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Characterization of Underwater Sounds Produced by a Backhoe Dredge Excavating Rock and Gravel

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PURPOSE: This technical note characterizes underwater sound produced by a backhoe dredge during rock removal as part of the widening and deepening of New York/New Jersey Harbor. Both continuous sounds (e.g., engine and generator sounds transmitted through the hull) and repetitive, punctuated sounds (e.g., associated with bucket bottom contact and the repositioning of spuds) comprise a broad spectrum of dredging-emitted underwater sound sources. The various sound sources can be characterized in terms of intensity, periodicity, and attenuation with distance from the source. Likewise, the sounds must be placed into context with ambient levels of sound in the surrounding body of water. Such characterizations are required components of environmental assessments that address newly emerging concerns for detrimental impacts of underwater noise on many aquatic organisms. In order to adequately assess the risks associated with backhoe dredging operations, sounds were characterized with respect to sound pressure levels (SPLs) generated by this dredge type across the broad 20-Hz to 20-kHz spectrum. In addition, SPLs were measured in the 50- to 1,000-Hz range generally detectable by fishes and the 100- to 400-Hz range in which certain fish species show a greater sensitivity. Given the scarcity of existing accurate information quantifying underwater sounds generated by different dredge types and sizes, differences in geotechnical properties of material being excavated, and site specificity of working environments (i.e. bathymetry, hydrodynamic conditions, prevalence of non-dredging ambient sounds), this study fills important knowledge gaps that contribute to better-informed dredging project management practices.

BACKGROUND/INTRODUCTION: In recent years, concerns have been raised regarding underwater noise of anthropogenic origin and its potential impact on aquatic organisms. Originally focused on sounds associated with seismic exploration, military exercises, and pile-driving and similar construction activities, concerns have expanded to include dredging and dredged material disposal processes (Richardson et al. 1995). For example, it has been hypothesized that dredging-induced sounds could block or delay the migration of fishes through navigable waterways, interrupt or impair communication, or disrupt foraging behavior. Persistent concerns have dealt with disturbance of communication among marine mammals. Concerns are often heightened where projects occur in proximity to species listed as either threatened or endangered at either the Federal or state levels. Protective measures have been developed to avoid impacts by known intense sound sources. For example, the National Marine Fisheries Service (NMFS) requires an Incidental Harassment Authorization (IHA) for pile-driving activities where marine mammals are likely to occur. The authorization requires that a 500-m safety zone must be established in all areas where underwater SPLs were anticipated to exceed 190 dB re 1µPA. California Department of Transportation (Caltrans) (2001) examined fish that died as a result of exposure to underwater sounds from pile-driving operations. Mortalities were observed in several species, attributed primarily to injury to the swim bladders of fishes within 50 m of the pile-driving operation. SPLs ranged between 160 and 196 dB re 1μPA rms. Ruggerone et al. (2008) investigated the effects of pile-driving noise on caged yearling coho salmon (*Oncorhynchus kisutch*). Although SPLs reached 208 dB re 1 μPa, no mortality was reported. Nedwell et al. (2003) studied the effects of vibro-piling on brown trout (*Salmo trutta*). While the trout showed no immediate reaction to vibro-piling, both altered behavior and physical injury were seen among brown trout as far as 400 m from the source. Abbott et al. (2005) studied Chinook salmon (*Oncorhynchus tshawytscha*) and northern anchovy (*Engraulis mordax*) exposed to pile-driving sounds and observed no differences in behaviors of treatment and control animals. Pile driving can typically produce sounds which exceeded 180 dB. Gas oscillations induced by high sound pressure levels can cause the swim bladder to tear or rupture (Govoni et al. 2003, 2008). Engas et al. (1996) reported a significant reduction in catch rates of haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*) for up to five days after seismic surveys. Skalski et al. (1992) showed a 52% decrease in rockfish (*Sebastes* spp.) abundance following a single airgun emission at 186 to 191 dB re 1 μPA. The authors concluded that rockfish exhibited a startle response to an SPL of 160 dB re 1 μPA, but this sound level did not appear to affect catch rates. A comprehensive review on the effects of anthropogenic sound on fishes can be found in Popper and Hastings (2009).

The National Marine Fisheries Service's (NMFS) current thresholds for determining impacts to marine mammals are based on root-mean-square (RMS) received levels of 180 dB re 1 μPA for potential injury, 160 dB re 1μPA for behavioral disturbance/harassment from an impulsive noise source, and 120 dB re 1 μPA for behavioral disturbance/harassment from a continuous noise source. In general, these thresholds have been established to assess potential impacts to a variety of organisms. For example, underwater sounds from sand mining have been hypothesized to potentially impact sea turtles (hearing range = 100 to 1,000 Hz), right, humpback, and fin whales (hearing range 7 Hz to 22 kHz) and multiple fish species (50 to 1,000 Hz). The thresholds can vary among regions and among specific projects. For example, during the construction of the San Francisco-Oakland Bay Bridge East Span, the NMFS required an IHA due to potential disturbance to marine mammals when underwater SPLs generated from pile-driving operations were projected to exceed 190 dB re 1 μPA. The authorization required that a 500-m safety zone be established in these areas. Although dredging projects would likely be subject to similar noise threshold restrictions if marine mammals are known to inhabit the area, generic criteria for protection of fishes have not been rigidly identified.

While the above studies provide some insights into possible effects of sound on fish behavior and mortality, they provide little evidence of potential effects of sounds emitted by dredges. Few data exist that adequately characterize sounds emitted by dredges that would support objective decisions balancing the need to dredge against relative risk to a fishery resource. Studies by Greene (1985, 1987), Miles et al. (1987), Dickerson et al. (2001), and Clarke et al. (2002) are among the very few relevant references that exist. None of the identified studies involved backhoe dredges, a form of mechanical dredging. Given the general lack of knowledge on this topic, the present investigation was undertaken to characterize underwater sounds produced by a large-capacity backhoe dredge. The opportunity to characterize sounds produced by an excavator dredge removing rock as part of the New York/New Jersey Harbor Channel Deepening Project represented something of a worst-case scenario. The backhoe dredging method involves direct contact of a large bucket with the substrate, which in this case consisted of coarse gravel-sized rock. The study was conducted by the U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, in collaboration with the U.S. Army Engineer District, New York. This work was supported by the Dredging Operations and Environmental Research (DOER) Program.

Dredge types and potential sound sources: Three major categories of dredge plants (mechanical bucket, hydraulic pipeline cutterhead, and trailing suction hopper) remove sediment from waterways in very different manners. Hopper dredges are self-propelled seagoing vessels that hydraulically remove sediment from the seafloor through dragheads. The dragheads are "trailed" beneath the dredge and held in contact with the substrate as the dredge advances. Thus, hopper dredges are similar to large commercial shipping vessels. Much of the sound produced by this type of dredge is associated with propeller and engine noise in tandem with sounds emitted by pumps and generators. Relatively muted sounds are produced by the draghead, at least when the dredge is working in fine maintenance sediments. Hopper dredge sounds are therefore relatively continuous in nature (Clarke et al. 2002). In contrast, hydraulic cutterhead dredges are often perceived to be stationary, as the embedded, rotating cutterhead swings laterally across an arc in front of the dredge. Consequently the rate of forward advance, managed either by swiveling between anchor wires or spuds, is much slower than that of the hopper dredge. Hydraulic cutterhead dredge sounds are therefore largely continuous (Clarke et al. 2002). Winch and generator sounds transmitted through the hull of the dredge are an additional source of sound associated with this type of dredging operation. In contrast to hydraulic dredges, much of the sound produced by mechanical bucket dredges is repetitive rather than continuous. Bucket dredging involves lowering the open bucket through the water column, digging into the sediment after impact with the bottom, lifting the bucket up through the water column, and emptying the bucket into a barge on a regular cycle. The duration of individual events with a typical bucket deployment-and-retrieval cycle may range from seconds to a few minutes. Each phase of the bucket cycle produces a repeated set of sounds, which can be identified within the acoustic record (Dickerson et al. 2001). However, during hydraulic dredging one typically cannot separate the individual processes involved in dredging by their temporal location in the acoustic record (Clarke et al. 2002).

The processes which comprise sound sources associated with mechanical backhoe (excavator) dredging activities fall within several categories. Physical removal of sediment from the substrate as the bucket is inserted into the bed, forced through the bed in a "scooping" arc, and removed from the bed produces grinding and scraping sounds. Lifting of the material from the bed up through the water column can produce sounds emanating from hydraulic pumps and the articulated bucket support arm. Placing the dredged sediment into a barge can produce sounds that are transmitted through the hull of the barge, particularly during the early stages of the barge-filling process. Onboard machinery will produce various sounds throughout the dredging process, such as sounds associated with winches, generators, and the powerplant. Periodically, sounds may be produced when the dredge advances, either by raising and lowering spuds or by swinging along deployed anchor cables. The periodic maneuvering and replacement of barges requires the assistance of tugboats and tenders, which entails sounds associated with their powerplants. The various underwater sounds produced are influenced by a host of factors, including substrate type, geomorphology of the waterway, site-specific hydrodynamic conditions, equipment maintenance status, and the skill of the dredge operator.

METHODS

Study site: New York Harbor lies at the confluence of three major bodies of water: 1) the New York Bight to the southeast, 2) Long Island Sound to the northeast, and 3) the Hudson River extending northward. The Port of New York and New Jersey is the largest port on the east coast of the United States. Sub-surface acoustic monitoring of a backhoe dredge (also known as an excavator dredge) operation occurred in the New York Harbor Anchorage Channel in March 2011. The Anchorage Channel is located in the Upper Bay of New York Harbor, east of the entrance to the Kill Van Kull Waterway and south of the Global Marine Terminal. The study site is located on NOAA chart 12327 at approximately $74^{0}04.28$N and $40^{0}39.11$W (Figure 1).

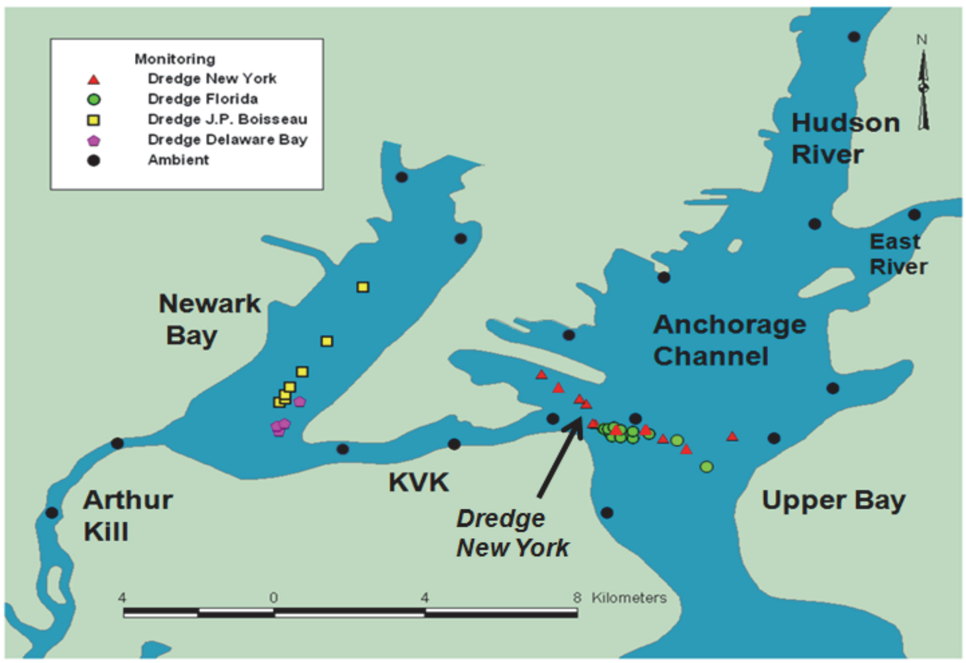

Figure 1. Plan view of the study site, with locations of sound recording stations occupied.

Dredge plant: The Dredge *New York* is a 3,434-hp backhoe dredge, owned by the Great Lakes Dredge and Dock Company (Figure 2). The *New York* was engaged in deepening the Anchorage Channel to 50 ft MLW using a 25-yd^3 (18-m^3) bucket. At this site the dredge was removing gravel and rock previously fractured by the cutterhead dredge *Florida*. Overall dimensions of the dredge were: 200 ft (61 m) long, 57 ft (17.4 m) wide, with a draft of 7 ft (2.1 m). The *New York* is capable of operating at a maximum depth of 83 ft (25.3 m).

Sound recording equipment and processing software: Sound data were collected using a Sound Technologies ST1400ENV mobile audio data recorder and a Cetacean Research C55 hydrophone. The ST1400ENV consists of a sound DAQ (Data Acquisition Board), data processor (Panasonic Toughbook Computer), Global Positioning System (GPS), auxiliary data storage hard drive (500GB), and an internal battery power supply. These components are integrated and collectively housed in a Pelican case. External components include the GPS antennae, hydrophone, and associated cables. The C55 hydrophone was calibrated by the manufacturer and the calibration information was stored in the ST1400ENV. The system's calibration is certified using a standard developed by the National Institute of Standards and Technology (NIST). The system is a self-contained unit designed specifically to record underwater sounds while simultaneously monitoring and logging sound pressure levels (SPLs in dB) and other sound level parameters. The pre-amplified C55 hydrophone is optimally suited for measuring quieter sources such as underwater ship and dredge sounds and ambient conditions. The ST1400ENV records digital WAV format audio files, which can be post-processed using the hydrophone and ST1400ENV system calibration information to produce calibrated sound spectra analysis.

Figure 2. The backhoe dredge *New York*.

Sound data were recorded with MDR_SLM software provided by Sound Technology Incorporated. The software runs on a data processor, which controls data collection settings such as gain, filtering, and file collection sizes, as well as real-time monitoring of sound pressure levels (SPLs in dB re 1 µPA rms). The MDR_SLM data collection parameters used in this study were: 1) Gain = 0dB, 2) Filtering = Off (none), 3) File sample rate = 48,000 Hz, and 4) File bit density = 24 bit.

Data acquisition: Recordings were made from the *M/V Hudson* provided by the U.S. Army Engineer District, New York. After selecting an appropriate recording location, the hydrophone cable was attached to a lift line, which was attached to a 5-lb weight and lowered into the water. A similar deployment configuration was used by Robinson et al. (2011). The hydrophone was deployed at depths of 10 ft (3 m) and 30 ft (9.1 m) in the water column. At each monitoring station, a depth reading was taken with the recording vessel's depth sounder to determine if an adequate water depth was present to collect sound recordings at both depths. Dredging activity was recorded using a Sony Model HDR-HR550V digital hand-held video recorder.

During recording sessions the survey vessel was either anchored at a known distance from the dredge or was allowed to drift freely, carried by the prevailing current. Recordings were made at 11 stations located 55 m to 2.67 km from the dredge *New York* (Figure 1). Sound data were also collected for the cutterhead dredge *Florida,* which was used to fracture the limestone rock being removed in the current study. In addition, sound recordings were taken for ocean-going, deep-draft container ships as well as a variety of smaller vessels (e.g., tugs, ferries). With the exception of the dredge *New* York, all other data were analyzed separately and will be reported at a later date. For comparison, background SPL measurements were obtained from seven ambient stations, located throughout the harbor. Ambient data were collected in the upper (3 m) and lower (9 m) portions of the water column. Distances from the monitoring vessel to the sound source were measured at regular intervals using a Bushnell Elite Model 1500 laser range finder, capable of measuring distances as far as 1,500 m. Beyond the maximum distance obtainable from the laser range finder, distances were determined using the survey vessel's onboard radar. These distances were confirmed during data post-processing by plotting positioning information of the dredge and each anchored monitoring station. When employing the "drift transect" method, distances to the sound source were taken approximately every 15 seconds by laser range finder. GPS coordinates were logged automatically through the STV1400ENV, which had an attached external GPS antenna mounted on the roof of the survey vessel. Wind speed and sea state records were kept throughout the recording sessions.

The sound analysis system was powered by a deep-cycle marine battery connected to a StatPower pure sine-wave inverter, which provided a 120V AC power source to an APC Smart-UPS 1000 uninterruptible power supply. Use of a marine battery as the only power source allowed the entire system to be operated with the survey vessel completely shut down to a "quiet" mode. This eliminated extraneous noise effects that would be introduced by the engine or generator operating on the vessel used as the listening platform.

Data analysis: Sound WAV files were inventoried in a spreadsheet and matched with an associated video file. Video files and underwater audio sound (WAV) file start time offsets were calculated using the file start times included in the file names. Sony Vegas Movie Studio HD Platinum software and the time offsets calculated in the above step were used to replace the audio track of the video files and synchronize them with the associated underwater sound recording WAV file. The synchronized underwater audio and surface video was reviewed in detail to identify underwater sounds occurring during typical, identifiable dredging processes. Types of sounds detected included engine/generator sounds, bottom grab sounds associated with the sediment removal process, hydraulic ram retractions, deposition of material in the dredge scow, and spud lifting or dropping sounds during forward advancement and anchoring maneuvers of the dredge plant. All detected sounds were logged by time stamp and clipped from the original calibrated WAV file recorded by the ST1400ENV. Software used to clip the segments of interest included a combination of Sony Sound Forge Audio Studio and Syntrillium Cool Edit 2000. The newly created subsections of the original WAV files were saved using the same input parameters, thereby preserving the original file calibration integrity. The files produced in the previous step were sorted and organized into a directory file structure and cataloged in a spreadsheet. The spreadsheet also included information on the range to the dredge for each detected sound/file, the hydrophone depth, and the sound/file duration in minutes and seconds. The individual sound files were analyzed using Sound Technologies SpectraLab 4.32 sound spectrum analysis software.

SpectraLab uses Fast Fourier Transform (FFT) to convert the time-domain (amplitude versus time) WAV files into the frequency domain (amplitude versus frequency). Files were processed to generate an average sound spectrum and SPL across the entire file from the time series values, and using 1/3-octave analysis averaged across the entire sound clip. Each of these spectral analyses was saved in a separate text file for creating graphic displays of the results. Also noted during analysis of each sound clip file were the peak frequency (in Hz) and peak amplitude (dB re 1µPA rms) for both the collection of peaks and the 1/3-octave analysis. The 1/3-octave analysis computes SPL frequency "bands" of equal length. The lower frequency bands are narrower than the higher frequency bands. The frequency bands follow a logarithmic progression. The 1/3-octave analysis sums the dB values for each frequency in the individual frequency bands and produces a dB value of the collective frequencies in each band. Each band is defined by a center frequency. The 1/3-octave analysis-infinite average-peak frequency is the center frequency of the 1/3-octave band with the highest calculated dB band. A 1/3-octave analysis mimics the calculation of a hand-held sound level meter. In the majority of cases, particularly involving sounds of a non-impulse nature such as engine/generator sounds, bottom grab sounds, and spud moving sounds, single peak values are not very meaningful because they simply measure the peak amplitude of the strongest single frequency observed throughout the given sound clip. The total power is then calculated from all of the collective peaks and would exaggerate any real sound levels at any single instant during the clip. The 1/3-octave analysis across the sound clip is a more meaningful value for comparing one clip of a particular sound type to another. Conversely, if the sounds were of a more instantaneous impulse type (e.g., pile driver strike), an analysis of peak amplitudes and frequencies might be more appropriate. Results from the 1/3-octave analysis were also portioned into two subcategories. First, 50-1000 Hz, the general frequency range audible to most fishes, and second, 100-400 Hz, the frequency range in which many fish species show greater sensitivity. Dredge sounds were compared to background data selected from files collected in the study area either prior to dredging, or when the dredge was shut down. Additional ambient files were collected throughout New York Harbor and Newark Bay. For the file to be considered ambient, there had to be no vessel traffic transiting the area during recording.

Data analysis was performed with SpectrLab 4.32 using the following settings: a) Decimation ratio = 1, which resulted in an upper frequency analysis limit of 24,000 Hz due to Nyquist's sampling theorem and the original file recording parameter of 48,000 Hz; b) FFT Size (samples) = 32,768, which resulted in a spectral line resolution of 1.465 Hz; c) FFT overlap = 50%, which allowed a time resolution of 341.33 msec; d) Smoothing window = Hanning; e) Peak analysis = Peak hole checked (on) and average of 1; f) 1/3-octave analysis = peak hold unchecked (off) and average all samples in the file (Infinite); and g) Frequency weighting = None (Flat).

RESULTS

Ambient sound: Ambient sound includes a variety of background sources. In New York Harbor, these included, but were not limited to, wind- and wave-driven turbulence, hydrodynamic noise associated with tidal flow conditions, and precipitation. Although not considered as natural background noise, "traffic noise" generated from commercial shipping and recreational or commercial fishing vessels contributes to ambient sound primarily at frequencies < 1kHz (Richardson et al. 1995). Ambient sound may vary with changes in season, location, and time of day. Ambient noise measurements were taken at locations away from the influence of dredging activities.

For this technical note, 146 ambient file segments (each 1 minute in length) were selected and analyzed. Figure 3 is a spectrum plot of representative ambient sound measurements recorded at each site. Table 1 is a data summary of 1/3-octave SPLs. Ambient sound ranged from 97 to 131 dB re 1µ Pa rms (mean = 117.1 dB re 1µ Pa). Upper and lower 95% confidence intervals ranged from 116 to 118.3 dB re 1µ Pa. Ambient SPLs were calculated for the frequency ranges of 50-1000 Hz (mean SPL = 113.6 dB re 1µ Pa), which is the typical hearing range of most fishes and 100 to 400 Hz (mean = 107.2 dB re 1µ Pa), the range in which fish species have the greatest sensitivity.

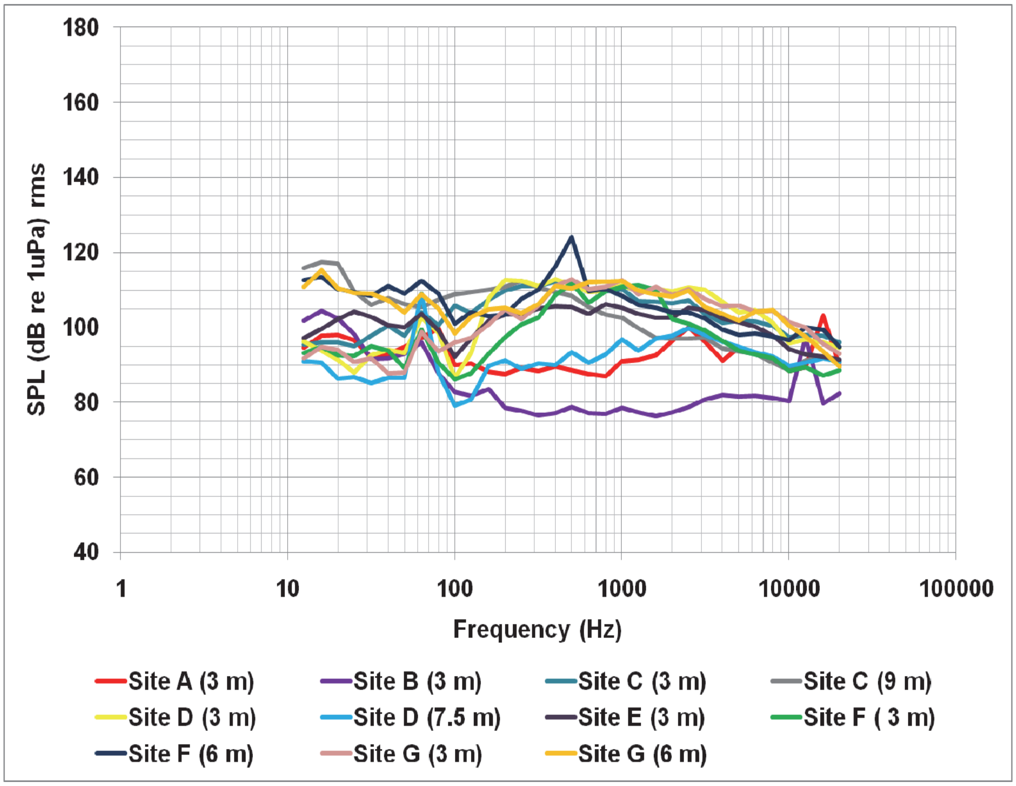

Figure 3. Representative examples of SPL results (dB re 1 µPa) from 1/3-octave analysis for monitoring sites throughout New York Harbor.

Table 1. Summary of 1/3-octave ambient SPLs (dB re 1µPa).

Parameter	All Frequencies	50-1000 Hz	100-400 Hz
Minimum	97.5	95.1	81.8
Maximum	131.2	125.9	123.3
Average	117.1	113.6	107.2
SE	0.574	0.631	0.83
Upper 95% CI	118.3	114.8	108.8
Lower 95% CI	116.0	112.3	105.6

By site, lowest background sound levels (SPLs in dB, 1/3 octave) occurred in the upper water column (3 m) at Site B, located near Liberty State Park, Pier 7, and averaging 107.4 dB re 1µPa. Site A (mean = 110.4 dB re 1 µPa), located north of Constable Hook near the Global Marine Terminal, had the next lowest background sound levels. Other sites where SPLs averaged less than 120 dB re 1 µPa included Gowanus Bay (Site D, mean = 111.9 dB re 1 µPa), at a water depth of 7.5 m, and in the upper water column (3 m) at Sites E, located east of the Bay Ridge Flats, averaging 117 dB re 1 µPa and Site F (119.8 dB re 1 µPa), located in the Arthur Kills. Highest SPLs occurred in the lower water column (6 m) at Site F, located in the Arthur Kills, averaging 126.5 dB re 1µPa, followed by Site C (hydrophone depth = 9 m), located at the entrance to the East River, averaging 125.3 dB re 1 µPa. Ambient data collection sites are plotted in Figure 1. SPLs are summarized by site in Table 2.

Table 2. Results of 1/3-octave ambient SPLs (dB re 1µPa) by site.

Location	Water Depth (m)	Minimum SPL	Maximum SPL	Average SPL
Site A	3	108.6	112.5	110.4
Site B	3	97.5	116.8	107.4
Site C	3	121.7	122.2	121.9
Site C	9	122.2	130.9	125.3
Site D	3	116.7	123.3	120.2
Site D	7.5	116.7	123.3	120.2
Site E	3	115.3	119.3	117.2
Site F	3	118.2	123.6	119.8
Site F	6	124.1	131.2	126.5
Site G	3	120.3	124.7	121.3
Site G	6	120.9	123.3	121.9

Engine/generator sounds

One-third octave analysis 20 Hz-20 kHz (average SPLs dB re 1µPA rms). The most frequently detected sound was engine/generator noise. The onboard engine/generators produce a relatively strong and continuous sound, which was transferred through the ship's hull to the water. An example sound pressure waveform for a 150-second time interval clearly indicates the continuous nature of sounds measured for engine/generator noise (Figure 4). Received SPLs for the 1/3-octave analysis for engine/generator noise are summarized in Table 3. For comparison purposes, average and maximum background SPLs were 117.1 dB and 131.2 dB, respectively. A total of 27 file segments were analyzed at distances ranging from 55 m to 680 m from the source. At 55 m from the source, SPLs differed by just over 3 dB between the upper (128.3 dB at 3m) and lower (125 dB at 9.1m) hydrophone depths. Nine segments were analyzed at 60 m from the source, of which six were taken at 3 m, and three at 9.1 m hydrophone depth. SPLs ranged from 130.4 to 132.3 dB re 1µPA rms, exceeding ambient by 13.3 to 15.2 dB (mean = 14.2 dB) at the upper listening depth (3 m). At the lower hydrophone depth (9.1 m), the received SPL value was 133.5 dB, or 16.4 db re 1µPA above ambient. The received SPL value at the lower hydrophone depth showed little variation between readings. At 75 m from the sound source, engine/generator noise was detected on three file segments, two at the upper listening depth and one at the lower listening depth. SPL values for one file at each of the upper (SPL 133 at 3 m) and lower (SPL 133.5 at 9.1 m) listening depths differed by only 0.5 dB re 1µPA, exceeding ambient by approximately 16 dB. SPL from a second file segment recorded at the upper hydrophone depth differed by 3 dB (SPL = 130 dB re 1 µPA).

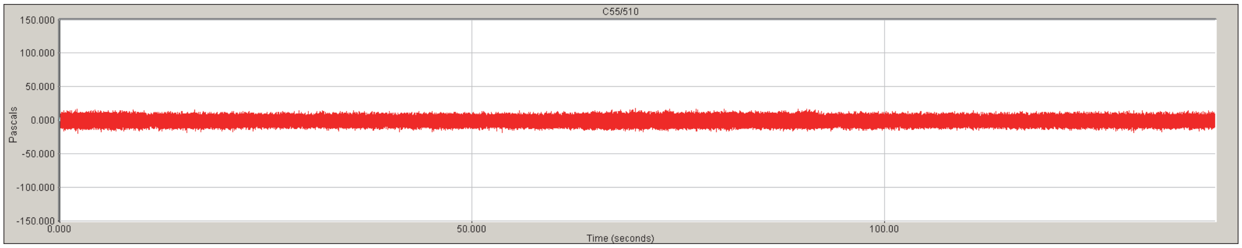

Figure 4. Pressure waveform for engine/generator sounds.

Table 3. Sound pressure levels (SPL in dB re 1µPA rms) associated with engine/generator noise (HD = Hydrophone Depth).

Distance (m)	HD (m)	File Length (min/sec)	1/3-octave Analysis SPL re 1µPa rms					
			All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
55	3	1:20	128.3	11.2	119.7	6.1	115.9	8.7
55	9.1	2:20	125.0	7.9	121.3	7.7	119.4	12.2
60	3	0:30	130.9	13.8	129.2	15.6	126.9	19.7
60	3	0:10	131.8	14.7	129.9	16.3	127.1	19.9
60	3	0:30	132.3	15.2	130.1	16.5	127.5	20.3
60	3	0:30	131.1	14.0	129.4	15.8	127.4	20.2
60	3	0:24	130.4	13.3	129.0	15.4	127.0	19.8
60	3	0:25	131.2	14.1	128.5	14.9	125.9	18.7
60	9.1	0:20	133.6	16.5	128.6	15	126.3	19.1
60	9.1	0:22	133.4	16.3	128.6	15	125.7	18.5
60	9.1	0:24	133.6	16.5	129.4	15.8	126.3	19.1
75	3	1:00	133.0	15.9	131.8	18.2	128.8	21.6
75	3	0:50	130.0	12.9	129.1	15.5	125.7	18.5
75	9.1	1:00	133.5	16.4	131.2	17.6	126.6	19.4
135	3	2:20	131.7	14.6	131.1	17.5	128.0	20.8
135	9.1	6:00	134.0	16.9	132.5	18.9	129.5	22.3
330	3	1:00	130.7	13.6	128.9	15.3	125.2	18
330	9.1	1:00	122.4	5.3	121.5	7.9	119.3	12.1
330	9.1	1:00	121.5	4.4	120.7	7.1	118.4	11.2
330	9.1	1:00	121.6	4.5	120.9	7.3	118.8	11.6
330	9.1	1:00	121.7	4.6	121.0	7.4	119.0	11.8
330	9.1	1:00	124.5	7.4	123.4	9.8	121.2	14
330	9.1	1:00	123.3	6.2	122.2	8.6	119.7	12.5
330	9.1	1:00	123.8	6.7	122.3	8.7	119.4	12.2
330	9.1	1:00	123.7	6.6	121.6	8	119.7	12.5
680	3	1:00	130.7	13.6	123.8	10.2	116.9	9.7
680	9.1	0:55	131.6	14.5	126.6	13	124.6	17.4

SPL peaked at 134 dB, exceeding ambient by nearly 17 dB at the lower listening depth at a distance of 135 m from the source. Assuming a 31.96-dB loss due to practical spreading (15 Log R), the most intense engine/generator noise would back-calculate to 167 dB re 1 µPA@1m rms, or 49.9 dB above mean ambient and 40.6 dB above maximum ambient. Figure 5 is an example sound spectrum for engine/generator sounds measured at 135 m (hydrophone depth = 3 m) from the source. The greatest distance that engine/generator sounds could be positively identified as coming from the dredge *New York* was 330 m. Nine segments were analyzed: one at a depth of 3 m and eight at 9.1 m. SPL was 130.7 dB re 1µPA at the upper listening depth (3 m). At the lower hydrophone depth, SPL (1/3 octave) ranged from 121.5 to 125.5 dB re 1µPA rms, exceeding ambient by 4 to 7 dB. Highest received SPL fell by as much as 12.5 dB as distance from the source increased from 135 m to 330 m. Engine noise was detected on two file segments at 680 m from the source. However, at monitoring stations between 350 m and 600 m from the source, sounds associated with this noise type were not detected. It is unclear if the engine/generator noise detected at 680 m was being emitted from the Dredge *New York* or from some other source in the area. Lowest to highest SPL increased by as much as 10 dB from 330 m to 680 m.

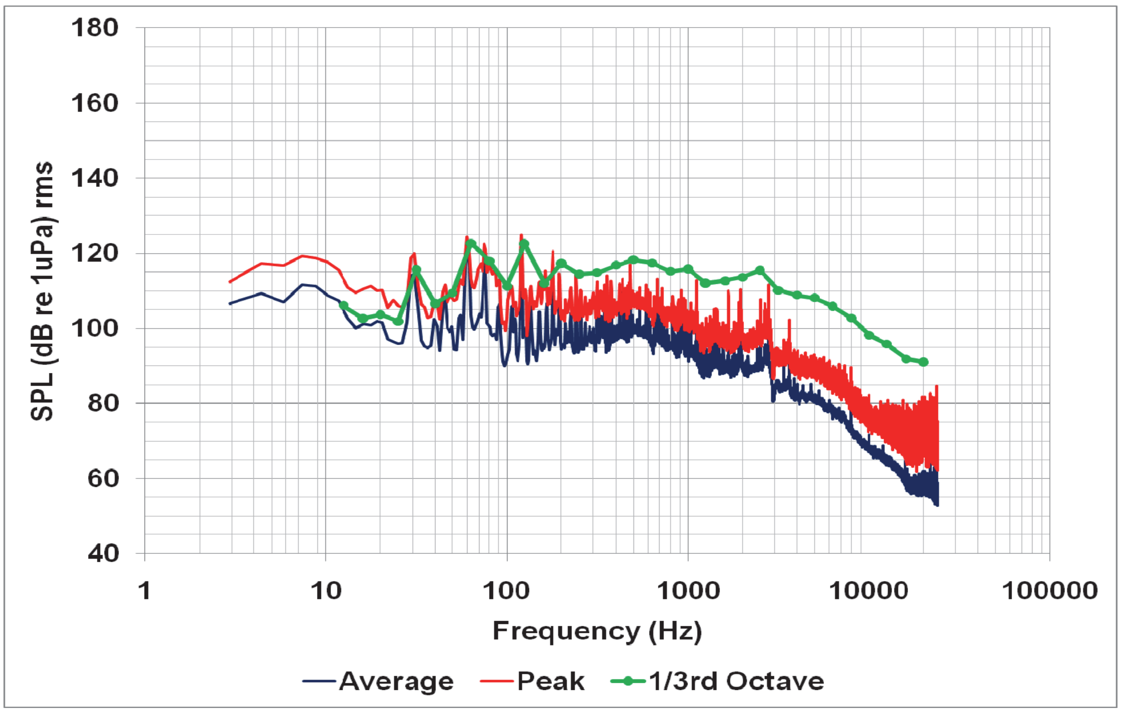

Figure 5. Sound pressure level (SPL) produced by engine/generator noise 75 m from the source (Hydrophone depth = 3 m).

One-third octave analysis 50-1000 Hz and 100-400 Hz (average SPL dB re 1µPA rms). SPLs were also determined for two narrower frequency ranges (50-1000 Hz and 100-400 Hz) that are relevant to fish hearing capabilities. Received SPLs associated with engine/generator sounds ranged from 119.7 at 55 m from the sound source to a peak of 132.5 at the 135-m listening station in the 50- to 1-kHz frequency range. These SPLs were 0.7 to 8.6 dB lower than corresponding SPLs obtained from the broader frequency spectrum (20 Hz-20 kHz). However, when factoring in the lower ambient SPLs (mean =113.6 dB in the 50-Hzto1-kHz range), there was an overall increase of 0.2 to 2.9 dB (mean = 1.4 dB) in SPL exceeding ambient. The only exception occurred at the closest listening station (55 m), where SPLs exceeding ambient decreased by 0.2 and 5.1 dB for two sound recordings. Increases and/or decreases in SPL exceeding ambient are compared to the results obtained from the entire frequency spectrum (20 Hz-20 kHz).

In the 100- to 400-Hz frequency range, received SPLs ranged from 115.9 to 129.5 dB at distances from 55 m to 135 m from the source. Received SPLs were 2.7 to 12.4 dB (mean = 10 dB) lower when compared to SPLs from the broader frequency range (20 Hz-20 kHz). Ambient SPLs averaged only 107.2 dB in the 100- to 400-Hz frequency; therefore, even with the lower overall received SPLs there was still a 5.4-dB increase in SPLs exceeding ambient in the 100- to 400-Hz frequency range. For example, the received SPLs at 135 m from the source were 134 dB (mean ambient = 117.1, 20 Hz-20 kHz), 132.5 dB (mean ambient = 113.6, 50-1 kHz) and 129.5 dB (mean ambient = 107.2 dB, 100-400 Hz). Received SPLs above ambient were 16.9 dB (20 Hz-20 kHz), 18.9 dB (50-1 kHz), and 22.3 dB (100-400 Hz), an increase of 2 dB and 5.4 dB from the broader to the narrow frequency ranges.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). Engine/generator sounds had a peak frequency centered around 400 Hz (1/3-octave band of 355 Hz to 447 Hz) for the majority of file segments analyzed. A few analyzed files had peak frequencies ranging from 12.5 to 80 Hz. Those below 20 Hz are in the infrasonic range outside of the calibration range of the C55 hydrophone. Those around 20 to 80 Hz are probably attributable to sound propagation conditions in very shallow water, or represent low frequencies associated with tidal flow conditions. Peak amplitudes were approximately 120 dB at the closest monitoring stations, increasing to the 125- to 129-dB range at distances of 75 to 135 m before falling to approximately 115 dB at a distance of 330 m.

Bottom grabs (scoops)

One-third octave analysis across all frequencies (Average SPL dB re 1µPA rms). During monitoring, the backhoe dredge was removing limestone rock previously fractured by the cutterhead dredge *Florida*. The material being excavated consisted of relatively uniform pea gravel. Although monitoring stations extended beyond 2,600 m, this sound source was not detected beyond 175 m from the operating bucket. Bottom grab sounds were detected on 15 file segments. Results are summarized in Table 4. An example pressure waveform for bottom grab sounds is presented in Figure 6. Eight file segments were analyzed at a distance of 60 m from the source: three at the upper listening depth (3 m) and five at the lower listening depth (9.1 m). At a depth of 3 m, the lowest recorded SPL was 132.5 dB re 1µPA rms, but SPLs varied by as much as 5 dB among sound recordings (range = 132.5-137.3 dB) taken at the same depth and distance. This range exceeded average background SPL by 15.4 to 20.2 dB and the maximum background SPL by 1.3 to 6.1 dB. SPLs typical of sound produced by bottom grabs are depicted in Figure 7. At the deeper hydrophone depth (9.1 m), SPL values (range = 136.7-148.4 dB) between file segments differed by as much as 12 dB. SPLs for bucket grabs exceeded average and maximum background levels by 19.6 dB and 5.5 dB on the lower end of the range and by 31.3 dB and 17.2 dB on the high end of the range. At distances between 90 and 175 m from the source, bottom grab sounds were only detected at the lower listening depth (9.1 m). SPL peaked at 148.8 dB re 1 µPa, or 31.7 dB above ambient at 110 m from the source. Assuming a loss (15 Log R) of 30.6 dB re 1 µPa, the most intense bottom grab sound would back-calculate to 179.4 dB re 1µPA@1m, exceeding average and maximum background SPL by 62.3 dB and 48.2 dB, respectively. SPL decreased by nearly 15 dB over the next 65 m (at a total distance of 170 m from the source). Bottom grab sounds were not detected beyond 175 m from the source.

Table 4. Sound pressure levels (SPL in dB re 1μPA rms) associated with bottom grab noise (HD = hydrophone depth).

Distance (m)	HD (m)	File Length (min/sec)	1/3-octave Analysis SPL re 1μPa rms					
			All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
60	3	0:5.168	132.5	15.4	131.6	18.0	129.1	21.9
60	3	0:4.333	133.3	16.2	131.7	18.1	129.5	22.3
60	3	0:14.69	137.3	20.2	132.0	18.4	129.6	22.4
60	9.1	0:3.668	139.3	22.2	137.4	23.8	135.2	28.0
60	9.1	0:12.58	136.7	19.6	134.7	21.1	133.0	25.8
60	9.1	0:15.17	137.4	20.3	135.4	21.8	133.6	26.4
60	9.1	0:11.94	142.4	25.3	141.7	28.1	140.6	33.4
60	9.1	0:11.00	148.4	31.3	148.1	34.5	147.1	39.9
75	3	0:9.356	136.6	19.5	135.1	21.5	133.0	25.8
75	3	0:1.912	134.7	17.6	134.0	20.4	131.5	24.3
90	9.1	0:10.71	134.2	17.1	131.2	17.6	128.6	21.4
90	9.1	0:10.18	134.5	17.4	133.6	20.0	131.5	24.3
110	9.1	0:2.715	148.8	31.7	145.8	32.2	140.8	33.6
170	9.1	0:10.11	133.5	16.4	127.6	14.0	124.9	17.7
175	9.1	0:7.896	134.0	16.9	129.4	15.8	125.9	18.7

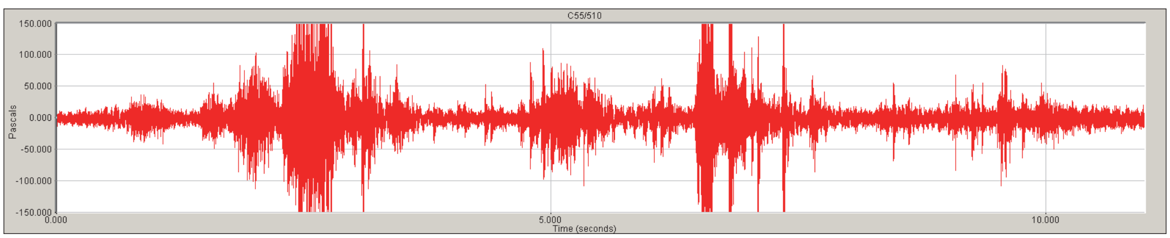

Figure 6. Pressure waveform for bottom grab (scoops) sounds.

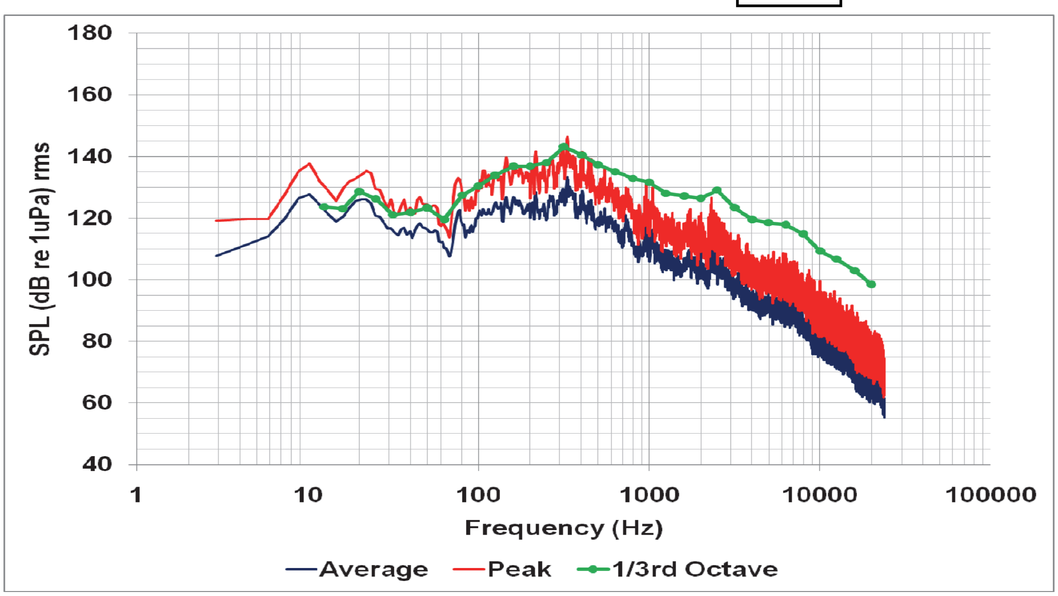

Figure 7. Sound pressure level produced from bottom grab noise at 60 m from the source (Hydrophone depth = 9.1 m).

One-third octave analysis 50-1000 Hz and 100-400 Hz (Average SPL dB re 1µPA rms). A general trend of decreasing received SPLs was observed for both narrower frequency ranges. For example, received SPLs at 60 m from the source fell from 132.5 dB (20 Hz-20 kHz), to 131.6 dB (50-1 kHz), to 129.1 dB for the 100- to 400-Hz frequency. Received SPLs differed by as much as 3.4 dB from the broader to the narrower frequency range at 60 m from the source. Differences in SPLs increased with distance from the source. At 170 m from the source at the deeper listening depth (9 m), SPLs decreased by nearly 6 dB from the broader frequency range (20 Hz- 20 kHz) to narrower frequency range (50 Hz- 1 kHz). SPLs decreased by an additional 3 dB from the 50 Hz-kHz frequency range to the 100-400 Hz range, i.e., a total of 9 dB quieter from the broadest to narrowest frequency ranges. However, when factoring in the lower ambient SPL for the two narrower frequency ranges, received SPL exceeding ambient tended to range from 0.5 to 3.2 dB higher when comparing the 50-Hz to 1-kHz range to all frequencies. The only exception was at the 170-m station, where SPL exceeding ambient decreased by as much as 2.4 dB. For the 100- to 400-Hz range, SPL exceeding ambient increased by an additional 1.3 to 8.6 dB. Increases tended to be smaller with increasing distance from the sound source.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). For most file segments, peak noise was centered around 315 Hz (1/3-octave band of 282 Hz to 355 Hz). Five files had peak frequencies in the infrasonic range from 12.5 to 40 Hz. At the 60-m listening station, peak amplitude was measured at 143.2 dB re 1 µPA at a peak frequency of 315 Hz. Peak amplitudes ranged from 123.7 to 143.2 dB re 1 µPA. Highest frequency (400 Hz) occurred at the 60-m monitoring station with a peak amplitude of 123.7 dB, the least intense SPL measured for bottom grab sounds.

Hydraulic ram sounds

One-third octave analysis across all frequencies (Average SPL dB re 1µPA rms). The hydraulic ram is used to extend and retract the excavator arm of the dredge. This sound source was detected in 13 file segments out to a distance of 170 m from the source (Table 5). Hydraulic ram noise was easily detected at the listening station located 60 m from the source, but attenuated rapidly with increasing distance. Figure 8 is an example sound pressure waveform for a 6-second time interval for hydraulic ram sounds at 170 m from the source. Nine file segments were analyzed: five with the hydrophone suspended 3 m below the water's surface and four at 9.1 m. Received levels of hydraulic ram sounds ranged from 131.3 to 133.5 dB re 1 µPa (mean = 132.5 dB) at the upper hydrophone and 134.2 to 137.5 dB re 1 µPA (mean = 136 dB) at the deeper hydrophone depths. SPLs between upper and lower listening depths varied by as much as 6 dB. At the upper listening station, received levels exceeded average background by 14.2 to 16.4 dB, but exceeded maximum background SPL by less than 2.3 dB. At a distance of 75 m from the source, hydraulic ram noise (SPL = 133.2 dB re 1 µPa rms) was only detected at the upper listening depth (3 m). At 90 m, these sounds were detected in only two file segments, one each at the upper (SPL = 133.2 dB re 1 µPA) and lower (SPL = 129.8 dB re 1 µPa rms) hydrophone depths. The maximum distance at which hydraulic ram sounds (SPL = 135.6 dB re 1 µPa rms @ 9.1 m hydrophone depth) were detected was 170 m from the dredging operation. At 330 m from the source and beyond, hydraulic ram noise was not detected, indicating substantial attenuation between 170 and 330 m. The most intense hydraulic ram sound was measured at 137.5 dB. If adjusted by 26.7 dB to account for loss due to practical spreading (15LogR), this SPL would back calculate to 164.2 dB re 1µPA rms@1m, exceeding average background SPL by 47.1 dB and maximum SPL by 33 dB.

Table 5. Sound pressure levels (SPL in dB re 1µPA rms) associated with hydraulic ram noise (HD = Hydrophone Depth).

			1/3-octave Analysis SPL re 1µPa rms					
Distance (m)	HD (m)	File Length (min/sec)	All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
60	3	0:2.456	132.4	15.3	130.9	17.3	128.4	21.2
60	3	0:1.921	132.8	15.7	131.7	18.1	128.6	21.4
60	3	0:3.478	133.5	16.4	131.4	17.8	128.6	21.4
60	3	0:6.491	131.3	14.2	130.1	16.5	127.5	20.3
60	3	0:2.606	132.6	15.5	130.9	17.3	128.1	20.9
60	9.1	0:3.434	135.2	18.1	131.8	18.2	128.7	21.5
60	9.1	0:8.747	137.5	20.4	131.4	17.8	127.4	20.2
60	9.1	0:10.81	134.2	17.1	130.2	16.6	127.1	19.9
60	9.1	0:6.918	136.3	19.2	134.1	20.5	127.2	20.0
75	3	0:20.59	133.2	16.1	131.5	17.9	127.9	20.7
90	3	0:4.795	133.2	16.1	129.1	15.5	122.9	15.7
90	9.1	0:7.826	129.8	12.7	128.0	14.4	123.4	16.2
170	9.1	0:6.315	135.6	18.5	125.4	11.8	121.5	14.3

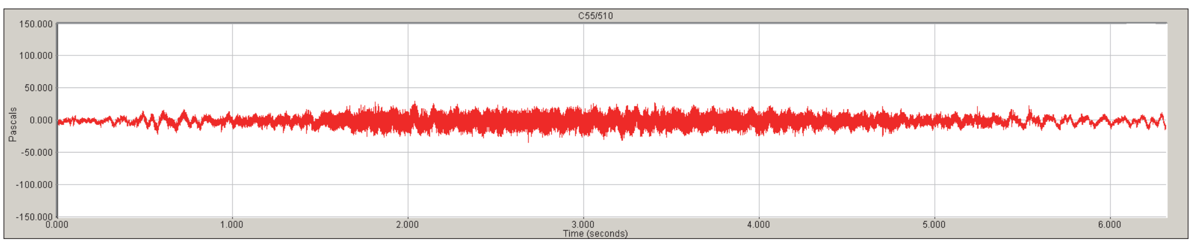

Figure 8. Pressure waveform for hydraulic ram noise.

One-third octave analysis 50-1000 Hz and 100-400 Hz (average SPL dB re 1µPA rms). As was the case with barge loading and engine/generator sounds, the trend of decreasing SPL in the narrower frequency bands and increases in SPL relative to ambient was consistent for hydraulic ram sounds. Differences in received SPL tended to average less than 2 dB (maximum 4.1 dB) at a depth of 3 m, compared to nearly 5 dB (maximum 10.2 dB) at 9 m. For example, received SPL at the deeper listening depth fell from 135.6 dB (20 Hz-20 kHz) to 125.4 dB (50 Hz-1kHz), to 121.5 dB (100-400 Hz) from the broader to narrower frequency ranges, 170 m from the sound source.

In both narrower frequency ranges, received SPL increases relative to background were consistent across five recording events at a depth of 3 m, i.e. around 2 dB for the 50-Hz to 1-kHz range and almost 6 dB for the 100- to 400-Hz range. At a depth of 9 m and at distant listening stations, SPL relative to ambient showed greater variability in that some measurements exceeded ambient by as much as 4.6 dB, while others were lower than ambient by a roughly equivalent amount.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). Hydraulic ram sounds produced peak frequencies in the 1/3 octave centered around 630 Hz (range = 562 Hz to 708 Hz) for the majority of the file segments analyzed. Peak amplitude in the 1/3-octave analysis ranged from 121 to 131 dB re 1µPA rms for all segments analyzed. Figure 9 is a representative sound spectrum showing peak amplitude and frequency and 1/3-octave analysis results. For this example, the peak amplitude SPL in the 1/3 octave was 125.3 dB re 1µPA rms with a harmonic frequency peak of 2,500 Hz. Figure 9 also shows noise in the infrasonic around 10 Hz, but this is not associated with the dredging operation.

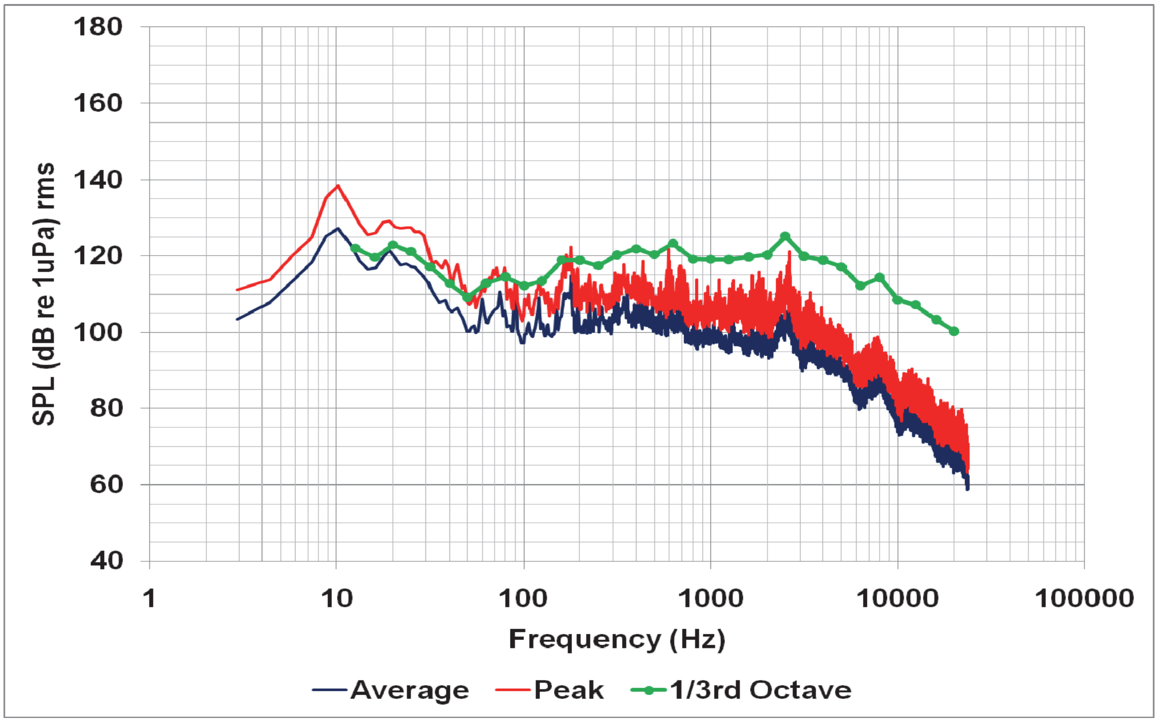

Figure 9. Sound pressure level produced from hydraulic ram sounds at 60 m from the source (Hydrophone depth = 9.1 m).

"Pop" noise

One-third octave analysis (average SPL dB re 1µPA rms). Unidentified "pops" were detected in one file collected at 60 m with the hydrophone suspended at 3 m from the water's surface. Six dredge cycles were recorded in this file with this "popping" noise reoccurring at the same point in each cycle, at or near the point when the fully loaded excavator bucket was breaking the water's surface. The unidentified "pops" were clearly related to the dredging operation, but the source of the sound was undetermined. Figure 10 is an example sound pressure waveform for "popping" sounds detected 60 m from the dredge (hydrophone depth 3 m). SPLs ranged from 135.3 to 140.1 dB re 1 µPA rms (Table 6). SPL exceeded ambient SPL (1/3 octave) by 18.2 to 23 dB. "Pops" were not detected beyond 60 m from the source, either due to rapid attenuation or possibly due to corrective action for equipment maintenance aboard the dredge. Because this sound did not appear to be a consistent component of the dredging process, it is discussed only briefly herein. Source levels were back-calculated (15 Log R) to 167.1 dB re 1 µPA rms @1m, or 50 dB above average background SPLs and 35.9 dB above maximum background SPLs.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). The highest peak amplitude for "pop" sounds was 133.8 dB with a center frequency of 250 Hz (octave range = 224 Hz to 282 Hz). The lowest SPL for "pop" noise was 127.7 dB at a peak frequency of 315 Hz (octave range = 282 Hz to 355 Hz). Figure 11 is a representative sound spectrum for this sound event.

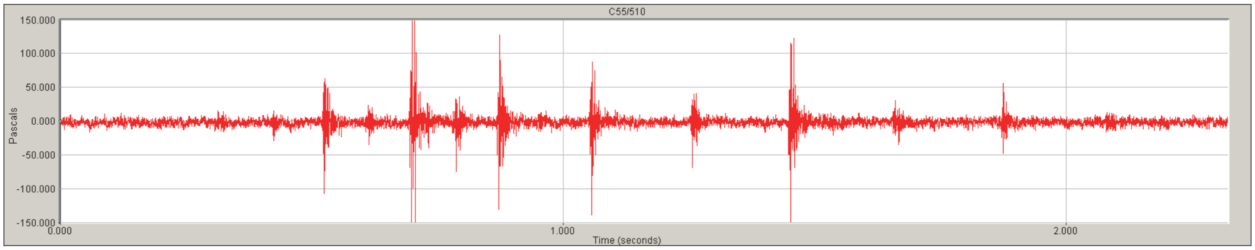

Figure 10. Pressure waveform for "popping" noises.

Table 6. Sound pressure levels (SPL in dB re 1μPA rms) associated with "popping" noise (HD = hydrophone depth).

Distance (m)	HD (m)	File Length (min/sec)	1/3-octave Analysis SPL re 1μPa rms					
			All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
60	3	0:2.320	140.4	23.3	139.6	26.0	137.8	30.6
60	3	0:4.279	138.5	21.4	137.4	23.8	135.3	28.1
60	3	0:2.057	139.7	22.6	138.8	25.2	137.3	30.1
60	3	0:2.109	135.3	18.2	134.5	20.9	132.6	25.4
60	3	0:3.688	136.9	19.8	133.3	19.7	130.6	23.4
60	3	0:4.060	140.1	23.0	136.5	22.9	134.2	27.0

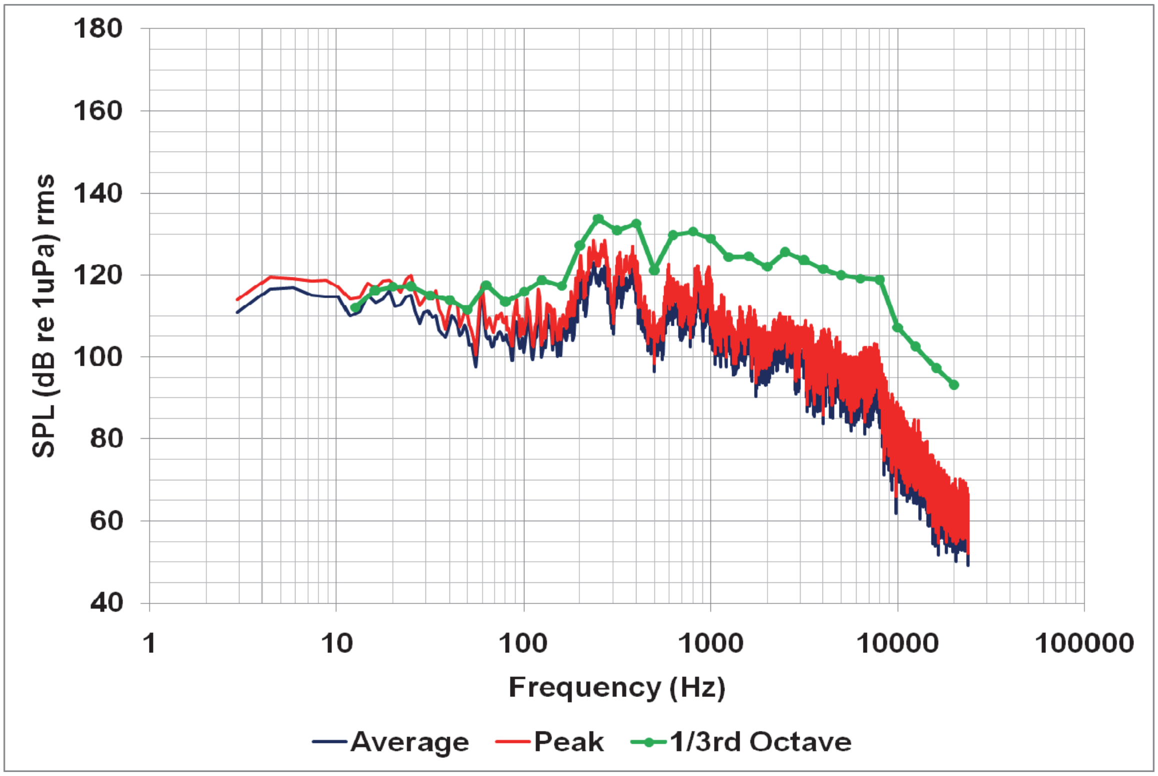

Figure 11. Sound pressure level produced from "pop" noise at 60 m from the source (hydrophone depth = 3 m).

Barge loading sounds

One-third octave analysis (Average SPL dB re 1µPA rms). Characteristics of sounds associated with this activity are dependent on the volume of material in the barge at the time the measurements were taken. Material placed into an empty or partially full barge would have the highest probability of transmitting sound through the barge hull into the surrounding waters, whereas material placed upon previously piled material may or may not produce a detectable sound due to buffering provided by the "softer" receiving surface. In the current study, deposition of material into the scow was detectable in nine file segments at listening stations less than 100 m from the source. Results are summarized in Table 7. Figure 12 is an example sound pressure waveform for a 7-second time interval during which dredged sediment is being placed into the scow. Representative examples of 1/3-octave, peak, and average SPLs are compared to ambient conditions in Figure 13. Highest SPLs occurred at the 3-m listening depth at 139.5 db re 1 µPA rms, or nearly 22.4 dB above ambient at a distance of 60 m from the source. Received levels exceeding ambient fell by as much as 10 dB from 60 m to 75 m (SPL 130.1 dB re 1 µPA) from the source. Barge loading sounds were not detected at the 170-m listening station and beyond. Accounting for attenuation loss (15 Log R) due to practical spreading, the most intense barge loading noise (139.5 dB re 1µPA rms) would back-calculate to 166.2 dB re 1 µPA@1m, exceeding average background by 49.1 dB and maximum background by 35 dB.

One-third octave analysis 50-1000 Hz and 100-400 Hz (Average SPL dB re 1µPA rms). Similar to the other sound sources, SPL fell by an average of 3 dB (mean =132.5 dB, 50 Hz-1 kHz) and slightly more than 6 dB (mean = 129.3 dB, 100-400 Hz) when compared to the broader frequency range of 20 Hz-20 kHz (135.5 dB). SPLs were consistently higher (range 1-6.7 dB) regardless of hydrophone depth or distance from the source when examining results from the 100- to 400-Hz frequency range across all frequencies analyzed. Results were more varied for the 50-Hz to 1-kHz frequency range in that nearly half of the measurements showed increases in SPL (0.4 to 2.4 dB) when compared to background SPLs, whereas half showed decreases from 0.7 to 2.2 dB.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). One-third octave peak intensity ranged from 123.7 to 134.7 dB re 1 µPA rms for SPL received at 60 m to 90 m from the source. Excluding file segments with peak frequencies in the infrasonic range (< 20 Hz), peak frequencies were centered around 100 Hz (octave range = 89 to 112 Hz) and 500 Hz (octave range = 447 to 562 Hz).

Table 7. Sound pressure levels (SPL in dB re 1µPA rms) associated with barge loading noise (HD = hydrophone depth).

			1/3-octave Analysis SPL re 1µPa rms					
Distance (m)	**HD (m)**	**File Length (min/sec)**	**All Freq.**	**All Freq. SPL> Ambient**	**50 Hz - 1 kHz**	**50-Hz-1kHz SPL >Ambient**	**100-400 Hz**	**100-400 Hz SPL> Ambient**
60	3	0:3.986	135.9	18.8	133.0	19.4	129.6	22.4
60	3	0:2.683	139.5	22.4	133.8	20.2	130.6	23.4
60	3	0:0.798	134.9	17.8	132.5	18.9	129.7	22.5
60	3	0:0.895	134.1	17.0	131.0	17.4	128.5	21.3
60	9.1	0:2.083	133.6	16.5	131.7	18.1	128.1	20.9
60	9.1	0:1.206	138.8	21.7	137.4	23.8	135.6	28.4
60	9.1	0:6.925	136.8	19.7	132.4	18.8	128.9	21.7
75	3	0:3.145	130.1	13.0	129.0	15.4	124.4	17.2
90	9.1	0:0.964	135.7	18.6	131.5	17.9	128.0	20.8

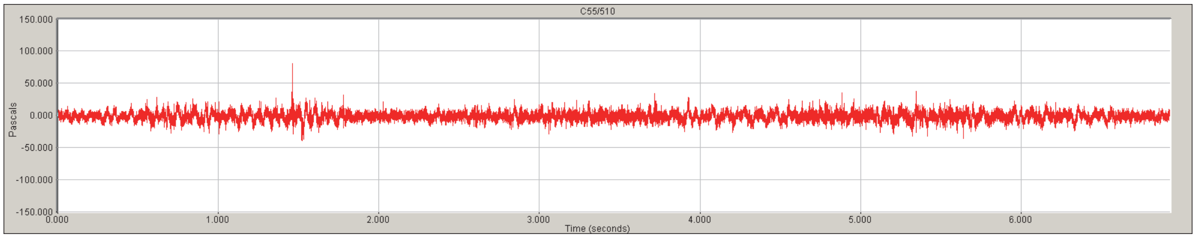

Figure 12. Pressure waveform for barge loading noise.

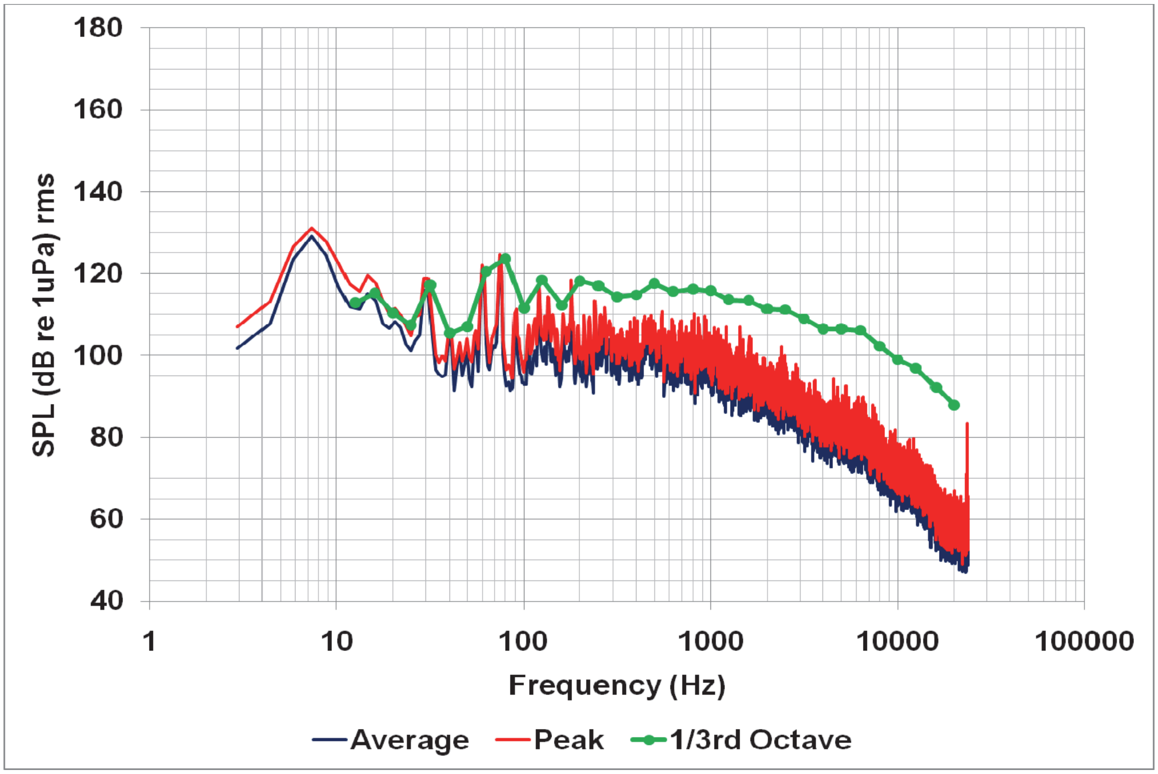

Figure 13. Sound pressure level produced from barge loading sounds at 75 m from the source (hydrophone depth = 3 m).

Anchoring spud sounds

One-third octave (average SPL dB re 1µPA rms). Some of the more intense sounds recorded during the current study were associated with the use of dredge spuds. Dredge spuds as configured on the dredge *New York* are heavy walled pipes that slide vertically in spud wells located at the rear corners of the dredge hull (visible in Figure 2). The spuds are lowered into the sediment to anchor the dredge. A second "type" of spud, called the walking spud, is used to advance the dredge forward when all material has been removed from its current digging location. Results of underwater sound measurements for the two spud types will be discussed separately. Underwater sounds produced by the lifting or lowering of anchoring spuds were detected as far as 220 m from the source. It should be noted that unlike other sound events, spud sounds are not considered a part of the bucket deployment and retrieval cycle, because spud maneuvers necessary for dredge anchoring and advancement occur much less frequently than bucket digging cycles. Consequently at most listening stations this activity did not occur during the monitoring period. The raising and lowering of spuds did occur at the 330-m listening station, but spud sounds were not detected during the monitoring session at either hydrophone depth. Five file segments were analyzed that contained underwater sounds produced by re-positioning of spuds, three of which occurred at 75 m from the source at the 3-m listening depth. SPLs ranged from 134.2 to 136.2 dB re 1 µPa, (mean = 135 db), exceeding ambient by approximately 18 dB. Spud re-positioning sounds were again detected when the survey vessel was anchored 220 m from the dredge. Figure 14 is an example sound pressure waveform for a 40-second time interval for spud re-positioning sounds. Received SPLs obtained from two file segments were 133.2 dB and 137.6 dB with the hydrophone at 9 m (Table 8). Figure 16 is a representative example of spud re-positioning SPLs compared to ambient levels. Assuming a theoretical loss (15LogR) of 35.1 dB at a distance of 220 m from the sound source, the most intense spud re-positioning sound (137.6 dB) would back-calculate to 172.7 dB re 1 µPA@1m rms, exceeding average background by 55.6 dB and maximum background by 41.5 dB.

One-third octave analysis 50-1000 Hz and 100-400 Hz (Average SPL dB re 1µPA rms). Consistent with other backhoe dredge sounds, average SPLs fell from 135.2 dB (20 Hz-20 kHz) to 130.6 dB (50 Hz-1 kHz), to 127.3 dB (100-400 Hz), or by nearly 8 dB from the broader to narrower frequency ranges. Although previous sound events saw an increase in SPLs when factoring in ambient values in the narrower frequency ranges, anchoring spud sounds produced a lower SPL (0.2-3.4 dB) relative to ambient. In the 100- to 400-Hz frequency range, SPL exceeded ambient by slightly more than 3 dB at a depth of 3 m. At a hydrophone depth of 9 m, at 220 m from the source, SPL relative to ambient varied from 0.3 dB higher to 0.8 dB lower.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). Spud re-positioning created a resonant sound centered around 1.2 kHz (octave band range = 1122 Hz -1413 Hz). Peak amplitude was 134.6 dB re 1µPA rms at 75 m (hydrophone depth = 3 m) from the source (Figure 15).

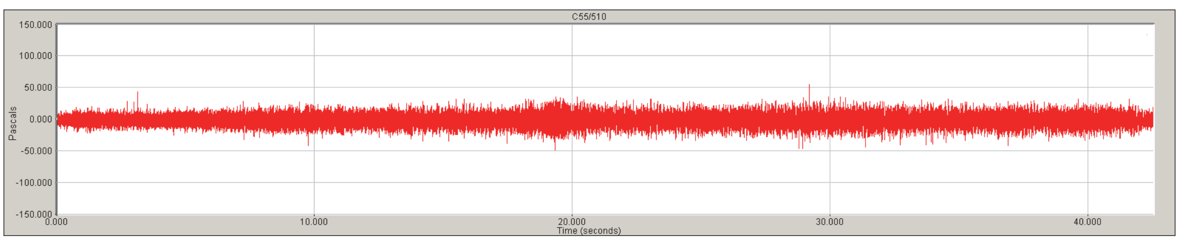

Figure 14. Pressure waveform for re-positioning of anchor spuds.

Table 8. Sound pressure levels (SPL in dB re 1µPA rms) associated with spud (re-positioning anchor) noise (HD = hydrophone depth).

Distance (m)	HD (m)	File Length (min/sec)	1/3-octave Analysis SPL re 1µPa rms					
			All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
75	3	0:9.125	136.2	19.1	131.9	18.3	130.0	22.8
75	3	0:35.68	134.2	17.1	130.2	16.6	127.8	20.6
75	3	0:17.73	134.6	17.5	130.9	17.3	128.1	20.9
220	9.1	0:40.44	133.2	16.1	126.3	12.7	122.5	15.3
220	9.1	0:42.55	137.6	20.5	133.9	20.3	128.0	20.8

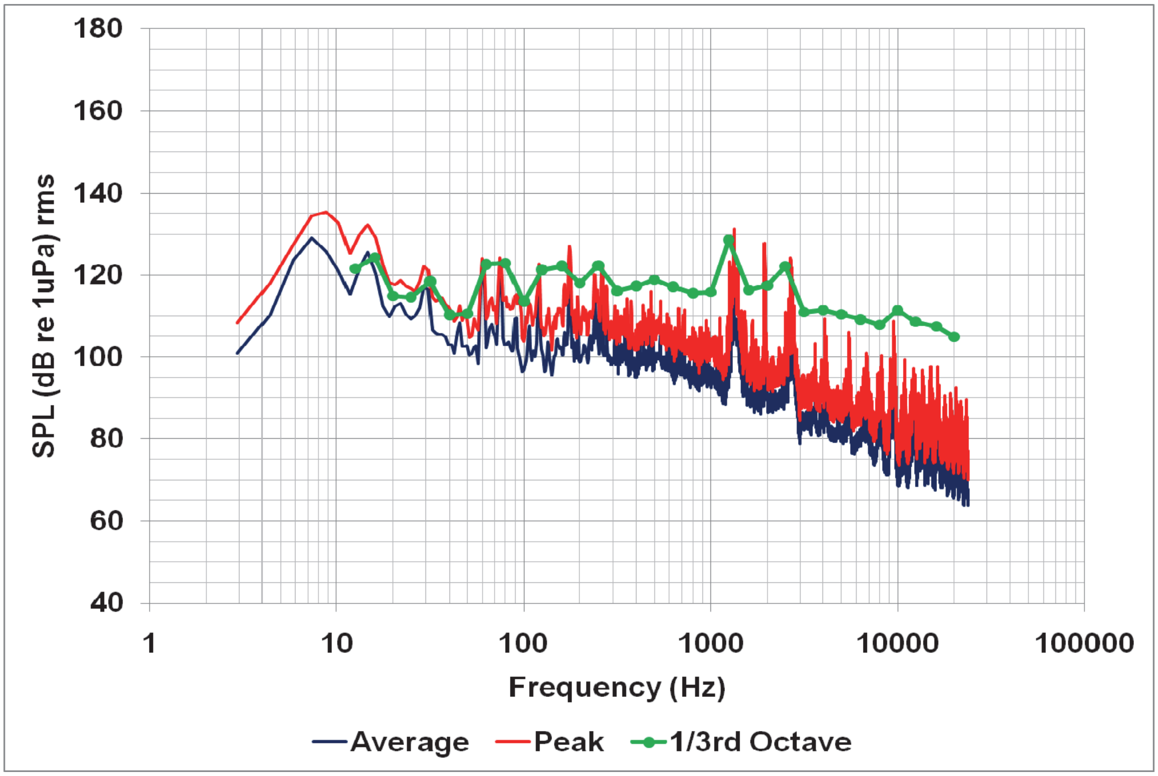

Figure 15. Sound pressure level produced from anchoring spud sounds (lowering) at 75 m from the source (hydrophone depth = 3 m).

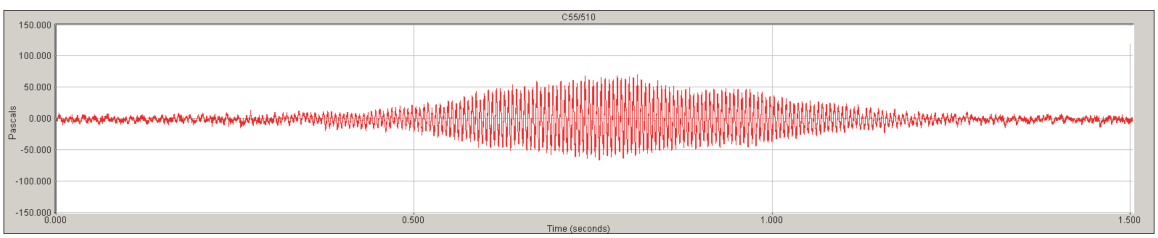

Figure 16. Pressure waveform for spud "walking" sounds.

Walking (advancing) spud sounds

One-third octave (Average SPL dB re 1µPA rms). At three distances (75 m, 210 m, and 330 m) sound recording sessions coincided with times when the dredge was actively "walking" on its spud. At the 75-m listening station, spud walking occurred when the hydrophone was deployed 3 m below the water surface. Figure 16 is a pressure waveform depicting spud "walking." Received levels (1/3-octave average SPL) ranged from 136.3 to 147.4 dB re 1µPA rms, exceeding ambient by 19.2 to 30.3 dB re 1 µPA (Table 9). Advancement of the dredge on its walking spud did not occur again until the survey vessel was located 210 m from the source, while the hydrophone was suspended at a depth of 9 m. The received SPL value was 136.6 dB re 1µPA rms, or approximately 19.5 dB above ambient. Assuming a theoretical loss (15LogR) of 28.1 dB at 75 m distance from the sound source, the most intense spud "walking" sound would back-calculate to 175.5 dB re 1 µPA@1m rms, exceeding average background by 58.4 dB and maximum background by 44.3 dB.

Table 9. Sound pressure levels (SPL in dB re 1µPA rms) associated with spud (walking) noise (HD = hydrophone depth).

Distance (m)	HD (m)	File Length (min/sec)	1/3-octave Analysis SPL re 1µPa rms					
			All Freq.	All Freq. SPL> Ambient	50 Hz - 1 kHz	50-Hz-1kHz SPL >Ambient	100-400 Hz	100-400 Hz SPL> Ambient
75	3	0:1.503	147.4	30.3	147.4	33.8	147.4	40.2
75	3	0:3.679	137.3	20.2	136.9	23.3	135.6	28.4
75	3	0:2.965	136.3	19.2	135.7	22.1	134.3	27.1
210	9.1	0:17.23	136.6	19.5	136.1	22.5	135.7	28.5

One-third octave analysis, 50-1000 Hz and 100-400 Hz (Average SPL dB re 1µPA rms). Unlike the other backhoe dredging sound sources, walking spud SPL did not differ greatly in intensity between the broader and narrower frequency ranges. SPL averaged 139.4 dB in the 20-Hz to 20-kHz range and 139.0 dB and 138.3 dB, respectively, in the 50- to 1-kHz and 100- to 400-Hz frequency ranges. Given the lower ambient SPL in the two narrower frequency ranges, SPL exceeded ambient by an additional 3 dB in the 50-Hz to 1-kHz range and by nearly 9 dB in the 100- to 400-Hz range when compared to the broader frequency range.

Peak amplitude and frequency (1/3-octave SPL dB re 1µPA rms). When compared to anchoring sounds (resonance at 1.2 kHz), sounds generated by spud walking created a resonance at a much lower frequency. Results indicated that peak frequencies in the 1/3 octave were centered within three adjacent octave bands to include: 112-141 Hz (center frequency 125 Hz), 141-178 Hz (center frequency = 160 Hz), and 178-224 Hz (center frequency = 200 Hz). Peak amplitude SPL was 144.6 dB re 1µPA rms at a peak frequency of 200 Hz, 75 m (hydrophone depth = 3 m) from the source (Figure 17). This file segment differed from two other sound recordings made at the same distance and same hydrophone depth, where peak amplitude SPLs were only 125 dB re 1 µPA, at a peak frequency of 134 Hz. Spud walking sounds at 210 m distance from the sound source (hydrophone depth = 9.1 m) had a peak amplitude SPL of 135 dB re 1µPA rms with a peak frequency of 160 Hz.

DISCUSSION

SPL in the range of fish hearing

Over a span of several decades, concerns about underwater noise have largely focused on potential impacts on marine mammals. Recently, similar concerns about detrimental effects of underwater noise on fish populations have emerged. Such concerns have highlighted the general lack of comprehensive studies of the effects of underwater sound on the behavior of fishes. Anthropogenic sound sources may be problematic for fishes due to the dependence of many species on sounds as a means to find prey, to avoid predators, and for social interactions (Popper 2003). Sensory receptors used by fishes to detect sounds are very similar to those of marine mammals. Therefore, sounds that can damage or affect the behavior of marine mammals could produce a similar response in fishes. Based on the limited existing knowledge of dredging process sounds, dredging operations do appear to produce primarily low-frequency sounds, with the bulk of the energy at or below 1000 Hz. This is well within the audible range of most fish species, which generally hear in the frequency range of 50-1,000 Hz, with best sensitivity at 100-400 Hz. Certain species can detect sounds to over 3 kHz. Because dredge-induced underwater sounds are within the hearing range of fishes, assessment of the responses of selected species during encounters with dredges requires accurate characterizations of dredging sounds. Hence the objectives of the present study were to fill a prominent knowledge gap regarding backhoe dredges, a somewhat specialized mode of mechanical dredging. In the present study, the backhoe dredge was excavating coarse material; this presented an excellent opportunity to collect sound data for what might be considered a "worst-case" scenario in terms of noise production.

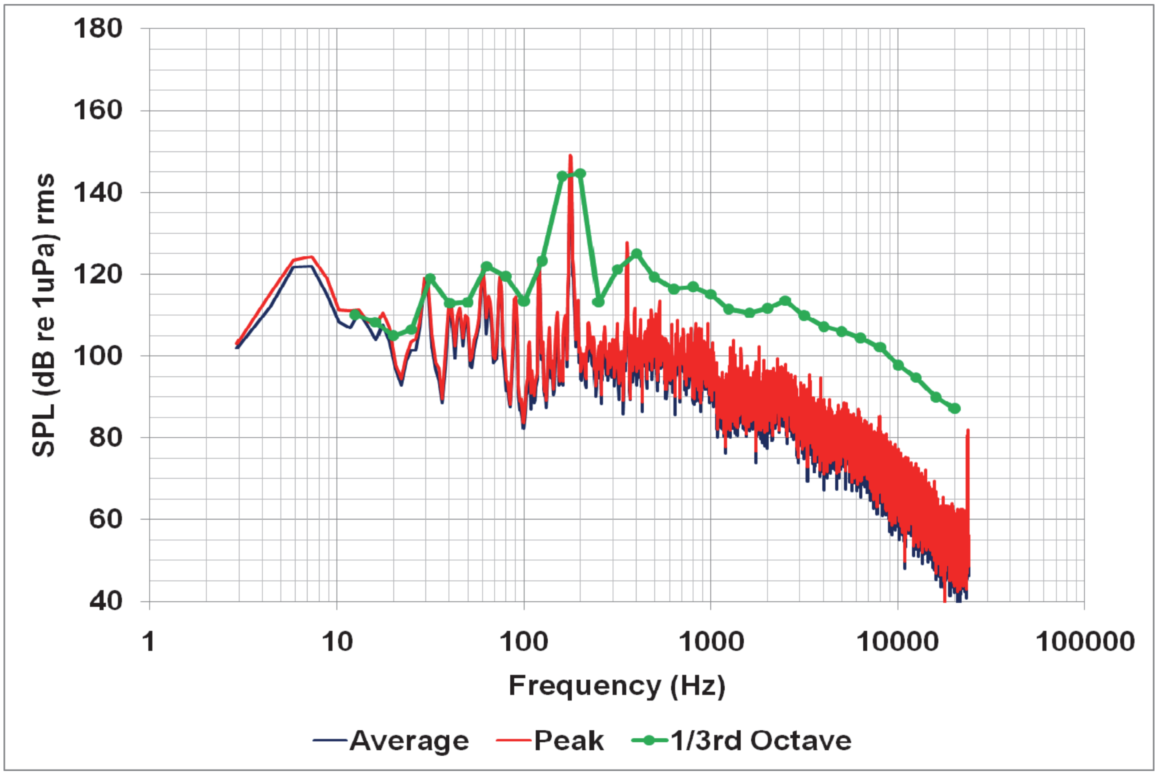

Figure 17. Sound pressure level produced from walking spud sounds at 75 m from the source (hydrophone depth = 3 m).

With regard to hearing, fishes are divided into two categories: hearing generalists and hearing specialists. Generalists hear within a narrow bandwidth and are sensitive to particle motion. Typically hearing generalists do not show a significant response to sound pressure levels. In contrast, hearing specialists have well-developed sound pressure sensitivity and relatively low hearing thresholds. Their sensitivity is related in part to the fact that they have anatomical connections between their inner ear and swimbladder structures. Hearing specialists include all the Otophysi (e.g., catfishes) and Clupeiformes (e.g., anchovies, herrings, and sardines), and representatives of several other fish taxa such as sciaenids (e.g., drums and croakers) and holocentrids (e.g., squirrelfishes) (Popper and Hastings 2009). Fishes known to have the widest hearing range are limited to the family Clupeidae, and more specifically to the genus *Alosa* (Mann et al. 2001). Members of this genus, which includes American shad (*Alosa sapidissima*), can detect ultrasound. Other Clupeiformes such as Spanish sardine (*Sardinella aurita*) and bay anchovy (*Anchoa mitchilli*) are able to detect sounds to about 4 kHz.

In the present study, SPLs were extracted from the 1/3-octave spectral analysis in the 50- to1000-Hz frequency range, within the audible range reported for most fish species, as well as in the 100- to 400-Hz range, which is appropriate for fishes with greatest auditory sensitivity. A distinction can be made between dredge sounds recorded to date and other sound sources such as pile-driving and underwater blasting that have been documented to cause physical injury to fishes. To the authors' knowledge, no evidence exists that dredging performed by routine hydraulic or mechanical methods has resulted in physical damage or mortality to fishes. It seems likely that potential impacts would be limited to behavioral responses to sound stimuli associated with dredging processes. Existing NMFS guidance, which identifies thresholds of 180 dB re 1 μPa for potential injury (Level A Criterion), 160 dB re 1μPA (Level B Criterion) for behavioral disturbance/harassment from an impulsive noise source (e.g., seismic survey), and 120 dB re 1 μPA for behavioral disturbance/harassment from a continuous noise source (e.g., dredging), is based on very few documented studies. The continuous noise threshold of 120 dB re 1 μPA proposed by the NMFS would only apply to one sound source, i.e. engine/generator sounds, measured in the present study. The continuous sound threshold might be more suited for hopper or pipeline-cutterhead dredging operations, although the proposed threshold of 120 dB at least in major harbors with high ambient SPL may need to be reconsidered. Using these thresholds as a guideline, received SPL did not exceed 180 dB (Level A Criterion) for any sound source associated with the backhoe dredging operation, or 160 dB (Level B Criterion) within 55 m of the dredging operation, the closest listening station occupied in the current study. It should also be noted that time-specific ambient SPLs averaged 117.1 dB re 1μPa, with a maximum SPL of 131.2 dB re 1μPa. These SPLs approach or exceed the proposed sound threshold set by NMFS for a continuous sound source. Engine/generator sounds at frequencies from 50-1000 Hz peaked at 135 m from the source at 132.5 dB re 1 μPa. This value exceeded the 120-dB threshold by 12.5 dB. In the peak sensitivity range (100-400 Hz), SPLs exceeded the 120-dB threshold for potential behavioral disturbance by 9.5 dB, also at 135 m. At 330 m from the source, engine/generator noise had fallen below the 120-dB threshold for the 100- to 400-Hz (SPL = 119.7 dB) frequency range and averaged only 2.5 dB above the threshold for the 50-Hz to 1-kHz frequency range.

The remaining backhoe dredging sound sources were not continuous in nature, but rather repetitive occurrences over a period of time, usually lasting for only a few seconds per event. These dredge sounds fall somewhere between the definitions of continuous and impulsive sounds. SPLs for all recorded dredge sounds were typically 0.4 to 6 dB lower in the 50- to 1-kHz frequency range and 1.1 to 12.4 lower in the 100- to 400-Hz frequency range when compared to the entire frequency spectrum (20 Hz-20 kHz). Decreases in SPLs in the narrower frequency ranges were lowest for spud "walking" (mean =0.4 dB 50 Hz-1kHz, 1.1 dB 100-400 Hz) and highest for both engine/generator (means =3.5 dB 50 Hz-1 kHz, 10 dB 100-400 Hz) and bottom grab sounds (mean = 6 dB 50Hz-1kHz, 9 dB 100-400 Hz). The larger difference indicates that more of the sound energy is spread across the entire frequency spectrum and is not as concentrated within the narrower frequency ranges. Although lower SPLs occurred in the narrower frequency ranges, lower background SPLs in the narrower bands resulted in an increase of 0.5-3 dB and 1.3-9 dB in the 50-Hz to 1-kHz and 100- to 400-Hz frequency ranges, respectively.

With respect to the 120-dB and 160-dB thresholds for behavioral and harassment impacts, received SPLs for the remaining sound sources did not exceed the 160-dB threshold for any sound event. The most intense recorded sounds were associated with bottom grabs (peak = 148.1 dB, 50 Hz-1 kHz) and walking spud maneuvers (peak = 147.4 dB, 50 Hz- 1 kHz) at 60 m and 75 m, respectively, from the source. Peak SPLs in the 100- to 400-Hz frequency range were similar to those of the 50-Hz to 1-kHz range, differing by less than 1 dB. SPLs for these two sound events did exceed the proposed 120-dB threshold in both fish hearing frequency ranges by 27 to 28 dB. For bottom grab sounds, SPLs exceeded the 120-dB threshold by less than 6 dB ay 175 m from the source in the 100- to 400-Hz range. Spud "walking" sounds occurred so infrequently that SPL measurements were only obtained at 75 and 210 m from the dredge. In both narrow frequency ranges, SPLs exceeded the 120-dB threshold by 16 dB at 220 m from the source. Due to the infrequency of this sound event, attenuation to ambient distances could not be determined.

Peak SPLs for barge loading, hydraulic ram, and anchoring spud sounds were generally 9 to 14 dB lower than bottom grab and spud "walking" sounds. For these dredge sounds, peak SPLs exceeded the 120-dB threshold in the 50-Hz to 1-kHz range by 14 to 17.6 dB. This generally occurred within 100 m from the source. In the 100- to 400-Hz range, peak SPLs exceeded the 120-dB threshold by 8 to 10 dB at the same listening station. Hydraulic ram sounds attenuated to below the 120-dB threshold within 200 m from the sound source. Received SPLs for hydraulic ram sounds were only 121.5 dB at 170 m from the source in the 100- to 400-Hz frequency range. For barge loading sounds, received SPLs (100-400 Hz) were only 8 dB above the 120-dB threshold at 90 m from the source. Although received SPLs in the two examples above exceeded both ambient and the proposed threshold, these sounds were not detected against background at listening stations located at greater distances from the source. The somewhat limited maximum detection distance is probably influenced greatly by the fact that New York Harbor is an extensive, complex sound field. Drifting away from one sound source typically involves moving toward a myriad of other sound sources.

Other dredging studies

Greene (1985, 1987), measured broadband sounds emitted by two hydraulic cutterhead-pipeline dredges at ranges extending to 25 km in the Beaufort Sea. For the dredge *Beaver Mackenzie,* peak spectral levels were 122 dB at 190 m with a peak frequency of 120 Hz. Received levels in the 20- to 1000-Hz band were 133 dB (rms) re 1 µPA at 190 m from the sound source. Source level (rms) was calculated to be 168 dB re 1 µPA@1m. Measurements were also taken for the cutterhead dredge *Aquarius* at distances ranging from 0.2 to 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-m.

Greene (1987) also reported underwater sound levels for hopper dredges. Hopper dredges produced relatively loud sounds, but with fluctuating levels. The most intense sounds were produced during loading or unloading, whereas the hopper dredges were relatively quiet while underway. Greene (1987) reported that the 8000-m^3 capacity *Geopotes X* was operating in a 21-m water depth when sound measurements were taken. At a range of 0.43 km, the 20- to 1000-Hz band level was 139 dB re 1 µPa@430 m. The peak amplitude was 125 dB re 1 µPA at a peak frequency of 100 Hz. The same dredge, which had damaged its propeller earlier in the season, produced sound levels of 150 dB re 1 µPA at 0.46 km in the 20- to 1,000-Hz band. The 9,000-m^3 hopper dredge *Cornelia Zanen* recorded peak spectral levels of 125 dB @ 200 m with a peak frequency of 175 Hz. The received sound level at 930 m was 142 dB re 1 µPA. The author also reported received levels for the 6,000-m^3 hopper dredge *W. D. Gateway* at 131 dB re 1 µPA at 1,500 m. Peak spectral level was 131 dB at 1,500 m at a peak frequency of 350 Hz.

The Center for Environment, Fisheries, and Aquaculture Science (CEFAS) measured sounds produced by the 2,890-m^3 trailing suction hopper dredge *Acra Adur* operating at two different locations in the Southern North Sea. The authors reported the occurrence of predominantly low-frequency sounds (< 500 Hz), with peak spectral levels of 122 dB re 1 µPa at a range of 56 m and at a frequency of 320 Hz (Department for Environment Food and Rural Affairs (DEFRA) 2003). Parvin et al. (2008) measured the source levels of the 2,700-m^3 hopper dredge *The City of Westminster* operating on the Hastings Shingle and calculated the broadband source level to 186 dB re 1µPA@1m. The received level was 144 dB re 1µPA at 150 m. Results indicated that the dredge noise would be audible beyond a range of 6 km.

Miles et al. (1987) recorded sounds produced by a bucket dredge, noting that most intense sounds occurred in the 1/3 octave at 250 Hz, ranging from 150-162 dB re 1µPA. The authors reported that the loudest sounds measured in their study were produced during the winching of the loaded bucket up through the water column.

Dickerson et al. (2001) identified five distinct sounds associated with the 10-m^3 bucket used by the dredge *Viking* operating in Cook Inlet, Alaska. The most intense sound was associated with the bucket striking the channel bottom. SPLs (dB relative rms) were 124 dB at 158 m from the source. Winch noise was 7.4 dB lower at the same distance (116.6 dB relative), while bucket closing (113.2 dB relative) and barge loading (108.6 dB relative) were 10.8 dB and 15.4 dB lower, respectively. The authors reported that SPLs (relative dB rms) diminished from 15 to 30 dB at 150 m and 5,500 m distance from the source. All dredge sound sources were no longer detectable beyond 5.5 km, with the exception of the bucket striking the channel bottom, which was detectable to 7 km.

To the authors' knowledge, no previous studies exist in the scientific literature referencing backhoe (excavator) dredges. As summarized above, limited data exist for both hopper and pipeline cutterhead dredges, although most of these studies were conducted in oceanic, open-water environments. Very few studies have been conducted examining sounds of bucket dredges, especially in estuarine environments. The paucity of dredge sound data extends to projects in major ports and harbors where anthropogenic sounds from a multiplicity of sources are present. Thus, the present study addresses several knowledge gaps. The majority of underwater sounds produced by the excavator dredge in this study were in relatively low frequency ranges, primarily 130 Hz to 1.25 kHz. Lowest frequencies (< 200 Hz) were associated with spud "walking" sounds, whereas highest frequencies (1.25 kHz) were associated with the raising of spuds in preparation for movement of the dredge plant or lowering of the spuds for anchoring.

The most intense sounds produced by the backhoe dredge *New York* were associated with bottom grabs and the use of dredge spuds. Source levels for bottom grabs were 179.4 dB re 1 µ PA@1m, or 62.3 dB and 48.2 dB above average and maximum background SPLs, respectively. The second most intense underwater sound was associated with the raising or lowering of the anchoring spuds, followed by the use of the "walking spud." Source levels were 175.5 dB re 1 µ PA@1m for raising and lowering of spuds, and 172.4 dB for spud walking. The use of spuds exceeded average ambient SPLs by 55 to 58 dB, or 41-44 dB above maximum background SPLs.

The remaining four noise events had similar source levels differing by less than 3 dB. In order of decreasing intensity, the sound sources included: “popping” sounds (SPL = 167.1 dB re 1 µ PA@1m); engine/generator sounds (SPL = 167 dB re 1 µ PA@1m), barge loading sounds (SPL = 166.2 dB re 1 µ PA@1m); and hydraulic ram sounds (SPL of 164.2 dB re 1 µ PA@1m). These SPL levels exceeded average background SPLs by 47 to 50 dB re 1 µ PA@1m. Source levels differed from the most to least intense sounds by 15.1 dB.

The source range for the excavator dredge *New York* was 164.2 to 179.4 dB re 1µPA@1m, which was somewhat quieter for most of the backhoe dredging processes when compared to source levels reported for cutterhead dredging (168-178 dB re 1 µPA@1m) and hopper dredging (186 dB re 1 µPA@1m). This was somewhat unexpected given that the material being removed during the deepening project was rock, whereas sandy material was the primary fraction for the comparison studies. The major difference in the current study is the short detection ranges. Sounds were only audible to relatively short distances from the dredging operation, so attenuation curves could not be plotted. The furthest distance in which audible sound was measured was 680 m and was associated with engine/generator noise; although it was uncertain if the measured sound, although clearly engine/generator noise, originated from the dredge *New York* or from another source. If excluded, the maximum distance in which underwater sound was measured during the current study was 330 m.

Navigation dredging is a common practice in coastal waters where maintenance of many channels must be performed on a yearly basis. Deepening projects may require the removal of hard, consolidated sediments such as “virgin” clay or rock, as in the case of the current study. Measured sound levels from excavator dredging activities exceeded ambient levels by as much as 62 dB at the source. However, distances to which the various dredging sounds remained audible against ambient were relatively short. Dredge sounds were more pronounced at lower frequencies. Given that low frequencies can rapidly attenuate in shallow water, dredge sounds should attenuate rapidly. Dredging in rock or coarse sediment would produce a more intense sound compared to dredging in softer sediment (e.g., silt) typical of most navigation dredging projects. In comparison to other dredging sound sources, engine/generator sounds, although continuous in nature, were the least intense. At the site investigated in this study, no audible dredging sounds were detected beyond 330 m.

Factors that may have influenced received sound levels include hydrodynamic conditions, suspended sediment loads, sea state condition, sound reflection and refraction, diffraction, scattering, reverberation, and complex bathymetric features of the study site. With respect to dredging sounds, maintenance condition of the physical plant and skill of the operator can strongly influence emitted sounds. Sea state during the present study averaged 1-2 ft with a northwest wind of 10-15 mph. Suspended sediment load within an estuarine environment may also attenuate sound. For example, Richards et al. (1996) reported that concentrations on the order of 20 mg/l could cause an attenuation of 3 dB over a path length of 100 m at 100 kHz. Although water samples were not taken during this study, natural background suspended sediment concentrations are known at times to surpass these levels in New York Harbor.

Hydrodynamic conditions at the study site were capable of producing problematic flow noise over the hydrophone outside of a 1- to 2-hr window surrounding slack tide. Average maximum currents in Anchorage Channel, Upper Bay ranged from 0.67 m/sec (ebb) to 0.82 m/sec (flood). Drift transects were used to reduce flow noise by having the survey vessel and hydrophone drift at the same rate as the current. The geomorphology of the study site consisted of a broad navigation channel with depths approaching 60 ft (18.3 m) MLW in some locations. Water depths present on shoals north and south of the navigation channel decreased to approximately 22 ft (6.7 m) or shallower. Water depths decreased to as shallow as 11 ft (3.3 m) on Robbins Reef located northeast of the dredging operation and to 5 ft (1.5 m) to 8 ft (2.4 m) over the flats south of the Global Marine Terminal and East of Constable Hook. In New Brighton south of the dredging operation, water depths just outside of the navigation channel decreased rapidly to 4 ft (1.2 m). At anchored monitoring stations, water depths ranged from 57 ft (17.4 m) MLW to 35 ft (10.7 m) MLW moving west to east from the dredging operation. These bathymetric features obviously influenced propagation of sound at the study site.

This study represents an initial stage in efforts to address the salient knowledge gaps pertaining to underwater sound produced during dredging operations. In ensuing technical notes, sounds produced by a variety of dredge types operating in different substrates and locations (e.g., estuarine and open-water environments) will be assessed. These data are intended to provide a basis for informed decisions regarding management of dredging projects.

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