et al., 2004; Smith et al., 2004). Electrodes (wires) are placed on the head of the animal just outside of the base of the brain (brainstem) to record electrical signals (emitted by the brain) in response to sounds that are detected by the ear. These signals are averaged and used to determine if the animal has detected the sound. It is possible to determine auditory thresholds for fishes using this method. The same is used for numerous other species, including measurement of hearing capabilities of newborn human babies.

Bandwidth: The range of frequencies over which a sound is produced or received.

Biotelemetry: The terms "biotelemetry" or "telemetry" refer to methods used for monitoring fish (or other animals) (Thorne, 1983). Acoustic (ultrasonic) telemetry is the preferred technology in highly conductive environments, such as estuaries and marine systems (Reine, 2005). Underwater telemetry involves attaching a device (an acoustic tag) that relays information to an aquatic organism, such as a fish (Winter, 1983). If the device attached to the fish emits a signal, it is called a transmitter. If the transmitter returns a signal in response to the one sent to it, it is called a transponder. The acoustic, or sonic, signals from the fish are received by a hydrophone submerged in the water. Fixed hydrophones can be either hard-wired directly to a receiver datalogger or they can be wireless, transmitting data via the hydrophone to a shore-based antenna connected to the datalogger. Thus, the information from the fish (via an ultrasonic tag) transmits information in the form of sound energy transmission (in kHz) frequencies. Frequencies for acoustic tags range from 30-300 kHz (Reine, 2005).

Decibel (dB): A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10 \log_{10}$ (actual/reference), is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20 \log_{10}$ (actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 µPa).

Echo Sounder: The technique of using sound pulses directed from the surface or from a submarine vertically down to measure the distance to the bottom by means of sound waves. This information is then typically used for navigation purposes or in order to obtain depths for charting purposes. Echo sounding can also refer to hydroacoustic "echo sounders" defined as active sound in water (sonar) used to study fish.

Far Field: A region far enough away from a source that the sound pressure behaves in a predictable way, and the particle velocity is related to only the fluid properties and exists only because of the propagation sound wave (see Near Field).

Fisheries Hydroacoustics: See Hydroacoustics.

Frequency Spectrum: See “Spectrum.”

Gill Netting: A passive gear type that involves the capture of fish by entanglement in a device (the gill net) that is not actively moved by humans or machine (Hubert, 1983).

Hertz: The units of frequency where 1 hertz = 1 cycle per second. The abbreviation for hertz is “Hz.”

Hydroacoustics: A term generally applied to methods that use sonars or depth sounds (Thorne, 1983). These are techniques in which sound is actively transmitted to, and information is extracted from the returning echoes. The basis for hydroacoustics is a sonar system. Usually the system is oriented vertically, in which case it is called an echosounder. A sonar, or echosounder system, consists of the following four components: (1) transmitter; (2) transducer; (3) receiver-amplifier; and, (4) control and display. The transmitter produces a burst, or pulse, of electrical energy that is converted by the transducer (or hydrophone) to an acoustical signal in the form of a short “ping” or beep. This signal travels through the water, and when it hits its target (e.g., fish, sea bottom), it is reflected towards the source as an “echo”. The receiver-amplifier increases and modifies the signal to a form suitable for display. The display is usually an oscilloscope.

Infrasound: Sound at frequencies below the hearing range of humans. These sounds have frequencies below about 10 Hz.

Lagena: One of the three otolithic end organ of the inner ear of fishes. The precise role of the lagena is not defined, but it is likely that it is involved in sound detection in many species. The lagena is also found in all terrestrial vertebrates other than mammals, where it may have evolved into the mammalian cochlea.

Lateral Line: A series of sensors along the body and head of fishes that detects water motion. The lateral line uses sensory hair cells (identical to shoes in the ear) for detection. The cells are located in neuromasts that lie either in canals (e.g., along the side and head of the fish) or freely on the surface in a widely distributed pattern.

Longline Fishing: A commercial fishing technique that uses hundreds, or even thousands, of baited hooks hanging from a single line (Hayes, 1983).

Near Field: A region close to a sound source that, depending on the size of the source relative to the wavelength of the sound, has either irregular sound pressure or exponentially increasing sound pressure towards the source. In addition, there is a high level of acoustic particle velocity because of kinetic energy added directly to the fluid by motion of the source. This additional kinetic energy does not propagate with the sound wave. The extent of the near field depends on the wavelength of the sound and/or the size of the source.

Otolith: Dense calcareous structures found in the otolithic end organs (saccule, lagena, utricle) of the ears of fishes. They are located next to sensory hair cells of the ear and are involved in stimulation of the ear for detection of sound or head motion.

Peak Pressure: The highest pressure above or below ambient that is associated with a sound wave.

Pulse: A transient sound wave having finite time duration. A pulse may consist of one to many sinusoidal cycles at a single frequency, or it may contain many frequencies and have an irregular waveform.

Purse Seine: A common type of seine, so named because along the bottom are a number of rings. A rope passes through all of the rings and when pulled, draws the rings close to one another, thus preventing the fish from swimming down to escape the net.

Saccule: One of the three otolithic end organs of the inner ear. It is generally thought that the saccule is involved in sound detection in fishes, although it also has roles in determining body position relative to gravity, its primary role in terrestrial vertebrates.

Seine: A large fishing net that hangs vertically in the water by attaching weights along the bottom edge and floats along the top (Hayes 1983). Bottom seining in deep water, purse seines in open water and shallow water situations, are all used in commercial fishing. Seine nets are usually long flat nets, like a fence, that are used to encircle a school of fish, with the boat driving around the fish in a circle. Various types of seiners have been developed for research applications.

Sound Exposure Level (SEL): The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.

Sound Pressure Level (SPL): The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1µPa for water and biological tissues, and 20 µPa for air and other gases.

Spectrum: A graphical display of the contribution of each frequency component contained in a sound.

Swim Bladder: A gas (generally air) filled chamber found in the abdominal cavity of many species of body fish, but not in cartilaginous fishes. The swim bladder serves in buoyancy control. In many species the swim bladder may also serve as a radiating device for sound production and/or as a pressure receiving structure that enhances hearing bandwidth and sensitivity.

Telemetry: See Biotelemetry.

Threshold: Generally represents the lowest signal level and animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50% level.

Trawling: A method of fishing that involves actively pulling a trawl through the water behind one or more trawlers. A trawl is used to collect fish or other biological samples (Hayes, 1983). It is a bag-shaped net that is dragged along the bottom or through the water column and fish are collected by "straining" them from the water. The trawl is normally towed by one or two powered vessels and may be designated as a bottom, midwater, or surface sampler. Trawls vary in size from small hand-operated nets towed from small boats to very large mechanically handled trawls towed from commercial fishing vessels. In otter trawls, the mouth opening is maintained by outward forces generated by water pressure and bottom friction against door-shaped boards (otter boards) towed at an angle to the net direction. There are many door designs, and those used in fish sampling are normally chosen according to local experience.

Trolling: A method of fishing where one or more fishing lines, baited with lures or bait fish, are drawn through the water (Hayes, 1983). This may be behind a moving boat, or slowly winding the line in when fishing from a static position, or even sweeping the line from side-to-side.

Utricle: One of the three otolithic end organs of the inner ear of fish (the others are the saccule and lagena). The utricle is probably involved in determining head position relative to gravity as well as in sound detection. It is the primary sound detection region in the Clupeiform fishes (herrings, shads, sardines, anchovies, and relatives). A utricle is found in all vertebrates, including humans.

APPENDIX C

EQUIPMENT USED TO DETERMINE THE BEHAVIORAL RESPONSES OF FISHES EXPOSED TO SUSPENDED SEDIMENTS/SOLIDS CAUSED BY DREDGING ACTIVITIES

Table C-1. Equipment Used to Determine the Behavioral Responses of Fishes Exposed to Suspended Sediments/Solids Caused by Dredging Activities.

Type of Study	Fish Species	Equipment Used	Reference
Fish avoidance and attraction studies	Herring, Atlantic (*Clupea harengus harengus*)	- Laboratory apparatus consisting of a trough with two interconnecting areas forming a figure-of-eight maze, with a door that allowed fish passage, but limited water exchange between sides of the maze. - The trough was supplied with flow-through seawater	Johnston and Wildish, 1981 Messieh et al., 1981
	Smelt, Rainbow (*Osmerus mordax*)		Wildish and Power, 1985
Fish studies on swimming behavior	Smelt, Rainbow (*Osmerus mordax*)	- Laboratory apparatus consisting of a V-shaped trough (divided into four zones) with a fan design so that different current velocity areas were created. - Seawater was pumped from a catch-box through a chiller and then emptied into a head-box. - An electric event recorded was used.	Chiasson, 1993
Fish studies on feeding and predation behavior	Herring, Atlantic (*Clupea harengus harengus*)	- Laboratory apparatus consisting of conical tanks aerated from the bottom - Formalin solution used to preserve fish for stomach analysis. - Measuring board - Dissecting scope - Dissecting instruments	Johnson and Wildish, 1982 Messieh et al., 1981
	Larval marine and estuarine fishes	- Laboratory apparatus consisting of two motorized roller-based acrylic "wheels", each partitioned into six chambers	Colby and Hoss, 2004