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Characterization of Underwater Sounds Produced by a Hydraulic Cutterhead Dredge during Maintenance Dredging in the Stockton Deepwater Shipping Channel, California

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PURPOSE: The purpose of this study was to record and analyze underwater sounds generated by a small hydraulic cutterhead dredge during maintenance dredging in the Stockton Deepwater Shipping Channel (SDWSC), California. Of particular interest was determining 1) the sound frequency characteristics of the excavation process, 2) the received sound pressure levels at various distances from the source, 3) the predicted source level, and 4) ambient sound sources in the study area. These data will fill important knowledge gaps and inform future dredging project management decisions.

BACKGROUND/INTRODUCTION: In recent years, the potential impact of underwater sounds associated with dredging and disposal operations has come under increasing scrutiny by regulatory agencies. Underwater noise has been previously identified as a concern, but has primarily been linked to petroleum industry seismic surveys and construction activities such as pile driving (Richardson et al. 1995). In fact, the scant scientific literature pertaining to the effects of underwater sound on fishes and other aquatic organisms has largely resulted from monitoring of pile-driving operations (e.g. Caltrans 2001, Nedwell et al. 2003, Abbott et al. 2005, Ruggerone et al. 2008). Currently nine US Army Corps of Engineers (USACE) Districts and two Federal Agencies (National Aeronautics and Space Administration (NASA), Bureau of Ocean Energy Management (BOEM)) have had formal or informal consultations with resource agencies concerning underwater sound and its potential impacts on fishes or species with threatened or endangered status. The most recent of these involves the USACE Charleston and Wilmington Districts, which have had to prepare Noise Assessment Studies during consultations under the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA) for upcoming Harbor Deepening Projects (HDP). A concern cited by the National Oceanic and Atmospheric Administration (NOAA)-Fisheries involves potential blockage or delay in the migration of anadromous fishes such as American shad (*Alosa sapidissima*), blueback herring (*Alosa aestivalis*), and Alewife (*Alosa pseudoharengus*) through navigable waterways. Their concerns focus on American shad, which is currently experiencing stock declines and is presumed to be sensitive to dredge sounds. The same concern was also cited by NOAA-Fisheries in a 2010 Memorandum for Record to the USACE: New York District. In November 2012, the BOEM Environmental Studies Program held a workshop to identify the most critical information needs and data gaps on the effects of various man-made sounds on fish, fisheries, and invertebrates resulting from the use of sound-generating devices. To help focus the workshop and maximize the contributions of the participants, a document was generated that presented a literature synthesis summarizing the current knowledge of underwater sound (Normandeau Associates, Inc. 2012). Other notable literature syntheses include: Popper and Hawkins (2012), Bingham (2011), Small et al. (2011),

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Slabbekoorn et al. (2010), Oslo and Paris Commission (OSPAR) (2009), Popper and Hastings (2009), Hawkins et al. (2008), and Southall et al. (2007). On the Pacific coast, the USACE San Francisco District has experienced restrictions regarding potential impacts to fishes from underwater noise related to pile driving and other construction activities, but until recently the issue of underwater sound had not been linked to dredging projects. However, concerns for negative impacts of underwater noise on aquatic species (e.g. salmon, *Salmonidae spp*.; smelt, *Osmeridae spp*.; and green sturgeon, *Acipenser medirostris*) were raised during interagency coordination of the Sacramento River Deepwater Shipping Channel Deepening Project. Concerns ranged from sounds associated with two or more dredges working concurrently to sounds generated by booster pumps.

Concerns about underwater noise have not been limited to impacts on fish species. The USACE New England District recently performed advanced maintenance dredging with a small hopper dredge to remove sand waves in the lower reaches of the Kennebec River, Maine (Reine et al., in preparation a). Comments citing potential underwater sound impacts on harbor seals (*Phoca vitulina*) led to consultation with the National Marine Fisheries Service (NMFS). The NMFS stated that underwater noise levels exceeding 120 dB may cause behavioral disturbances and levels beyond 160 dB could harass marine mammals. Currently the NMFS does not require Incidental Harassment Authorization (IHA) with regard to dredging operations, but it is an issue being considered for application to future dredging operations. Currently IHAs are only required for underwater noise associated with pile-driving operations.

NASA's Goddard Space Flight Center was required to enter into a consultation with NOAA under Section 7(a) (2) of the ESA when securing permits for a proposed Wallops Island Shoreline Restoration and Infrastructure Protection Program for threatened and endangered species. The NMFS concluded in a 2010 Biological Opinion that the proposed dredging operation may produce sounds that affect listed species of sea turtles and whales. Underwater sounds generated by hopper dredging operations are of low frequencies (< 1000 Hz) and as such are within the audible range of listed species of both whales (7-22 kHz) and sea turtles (100-1000 Hz). Given NMFS concerns, the Engineer Research and Development Center (ERDC), NASA, and BOEM conducted a joint study to monitor underwater sounds produced by three trailing suction hopper dredges (TSHDs) working concurrently during sand mining and pump-out operations in support of the Wallops Island Shoreline Restoration Project (Reine et al., in preparation b).

The issue of noise associated with dredging and disposal operations has now expanded into issues related to aerial sound. In 2013, the U.S. Fish and Wildlife Service (USFWS) required the USACE New England District to address the issue of the impact of aerial noise from hopper dredging activities to nesting piping plovers (*Charadrius melodus*). Within several small inlets in Massachusetts, it was determined that a small hopper dredge could approach to within 100 m of piping plover nests, causing the species to abandon nesting activities. A similar issue was recently reported by the USACE Norfolk District regarding disturbance to bald eagles (*Haliaeetus leucocephalus*) from aerial dredging noise.

Dredge type and potential sources of sound. Hydraulic pipeline cutterhead dredges are commonly used throughout the United States for both new and maintenance projects. They are capable of excavating most types of material and pumping the resultant sediment-water slurry through pipelines for distances of several miles or longer with the use of booster pumps. During excavation the cutterhead rotates in contact with the sediment bed while swinging laterally into the sediment face. Large, powerful cutterhead dredges are capable of dredging rock-like formations such as coral and the softer types of basalt and limestone without the need for blasting. The dredge advances by alternately swiveling on posts called “spuds” while anchored cables on each side of the dredge control lateral movement. Winch and generator sounds transmitted through the hull of the dredge are a typical sound source associated with this type of dredging operation. During hydraulic dredging, it is very difficult to separate the individual processes involved based on their temporal location in the acoustic record (Clarke et al. 2002). The major processes contributing to hydraulic pipeline dredging sounds include: 1) dredged material collection sounds that result from the rotating cutterhead coming in contact with the sediment bed and intake of the sediment-water slurry, 2) sounds generated by pumps and impellers driving the suction of material through the pipes, 3) transport sounds involving the movement of sediment through the pipes, and 4) ship and machinery sounds, including those associated with the lowering and lifting of spuds and moving of anchors by dredge tenders.

The hydraulic dredge *Veracious,* owned and operated by the Vortex Marine Construction Company, was monitored in the present study (Figure 1). The *Veracious* has an overall length of approximately 100 ft (30.3 m) and total power of 1000 hp operating the main pumps. Material was moved through a 16-in. pipeline to an upland Confined Disposal Facility (CDF).

Figure 1. Hydraulic dredge *Veracious.*

METHODS

Study site. The Port of Stockton is a major inland deepwater port in Stockton, California, located on the San Joaquin River before it joins the Sacramento River to empty into Suisun Bay, 80 miles inland. The port sits on approximately 1,440 acres (5.8 km^2), and occupies an island in the San Joaquin Delta, and a portion of a neighborhood known as Boggs Tract. Underwater acoustic monitoring occurred near the port facility in November 2012. The study site is located on NOAA Chart 18663 at approximately $37^0$95' north, 121^0 33' west (Figure 2).

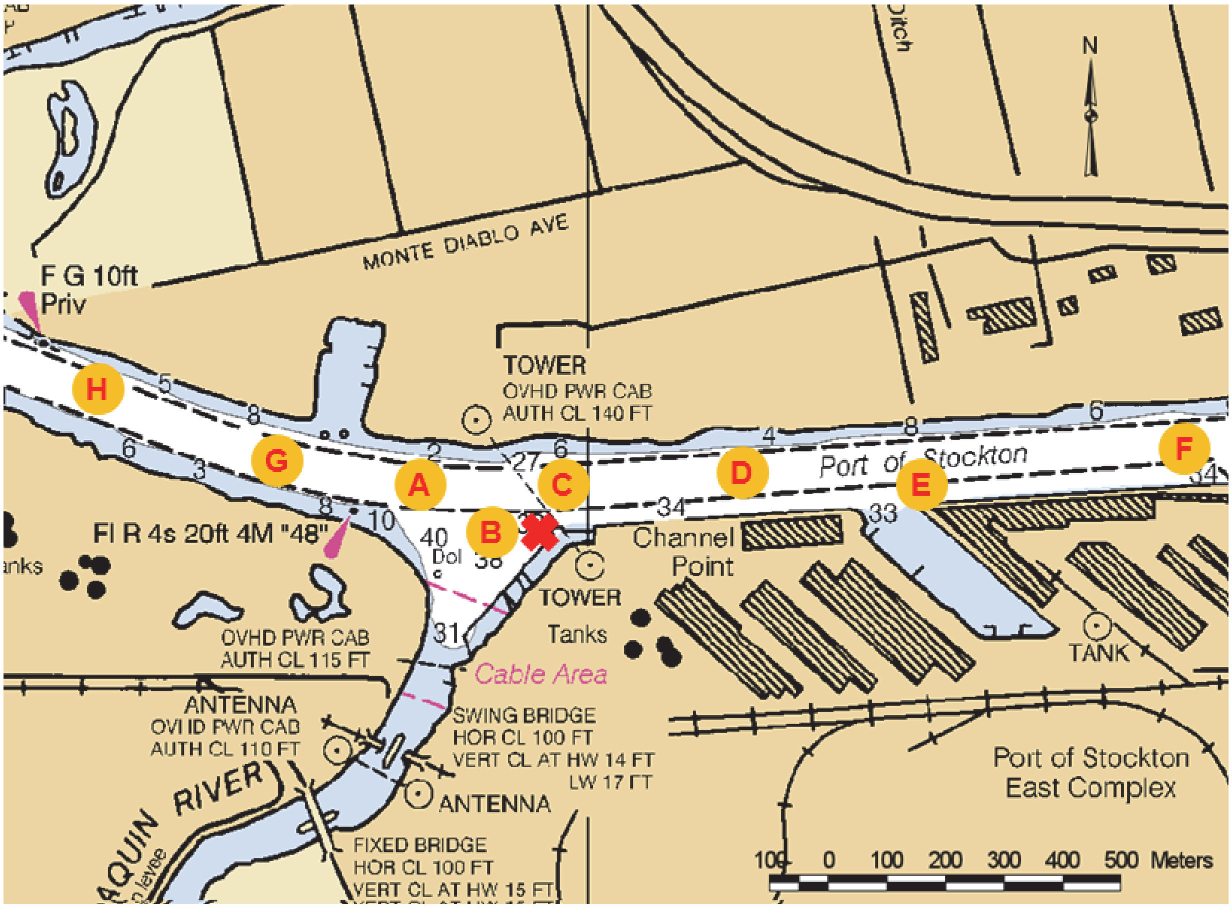

Figure 2. Study area depicting the SDWSC with the confluence of the San Joaquin River. Ambient monitoring stations are identified by yellow circles. (Red "X" = location of *Lusitania G*).

Sound equipment and data acquisition. The acquisition system onboard the listening platform was a Sound Technologies ST1400ENV digital mobile audio recorder running MDR_SLM Software. The ST1400ENV is a self-contained system designed specifically to record underwater sounds while simultaneously monitoring and logging sound pressure levels (SPLs) and other sound level parameters. The ST1400ENV records digital WAV format audio files, which can be post-processed using the hydrophone and system calibration information to produce a calibrated sound spectra analysis. Measurements were made with two Reson TC4032 low-noise, sea-state-zero, pre-amplified hydrophones connected to the system through an EC6073 input module. Hydrophones were powered through the EC6073 by a Reson EC6069 battery module. No gain was applied in the ST1400ENV during data collection. The sampling rate was set to 50,000 samples per second. A 20- to 22.5-kHz band pass filter was applied. The WAV file recording bit density was 24 bit. Sound data files were time-date stamped (Coordinated Universal Time (UTC)) with Global Positioning System (GPS) position and data values logged every 1 second. All hydrophones were factory calibrated by Reson, Inc. over their full frequency range using National Institute of Standards and Technology (NTIS) protocols. Hydrophone deployment depths at the borrow site were 3 m for the upper listening depth (ULD) and 9.1 m for the lower listening depth (LLD). All sound recordings were made from drift transects to reduce hydrodynamic flow noise. Sound recordings were made both up- and downstream of the dredge during sediment excavation. Hydrophone measurements were performed as a function of range from the dredge at multiple distances. Recordings were made at nine listening locations at distances ranging from 25 to 500 m. Distances from the survey vessel to the sound source were measured every 15 seconds using a laser range finder manufactured by Bushnell (Elite Model 1500), with a maximum range of 1500 m. Distances were confirmed during post-processing by GPS coordinates that were logged automatically through the STV1400ENV, which had an attached external GPS antenna mounted on the roof of the survey vessel. Results were compared with ambient SPLs measured at eight sites located up- and downstream of the excavation site on 14 November 2012 when the dredge was not in operation due to mechanical problems. Again the listening platform was not anchored to minimize flow noise.

Deployment. During all recording sessions onboard the listening platform, quiet conditions were maintained. This required that the vessel engines, generator, and echosounders were in the off position. All attempts were made to avoid noises due to movement of people onboard the listening platform. All acquisition equipment was run from deep-cycle marine batteries to avoid noise from external power sources (generators) and any extraneous electrical noise. Whenever possible, precautions were taken to avoid interference from external noise sources. These included an internal 20-Hz band pass filter used to reduce noise associated with wave action and the avoidance of metal parts (e.g. shackles or chains), which would eliminate metal-on-metal contact.

Data analysis. The following steps were taken in analyzing the data collected:

1. Dredge position information was imported and interpolated to 1-second intervals to match the GPS and sound data collection rates.
2. Dredge "actions" or operational modes were determined (see listing below). (Given that this study represents a minimal effort in which ambient and dredging sound data were collected over two days, not all "actions" or operational modes of dredging were encountered during the data collection process. These dredging events, however, would be expected to be encountered during a full study.)
    a. Shutdown mode.
    b. Excavating sediment.
    c. Flushing pipes with clear water.
    d. Raising or lowering spuds.
    e. Moving dredge anchors and cables by tender vessels.
3. Wind data were imported (where necessary) and interpolated to 1-second intervals.
4. Data were imported from the ST1400ENV.

5. Dredge position data, wind data, and STV1400ENV data were merged based on time stamps.
6. Data were sorted, summarized, and averaged and SPL files were generated by distance.
7. Output files of "ambient" data results were generated. Data were collected when the dredge was in complete shutdown mode.
8. Data were summarized in tables and results were graphed. Note that there are currently no international standards that describe procedures for measuring underwater sounds produced by dredgers in shallow-water environments. A recent document (American National Standards Institute (ANSI)/American Standards Association (ASA) S12.64/Part 1, (ANSI/ASA 2009)) describes procedures for measuring underwater noise emitted from commercial vessels in deep water. In brief, a minimum depth of 75 m (or one ship length) is required. For most dredging operations (even those conducted by large hopper dredges) in estuarine, riverine, or near-shore environments, this requirement is not feasible given that water depths are typically less than 50 m.
9. Calculate the Source Level (SL). The theoretical propagation loss was calculated as the fitted curvilinear regression of SPL versus distance. Three regression equations were derived for the following three types of data: 1) for data off the bow of the dredge with the cutterhead assembly as a point of reference, 2) for data astern of the dredge, and 3) for all data combined. For data collected off the bow of the dredge, the regression equation was expressed as natural log y = -6.85Ln(x) + 157.43, R^2 = 0.6797. For data collected astern of the dredging operation, the regression equation was expressed as natural log y = -4.818Ln(x) + 151.48, R^2 = 0.6253. For all data combined, the regression equation was expressed as natural log y= -5.648Ln(x) + 152.9, R^2 = 0.5701. Natural logs were then converted to $\log_{10}$ to yield the calculated loss based on $\log_{10}$. Loss was estimated at 15.77Log R (bow), 11LogR (stern), and 13.01LogR for all data combined. Propagation loss for data collected in this study falls between the general equations of cylindrical spreading (10LogR) and practical spreading (15LogR). Note that SLs can be derived by correcting the Received Levels (RLs) for the range from the source using a simple spherical spreading correction (20LogR). This is the most frequently used procedure to describe vessel noise reported in the scientific literature. However, this method is more suited to deepwater environments and commercial shipping and is less suited for the current study given the shallow water depths typical of a riverine or estuarine environment.

RESULTS

Listening depths. Hydrophones were deployed at two listening depths (3 m and 9.1 m). A comparison of the results indicated that differences between the two listening depths were approximately 0.5 dB, with the hydrophone deployed at the upper listening depth recording the higher SPLs. Results are therefore presented for the upper listening depth.

Ambient sound. Ambient SPLs were recorded on 14 November 2012 when the dredge was completely shut down due to a mechanical issue. Prevailing weather conditions were ideal with light winds and no wave action. In order to document naturally occurring levels of underwater sound at the study site, ambient data were collected at eight stations, A-H (Figure 2). Approximately 5000 discrete ambient SPLs were recorded. Two examples of time-series sound pressure waveforms are depicted in Figures 3 and 4. The time-series profile recorded at Site F (Figure 3) shows very quiet ambient conditions at the downstream extent of the study site. At Site B (Figure 4), background SPLs were recorded at the confluence of the San Joaquin River (SJR) and SDWSC, near a moored commercial vessel. The increase in the overall width (number of Pascals) of the pressure band indicates an increase in the noise level, primarily associated with a running generator from the bulk carrier *Lusitania G*. There is also a noise event, approximately 125 seconds on the time-series profile, that is unknown in origin, but is clearly associated with port operations.

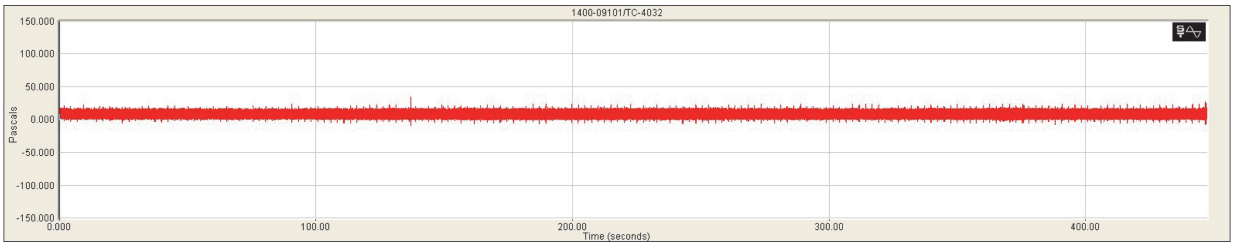

Figure 3. Ambient time-series pressure waveform recorded at Site F (See Figure 2 for site location).

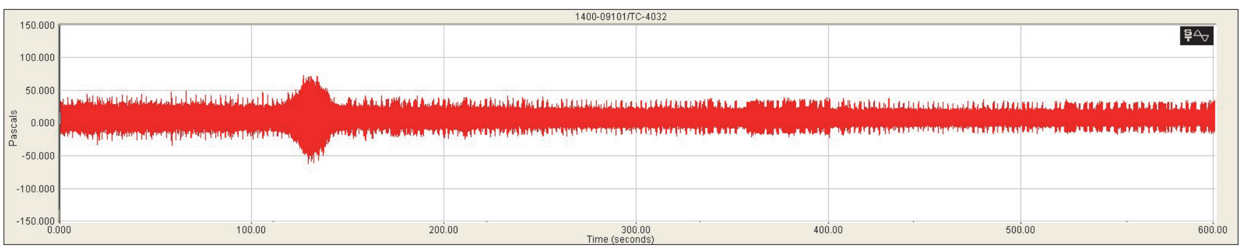

Figure 4. Ambient time-series pressure waveform recorded at Site B (See Figure 2 for site location).

To further characterize the ambient sound field, SPLs were referenced as a percentile of ambient; i.e., whether the value recorded was above or below, for example the 5th, 50th, or 95th percentile level (Figure 5). This approach is commonly reported in literature for ambient sound measurements (Richardson et al. 1995) to eliminate a small number of extraneous values (minimum and maximum SPLs) on both the upper and lower end of the spectrum that are mostly likely outliers. These outliers on the upper end of the range may result, for example, from causes ranging from contact with the hydrophone to debris in the water column. Ambient SPLs are summarized in Table 1. The "overall" values combined the results for all sites (A-H). For comparison to sounds produced during the excavation process and between ambient sites, values representing the 50th percentile will be used unless otherwise stated.

Sites A-E. For descriptive purposes, distances to ambient monitoring sites were determined from the centerline of the confluence of the SJR and the SDWSC. Sites A, G, and H were located 100-675 m downstream of this reference point. All other sites (Sites B-F) were located upstream at distances ranging from 60-1225 m. Site F was located furthest west nearest the turning basin, while Site H was located furthest east. Locations of ambient monitoring sites are depicted in Figure 2. Site C had the highest SPLs (P_{50} = 132.7 dB root-mean-square (rms)) (Figure 5) due to detection of generator noise emitted from the bulk carrier *Lusitania G,* moored on the east side of the SJR. Site C was located directly astern of the bulk carrier, nearest the engine/generator room. Generator

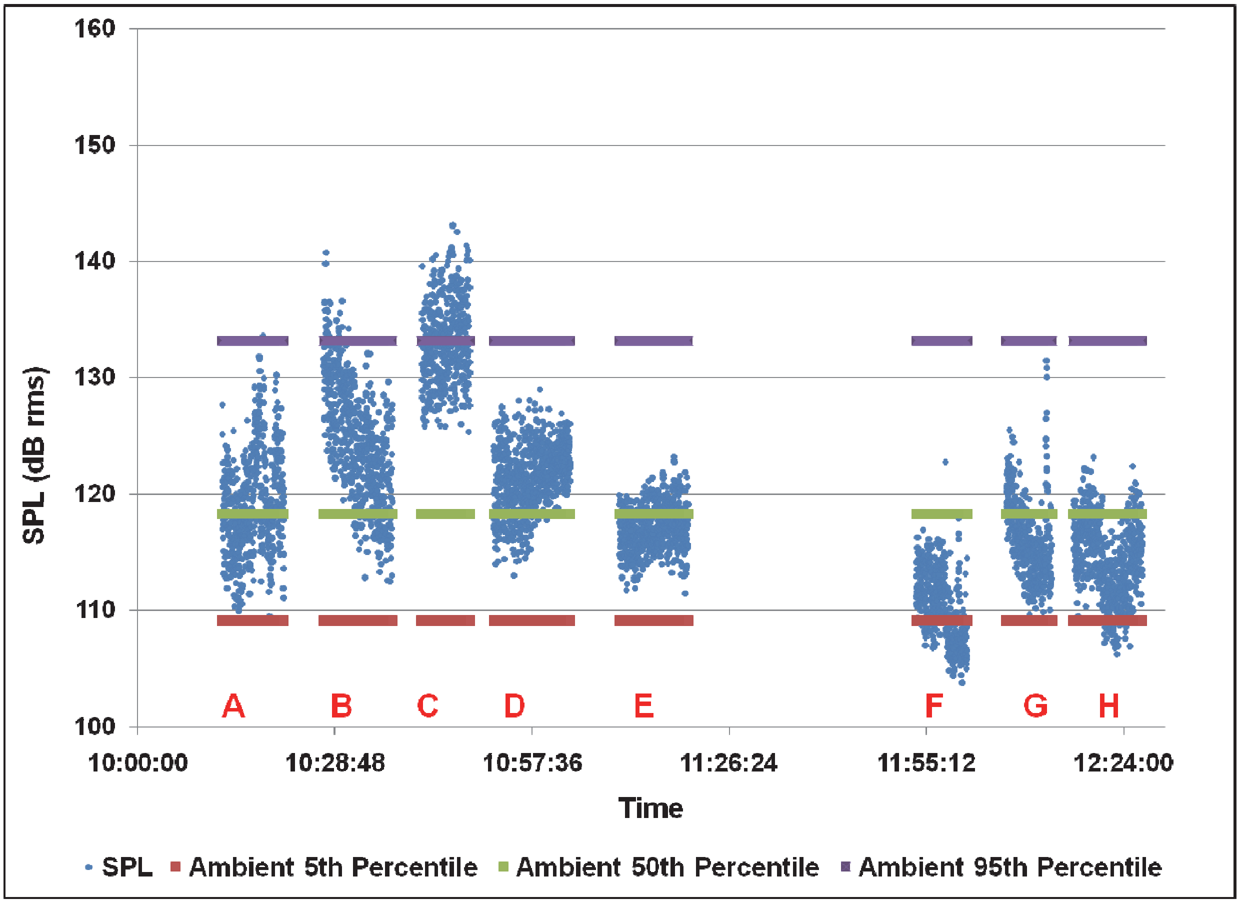

Figure 5. Ambient SPLs recorded at Sites A-H on 14 November 2012. See Figure 2 for site locations.

Table 1. Summary of ambient noise sound pressure levels (SPLs) recorded on 14 November 2012.

File	Overall (SPL rms)			Percentiles (SPL rms)				
	Mean	Max.	Min.	P_{95}	P_{90}	P_{50}	P_{10}	P_5
Overall	119.5	143.1	103.8	133.2	130.2	118.3	111.4	109.1
A	122.3	143.1	103.8	143.1	137.0	120.5	108.6	103.8
B	124.4	140.8	112.5	132.8	131.0	124.2	117.8	116.5
C	133.0	143.1	125.4	139.1	137.8	132.7	128.7	122.6
D	121.5	129.0	113.0	137.0	134.0	121.7	117.3	116.4
E	117.0	123.2	111.4	120.3	119.6	116.9	114.6	113.9
F	110.2	122.7	103.8	114.9	114.1	110.5	106.2	105.8
G	116.1	131.4	109.6	122.1	120.7	115.7	112.1	111.6
H	114.4	123.2	106.2	119.5	118.6	114.5	109.8	108.8

noise was also detected at both Sites A and B, but to a lesser degree. At the 50th percentile level, SPLs at Site C were 8.5-22.2 dB higher when compared to all other ambient monitoring sites. Sites A and B were located approximately 120 m and 250 m west of Site C, respectively. Note the increasing number of SPLs recorded that exceeded the 95th percentile from Site A to Site C, as distance from the survey vessel to the generator sound source decreased (Figure 5). Two additional sites (G and H) were occupied downstream of the reference point at distances of 350 and 675 m, respectively. SPLs at Site G were 17 dB quieter compared to Site C and 18.2 dB quieter compared to Site H. SPLs (P_{50}) at Site C were slightly greater than 22 dB higher compared to Site F (P_{50} = 110.5 dB rms), the furthest upstream station. Site F was located nearly 1225 m from the reference point, or approximately 1075 m from Site C. Note decreasing SPLs from Site C to Site F on Figure 5. At Site C, nearly half of the SPLs were above the 95^{th} percentile, whereas a third of SPLs were below the 5^{th} percentile at Site F.

Based solely on Sites E and F, a conservative range of ambient values for the SDWSC during the current study would be 110.5-116.7 dB (mean = 114 dB rms). These values, however, would only apply during the absence of moored ships, thereby eliminating generator noise from the overall ambient profile. Note that underwater noise generated from vessels transiting the study area is not considered background noise. However, generator noise is part of the overall ambient condition when ships are moored at the Port, as well as sounds produced during normal day-to-day activities associated with port operations. When combining all data (generator noise, port activity noise), SPLs at the 50^{th} percentile level were 118.3 dB. This value will be compared to underwater sound emitted during the excavation process.

Hydraulic cutterhead dredge sounds. Sounds produced by hydraulic cutterhead dredges are essentially continuous in nature. The cutterhead assembly embedded in the substrate rotates while the dredge is in production mode with pumps activated. Occasionally the cutterhead is raised off the bottom to entrain water to flush the system, or while the dredge is repositioned by spud or tender vessel maneuvers. The system is flushed periodically to clear the pipeline pathway or to prime pumps. The duration of production “cuts” depends on a number of factors, including depth of insertion of the cutterhead, type of sediment being excavated, and width of the navigation channel. While these operations are occurring, continuous sounds are being produced by the pumps and dredge power plant (e.g. dredge generators).

Multiple sound recordings were made while the cutterhead assembly was operating in contact with the bottom while also positioning the listening vessel at increasing distances from the dredge plant. A total of 5,530 discrete SPLs were recorded during the current study while the dredge was in full production mode. Of these, 3,530 SPLs were recorded moving upstream of the dredge at increasing distance from the cutterhead assembly. An additional 2,000 SPLs were recorded astern of the dredge. The initial recording session positioned the listening vessel to within 26 m of the cutterhead. The survey vessel was then allowed to slowly drift away from the sound source. This “drift” methodology reduces flow noise on the head of the transducer that would occur if the listening vessel was anchored. Nine listening stations (six upstream and three downstream of the dredge) were occupied, as depicted in Figure 6. The dredge was oriented in the upstream direction (facing east). The bulk carrier, *Lusitania G,* was moored near the confluence of the SJR and SDWSC and is identified on Figure 6 with a red X. The dredge *Veracious* is identified with a red square.

Time-series profiles. Figures 7 and 8 are two examples of time-series sound pressure waveforms recorded during sediment excavation. With minor exceptions, these time-series profiles clearly indicate the continuous nature of sounds measured during hydraulic cutterhead dredging operations. These sounds could not be partitioned into discrete components attributable to individually identifiable sound sources, common with other types of dredging operations (e.g. bucket dredging). Thus, characterizing the cutterhead sounds collected in this study was constrained to analyses of cumulative sources.

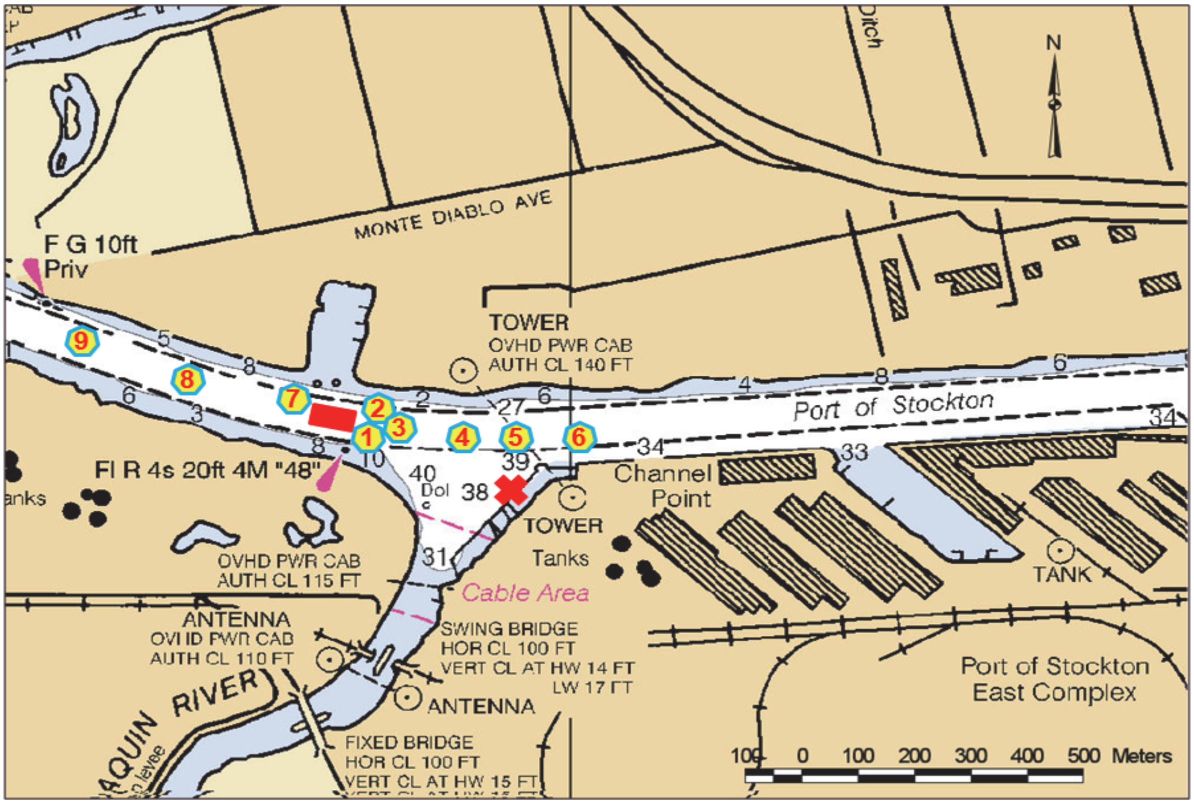

Figure 6. Sound monitoring stations.

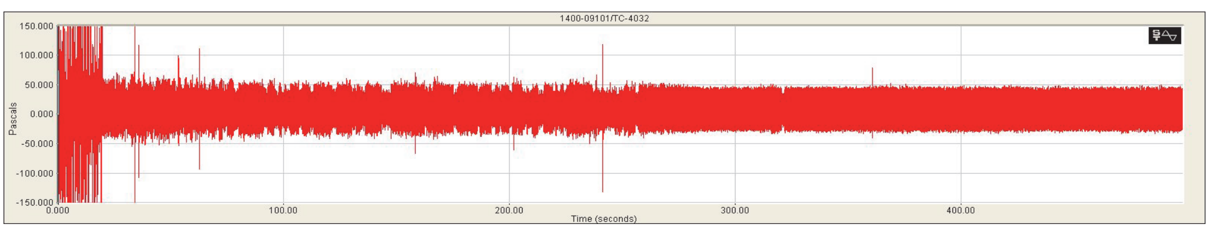

Figure 7. Time-series pressure waveform recorded 26 m from the cutterhead during sediment excavation (see Site 1, Figure 6).

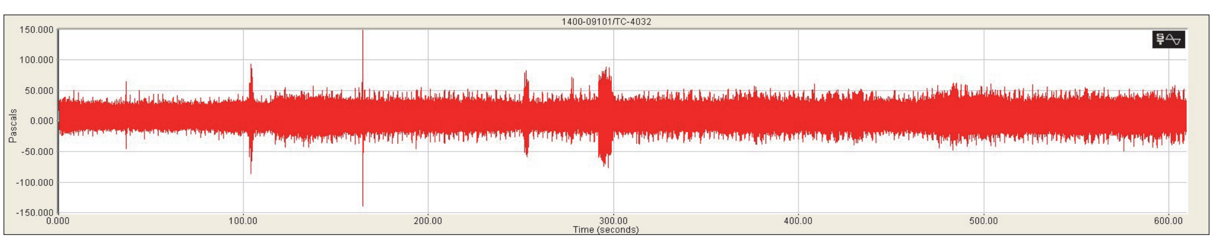

Figure 8. Time series pressure waveform recorded immediately astern of the dredging operation (see Site 7, Figure 6).

Within the sound record, sound intensity may vary depending on the amount or hardness of the material to be removed during the cut. Another factor is the orientation of the cutterhead assembly in relation to the survey vessel. Figure 7 depicts a time-series profile recorded 26 m from the cutterhead assembly. Excluding the initial start-up noise, the two halves of the time-series profile show the noise signature as the dredge swings in an arc through its cut. The signature on the left half of the profile shows slightly more variation to the sound signature as opposed to the right half of the time-series profile, which has a more consistent (smooth) signature.

Figure 8 shows a time-series profile recorded at Site 7 (see Figure 6) located astern of the dredge. In addition to the continuous noise (e.g. engine/generator) produced by the dredging operation, there were three noise events of a more impulsive nature. These are located at 110, 260, and 290 seconds on the time-series profile. Because they appear intermittently during monitoring, it is difficult to determine if these noise events are associated with the dredging process (e.g. metal-on-metal contact during dredge plant maintenance) or represent noise generated by the Port of Stockton. Since maintenance activities were not observed during this recording session, these noise events are most likely associated with port activities.

Sound recordings off the bow of the dredge. Sound recordings were obtained off the bow of the dredge (upstream of the cutterhead assembly) to a distance of 423 m (Table 2). Most of the sound energy fell below 1000 Hz, but more commonly at frequencies ranging from 100 Hz to 350 Hz. The closest distance from the sound source at which sound recordings were made was 26 m. SPLs versus distance (m) for recordings made upstream of the dredge can be found in Figure 9. Maximum received SPLs (143.5 dB rms) occurred at 49.9 m from the sound source, exceeding ambient SPLs (P_{50} = 118.3 dB rms) by 25.2 dB. SPLs exceeding 140 dB occurred infrequently and only at distances less than 75 m from the source (Recording sessions 1 and 2). At equivalent distances, SPLs varied by as much as 20 dB rms for recordings made nearest the source. All distances from the survey vessel are measured to the cutterhead assembly when it is positioned directly in front of the dredge plant. As the cutterhead swings across its arc, the distance from the cutterhead to the survey vessel can increase or decrease. Another factor contributing to variation in SPLs is the potential change in the pathway the sound takes before it reaches the hydrophone. As shown in Figure 9, a small number of SPLs fell below average (P_{50}) background levels during a short time period when the dredge briefly stopped excavating material and lowered its total power output. SPLs were consistently below 130 dB rms by 100 m from the sound source, exceeding background by less than 12 dB. From 140-163 m (Site 4, Figure 9) from the sound source, SPLs averaged 125$\pm$3 dB rms, or approximately 6.7$\pm$3dB rms above background. By 200 m (Site 5, Figure 9) from the sound source, an increasing number of SPLs fell below average background levels (P_{50} = 118.3 dB). SPLs averaged approximately 120 dB, or only 1.7 dB above ambient. At Site 6, located 421 m upstream of the dredge, 76% of all SPLs recorded were below average background levels (P_{50}). Approximately 10% of SPLs were within 1-3 dB of the 5th percentile (P_5 = 109.1 dB). Source level (SL), determined by calculating the theoretical propagation loss as a fitted curvilinear regression of SPL versus distance, was 157.4 dB re 1µPa at 1-m. Transmission loss was 15.77LogR, similar to Practical Spreading (15LogR).

Table 2. Subset of SPL (rms) versus distance for sound recordings made at increasing distances (upstream of the cutterhead) from the bow of the dredge.

Distance (m)[1]	SPL[2] (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)
26	133.1	**69**	129.1	**161**	125.0	**214**	122.4	**381**	119.7
27	139.6	**70**	131.1	**162**	125.1	**215**	122.3	**382**	114.9
28	132.7	**71**	121.6	**163**	124.5	**216**	120.2	**383**	116.1
29	130.4	**72**	118.5	**164**	121.8	**217**	116.4	**384**	118.1
30	136.2	**73**	124.3	**165**	123.4	**218**	119.6	**385**	117.8
31	131.6	**74**	126.9	**166**	123.6	**219**	122.3	**386**	115.5
32	136.5	**75**	126.4	**167**	122.8	**220**	120.9	**387**	117.7
33	134.2	**76**	125.7	**168**	122.7	**221**	119.3	**388**	114.6
34	141.7	**77**	128.8	**169**	120.9	**222**	120.2	**389**	115.2
35	135.1	**78**	126.6	**170**	120.2	**223**	118.6	**390**	116.4
36	131.5	**79**	124.5	**171**	121.8	**224**	119.0	**391**	114.1
37	135.2	**80**	128.3	**172**	120.1	**225**	117.5	**392**	118.4
38	135.6	**81**	124.5	**173**	120.9	**226**	120.9	**393**	116.8
39	131.6	**82**	126.7	**174**	124.1	**227**	124.0	**394**	115.7
40	131.6	**83**	128.7	**175**	123.5	**228**	123.1	**395**	116.8
41	130.1	**84**	122.9	**176**	123.6	**229**	122.6	**396**	115.7
42	128.5	**85**	125.2	**177**	124.5	**230**	115.6	**397**	113.2
43	135.5	**86**	127.9	**178**	122.2	**231**	121.9	**398**	114.4
44	127.7	**87**	125.7	**179**	120.0	**232**	116.0	**399**	116.7
45	132.3	**88**	122.5	**180**	124.0	**233**	118.5	**400**	115.9
46	130.0	**89**	123.2	**181**	122.4	**234**	118.9	**401**	113.9
47	131.3	**90**	128.9	**182**	122.7	**235**	119.1	**402**	114.0
48	132.9	**140**	125.7	**183**	122.3	**236**	120.2	**403**	117.3
49	126.9	**141**	122.1	**184**	119.9	**237**	119.9	**404**	116.5
50	131.2[3]	**142**	124.3	**185**	120.9	**238**	120.5	**405**	115.6
51	130.1	**143**	117.5	**186**	123.7	**239**	122.8	**406**	121.3
52	126.0	**144**	125.2	**187**	120.4	**240**	120.9	**407**	119.8
53	133.3	**145**	128.3	**188**	120.6	**241**	119.5	**408**	118.1
54	132.8	**146**	126.8	**189**	121.4	**242**	121.6	**409**	119.2
55	137.3	**147**	123.2	**200**	116.9	**243**	118.6	**410**	119.4
56	134.3	**148**	126.1	**201**	114.1	**244**	120.7	**411**	115.7
57	132.9	**149**	128.1	**202**	117.5	**245**	117.3	**412**	116.5
58	129.7	**150**	125.3	**203**	117.8	**246**	117.8	**413**	114.8
59	131.6	**151**	123.5	**204**	118.3	**247**	119.2	**414**	115.9
60	122.2	**152**	120.9	**205**	121.7	**248**	122.5	**415**	115.6
61	127.5	**153**	121.9	**206**	120.1	**249**	115.3	**416**	113.9
62	130.9	**154**	126.7	**207**	118.0	**250**	121.1	**417**	115.1
63	135.3	**155**	124.4	**208**	120.8	**375**	113.3	**418**	111.2
64	132.9	**156**	118.5	**209**	119.9	**376**	115.8	**419**	114.4
65	132.6	**157**	124.2	**210**	117.4	**377**	116.5	**420**	114.8
66	137.2	**158**	122.2	**211**	118.4	**378**	116.2	**421**	111.9
67	123.0	**159**	123.4	**212**	117.6	**379**	114.7	**422**	112.0
68	127.6	**160**	120.6	**213**	120.2	**380**	111.6	**423**	111.8

[1] Distance given in bold type is from the listening vessel to the cutterhead.
[2] SPL values in Table 2 are the log average of multiple measurements recorded at each distance.
[3] Note that this is the log-averaged value. The maximum value reported in the text was 143.5 dB at 50 m from the source.

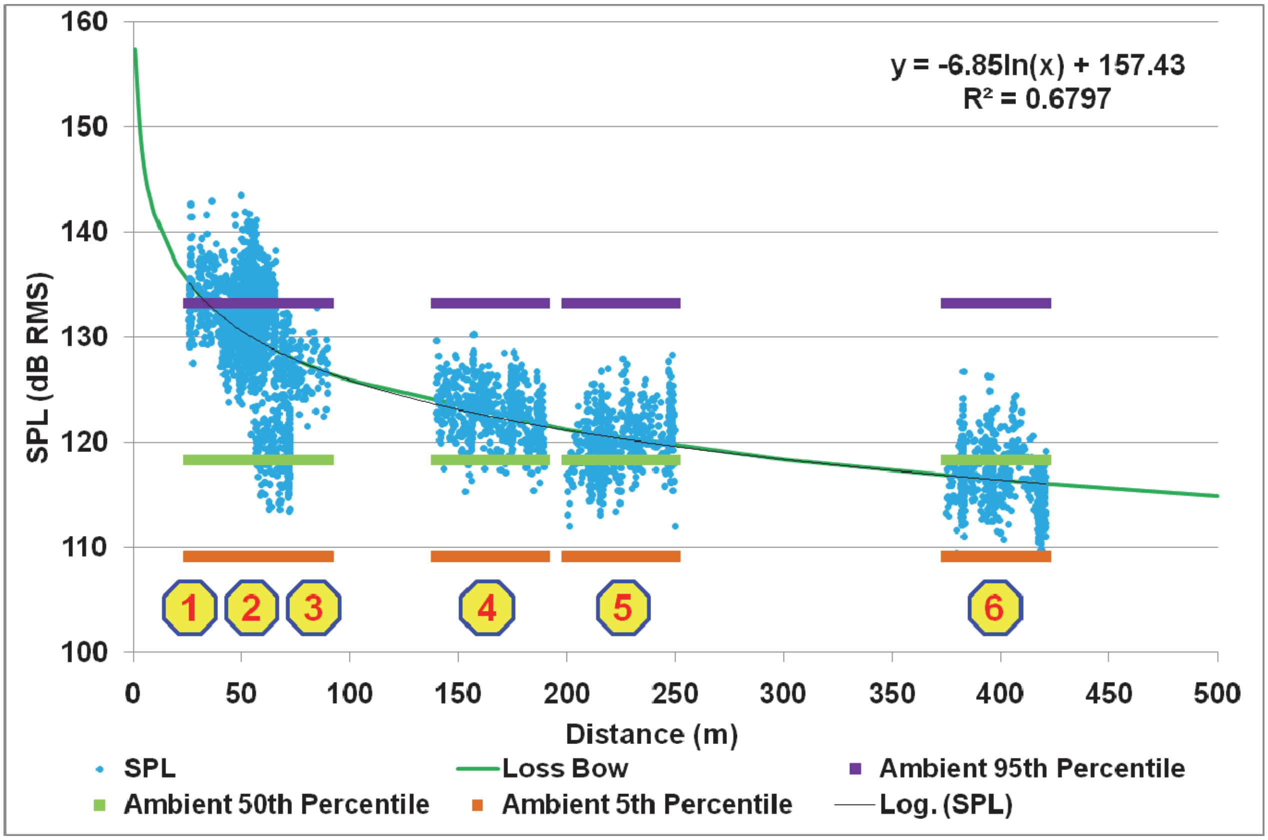

Figure 9. SPLs (dB rms) versus distance (m) for sound recordings made at increasing distances from the bow of the dredge. (Note: Number within the Heptagon corresponds to the monitoring site in Figure 6).

Sound recordings astern of the dredge. Sound recordings were made to a distance of nearly 500 m astern of the dredge (Table 3). SPLs versus distance (meters) can be found in Figure 10. Again, most of the sound energy fell below 1000 Hz, with peak frequencies between 100 and 350 Hz being most common. A maximum received SPL of 148.3 dB rms occurred 87 m (total distance to cutterhead = 117.3 m) astern of the dredge, or 30 dB rms above background (P_{50}). Note that all distances are from the listening platform to the stern of the dredge plant. Therefore, 30.3 m must be added to estimate the distance to the cutterhead when the cutterhead was positioned directly in front of the dredge. Actual distance to the cutterhead assembly is not crucial in the current study, as most of the sound generated by this dredge was associated with generator noise (generators were centrally located on the dredge plant), and not from the sediment excavation process (i.e. the rotation of the cutterhead in the soft silty sediment). A total of nine discrete SPLs, eight at Site 7 and one at Site 8, exceeded 140 dB rms (Figure 10). The majority of SPLs averaged 130 dB$\pm$3dB rms over distances of less than 100 m astern of the dredge (total distance to the cutterhead = 130 m). SPLs were approximately 9-15 dB rms above background. At distances of 278-308 m from the sound source (Site 8, Figure 10), the majority of SPLs were centered around 125$\pm$3 dB, or 3.7-9.7 dB above background. The trend of decreasing SPLs continued at Site 9 (Figure 10); however, SPLs fell to near the 5^{th} percentile level in a series of readings that occurred at approximately 370-390 m from the source. Since the survey vessel was positioned nearly 400 m astern of the dredge, it was not noticed if the dredge had temporarily stopped production.

Table 3. Subset of SPL (rms) versus distance for recordings made astern of the dredge.

Distance (m)[1]	SPL[2] (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)	Distance (m)	SPL (rms)
44	133.3	**87**	131.8[3]	**292**	126.2	**396**	121.0	**439**	119.7
45	132.8	**88**	130.9	**293**	123.9	**397**	121.4	**440**	120.6
46	132.5	**89**	133.3	**294**	127.3	**398**	122.8	**441**	120.3
47	137.6	**90**	131.0	**295**	122.6	**399**	121.3	**442**	119.8
48	136.1	**91**	131.6	**296**	121.0	**400**	119.9	**443**	119.6
49	130.0	**92**	131.2	**297**	124.6	**401**	120.0	**444**	119.8
50	130.8	**93**	129.6	**298**	123.4	**402**	121.7	**445**	120.0
51	130.7	**94**	129.2	**299**	121.4	**403**	123.2	**446**	119.9
52	130.2	**95**	132.2	**300**	122.8	**404**	120.8	**447**	122.5
53	129.3	**96**	131.4	**301**	121.5	**405**	120.4	**448**	125.0
54	129.8	**97**	131.4	**302**	121.2	**406**	121.3	**449**	123.0
55	135.9	**98**	130.9	**303**	123.8	**407**	120.8	**450**	121.9
56	132.1	**261**	130.9	**304**	125.9	**408**	121.3	**451**	123.9
57	133.8	**262**	122.2	**305**	122.9	**409**	118.6	**452**	122.1
58	130.2	**263**	127.7	**306**	122.5	**410**	122.8	**453**	122.0
59	132.2	**264**	131.9	**307**	123.4	**411**	122.3	**454**	119.5
60	131.7	**265**	129.1	**308**	128.1	**412**	120.5	**455**	118.9
61	131.3	**266**	138.4	**370**	111.5	**413**	121.9	**456**	119.1
62	134.2	**267**	127.9	**371**	112.7	**414**	120.2	**457**	119.3
63	127.4	**268**	129.1	**372**	113.8	**415**	119.9	**458**	120.3
64	134.9	**269**	129.5	**373**	110.6	**416**	122.3	**459**	123.1
65	129.2	**270**	129.0	**374**	111.2	**417**	121.0	**460**	122.8
66	139.0	**271**	126.9	**375**	118.4	**418**	122.1	**461**	123.4
67	129.0	**272**	126.7	**376**	115.5	**419**	123.8	**462**	121.2
68	130.0	**273**	128.6	**377**	119.2	**420**	123.2	**463**	120.2
69	127.2	**274**	129.0	**378**	116.7	**421**	117.8	**464**	125.1
70	127.8	**275**	130.2	**379**	115.5	**422**	123.3	**465**	124.3
71	130.1	**276**	129.0	**380**	118.4	**423**	122.1	**466**	119.3
72	127.8	**277**	128.5	**381**	114.4	**424**	120.5	**467**	126.9
73	130.4	**278**	129.3	**382**	117.0	**425**	120.3	**468**	123.5
74	131.6	**279**	122.8	**383**	116.7	**426**	122.2	**469**	126.8
75	128.9	**280**	122.6	**384**	116.9	**427**	123.1	**470**	121.6
76	127.6	**281**	123.9	**385**	116.8	**428**	123.1	**471**	122.7
77	128.8	**282**	126.4	**386**	115.7	**429**	123.1	**472**	121.4
78	130.1	**283**	121.7	**387**	116.5	**430**	119.7	**473**	120.4
79	129.6	**284**	125.4	**388**	117.8	**431**	119.7	**474**	120.3
80	130.2	**285**	123.6	**389**	116.5	**432**	120.1	**475**	118.6
81	129.5	**286**	126.9	**390**	117.8	**433**	122.5	**476**	117.9
82	130.3	**287**	124.1	**391**	116.9	**434**	124.0	**477**	122.9
83	132.5	**288**	121.0	**392**	117.2	**435**	124.4	**478**	118.9
84	130.9	**289**	124.4	**393**	116.7	**436**	119.7	**479**	117.5
85	131.2	**290**	125.2	**394**	117.3	**437**	117.3	**480**	118.0
86	133.4	**291**	127.4	**395**	119.8	**438**	115.7	**481**	118.2

[1] Distance given in bold type is from the listening vessel to the stern of the dredge. Add 30.3 m to get distance to the cutterhead.
[2] SPL values given in Table 3 are the log average of multiple measurements recorded at each distance.
[3] Note that this is the log-averaged value. The maximum value reported in the text was 148.3 dB at 87 m from the stern of the dredge (117.3 m from the cutterhead).

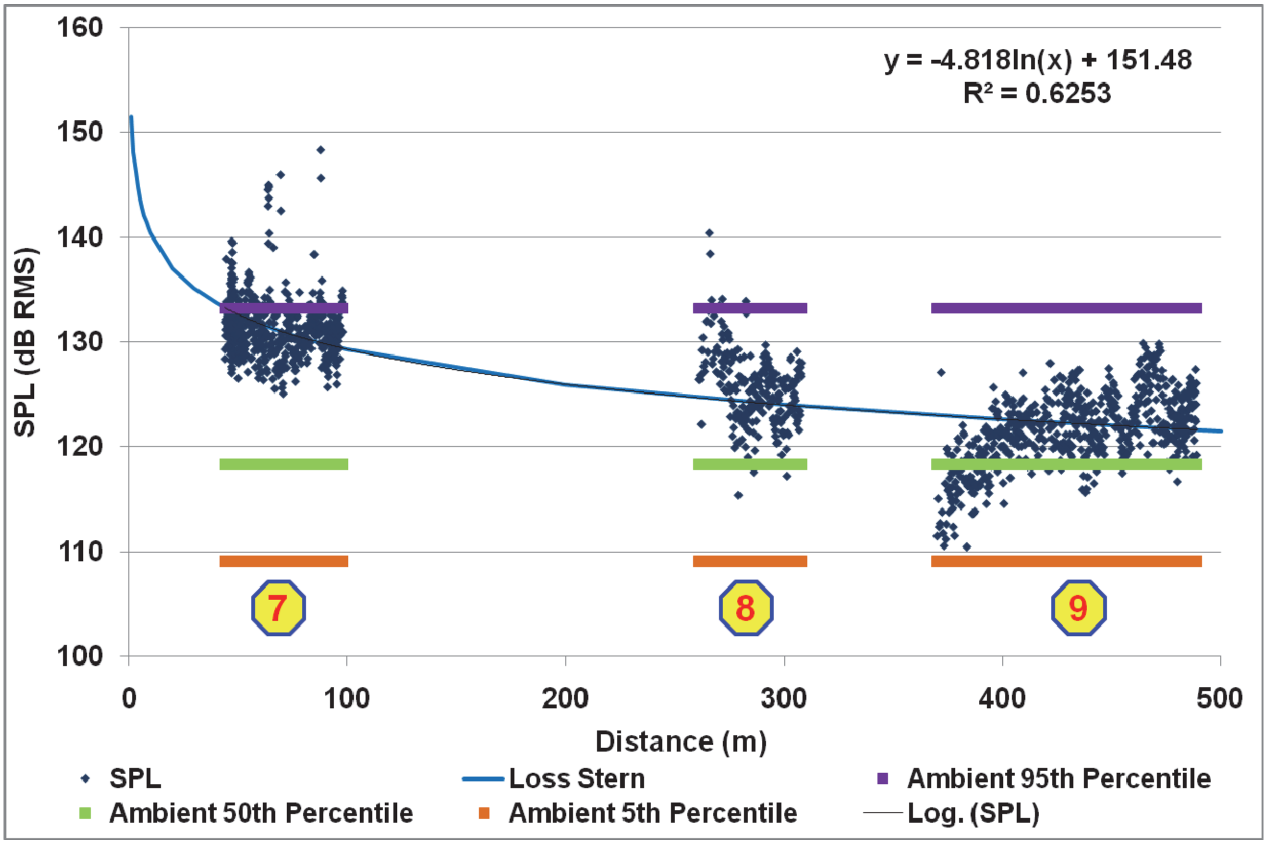

Figure 10. SPL (dB rms) versus distance (m) for sound recordings astern of the dredge.

Excluding these SPLs, the remainder recorded from 400-480 m averaged 122±2 dB, or 1.7 to 5.7 dB (mean = 3.7 dB) above background. By 480 m from the source, a small number of SPLs were again below the 50th percentile level. All SPLs astern of the dredge remained above the 5th percentile ambient value (109.1 dB rms). Source level (SL) was determined by calculating the theoretical propagation loss as a fitted curvilinear regression of SPL versus distance and determined to be 151.48 dB re 1µPa at 1 m. Transmission loss was calculated at 11LogR, similar to cylindrical spreading (10LogR).

Combined data. All SPL data were combined to determine an overall source level. Using the same methodology as that used for both the upstream and downstream data, the source level for the combined data set was determined by calculating the theoretical propagation loss as a fitted curvilinear regression of SPL versus distance. This source level was determined to be 152.9 dB re 1µPa at 1-m (Figure 11). Transmission loss was calculated at 13.01LogR, between cylindrical spreading (10LogR) and practical spreading (15LogR).

DISCUSSION: Ambient noise can be described as sounds that occur in the environment without distinguishable sources. Ambient noise is continuous, but with considerable variation, on time scales ranging from several seconds to over the course of an entire year. Primary sources of ambient noise in shallow-water environments are shipping and industrial activities, wind and wave activity, and biological factors (Richardson et al. 1995). To understand ambient underwater noise, repeated measurements must be taken on appropriate temporal and spatial scales under varying environmental conditions. Under ideal research conditions, a comprehensive characterization of ambient noise would require long-term deployment of acoustic data-logging sensor arrays. This approach, however, is extremely labor-intensive and costly, and is not always practical given time and budget constraints. For the purpose of the present study, the adopted approach used site- and time-specific measurements. Although the obtained ambient noise levels do not represent the acoustic sound field for the entire area over an extended period of time, site-specific measurements provide an accurate baseline for comparisons to sound emitted by dredges during this study.

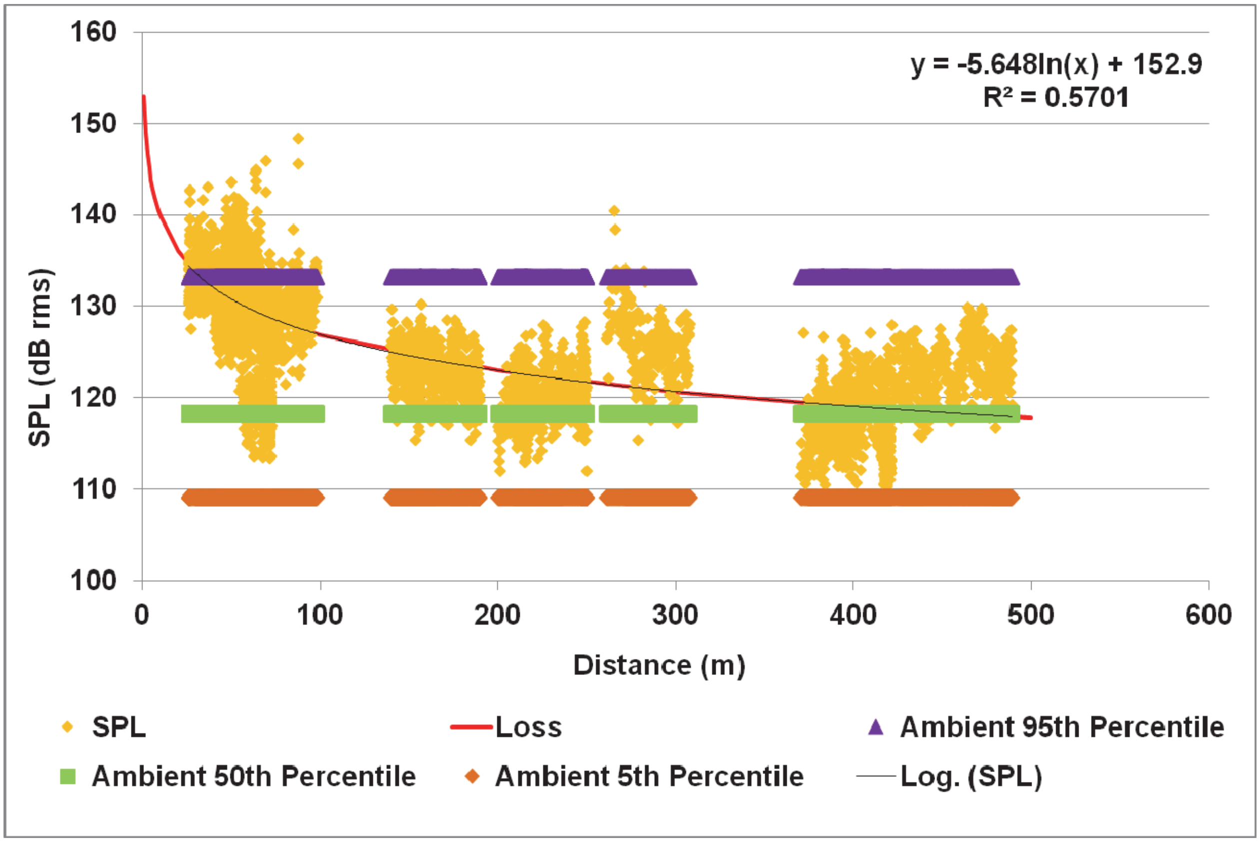

Figure 11. SPLs (dB rms) versus distance (m) for combined data.

Background SPLs were relatively high, given sea state conditions (calm waters, light winds) as predicted by the relationship between sea state and the Beaufort wind scale. Wenz (1962) compiled data from multiple sources and estimated a received level (RL) between 60 and 70 dB re $1\mu Pa^2/Hz$ at Sea State 4, which closely corresponds to Beaufort wind force 4, meteorological conditions not observed during the present study. As a result, received SPLs (P_{50}) ranging from 110.5 to 132.7 dB rms (all sites combined = 118.3 dB rms) are higher than one would expect. Even at the 5^{th} percentile level, ambient SPLs ranged from 103.8-122.6 dB rms (P_5 = 109.1 dB rms), or approximately 40 to 48 dB higher than levels predicted by Wenz (1962) at Sea State 4. Activities associated with port operations are a major contributing factor to higher ambient noise in the study area. At all sites (A-H), noise associated with port activities could be clearly heard. These activities are in addition to underwater sounds (e.g. generator noise) associated with commercial shipping utilizing the port.

Although ambient sound levels were relatively high, they fall within the range of values measured at other ports and within riverine systems. Blackwell and Greene (2002) reported ambient SPLs at six locations isolated from industrial activities in Anchorage Harbor and the Knik Arm of Cook Inlet, Alaska. The authors reported that ambient sound levels ranged from 95 dB in the Knik Arm to 124 dB near Point Possession on an incoming tide. Sound pressure levels in Anchorage Harbor averaged 113 dB. Greene (1987) reported ambient SPLs of 99 dB in the Canadian Beaufort Sea. Richardson et al. (1995) reported ambient SPLs ranging from 50-115 dB (1/3 octave) off Barrow, Alaska. While average ambient SPLs reported in this study exceeded those reported by Blackwell and Greene (2002) in Knik Arm, Cook Inlet, Alaska; Greene (1987) in the Beaufort Sea; and Richardson et al. (1995), it should be noted that the above studies were conducted in open-water environments away from major industrial activities.

Several recent studies have monitored ambient SPLs within major harbors and riverine environments. For example, ambient SPLs (P_5 to P_{95}) ranged from 110.4-129.6 dB rms (P_{50} = 118.8 dB) for seven sites in upper New York Harbor during rock fracturing by a hydraulic cutterhead and during rock and gravel removal by a backhoe dredge as part of the New York Harbor Widening and Deepening Project (Reine et al. 2012 a, 2012 b). SPLs in upper New York Harbor did not differ substantially when compared to SPLs recorded in the SDWSC. Even within small riverine environments where the issue of sea state is not likely to be a major contributing factor, background noise levels can be high. Received ambient SPLs ranged from 128.6 dB (P_5) to 138.2 dB (P_{95}) rms during monitoring of a small 1300-m^2 TSHD during sand wave removal in the Kennebec River, Maine (Reine et al., in preparation). Ambient SPL averaged 133.8 dB. These high received levels were largely attributed to high hydrodynamic flow noise in the Kennebec River.

Few prior studies have described hydraulic dredging sounds. Greene (1985, 1987) measured broadband sounds emitted by two hydraulic cutterhead pipeline dredges at ranges extending to 25 km in the Beaufort Sea. Sound recordings were made for the cutterhead dredge *Aquarius* at distances ranging from 0.2-14.8 km. At the closest range, the 20- to 1000-Hz band received level was 140 dB at two hydrophone depths (3 and 18 m). Peak spectral levels were 122 dB at 200 m at a peak frequency of 120 Hz. Source level (rms) was calculated to be 178 dB re 1 μPa at 1 m. Attenuation occurred by 7.1 km at the 90^{th} percentile of ambient and 23 km by the median ambient level (99 dB).

Clarke et al. (2002) characterized sounds produced by the Lake Michigan Contractors Dredge *James B*, a 10,000-hp, 24-in. cutterhead plant during channel maintenance dredging. Hydraulic cutterhead sounds were recorded in Mississippi Sound, Mississippi. Unlike mechanical dredging operations, sounds could not be partitioned into discrete components attributable to separate sound sources. Thus, characterizing cutterhead sounds was constrained to analyses of cumulative sources, similar to the current study. Most of the produced sound energy fell within the 70- to 1000-Hz range, and peaked in the 100- to 110-dB range (relative dB rms). Sounds attributable to the cutterhead operation became almost inaudible at relatively short distances (approximately 500 m) from the source.

Reine et al. (2012b) monitored underwater sounds produced by the hydraulic cutterhead dredge *Florida*. The *Florida* has an overall length of 524 ft (159.4 m), a width of 60 ft (18.3 m), and a draft of 14 ft (4.3 m). Suction and discharge diameters were 37 in. (940 mm) and 36 in. (914 mm), respectively. The *Florida* used a 3,000-hp Esco 54D cutter with an 11-ft (3.3-m) diameter, rotating at 26 rpm. Total installed power is 25,400 hp, of which 10,000 hp operates the main pump. Maximum SPLs were 151 dB at the upper listening depth (10 ft) at a range of 100 m and 151 dB at the lower listening depth (30 ft) at 150 m from the source. Using practical spreading (15LogR), and assuming a loss of 30 dB at 100 m and 32.64 dB at 150 m, SLs back-calculated to 181 dB (ULD) and 183 dB (LLD) re 1 µPa-1 m. Attenuation to background levels (average = 117.1 dB) was not determined. SPL still exceeded background by 10 to 15 dB at 800 m from the source.

The majority of underwater sounds produced by the hydraulic cutterhead dredging operations monitored in this study were of relatively low frequency (< 1000 Hz). In the current study, the source level (SL) was determined by fitted curvilinear regression and ranged from 151.48 dB- (upstream, bow) to 157.43 dB- (downstream, astern) re 1 µPa@ 1-m. Combining all data, the SL was 152.9 dB re 1µPa at 1 m. These source levels could be refined with a longer-term data collection effort. The current sound study allocated only two days of monitoring; these days were tacked on to the end of a study completed at Richmond Inner Harbor. Due to mechanical issues, the dredge was completely shut down on the first day of monitoring. On the second day of monitoring, the dredge entangled its anchor cable with the cutterhead assembly, shutting down dredging operations at mid-day (1330 hr). As a result, the amount of data collected was limited and monitoring efforts (number of SPLs recorded) were not equal for data collected both up- and downstream of the dredging operation, the latter of which may account for the 6-dB difference in source levels. Using 13LogR (near practical spreading), SPL generated from dredging in this study would attenuate to 117.8 dB and fall slightly below average ambient SPL (118.3 dB) by 500 m from the source.

To place underwater sounds produced by dredges into context with other anthropogenic sources (e.g. shipping), sound data were collected for several commercial ships and ferries operating in New York Harbor, New York and Newark Bay, New Jersey. Note that in the current study, underwater sound for SDWSC shipping was not measured. The size of vessels that frequent the SDWSC and the tonnage of material transported (total power required to move cargo) will influence the intensity of sound generated as well as attenuation rates (how far the sound can be heard above background). In New York Harbor, sound measurements were obtained from the ferry servicing the Staten Island St. George Ferry Terminal to the Battery in lower Manhattan. The ferry is approximately 310 ft (94 m) in length and 70 ft (21 m) in width and weighs 3,200 tons. Propulsion is provided by a 10,000-hp diesel electric engine. Vessel draft is 13.6 ft (4.1 m). SPLs were recorded from either the port or starboard side, depending on the ferry's direction of travel at distances ranging from 298 to 830 m. Received levels were lowest when the ferry was approaching the listening platform. For example, at 750 m from the source, SPLs were 136 dB when the ferry was approaching the listening platform and 139.62 dB when the vessel was moving away. A peak SPL of 144.2 dB was recorded at a distance of 298 m from the source. Assuming a loss of 37.1 dB (practical spreading, 15 LogR), the source level would back-calculate to 181.3 dB re 1µPa-1m.

During a second monitoring event, the hydrophone was lowered to 30 ft (9.1 m) in 45 m (13.6 m) of water. SPLs were recorded as the ferry departed the Battery and concluded when the ferry arrived at the St. George Terminal. SPLs increased from 125.2 dB as the ferry was departing the Battery (900 m from the source), peaking at 142 dB at 352 m off the port side of the ferry, before decreasing to 132.2 dB before arrival in St. George Terminal. The lowest SPL measured (125.2 dB at 930 m) exceeded the average background by 7.2 dB. SL reached 180.2 dB re 1 μPa-1 m.

The *NYK Constellation* is a 55,000-gross-ton cargo vessel 294 m long and 32 m wide. Its fully loaded draft is 35 ft (10.6 m). Output power is 41,129 kW. Underwater sounds were recorded as the ship entered Newark Bay, New Jersey. SPLs were recorded at distances ranging from 122 to 1,442 m. Hydrophone depth was 10 ft (3 m) in 22 ft (6.7 m) of water. The vessel approached the listening platform from the bow at a distance of 1,400 m. At this distance the SPL was 134 dB, exceeding background by 16 dB. A peak SPL (150 dB at 122 m) occurred after the vessel passed the listening platform. Assuming a loss of 31.3 dB (practical spreading), the SL back-calculated to 181.3 dB re 1 μPa-1m.

The *Maersk Idaho* is a dry cargo container vessel, 300 m long and 32 m wide. It has a gross weight of 51,000 tons and a draft of 35 ft (10.6 m). Output power is 43,070 kW. This vessel was monitored during departure from the South Elizabeth Terminal in Newark Bay. Two tugs were used to assist the Maersk Idaho from her berth. Peak SPL (147 dB at 622 m from the source) occurred during this phase of the departure in which underwater sounds were generated by both the cargo ship and the tugs assisting the vessel. Assuming a loss of 41.9 dB (practical spreading) at 622 m, the SL back-calculated to 188.9 dB re 1 μPa-1m.

The *CSAV Licanten* is a 39,941-gross-ton cargo vessel measuring 260 m in length and 32 m in width. It has a maximum draft of 12.6 m. The vessel was monitored as it passed through Anchorage Channel, New York Harbor into the Kill van Kull waterway (KVK). The hydrophone was deployed at a depth of 30 ft (9.1 m) in 45 ft (13.6 m) of water. SPLs were recorded at distances ranging from 353 to 900 m. A peak SPL of 141.8 dB was recorded 353 m from the source, exceeding background by 23.8 dB. The SL reached 180 dB re 1 μPa-1 m assuming a loss of 38.2 dB (practical spreading). At a distance of 900 m, the SPL (133.76 dB) still exceeded background by approximately 16 dB.

The *Zim Savannah* is a 55,592-gross-ton container vessel, 294 m long and 32 m wide. It has one main engine (104 rpm) capable of outputting 51,485 kW. It has four auxiliary engines capable of generating 1,780 kW. Bow-thruster output is 2000 kW. The vessel has a draft of 12.5 m. This vessel was monitored passing through the KVK into Anchorage Channel, upper New York Harbor. Hydrophone depth was 30 ft (9.1 m) in 46 ft (13.9 m) of water. SPLs were recorded at distances ranging from 230 to 1269 m. SPLs decreased across this range from 141.7 to 129.2 dB. The SL, assuming a loss of 35.43 dB (practical spreading) and a peak SPL of 141.7 dB (321 m), back-calculated to 179.3 dB.

CONCLUSIONS: Hydraulic cutterhead dredges remove sediment from the channel bottom by embedding a rotating cutterhead into the sediment. Sediment is sucked upward through a pipe by means of centrifugal pumps, and the sediment water mixture (i.e. slurry) is transferred through the pipeline to either an open-water or upland disposal site. Much of the sound produced during hydraulic cutterhead dredging is associated with pumps and generators, with additional sounds from the rotation of the cutterhead in the substrate and movement of material through the pipeline. Sounds emitted from the latter two noise events are greatly dependent on substrate type. For example, movement of sand/gravel through the pipeline would produce more intense sounds than slurry comprised of mostly water and silty maintenance material. These sounds are omnidirectional and continuous in nature. With minor exceptions, sounds could not be portioned into discrete events attributable to separate sound sources.

In the present study, source levels (SLs) ranged from 151.48 to 157.43 (Overall = 152.9 dB re 1µPa-1 m). When compared to the studies discussed above, the Dredge *Veracious* was considerably quieter. This was not unexpected, given its relatively small size class when compared to other hydraulic dredges in which data exist. The Dredge *Aquarius* is nearly three times the length of the *Veracious* with 17 times the total horsepower (17,277 hp). It is also self-propelled, powered by two 3,753-hp diesel electric motors. The source level for the *Aquarius* was 178 dB re 1µPa-1 m, or 25.1 dB louder than the Dredge *Veracious*. The Dredge *Florida* was also a much larger size class, measuring 524 ft in length with a total installed power of 25,400 hp, of which 10,000 hp operates the main pumps used for suction. Source levels for the *Florida* ranged from 181 to 183 dB re 1µuPa- 1m, or a maximum of 30.1 dB louder than the *Veracious.* The Dredge *James B* is a 24-in. cutterhead plant with 10,000 hp. Source levels were not determined by Clarke et al. (2002).

When compared to underwater sounds generated by commercial shipping, the Dredge *Veracious* was a relatively quiet operation. Source levels for commercial shipping ranged from 179.3 to 188.9 dB re 1 µPa at 1 m. Source levels generated by commercial vessels exceeded sounds produced by the small cutterhead Dredge *Veracious* by 27.1 to 36 dB re 1 µPa at 1 m.

Attenuation rates varied from 800+ m for the Dredge *Florida* during rock fracturing within New York Harbor to 23 km for the Dredge *Aquarius* in the Beaufort Sea during sand mining, with the latter dredging operation occurring in an open-water environment. Clarke et al. (2002) reported attenuation by 500 m during channel maintenance in the Mississippi Sound, Mississippi, similar to that measured in the current study. Sediment type was similar for both the SDWC and the Mississippi Sound Navigation Channel.

The NMFS is currently developing guidelines for determining sound pressure level thresholds for fishes and marine mammals. Based on a few existing studies, the NMFS current thresholds for determining impacts to marine mammals is centered around root-mean-square (rms) received levels between 180 and 190 dB re 1 µPa for potential injury to cetaceans and pinnipeds, respectively, and 160 dB re 1 µPa for behavioral disturbance/harassment from an impulsive noise source (e.g. pile driving), and 120 dB re 1 µPa for a continuous noise source (e.g. dredging). At no time during the study did received or calculated SPLs exceed the 180- or 190-dB criteria for potential injury for cetaceans and pinnipeds. Received levels did not surpass 150 dB re 1µPa and calculated source levels (all data combined) did not exceed 153 dB re 1 µPa-1 m (combined data). The 120-dB re 1 µPa proposed threshold for behavioral disturbance/harassment from a continuous noise source such as dredging was reached and frequently exceeded by ambient conditions in the absence of dredging activities. For all data combined, ambient SPL ranged from 109.1 (P_5) to 133.2 (P_{95}). The 50th percentile level for all data combined was 118.3 dB, although four of the eight individual monitoring sites exceeded the proposed 120-dB criteria in the absence of dredging. The four other sites were only 3 to 5 dB below the proposed 120-dB criteria at the 50th percentile of ambient. At the 95th percentile of ambient, only one site was below the proposed 120-dB criteria. Given that the 120-dB proposed criteria has been exceeded in several studies for both harbors and riverine environments in the absence of dredging, this criterion may need to be reconsidered.

The NMFS' interim criterion for physical injury to fish is a 206-dB peak, regardless of fish size. Few studies have documented the effects of anthropogenic sounds on the behavior of fishes. However, based on the present state of knowledge, SPLs in the current study were well below levels that would cause physical injury to any fish species. Herring and shad species of the family Clupeidae are capable of hearing in both the sonic range as well into the ultrasonic range from 0.2 to 180 kHz (Mann et al. 2001). Highest sensitivity of the American shad ranged from 200-800 Hz in the sonic range and from 25-130 kHz in the ultrasonic range. Because most sound produced by dredges is at frequencies less than 1 kHz, American shad could potentially be affected by dredging sounds in the sonic range. A behavioral response to sound in the ultrasonic range has been observed for some clupeids and has been used to prevent fish entrainment by repelling them from power plant intakes (Dunning et al. 1992). Behavioral responses to low-frequency sounds generated by dredging operations are not well documented, although the concern is frequently cited by resource agencies as having potentially negative impacts on anadromous fish migrations. Mann et al. (2001) demonstrated that Gulf menhaden (*Brevoortia patronums*) can detect sounds in the ultrasonic range. Bay anchovies (*Anchoa mitchilli*), scaled sardines (*harengula jaguana*), and Spanish sardine (*Sardinella aurita*) may be able to detect sounds to 4 kHz. A critical issue in assessing dredging-induced sound effects on fish behavior is not only whether the sound is within the hearing frequency range of a fish species, but whether the sound is loud enough to be detectable above ambient thresholds. Hearing data exist for about 100 of the 29,000 known fish species. Based on reviews by Popper and Hastings (2009), Popper et al. (2006), and Southall et al. (2007), it is unlikely that underwater sounds from conventional dredging operations can cause physical injury to fish species. Some temporary hearing loss could occur if fishes remain in the immediate vicinity of the dredge for lengthy durations, although the risk of this outcome is low (Central Dredging Association (CEDA) 2011). Pre-productive migratory blockage of anadromous fishes by underwater sound remains an often-cited, but untested, theory.

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