OCS Study
BOEM 2014-055
ERDC/EL TR-14-3

Characterization of Underwater Sounds Produced by Trailing Suction Hopper Dredges during Sand Mining and Pump-out Operations

US Department of the Interior
Bureau of Ocean Energy Management
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Abstract

Underwater sounds were characterized for three trailing suction hopper dredges (TSHD) during the removal of 3.1 million yd^3 of sand from an offshore borrow area and during offloading of the escavated sediment at the pump-out stations in support of the Wallops Island, Virginia Beach Stabilization Project. Sounds were recorded simutaneoulsy at two depths, 3 and 9.1 m from the surface. Sound sources included sediment removal, pump-out of material, pump-out of clear water during pipe flushing, and transit to the borrow site (hopper empty) and to the pump-out stations fully loaded. Received and 1/3-octave Sound Pressure Levels (dB re 1 µPa, rms) are reported for each sound source. Source Levels (dB re 1µPa-1m, rms) were back-caculated using fitted regression (15.788LogR). Source Levels (SL) ranged from 161.3 dB to 176.7 dB re 1µPa-1m rms. Highest SL were obtained for the dredge Liberty, which is nearly twice the size (e.g. hopper volume, displacement) of the dredges *Padre* and Dodge *Islands*. Sounds emitted during transit produced the highest SL, whether the hopper was empty or full. Attenuation to ambient was dependent on the sound source, and ranged from 0.85 km (flushing pipes) to 2.65 km during transit with the hopper at maximum capacity.

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Preface

This underwater sound characterization study was a joint effort between the US Army Engineer Research and Development Center (ERDC), the Bureau of Ocean Energy Management (BOEM), and the NASA Wallops Island Flight Facility (NASA-WFF) under the Dredging Operations and Environmental Research (DOER) Program.

Principal Investigators for this study were Kevin Reine and Dr. Douglas Clarke of the Wetlands and Coastal Ecology Branch (W&CEB) of the Ecosystem Evaluation and Engineering Division, US Army Engineer Research and Development Center, Environmental Laboratory. At the time of publication, Dr. Jacob Berkowitz was Acting Chief, CEERD-EE-W; Dr. Edmond Russo was Chief, CEERD-EE-E; The Deputy Director of ERDC-Environmental Laboratory was Dr. Jack Davis (CEERD-EV-A), and the Director was Dr. Beth Fleming (CEERD-EV-Z).

At the time of publication, Dr. Geoff Wikel was Chief of the Branch of Environmental Coordination, Division of Environmental Assessment for the Bureau of Ocean Engery Management and Dr. Joshua Bundick was Lead of Environmental Planning for NASA Wallops Island Flight Facility.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
knots	0.5144444	meters per second
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (mass)	0.45359237	kilograms
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
tons (2,000 pounds, mass)	907.1847	kilograms

Acronyms and Abbreviations

BOEM	Bureau of Ocean Energy Management
CEDA	Central Europe Dredging Association
dB	Decibel
dBrms	Decibels measured in terms of root-mean-square pressure
DOSITS	Discovery of Sound in the Sea
DQM	Dredging Quality Management
ERDC	Engineer Research and Development Center
Ft	Feet
G/cc	Grams per cubic centimeter
Hp	Horsepower
Hz	Hertz
kHz	Kilohertz
kW	Kilowatt
LLD	Lower listening depth
LP	Listening platform
LT	Long ton
MARS	Mid-Atlantic Regional Spaceport
m	Meter
MPH	Miles per hour
cm	Centimeter
cu m	Cubic meter
m/sec	Meters per second
NASA	National Aeronautics and Space Administration
NMFS	National Marine Fisheries Service (United States)
NOAA	National Oceanographic and Atmospheric Administration (United States)
NIST	National Institute of Standards and Technology

POM	Pump-out of material
POW	Pump-out of water
RL	Received level
RPM	Revolutions per minute
RMS	Root mean square
SL	Source level
SR	Sediment removal
SPL	Sound pressure level
TBS	Transient to borrow site
TPO	Transient to pump-out station
TSHD	Trailing suction hopper dredge
T1	Transition from transient to digging
T2	Transition from digging to transient
T3	Transition from transient to pump-out
T4	Transition from pump-out to transient
μPa	microPascal
ULD	Upper listening depth
USACE	United States Army Corps of Engineers
WWF	Wallops Flight Facility
Yd	Yards
Yd^3	Cubic yards

1 Introduction

Dredging is a process that involves the excavation of sediment from a sea, estuary, river, or lake bed and the handling and transport of the excavated sediment to a placement site elsewhere (Central Dredging Association (CEDA) 2011). In the United States, dredging generally falls into three major categories: 1) navigation dredging, which involves either capital dredging to deepen or widen channels, or maintenance dredging to return channels to authorized depths following periodic sedimentation; 2) remedial dredging to handle contaminated sediments; and 3) mining of sand and aggregate for commercial uses or to replace sand lost over time due to coastal erosion. The latter type of dredging is referred to as beach nourishment. The trailing suction hopper dredge (TSHD) is commonly used in dredging operations to support beach nourishment operations. 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. Large suction pumps transport the sediment from the seafloor and deposit the dredged material into one or more hoppers. Once capacity is reached, the TSHD sails to either an offshore placement site where the material is released through doors located in the hull of the ship, or the TSHD pumps out the material through pipes using a floating booster pump barge to the desired location. This “pump-out” method is generally employed during beach nourishment operations.

In recent years concerns have been raised regarding underwater noise of anthropogenic origin and potential impacts on aquatic organisms including marine mammals (e.g., whales and seals), sea turtles, and fishes. Until recently these concerns have centered on noise from offshore seismic exploration, military communication systems, and marine construction activities (e.g., pile driving). Concerns have now expanded to include noise from dredging activities, for which few studies exist. The main processes which contribute to sounds associated with hopper dredging activities include: 1) sounds arising from the removal of material while the draghead is in contact with the seafloor; 2) sounds produced by suction pipes and pumps, and the movement of dredged material through the dragarm riser to the hopper; 3) deposition sounds associated with loading of the material into the hopper (including overflow if used); 4) sounds associated with the dredge machinery itself, such as winches, generators, thrusters and particularly propeller-induced cavitation; and 5) sounds associated with the off-loading of material from the hopper for placement on the beach (including accessory pumps). Additional sound sources may be caused by water turbulence around the ship's hull and the use of echosounding instrumentation. To some extent, similar sounds may be associated with dredging project support vessels, including tugboats, tenders, and supply/crew boats. These sounds are omni-directional and continuous in nature. In some cases it may be possible to identify infrequent discrete sound events such as contact of the draghead with the channel bottom or the turning on or off of suction pumps. In general, it is difficult to separate the individual processes involved in dredging by their temporal location in the record. However, the dredging operation as a whole can be separated into discrete dredging activities such as sediment excavation, or transiting to and from the borrow area.

A limited number of studies have indicated that dredge noise occurs in the low frequency range (< 1200 Hz), which is within the audible range of listed species of whales and sea turtles, as well as many species of fish. Exposure to underwater sound may potentially affect communication, foraging, predator evasion, and navigation of marine organisms, which to various degrees rely on sound to communicate and to derive information about their environment. Sound generated by hopper dredging is continuous rather than punctuated and is primarily within the low frequency range. Such sounds are within the audible range of several species of marine mammals such as whales and dolphins as well as sea turtles. Right (*Eubalaena glacialis*), humpback (*Megaptera novaeangliae*), and fin (*Balaenoptera physalus*) whales have hearing capabilities in the 7-22 Hz range (Southall et al. 2007). The hearing threshold for sea turtles is in the 100- to 1000-Hz range (Ketten and Bartol 2005). With regard to fish, it has also been hypothesized that dredging-induced sound could block or delay the migration of anadromous fishes, interrupt or impair communication, or impact foraging behavior. The majority of fish species detect sounds from below 50 Hz up to 1500 Hz. There are, however, a small number of fish species that can detect sound exceeding 100 kHz. These fishes, which have the widest hearing frequency range, are generally regarded as hearing specialists, exemplified by members of the clupeiform genus *Alosa*, including blueback herring (*Alosa aestivalis*) and American shad (*Alosa sapidissima*) (Mann et al. 2001). Much of the available information pertaining to effects of underwater sound on fishes is derived from a small number of studies involving pile-driving operations. These studies have recently been reviewed by Popper and Hastings (2009).

An additional resource protection issue is centered around aerial sound levels and their potential negative impacts on migratory, threatened, or endangered bird species. Diving sea birds may also be transiently affected by underwater noise. Effects of dredge sounds are presumed to be insignificant under most circumstances, but hypothetically may produce temporary changes in behavior, mask signals birds use to communicate with each other, impair detection of sounds of predators or prey by masking, decrease hearing sensitivity temporarily or permanently, and increase stress and alter reproductive and other hormone levels. As reported in Dooling and Popper (2007), the low to high frequency cut-offs for bird hearing is about 300 Hz and 6 kHz (best frequency 2-3 kHz), respectively.

The National Marine Fisheries Service (NMFS) plans to introduce new compliance criteria for underwater sound pressure thresholds for fish and marine mammals, analogous to other water quality criteria, such as turbidity or dissolved oxygen concentrations. Different target species for protection have widely divergent tolerance levels for sounds (owing to different hearing sensitivities, hearing integration times, etc.). Moreover, different mitigation measures, such as the use of observers and exclusion zones, may effectively avoid level A and possibly Level B harassment. For example, North Atlantic right whale avoidance (for strike) may also contribute to avoidance noise exposure and behavioral modification. In the interim, NMFS generally considers 180- and 190-dB re1µPa root mean square (rms) the sound pressure level at which cetaceans and pinnipeds, respectively, could be subjected to potential injury (Level A Criterion). NMFS recognizes 160 dB re1µPa to be the sound pressure level for behavioral disturbance/harassment (Level B Criterion) from an impulsive noise source (e.g. pile driving), and 120 dB re1µPa as the sound pressure level for behavioral disturbance/ harassment (Level B Criterion) from a continuous noise source (e.g. dredging). The relevance of the 160 dB re1µPa disturbance criterion for odontocetes and pinnipeds exposed to pulsed sounds is not well-established (Southall et al. 2007); however, these criteria have been imposed, albeit inconsistently, for over a decade. Few data exist that adequately characterize sounds emitted by dredges that would support objective decisions balancing the need to dredge against relative risk to an aquatic resource. Studies by Greene (1985, 1987); Miles et al. (1986, 1987); Dickerson et al. (2001); Clarke et al. (2002); Department for Environment, Food, and Rural Affairs (DEFRA)

(2003); Parvin et al. (2008); and more recently, de Jong et al. (2010); Robinson et al. (2011); and Reine et el. (2012a, 2012b, in preparation) are among the very few relevant references that exist. Given the limited number of studies, it would be premature to set such criteria in the absence of robust datasets characterizing sounds associated with diverse modes of the dredging process.

The U.S. Army Corps of Engineers (USACE) Dredging Operations and Environmental Research (DOER) Program has developed a program to characterize sounds produced by different dredging and dredged material placement operations. The USACE is collecting data across dredge types (e.g., hopper, bucket/clamshell, hydraulic pipeline), substrate types (e.g., silty maintenance materials through consolidated new work material), and settings (e.g., deep “blue” water areas through shallow turbid waterways and ports). Recent efforts include characterizing underwater sounds produced by a hydraulic cutterhead fracturing limestone rock as well as underwater sounds associated with a backhoe dredge excavating rock and gravel in Anchorage Channel, New York/New Jersey Harbor as part of the Harbor Deepening Program (HDP) (Reine et al. 2012a, 2012b).

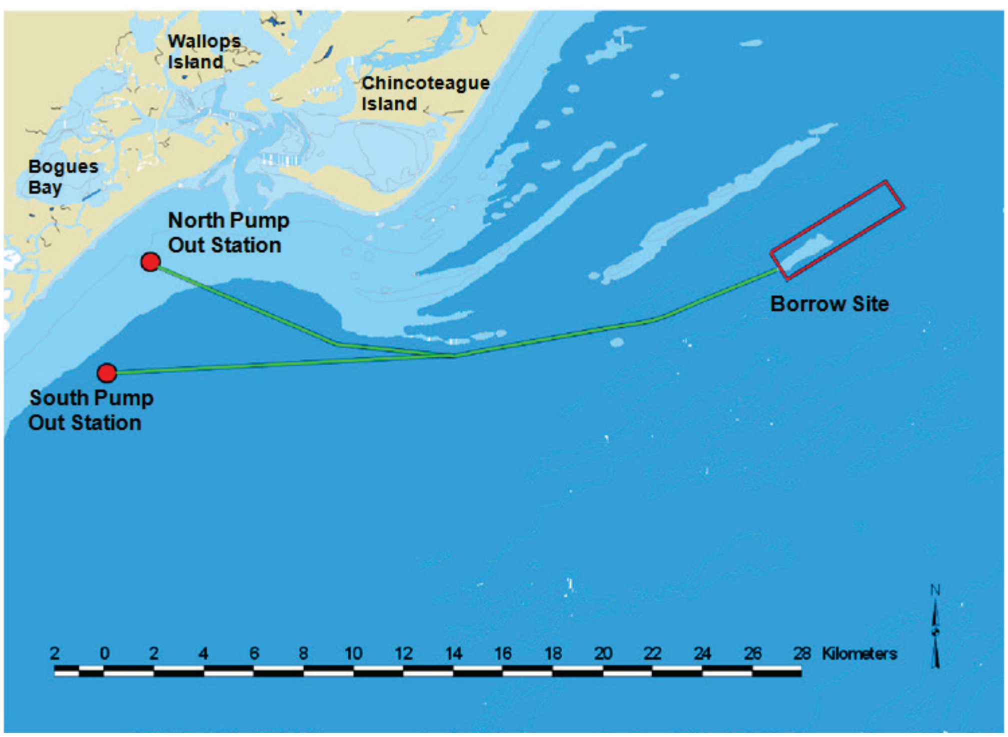
In this study, underwater sounds were characterized for three TSHDs during the removal of 3.1 million yd^3 of sand from an offshore borrow area and during offloading of the excavated sediment at two pump-out stations. The study represents a collaborative effort between the US Army Engineer Research and Development Center (ERDC), the Bureau of Ocean Energy Management (BOEM), and the National Aeronautics and Space Administration (NASA). Terms that are critical in understanding this report are listed alphabetically in Appendix A.

2 Methods

Study area

NASA's Wallops Flight Facility (WFF) is located in the northeastern portion of Accomack County, Virginia on the Delmarva Peninsula (Figure 1). The main base is located 5 miles (8 km) west of Chincoteague, Virginia; approximately 90 miles (140 km) north of Norfolk, Virginia and 40 miles (64 km) southeast of Salisbury, Virginia. Wallops Island is bounded by Chincoteague Inlet to the north and Assawoman Inlet to the south. NASA has occupied the WFF since the 1940s, and it is currently used by NASA, the US Coast Guard (USGS), the US Navy, NOAA, and the Mid-Atlantic Regional Spaceport (MARS). Compatible sand used for the purposes of beach nourishment was obtained from a nearby shoal located approximately 7 miles east of Assateague Island and approximately 11 miles northeast of Wallops Island.

Figure 1. Study area.



The corner boundaries of the borrow area are 37 50 37.0 / 75 13 38.3 (NE), 37 50 01.6 / 75 13 15.6 (SE), 37 51 40.6 / 75 10 48.3 (SW), and 37 52 09.3 / 75 11 11.0 (NW). Water depths at the borrow site ranged from 25-30 ft MLW (Unnamed Shoal A) to 40-70 ft MLW in the immediate vicinity of the shoal.

The north pump-out station was located at 37 50.24/75 26.36, approximately 2200 m from shore and was used by both the *Dodge* and *Padre Island*. The south pump-out station was used exclusively by the *Dredge Liberty Island* and was located at 37 47.92/75 28.00 or approximately 3600 m from shore. Water depths ranged from 22 to 28 ft MLW at the North Pump Out Station to 32 to 36 ft at the South Pump Out Station. Both locations can be found on NOAA chart 12210.

Dredging operations

Underwater sound recordings were made on three intermediate-size class TSHDs in the current study. Specifications, such as displacement, hopper volume, and draft for each dredge are summarized in Table 1.

Table 1. Summary of vessel specifications (*SSC = Southern Shipbuilding Corporation, BSC = Bay Shipbuilding Company).

Vessel	Dodge Island	Padre Island	Liberty Island
IMO Number	7917800	8101783	9224831
Year Built	1980	1981	2001
Built by*	SSC	SSC	BSC
Length (m)	85.6	85.6	96.0
Width (m)	16.2	16.2	18.0
Depth (m)	6.7	6.6	8.5
Draft (Light) (m)	2.9	2.9	3.2
Draft (loaded) (m)	5.9	6.0	7.8
Propulsion Power (kW)	3,244	2,237	7,400
Pump-Out Power (kW)	1,268	1.322	6,300
Total Power (kW)	6,972	7,006	12,353
Number of Engines	2	2	2
Engine Specs	GE-12-645-E6	GE-12-645-E6	Caterpillar-3612 DITA
Engine Cylinders	12	12	12
Hopper Capacity (cu.m.)	2,754	2,754	5,003
Max Dredge Depth (m)	21.3	21.3	32.9
Suction Diameter (cm)	69.0	69.0	80.0
Discharge Diameter (cm)	61.0	61.0	76.2
Gross Tonnage	2820	2820	5020

National Dredging Quality Management (DQM) Program data

Using data obtained from the National Dredging Quality Management Program, distances to the nearest dredge from the LP were determined. DQM data were obtained from the USACE: Mobile District for all three dredges for the 2-week time period covering field data collection. Data intervals varied from 4-10 seconds. The DQM Program is a Corps-Dredging Industry partnership for automated dredging monitoring of Corps dredging projects. Onboard sensors monitor dredge activities, operations, and efficiency. Data are routed to the DQM Support Center for retrieval and storage. Data parameters collected by the DQM include, but are not limited to, positioning information, vessel speed, course and heading, draft (ft), displacement (LT), volume (CY) of material in the hopper, and port and starboard pump speeds (rpm).

Water quality

A calibrated YSI (Model 6920 V2) water quality sonde was used to measure temperature (^{o}C) and salinity (ppt) at approximately 1-m increments from surface to bottom at both the borrow site and inshore pump-out stations. Sound speed in the oceans depends on temperature, salinity, and pressure, and has large seasonal and spatial variations. Given these variations, it was necessary to measure these parameters as well as examine the water column for stratification. While the effect of salinity on the speed of sound is relatively minor, temperature has a far greater effect. Under most conditions, sound will travel faster in warmer water and slower in cooler water.

Meteorological data

Wind data were obtained from the Assateague Island Station ASTM2, which records hourly measurements.

Sound recording equipment and processing software

Sound data were collected using a Sound Technologies ST1400ENV mobile audio data recorder and 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. Hydrophones were factory calibrated by Reson over their full frequency range using National Institute of Standards and Technology (NIST) protocols. Horizontal directivity is omnidirectional $\pm$ 2 dB at 100 kHz. Vertical directivity is 270^{o} $\pm$ 2 dB at 15 kHz. The receiving sensitivity of the TC4032 is -170 dB re 1V/µPa. Additional hydrophone parameters are provided in Appendix B. The ST1400ENV consists of a sound DAQ (Data Acquisition Board), data processor, global positioning systems (GPS), auxiliary data storage hard drive (500 GB), and an internal battery backup power supply. These components are integrated and collectively housed in a Pelican case. 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 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.

Sound data acquisition

Sound recordings were made from 3-13 May 2012. Recordings were made from the 32-ft M/V Shammy provided by Shammy Sportfishing, Fishing Charters, Chincoteague Island, Virginia, through contract with the National Aeronautics and Space Administration (NASA). 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. Two hydrophones were deployed at depths of 10 ft (3 m) and 30 ft (9.1) in the water column for all monitoring sessions, with the exception of the north pump-out station, where the lower hydrophone was deployed at 20 ft (6.7 m). This was necessary given the shallower water depths at the north pump-out station. 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 recording at both depths. During recording sessions, the survey vessel was allowed to drift freely, carried by the prevailing currents. Distances from the monitoring vessel to the sound source were measured every 15 seconds using a Bushnell Elite Model 1500 laser range finder, capable of measuring distances as far as 1,500 m. GPS coordinates were logged automatically through the ST1400ENV, which had an attached external GPS antenna mounted on the roof of the survey vessel. Dredge position relative to the listening platform was confirmed during post-processing by plotting GPS coordinates logged by the ST1400ENV and from positioning information obtained through the DQM.

The sound analysis system was powered by a deep-cycle marine battery, which provided 120V AC power to an APC Smart-Ups 1000 uninterruptible power source. 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.

No gain was applied in the ST1400ENV during data collection. The sampling rate was set to 50,000 samples per second. A 20-Hz to 22-kHz band pass filter was applied. The 20-Hz band pass filter was used to reduce noise associated with wave action. The 22-kHz band filter was necessary given that a recent upgrade to the system replaced the original computer with a different model that was experiencing a data buffering problem. It was determined that data for frequencies above 22 kHz were not as crucial given that most of the energy associated with dredging is below 1500 Hz. As a result of the band pass filters, noise from echosounders used by dredge plants and support vessels was not detected. The WAV file recording bit density was 24 bit. Sound data files were time-date stamped (UTC) with GPS position and data values logged every 1 second.

A TSHD may generate noise from a number of its structural components (e.g., propellers, suction pumps, and dragheads during operation). Therefore, measurements were obtained at various orientations between the dredge and the listening platform (LP), including the following: LP directly astern of the dredge (dredge advancing away from the LP), bow (dredge approaching the LP), and either the port or starboard side of the dredge. For each vessel, hydrophone measurements were performed as a function of range from the TSHD at multiple distances. In addition to measuring noise from the dredging process, ambient noise was also measured at both the borrow area and pump-out stations. A total of 77 dredge recording sessions were conducted during the various phases of dredge operation. The monitoring ranges (25-5100 m) varied for each vessel and dredge activity, but measurements for most dredge modes typically did not exceed 2 km. Analysis included only data collected for ambient purposes that exceeded a distance of 3 km (range = 3-20 km, mean = 8.9 km) from the nearest dredge. A total of 24 ambient recording sessions were made. Each session generally consisted of two to six 15-minute files. Hydrophone deployment depths at the borrow area were 3 m for the upper listening depth (ULD) and 9.1 m for the lower listening depth (LLD). Given the shallower water conditions at the pump-out stations, the lower hydrophone depth was decreased to 6.7 m.

Sound data analysis

Real-time data collection files were obtained from the ST1400ENV for each recording session. GPS position data were embedded within these files. Both SPL (rms) and GPS data were logged at 1-second intervals for both the upper (ULD) and lower (LLD) listening depths. 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 whole sound clip. Each of these spectral analyses was saved in a separate text file to create 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. Note that in most cases, single-peak values are not very meaningful, as they simply measure the peak amplitude of the strongest single frequency observed throughout the given sound clip. This is particularly true for sounds that are not of an impulse nature, such as the rotation of the cutterhead. In these cases, the total power is 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 to another. Conversely, if the sounds are of a more instantaneous impulse type (e.g., pile driver), an analysis of peak amplitudes and frequencies might be more appropriate.

Three data sets were assembled to complete the analysis. Data set 1 contained both the real-time SPL (rms) and the 1/3-octave analysis results at 1-second intervals. Data set 2 contained DQM data for all three dredges for the 2-week time period in which field data were collected. DQM data intervals varied from 4 to 10 seconds. DQM data were interpolated to 1-second intervals to match the GPS and sound data collection rate. Data set 3 (wind data) was obtained by downloading hourly measurements recorded at the Asseateague

Island Weather Station (ASTM2). Wind data were also interpolated to 1-second intervals to match the sound data collection rate. All three data sets were merged based on time stamps by software developed in-house. The parameters listed below under numeral 1 were used to determine specific dredging activities. For example, if vessel speed exceeded 6 knots, the dredge was considered to be in "transit" either to or from the borrow area. If water density (determined by DQM data) was less than 1.05 g/cc, the dredge was flushing pipes with clear water at either the borrow site or pump-out station. A slurry density exceeding this value would indicate movement of material through the pipes. Vessel heading was used to determine the destination of the dredge. For example, a heading between 20^{o} and 160^{o} indicated that the dredge was moving east in the direction of the borrow area. Conversely, a vessel heading of 200^{o}-340^{o} indicated a westerly movement towards the pump-out stations. Additional parameters are listed below.

1. Dredging activities and dredge position were determined based on the following parameters:
    a. Minimum transit speed = 6 knots
    b. Maximum digging speed = 4 knots
    c. Minimum digging depth = 25 ft
    d. Minimum digging pump RPM = 100 RPM
    e. Maximum pump-out speed = 3 knots
    f. Maximum pump-out depth = 3 ft
    g. Minimum pump-out for water only = 100 RPM
    h. Minimum pump-out for sediment = 250 RPM
    i. Maximum water density = 1.05 g/cc
    j. Transit to borrow area (direction = east), heading = 20^{o} to 160^{o}
    k. Transit to pump-out (direction = west), heading = 200^{o} to 340^{o}
    l. Transit unknown = 160^{o} to 200^{o} or 340^{o} to 20^{o} (course/heading typical during maneuvering of vessel approaching or departing pump-out station)
    j. Dredge located > 3 km from LP = Sufficient separation distance between dredge and listening platform to collect ambient data
2. Based on the above parameters, data were organized using the following dredge operational modes:
    a. Digging (drag arms down (> 25 ft), pumps on, RPM > 100)
    b. Transition from digging to transit (drag arms raised (< 25 ft), pumps turned off, and vessel speed increased)

c. Transit to pump-out (maximum safe speed (> 6 knots, typically 10-14 knots) heading west towards pump-out station)
d. Transition from transit to pump-out (minimum maneuvering speed and hooking up to the pump-out apparatus)
e. Pump-out water (drag arms up, pumps running, and material density < 1.05 g/cc.
f. Pump-out of material (same as previous but with a material density > 1.05 g/cc
g. Transition from pump-out to transit (disconnecting from the pump-out apparatus, maneuvering dredge towards the borrow area, increasing vessel speed)
h. Transit to borrow site (maximum safe vessel speed > 6 knots, typically 10-14 knots) moving east toward borrow area)
i. Transition from transit to digging (decreasing vessel speed, deploying dragarms)

3. Dredge determined “closest” to the LP. Given the distance from the borrow area to the offshore pump-out stations, two dredges were rarely in close proximity during the same or different operational phases. In the few instances when this did occur (e.g., two dredges removing sediment at the borrow area concurrently), the distance separating the two dredges was still sufficient to allow detection of only one. By default, this dredge was the one being monitored. There was no evidence of increased SPL (rms) when two dredges were working concurrently. This is not surprising, given that cavitation (propeller noise) contributed the most to the overall sound field. If, for example, the LP was closest to the dredge *Liberty*, one would not be able to detect any sounds associated with the dredging process from a second dredge located further away. Dredges working concurrently didn’t raise the level of noise produced in a specific area, but did produce two separate zones or areas of influence.
4. Generation of numerous CSV output files for SPL (rms) and 1/3-octave data binned by range (distance from LP to dredge), and sorted by dredge plant and dredge operational mode.
5. Generation of output files for “ambient” data results. Data collected when all dredges were beyond a specified range of 3,000 m. Ambient data were sorted by location and Beaufort wind scale. Results were determined for:

   a. Offshore/Borrow Area
   b. Inshore/Pump-out Stations (Combined)
   c. Inshore Pump-out site (North site used by dredges *Padre and Dodge Island*)

   d. Inshore Pump-out site (South site used exclusively by the Dredge *Liberty Island*)
   e. Beaufort Scales (1-4)

6. Summarize data in tables and graph results for each dredge and dredge action for report preparation.
7. Estimate the Source Level (SL). Transmission loss (TL) was estimated by regressing SPL versus distance for all measurements taken throughout the study. The regression equation was expressed as natural log SPL= -6.852lN (range) + 171.52, R^2 = 0.9777, and the natural log was then converted to $\log_{10}$ to yield the calculated loss based on $\log_{10}$. Transmission loss was estimated as 15.778 Log R, which approximates practical spreading. The SL is derived by correcting the Received Levels for the range from the source using the spreading correction (SL = RL + TL). This is the most frequently used procedure to describe vessel noise reported in the scientific literature. SLs were also estimated for dredge operational modes.

Note that the SLs in this report were generally estimated using SPLs recorded at 50 m from the source, 150 m from the source, and/or the closest distance at which data were otherwise collected. As a general rule, SLs generated from SPL recorded at a distance of 150 m from the source were also used to compare dredges and dredging activities. For instances in which data were available at 50 m from the source, SLs were also estimated using the SPL. The intent was to show the variability in estimated SL, particularly when using the closest distance (50 m) at which data were available. In the few instances in which data were not available at either 50 m or 150 m from the source, the closest distance at which data were recorded was used to back-calculate SL. SLs were then determined using that distance to compare dredges and dredging events.

3 Results and Discussion

Water quality

No evidence of stratification was found at either the offshore borrow area or the inshore pump-out stations. Water temperatures were somewhat cooler during the first 4 days of the study than later and varied by less than 1.5 ^{o}C from surface to bottom. During the remainder of the study, the slightly warmer temperatures varied by less than 0.5 ^{o}C (average 13.5$\pm$0.5 ^{o}C) from surface to bottom. No evidence of salinity stratification at either the borrow area or inshore pump-out stations was observed. Salinity ranged from 34 ppt (surface) to 34.5 ppt (bottom). Bottom depths ranged from < 30 ft (< 9 m) MLW at both the North pump-out station and Unnamed Shoal A and from 32 to 36 ft (9.7 to 10.9 m) MLW at the south pump-out station. In the immediate vicinity of Unnamed Shoal A, water depths increased to between 40 ft (12.1 m) and 70 ft (21.2 m) MLW. Temperature and salinity readings were generally taken to within 1m of the bottom depth.

Ambient sound

A total of 23,480 ambient data measurements were recorded during the course of the study. No measurements were obtained when weather conditions were calm (Beaufort 0); only 3% (n= 757) of the total measurements were obtained during Beaufort 1 conditions where wind speeds reach 3 mph (1-2 knots) with a maximum wave height of 1 ft. The majority of ambient measurements (59%) occurred during Beaufort 2 conditions with wind speeds of 4-7 mph (3.6 knots) with wave heights of 1 to 2 ft. Slightly greater than one-quarter of the measurements were obtained during Beaufort 3 conditions, with wind speeds of 8 to 12 mph (7-10 knots) and wave heights ranging from 2 to 3.5 ft. Beaufort 4 conditions with wind speeds of 13 to 17 mph (11-15 knots) and wave heights ranging from 3.5 to 6 ft accounted for slightly more than 11% of the total measurements.

Ambient SPLs averaged 117 dB re 1µPa across all sampling days, sites, water depths, and weather conditions. At the two pump-out stations, ambient SPLs differed by less than 0.5 dB between the upper (3 m) and lower (6 m) recording depths. At the offshore borrow area, ambient SPLs were as much as 2 dB higher in the upper water column (RL = 117 dB at 3 m) than at the deeper listening depth (30 ft; RL = 114.9 dB at 9.1 m). Ambient SPLs and 1/3-octave band levels are summarized in Table 2.

Table 2. Summary of ambient SPL (dB rms) results by site.

Location	Data Points	[3]ULD (SPL rms)			[4]LLD (SPL rms)			AVG[5] SPL	1/3 Octave (SPL)		
		MIN	MAX	AVG	MIN	MAX	AVG		ULD	LLD	AVG
Overall[1]	23480	91.3	147.5	117.4	99.1	145.4	116.6	117.0	121.2	120.4	120.8
Inshore only[2]	9846	91.8	135.8	117.9	99.1	145.4	118.1	118.1	118.1	120.9	119.8
NPO[a]	8894	91.8	135.8	118.1	99.1	145.4	118.2	118.1	118.0	120.9	119.7
SPO[b]	952	103	127.9	117.1	107	132.7	117.4	117.3	119.0	121.3	120.3
Borrow Area	13634	91.3	147.5	117.0	99.1	138.3	114.9	116.1	122.6	119.9	121.4

[1]Overall = All inshore (pump-out stations) and the offshore borrow area combined.

[2]North (NPO[a]) and South (SPO[b]) pump-out stations combined.

[3]ULD = Upper listening depth, hydrophone deployed at 3-m water depth.

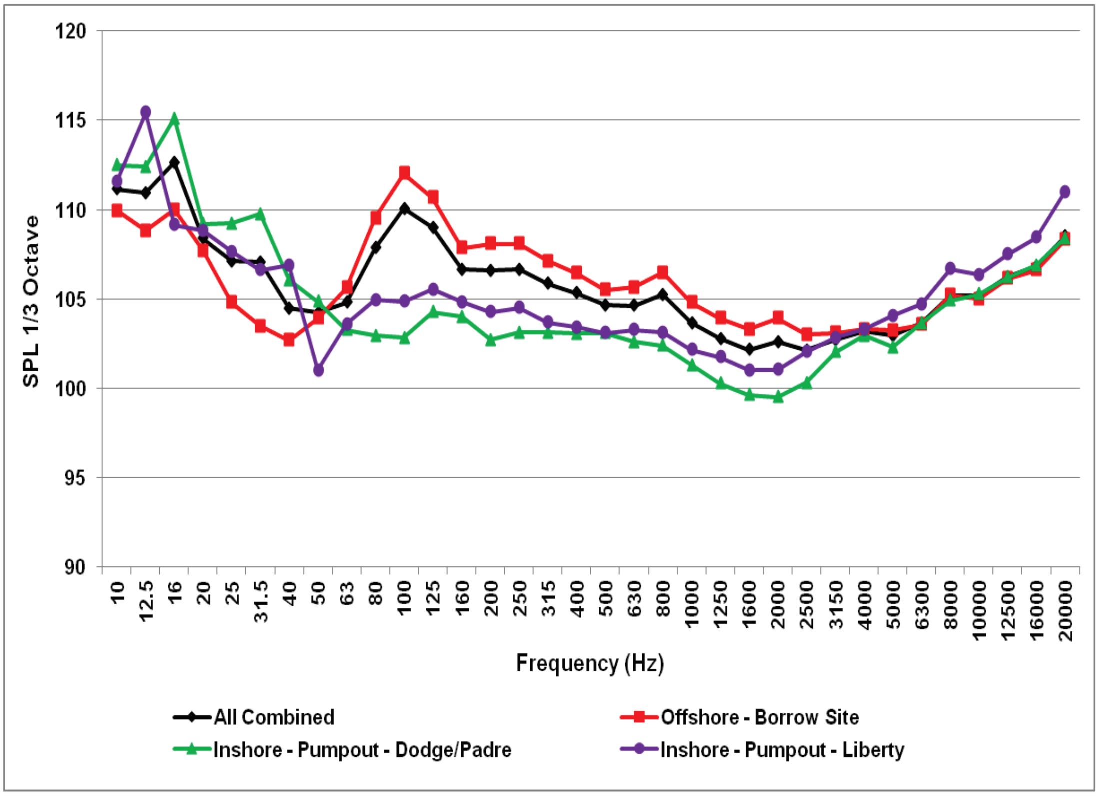
[4]LLD = Lower listening depth, hydrophone deployed at 6-m (inshore) and 9-m (offshore) water depth.

[5]Logarithmic average of SPL of the upper and lower listening depths.

Minimum RLs (ULD) were typically around 91 dB with the exception of the southern pump-out (SPO) station (103 dB). The SPO station was located in less protected or sheltered waters. Data collection at this site was limited to 952 ambient measurements, all at Beaufort 3 wind conditions. For the LLD, minimum RLs were typically 8 dB higher, again with the exception of the SPO station, which had a 4-dB increase. Maximum RL peaked at 135.8 dB inshore and 147.5 dB offshore. Maximum RLs were higher for LLD compared to ULD at both pump-out stations, but lower at the offshore borrow area. Percentile values are given to further characterize ambient conditions and define the extreme observations of the overall range. The upper (P5%) and lower (P95%) percentile values for the ULD were 97.5 and 125.3 dB, respectively, at the inshore sites and 97.5 and 121 dB at the offshore borrow area. Ambient SPLs (P5 and P95) for the LLD were slightly higher at 103.7 and 124.1 dB inshore and 104.5 and 120.5 offshore. Logarithmic averaging of both the ULD and LLD produced values of 102.5 and 124.5 dB inshore and 103.2 and 120.7 dB offshore.

For both inshore and offshore sites, 1/3-octave SPLs were determined (Figure 2). At the northern pump-out (NPO) station, 1/3-octave SPLs were nearly 3 dB higher at the LLD than at the ULD. A similar pattern occurred at the SPO station, where 1/3-octave SPLs were slightly more than 2 dB higher at the lower listening depth (6 m). At the offshore borrow area, 1/3-octave SPLs (119.9 dB) were nearly 3 dB quieter at the 9.1-m listening depth compared to the upper (122.6 dB) listening depth (3 m).

Figure 2. Ambient SPL (dB re 1μPa rms) results from the 1/3-octave analysis.



Ambient sound levels in shallow coastal areas can be expected to vary temporally and spatially. Three primary sound sources in shallow coastal environments are associated with shipping and industrial sounds, wind- and wave-induced sounds, and sounds of biological origin (Richardson et al. 1995). Consequently, measurement of ambient sound levels should occur at a number of locations and for a substantial time period. Ideally, characterizing ambient sound levels would involve substantially more time than that available in the present study. Therefore, ambient levels reported herein must be considered "time-specific," having been sampled intermittently both spatially and temporally. Results of the present study indicate the prevailing ambient sound levels during the monitoring period.

Ambient SPLs were relatively high given sea state conditions; this can be expected in part due to the relationships among noise, sea state, and the Beaufort wind scale. Wenz (1962) compiled data from multiple sources and estimated an RL between 60 and 70 dB re 1μPa^2/Hz at Sea State 4, which closely corresponds to Beaufort wind force 4, the maximum observed during the present study. A major factor in the higher ambient SPL is attributed to waves slapping the side of the survey boat. This phenomenon unavoidably created a nearly constant amount of "self-noise," which cannot be separated from the “true” ambient sounds. Swells also tended to lift and drop the hydrophone assembly, essentially dragging it through the water column. Infrasonic noise at frequencies less than 20 Hz is caused largely by surface waves, especially in shallow water and turbulent pressure fluctuations (Richardson et al. 1995).

Spikes (tones) are distinguishable in data from the present study at 100 Hz and 800 Hz at frequencies in the range commonly associated with wave and shipping noise. Even during times when all three dredges were at the borrow area or in transit to or from the borrow area at distances greater than 3 km from the hydrophones, sounds associated with support vessels (dredge tugs) and recreational boating traffic were evident. This issue was more problematic inshore than offshore. Every attempt was made to record ambient data files during minimal boating or dredge support vessel activities. Highest SPLs were found in 1/3-octave frequency bins of less than 200 Hz. However, there was an increase in SPLs from 5 to 20 Hz and from 63 to 160 Hz, as shown in Figure 2. As reported by Hildebrand (2009), in the absence of anthropogenic and biological sounds, ambient noise is wind-dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz. The authors concluded that oscillating bubbles in the water column are the primary sound source, both as individual bubbles and as bubble clouds. This may explain the rise in SPLs at frequencies above 5 kHz. Another possible source may be an internal electrical source of unknown origin.

Ambient sound levels were relatively high and fell within the range of values measured by Blackwell and Greene (2002) in Cook Inlet, Alaska (an area known for high hydrodynamic flow conditions). Their RLs ranged from 95-120 dB at eight locations. Highest RLs were reported near Elmendorf Air Force Base and north of Point Possession, Alaska. Robinson et al. (2011) reported 1/3-octave band RLs exceeding 110 dB at the center bin frequency of 16 Hz and over 100 dB re 1µPa^2 for center bin frequencies to 2 kHz. Neither of these studies reported a sharp rise in SPLs at frequencies greater than 5 kHz. Ambient Received SPLs of 131-134.5 dB were recorded during monitoring of a small 1,300-m^3 TSHD during sand wave removal in the Kennebec River, Maine (Reine et al., in preparation). Minimum and maximum SPLs were 125.2 and 141.4 dB, respectively. These high RLs were largely attributed to high hydrodynamic flow noise in the Kennebec River.

Transit to borrow area

All three dredges were monitored during the transit phase to the borrow area. Several factors differentiated dredge transit operations, especially the dredge *Liberty Island* from the smaller *Padre Island* and *Dodge Island*. Propulsion power (kW) was 2.3 times greater for the *Liberty Island* than the *Padre Island* and 3.3 times greater than the *Dodge Island*. The dredge *Liberty Island* recorded the fastest transit speeds at 12 knots, followed by the *Dodge Island* at 11 knots, and the *Padre Island* at 10.1 knots. Forward vessel draft differed by less than 0.5 ft among the dredges. Stern vessel draft was greatest for the dredge *Liberty Island* (19.6 ft), followed by the *Dodge Island* (15.1 ft), and *Padre Island* (13.9 ft). Displacement was highest for the *Liberty Island* at 6,352 LT, as compared to 4,630 LT for the *Dodge Island* and 4,496 LT for the *Padre Island*. Suction pumps were used intermittently by the *Padre Island* and *Dodge Island* during transit to provide ballast water for vessel stability. When in use, the port and starboard suction pumps peaked at 135 rpm for the dredge *Padre Island*. Higher port and starboard pump speeds (630-650 rpm) were recorded for the dredge *Dodge Island*. The dredge *Liberty Island* did not use its suction pumps during transit to the borrow area. Hopper volume ranged from an average of 1,775 yd^3 (*Dodge Island*) to 2,008 yd^3 (*Liberty Island*).

At the start of the monitoring period, weather conditions were generally favorable (Beaufort Scale 1-2), before degrading (Beaufort scale 3-4) as the monitoring session progressed. Time spent at each wind force category was equalized in order to compare dredges. Sessions for both the *Dodge Island* and *Liberty Island* had a 2.3 Beaufort scale average, whereas the Padre Island session averaged 2.4. Average wind speeds were highest during the Dodge Island session at 3.3 m/sec, followed by the *Padre Island* session at 3.0 m/sec, and the Liberty Island session at 2.5 m/sec. Wind gusts were highest during the *Padre Island* session at 10.4 m/sec, followed by the *Dodge Island* at 9.8 m/sec, and *Liberty Island* at 6.2 m/sec.

Received SPL versus distance for each dredge is presented in Figure 3 and summarized in Table 3. Figure 4 and Table 4 summarize selected distances for 1/3-octave analysis results.

Padre Island

A total of 4,418 SPL measurements were recorded for the dredge *Padre Island* during transit to the borrow area. RLs decreased from 137.25 dB at 50 m from the source to below ambient (117 dB) at 2.1 km from the source.

Figure 3. Comparison of SPLs for dredges in transit to borrow area.

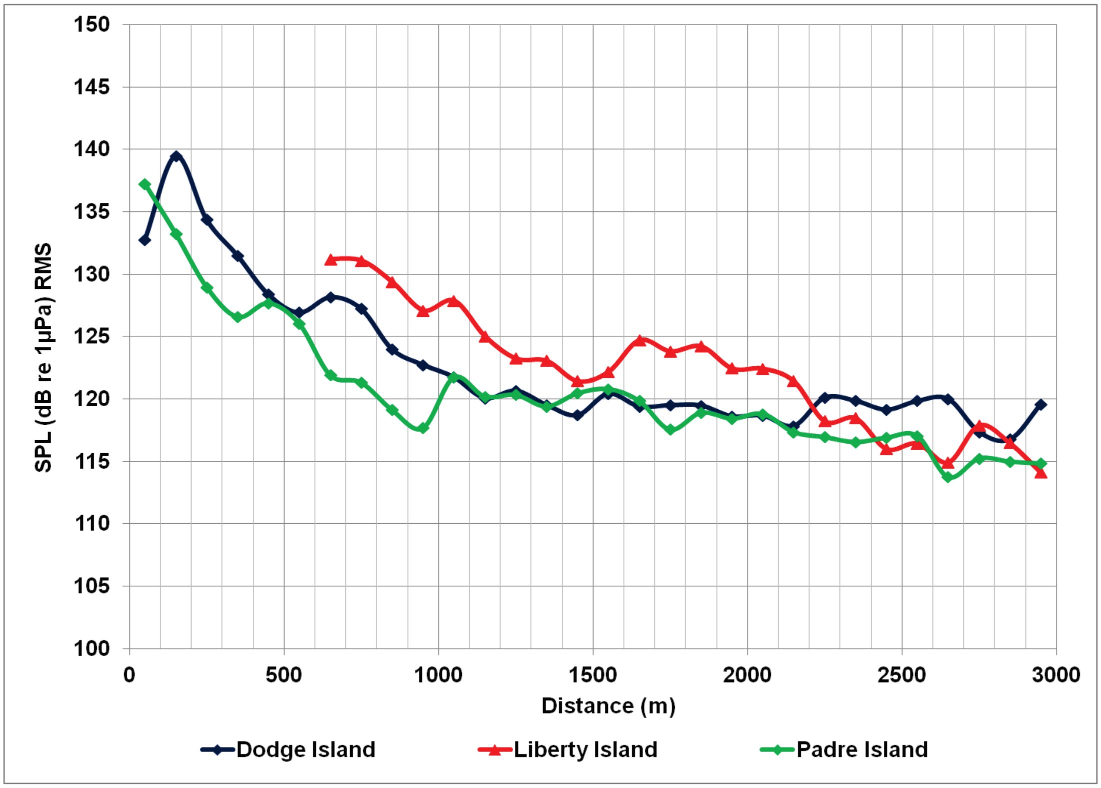


Figure 4. Results of 1/3-octave analysis at selected distances during transit to borrow area. Note: No recordings were obtained for the Dredge *Liberty Island* at distances less than 550 m.

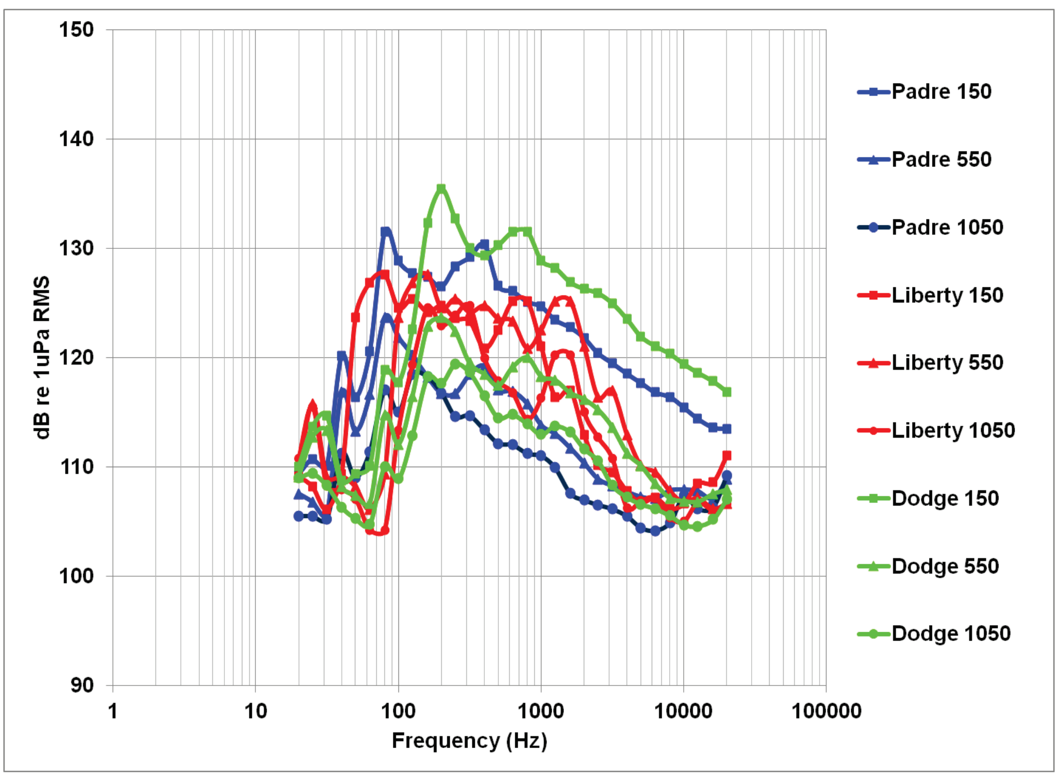


Table 3. SPL (dB rms) results for dredges in transit to borrow area.

Range	Padre			Dodge			Liberty		
	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	137.16	137.33	137.25	131.48	133.71	132.74			
150	132.62	133.79	133.24	139.76	139.21	139.49			
250	128.53	129.36	128.96	134.39	134.4	134.39			
350	126.17	126.91	126.56	131.39	131.6	131.5			
450	128.07	127.23	127.67	128.07	128.67	128.38			
550	126.55	125.42	126.02	126.65	127.18	126.92	130.98	130.96	130.97
650	121.85	121.98	121.91	128.02	128.29	128.16	130.97	131.42	131.2
750	121.65	120.95	121.31	127.2	127.26	127.23	130.68	131.43	131.07
850	117.13	120.48	119.12	123.64	124.31	123.99	128.96	129.7	129.35
950	115.68	119.01	117.66	122.28	123.15	122.74	126.47	127.64	127.09
1050	120.63	122.6	121.72	121.26	122.19	121.75	127.16	128.47	127.86
1150	119.12	121.05	120.19	119.7	120.42	120.07	124.37	125.56	125.01
1250	119.64	120.93	120.33	120.07	121.17	120.66	122.21	124.08	123.24
1350	119.04	119.73	119.4	118.93	120.05	119.52	121.87	123.98	123.05
1450	119.76	121.05	120.45	117.74	119.49	118.7	121.59	121.25	121.42
1550	120.3	121.22	120.79	120.38	120.49	120.43	122.92	121.29	122.18
1650	119.65	120.05	119.85	119.51	119.28	119.4	125.53	123.7	124.71
1750	117.14	117.91	117.54	119.71	119.28	119.5	124.87	122.41	123.81
1850	118.88	118.91	118.9	119.96	118.91	119.47	125.28	122.78	124.21
1950	118.29	118.57	118.43	118.82	118.38	118.61	123.24	121.45	122.44
2050	117.47	119.81	118.8	119.16	118.13	118.67	123.34	121.28	122.43
2150	117.31	117.38	117.34	117.64	118.03	117.84	119.72	122.64	121.42
2250	116.71	117.18	116.95	118.19	121.42	120.1	118.51	117.89	118.21
2350	116.58	116.52	116.55	119.7	120	119.85	119.31	117.38	118.45
2450	116.47	117.29	116.9	119.38	118.89	119.14	114.55	117.08	116
2550	116.32	117.67	117.04	120.71	118.75	119.84	116.8	116.05	116.44
2650	113.32	114.13	113.74	121.33	118.1	120	114.64	115.18	114.92
2750	115.64	114.78	115.23	118.61	115.56	117.35	118.5	117.19	117.89
2850	114.0	115.79	114.98	117.22	116.25	116.76	116.03	116.83	116.45
2950	115.44	114.13	114.83	121.17	117.07	119.58	112.15	115.46	114.11

Table 4. 1/3-octave results for dredges in transit to borrow area.

Range	Padre			Dodge			Liberty		
	ULD	ULD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	140.77	141.16	140.97	140.79	141.02	140.9			
150	139.67	139.62	139.65	144.57	144.27	144.43			
250	136.74	141.27	139.57	140.26	139.98	140.12			
350	132.18	132.28	132.23	137.7	137.43	137.57			
450	132.71	131.55	132.17	134.28	134.16	134.22			
550	131.25	130.29	130.8	132.4	132.23	132.32	136.21	136.3	136.37
650	127.93	127.32	127.63	132.78	132.65	132.72	136.23	136.27	136.25
750	126.74	126.05	126.41	131.81	131.47	131.64	136.28	136.52	136.4
850	123.57	125.66	124.74	129.6	129.49	129.54	134.51	134.73	134.62
950	123.17	124.92	124.13	127.97	128.05	128.01	132.93	133.29	133.11
1050	126.6	127.55	127.1	127.19	127.19	127.19	132.2	132.64	132.43
1150	124.53	125.6	125.1	125.66	125.76	125.71	130.37	130.72	130.55
1250	125.38	126.09	125.75	125.43	125.64	125.54	128.85	129.51	129.19
1350	124.13	124.84	124.5	123.8	124.22	124.01	128.01	128.64	128.34
1450	125.66	125.99	125.83	123.2	123.84	123.53	129.04	127.58	128.37
1550	125.54	125.73	125.64	122.57	124.07	123.38	128.33	126.73	127.61
1650	124.04	124.54	124.3	121.56	122.53	122.07	129.39	127.92	128.72
1750	122.15	122.74	122.45	121.39	123.02	122.28	128.77	127.07	128
1850	123.44	123.71	123.57	121.41	122.74	122.12	129.03	127.11	128.17
1950	122.43	123.14	122.8	120.86	122.32	121.66	128.22	126.5	127.44
2050	121.66	122.53	122.12	120.48	121.11	120.81	127.41	126.08	126.8
2150	120.89	121.62	121.27	120.25	120.99	120.63	123.79	124.95	124.41
2250	120.52	121.49	121.03	120.25	122.02	121.23	121.73	122.26	122
2350	120.68	121.89	121.32	120.16	121.9	121.12	122.05	122.86	122.47
2450	122.09	122.65	122.38	119.67	121.01	120.39	121.48	122.54	122.04
2550	122.47	122.9	122.69	127.25	121.3	125.23	121.01	121.72	121.38
2650	119.58	119.9	119.75	129.72	121.67	127.34	120.21	121.41	120.85
2750	119.34	120.05	119.71	121.9	121.4	121.66	120.16	121.82	121.07
2850	119.11	119.8	119.47	126.24	120.55	124.27	120.08	121.19	120.67
2950	119.16	119.75	119.46	122.62	121.91	122.28	120.23	121.54	120.93

Sound generated during transit exceeded ambient noise by as much as 20 dB at the closest recording distance. Derived from the log-averaged (ULD and LLD) SPL at 150 m (133.24 dB), SL is estimated at 167.6 dB re 1 µPa-1 m. This

SL is 3.6 dB louder than the SL (164 dB re 1 µPa-1 m) estimated from using the maximum SPL rms recorded at a distance of 50 m.

Sound attenuated fairly rapidly. At 850 m from the source, SPLs exceeded ambient by only 1 to 3 dB. RLs were slightly higher (1-3 dB) at the LLD, with most listening stations differing by only 1 dB. Minimum RLs were slightly less than 97 dB for ULD and 104.2 dB for LLD at distances greater than 2.7 km from the source. Maximum RLs were recorded at 150 m from the source at 142.1 dB and 141.6 dB for ULD and LLD, respectively. Maximum SPLs exceeded ambient by as much as 25 dB.

Peak frequencies centered around 80 Hz (1/3 octave) with a second peak around 400 Hz. Peak SPL (1/3 octave) occurred at the LLD at 141.3 dB at 250 m from the source. At that distance, 1/3-octave SPL at the ULD was nearly 5 dB quieter (136.7 dB). This value was somewhat of an outlier, given that SPL differences between the ULD and LLD generally varied by only 0.5 to 1 dB. Generally higher SPLs occurred nearer the source at the ULD and farther from the source at the LLD. At 2.65 km from the source, 1/3-octave levels fell below ambient (120.8 dB).

Dodge Island

A total of 3,222 sound measurements were recorded for the dredge *Dodge Island* while in transit to the borrow site. RLs decreased from 132.7 to 117 dB, attenuating to ambient at 2.7 km. Relatively low SPLs (log average 132.7 dB) were recorded at 50 m from the source. At 150 m from the source, RLs averaged 139.5 dB or 22.5 dB above ambient, which was approximately 7 dB louder than the SPL recorded at 50 m. Derived from the maximum SPL rms (139.5 dB) at 150 m, SL is estimated at 173.83 dB re 1 µPa-1m.

From 1.1-2.3 km, SPL exceeded ambient by only 1 to 2 dB, with louder sounds recorded at the LLD. From 2.45-3 km, SPL increased by as much as 4 dB at the ULD. Minimum RLs were slightly less than 96 dB for ULD and 106 dB for LLD at distances greater than 2.6 km from the source. Maximum RLs were detected at 150 m from the source at 149 dB (ULD) and 147.4 dB (LLD). Maximum RL exceeded ambient by 32 dB.

Peak frequencies centered around 200 Hz with a second peak centered around 600-800 Hz. SPLs peaked at 144.4 dB at 150 m from the source. Maximum SPL (rms) exceeded ambient (120.8 dB) by nearly 24 dB and was approximately 5 dB higher than the dredge *Padre Island* at the equivalent distance. SPLs decreased to 11.5 dB above ambient over the next 400 m and to less than 5 dB at 1.2 km from the source. One-third octave SPLs were generally less than 0.5 dB higher at the ULD compared to the LLD at a range of 1.5 km. However, they were up to 1.7 dB lower at distances from 1.5 to 2.5 km. RL increased from 2.55 to 2.95 km, ranging from 0.5 to 8.1 dB higher at the ULD.

Liberty Island

A total of 998 sound measurements were recorded while the *Liberty Island* was in transit to the borrow area. No sound recordings were made at distances closer than 550 m. Maximum SPL (rms) was 131.3 dB at the ULD at a distance of 550 m from the dredge. At this distance, and assuming a loss of 41.86 dB, the SL would be estimated at 173.2 dB re 1 µPa-1m.

Attenuation of SPLs to ambient occurred at 2.45 km from the source. Slightly higher (less than 2 db) SPLs were recorded at the LLD compared to the ULD at a distance of 1.35 km from the source. From 1.45 km to 2.1 km, SPLs at the LLD were as much as 2.5 dB lower when compared to the ULD. RLs showed greater variation at distances greater than 2.1 km. Minimum RLs were slightly less than 106 dB at the ULD and 114 dB at the LLD at distances greater than 2.6 km.

Because no measurements were obtained at distances closer than 500 m from the source, maximum 1/3-octave SPLs were not obtained in the near-field. One-third octave measurements were similar at 550 m from the source at 136 dB (both listening depths), falling to 120.23 (ULD) to 121.5 (LLD) at 2.95 km. At the maximum range (3 km), SPLs still exceeded ambient by 0.7 dB, but only at the LLD. SPL were generally less than 0.5 dB higher at the LLD than at the ULD at distances less than 1.4 km from the source. The reverse was true at distances from 1.4-2.1 km from the source, where SPLs ranged from 1.5-2 dB higher at the ULD. At 2.1-3 km from the source, this pattern reversed again in that SPLs at the LLD were 0.5-3 dB higher. Peak frequencies centered around 100 Hz, with secondary peaks centered around 600-800 Hz and 1000-1100 Hz.

Transit to borrow area discussion

SPL values were compared to distance among the three TSHDs. SPLs for the *Liberty Island* exceeded the *Dodge Island* by 2-6 dB at listening stations from 550 m to 2.35 km from the source. At the farthest listening stations (2.45-

3 km), SPLs for the *Dodge Island* exceeded those for the *Liberty Island* by 2-5 dB. No SPL data were obtained for the dredge *Liberty Island* at distances of less than 550 m. A similar pattern occurred when comparing the *Liberty Island* to the *Padre Island*. At listening stations ranging from 550 m to 2.85 km from the source, SPLs for the *Liberty Island* exceeded the *Padre Island* by as much as 10 dB (at the 850-m listening station), although more typically from 3-5 dB. Two exceptions occurred at the 2.45- and 2.55- km listening stations, where SPLs for the *Padre Island* exceeded the *Liberty Island* by less than 1 dB. When comparing the two smaller dredges (*Padre Island* and *Dodge Island*), SPLs were higher for the *Dodge Island* at 23 of 29 listening stations. Differences in SPL were as high as 6 dB. At the six stations where the SPL for the *Padre Island* exceeded the *Dodge Island*, differences were less than 2 dB. At the farthest listening station (2.95 km), SPLs for the *Dodge Island* exceeded the *Padre Island* by 5.5 dB.

SLs were also compared among the three TSHDs. Using peak SPL recorded at the 150-m distance, SLs for the *Dodge Island* (173.83 dB re 1 μPa-1 m) exceeded the *Padre Island* (167.6 dB re 1 μPa-1 m) by 5.9 dB. Because no data were available for the *Liberty Island* at distances closer than 550 m, SLs were recalculated based on SPL at this distance (550 m) for all three dredges. SLs for the *Liberty Island* exceeded those of the *Dodge Island* and the *Padre Island* by 4 dB and nearly 5 dB, respectively. Almost no difference was observed between the *Dodge Island* and *Padre Island* when using maximum SPLs obtained from the 550-m listening station to back-calculate SL. SL for the *Dodge Island* exceeded the *Padre Island* by only 0.64 dB.

Both the dredge *Padre* and the *Liberty* had peak frequencies centered around 80 Hz at 150 m. The lowest peak frequency for the dredge *Dodge* was 200 Hz. Secondary peaks (at 150 m) occurred at 400 Hz for the dredge *Padre* and between 600 and 800 Hz for dredges *Dodge* and *Liberty*. Energy declined rapidly above 1 kHz for both dredges *Padre* and *Dodge Island*. Only the *Liberty Island* had a subsequent peak exceeding 1000 Hz at both 550 m and 1050 m (Figure 4). The only major factor contributing to differences in peak frequencies can be attributed to the much higher propulsion power associated with the dredge *Liberty*.

Sediment removal (digging)

DQM parameters logged during the sediment removal process indicated that average dredge speed for both the *Dodge Island* and *Padre Island* was 1.2 knots, whereas the *Liberty Island* averaged 1.8 knots. The dredges *Dodge*

Island and *Padre Island* had similar vessel drafts at 18 ft (forward) and19±0.5 ft (aft). The dredge *Liberty Island* had a deeper draft of 25.5 ft (forward) and 27.2 ft (aft). Displacement was similar for both the *Padre Island* and *Dodge Island* at 6,642 LT and 6,335 LT, respectively. The dredge *Liberty Island* had nearly twice the displacement at 11,223 LT. Pump speeds averaged less than 187 rpm for both the port and starboard pumps (maximum = 195 rpm) for the *Liberty Island* and 241 rpm (maximum = 249 rpm) for the *Padre Island*. The *Dodge Island* logged much higher pump speeds averaging 992 rpm (starboard) and 1,047 rpm (port).

Velocity of the water-sand slurry varied from 21 ft/sec (pump speed = 959 rpm) to 29 ft/sec (pump speed = 1258 rpm) for the dredge *Dodge*. The *Dodg*e did briefly reduce the starboard pump speed to 149 rpm, which reduced flow velocity to only 2.4 ft/sec. For the dredge *Padre*, slurry velocity varied from 20-26 ft/sec with minimal changes in pump speed (10-15 rpm). Flow rates were lowest for the dredge *Liberty*, averaging 21-22 ft/sec (range 15-23 ft/sec) at pump speeds between 180 and 190 rpm. The *Liberty* did reduce the port-side pump speed to 150.9 rpm for a brief period of time during monitoring, which reduced material flow through the pipe to 15.4 ft/sec. In rank order, pump speed and flow velocity were highest for the dredge *Dodge*, followed by the *Padre* and *Liberty*.

Production rates varied between dredges and monitoring sessions. For example, the dredge *Dodge* averaged 29-59 yd^3/min (1380-3531 yd^3/hr) during three monitoring sessions from 3 May to 12 May. The production rate was highest on 7 May at 59 yd^3/min (3531 yd^3/hr). Production rates for the dredge *Dodge* were similar to the dredge *Padre* during three monitoring sessions (rates averaged 31.3 yd^3/min (1878 yd^3/hr) to 52 yd^3/min (3096 yd^3/hr). Also similar to the dredge *Dodge*, the highest production rate occurred on 7 May. Production rates for the dredge *Liberty* ranged from 44 yd^3/min (2665 yd^3/hr) on 12 May to 72.1 yd^3/min (4325 yd^3/hr) on 13 May. Sediment density (grams/cubic centimeter) was lowest for the dredge *Dodge* at 1.14 g/cc. Both dredges *Padre* and *Liberty* had equalivent values for slurry density at 1.24 g/cc.

Wind conditions were slightly more favorable during monitoring of the dredge *Dodge Island*, averaging 2.5 m/sec with gusts to 4.6 m/sec, and least favorable for the dredge *Liberty Island*, averaging 4 m/sec with gusts to 6 m/sec. A Beaufort wind force condition of 2 was typical during the beginning of the monitoring period for both the *Padre Island* and *Dodge*

Island before increasing to Beaufort wind force condition 3 towards the end of the monitoring period. Beaufort wind force condition 3 was present during the monitoring of the dredge *Liberty Island*.

For each dredge, received SPLs during sediment removal versus distance are presented in Figure 5 and summarized in Table 5. Results of the 1/3-octave analysis for each dredge are presented in Figure 6 and summarized in Table 6.

Padre Island

A total of 5,222 SPL measurements were recorded for the dredge *Padre Island* during sediment removal. A maximum SPL (dB rms) of 144.45 dB was measured at the LLD at 50 m from the source, exceeding ambient by 27.5 dB (rms). Assuming transmission loss of 26.81 dB at 50 m, SL is estimated at 171.3 dB re 1 µPa-1m (54 dB > than ambient). Using an SPL (138.7 dB rms) measured 150 m from the source and assuming a transmission loss of 34.33 dB, SL is estimated at 173 dB re1µPa-1m.

At 1 km from the source, RL fell by nearly 15 dB (RL = 129.6 dB), or approximately 12.6 dB above ambient. RL fell sharply from an average of 130.03 dB to 119.2 dB at a distance of 1.05-1.15 km from the source, or just 2 dB above ambient. SPL remained in the 117- to 119-dB range, at or just above ambient, over the next 300 m before increasing to nearly 124 dB at 2.05 km, the greatest distance for which data were obtained for the dredge *Padre Island*. With few exceptions, SPLs were 1 dB higher for the ULD as far as 1.5 km from the source, and from 1.7-2.7 dB higher at distances from 1.45-2.1 km from the source. Minimum SPL recorded for the dredge *Padre Island* was 93.4 dB (ULD) and 101.5 dB (LLD). Maximum SPLs were 154.1 dB (ULD) and 151.96 (LLD) recorded at a distance of 50 m from the dredge.

Maximum 1/3-octave SPL was 150.6 dB during monitoring of the dredge *Padre Island* and fell to 128.45 dB at 2.1 km from the source. No data were collected for the dredge *Padre Island* beyond this distance during sediment excavation. SPLs remained 6 dB (LLD) to 9 dB (ULD) above ambient at this distance. Peak frequencies centered around 150 Hz and 250 Hz, with a minor peak around 500 Hz at 150 m from the source. Sound energy decreased rapidly above 1 kHz.

Figure 5. Comparison of SPL (dB rms) during sediment excavation.

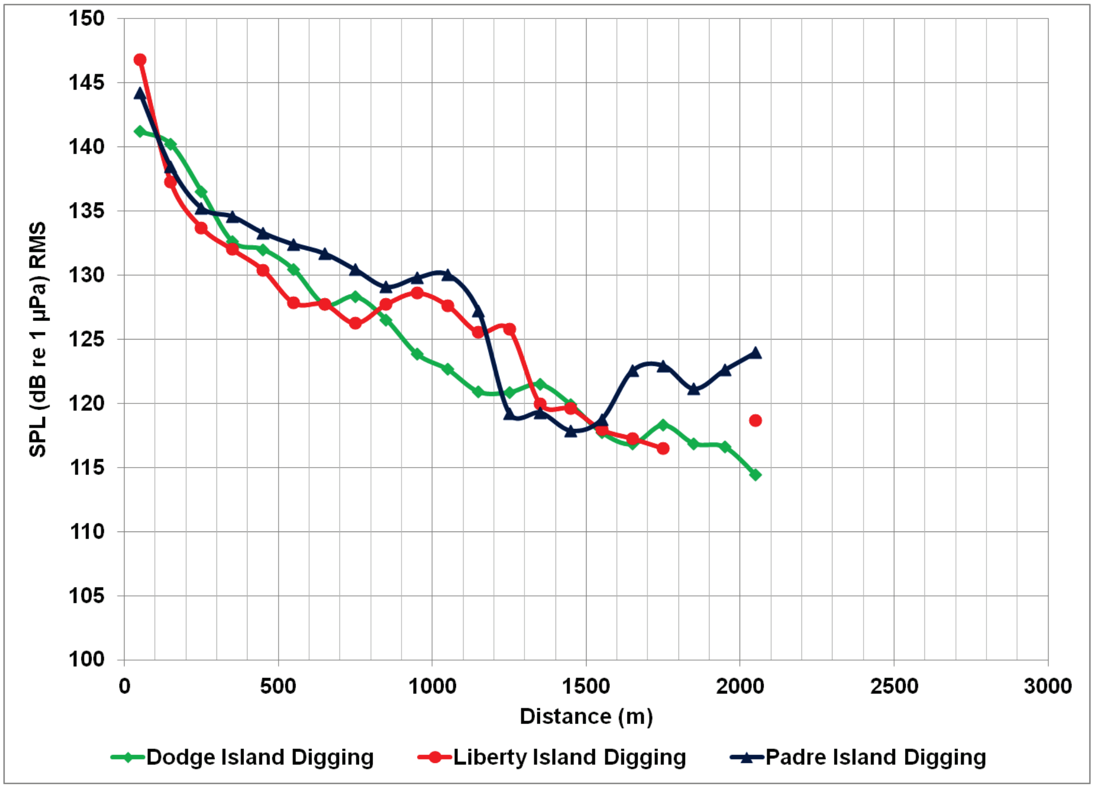


Figure 6. Results of 1/3-octave analysis during sediment removal at selected distances.

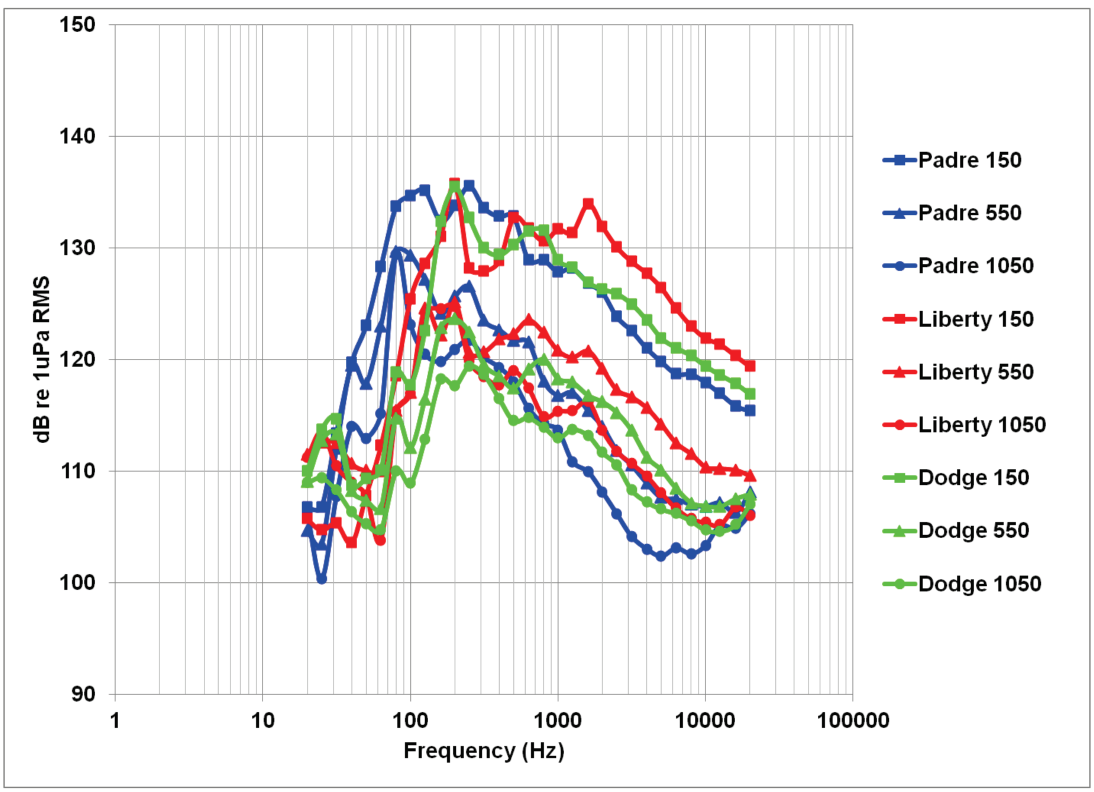


Table 5. SPL (dB rms) results by dredge during sediment excavation.

	Padre			Dodge			Liberty		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	143.93	144.45	144.2	141.17	141.19	141.18	147.4	146.1	146.8
150	138.17	138.7	138.44	140.16	140.22	140.19	137.14	137.38	137.27
250	135.23	135.2	135.22	136.18	136.79	136.5	133.73	133.67	133.7
350	134.4	134.71	134.56	132.31	132.89	132.61	131.84	132.15	132
450	133.55	133	133.28	131.51	132.43	131.99	129.62	131.07	130.4
550	132.71	132	132.37	129.91	130.88	130.42	127.65	127.99	127.82
650	132.08	131.22	131.67	126.86	128.42	127.71	127.56	127.89	127.73
750	130.86	129.92	130.41	127.5	129.01	128.32	126.17	126.32	126.25
850	129.48	128.63	129.07	125.53	127.33	126.52	127.86	127.58	127.72
950	130.33	129.16	129.78	123.33	124.3	123.84	128.61	128.61	128.61
1050	130.44	129.58	130.03	121.79	123.35	122.64	127.93	127.29	127.62
1150	127.71	126.6	127.19	120.97	120.82	120.9	125.73	125.33	125.53
1250	118.89	119.51	119.21	120.29	121.37	120.86	126.17	125.33	125.77
1350	119.21	119.34	119.28	120.23	122.45	121.48	120.12	119.83	119.98
1450	118.1	117.61	117.86	118.85	120.73	119.89	119.16	119.97	119.59
1550	119.47	117.85	118.74	117.78	117.69	117.73	117.14	118.64	117.95
1650	123.58	121.14	122.53	115.94	117.58	116.83	116.2	118.11	117.26
1750	124.12	121.3	122.93	117.23	119.17	118.31	116.21	116.76	116.5
1850	122.07	119.9	121.12	116.4	117.28	116.86			
1950	123.64	121.19	122.59	116.5	116.69	116.60			
2050	125.07	122.4	123.94	115.37	113.23	114.43	118.75	118.64	118.69

Dodge Island

A total of 6,041 SPL measurements were recorded for the dredge *Dodge Island* during sediment removal. Maximum Received SPL was at 141.2 dB (24 dB > ambient) at a distance of 50 m from the source at both the upper and lower listening depths. Assuming transmission loss of 26.81 dB at 50 m, SL is estimated at 168.14 dB re 1 µPa-1m (51 dB > ambient). Using an SPL (dB rms) at 150 m (140.2 dB) from the source and assuming a transmission loss of 34.33 dB, SL is estimated at 174.5 dB re 1µPa-1m.

RLs were not detected above ambient at 1.55 km from the source. Unlike the dredges *Padre* and *Liberty lslands*, there were no increases in SPLs at the 900-m and 1.05-km listening stations. Differences in received levels, although higher at the LLD, were small and generally averaged less than

Table 6. One-third octave results by dredge during sediment excavation.

	Padre			Dodge			Liberty		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	150.31	150.63	150.48	147.9	147.01	147.48	152.64	152.51	152.58
150	144.5	144.46	144.48	145.29	145.09	145.19	143.56	143.87	143.72
250	140.38	140.5	140.44	142.25	142.03	142.14	139.65	139.57	139.61
350	139.31	139.54	139.42	138.97	138.66	138.81	138.03	138.03	138.03
450	137.72	137.5	137.61	138.23	137.97	138.11	136.67	136.9	136.79
550	136.98	136.54	136.76	136.34	135.94	136.14	134.14	133.96	134.05
650	135.8	135.09	135.46	133.74	133.68	133.71	133.52	133.45	133.48
750	135.03	134.23	134.65	133.8	133.87	133.83	131.94	131.79	131.87
850	133.86	133.06	133.48	132.78	132.84	132.81	133.07	132.59	132.84
950	133.47	132.63	133.07	129.92	129.56	129.75	132.92	132.32	132.63
1050	133.47	132.67	133.09	129.12	128.64	128.88	132.23	131.55	131.90
1150	129.92	129.2	129.58	126.93	126.52	126.73	130.73	130.08	130.42
1250	122.28	122.58	122.43	128.59	127.99	128.3	130.5	129.61	130.08
1350	125.85	123.84	124.96	128.18	127.66	127.93	125.32	125.04	125.18
1450	127.85	125.19	126.72	126.51	126.09	126.3	124.5	124.92	124.71
1550	127.28	124.89	126.25	124.12	123.63	123.88	124.62	124.92	124.77
1650	130.21	127.17	128.95	123.53	123.35	123.44	124.9	125.14	125.02
1750	130.2	127.3	128.99	124.84	123.83	124.36	124.22	124.44	124.33
1850	129.29	126.41	128.08	123.39	122.65	123.04			
1950	130.63	127.52	129.35	121.69	121.77	121.73			
2050	129.67	126.75	128.45	118.61	119.19	118.91	125.5	125.73	125.62

1 dB. Minimum SPL recorded for the dredge *Dodge Island* were 99.6 dB (ULD) and 104.9 dB (LLD). A maximum SPL of 149 occurred at a distance of 150 m from the source at both the ULD and LLD.

Maximum 1/3-octave SPL was 147.9 dB (ULD), 27.1 dB above ambient at 50 m from the source. Peak frequencies centered around 100 Hz, with a second peak centered around 700-800 Hz, 150 m from the source. RL (1/3-octave) fell below ambient (120.8 dB) at approximately 2 km from the dredge. At 2 km, a peak frequency of 30 Hz was detected. This peak in noise was attributed to wave action slapping against the boat. A second peak was centered around 200 Hz at 2.05 km.

Liberty Island

A total of 6,656 SPL measurements were recorded for the dredge *Liberty Island* during sediment removal. Maximum received SPL was 147.4 dB at the ULD at 50 m distance from the source, or approximately 30.4 dB above ambient. Assuming transmission loss of 26.81 dB rms at 50m, SL is estimated at 174.21 dB re 1 µPa-1m (57.2 dB > ambient). Received SPL fell by nearly 10 dB (RL = 137.3 dB) over the next 100 m (total distance = 150 m) from the source. If using SPL (dB rms) at 150 m (137.3 dB) from the source and assuming transmission loss of 34.33 dB, SL is estimated at 171.6 dB re1µPa-1m.

RL fell to within 1 dB of ambient at 1.55 km and to below ambient at 1.75 km. There was no clear pattern of higher or lower RL at either the upper or lower listening depths. Differences between the two listening depths were generally less than 0.5 dB. Minimum SPLs were 120.7 dB (LLD) and 121.9 dB (ULD). Maximum SPL (dB rms) at 50 m from the source was higher at the ULD at 157.1 dB when compared to the LLD at 152.9 dB.

Maximum SPL (1/3 octave) was slightly greater than 152 dB at both the upper and lower listening depths, or approximately 31 dB above ambient. At 150 m from the source, peak frequencies were centered around 200 Hz, 500 Hz, and 1.1 KHz. SPL (1/3 octave) fell to 125 dB at 2.1 km, approximately 5 dB above ambient. Excluding the near infrasonic peak at 30 Hz, peak frequency centered around 200 Hz at a distance slightly greater than 2 km from the dredge.

Sediment removal (digging) discussion

SPL (dB rms) was compared to distance for the three TSHDs. RL for the *Dodge Island* exceeded that of the *Liberty Island* by 2 dB at distances closer than 750 m. At distances greater than 850 m, SPL (dB rms) values for the *Liberty Island* were as much as 9.5 dB louder, but more commonly 2 to 4 dB louder. The same trend of higher SPL (approximately 3 dB) at short distances and lower SPL (up to 5 dB) at greater distances was found when comparing the *Padre Island* to the *Liberty Island*. At the few stations where SPL for the *Padre Island* exceeded the *Dodge Island*, differences were less than 2 dB. At shorter distances, higher pump speeds for the *Dodge Island* (992-1,047 rpm) may explain the significantly higher SPL when compared to the *Liberty Island*, which used considerably lower pump speeds (200 rpm maximum). At greater distances, the much larger displacement of the *Liberty Island*

(11,223 LT) may be a key factor in producing higher SPLs than the *Dodge Island*. The *Liberty* has nearly twice the hopper capacity and gross tonnage, requiring much greater power for propulsion (7,400 kW) than either the *Padre* (2,237 kW) or *Dodge Island* (3,244 kW). SPLs attenuated to ambient levels at 1.55 km for the *Dodge Island* and 1.65 km for the *Liberty Island*. SPLs for the *Padre Island* decreased to ambient levels at 1.45 km, but increased above ambient levels at the remaining listening stations (> 1.5 km). Consequently, attenuation distance to ambient levels for the *Padre Island* during sediment removal cannot be estimated accurately.

Although the *Liberty Island* is the largest of the three dredges, it was the quietest during the sediment removal process in terms of SL estimated from SPL obtained 150 m from the source. SLs of the dredge *Dodge Island* (SL = 174.5 dB re 1 μPa-1m) were nearly 3 dB louder compared to the dredge *Liberty Island* (SL= 171.6 dB re 1 μPa-1m) and 1.4 dB louder than the dredge *Padre Island* (SL = 173 dB re 1 μPa-1m). SPLs at 150 m exceeded ambient by 23.2 dB for the *Dodge Island*, followed by 21.7 dB for the *Padre Island* and 20.3 dB for the *Liberty Island*. However, if maximum SPLs recorded at the 50-m listening station are used to estimate SL, then the dredge *Liberty Island* (SL = 174.2 dB re 1 μPa-1m) was louder than the *Padre Island* (171.26 dB re 1 μPa-1m) by 2.9 dB and the *Dodge Island* (168 dB re 1 μPa-1m) by 6.2 dB. The *Padre Island* was 3.2 dB louder than the *Dodge Island*. Differences in maximum SPL at the 50-m and 150-m ranges varied considerably, by as little as 1 dB for the dredge *Dodge Island* to as much as 10 dB for the *Liberty Island*. Based solely on the regression equation, transmission loss should have been 7.5 dB, illustrating the variation in received SPL nearer the source.

There was some variation in peak frequencies among the three dredges. Peak frequencies for the *Padre Island* centered around 250 Hz at 150 m from the dredge. The *Dodge Island* also had a peak frequency centered around 200 Hz, with a second peak frequency centered around 700-800 Hz. This higher frequency may be attributed to the much higher pump speed used by the *Dodge Island* when compared to the *Padre*, a dredge of a similar size class. Peak frequencies for the *Liberty Island* were 200 Hz, 500 Hz, and 1.6 kHz. For all three TSHD, frequencies centered around 100-200 Hz were associated with propeller cavitation. Pumps and compressors contributed significantly to the higher frequencies.

Transit to pump-out station

Each dredge was monitored after the loading process during transit from the borrow area to the inshore pump-out stations. Transit speed was highest for the *Liberty Island,* averaging 11.5 knots followed by the *Dodge* (9.9 knots) and *Padre Island* (9.4 knots). Vessel draft was similar for the *Dodge Island* and *Padre Island,* ranging from 18 ft forward to 19.5 ft aft, whereas the *Liberty Island drafted* 27.6 ft forward and 27.2 ft aft. The *Liberty Island* had nearly twice the displacement (11,746 LT) when compared to either the *Padre Island* (6,690 LT) or the *Dodge Island* (6,414 LT). Volume of dredged material in the hopper of the *Liberty Island* (4,933 yd^3) more than doubled that of the *Dodge Island* (2,170 yd^3) and almost doubled that of the *Padre Island* (2,628 yd^3). DQM data indicated no activation of the dredge pumps while the *Liberty Island* was in transit, but intermediate usage of pumps for both the *Padre* and *Dodge Islands* occurred. When in use, maximum pump speed was 135 rpm for the *Padre Island* and 650 rpm for the *Dodge Island*.

Slightly more favorable weather conditions were present during the monitoring of the *Dodge Island*. Wind speeds averaged 2.4 m/sec, with gusts to 4.6 m/sec. Winds increased from Beaufort Scale 2 to 3 during the monitoring period. Less favorable conditions were present during the monitoring period for both the *Liberty Island* and *Padre Island*. Wind speeds averaged 4.4 m/sec, with gusts to 7.1 m/sec during *Liberty Island* measurements and 4.0 m/sec, with gusts to 6 m/sec for the *Padre Island*. Maximum gusts were less than 8 m/sec during *Liberty Island* measurements, while exceeding 10 m/sec for the *Padre Island*. A Beaufort wind force condition of 3 was sustained throughout the monitoring of the *Liberty Island*, while conditions increased from Beaufort 2 to 4 during the monitoring of the *Padre Island*.

Received SPLs versus distances are presented in Figure 7 and summarized in Table 7. Figure 8 presents 1/3-octave results and 1/3-octave results are summarized in Table 8.

Figure 7. Comparison of SPLs (dB rms) for dredges in transit to pump-out stations.

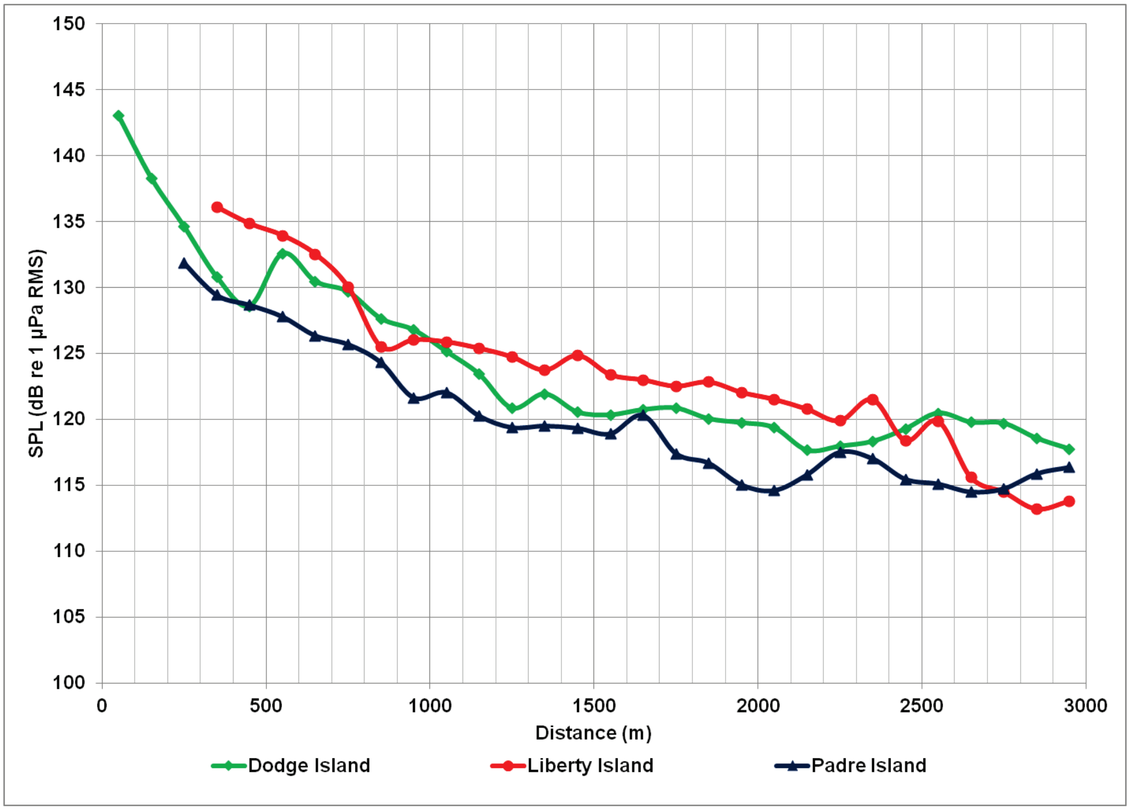


Figure 8. One-third octave analysis results at selected distances for dredges in transit to pump-out stations.

Table 7. SPL (dB rms) results by dredge during transit to pump-out station.

Range	Padre			Dodge			Liberty		
	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50				143.18	142.86	143.02			
150				138.6	137.94	138.29			
250	132	131.72	131.86	134.64	134.6	134.62			
350	129.15	129.68	129.42	130.36	131.17	130.78	136.42	135.71	136.08
450	128.3	129.01	128.67	128.05	129.08	128.59	135.31	134.32	134.84
550	127.43	128.12	127.79	133.19	131.85	132.57	134.45	133.37	133.95
650	126.21	126.5	126.35	130.91	129.95	130.46	132.88	132.15	132.53
750	125.49	125.88	125.69	130.15	129.14	129.68	130.28	129.78	130.04
850	124.35	124.29	124.32	128.09	127.15	127.64	125.89	125.09	125.51
950	121.26	122.01	121.65	127.33	126.15	126.78	126.57	125.43	126.04
1050	121.85	122.2	122.03	125.45	124.81	125.14	126.33	125.34	125.87
1150	120.21	120.3	120.26	123.57	123.26	123.42	125.75	125.01	125.39
1250	119.7	119.03	119.38	120.72	120.97	120.85	125.3	124.07	124.73
1350	119.58	119.41	119.5	121.94	121.92	121.93	124.38	122.98	123.73
1450	119.18	119.47	119.33	120.38	120.69	120.54	125.12	124.56	124.85
1550	119.05	118.76	118.9	120.26	120.41	120.34	123.58	123.17	123.38
1650	120.52	120.07	120.3	120.71	120.74	120.73	123.03	122.96	122.99
1750	117.48	117.34	117.41	121.24	120.43	120.85	122.8	122.21	122.51
1850	116.1	117.18	116.68	120.32	119.74	120.04	122.85	122.81	122.83
1950	114.15	115.76	115.03	120.02	119.43	119.74	122.16	121.92	122.04
2050	113.82	115.27	114.6	119.52	119.19	119.36	121.24	121.76	121.51
2150	115.73	115.85	115.79	117.63	117.68	117.65	120.83	120.71	120.77
2250	117.34	117.67	117.51	117.19	118.62	117.96	119.69	120.09	119.89
2350	116.7	117.32	117.02	117.73	118.84	118.32	120.19	122.51	121.5
2450	114.16	116.45	115.46	119.48	119.05	119.27	118.1	118.67	118.39
2550	115.44	114.72	115.1	121.16	119.64	120.47	118.7	120.77	119.86
2650	114.5	114.49	114.49	120.46	118.97	119.78	115.62	115.55	115.59
2750	115.1	114.32	114.73	120.06	119.31	119.7	113.85	115.03	114.48
2850	116.52	115.1	115.87	118.64	118.5	118.57	111.39	114.46	113.19
2950	115.22	117.26	116.36	118.51	116.84	117.76	114.11	113.44	113.79

Table 8. One-third-octave results by dredge during transit to pump-out station.

Range	*Padre*			*Dodge*			*Liberty*		
	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50				148.54	148.48	148.51			
150				142.66	142.36	142.51			
250	137.68	137.69	137.68	139.83	139.90	139.86			
350	135.88	136.40	136.15	137.73	137.80	137.77	139.87	139.58	139.73
450	134.96	135.56	135.27	134.67	134.84	134.76	138.7	138.35	138.53
550	133.81	134.44	134.13	137.53	136.21	136.92	137.46	137.03	137.25
650	131.90	132.37	132.14	136.06	134.78	135.46	136.71	136.42	136.57
750	130.99	131.36	131.18	135.38	134.01	134.75	135.75	135.2	135.49
850	129.90	130.22	130.06	133.71	132.56	133.17	128.86	128.44	128.66
950	127.84	128.56	128.21	132.63	131.42	132.07	128.85	128.38	128.62
1050	126.98	127.55	127.27	131.41	130.33	130.91	129.57	128.40	129.02
1150	126.30	126.87	126.59	129.74	128.99	129.38	128.61	128.20	128.41
1250	125.58	126.18	125.89	127.68	127.33	127.51	127.9	127.24	127.58
1350	125.41	125.8	125.61	128.17	127.68	127.93	126.94	126.85	126.89
1450	124.77	125.07	124.92	127.39	127.19	127.29	127.28	127.04	127.16
1550	124.65	124.61	124.63	127.44	127.29	127.37	126.26	126.40	126.33
1650	124.33	124.16	124.25	126.88	126.62	126.75	125.69	125.85	125.77
1750	123.64	123.66	123.65	126.22	126.18	126.20	125.27	125.30	125.28
1850	123.41	123.43	123.42	125.8	125.82	125.81	124.48	125.21	124.86
1950	122.78	122.70	122.74	125.77	125.70	125.73	123.67	124.14	123.91
2050	121.69	122.05	121.87	125.3	125.31	125.30	124.01	124.32	124.17
2150	121.57	122.0	121.79	124.66	124.65	124.66	123.32	123.41	123.36
2250	121.45	122.03	121.75	124.15	124.21	124.18	122.85	123.07	122.96
2350	121.24	122.16	121.72	125.43	125.23	125.33	122.42	123.73	123.12
2450	120.63	121.59	121.14	125.85	125.68	125.77	121.27	122.06	121.69
2550	120.18	120.64	120.42	126.63	125.84	126.26	120.72	122.87	121.92
2650	119.78	121.11	120.49	125.89	125.16	125.54	118.75	119.68	119.24
2750	119.63	120.64	120.16	125.54	125.68	125.61	118.18	119.04	118.63
2850	119.48	120.84	120.21	124.93	124.79	124.86	117.71	119.55	118.73
2950	119.4	120.09	119.76	124.87	124.51	124.69	117.02	117.92	117.49

Padre Island

A total of 1,987 measurements were recorded during transit of the *Padre Island* from the borrow area to the pump-out station. A maximum SPL (dB rms) of 131.86 (Log Avg. ULD and LLD) occurred at a distance of 250 m, exceeding ambient by almost 15 dB. Sound recordings were not made at distances closer than 200 m to the source. Assuming a transmission loss of 37.83 dB at 250 m, the SL is estimated at 169.7 dB re 1 µPa-1m (53 dB > ambient). For comparison between dredges, SL was recalculated using SPLs obtained at the 350-m range due to the fact that no sound recordings were made at distances closer than 300 m to the *Liberty Island*. At a distance of 350 m, SPL (dB rms) was 129.4 dB. Assuming a transmission loss of 40.14 dB at 350 m, SL is estimated at 169.5 dB re 1 µPa-1m.

Received levels attenuated fairly rapidly and had fallen to ambient levels by 1.75 km from the source ambient. SPL (dB rms) differences between the ULD and LLD averaged less than 0.5 dB up to 1.8 km from the source. Only a small number of values at distances of 1.2 to 1.8 km were higher at the ULD. The minimum recorded SPL during transit to the pump-out station was 97.7 dB at the ULD and 130.9 dB at the LLD. Maximum SPLs were 135.2 dB at the LLD and 138.0 dB at the ULD at 250 m from the source.

A 1/3-octave SPL of 137.7 dB (16.9 dB > ambient) occurred 250 m from the source. At 2 km from the source, 1/3-octave SPL was less than 2 dB above ambient levels. Attenuation to ambient levels occurred 2.45 km from the source. The main sound energy occurred at peak frequencies of 80 Hz, 300 Hz, and 400 Hz.

Dodge Island

A total of 2,783 SPL measurements were recorded for the *Dodge Island* during transit from the borrow area to the pump-out station. Maximum SPL at 50 m averaged 143 dB re 1 µPa rms, or 26 dB above ambient. Assuming a transmission loss of 26.81 dB at 50 m, SL is estimated at 169.8 dB re 1 µPa-1m (52.8 dB > ambient). SL was also recalculated using SPL recorded at 350 m from the source for comparison to the dredges *Padre Island* and *Liberty Island*. At 350 m from the source, maximum SPL averaged 130.8 dB. Assuming a transmission loss of 40.14 dB, SL is estimated at 170.9 dB re 1 µPa-1m (52.5 dB > ambient).

Sound attenuated to ambient levels at 2.95 km (SPL = 116.8 dB), although one measurement taken at 2.15 km was within 0.65 dB of ambient. However, at the 2.2-km listening station, SPL increased by 1.5 to 3 dB above ambient. Only 9 of 21 measurements taken at distances as far as 3 km from the source recorded higher SPL at the LLD. Differences were generally less than 0.5 to

1 dB between the upper and lower listening depths. Minimum SPL during transit to the borrow area was 104 dB. Maximum SPLs were 149.2 dB at the LLD and 150.5 dB at the ULD.

Maximum 1/3-octave SPL was 148.5 dB at 50 m from the source, exceeding ambient by 27.7 dB. SPL (124.7 dB) remained above ambient levels by nearly 4 dB at 3 km from the source. Peak frequencies centered around 200 Hz and 800 Hz at 250 m from the source. The smaller peaks were located at 30 Hz and 80 Hz, the lower of which is mostly likely associated with noise generated by wave action.

Liberty Island

A total of 1,467 SPL measurements were recorded during transit of the *Liberty Island* from the borrow area to the pump-out station. No sounds were made at distances less than 300 m. At 350 m, average SPL was 136.1 dB or 19 dB above ambient. Assuming a loss of 40.14 dB at 350 m, SL is estimated at 176.24 re 1 µPa-1m (59.2 dB above ambient).

At 1 km from the source, SPL fell to 125.9 dB or slightly less than 9 dB above ambient. At 2 km, SPLs (122.0 dB) were still 5 dB above ambient. Attenuation to ambient levels occurred at 2.7 km from the source. SPLs at the ULD were higher (range = 0.04 -1.4 dB, Avg. 0.7 dB) than at the LLD as far as 2 km from the source. Beyond this distance, SPLs were higher (range = 0.5 to 2.3 dB) at the LLD. Minimum SPLs were 100.7 dB at the ULD and 104 dB at the LLD. Maximum SPLs were 141 dB at the ULD at 450 m from the source and 139.5 dB at the LLD at 550 m from the source.

Maximum 1/3-octave SPL was 139.9 dB (19.1 dB above ambient) at a distance of 350 m from the source. At 1 km from the source, SPLs were still nearly 8 dB above ambient, but fell to just 3 dB above ambient at a distance of 2 km from the source. At 2.7 km, 1/3-octave SPLs fell below ambient levels. Peak frequency was centered at approximately 100 Hz. Two additional peaks were centered around 400 Hz and 1.1 KHz.

Transit to pump-out station discussion

The deeper draft, larger load capacity, greater displacement, and higher vessel speed of the *Liberty Island* are most likely the key factors responsible for the *Liberty Island*'s higher RL and SL values. SL estimated using SPL (dB rms) at the 350-m range for the *Liberty Island* (176.24 dB re 1 µPa-1m) was 5.3 dB and 7 dB higher than the *Dodge Island* (170.9 dB re 1 µPa-1m) and *Padre Island* (169.5 dB re 1 µPa-1m). The main difference between the *Dodge Island* and *Padre Island* was higher pump speeds, although pumps were only intermittently used during transit. The *Dodge Island* also had a slightly greater vessel speed (+0.5 knots) than the *Padre Island*. SLs for the *Dodge Island* were 1.4 dB higher than for the *Padre Island*. SLs exceeding ambient were highest for the *Liberty Island* (57.2 dB), followed by the *Dodge Island* (53.9 dB) and *Padre Island* (52.5 dB). Peak frequencies for the *Padre Island* were below 500 Hz. Peak frequencies below 500 Hz were also common for the *Dodge* and *Liberty Islands*; however, the *Dodge Island* also recorded a peak centered around 800 Hz and the *Liberty Island* around 1.1 KHz.

With the exception of two measurements taken at 850 m and 950 m, all received SPLs (dB rms) for the dredge *Liberty Island* exceeded received SPLs for the *Dodge Island* by as much as 6 dB (average = 2.7 dB) at distances less than 2.4 km from the source. For distances greater than 2.4 km, the *Dodge Island* had SPLs ranging from 0.6 to 5.4 dB (average 3.4 dB) higher. When comparing the *Liberty Island* to the *Padre Island*, the same pattern of higher (average = 4.8 dB maximum = 7 dB) SPLs at distances of less than 2.7 km was observed. Lower SPLs (average = 1.8 dB, maximum = 2.6 dB) were observed at distances greater than 2.7 km. At all listening stations, SPLs for the *Dodge Island* exceeded those for the *Padre Island*. Sound attenuation to ambient levels occurred over shorter distances (1.75 km) for the *Padre Island* compared to either the *Liberty Island* (2.65 km) or the *Dodge Island* (2.95 km).

Dredged material pump-out

All three dredges were monitored during the pump-out phase of the dredging operation. Hopper volumes were 2,754 yd^3 for both the *Padre Island* and *Dodge Island* and 5,003 yd^3 for the *Liberty Island*. DQM data indicated that maximum volume at the start of pump-out was as high as 3,400 yd^3 for the *Padre* and *Dodge Islands* and 6,200 yd^3 for the *Liberty Island*. During some monitoring sessions, pump-out activity was already in progress at the start of the sound recordings. Port and starboard pump speeds were considerably higher for the *Dodge Island* (1,487 and 1,500 rpm) compared to the *Padre Island* (312 and 320 rpm) or *Liberty Island* (344 and 350 rpm).

Wind gusts (average =10.3 m/sec) were highest during monitoring of the *Liberty Island,* reflecting the fact that the pump-out station was located offshore in less protective waters. When factoring in average wind speeds and gusts, Beaufort scales averaged 2.8 (Beaufort scale 2-4) for the *Liberty Island,* 2.6 for the *Dodge Island* (Beaufort scale = 2-4) and 2.5 for the *Padre Island* (Beaufort scale 1-4). The amount of data collected for each dredge varied from 1.6 hr (99 min) for both the *Dodge* and *Liberty Islands* and 3.1 hr (188 min) for the *Padre Island*. The much larger amount of data collected for the *Padre Island* was based on two factors: first, a slightly more favorable monitoring environment (i.e., the amount of time during pump-out when weather conditions were at Beaufort 1), and second, a much shorter turnaround time (i.e., the amount of time to complete a full dredging cycle).

Received SPLs versus distances by dredge are presented in Figure 9 and summarized in Table 9. Figure 10 presents 1/3-octave results, which are summarized in Table 10.

Padre Island

A total of 10,559 SPL measurements were recorded for the dredge *Padre Island* during pump-out of dredged material. Maximum SPLs (dB rms) reached 141.5 dB at 50 m from the source, exceeding ambient by 24.5 dB.

Figure 9. Comparison of SPLs (dB rms) during pump-out of material.

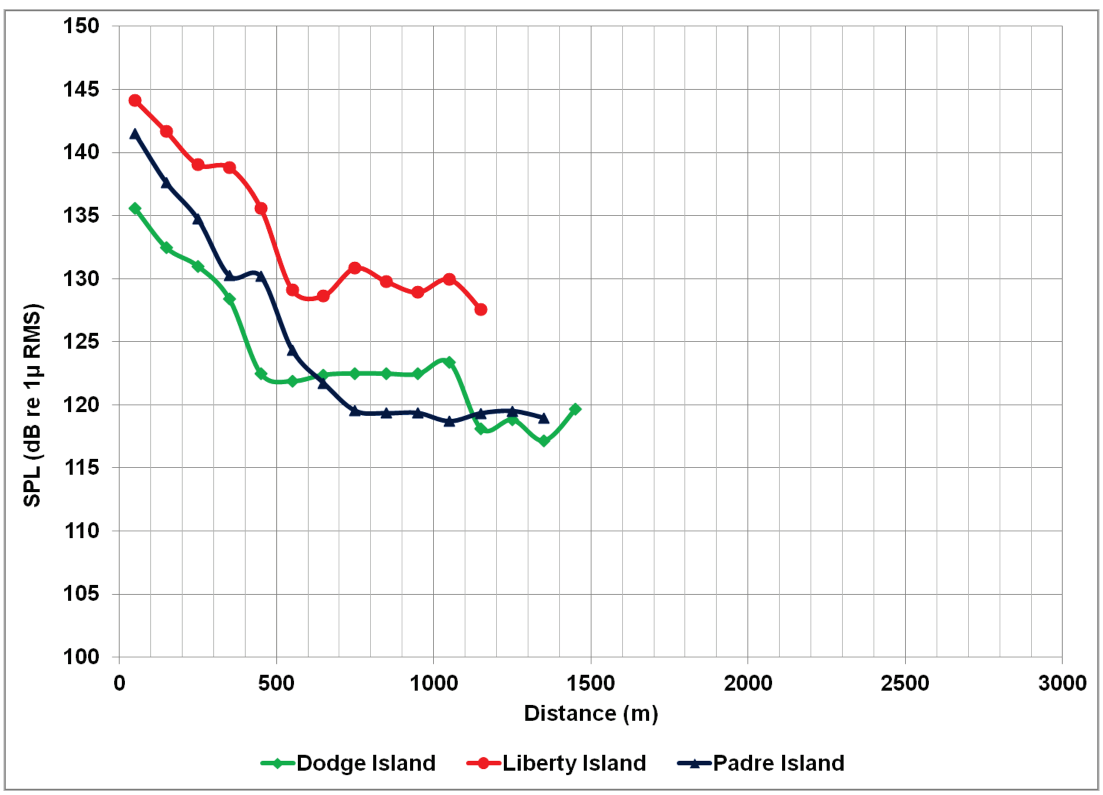


Table 9. SPL (dB rms) results by dredge during pump-out of dredged sediment.

Range	*Padre*			*Dodge*			*Liberty*		
	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	141.71	141.30	141.50	135.60	135.57	135.58	144.01	144.29	144.15
150	137.55	137.66	137.6	132.04	132.83	132.45	141.79	141.53	141.66
250	134.45	134.98	134.72	130.7	131.26	130.99	138.41	139.61	139.05
350	129.97	130.45	130.22	128.04	128.72	128.39	138.93	138.69	138.81
450	128.63	131.31	130.17	122.19	122.73	122.47	135.58	135.63	135.6
550	123.61	124.98	124.34	122.45	121.20	121.87	129.13	129.09	129.11
650	121.05	122.29	121.71	123.02	121.63	122.38	128.42	128.85	128.64
750	119.32	119.70	119.52	122.74	122.23	122.49	130.19	131.41	130.84
850	119.99	118.55	119.33	123.35	121.36	122.47	128.93	130.45	129.76
950	119.42	119.27	119.34	122.67	122.21	122.44	127.86	129.77	128.91
1050	118.87	118.5	118.69	124.71	121.36	123.35	128.77	130.87	129.95
1150	119.48	119.16	119.32	119.11	116.82	118.11	125.67	128.88	127.56
1250	119.62	119.37	119.50	119.15	118.41	118.80			
1350	117.13	120.24	118.96	117.67	116.59	117.16			
1450				120.52	118.57	119.65			

Figure 10. Results of 1/3-octave analysis during pump-out of material at selected distances.

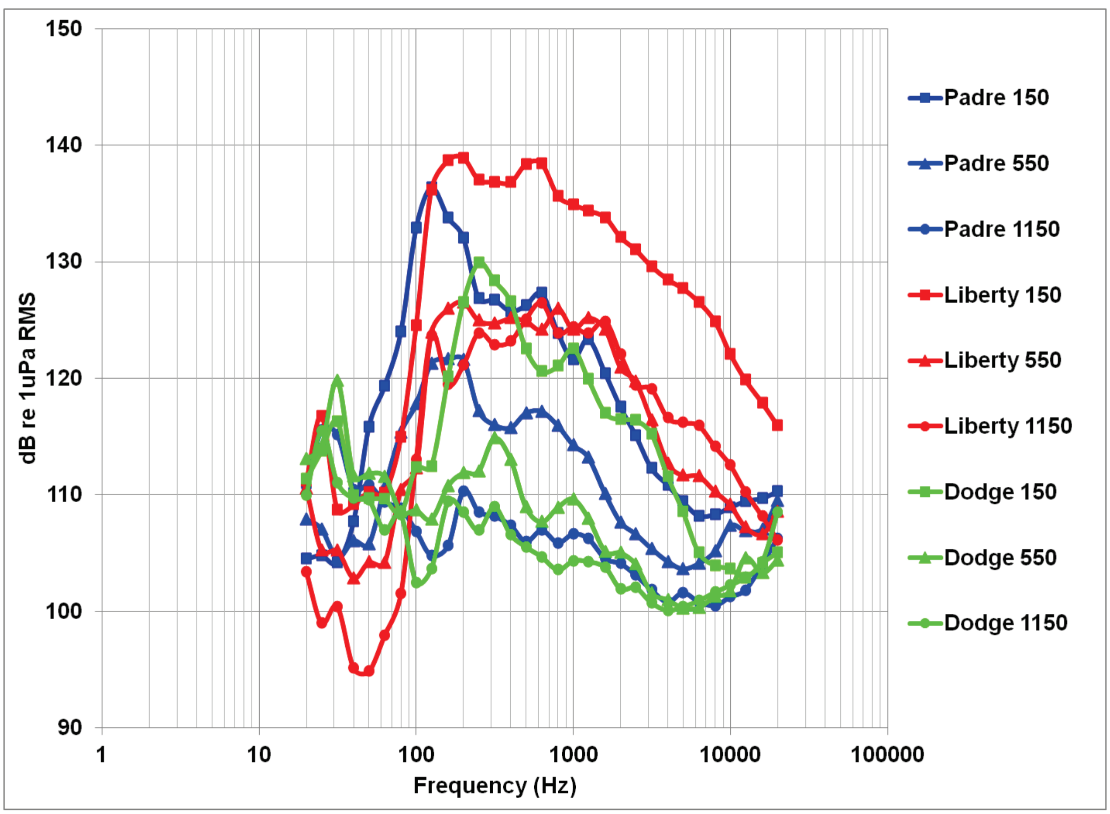


Table 10. One-third octave results by dredge during pump-out of dredged sediment.

Range	*Padre*			*Dodge*			*Liberty*		
	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	145.50	145.25	145.38	139.73	139.6	139.66	151.31	150.74	151.03
150	141.37	141.46	141.41	135.5	135.8	135.65	148.31	148.09	148.2
250	137.73	138.22	137.98	133.4	133.41	133.40	146.05	146.03	146.04
350	133.84	134.05	133.95	130.66	131.11	130.89	144.01	144.02	144.01
450	132.56	135.08	134.01	125.87	126.76	126.34	141.72	141.46	141.59
550	129.64	129.74	129.69	122.58	124.61	123.71	136.67	135.89	136.30
650	126.28	126.75	126.52	122.17	125.69	124.28	135.77	135.27	135.53
750	123.77	124.49	124.14	121.84	124.76	123.54	136.32	136.67	136.50
850	122.01	123.69	122.93	120.64	124.12	122.72	135.12	135.89	135.52
950	122.18	123.09	122.66	120.55	124.56	123.01	134.28	134.89	134.60
1050	120.58	121.66	121.15	120.4	123.64	122.32	134.55	135.56	135.09
1150	120.60	122.17	121.46	120.37	121.49	120.96	135.03	135.78	135.42
1250	123.21	122.43	122.84	119.74	122.01	121.01			
1350	119.72	124.4	122.66	118.68	120.74	119.83			
1450				119.13	120.77	120.03			

Assuming a transmission loss of 26.81 dB at 50 m, SL is estimated at 168.3 dB re 1 µPa-1m. To compare SL to other pump-out operations for which data were not obtained at a distance of 50 m, SL were also calculated using SPL obtained at 150 m (SPL = 137.6 dB rms) from the source. Assuming a transmission loss of 34.33 dB at 150 m, SL is estimated at 172 dB re 1 µPa-1m.

SPLs fell steadily as distance from the source increased until reaching 750 m from the source. At 750 m, SPLs decreased to 119.5 dB, exceeding ambient levels by 2.5 dB. The greatest distance at which data were obtained during pump-out operations was 1.35 km from the source. Log-averaged SPLs for both the upper and lower listening depths were 118.9 dB, exceeding ambient by as much as 2 dB. Differences in SPL between the ULD and LLD were greater in the first 750 m from the source, where SPLs at the LLD were as much as 2.7 dB (average ~1 dB) higher than SPLS at the ULD. Beyond 800 m, the ULD had only slightly higher SPLs averaging less than 0.5 dB. The only exception was at the most distant station (1.3 km) where SPLs at the ULD (117.1 dB) were near ambient (117.03 dB), while the LLD still exceeded ambient by 3.4 dB. During this component of the dredging operation, minimum SPLs were 105 dB at the ULD and 108 dB at the LLD. Maximum SPLs were 150 dB at both the ULD and LLD.

At a distance of 50 m from the source, 1/3-octave SPL at the ULD was 145.5 dB, exceeding ambient by 24.7 dB. Peak frequencies were centered around 150 Hz, 600 Hz, and 1.02 kHz at 150 m from the dredge. The main sound energy associated with pump-out operations fell between 100 and 1 kHz. With the exception of two measurements taken at 50 m and 1.25 km, SPLs were consistently higher at the LLD than at the ULD.

Dodge Island

A total of 5,493 SPL measurements were recorded for the dredge *Dodge Island* during pump-out operations. A maximum SPL of 135.6 dB at 50 m from the source was recorded, or slightly less than 19 dB above ambient. Assuming a transmission loss of 26.81 dB (15.778LogR at 50 m), SL is estimated at 162.4 dB re 1 µPa-1m. SL increases by 4.4 dB (SL = 166.8 dB re 1 µPa-1m) when using the maximum SPL (132.5 db) recorded at 150 m to estimate transmission loss.

SPLs fell steadily from 135 dB to 122.5 dB (5.5 dB above ambient) as distance increased from 50 m to 450 m from the source. SPL remained nearly constant (122 dB) between 500 m and 1.05 km. From 1.15 to 1.45 km, SPLs ranged from near ambient to 1-2 dB above ambient. With the exception of the nearest measurement (50 m), SPL at the LLD exceeded the ULD by 0.65 to 0.79 dB out to a distance of 500 m. Beyond 500 m, SPLs were higher at the ULD (0.5 to 3.3 dB) than at the LLD.

Maximum 1/3-octave SPL at the ULD was 139.7 dB, exceeding ambient by 18.9 dB. Peak frequencies were centered around 150 Hz and 1 kHz. At 550 m, SPLs decreased to less than 4 dB above ambient. Sound levels attenuated to ambient levels at both the upper and lower listening depths at 1.35 km from the source. During pump-out, minimum SPL was 102 dB at both the ULD and LLD. Maximum SPLs were 148.7 at the ULD and 146.6 at the LLD.

Liberty Island

A total of 4,754 SPL measurements were taken from the dredge *Liberty Island* during pump-out operations. Maximum SPL was at 144.2 at 50 m from the source, or 27.2 dB above ambient. Assuming a transmission loss of 26.81 dB at 50 m, SL is estimated at 171 dB re 1µPa-1m. Using maximum SPL (141.7 dB rms) recorded at 150 m from the source, SL is estimated at 176 dB re 1 µPa-1m, an increase of 5 dB.

Figure 9 shows a rapid decline in SPL as distance increased from 50-450 m from the source. From 550 m to 1.15 km, SPLs remained fairly constant (135-136 dB) with a slight overall decreasing trend. Maximum SPL was 129.1 dB or 12 dB above ambient at 550 m from the source. There was only a 1- to 2-dB variation in SPL from 550 m to 1.15 km. At the 1.15-km listening station, SPLs (127.5 dB) averaged 10.5 dB above ambient. No data were collected beyond this distance, so attenuation to ambient levels cannot be determined. During pump-out, minimum SPLs were 96.9 dB at the ULD and 104 dB at the LLD. Maximum SPLs were 149.6 at the ULD and 151.6 at the LLD. Differences in SPL from the upper and lower listening depths indicated that at three listening stations (150, 350, and 550 m), RLs were higher at the ULD, although absolute differences were small, averaging 0.25 dB. At all other listening stations, SPLs were higher at the LLD, ranging from 1-2 dB, but they were as high as 3.3 dB at the greatest distance (1.15 km).

Maximum 1/3-octave SPL was 151 dB at 50 m from the source, exceeding ambient by 30.2 dB. No data were collected beyond 1.15 km, so attenuation to ambient levels was not determined. At 1.15 km, maximum SPL was 135.8 dB, exceeding ambient by 15 dB. At 50 m, peak frequencies were between 500 and 600 Hz, centered around 200 Hz, with a minor peak at 1.2 KHz.

Dredged material pump-out

SPL were higher at the ULD than at the LLD for all three dredges at distances less than 550 m. The reverse was true at distances greater than 600 m, where higher SPLs were recorded at the LLD. Attenuation rates were estimated for all dredges during pump-out. For the *Padre Island*, attenuation to ambient occurred at the ULD at 1.35 km; however, at the LLD, received levels still exceeded ambient by 2 to 3 dB. For the *Dodge Island*, attenuation to ambient occurred at 1.35 km at both the ULD and LLD; however, at 1.45 km, RL increased to above ambient levels by 1.5 dB (LLD) to 3.5 dB (LLD). Attenuation rates for the *Liberty Island* were not determined. The greatest distance at which data were obtained for the *Liberty Island* was 1.15 km, at which SPL exceeded ambient by 10.5 dB. At an equivalent distance (1.15 km), SPLs for both the *Padre Island* and *Dodge Island* exceeded ambient by 1-2 dB.

SLs were compared between dredges using maximum SPL recorded from the 150-m listening station. Source levels were 4 dB higher for the dredge *Liberty* (176 dB re 1 μPa-1m) when compared to the *Padre Island* (166.8 dB re 1 μPa-1m) and 9.2 dB higher when compared to the *Dodge Island* (166.8 dB re 1 µPa-1m). SL for the *Padre Island* exceeded SL for the dredge *Dodge* by 5.2 dB during pump-out. All three dredges had peak frequencies centered around 100-200 Hz and 500-600 Hz. Only the *Padre* and *Dodge Island* had an additional peak frequency centered around 1 kHz.

Several factors that varied between dredges could account for observed differences in SLs. These factors included pump speed, velocity of material moving though the suction pipes, and pump-out power (kW). While pump speed was significantly higher for the *Dodge Island*, this dredge had the lowest SL. In addition, SPLs measured at increasing distance from the source were lower for the *Dodge Island* at all equivalent listening stations when compared to the *Liberty Island* and within the first 500 m from the source when compared to the *Padre Island*. If pump speeds recorded by the DQM instrumentation are accurate, then pump speed did not appear to be a major contributor to the overall sound field. The second operational difference was velocity of material moving though the pipes. Both the *Padre Island* and *Dodge Island* recorded velocities ranging from 22.9-24.6 ft/sec for both the port and starboard pumps. However, the *Liberty Island* recorded velocities of material moving through the suction pipes at only 5 ft/sec for the starboard pipe and 17.7 ft/sec for the port pipe. The sand-water slurry had a slightly lower density of 1.14 g/cc for the *Dodge Island* when compared to either the dredge *Liberty* or *Padre Island*, both with densities of 1.24 g/cc. Pump-out power for the *Liberty Island* is 6,300 kW, significantly higher than the *Dodge Island* (1,268 kW). Pump-out power for the *Padre Island* is unknown, but can be assumed to be similar to that of the *Dodge Island*.

Water pump-out (flushing pipes)

Flushing the pipes occurred immediately after cessation of pumping sediment. A major difference between the dredges was pump speed. The *Dodge Island* recorded the highest average pump speeds at 801 rpm (port side) and 824 rpm (starboard side). These pump speeds were more than double those of the *Padre Island* at 320 rpm (port side) and 312 rpm (starboard side) as well those of the *Liberty Island* at 280 rpm (port side) and 284 rpm (starboard side).

Weather conditions were less favorable during monitoring of the dredge *Dodge Island*. Wind speed averaged 3.9 m/sec (range 2.2-6.1 m/sec) with gusts of 7.2 m/sec (gusts range = 4.5–9.6 m/sec). Beaufort wind force conditions averaged 2.7 (range = 2 to 4), with conditions becoming less favorable throughout the monitoring period. Weather conditions were similar during monitoring of the dredge *Liberty* and *Padre Islands*, with average wind speeds of slightly less than 3 m/sec, or slightly more than 1 m/sec slower than that recorded during the monitoring of the *Dodge Island*. Calmer conditions were present at the beginning of the monitoring session for both the *Liberty* and *Padre Island*. Poorest conditions were found near the end of the monitoring session, with gusts as high as 7.5 m/sec (*Liberty*) and 10.1 m/sec (*Padre*). The Beaufort wind force condition averaged 1 at the beginning of the monitoring session and had increased to conditions 3 and 4 for the *Liberty* and *Padre Island,* respectively, by the end of the monitoring session.

Received SPLs versus distances (by dredge) are presented in Figure 11 and summarized in Table 11. Figure 12 presents 1/3-octave results, which are summarized in Table 12.

Padre Island

A total of 7,213 SPL measurements were recorded when the dredge *Padre Island* was flushing its pipes with seawater (no sediment moving through the pipes). SPL reached 134.8 dB at the LLD at 50 m distance from the source, or 17.8 dB above ambient. Assuming a transmission loss of 26.81 dB at 50 m, SL is estimated at 161.2 dB re 1µPa-1m. A source level was also calculated using the SPL obtained at 150 m from the source for comparison between dredges. At 150 m, SPL reached 130.02 dB. Assuming a transmission loss of 34.33 dB, SL is estimated at 164.4 dB re 1µPa-1m, or 3.2 dB higher than the SL generated using the maximum SPL obtained from the 50-m listening station. Log-averaged SPL fluctuated by 1-2 dB both above and below ambient from 650 m to 1.15 km from the source, before increasing to as much as 4 dB above ambient at the 1.25-km and 1.35-km listening stations. SPLs were higher at the LLD, with the exception of one listening station located 1.05 km from the source, where SPL at the ULD averaged slightly more than 1 dB greater than at the LLD. At shorter distances (less than 900 m), SPLs at the LLD ranged from 1.5 to 7.4 dB higher than at the ULD. At distances greater than 900 m, absolute differences in SPL between the ULD and LLD were less than 1 dB.

At both listening depths, 1/3-octave SPLs reached 141 dB, exceeding ambient by 20.2 dB. At this distance, SPL exceeded ambient by less than 8 dB. SPLs attenuated to below ambient levels at 1.1 km, although the final measurement taken at 1.35 km exceeded ambient by 3 dB. Peak frequencies at 50 m from the source were 150 Hz and 500 Hz, with a minor peak at 1 kHz. At 1.1 km, two peak frequencies were present (100 Hz and 1 KHz).

Figure 11. SPLs (dB rms) during pump-out of clear water (flushing pipes).

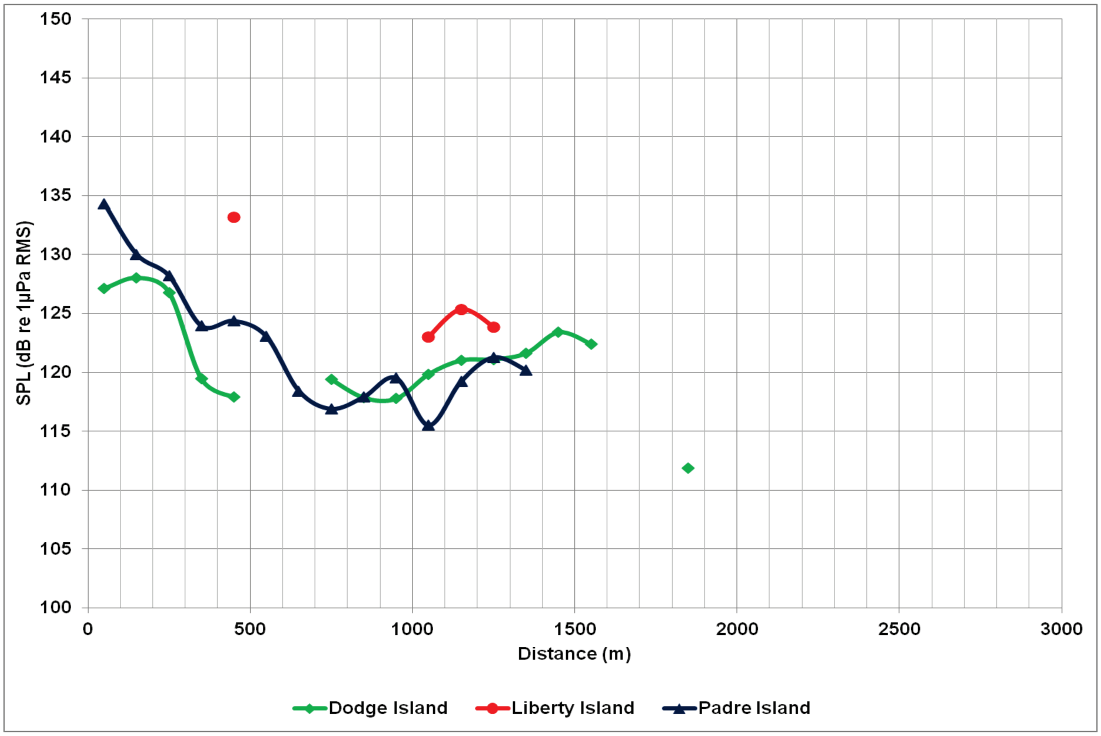


Table 11. SPL (dB rms) results by dredge during pump-out of clear water (flushing pipes).

	Padre			*Dodge*			*Liberty*		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	133.79	134.83	134.34	126.2	127.86	127.11			
150	128.99	130.86	130.02	127.65	128.36	128.02			
250	125.15	129.97	128.19	124.75	128.17	126.79			
350	122.94	124.75	123.94	118.97	119.88	119.45			
450	119.21	126.65	124.36	117.48	118.27	117.9	133.17	133.17	133.17
550	121.09	124.4	123.05						
650	115.38	120.21	118.43						
750	113.56	118.77	116.90	120.15	118.52	119.41			
850	117.07	118.59	117.90	117.82	117.87	117.85			
950	119.16	119.84	119.52	118.43	117.01	117.78			
1050	116.13	114.78	115.51	120.38	119.27	119.86	122.44	123.47	122.99
1150	119.23	119.22	119.22	122.13	119.51	121.02	123.84	126.47	125.35
1250	121.18	121.37	121.27	122.09	119.84	121.11	122.29	125.01	123.85
1350	119.74	120.60	120.19	122.01	121.22	121.63			
1450				124.49	121.97	123.41			
1550				122.78	121.96	122.39			
1850				111.05	112.58	111.88			

Figure 12. One-third octave results at selected distances for pump-out of clear water (flushing pipes).

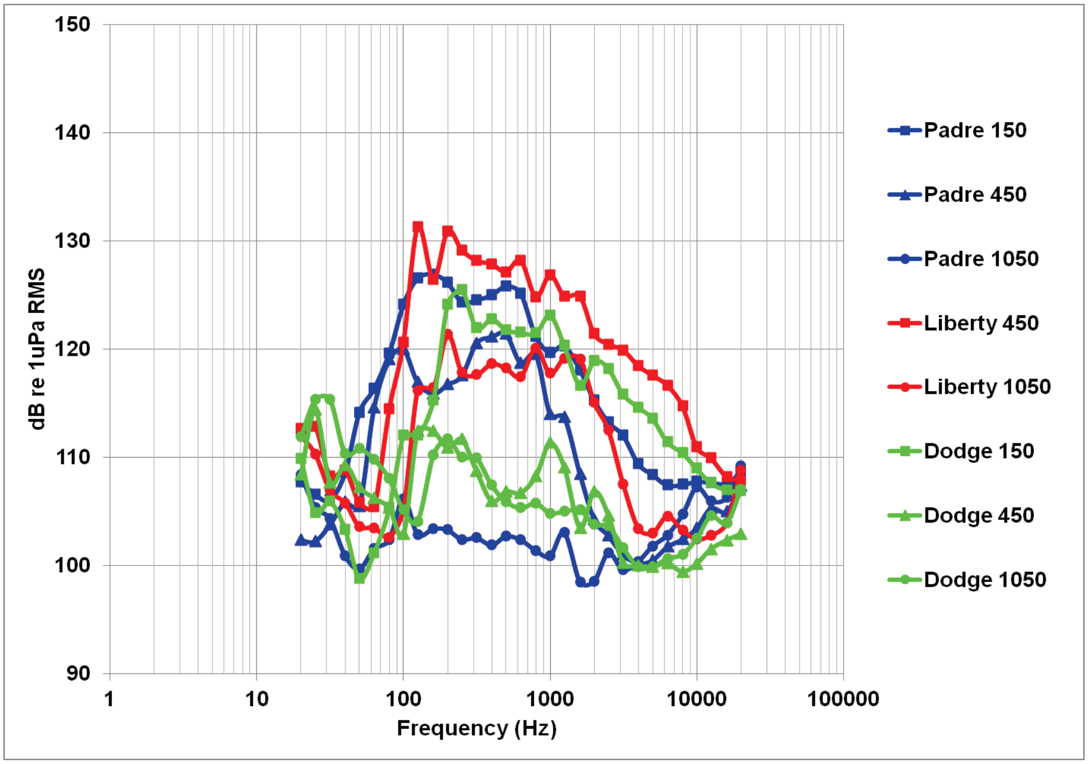


Table 12. One-third octave results during pump-out of clear water (flushing pipes).

	Padre			*Dodge*			*Liberty*		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50	141.21	140.73	140.98	134.15	134.04	134.09			
150	135.94	135.87	135.90	133.22	133.34	133.28			
250	133.22	134.85	134.11	134.44	135.47	134.99			
350	130.81	130.72	130.77	123.21	124.59	123.95			
450	128.49	131.4	130.19	121.64	122.70	122.20	139.39	139.17	139.28
550	127.83	128.87	128.38						
650	124.83	125.46	125.16						
750	122.12	124.6	123.53	123.02	123.69	123.37			
850	123.04	124.33	123.74	121.17	122.15	121.69			
950	124.69	124.7	124.69	120.17	121.29	120.77			
1050	118.33	119.14	118.75	120.90	122.80	121.96	130.08	129.65	129.87
1150	119.15	120.41	119.82	119.76	122.36	121.25	131.43	132.19	131.82
1250	119.01	120.2	119.64	119.35	122.11	120.94	129.93	130.94	130.46
1350	124.46	123.13	123.84	119.61	122.60	121.36			
1450				121.14	123.75	122.64			
1550				122.01	125.02	123.77			
1850				117.59	118.13	117.87			

Dodge Island

A total of 5,493 SPL measurements were obtained for the *Dodge Island* during pipe flushing with seawater. SPL reached 127.9 dB (LLD) at 50 m from the source, or 10.9 dB above ambient. Assuming a transmission loss of 26.81 dB at 50 m, SL is estimated at 154.7 dB re 1µPa-1m. SL was also calculated from the maximum SPL (128.0 dB) obtained at a distance of 150 m to compare water pump-out noise from different dredges. Assuming a transmission loss of 34.33 dB at 150 m, SL is estimated at 162.4 dB re 1µPa-1m. SL determined from maximum SPL (dB rms) derived from the two closest RLs varied by as much as 8 dB. A conservative SL for the dredge *Dodge Island* during this dredging activity is approximately 160 dB re 1µPa-1m.

At distances less than 500 m from the source, SPLs at the LLD generally exceeded those at the ULD by less than 1 dB, but as high as 3.4 dB. At distances greater than 750 m, RLs at the ULD exceeded the LLD by 1-2.5 dB. Figure 11 shows that SPLs decreased to nearly ambient levels at 500 m, before increasing to 123.4 dB (6.4 dB above ambient) from 500 m to 1.45 km from the source. Received SPL (112 dB) attenuated to below ambient levels at 1.85 km from the source.

At 50 m, 1/3-octave SPL was at 134.1 dB, or 13.3 dB above ambient. From 350 m to 1.55 km from the source, SPLs varied from 0.03 dB below ambient (950 m) to 3 dB above ambient (average = 1.5 dB). One-third octave SPLs attenuated to ambient levels at 1.85 km from the source. Peak frequencies were centered around 250 Hz, 400 Hz, and 1 KHz. At greater distances (e.g., 1.1 km), a peak occurred near infrasonic frequencies at 30 Hz.

Liberty Island

Considerably fewer data (933 SPL measurements) were obtained for the dredge *Liberty Island* during the flushing of pipes with seawater. No data were obtained at distances closer than 400 m from the source. At 450 m, SPL was 133.2 dB at the ULD, or 22.4 dB above ambient. Assuming a transmission loss of 41.86 dB, SL is estimated at 175.1 dB re 1µPa-1m. SPLs were obtained at three additional listening stations; 1.05 km, 1.25 km, and 1.35 km. At the greatest distance from the source (1.35 km), SPL (Log average ULD and LLD) was 123.9 dB, or nearly 7 dB above ambient.

At 450 m from the source for the ULD, 1/3-octave SPL reached 139.4 dB, or 18.6 dB above ambient. Lowest measured SPL (129.9 dB) occurred at 1.25 km from the source, exceeding ambient levels by slightly more than 9 dB. No data were obtained at distances greater than 1.25 km for the *Liberty Island*. Peak frequencies were centered between 100 and 200 Hz and at 600 Hz and 1 kHz.

Water pump-out (flushing pipes) discussion

SLs were determined for the *Padre Island* and *Dodge Island* using maximum SPL obtained at the two closest distances (50 m and 150 m). SPLs (dB rms) were unavailable for the *Liberty Island* at distances of less than 400 m. Using maximum SPL obtained at 150 m from the source, SLs were higher (2 dB) for the *Padre Island* at 164.4 dB re 1µPa-1m than for the *Dodge Island* (SL = 162.4 dB re 1 µPa-1m).

To compare differences in levels of underwater sound among all three dredges for this dredging activity, SLs were derived using the maximum SPL (dB rms) recorded at the 450-m listening station. A maximum SPL of 133.2 dB was measured at 450 m distance from the *Liberty Island*. This SPL exceeded SPLs for both the *Padre Island* and *Dodge Island* at even the closest listening station (50 m). SL for the *Liberty* was 175.1 dB re 1µPa-1m. SLs based on SPLs measured at 450 m for the *Padre Island* and *Dodge Island* were 166.22 re 1µPa-1m and 162.3 re 1µPa-1m, assuming a loss of 41.86 dB. At this distance (450 m), SL for the *Liberty Island* would exceed the *Padre Island* by 8.9 dB and the *Dodge Island* by 12.8 dB.

Underwater sounds generated from flushing pipes with seawater generally attenuated to ambient by 750-850 m from the source for the *Padre Island* and *Dodge Island*. However, it was not uncommon for SPL to increase to 1 or 2 dB above ambient at the farthest listening station. Insufficient data were obtained for the dredge *Liberty Island* to determine an accurate attenuation distance.

SLs were compared between the two pump-out operations: flushing pipes with clear water and the pump-out of the sediment-water slurry. Since dredges were stationary during pump-out operations, only idle engine/ generator noise, noise generated from the centrifuge pumps, and the movement of material through the pipes would contribute to the sound field. There was essentially no difference in SL for the dredge *Liberty* during pump-out of material (176 dB re 1µPa-1m) and during flushing pipes with clear water (175.1 dB re 1µPa-1m). SL for both the *Padre Island* (material = 172-, water = 166.2- dB re1 µPa-1m) and *Dodge Island* (material = 166.8 dB-, water = 162.3 dB- re 1 µPa-1m) were 4.5 dB (*Dodge Island*) to 5.8 dB (*Padre Island*) higher during sediment pump-out when compared to flushing the dredge pipes with clear water. Rank order by SL followed the same pattern for both pump-out operations; that is, the dredge *Liberty* had the highest SL, followed by the dredge *Padre Island* and then the dredge *Dodge*.

Flow rates (ft/sec) were compared during pump-out operations. For the dredge *Padre*, flow velocity for the pumps located on the port side of the vessel averaged 13.6±.2 ft/sec during POW and POM. Velocity (14.9 ft/sec) was slightly higher during the POM when compared to velocity (13.1 ft/sec) during the POW by the starboard pump. For the dredge *Liberty*, the starboard pump averaged only 5 ft/sec during both the POW and POM. Flow velocity for material transported through the pipes averaged 4 ft/sec faster than during POW. The biggest difference in flow velocities occurred for the dredge *Dodge*. During POW, flow averaged 13.7 ft/sec for the port pump and 11.4 ft/sec for the starboard pump. During POM, flow velocity increased to an average of 23.5 ft/sec for both the port and starboard pumps. This much higher flow rate for the dredge *Dodge* is a possible candidate for the higher SL (166.8 dB re 1µPa-1 m) estimated during POM when compared to SL (162.3 dB re 1µPa-1 m) during flushing pipes with clear water only. Flow velocity alone cannot completely account for higher SL, as the *Padre Island* had similar flow velocity during POM and POW (less than 2 ft/sec difference and only for the port pump); however, SL were nearly 6 dB higher during the POM.

A more important factor may be the noise generated by the type of sediment transported through the pipes. When compared to clear water only, all sediment types would be expected to contribute to some degree (rock > sand > mud) to the overall sound field. For the dredges *Padre* and *Dodge*, this would likely be a reasonable explanation to account for the 4-to 6-dB difference between higher SL estimated during the POM when compared to the SL estimated during the POW; however, SL differences during POW and POM were less than 1 dB for the dredge *Liberty*. It should be noted that fewer measurements were made for the dredge *Liberty* given the frequently less favorable weather conditions throughout the study at the south pump-out station. A more complete data set for the dredge *Liberty* during this dredging activity would possibly reveal a greater difference in SL between the POM and the POW.

Transition from pump-out to transit

This event involves disconnecting the dredge from the pump-out apparatus, while performing a series of maneuvers (e.g., reversing propellers to back away from the pump-out connection) to position the dredge for the return trip to the borrow area. During this time, water may be taken onboard for ballast. During this phase of the operation, dredge speed increases from almost zero, shortly after disconnecting from the pump-out station, and continues until the dredge reaches a maximum vessel speed of 6 knots. Note that a vessel speed greater than 6 knots is considered "in transit" and not in transition from one activity to another. Vessel speeds averaged approximately 2 knots for the *Dodge Island* and *Padre Island* and only 1 knot for the *Liberty Island* during monitoring. Reverse speeds were as high as 2 knots. Constrained by the short time frame in which this activity occurs (typically < 10 minutes), fewer data points were collected and fewer listening stations were occupied.

Weather conditions were generally less favorable for the south pump-out station, used exclusively by the dredge *Liberty*. Wind speeds averaged 4.0 m/sec (range = 3.1-5.0 m/sec) during monitoring of the *Liberty*, followed by 3.3 m/sec (range = 3-4 m/sec) for the *Padre Island,* and 2.5 m/sec (range = 1.8-4.0 m/sec) for the *Dodge Island*. Wind gusts peaked at nearly 8 m/sec (range 5.1-7.6 m/sec) during monitoring of the dredge *Liberty,* exceeding peak gust speeds by nearly 2 m/sec during monitoring of the dredge *Padre Island*. Beaufort wind force conditions (average = 2.0) were lowest during monitoring of the dredge *Dodge*, and highest during monitoring of the *Liberty* (average 2.9).

Received SPLs versus distances (by dredge) are summarized in Table 13. Figure 13 presents 1/3-octave results, which are summarized in Table 14.

Padre Island

A total of 428 SPL measurements were recorded during this operational activity for the dredge *Padre Island*. Data were collected at distances from 150-450 m and from 850 m to 1.45 km. A maximum SPL of 131.65 was measured at the LLD, 150 m from the source, exceeding ambient by 14.7 dB. Assuming transmission loss of 34.33 dB at 150 m, the SL is estimated at 166 dB re 1μPa-1m.

Figure 13. Results of 1/3-octave analysis (by dredge) at selected distances during transition from pump-out to transit.

Table 13. SPL results (db rms) during transition from pump-out to transit.

	Padre			*Dodge*			*Liberty*		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50				127.62	129.84	128.87			
150	126.28	131.65	129.75	121.22	124.54	123.19			
250	125.08	129.08	127.52						
350	124.29	125.23	124.78						
450	117.93	120.3	119.28	119.74	119.05	119.41	129.22	129.15	129.19
550				119.15	120.20	119.70	126.9	127.46	127.19
650				120.78	121.90	121.38	126.24	127.58	126.96
750				118.8	119.02	118.91	132.46	133.98	133.29
850	113.24	122.26	119.76						
950	124.73	126.37	125.63	116.26	119.07	117.89			
1050	114.95	116.59	115.85	116.47	119.6	118.31			
1150	114.99	115.15	115.07	115.44	117.97	116.88	115.40	116.28	115.86
1250	113.67	113.85	113.76	121.01	120.01	120.53	112.58	116.42	114.91
1350	116.48	115.50	116.02	120.97	122.24	121.65	111.54	115.39	113.88
1450	121.01	115.90	119.17				116.01	119.20	117.89
1550				123.04	121.53	122.35	116.76	119.39	118.27
1950				112.24	113.52	112.93			

Table 14. One-third octave results during transition from pump-out to transit.

	Padre			*Dodge*			*Liberty*		
Range	ULD	LLD	AVG	ULD	LLD	AVG	ULD	LLD	AVG
50				137.34	137.78	137.57			
150	136.37	136.98	136.69	131.01	131.64	131.33			
250	134.74	135.25	135.01						
350	130.41	132.52	131.59						
450	125.89	125.94	125.91	121.61	122.58	122.12	137.14	136.14	136.67
550				132.43	133.13	132.79	134.08	133.67	133.88
650				126.37	126.2	126.29	134.01	133.77	133.89
750				123.39	123.88	123.64	137.76	138.59	138.19
850	122.79	127.87	126.03						
950	131.83	131.94	131.89	124.67	125.17	124.92			
1050	120.01	121.54	120.84	123.16	124.37	123.81			
1150	118.42	119.70	119.11	122.30	123.25	122.80	121.87	122.81	122.36
1250	118.41	118.92	118.67	123.93	124.23	124.08	121.28	122.31	121.82
1350	125.67	122.99	124.53	129.37	128.34	128.89	121.87	122.48	122.19
1450	120.95	120.75	120.85				125.62	125.48	125.55
1550				122.64	125.24	124.13	126.63	125.93	126.29
1950				117.26	117.79	117.53			

Attenuation to ambient levels occurred in as little as 450 m at the ULD and 1.05 km at the LLD. SPLs measured at the LLD exceeded those at the ULD by as much as 9 dB, although less than 2 dB was more typical.

Maximum received 1/3-octave SPL for the dredge *Padre Island* was 137 dB, or 16.2 dB above ambient. SPL decreased to 126 dB at a distance of 450 m, before increasing to 132 dB at 950 m from the source. After this slight increase in SPL, values decreased to ambient with the exception of the listening station located at 1.35 km. Attenuation to ambient levels occurred at 1.05 km for the ULD and at 1.15 km at the LLD. Peak frequencies were centered around 200 Hz and 400 Hz.

Dodge Island

A total of 1,368 SPL measurements were recorded at distances ranging from 50 m to 2 km. Note that SPLs were not available for all distances. A maximum

SPL of 129.8 dB was recorded at the LLD at 50 m from the source, exceeding ambient by 12.8 dB. SPL fell by as much as 5 dB over the next 100 m (total distance = 150 m). Using the maximum SPL obtained at 150 m (log average of ULD and LLD = 123.2 dB) and assuming a transmission loss of 34.33 dB, the SL is estimated at 157.5 dB re1µPa-1m.

Sound attenuation to ambient levels occurred at 905 m from the source at the ULD and at 1.95 km at the LLD. Data were not available at distances between 1.65 and 1.85 km; therefore, it is possible that attenuation to ambient levels may have occurred prior to the 1.95-km distance stated above. With the exception of two distances (1.25 and 1.55 km), all SPLs measured at the LLD exceeded those at the ULD. Differences were generally around 1 dB, but as high as 3 dB.

Maximum 1/3-octave SPL occurred at the LLD at 137.8 dB, or 17 dB above ambient. At 1 km from the source, averaged SPL (122.8 dB, 1/3 octave) was only 2 dB above ambient. Attenuation to ambient occurred at 1.95 km from the source. Peak frequency centered around 200 Hz and 500 Hz.

Liberty Island

A total of 2,249 SPL measurements were recorded for the dredge *Liberty Island* during transition from pump-out to transit. Data are not available for distances closer than 400 m from the source. SPL measured at 450 m was 129.2 dB, or slightly more than 12 dB above ambient. Maximum SPLs were recorded at 750 m at 134 dB (LLD) or 17 dB above ambient. SPL had attenuated to ambient at 1.15 km; however, at the LLD there was a slight increase in SPL by as much as1 dB above ambient for measurements taken at the 1.45- and 1.55-km listening stations. SPL measured at the LLD exceeded SPL at the ULD by 0.5 to almost 4 dB.

Maximum (137 dB) 1/3-octave SPL did not occur at the closest listening station (450 m), but rather at 138.6 dB at 750 m from the dredge. No data were collected at distances closer than 400 m from the source. Peak 1/3-octave SPLs exceeded ambient by 17.8 dB. Peak frequencies were centered around 200 Hz and 1 KHz.

Discussion

Transition from pump-out to transit: SLs were calculated for the *Padre Island* and *Dodge Island* using SPLs measured at 150 m from the source.

The SL for *Padre Island* (166 db re1µPa-1m) exceeded that for the *Dodge Island* (157.5 dB re1µPa-1m) by 8.5 dB. Given that no data were collected for the *Liberty Island* at distances less than 400 m, an SL value could not be calculated for comparison. SLs were recalculated using SPLs measured at 450 m because this was the closest distance at which data were available for all three dredges. Based on a transmission loss of 41.86 dB at 450 m, SLs were highest for the *Liberty Island* at 171.06 dB re 1µPa-1m, followed by nearly equivalent SLs of 161.3 and 161.2 dB-re 1µPa-1m dB for the *Dodge Island* and *Padre Island*, respectively. SLs calculated from this distance were nearly 10 dB greater for the *Liberty Island* than for either the *Padre Island* or *Dodge Island*.

Sound attenuation to ambient occurred within as little as 450 m from the source for the *Padre Island* and within 905 m for the *Dodge Island* at the ULD. For the *Liberty Island,* sound had attenuated to ambient at the ULD by 1.1 km. This distance may be over-estimated given that no SPLs were obtained at distances from 850 m to 1.1 km. At the LLD, sound attenuated to ambient at 1 km for the *Padre Island* and 1.95 km for the *Dodge Island*. Attenuation at the LLD for the *Dodge Island* could have occurred at a shorter distance; however, data gaps are present in monitoring of the *Dodge Island* from 1.65 to 1.9 km. Attenuation of sound at the LLD for the *Liberty Island* occurred at 1.15 km.

There was essentially no difference in SL (when using maximum SPL obtained at 450 m from the source) between the *Padre Island* and the *Dodge Island*, with both averaging slightly greater than 161 dB re 1µPa-1m. DQM parameters indicated a vessel draft of 14.6 ft (port) and 16.5 ft (starboard) for the *Padre Island* and 18 ft (port) and 20 ft (starboard) for the *Dodge Island*. Displacement (6500 LT) was approximately 1000 LT greater for the *Dodge Island* compared to the *Padre Island* (5300 LT). Hopper volume (cubic yards) averaged 2,452 yd^3 for the *Dodge Island* and 2,195 yd^3 for the *Padre Island*. Much higher pump speeds were recorded for the *Dodge Island,* averaging 550 rpm when compared to pump speeds used by the *Padre Island* at approximately 160 rpm. Both vessels had a peak frequency centered around 200 Hz and a second peak at 400 Hz (*Padre Island*) and 500 Hz (*Dodge Island*). Based on parameters such as pump speed, displacement, and volume, a slightly higher SL would have been expected for the *Dodge Island* when compared to the *Padre Island*. Given the slow vessel speed during this transition phase, the amount of power needed to move the nearly empty vessel should not have differed greatly. This amount of propulsion and total power may have contributed more to noise production than the relatively slight differences in displacement and volume. The only other possible contributing factor was the slightly less favorable weather conditions during monitoring of the *Padre Island*, although weather conditions were not sustainably different.

What is more difficult to account for is the nearly 10-dB increase in SL for the dredge *Liberty*. DQM data parameters indicated a lower displacement (6295 LT) and volume (2176 yd^3) when compared to the dredge *Dodge Island*. Pumps were used only intermittently, averaging less than 20 rpm. The port-side draft averaged only 11 ft, while the starboard draft was similar to the *Dodge Island* at 20 ft. Weather conditions were less favorable. Beaufort wind conditions averaged 2.9 compared to 2.5 for the *Dodge Island*. Based on these parameters, SL for the dredge *Liberty* should have been more similar to the SLs for the *Dodge Island* and *Padre Island*. A likely factor contributing to the higher SL of the *Liberty Island* was the orientation of the listening platform to the dredge plant. Predicting the movements of each vessel during this activity was difficult. As a result, one had to make an educated guess as to the best position to deploy the listening vessel while remaining clear of vessel maneuvers.

Transition from transit to digging

During the transition from transit to digging, vessel speed slows to below 6 knots (the minimum speed required for the dredge to be in transit mode) in preparation for lowering the dragarms. The time requirement from initial slowdown to the start of sediment excavation averaged 6 minutes. Average vessel speed during the transition phase averaged 2.9 knots for the *Padre Island* and 4.2 knots for the *Dodge Island*. Due to the short time window in which data could be collected, SPL data recorded for this dredging activity are very limited. Note that the data collected during this dredging activity for the dredge *Liberty Island* were insufficient to allow for comparison to the other two dredges. Displacement of the dredge *Dodge Island* was 5,056 LT compared to 3,726 LT for the *Padre Island* due to the larger amount of ballast water in the hopper. Volume (cubic yards) averaged 2,194 yd^3 for the dredge *Dodge Island* compared to only 739 yd^3 for the dredge *Padre Island*. The *Dodge Island* has a fore draft of 13.5 ft and an aft draft of 16.5 ft, while the *Padre Island* had a fore draft of 9.5 ft and an aft draft of 13.1 ft. The dredge *Dodge Island* used only her port pump during the transition phase, which averaged 488 rpm. Both pumps were in operation on the dredge *Padre Island*, each operating at 135 rpm.

Weather conditions were similar during monitoring of both the dredge *Dodge Island* and the *Padre Island*. Wind speed averaged 3 m/sec (range = 2.3-3.2 m/sec) during monitoring of the dredge *Dodge Island* and 2.5 m/sec (range = 1.8-4.4 m/sec) for the dredge *Padre Island*. Wind gusts averaged only 1 m/sec higher (5.2 m/sec) for the dredge *Dodge Island*. Maximum wind speed detected during the transition phase was 7.5 m/sec for the dredge *Padre Island* and 6 m/sec for the dredge *Dodge Island*. Beaufort wind force conditions averaged 2 for the dredge *Dodge Island* and 2.2 for the dredge *Padre Island*. The slight increase was due to less favorable weather conditions just prior to the conclusion of the monitoring session of the dredge *Padre Island*.

Received SPLs versus distances (by dredge) are summarized in Table 15. Figure 14 presents 1/3-octave results, which are summarized in Table 16.

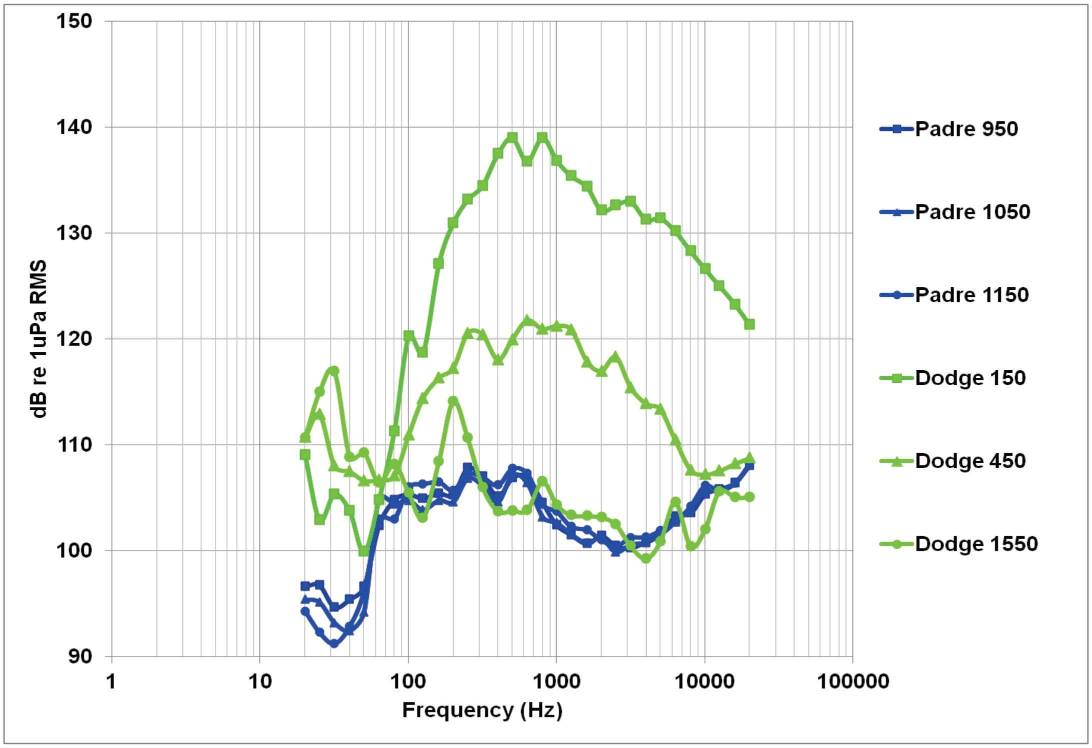
Table 15. SPL (dB rms) and 1/3-octave results for the *Padre Island* during transition from transit to digging.

	Padre Island SPL			*Padre Island* (1/3 Octave)		
Range	ULD	LLD	AVG	ULD	LLD	AVG
950	108.57	112.97	111.3	118.61	119.43	119.04
1050	107.64	111.51	109.99	118.54	118.94	118.75
1150	108.43	111.38	110.15	119.46	119.19	119.33
1250	111.74	114.26	113.18	120.01	120.21	120.11
1350	113.32	112.75	113.05	121.03	122.05	121.57

Table 16. SPL (dB rms) and 1/3-octave results for the dredge *Dodge Island* during transition from transit to digging.

	Dodge Island SPL			*Dodge Islan*d (1/3 Octave)		
Range	ULD	LLD	AVG	ULD	LLD	AVG
50	140.09	144.98	143.19	149.87	150.44	150.17
150	138.34	140.19	139.36	147.66	147.19	147.44
350	131.96	132.32	132.15	138.96	138.40	138.69
450	122.01	124.45	123.39	131.58	131.29	131.43
1550	121.75	121.2	121.48	121.74	121.3	121.53
1650	114.93	120.73	118.73	122.17	123.78	123.05
1850	113.15	114.92	114.12	117.57	118.46	118.04
2450	113.38	115.79	114.75	120.96	121.72	121.36

Figure 14. Results (1/3-octave) at selected distances during transition from transit to digging.



Padre Island

A total of 374 SPL measurements were recorded for the dredge *Padre Island* at distances ranging from 950 m to 1.35 km. No data were collected at distances closer than 950 m from the source. All SPLs measured at the ULD and LLD were below ambient levels. The maximum SPL was 114.3 dB and occurred at the 1.25-km listening station. Assuming transmission loss of 48.86 dB at 1.25 km, the SL is estimated at 163.2 dB re 1μPa-1m. SPLs for the LLD were generally 2.5 to 4.4 dB higher than at the ULD at comparable distances.

Maximum SPLs were only 0.8 dB above ambient. Log-averaged (ULD and LLD) SPLs (1/3 octave) increased slightly from 119.0 dB (at 950 m) to 121.6 dB (at 1.35 km). Peak frequencies centered around 200-300 Hz and between 400 Hz and 600 Hz at 950 m from the source.

Dodge Island

A total of 280 SPL measurements were recorded at eight distances during transition from transit to digging. A maximum SPL of 145 dB (28 dB above ambient) was recorded at the LLD at 150 m from the source. This equates to an estimated SL of 179.3 dB re 1μPa-1m. At 450 m from the source, SPL fell to

123.4 (log average of ULD and LLD), or 6.4 dB above ambient. Attenuation to ambient levels occurred at 1.65 km at the ULD and at 1.85 km at the LLD. Higher SPLs were measured at the LLD (range = 0.36 to 5.8 dB) than at the ULD.

Maximum 1/3-octave SPL was 150.44 dB (LLD) at 50 m from the source, exceeding ambient by 29.6 dB. At 1.55 km, SPLs decreased to less than 1 dB above ambient. At 2.45 km from the source, 1/3-octave SPLs were at or slightly above (less than 1 dB) ambient. Peak frequencies centered around 500 Hz and 800 Hz.

Transition from transit to digging

SL for the *Dodge Island* was 174.3 dB re 1µPa-1m, exceeding the SL estimated for the *Padre Island* (163.2 dB re1µPa-1m) by 11.1 dB. Note that the source level for the *Padre Island* was calculated using the SPL recorded at 1.25 km from the source. This SL may be unreliable, given that it was based upon a far-field SPL measurement. SL values for the dredge *Dodge Island* were calculated using maximum SPL obtained at the 150-m listening station. Likewise, differences in peak frequencies may be related to the distance from the source at which they were obtained. Data were insufficient to accurately calculate attenuation rates.

Transition from digging to transit

This dredging event involves several activities, including reducing vessel speed, raising the dragarms, turning off suction pumps, changing course/heading, and increasing vessel speed in preparation for transit to the pump-out station. Combined, these activities required 6 minutes on average to complete. Suction pumps were in the “on” position at the beginning of the raising of the dragheads to flush out the pipes, and then shut down. For the *Padre Island*, pump speeds averaged 52 rpm (maximum = 136 rpm) for both the starboard and port side pumps. Only the starboard pump (45 rpm) was used during the monitoring of the *Liberty Island*. Data collected for the *Dodge Island* for this dredging event were insufficient for analysis.

Wind speed averaged 3.5 m/sec (range = 2.9-4.0 m/sec), with gusts to 6.2 m/sec (average = 5.2 m/sec) during monitoring of the dredge *Padre Island*. Beaufort wind force condition averaged 2.6, increasing from 2 at the start of the monitoring to 3 by the end of monitoring. Much calmer weather conditions prevailed during the monitoring of the dredge *Liberty*. Wind speed averaged less than 2 m/sec, with gusts to only 3.4. The Beaufort wind force condition was 2 throughout the monitoring session.

Received SPLs versus distances (by dredge) are summarized in Table 17. Figure 15 presents 1/3-octave results, which are summarized in Table 18.

Table 17. SPL (dB rms) and 1/3-octave results for the dredge *Padre Island* during transition from digging to transit.

	Padre Island SPL			*Padre Island* (1/3 Octave)		
Range	ULD	LLD	AVG	ULD	LLD	AVG
50	137.81	135.53	136.82	142.95	141.49	142.28
150	135.65	133.72	134.79	140.95	140.01	140.50
250	135.97	134.79	135.42	140.80	140.44	140.62
950	120.25	120.45	120.35	122.77	123.52	123.16
1050	117.30	117.36	117.33	120.41	121.16	120.80
1150	118.27	117.31	117.82	119.92	121.03	120.51
1250	118.44	118.31	118.37	122.65	123.98	123.37
1350	119.91	120.66	120.3	124.31	125.46	124.92
1450	119.09	119.27	119.18	124.66	123.75	124.23
1550	126.10	125.67	125.89	129.38	128.40	128.91

Figure 15. Results (1/3-octave) at selected distances during transition from digging to transit.

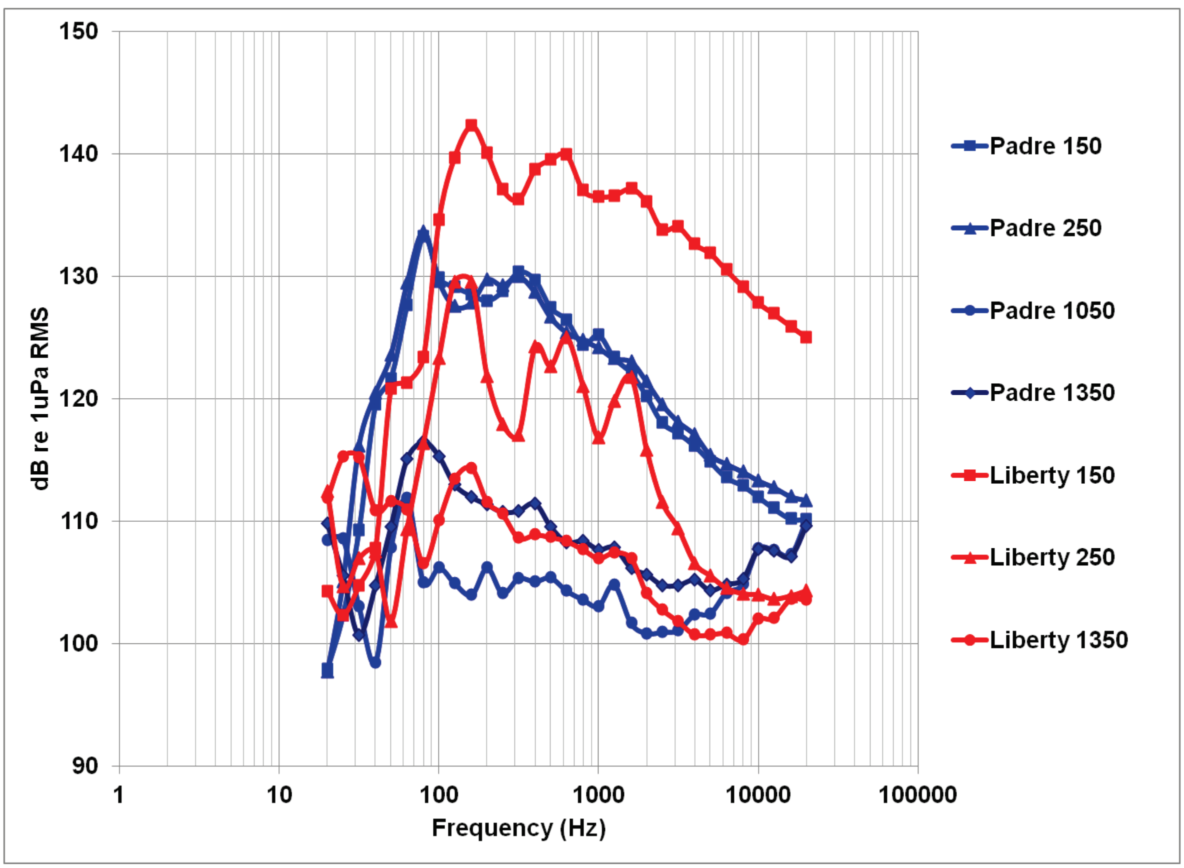


Table 18. SPL (dB rms) and 1/3-octave results for the dredge *Liberty Island* during transition from digging to transit.

Range	*Liberty Island* SPL			*Liberty Island* (1/3 Octave)		
	ULD	LLD	AVG	ULD	LLD	AVG
50	141.47	139.54	140.61	146.3	144.91	145.66
150	144.41	143.50	143.98	150.63	150.31	150.47
250	129.06	128.75	128.91	132.74	133.05	132.90
350	130.01	130.11	130.06	134.26	134.63	134.45
450	132.34	131.71	132.03	135.55	135.65	135.61
1450	120.65	119.56	120.14	122.51	123.87	123.24
1550	121.14	121.03	121.09	123.96	125.09	124.56
2550	118.25	119.29	118.80	125.81	126.02	125.92

Padre Island

A total of 664 SPL measurements were recorded for the dredge *Padre Island* during its transition from digging to transit. A maximum SPL of 137.81 dB occurred at the ULD, 50 m from the source, exceeding ambient by 20.8 dB. At 150 m, SPLs decreased by 2 dB to 135.7 dB (18.7 dB above ambient). SLs calculated using these SPLs at respective ranges were 165 and 170 dB re 1µPa-1m, respectively.

At 1.1 km, SPLs decreased to ambient levels. However, at the next three listening stations (1.2-1.4 km), SPL exceeded ambient by 1 to 2 dB. At 1.55 km, there was a sharp increase in SPL at both the ULD (126.1 dB) and LLD (125.7 dB), exceeding ambient levels by 8 to 9 dB. This was mostly likely related to noise contamination, although the source was not determined. Higher SPLs (1-2.3 dB) occurred in the upper water column at distances less than 300 m from the source. Farther from the source, SPLs at the ULD were generally lower, although differences were not substantial (0.18-0.75 dB).

Over the next 1 km, 1/3-octave SPLs reached 142.95 dB (22.2 dB above ambient) before decreasing at both the ULD and LLD to near ambient levels (<0.25 dB). From 1.25-1.55 km, 1/3-octave SPLs increased from 2.6-8.1 dB above ambient. Peak frequencies were centered around 80 Hz and 200 Hz. Noise generated by waves impacting the sides of the listening platform is most likely associated with the lower frequency.

Liberty Island

A total of 776 SPL measurements were recorded for the dredge *Liberty Island* during its transition phase from digging to transit back to the pump-out station. A maximum SPL of 144.4 dB occurred at a distance of 150 m from the source, exceeding ambient by 27.4 dB. Assuming a transmission loss of 34.33 dB at a distance of 150 m, SL is estimated at 178.7 dB re1µPa-1m.

At 500 m from the source, SPLs decreased to 132 dB, or 15 dB above ambient. The log-averaged SPLs for both the upper and lower listening depths decreased to 120 dB by 1.45 km from the source, or 3 dB above ambient. At 2.55 km, SPLs remained approximately 1-2 dB above ambient. No sound recordings were made at distances exceeding 2.55 km during this dredging activity.

At both the upper and lower listening depths, 1/3-octave SPL was 150.6 dB at 150 m from the source. Maximum SPLs exceeded ambient by 29.8 dB. Peak frequencies centered around 100 Hz and 600 Hz, with minor peak occurring at 1 kHz. Attenuation to ambient had not occurred at 2.55 km from the source. At this distance, 1/3-octave SPLs (average 126 dB) were still slightly more than 5 dB above ambient. SPLs at the ULD exceeded the LLD by 1 dB, with the exception of the closest recording station (50 m), where SPLs at the ULD were nearly 2 dB higher than at the LLD.

Discussion-transition from digging to transit

SLs for the *Padre Island* and *Liberty Island* were estimated from SPLs measured at 150 m from the source. SLs for the *Liberty Island* (178.7 dB re 1µPa-1m) exceeded the *Padre Island* (170 dB re1µPa-1m) by nearly 9 dB. Key factors contributing to higher SLs for the *Liberty Island* included vessel draft, speed, and vessel displacement. The *Liberty Island* (11,910 LT) had nearly twice the displacement of the *Padre Island* (6,938 LT). Both fore (17.3 ft) and aft (23.2 ft) drafts were significantly higher for the *Liberty Island* compared to the *Padre Island* (9.5 ft fore, 13.2 ft aft). Vessel speeds were slightly more than 0.5 knot higher for the *Liberty Island* (4.9 knots) than for the *Padre Island* (4.2 knots).

Transition from transit to pump-out

This phase of the dredging operation involves a reduction in vessel speed to that required for maneuvering and connecting to the pump-out apparatus. Speed must be reduced to less than 6 knots, the defined threshold between transit and transition to a different dredging activity. Time required from arrival at the pump-out site to final connection to the pump-out apparatus averaged 35 minutes. Data were obtained at seven listening stations for the *Padre Island* and at 14 listening stations for the *Liberty Island*. Data collected for the *Dodge Island* were insufficient for meaningful analysis.

Weather conditions were slightly less favorable at the less-sheltered south pump-out station during monitoring of the dredge *Liberty Island*. Wind speeds averaged 4.0 m/sec (range = 3.1-5 m/sec) when compared to the north pump-out station, where wind speeds averaged 3.3 m/sec (range = 3-4 m/sec). Wind gusts peaked at nearly 8 m/sec (range = 5.1-7.6 m/sec) at the south pump-out station, but were below 6 m/sec (range = 4.6-5.8 m/sec) at the north pump-out station. Beaufort wind force conditions were at a level of 2 at both sites at the start of the monitoring session, but increased to 3 by the end of the monitoring session. Beaufort wind force conditions averaged 2.3 and 2.9, respectively, during monitoring of the *Padre Island* and *Liberty Island*.

Received SPLs versus distances and 1/3-octave results for the *Padre Island* are summarized (by dredge) in Table 19 and for the *Liberty Island* in Table 20. Figure 16 presents 1/3-octave results for the *Padre Island* and *Liberty* Island at selected distances.

Table 19. SPL (dB rms) and 1/3-octave results for the dredge *Padre Island* during transition from transit to pump-out.

	Padre Island SPL			*Padre Island* (1/3 Octave)		
Range	CH1	CH2	AVG	CH1	CH2	AVG
50	130.79	134.29	132.88	137.62	138.32	137.98
150	127.37	128.98	128.25	134.32	134.32	134.32
250	127.22	127.80	127.52	133.38	133.71	133.55
350	130.63	131.86	131.29	136.36	136.49	136.43
450	130.67	130.63	130.65	136.30	136.05	136.18
1550	125.19	124.39	124.81	128.08	126.96	127.56
1650	127.30	126.12	126.75	129.01	127.77	128.43

Table 20. SPL (dB rms) and 1/3-octave results for the dredge *Liberty Island* during transition from transit to pump-out.

Range	*Liberty Island* SPL			*Liberty Island* (1/3 Octave)		
	CH1	CH2	AVG	CH1	CH2	AVG
50	146.25	145.92	146.09	151.03	151.18	151.11
150	140.29	140.70	140.50	145.89	146.26	146.08
250	133.11	135.04	134.18	141.12	141.35	141.24
350	132.99	134.04	133.54	139.88	140.01	139.94
450	134.10	134.82	134.48	139.76	140.02	139.89
550	137.11	138.01	137.58	141.12	141.89	141.52
650	135.10	136.45	135.83	141.60	142.06	141.84
1250	124.13	123.45	123.8	123.80	124.49	124.16
1350	123.55	123.90	123.73	123.15	123.86	123.52
1650	124.91	117.56	122.63	122.83	125.14	124.13
1750	122.35	122.16	122.25	121.15	122.81	122.06
1850	120.86	125.04	123.44	122.29	131.47	128.95
1950	121.48	123.40	122.55	121.96	128.67	126.50
2050	121.95	121.13	121.56	121.43	121.67	121.55

Figure 16. Analysis results (1/3-octave) for the *Padre Island* and *Liberty Island* at selected distances during transition from transit to pump-out.

Padre Island

During the transition phase from transit to the pump-out station, 256 SPL measurements were recorded. At 50 m from the source, a maximum SPL of 134.3 dB was recorded at the LLD, exceeding ambient by 17.3 dB. SPL at the ULD was 3.5 dB quieter. SPL (128.3 dB) decreased by 5.3 dB at the LLD and by 3.5 dB at the ULD over the next 100 m from the source. SPLs were highest at the LLD (range = 0.6 to 3.5 dB) near the source (< 400 m) and decreased (0.04-1.18 dB) with distance from the source (> 450 m). The SLs based on SPL observed at 50 m and 150 m are estimated at 161.1 and 163.3-dB re 1µPa-1m, respectively.

Maximum 1/3-octave SPLs occurred at 138.3 dB at 50 m from the source at the LLD, or 17.5 dB above ambient. SPLs decreased by 10.5 dB over the next 1.5 km. At 1.65 km, log-averaged SPL (ULD and LLD) remained nearly 8 dB above ambient. One-third octave peak frequency centered at 600 Hz. Minor frequency peaks centered around 200 Hz and 2.5 kHz at 150 m from the source.

Liberty Island

A total of 4,754 SPL measurements were recorded for the dredge *Liberty Island* during the transition phase from transit to pump-out. A maximum SPL of 146 dB occurred at the 50-m recording station, exceeding ambient by 29 dB. SPLs decreased by approximately 5 dB over the next 100 m. Assuming an SPL of 146 dB at a distance of 50 m and a transmission loss of 26.81 dB, the SL is estimated at 172.8 dB re 1µPa-1m. Using the SPL (SPL = 140.7 dB) recorded at 150 m and a transmission loss of 34.33 dB, the SL is estimated at 175.03 dB re 1µPa-1m.

SPLs decreased to 123.8 dB (log average of ULD and LLD) at 1.25 km from the source, or approximately 7 dB above ambient. Although an SPL (117.56 dB) approximating ambient was recorded at 1.65 km, SPLs at listening stations out to 2.05 km still exceeded ambient by as much as 5 dB. Nine of thirteen recording stations reported higher SPLs at the LLD when compared to the ULD. Differences in SPLs were generally between 1 and 2 dB, but as high as 4.2 dB.

Maximum 1/3-octave SPL occurred at the LLD at 151.2 dB, exceeding ambient by 30.4 dB. SPLs did not differ greatly at the ULD (151.18 dB). SPLs (124.2 dB) decreased by almost 27 dB by the 1.25-km listening station. At

2.1 km from the source, SPLs exceeded ambient by less than 1 dB. Peak frequencies centered around 100-200 Hz. Minor peaks occurred at 500 Hz, 800 Hz, and 1.5 kHz.

Discussion-transition from transit to pump-out

SPLs recorded at 150 m from the source were used to estimate the SL among the dredges. The SL for the *Liberty Island* exceeded that of the *Padre Island* by 12 dB during the transition phase from transit to pump-out. Factors contributing to the higher SPLs for the *Liberty Island* included displacement and vessel draft. Displacement for the dredge *Liberty Island* was 10,563 LT, significantly greater than that of the *Padre Island* (6,981 LT). Vessel draft for the *Liberty Island* was 22.3 ft (forward) and 27.6 ft (stern), exceeding the *Padre Island*'s draft by 2.4 ft (fore) and 7.1 ft (aft).

4 Results for All Dredges Combined by Event

Sound Pressure Levels

A cumulative total of 76,184 SPL measurements were recorded during all dredging phases for all three dredges. SPLs were logarithmically averaged, combining the results for all three dredges by dredging phase. Results (log average of both the ULD and LLD) are presented in Figure 17 and summarized in Table 21.

Combining all observations across all dredging activities, SPLs averaged 142.31 dB (SL = 169.1 re 1 µPa-1 m) at a distance of 50 m. Sediment removal (digging) produced the highest SPL at 144.9 dB, followed by the transition from transit to pump-out (SPL = 144.72 dB). An SL of 172 dB re 1µPa-1 m was estimated for these two dredging activities. Conversely, the two quietest dredging activities were seawater pump-out (flushing pipes) at 132.45 dB and the empty dredge in transit to the borrow site (SPL = 134.74). SLs for these two events were estimated at 159.3 and 161.6 dB re 1 µPa-1 m, respectively.

Figure 17. SPL (dB rms) versus distance by dredging activity. SPLs logarithmically averaged by activity for all three dredges.

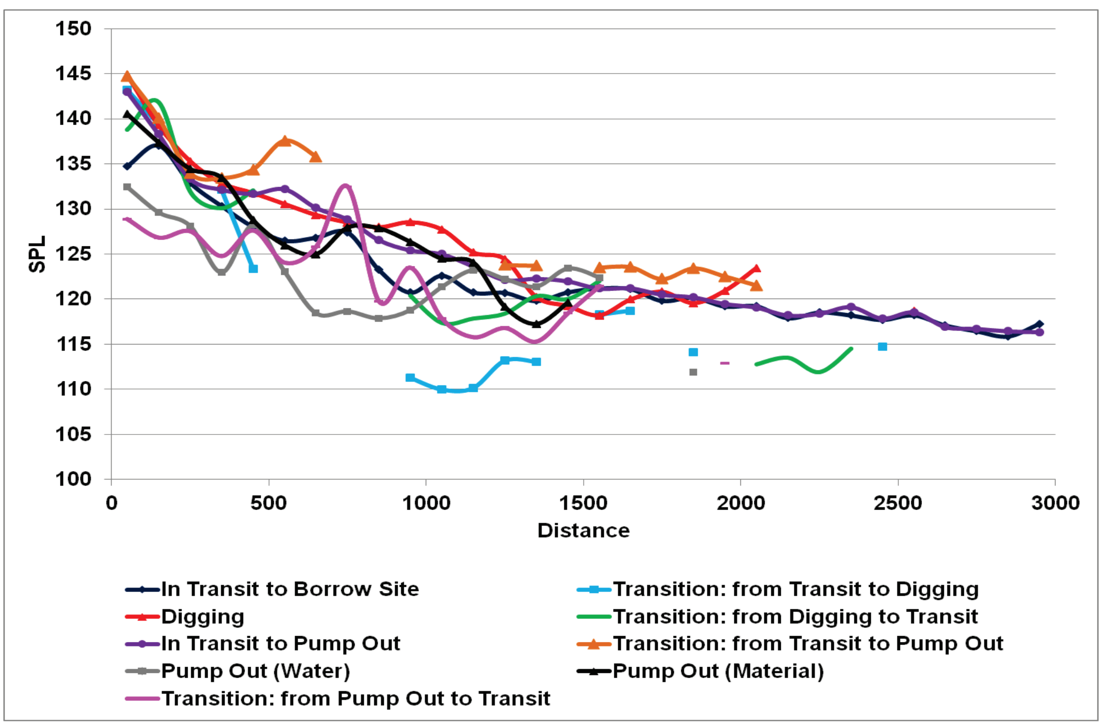


Table 21. Log average (ULD & LLD) SPL versus distance for all three dredges by event.

Range	Overall	TBA	T1	SR	T2	TPO	T3	POW	POM	T4
50	142.31	134.74	143.19	144.91	138.76	143.02	144.72	132.45	140.54	128.87
150	137.16	137.03	139.36	139.30	141.81	138.29	140.07	129.62	137.37	126.82
250	133.75	132.92		135.31	131.91	133.36	133.98	128.12	134.45	127.52
350	132.38	130.33	132.15	132.86	130.06	132.16	133.43	122.96	133.46	124.78
450	130.55	128.02	123.39	131.78	132.03	131.71	134.39	128.22	128.77	127.61
550	128.92	126.49		130.56		132.22	137.58	123.05	125.97	124.05
650	129.04	126.83		129.34		130.15	135.83	118.43	124.99	125.81
750	127.77	127.41		128.5		128.86		118.65	127.94	132.47
850	126.86	123.27		127.98		126.57		117.87	127.85	119.76
950	125.40	120.74	111.30	128.54	120.35	125.44		118.80	126.34	123.49
1050	124.38	122.62	109.99	127.73	117.33	125		121.37	124.47	117.85
1150	123.15	120.76	110.15	125.18	117.82	123.65		123.24	124.05	115.81
1250	121.35	120.72	113.18	124.44	118.37	122.15	123.8	122.24	119.13	116.83
1350	120.19	119.81	113.05	120.23	120.30	122.29	123.73	121.4	117.25	115.34
1450	120.59	120.77		119.23	119.98	122		123.41	119.65	118.47
1550	120.84	121.21	118.28	118.2	121.97	121.19	123.52	122.39		121.44
1650	120.84	121.13	118.73	119.96		121.23	123.58			
1750	120.47	119.82		120.82		120.51	122.25			
1850	120.4	120.18	114.12	119.56		120.22	123.44	111.88		
1950	120.14	119.2		120.94		119.49	122.55			112.93
2050	119.73	119.24		123.46	112.74	119.09	121.56			
2150	117.77	117.91			113.47	118.21				
2250	118.22	118.55			111.88	118.39				
2350	118	118.22			114.48	119.14				
2450	117.72	117.72	114.75			117.87				
2550	118.43	118.23		118.69	118.8	118.56				
2650	117.05	117.12				116.93				
2750	116.58	116.46				116.73				
2850	116.15	115.89				116.46				
2950	116.91	117.28				116.36				

Overall = Average dB SPL for all dredges and events combined.

TBA = In Transit to Borrow Area; T1 = Transition from Transit to Digging.

T2 = Transition from Digging to Transit; SR = Sediment Removal.

TPO = In Transit to Pump-out; T3 = Transition from Transit to Pump-out.

POW = Pump-out Water; POM = Pump-out Material, T4 = Transition from Pump-out to Transit.

At 150 m from the source, the only dredging activity with an SPL above 141 dB was the dredge in transition from digging to transit (SPL = 141.8 dB, SL = 176.1 dB re 1 µPa-1 m). This phase involved turning the fully loaded dredge shoreward toward the pump-out station while increasing to maximum transit speed. Several dredging activities, such as digging and transition from transit to pump-out, were approximately 1 dB quieter. The quietest event at this distance was the dredge in transition from the pump-out station with an empty hopper maneuvering for transit back to the borrow area. This event produced a combined average SPL of 126.8 dB (SL = 161.1 dB re 1 µPa-1 m). In comparison, the overall SPL for all dredges and events at 150 m from the source was 137.16 dB. SL calculated for the collection of dredging events at this distance (150 m) to the source was 171.5 re 1µPa-1 m, or 2.4 dB higher than SL calculated for the collection of all dredging events when using SPL obtained 50 m from the source.

At 250 m from the source, sediment excavation (SPL = 135.3 dB) ranged from 0.9 to nearly 8 dB louder than all other dredging activities. The second-loudest event at this distance was during pump-out of dredged material (SPL = 134.45 dB). Transition from pump-out to transit was the quietest activity at this distance (127.5 dB).

From 450 m to 650 m, the loudest dredging activity was the transition from transit to pump-out. This event required maneuvering of the fully loaded dredge into the correct orientation to connect to the pump-out apparatus. SPLs ranged from 134.4 dB to 137.6 dB. This range of SPLs exceeded those for all other dredging activities by as little as 2.6 dB (450 m) to 5.7 dB (650 m) and by as much as 11.5 dB (450 m) to 17.4 dB (650 m). The variability in SPL during this dredging event is related to changes in propulsion and total power used to maneuver the fully loaded vessel into the correct orientation to make the connection to the pump-out apparatus. For all events and dredges combined, the overall SPL fell from 130.6 to 129.0 dB. At 650 m, the average overall SPL was nearly 13.5 dB lower than at 50 m.

From 950 m to 1.25 km from the source, sediment excavation was the loudest of all dredging activities. SPLs decreased across this distance from 128.5 to 124.44. The second-loudest event was pump-out of dredged material. Pump-out SPLs decreased from 126.34 (950 m) to 119.13 dB (1.25 km) and were 2.2 to 5.3 dB less than sediment excavation. The quietest activity was transition from transit to digging, during which the empty dredge slowed to 2-4 knots in preparation for dredging. During this transition phase, all SPLs (109-113 dB) at these distances were below ambient. Combined SPLs for all events and dredges decreased from 125.4 dB (950 m) to 121.4 dB (1.25 km).

From 1.55-2 km from the source, the loudest dredging activity was transition from transit to pump-out. During this activity, the dredge was maneuvering with a fully-loaded hopper to connect to the pump-out apparatus. SPLs exceeded ambient by 5-6 dB and decreased from 123.6 dB at 1.55 km to 122.5 dB at 2 km from the source. At this distance from the source, noise produced by POM, POW, and all transition activities had attenuated to ambient levels. The three additional dredging activities (SR, transit to pump-out, and TBS) averaged 3 dB quieter than the fully-loaded dredge maneuvering into position at the pump-out station. Combined overall SPL for all events and dredges decreased from 120.8 dB (1.55 km) to 120.1 dB (1.95 km).

At 2.5 km from the source, underwater sounds generated by all three dredges for all events combined had attenuated to ambient levels (Figure 18). In a few instances, underwater sound generated during individual dredging activities by a single dredge did not attenuate to ambient until 3 km from the source. When all dredging activities for all three dredges are combined, a source level of 171.52 dB re 1µPa-1 m is estimated.

One-third octave analysis

Results from the 1/3-octave analysis for all three dredges are presented in Figure 19 and summarized in Table 22. At 50 m from the source, an overall SPL of 147.7 dB was obtained for all dredges and dredging events combined. At 50 m from the source, sediment removal (SR) produced the loudest underwater sound at almost 151 dB, followed by transition from transit to digging (T1) at 150.2 dB. Both of these events exceeded ambient by 29-30 dB. The two quietest events were transition from pump-out to transit (T4) and pump-out of seawater (POW) during flushing of dredge pipes. SPLs (1/3-octave) averaged 137.6 dB (T4) to 139.1dB (POW), or 12-13.5 dB quieter than during sediment removal (digging).

At 150 m from the source, the highest SPL (148.24 dB 1/3-octave) occurred when the dredge was in transition from digging to transit (T2), followed by transition from transit to digging (SPL = 147.44). Both activities involve

Figure 18. SPL (dB re 1 µPa RMS) versus distance for all dredges and dredging events combined.

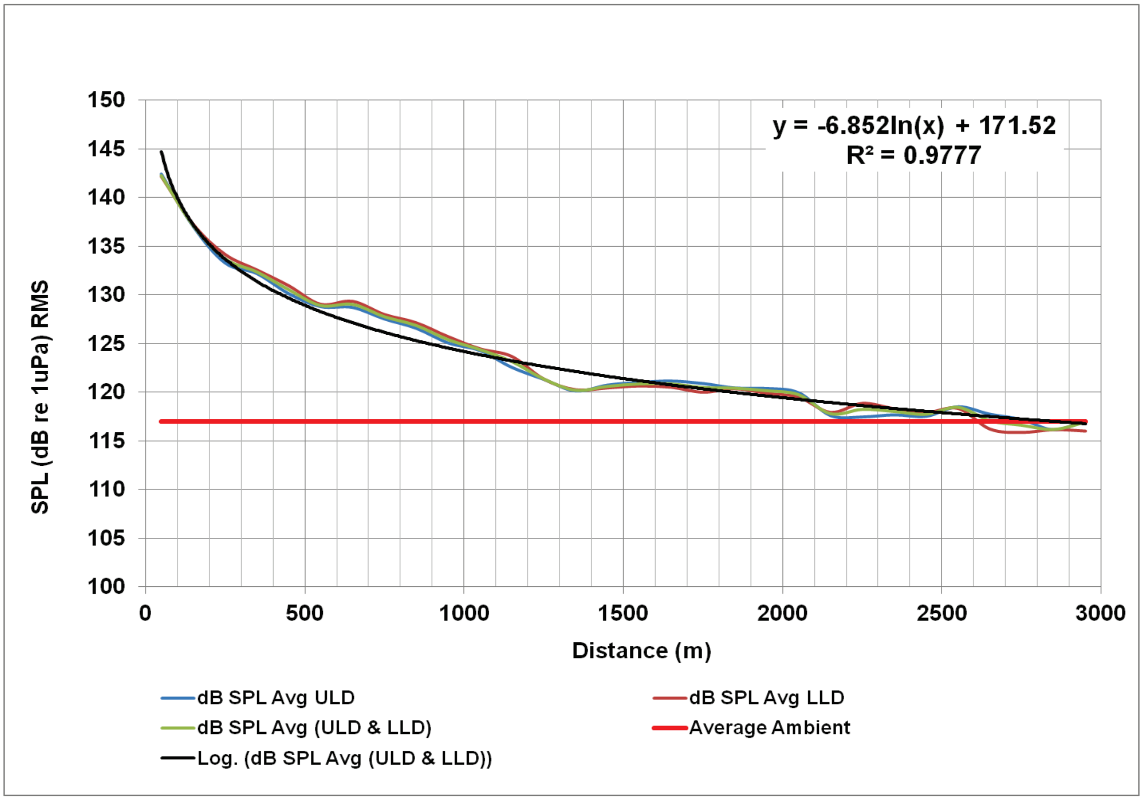


Figure 19. One-third octave analysis (log average ULD and LLD) for all dredges and dredging events combined.

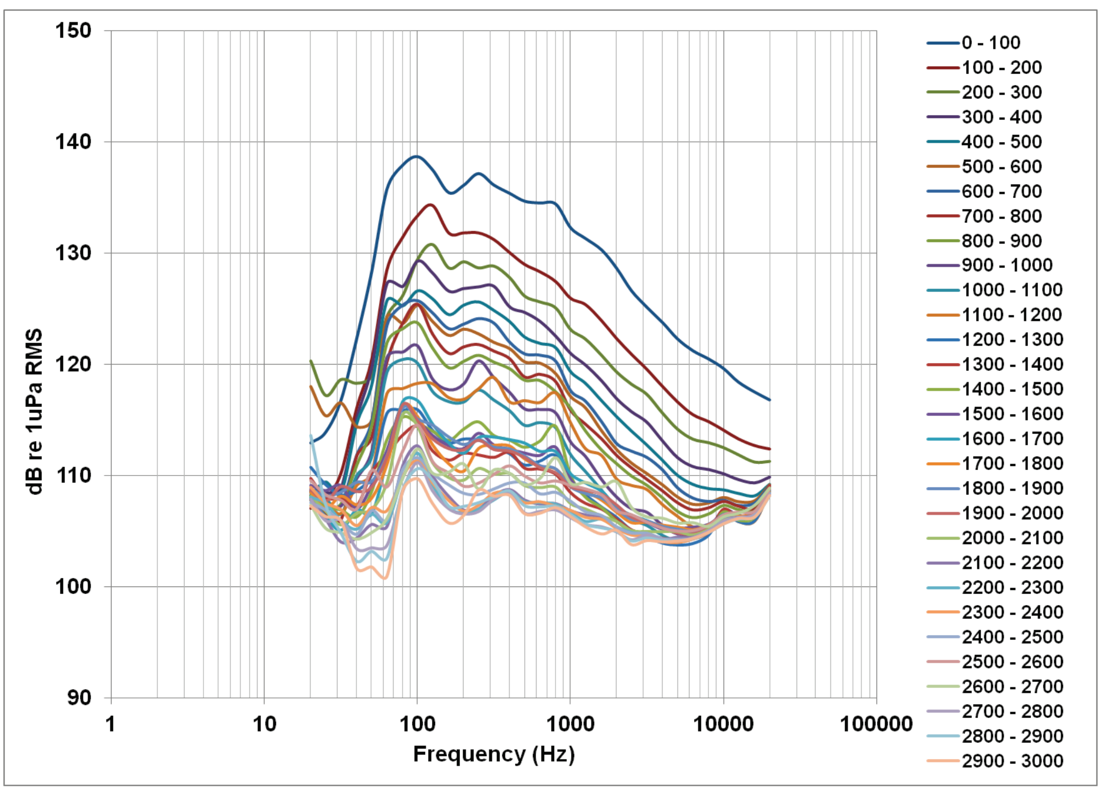


Table 22. Analysis (1/3-octave) for all three dredges by event (log average of ULD and LLD).

Range	Overall	TBS	T1	SR	T2	TPO	T3	POW	POM	T4
50	147.73	140.93	150.17	150.93	143.97	148.51	149.74	139.13	145.37	137.57
150	142.46	142.36	147.44	144.75	148.24	142.51	145.65	135.4	142.13	134.12
250	139.40	139.91		140.97	136.71	138.83	141.02	134.17	139.07	135.01
350	137.91	136.34	138.69	138.62	134.45	137.63	139.78	129.53	138.14	131.59
450	136.05	133.25	131.43	137.47	135.60	136.53	139.80	134.24	132.97	134.96
550	134.24	131.62		135.74		136.53	141.52	128.38	132.28	133.23
650	134.71	131.69		134.25		135.01	141.84	125.16	131.19	132.55
750	132.99	132.36		133.49		134.08		123.43	133.45	137.37
850	132.22	128.72		133.08		132.01		122.87	133.43	126.03
950	130.32	126.70	119.04	132.38	123.16	130.71		123.31	131.71	129.86
1050	128.98	127.82	118.75	131.73	120.8	129.48		127.12	129.1	123.28
1150	129.19	125.97	119.33	129.26	120.51	128.42		128.55	131.24	121.86
1250	125.78	126.08	120.11	129.16	123.37	127.24	124.16	126.26	121.94	122.35
1350	124.60	124.77	121.57	125.88	124.92	127.29	123.52	121.94	119.98	123.35
1450	125.86	127.13		126.05	123.43	126.85		122.64	120.03	124.14
1550	125.61	125.92	125.07	125.17	125.32	126.59	127.71	123.77		124.93
1650	125.85	125.01	123.05	126.68		125.84	127.94			
1750	125.08	123.82		127.01		125.23	122.06			
1850	125.55	124.09	118.04	126.34		124.87	128.95	117.87		
1950	125.30	123.38		127.49		124.43	126.50			117.53
2050	123.8	122.44		127.97	118.10	124.11	121.55			
2150	122.15	121.30			118.35	123.53				
2250	122.01	121.17			119.97	123.19				
2350	122.14	121.33			121.11	123.59				
2450	122.50	121.81	121.36			123.40				
2550	123.99	123.72		125.62	125.92	123.15				
2650	123.50	124.09				122.47				
2750	121.46	120.72				122.28				
2850	122.03	122.07				121.97				
2950	121.16	120.9				121.48				

Overall = Average dB SPL for all dredges and events combined.

TBS = In Transit to Borrow Site; T1 = Transition from Transit to Digging.

T2 = Transition from Digging to Transit; SR = Sediment Removal.

TPO = In Transit to Pump-out; T3 = Transition from Transit to Pump-out.

POW = Pump-out Water; POM = Pump-out Material.

T4 = Transition from Pump-out to Transit.

raising and lowering of dragarms either prior to the start of the cut or at the completion of the loading process. These two events exceeded ambient by 26-27 dB. The quietest dredging activities were seawater pump-out (POW) and transition from pump-out to transit (T4). Combined SPLs fell by 5.2 dB from 147.7 at 50 m to 142.5 dB at 150 m.

At 250-650 m from the source, the loudest underwater sounds were recorded during maneuvering of the fully-loaded dredge during transition from transit to pump-out (T3). SPLs averaged 140-141 dB, which exceeded ambient by 20 dB. The second-loudest dredging activity was sediment removal, but only at listening stations ranging from 250 m (SPL = 141 dB) to 450 m (SPL = 137.5 dB) from the source. From 450-650 m, transit to the pump-out station (TPO) was the second-loudest activity, with SPLs ranging from 134-136.5 dB. The overall SPL for all dredging events and dredges combined decreased from 139.4 dB at 250 m to 134.7 dB at 650 m, exceeding ambient by 13.9-18.6 dB. The lowest values represented a 16.3-dB decrease compared to that at 50 m.

From 950 m to 1.1 km from the source, the loudest sounds were produced during sediment removal (SPL = 129.3 to 132.4 dB), followed closely by pump-out of dredged material (POM), for which SPLs ranged from 129-131 dB. Over the next 200 m (total distance = 1.35 km), transit to the pump-out station produced the loudest underwater sounds (127 dB). Overall SPL decreased from 129.2 (950 m) to 124.6 dB at 1.35 km. Overall SPL remained relatively constant (124 to 125 dB) as distance increased from 1.1 to 1.95 km.

At 1.45 to 2.1 km from the source, the loudest underwater sounds fluctuated between sediment removal and transition from transit to pump-out. SPLs ranged between 126 and 127 dB, with an occasional measurement as high as 129 dB. The overall SPL decreased to 123.8 dB at the 2.1-km listening station, or nearly 34 dB quieter than at the 50-m listening station.

Only two dredging events, transit to the borrow site (TBS) and transit to the pump-out station (TPO), were characterized by listening stations at 2.1-3 km. SPL were somewhat higher during transit to the pump-out station (SPL = 121 to 123 dB) when compared to transit to the borrow site (SPL = 120-122 dB). Differences in SPL averaged approximately 2 dB. Other events (e.g., transition from digging to transit) had incomplete station coverage, but SPLs recorded at 2.1-2.3 km indicated that sounds had attenuated to ambient levels. At 3 km, the overall SPL for all dredges and events averaged 121.2 dB, exceeding ambient by 0.4 dB.

Source levels, attenuation distances, and peak frequencies

Source levels

Source levels are presented in rank order, highest to lowest by dredging activity (Table 23). SLs exceeding 175 dB re 1µPa-1m during multiple dredging activities were recorded during *Liberty Island* operations. Of nine dredging events with mid-range SLs (170 to 175 dB re 1µPa-1m), the majority were associated with the *Dodge Island* (n = 4). For the *Padre Island*, only two dredging activities, sediment removal and pump-out of dredged material, had mid-range SLs. All other dredging events for the *Padre Island* had SLs in the lower range below 170 dB re 1µPa-1m (163.2 to 169.5 dB re 1µPa-1m). The lowest SLs recorded in the current study were 161.3 dB and 162.3 dB re 1µPa-1m, both for the *Dodge Island* during transition from pump-out to transit and seawater pump-out of water (flushing pipes), respectively.

Given that the dredge *Liberty Island* was nearly twice the size of the *Dodge Island* and *Padre Island* in terms of hopper capacity, displacement, propulsion power, and gross tonnage, it is not surprising that the *Liberty Island* produced the highest source levels. Although the *Padre Island* and *Dodge Island* are very similar to one another in terms of dimensions and specifications, the *Dodge Island* had greater propulsion power (3,244 kW) than the *Padre Island* (2,237 kW). Because all other specifications were nearly equivalent, the primary factors contributing to the higher SLs recorded for the *Dodge Island* appear to be greater propulsion power and higher pump speeds. Pump speeds for the *Dodge Island* were as high as 1,050 rpm during sediment removal and 1,500 rpm during pump-out of dredged sediment. Neither the *Liberty Island* nor the *Padre Island* had pump speeds exceeding 400 rpm for any dredging event, with 200 rpm being the most common pump speed.

Attenuation distances

Attenuation distances were compared by dredging activity and are summarized in Table 22. Sounds generated while transiting to either the borrow area or pump-out stations required longer distances for attenuation to ambient levels. These two dredging activities involved operating the dredge at maximum safe speed, typically in excess of 10 knots. Attenuation to ambient distances for these two events ranged from 1.8-2.9 km (average 2.4 km). During transit to pump-out, attenuation to ambient for the *Padre Island* (1.8 km) differed considerably from that for the *Liberty Island*

Table 23. Rank order of source levels by dredging activity.

Dredge	Dredging Event	SPL Distance (m)[1]	SL[2]	Attenuation Distance (km)[3]	Peak Frequencies (Hz)
Liberty	Transition--Digging to Transit	150	178.7	2.5	100, 600, 1000
Liberty	Transit to Borrow Area	450	178.2	2.45	150, 1000
Liberty	Transit to Pump Out	350	176.2	2.65	400, 1100
Liberty	Pump-out Material	150	176.0	1.2^	200, 500, 1200
Liberty	Pump-out Water	450	175.1	1.2^	250, 400, 1000
Liberty	Transition--Transit to Pump-out	150	175.3	1.1	150, 500, 800, 1500
Dodge	Sediment Removal	150	174.5	1.55	100, 700-800
Dodge	Transition--Transit to Digging	150	174.3	1.85	500, 800
Liberty	Sediment Removal	50	174.2	1.65	200, 500, 1100
Dodge	Transit to Borrow Area	150	173.8	2.75	200, 700
Padre	Sediment Removal	150	173.0	2.05	150, 250, 500
Padre	Pump-out Material	150	172.0	ULD-1.35; LLD[4]	150, 600, 1000
Liberty	Transition—Pump-out to Transit	450	171.0	1.1	200, 500
Dodge	Transit to Pump-out	350	170.9	2.9	200, 800
Padre	Transition--Digging to Transit	150	170.1	1.1	80, 200
Padre	Transit to Pump-out	350	169.5	1.75	80, 300, 400
Padre	Transit to Borrow Area	450	169.5	2.1	100, 400
Dodge	Pump-out Material	150	166.8	1.35	150, 1000
Padre	Pump-out Water	450	166.2	0.75	150, 500, 1000
Padre	Transition-Pump-out to Transit	150	166.0	ULD-0.45; LLD-1	200, 400
Padre	Transition--Transit to Digging	1250	163.2	0.95	200, 400-600
Padre	Transition--Transit to Pump-out	150	163.3	1.65[4]	200, 600, 2500
Dodge	Pump-out Water	150	162.3	0.85	150, 600, 1000
Dodge	Transition--Pump-out to Transit	450	161.3	ULD-0.95; LLD-2	200, 1000

[1]Note that source levels were estimated from the SPL (dB re 1 μPa-1 m) measured at the specified distance for each event.

[2]SL based on 15.778LogR obtained from fitted regression.

[3]Single number indicates that attenuation occurred by this distance at both the upper and lower listening depth. ULD = Upper listening depth; LLD = lower listening depth.

[4]Sound had not attenuated below ambient by this distance.

(2.7 km) and *Dodge Island* (2.9 km). The *Padre Island* generally operated at a slower vessel speed (mean = 9.4 knots) than either the *Dodge Island* (mean = 10 knots) or *Liberty Island* (mean = 11.5 knots). The *Dodge Island* also had much higher pump speeds (634 rpm), although the pumps were used only intermittently. Maximum pump speed for the *Padre Island* was only 136 rpm, whereas the *Liberty Island* did not use pumps during this dredging activity.

During sediment removal (digging), sound attenuation to ambient levels occurred within 2 km. Even with the higher pump speeds used by the *Dodge Island* and the overall larger size of the *Liberty Island*, including a larger pipe suction diameter, sounds produced by the *Padre Island* took the longest to attenuate to ambient (2.1 km). The dredges *Dodge Island* and *Liberty Island* had similar attenuation distances (Table 21).

For most transition phases, sound attenuation to ambient levels occurred within 2-2.5 km. For example, sound attenuation during transition from digging to transit back to the pump-out station occurred within 2.5 km from the source for the *Liberty Island*. Sounds produced by the *Dodge Island* during transition from pump-out to transit back to the borrow area required 2 km to attenuate to ambient levels at the lower listening depth, but less than 1 km at the upper listening depth. Non-transition phase sounds such as pumping seawater to flush pipes also attenuated to ambient in less than 1 km. Underwater sounds produced during transition phases tended to attenuate at shorter distances from the source for the *Padre Island* than for the other dredges in this study.

Peak frequencies

The three trailing suction hopper dredges in the present study emitted sound levels at peak frequencies generally below 500 Hz (Table 21). These frequencies fall in a range commonly associated with cargo ships traveling at modest speeds between 8 and 16 knots. Several dredging activities in the current study infrequently did produce sounds with frequencies between 700 and 1,000 Hz. During three transition phases, one for each of the three dredges, peak frequencies measured from 1.7-3 kHz. These higher frequencies generally occurred during maneuvering of the vessel to the pump-out station, or after the loading process in which the dredge and full hopper are turned shoreward followed by an increase in speed. In the case of the *Dodge Island,* higher-frequency sounds were associated with lowering of the dragarms in preparation for sediment excavation. Higher-frequency sounds may also have been generated during episodes of propeller cavitation.

Source levels from other trailing suction hopper dredging operations

Greene (1987) reported underwater sound levels for hopper dredges that were relatively loud, but at fluctuating levels. The most intense sounds were produced during loading or unloading, whereas the hopper dredges were relatively quiet while under way. Greene (1987) reported that the 8,000-m^3 capacity *Geopotes X* was operating in waters 21 m deep when sound measurements were taken. At a range of 0.43 km, the 20- to 1,000-Hz band level was 139 dB re 1 µPa at 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 at 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 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 (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 Bank and calculated the broadband source level to be 186 dB re 1µPA at 1m. The received level was 144 dB re 1µPA at 150 m. Results indicated that the dredge sounds would be audible beyond a range of 6 km.

Clarke et al. (2002) characterized sounds produced by the Stuyvesant LLC dredge *Stuyvesant*, a 15,000-hp plant with an 11,140-yd^3 capacity, during maintenance dredging in upper Mobile Bay, Alabama and transporting dredged material to an offshore disposal site. The hopper dredge pressure waveform was very similar to that of a cutterhead dredge, i.e. a relatively continuous, uniform sound. At the closest recording distance, the hopper dredge passed immediately in front of the listening vessel platform at a distance of approximately 40 m. At this distance, sounds of the draghead scraping across the sandy substrate could be discerned from propeller noise. One salient difference between hopper and cutterhead pressure waveforms is the greater intensity of sounds emanating from the former. The authors concluded that the majority of the produced sound energy fell within the 70- to 1,000-Hz range. Peak SPLs (relative) ranged from 120-140 dB.

Reine et al. (in preparation) monitored the 2,300-yd^3 TSHD *Atchafalaya* during sand wave removal in the Doubling Point Reach of the Kennebec River, Maine. Nine monitoring sessions recorded SPLs during various dredging activities, such as: dredge underway with pumps on/off, dredge transiting with empty/full hopper, and dredge during sediment removal. Received levels ranged from 146.7-148 dB re 1 µPa rms. SLs ranged from 172.6 to 179.9 dB re 1 µPa-1 m during active dredging with a vessel speed of 1 knot. Source levels reached 180 dB on two occasions when the dredge was not digging and the suction pumps were in the off position. However, vessel speed exceeded 5 knots. Higher vessel speeds produced SLs that did not differ from SLs during active dredging. Combining all monitoring events, the SL was 173 dB re 1 µPa-1 m. SPLs decreased to below ambient (95th percentile) within 400-500 m. At 700 m, SPLs decreased to below mean ambient (133.6 dB) and during some monitoring events had fallen to below the minimum SPL (125.4 dB) recorded during ambient noise monitoring.

Source levels from mechanical and hydraulic cutterhead operations

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 1,000-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 at 1m. Measurements were also taken for the cutterhead dredge *Aquarius* at distances ranging from 0.2-14.8 km. At the closest range, the 20- to 1,000-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.

Miles et al. (1986, 1987) recorded sounds produced by a bucket dredge, noting that the 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); whereas bucket closing (113.2 dB relative) and barge loading (108.6 dB relative) activities were 10.8 dB and 15.4 dB lower, respectively. The authors reported that SPLs (relative dB rms) diminished from 15 dB to 30 dB at distances of 150 m and 5,500 m 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.

Clarke et al. (2002) characterized sounds produced by the Lake Michigan contractor's 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. Most of the produced sound energy fell within the 70- to 1,000-Hz range, and peaked in the 100- to 110-dB range. Sounds attributable to the cutterhead operation became almost inaudible at relatively short distances (approximately 500 m) from the source.

Reine et al. (2012a) monitored sounds produced by the Great Lakes Dredge and Dock dredge *New York*, a 3,434-hp backhoe dredge engaged in deepening 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). The most intense sounds were associated with bottom grabs and the use of dredge spuds. Source levels for bottom grabs were 179.4 dB re 1 µ PA at 1m, or 62.3 dB and 48.2 dB above average and maximum ambient SPL, 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 at 1m for raising and lowering of the spuds, and 172.4 dB for spud walking. Spud sounds exceeded average ambient SPL by 55-58 dB, or 41-44 dB above maximum ambient SPL. 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 at 1m); engine/generator sounds (SPL = 167 dB re 1 µ PA at

1 m), barge loading sounds (SPL = 166.2 dB re 1 µ PA at 1m); and hydraulic ram sounds (SPL of 164.2 dB re 1 µ PA at 1m). These SPL levels exceeded the average ambient SPL by 47 to 50 dB re 1 µ PA at 1m. Source levels differed from the most to least intense sounds by 15.1 dB. Sounds were detectable against ambient to relatively short distances from the dredging operation, so attenuation curves could not be plotted. The greatest distance to which detectable dredge sounds were measured was 680 m and were associated with engine/generator noise. It was uncertain if the measured sound, although clearly of engine/generator origin, emanated from the dredge *New York* or from some other source. The maximum distance at which underwater dredging sounds were positively identified was 330 m.

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. Peak SPLs were 151 dB at the upper listening depth (ULD = 10 ft) at a range of 100 m and 151 dB at the lower listening depth (LLD = 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. Sound intensity varied by as much as 10 dB at equivalent distances depending on the amount and density of the material being removed. Additional factors that contributed to variation in SPL included orientation of the listening vessel to the dredge, position of the cutterhead as it swings across an arc, and the non-uniform, intermittent sediment removal process. Attenuation to ambient levels (average = 117.1 dB) was not determined. SPL still exceeded ambient by 10-15 dB at 800 m from the source. At 100-740 m from the source, 1/3-octave SPLs decreased from 151-136 dB. These SPLs exceeded ambient by 18.9-33.9 dB. The majority of underwater sounds produced by this hydraulic cutterhead dredging operation were of relatively low frequency, generally less than 1,000 Hz, and occurred most frequently in three 1/3-octave bands (800 Hz, 1000 Hz, and 2500 Hz).

Source levels associated with shipping

Underwater sound measurements (20 Hz to 20 kHz) were recorded for several commercial vessels operating in New York Harbor.[1] The Staten Island Ferry system operates nine vessels, completing 35,000 trips annually. Underwater sound measurements were made of the ferry servicing the Staten Island St. George Ferry Terminal to the Battery in lower Manhatten. 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 298-830 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 298 m from the source. Assuming a loss of 37.1 dB (practical spreading, 15 LogR), SL 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 average ambient 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 122-1,442 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 ambient 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.

[1] Reine, K. J., D. G. Clarke, and C. Dickerson. Unpublished data, US Army Engineer Research and Development Center, Vicksburg, MS.

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 at 353 m from the source, exceeding ambient 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 ambient by approximately 16 dB.

The *Zim Savannah* is 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 141.7-129.2 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.

5 Conclusion

The main goal of the Wallops Island Study was to determine the acoustic source level of three trailing suction hopper dredges (TSHDs) during the various activities: sediment excavation, transport of material, flushing pipes with clear water and pump-out of material. Sounds emitted by the source were characterized by source level, frequency composition, attenuation distances, and temporal variation.

Given the lack of appropriate standards for characterizing dredges as sources of underwater noise in shallow-water environments, an analysis methodology had to be developed by ERDC for the present study. A recent document by the American National Standards Institute (ANSI 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 conducted in estuarine or near-shore environments, this requirement is not feasible given that water depths are typically less than 50 m and that dredges monitored in the current study had lengths that ranged from 86.5-96 m.

Noise levels from dredging activities are highest at low frequencies (< 500 Hz) when tones or conventional spectrum level measurements are considered. On a 1/3-octave basis, the strongest dredging noise sounds are also below 500 Hz. During most dredging activities, the highest sound pressure levels were found for the larger (*Liberty Island*) of the three TSHDs, while transiting at speeds up to 14 knots. Propeller cavitation accounts for much of the noise during this dredging activity. For medium to large ships (those monitored in the current study), most of the energy is at or below 100 Hz, with some energy to 500 Hz. Noise from smaller ships or boats tends to have higher frequencies.

Other activities, such as pump-out of water and material, also resulted in higher noise levels for the dredge *Liberty* when compared to the smaller TSHDs. With the exception of sediment removal, and while the dredge was in transition from pump-out to transient, SL for the dredge *Liberty* exceeded 175 dB re 1µPa-1m, with a maximum SL of nearly 178 dB re 1µPa-1m. Lowest SL (161-162 dB re 1µPa-1m) occurred for the dredge *Dodge* during pump-out of water and during transition from pump-out to transient. For most activities, the dredge *Padre* was the quietest of the three dredging operations. Given that the *Dodge* and *Padre* are of the same size class, one would have expected similar SLs. Higher overall propulsion power, higher pump speeds, and greater transit speed appear to be the key factors in the differing SL values. Note that the source levels found in this study are only representative of dredging activities similar to the above; that is, removing sand from a nearshore borrow area. Higher or lower source levels may be expected for activities in different sediment (e.g. gravel instead of sand, or silty (mud) sediment instead of sand or gravel) and at different water depths.

A second goal was to compare SLs obtained from the current study with SLs obtained from other dredging operations as well as commercial shipping. Few prior studies have described underwater sounds produced during hopper dredging operations. The few data that exist largely involve the mining of aggregate (sand and gravel) for use in the construction industry. Source levels for aggregate excavation operations generally range from 186-188 dB re 1µPa-1m. SLs (173 dB-174.5 dB re 1 µPa-1m) during excavation operations in this study were 12-14 dB quieter than those reported for the aggregate mining. The SLs (161 dB to 178.7 dB re 1 µPa-1m) measured across all dredge operations were 9-25 dB quieter than aggregate mining.

SLs estimated in the present study are similar to those generated from the small 1,300-yd^3 hopper dredge *Atchafalaya* (172-180 dB) when removing sandy shoals in the Kennebec River, Maine (Reine et al., in preparation). Although all three dredges in the current study were larger than the *Atchafalaya*, frequent short digging cuts involving multiple turns within a relatively small area may have generated higher sound levels than one would expect from this dredge size class. Frequent maneuvering of this dredge most likely produced higher-than-normal propeller cavitations. Attenuation to ambient levels, however, occurred at much shorter distances (700 m) than were observed (2 to 3 km) for most dredging events in the present study.

SLs (161 to 179 dB re 1 µPa-1m) estimated for TSHDs in the present study were less than the upper range of SLs (181 to 183 dB re 1 µPa-1m) generated by hydraulic cutterhead dredging during fracturing of limestone rock, but comparable to those generated for dredging activities (SL range 164-179.4 dB re 1 µPa) associated with rock removal by a backhoe dredge during the New York Harbor Deepening Project.

Underwater sound data were collected for several large cargo vessels and one high-speed ferry operating in Newark Bay, New Jersey and New York Harbor. The SL for the high speed ferry was 181 dB re 1 µPa-1m. For four cargo ships transiting the harbor, SLs ranged from 179 to nearly 183 dB re 1 µPa-1m. One fully loaded cargo ship being pulled from its mooring by two large tugs produced an SL of 188.9 dB re 1 µPa-1m. Based on these data, sounds produced by intermediate-size hopper dredges would fall in the lower range of SLs generated by large commercial ships.

In the present study, source levels of underwater dredging-induced sounds peaked at 178.7 dB re 1µPa at 1m (near practical spreading). The log-averaged SPL was 171.52 dB for all dredges and all dredging operations monitored. Using the current threshold set by the NMFS, peak source levels did not exceed Level A Criterion (190 dB re 1µPa rms) for injury/mortality to pinnipeds (e.g., harbor seals) or 180 dB re 1µPa rms for injury/mortality to marine mammals during any aspect of the dredging operations. Noise levels in excess of 120 dB, or the Level B Criterion for harassment, were exceeded. Underwater sounds produced by dredges in the present study generally decreased to 120 dB within 1.2 km from the source and remained at or near 120 dB out to 2.1 km from the source. It should be noted, however, that ambient levels averaged 117 dB or just 3 dB below the current criteria.

References

American National Standards Institute (ANSI). 2009. *Quantities and procedures for description and measurements of underwater sound from ships – Part 1: General requirements*. ANSI/ASA S12.64. New York.

Blackwell, S. B., and C. R. Greene, Jr. 2002. *Acoustic measurements in Cook Inlet, Alaska, during August 2001*. Greeneridge Report 271-1, prepared for the National Marine Fisheries Service under Contract number 40HANF100123.

Central Dredging Association (CEDA). 2011. *Underwater sound in relation to dredging*. Prepared by the CEDA Working Group on Underwater Sound under the remit of the CEDA Environment Commission. Available at: www.dredging.org/documents/ceda/html_page/2011-11_positionpaper_underwatersound_v2.pdf

Clarke, D., C. Dickerson, and K. Reine. 2002. Characterization of underwater sounds produced by dredges. In *Dredging 2002, American Society of Civil Engineers, Orlando, Florida, USA*, 64-81.

Department for Environment, Food, and Rural Affairs (DEFRA). 2003. *Preliminary investigation of the sensitivity of fish to sound generated by aggregate dredging and marine construction*. Project AE0914 Final Report. London, UK.

de Jong, C., M. Ainslie, J. Dreschler, E. Jansen, E. Heemskerk, and W. Groen. 2010. *Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background noise*. TNO Report TNO-DV-2010 C335.

Dickerson, C., K. J. Reine, and D. G. Clarke. 2001. *Characterization of underwater sounds produced by bucket dredging operations. DOER Technical Notes Collection* ERDC TN-DOER-E14. Vicksburg, MS: US Army Engineer Research and Development Center. www.wes.army.mil/el/dots/doer

Dooling, R. J., and A. N. Popper. 2007. *The effects of highway noise on birds*. Report prepared for the California Department of Transportation, Division of Environmental Analysis under Contract # 43A0139.

Greene, C. R. 1985. *Characteristics of waterborne industrial noise, 1980-1984, Behavior, disturbance responses and distribution of bowhead Balaena mysticetus in the eastern Beaufort Sea*, 1980-1984, W. J. Richardson, ed., 197-253. Outer Continental Shelf Study MMS 85-0034. Reston, VA: Minerals Management Service.

Greene, C. R. 1987. Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. *Journal of the Acoustical Society of America* 82(4):1315-1324.

Hildebrand, J. A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series* 395:5-20.

Ketten, D. R., and S. M. Bartol. 2005. *Functional measures of sea turtle hearing*. Technical Report 13051000 prepared under Grant # N00014-02-1-0510. Cambridge, MA: Woods Hole Oceanographic Institution.

Mann, D. A., D. M. Higgs, W. N. Tavolga, M. J. Souza, and A. N. Popper. 2001. Ultrasound detection by clupeiform fishes. *Journal of the Acoustical Society of America* 109:3048-3054.

Miles, P. R., C. I. Malme, and W. J. Richardson. (1987). *Predictions of drilling site specific interactions of industrial acoustic stimuli and endangered whales in the Alaskan Beaufort Sea*. BBN Report 6509. OCS Study MMS 87-0084. Report from BBN Labs. Inc., Cambridge, MA, for the U. S. Minerals Management Service, Anchorage, AK. 341 p. NTIS PB88-15898.

Miles, P. R., C. I. Malme, G. W. Shepard, W. J. Richardson, and J. E. Bird. 1986. *Prediction of drilling site-specific interaction of industrial acoustic stimuli and endangered whales: Beaufort Sea (1985)*. BBN Report 6185, Outer Continental Shelf Study MMS 86-0046. Anchorage, AK: Minerals Management Service.

Parvin, S. J., J. R. Nedwell, J. Kynoch, J. Lovell, and A. G. Brooker. 2008. *Assessment of underwater noise from dredging operations on the Hasting Shingle Bank*. Report No. 758R0137. Subacoustech. United Kingdom: Southhampton.

Popper, A. N., and M. C. Hastings. 2009. The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology* 75: 455-489.

Reine, K. J., D. G. Clarke, and C. Dickerson. 2012a. *Characterization of underwater sounds produced by a bucket dredge excavating rock and gravel*. DOER Technical Notes Collection. ERDC TN-DOER-E35. Vicksburg, MS: US Army Engineer Research and Development Center. www.wes.army.mil/el/dots/doer.

Reine, K. J., D. G. Clarke, and C. Dickerson. 2012b. *Characterization of underwater sounds produced by a hydraulic cutterhead dredge fracturing limestone rock*. DOER Technical Notes Collection. ERDC TN-DOER-E-34. Vicksburg, MS: US Army Engineer Research and Development Center. www.wes.army.mil/el/dots/doer.

Reine, K. J., D. G. Clarke, and C. Dickerson. *Characterization of underwater sounds produced by a trailing suction hopper dredge during maintenance dredging in the Kennebec River, Maine*. In preparation. Vicksburg, MS: US Army Engineer Research and Development Center.

Richardson, W, J., C. R. Greene, C. I. Malme, and D. H. Thomson. 1995. *Marine mammals and noise*. New York: Academic Press.

Robinson, S. P., P. D. Theobald, G. Hayman, L. S. Wang, P. A. Lepper, V. Humphrey, and S. Mumford. 2011. *Measurement of noise arising from marine aggregate dredging operations*. Marine Aggregate Levy Sustainability Fund (MALSF) (MEPF Ref. no. 09/P108). Published by the MALSF. ISBN 978 0907545 57 6.

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L., Gentry, C. R. Greene, Jr., D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. 2007. Marine mammal exposure criteria: Initial scientific recommendations. *Aquatic Mammals* 33:411-521.

Wenz, G. M. 1962. Acoustic ambient noise in the ocean: Spectra and sources. *Journal of the Acoustical Society of America* 34(12):1936-1956.

Appendix A: Definitions

This appendix defines a number of terms that are critical in understanding this report. Individuals needing additional background information on the basics of underwater acoustics and marine bioacoustics should look at the Discovery of Sound in the Sea website (www.dosits.org) or the Aquatic Acoustic Archive (commonly referred to as A3), located at http://aquaticacousticarchive.com.

Ambient noise – Environmental background noise not in direct interest during a measurement or observation; may be from sound near or far, man-made or biological.

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

By-pass Filter – Filter with high- and low-pass cutoff frequencies to pass only a specified range of frequencies.

Cavitation – Cavities form in a liquid when local static pressure is reduced sufficiently to rupture the liquid to cause bubbles to appear (e.g. produced by ship propellers).

Cylindrical Spreading – Phenomenon (TL = 10 LogR) that occurs when the medium is not homogeneous. Cylindrical spreading is typical of shallow-water environments where spreading is reduced by refraction and reflection.

Decibel (dB) – A logarithmic scale used most commonly for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the decibel value is defined as 10 $\log_{10}$. The standard reference for underwater sound is 1 μPa (micro-Pascal).

Frequency – Rate at which a repetitive event occurs, measured in Hertz (cycles per second).

Hertz – The unit of frequency where 1 Hertz = 1 cycle per second.

Hydrophone – Transducer for detecting underwater sound pressures; an underwater microphone.

Logarimetric Average – SPL (dB rms) are converted to the inverse log (10^(Log Value/10) and then averaged. The average of the inverse log is then converted back to Log_{10} (=10*Log10(average of inverse log).

Infrasound – Sound at frequencies below the hearing range of humans. The sounds have frequencies below 20 Hz.

Octave – A doubling of frequency; thus, the ratio of frequencies in different octaves is 2:1.

One-third octave – A frequency range in which each octave is divided into one-third octaves with the upper frequency limit being $2^{1/3}$ (1.26) times the lower frequency. Three adjacent 1/3-octave bands equal one octave.

Pascal – Unit of pressure equal to 1 Newton per square meter.

Practical spreading - (TL = 15 LogR), given that the sound energy is not perfectly contained by reflection and refraction, true spreading is often somewhere between the predictions of spherical and cylindrical and is referred to as practical spreading.

Sound – Form of energy manifested by small pressure and/or particle velocity variations in a continuous medium.

Sound attenuation – Reduction of the level of sound pressure. Sound attenuation occurs naturally as a wave travels in a fluid or solid through dissipative forces.

Sound pressure level (SPL) – The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 μPa for water. Sound pressure (or acoustic pressure) is the force per unit area exerted by a sound wave above and below the ambient equilibrium pressure. In underwater acoustics, the standard reference is one-millionth of a Pascal, called a micro-Pascal. The conventional definition of SPL is expressed in terms of root mean square (rms) pressure.

Source level (SL) – Characterization of the sound power radiated by an underwater sound source expressed in decibels. Often expressed as the SPL at a standard reference distance (1 m) from a point monopole, placed in a lossless uniform medium and extending to infinity in all directions.

Sound pressure spectrum – Distribution of sound pressure versus frequency for a waveform dominated by tones. Dimension is rms (root-mean-square) pressure.

Spherical spreading - (free-field spreading) (TL = 20LogR) when the sound energy spreads outward with no refraction or reflection from boundaries (e.g. the seafloor or water surface).

Transmission loss (TL) or propagation loss – The accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source. As the acoustic wave propagates outward from the source, the intensity of the signal is reduced with increasing range.

Waveform – Functional form, or shape, of a signal or noise versus time.

Appendix B: TC 4032 Technical Specifications and Calibration Information

The TC4032 general-purpose hydrophone offers a high-sensitivity, low-noise, flat-frequency response over a wide frequency range, measuring and detecting even very weak signals at levels below “Sea State 0.”

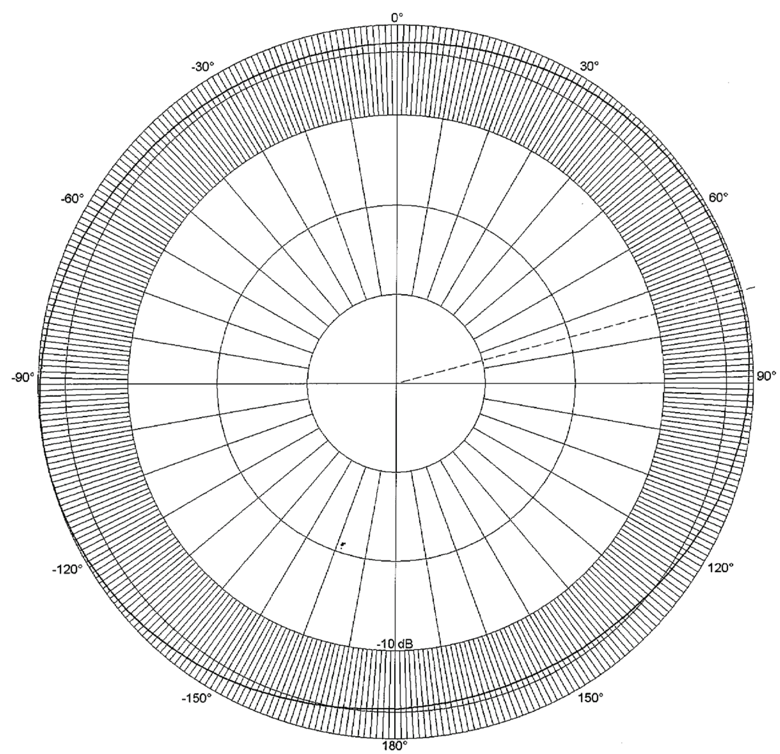
The TC4032 incorporates an electrostatically shielded, highly sensitive piezoelectric element connected to an integral low-noise 10-dB preamplifier. The TC4032 preamplifier is capable of driving long cables of more than 1.000 m, and the preamplifier features an insert calibration facility. Per default, the amplifier is provided with differential output. The differential output is an advantage where long cables are used in an electrically noisy environment. For use in single-ended mode: Use positive output pin together with GND. Versions with different filter characteristics are available: 4032-1 (5Hz to 120 kHz), 4032-2 (1Hz to 120 kHz) and 4032-5 (100Hz to 120 kHz).

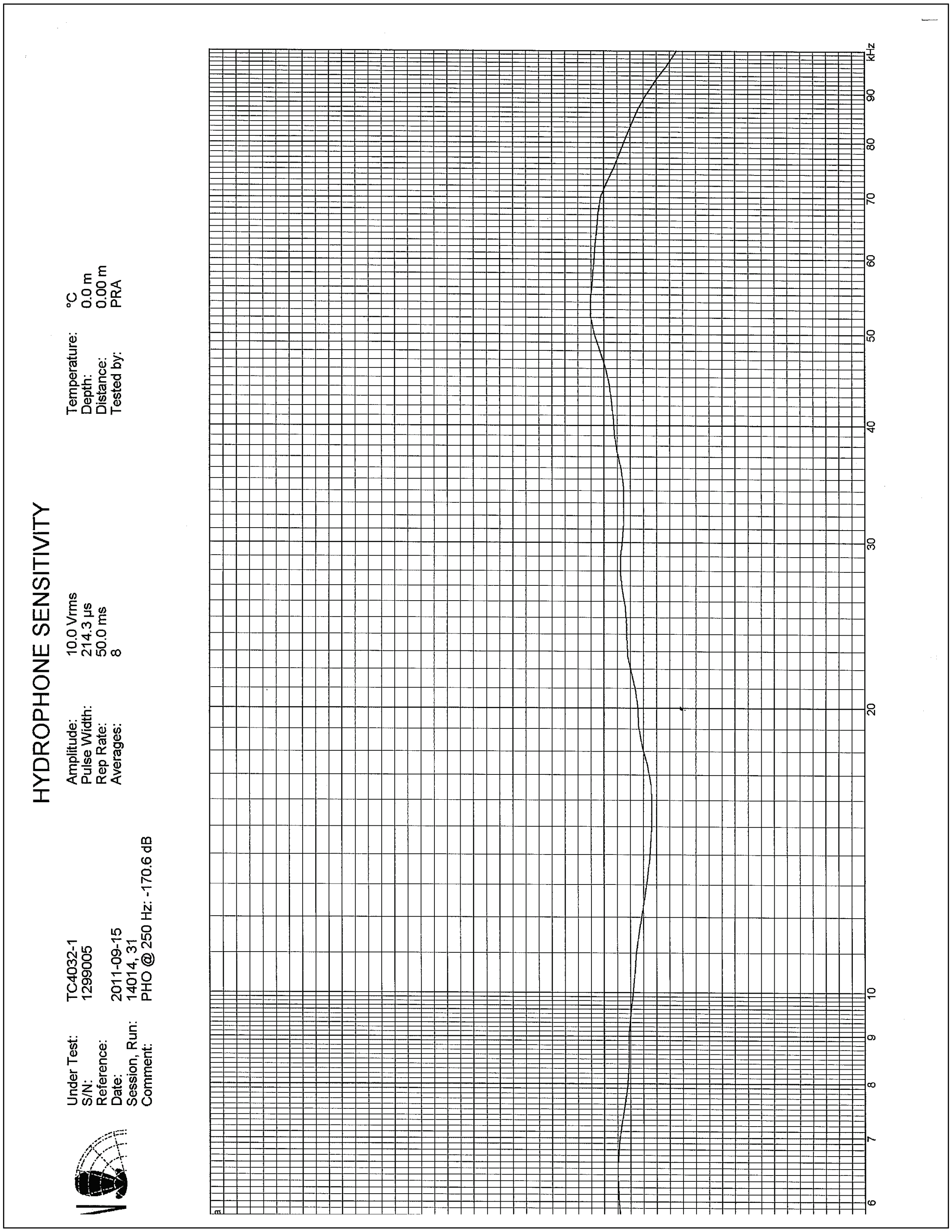
Usable Frequency range:	5Hz to120kHz
Linear Frequency range:	15Hz to 40kHz ±2dB 10Hz to 80kHz ±2.5dB
Receiving Sensitivity:	-170dB re 1V/ µPa (-164dB with differential output)
Horizontal directivity:	Omnidirectional ±2dB at 100kHz
Vertical directivity:	270° ±2dB at 15kHz
Operating depth:	600m
Survival depth:	700m
Operating temperature range:	-2 °C to +55 °C
Storage temperature range:	-30 °C to +70 °C
Weight in Air:	720g without cable
Preamplifier gain:	10 dB
Max. output voltage:	3.5 Vrms at 12 VDC
Supply voltage:	12 to 24 VDC
High pass filter:	7Hz -3dB
Quiescent supply current:	≤19 mA at 12 VDC ≤22 mA at 24 VDC
Encapsulating material:	Special formulated NBR
Housing material:	Alu Bronze AlCu10Ni5Fe4

HYDROPHONE DIRECTIVITY

Under Test:	TC4032-1	Amplitude:	10.0 Vrms	Temperature:	23.56°C
S/N:	1299005	Pulse Width:	150.0 µs	Depth:	1.2 m
Reference:	TC4033	Angle:	-180.0° to 180.0°	Distance:	0.60 m
Date:	2011-09-15	Frequency:	100.00 kHz	Tested by:	PRA
Session, Run:	14014, 30				
Max RR:	-174.2 dB re 1µPa/V at 1m				
SL Right:	75.0°, -0.3dB dB re 1µPa/V at 1m				
Comment:	Horizontal.				

For all plots!
2011-09-15 PRA

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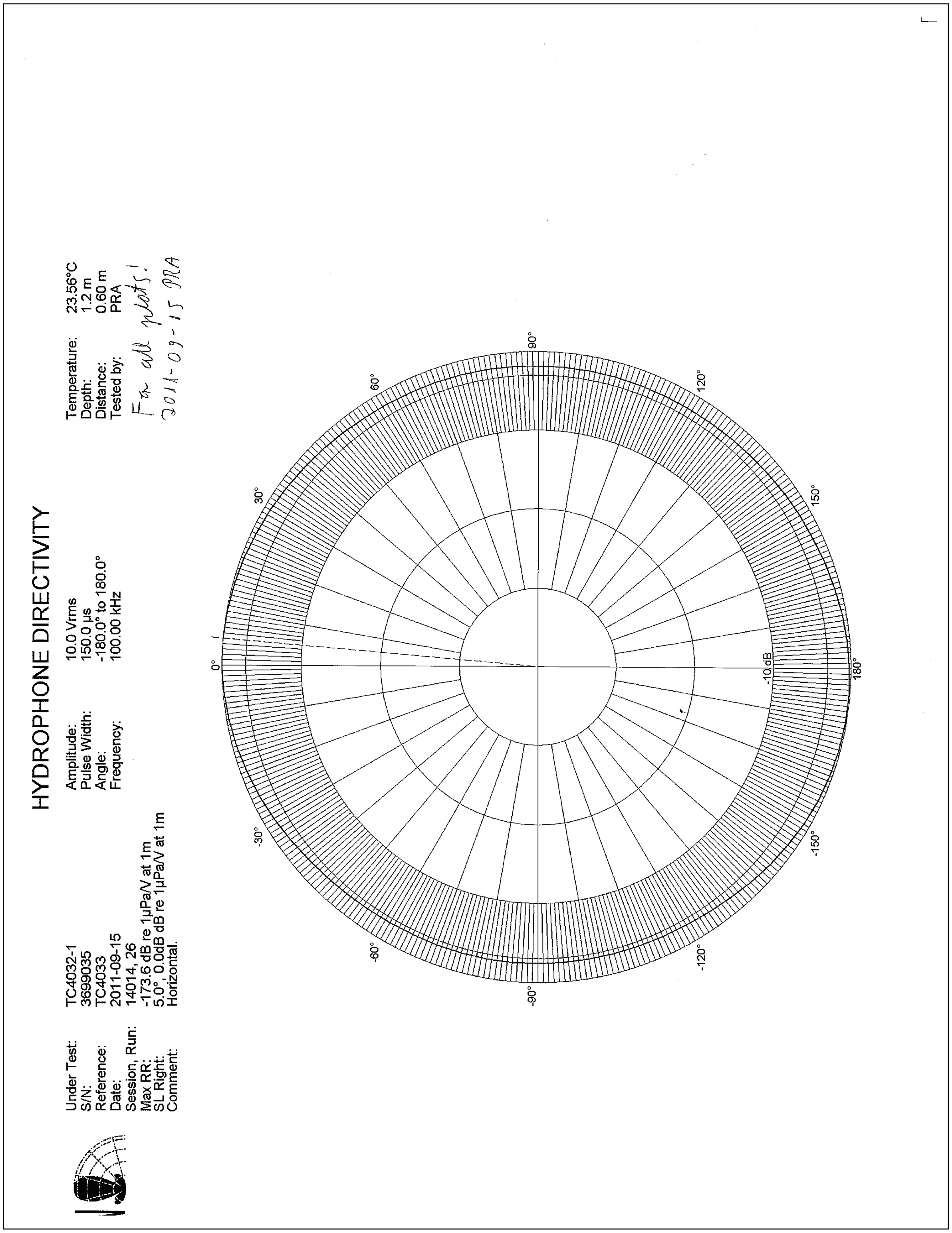
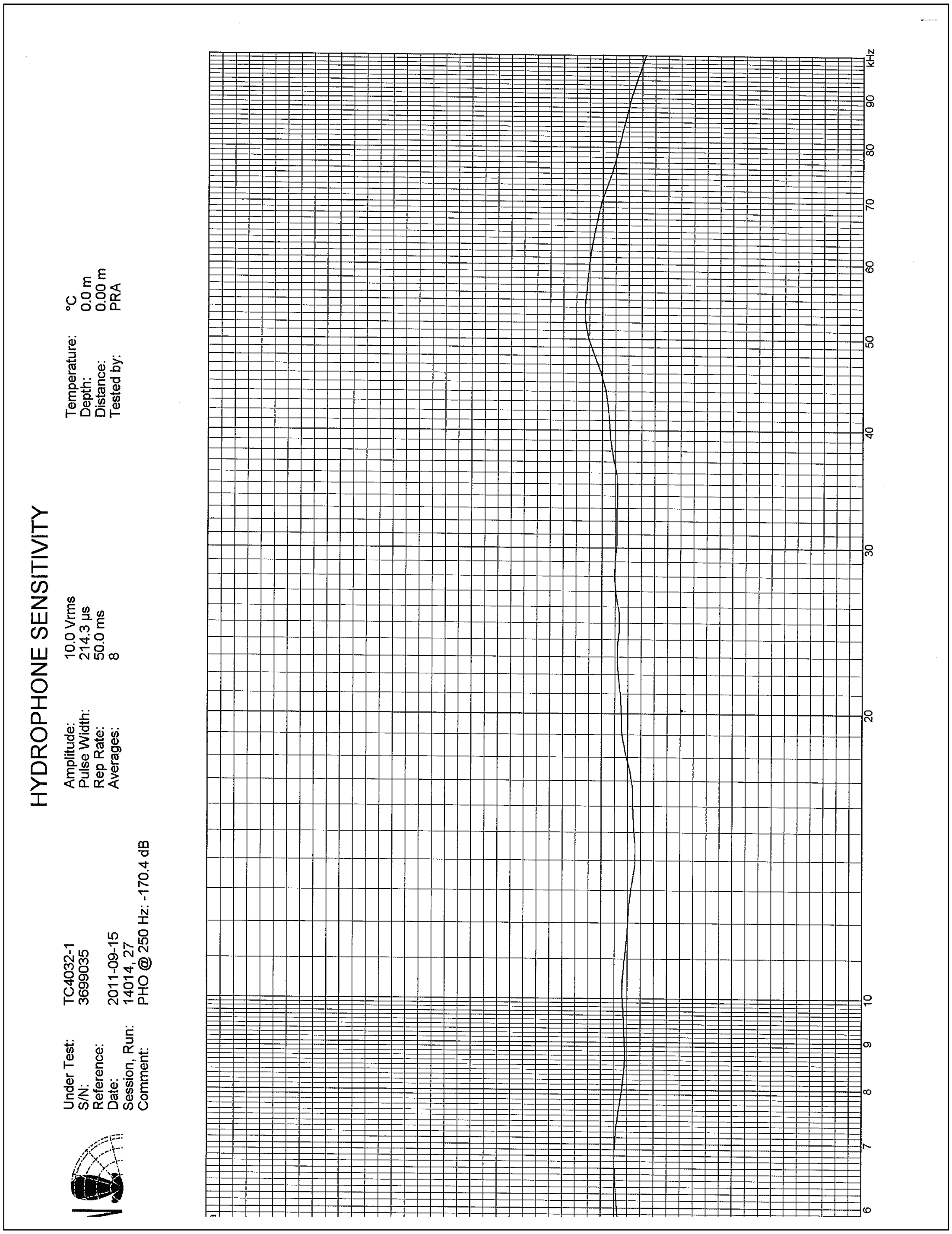
S/N: 1299005
Reference:
Date: 2011-09-15
Session, Run: 14014, 31
Comment: PHO @ 250 Hz: -170.6 dB
Amplitude: 10.0 Vrms
Pulse Width: 214.3 µs
Rep Rate: 50.0 ms
Averages: 8
Temperature: °C
Depth: 0.0 m
Distance: 0.00 m
Tested by: PRA
6
7
8
9
10
20
30
40
50
60
70
80
90
kHz


HYDROPHONE DIRECTIVITY
Under Test: TC4032-1
S/N: 3699035
Reference: TC4033
Date: 2011-09-15
Session, Run: 14014, 26
Max RR: -173.6 dB re 1µPa/V at 1m
SL Right: 5.0°, 0.0dB dB re 1µPa/V at 1m
Comment: Horizontal.
Amplitude: 10.0 Vrms
Pulse Width: 150.0 µs
Angle: -180.0° to 180.0°
Frequency: 100.00 kHz
Temperature: 23.56°C
Depth: 1.2 m
Distance: 0.60 m
Tested by: PRA
For all plots!
2011-09-15 PRA
0°
30°
60°
90°
120°
150°
180°
-30°
-60°
-90°
-120°
-150°
-10 dB


HYDROPHONE SENSITIVITY
Under Test: TC4032-1
S/N: 3699035
Reference:
Date: 2011-09-15
Session, Run: 14014, 27
Comment: PHO @ 250 Hz: -170.4 dB
Amplitude: 10.0 Vrms
Pulse Width: 214.3 µs
Rep Rate: 50.0 ms
Averages: 8
Temperature: °C
Depth: 0.0 m
Distance: 0.00 m
Tested by: PRA
6
7
8
9
10
20
30
40
50
60
70
80
90
kHz

RESON A/S Pistonphone test

Document : C:\Documents and Settings\JHP\Desktop\Shortcuts\[Copy of Ph_005_Pistonphone test.xls]Pistonphone test

Test object :	TC4032	Customer :		Frequency :	250 Hz	Total no. of meas. :	2 pcs.
Date of test :	11-09-15	Order nr. :	503811	Media :	AIR	Average RS :	-170.50 dB
Operator :	JHP	Operator sign. :	[signature]	Internal amp. :	0.0 dB	Standard dev. RS :	0.14 dB

(Notice: Negation sign is implied)

TEST EQUIPMENT:	Manufacturer	Model	S/N	VT no.
Sound level meter:	B&K	2239	2358930	
Sound level calibrator:	B&K	4230	1655876	
Hydrophone calibrator:	B&K	4223	1270166	
Fixture :				DB 1979

DATA TABLE

S/N	mVpp	dB	RS *)	S/N	mVpp	dB	RS *)
1299005	415.60	127.9	-170.6				-
3609035	428.10	128.0	-170.4				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-
			-				-

*) in dB re 1V/µPa at 1m

Comments:

Formula used: RS = 20 * log(X) - Y - 26

where X is the transducer output signal in V(rms), and Y is the sound level in dB as received from the sound level meter. Resulting RS value is in dB re 1V/µPa. The value 26 is a constant derived from a Pa to µPa conversion.

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14. ABSTRACT

Underwater sounds were characterized for three trailing suction hopper dredges (TSHD) during the removal of 3.1 million yd^3 of sand from an offshore borrow area and during offloading of the escavated sediment at the pump-out stations in support of the Wallops Island, Virginia Beach Stabilization Project. Sounds were recorded simutaneoulsy at two depths, 3 and 9.1 m from the surface. Sound sources included sediment removal, pump-out of material, pump-out of clear water during pipe flushing, and transit to the borrow site (hopper empty) and to the pump-out stations fully loaded. Received and 1/3-octave Sound Pressure Levels (dB re 1 µPa, rms) are reported for each sound source. Source Levels (dB re 1µPa-1m, rms) were back-caculated using fitted regression (15.788LogR). Source Levels (SL) ranged from 161.3 dB to 176.7 dB re 1µPa-1m rms. Highest SL were obtained for the dredge Liberty, which is nearly twice the size (e.g. hopper volume, displacement) of the dredges *Padre* and Dodge *Islands*. Sounds emitted during transit produced the highest SL, whether the hopper was empty or full. Attenuation to ambient was dependent on the sound source, and ranged from 0.85 km (flushing pipes) to 2.65 km during transit with the hopper at maximum capacity.

15. SUBJECT TERMS

Dredging
Pump-out operations
Sand mining
Sediment
Trailing suction hopper dredge (TSHD)
Underwater sounds

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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

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The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.