Characterizing large river sounds: Providing context for understanding the environmental effects of noise produced by hydrokinetic turbines

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Underwater noise associated with the installation and operation of hydrokinetic turbines in rivers and tidal zones presents a potential environmental concern for fish and marine mammals. Comparing the spectral quality of sounds emitted by hydrokinetic turbines to natural and other anthropogenic sound sources is an initial step at understanding potential environmental impacts. Underwater recordings were obtained from passing vessels and natural underwater sound sources in static and flowing waters. Static water measurements were taken in a lake with minimal background noise. Flowing water measurements were taken at a previously proposed deployment site for hydrokinetic turbines on the Mississippi River, where sounds created by flowing water are part of all measurements, both natural ambient and anthropogenic sources. Vessel sizes ranged from a small fishing boat with 60 hp outboard motor to an 18-unit barge train being pushed upstream by tugboat. As expected, large vessels with large engines created the highest sound levels, which were, on average, 40 dB greater than the sound created by an operating hydrokinetic turbine. A comparison of sound levels from the same sources at different distances using both spherical and cylindrical sound attenuation functions suggests that spherical model results more closely approximate observed sound attenuation. [http://dx.doi.org/10.1121/1.4939120]

[JFL] Pages: 85–92

I. INTRODUCTION

A recent report to Congress (Department of Energy, 2009) considered a variety of potential environmental concerns associated with the installation and operation of riverine and tidal hydrokinetic (HK) devices, including the effects on aquatic organisms of anthropogenic sound (noise). Sound from these energy technologies will likely result from installation and maintenance of the units, movements of internal machinery, turbulence caused by moving blades, water flowing past mooring and transmission cables, synchronous and additive non-synchronous sounds from multiple unit arrays, and environmental monitoring of the generators using hydroacoustic techniques. Because many freshwater and marine animals rely on sound for many aspects of their lives including reproduction, feeding, predator and hazard avoidance, communication, and navigation (Popper, 2003; Weilgart, 2007; Au and Hastings 2008), anthropogenic underwater sounds generated during installation and operation of HK devices have the potential to impact aquatic organisms. Because this technology is so new, there is little information on the sounds produced by construction and operation of HK devices or the resulting effects on aquatic organisms.

Construction noises and effects are likely to be similar to those that occur during the installation of similar sized structures such as bridge pilings, oil rig supports, and wind energy platforms, and include noises such as the periodic, high-intensity concussive sounds produced by pile drivers. These noises may interfere with sounds animals make to communicate or may drive animals from the area. If severe enough, loud sounds could damage hearing or cause mortalities among nearby animals. For example, it is known from experience with other marine construction activities that the noise created by pile driving creates sound pressure levels high enough to impact the hearing of harbor porpoises and harbor seals (Thomsen *et al.*, 2006). The effects are less certain for fish (Hastings and Popper, 2005), although fish mortalities have been reported for some pile-driving activities (Longmuir and Lively, 2001; Caltrans, 2001).

On the other hand almost nothing is known about how fish will respond to the continuous (or periodic as in the case of tidal devices) sounds created by an operating HK turbine or an array of several turbines. The sound generated during normal operations is expected to be of lower magnitude than construction activities, but could still disrupt the behavior of marine mammals, sea turtles, and fish in both the near field and at great distances from the source. Changes in animal behavior or creation of physiological stress could lead to decreased foraging efficiency, abandonment of nearby habitats, decreased reproduction, and increased mortality (National Research Council [NRC], 2005)—all of which

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could have adverse effects on both individuals and populations. Operational sounds from a small number of units may not exceed threshold levels, but the cumulative sound production from large numbers of units could have the potential to mask the communication and echolocation sounds produced by aquatic organisms in the vicinity of a project.

The aquatic environment includes many sources of sound, both natural and anthropogenic (NRC, 2003; Simmonds *et al*., 2004; Dahl *et al*., 2007). For example, natural sounds from a variety of sources have been characterized by several investigators and include: rain on the water surface; thunder from passing storms; flowing currents in rivers and tidal estuaries, noise created by flowing water as it passes over and transports bottom rocks and sediments, and surface turbulence. Traer *et al.* (2008) measured the increased sounds of waves produced by tropical storms. Lagardere *et al.* (1994) evaluated wind-produced underwater sound, and Nystuen (1986) was able to relate the intensity of underwater ambient sounds caused by rainfall to the rate of rainfall. Several researchers have looked at the underwater sounds created by strong winds (Lagardere *et al*., 1994; Curtis *et al*., 1999; Poikonen and Madekivi, 2010).

Sites being considered for HK energy development are found primarily in large rivers (e.g., the Mississippi River) and tidal environments (e.g., Puget Sound and the East River, NY) with regular predictable velocities of 1 to 5 m/s. Human-generated underwater sounds in these environments come from such diverse sources as ship traffic, dredging, construction, oil well operations, geophysical surveys, sonar, and scientific research (Arveson and Vendittis, 2000; Amoser *et al*., 2004; Wysocki *et al*., 2006; Haviland-Howell *et al*., 2007; Vasconcelos *et al*., 2007; Johnson *et al*., 2008; Codarin *et al*., 2009; Amoser and Ladich, 2010). Whereas, measurements of construction sounds have direct relevance to possible impacts during construction of HK projects (Greene *et al*., 2008), studies of other sources of man-made sounds provide valuable perspective on the significance of HK-produced sound relative to other sources. For example, Haviland-Howell *et al.* (2007) analyzed the sounds produced by recreational boat traffic in a heavily used stretch of the Intracoastal Waterway near Wilmington, North Carolina, and found that recreational boat traffic presents a significant, chronic source of underwater noise. Similarly, Codarin *et al.* (2009) took systematic measures of sound produced by a large recreational boat to bracket the range of sound levels depending on depth and distance from the source. In surveys of the sound environment at a proposed tidal energy site in Puget Sound, Washington, Xu *et al.* (2012) found that commercial shipping and ferry vessel traffic were the most significant underwater noise contributors within the frequency range of interest. The characterization of underwater sound in freshwater systems has not been studied to the extent of the marine environment, but several publications in the past decade indicate that there are analogous issues in lakes and rivers (Amoser *et al*., 2004; Graham and Cooke, 2008; Amoser and Ladich, 2010).

Many anthropogenic sources of sounds will likely be present in an area of new energy development. In addition, the environments where HK devices will be deployed are high energy environments (i.e., fast currents and tidal flows) and are likely to be naturally quite noisy. Sounds generated by HK technologies should be considered in the context of these background sounds, and thus it is important to be able to characterize HK sounds along with those from other sources for comparison. In the future, as HK turbines are deployed in natural environments, direct testing of the effects of the noise they produce on aquatic animals will be possible. In the meantime, characterization of the other noise sources to provide a baseline for comparison is important. The primary objective of this study was to characterize the sounds produced by natural and anthropogenic sound sources in large river environments where riverine HK devices might be installed and compare those sounds to the sound signature of a prototype HK turbine.

II. METHODS

A. Recording equipment

Sounds were recorded with an Underwater Sound Recording (USR) system like that described in Martinez *et al.* (2011) in combination with two Brüel & Kjær model 8104 standard hydrophones. The USR consists of eight key components: power converter board, battery voltage monitor, hydrophone signal processing board, data recorder, two waterproof connectors for sensors, one waterproof connector for a wired remote control, a waterproof connector for enabling power, and a power supply (four size D DC batteries). The system's bit-resolution was 24 bits. The Brüel & Kjær (Nærum, Denmark) type 8104 hydrophone has a sensitivity of −205 dB re 1 V/uPa with a usable frequency range of 0.1 Hz to 100 kHz (±4 dB). The underwater sound recording device features a three-pole low-pass Bessel filter with a cutoff frequency of 15 kHz. The useable frequency range of the underwater sound recording device is 6.4 Hz to 14.6 kHz (±3 dB). A Brüel & Kjær model 4229 pistonphone was used to ensure that the hydrophones maintained their factory calibration throughout the study.

The system noise floor was characterized for the recording system by itself and for the combination recording system plus hydrophone (Fig. 1). All data were collected at the sampling rate of 96 kHz, and all data were processed identically with a frequency resolution of 93.8 Hz, fast Fourier transform (FFT) length of 1024, and 50% overlap. The noise floor of the underwater sound recording system was characterized with the input grounded. The noise floor of the combination Brüel & Kjær 8104 hydrophone connected to the underwater sound recording system was measured in a laboratory tank specifically designed for hydrophone calibration (Deng *et al*., 2010). The quietest of the field measurements (ambient noise collected at Ft. Loudoun Lake when no vessels were present) was included in the figure for comparison. In order to be able to compare the noise data collected with the input grounded the same hydrophone sensitivity was applied to the voltage data. From these results all of the field measurements were not limited by the data acquisition system.

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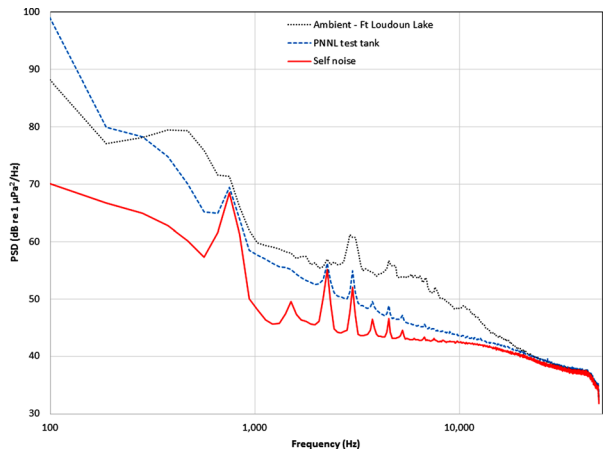

FIG. 1. (Color online) Power spectral densities (dB re 1 μPa^2/Hz) for the noise floor of the data acquisition system as characterized for the underwater recording system alone with the input grounded (solid line) and in combination with the Brüel & Kjær type 8104 hydrophone as tested in a laboratory acoustic test tank (dashed line). The ambient underwater noise at Ft. Loudoun Lake in the absence of any vessels, the quietest of the field noise measurements, is included as a natural reference (dotted line).

B. Hydrokinetic turbine sounds

Because HK turbines are still in the early stages of development and testing, recording an operating HK turbine in U.S. waters during the course of the study was not possible. Instead, a previous recording of the sound emitted by an operating bottom-mounted horizontal-axis HK turbine was obtained. The recording of Ocean Renewable Power Company's TidGen turbine in Cobscook Bay, Maine, was collected with a drifting calibrated hydrophone from a distance of approximately 21 m (Stein, 2015).

C. Natural sounds

Natural sounds of various types were collected when anthropogenic sound sources (e.g., boat traffic) were absent (Table I). Ambient or background conditions were characterized when rain was absent and wind was minimal in a still lake environment (Fort Loudoun Lake in east Tennessee) and while drifting in the Mississippi River (near Memphis, Tennessee). Recordings of hard rain fall were made at the same still lake location as the ambient recordings in the absence of any boat-generated or other anthropogenic noises.

D. Anthropogenic sounds

Anthropogenic sound sources consisted of a variety of engine powered watercraft recorded in both lake and riverine environments (Table I). Though not always the case, in general, vessels of greater mass with engines of higher horsepower create more sound. Therefore, vessels chosen for recording represented a range of vessel size and engine power. Sound produced by a small outboard-propelled workboat (60 hp) and a diesel engine powered cabin cruiser (600 hp) were measured in lakes in east Tennessee. Sounds of tugboats and the barge trains they pushed were obtained on the Tennessee River (small tugs of estimated 800–1500 hp) and the Mississippi River (estimated 3000–5000 hp). The Mississippi River site was at a proposed (but no longer actively pursued) HK deployment site near Memphis, Tennessee.

E. Measurement scenarios

One of the primary challenges in acoustic measurement in riverine and tidal environments is accounting for the additional noise created by water flowing over the hydrophone. For measurement of ambient sounds in flowing environments a drifting hydrophone was deployed to minimize flow noise, a preferred technique for recording in flowing water (Lepper *et al.*, 2014; Robinson *et al.*, 2014; Wilson *et al.*, 2014). Measurements of background sounds and rain were taken with the hydrophone lowered on a flexible cable to 1 m depth from a stationary boat or lakeside dock.

Sounds emitted from moving vessels were recorded as they passed a stationary hydrophone. During passage the distance of each vessel from the hydrophone was measured with an electronic range finder (Bushnell Yardage Pro 1000) and noted in synchrony with the timing of the recording as the vessel approached and then passed by the hydrophone. In this way, the range of a vessel at three points (the beginning of the recording, at the nearest distance from the hydrophone, and last after the vessel had passed and the recording was stopped) was used to calculate both the total linear distance traveled during the recording and the vessel's velocity.

Measurements of a small workboat and a cabin cruiser were obtained as each vessel was driven past a hydrophone deployed at 1 m depth from a stationary offshore platform. Recordings of these two vessels were obtained at various speeds and lasted less than a minute per recording. Recordings of tugboat/barge trains were collected serendipitously and

TABLE I. Basic conditions for recordings of underwater sound sources including range of target from hydrophone, velocity of passing vessel, and position of hydrophone.

Source Description	Waterbody	Hydrophone Position	Range (m) (Start, Nearest, End)	Velocity (m/s)
Ambient 1	Fort Loudoun Lake	Stationary boat at 1 m depth	—	—
Ambient 2	Mississippi River	Drifting boat at 1 m depth	—	—
Rain	Fort Loudoun Lake	Stationary dock at 1 m depth	1	—
Workboat—Yamaha 60 hp outboard	Melton Hill Lake	Stationary dock at 1 m depth	57, 8.5, 42	5.1
Cabin cruiser—Twin 600 hp Diesel Volvo Penta engines	Fort Loudoun Lake	Stationary dock at 1 m depth	100, 24, 170	7.2
Tug with small barge train (3 barges) moving downstream	Tennessee River	Stationary boat nearshore at 1 m depth	400, 64, 300	1.3
Tug with large barge train (18 barges) moving upstream	Mississippi River	Stationary boat nearshore at 1 m depth	850, 230, 290	2.2

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unstaged. For measurements of vessel sounds in flowing environments the hydrophone was positioned at 1 m depth off the side of the research boat (with motor off) in a still area at the edge of the main channel where flow was minimal. Sound recordings of passing barges on the Mississippi River lasted up to 8 min in duration. In all cases we took great care to minimize extraneous noises such as those caused by movements within the boat and waves splashing on the outside of the boat. Wind speed was minimal during all collection and was presumed to contribute only negligible amounts of noise to the recordings based on background recordings with no vessel activity taken during the same period.

F. Data processing

There are many ways to express the intensity and frequency of underwater sound waves. For example, acoustic signal characteristics that might be relevant to biological effects include frequency content, rise time, pressure and particle velocity time series, zero-to-peak and peak-to-peak amplitude, mean squared amplitude, duration, integral of mean squared amplitude over duration, sound exposure level, and repetition rate (NRC, 2003; Wahlberg and Westerberg, 2005; Thomsen *et al.*, 2006). Each of these sound characteristics may differentially impact different species of aquatic animals, but the relationships are not sufficiently understood to specify which are the most important.

Recordings were analyzed with the Aquatic Acoustic Metrics Interface (AAMI) software (V1.2.2; Ren *et al.*, 2012), which produces output of several types including full spectrum frequency pressure level distributions, power spectral density (PSD), sound pressure level (SPL), and FFT. Prior to analysis each audiogram was evaluated visually for any anomalies that could be noise emanating from the research boat (e.g., knocking from within) and those periods were not used in the analysis. Recordings that lasted several minutes were broken into shorter segments of normally 15 s for analysis. This was particularly necessary for recordings of passing vessels so that each recording segment produced an average over a narrow range of distances between the source and the hydrophone.

For comparison among sound sources, results were presented as PSD and the SPL root-mean-square (SPL_{rms}). The PSD is the power in the signal per unit frequency over the duration of the segment being analyzed and was computed using Welch's method, which is based on Bartlett's method and divides the signal into several overlapping windowed segments. For this paper, the defined window function is a Hamming window, which is optimized to decrease the amplitude of side lobes in the spectrum. The overlap for the estimation of the PSD was set to 50%. The length of the FFT was 1024, and the resultant frequency resolution was 93.8 Hz. For PSD calculations, a 10–20 s period of each recording was analyzed at the time that the sound source was nearest the hydrophone.

The SPL_{rms} is the measure of the effective pressure of a sound relative to a reference value and calculated as (Ren *et al.*, 2012)

$$SPL_{rms} = 20\log_{10}\left(\frac{P_{rms}}{1\mu Pa}\right), \quad (1)$$

where P_{rms} is the RMS of the instantaneous sound pressures over a specified period of time, the reference pressure is 1 μPa, and the unit of SPL_{rms} is dB re 1 μPa. For this study, a 1-s period was analyzed at various points in each recording and paired with the corresponding distance from acoustic source to hydrophone for each period analyzed.

G. Data extrapolation

Because sounds from different sources were recorded at different distances (and in some cases at a single distance), sound levels often need to be extrapolated beyond the range of sampling distance for comparison. As the acoustic wave from a sound source propagates through water, its intensity is reduced by geometric spreading (dilution of the energy of the sound wave as it spreads out from the source through an increasingly larger volume) and, to a lesser extent, absorption, refraction, and reflection (Wahlberg and Westerberg, 2005). Attenuation of sound (i.e., the loss in dB) due to spherical spreading in deep water is estimated by $20\log_{10}(r)$, where r is the distance in m from the source (NRC, 2000). In shallower water, however, sound transmission is confined by the surface and bottom, is more cylindrical in form, and is better estimated by $10\log_{10}(r)$. For example, under the assumption of cylindrical spreading and the consequent transmission loss of SPL, a 190 dB level at the source (i.e., within 1 m) would be attenuated to 170 dB at 100 m away and 163 dB at 500 m. Because tidal and large river deployment sites are not likely to be particularly deep (i.e., <30 m), we expected that cylindrical spreading would better explain the attenuation of sound from the sources measured. However, both models were used in this analysis for comparison. Similarly, the level of acoustic output from an acoustic source can be back-calculated from an SPL measurement at a known distance from the source back to a reference distance of 1 m from the source using the appropriate propagation or attenuation model (Robinson *et al.*, 2014).

III. RESULTS

For this study a variety of natural and anthropogenic sound sources were recorded and analyzed and representative samples were compared to the TidGen turbine that has been tested in Cobscook Bay, ME. The PSD estimates reveal differences in the power at each frequency among the various sources and provide some relative indication of the total output (Fig. 2). Note that the sources were recorded from different distances, so direct comparison of decibel levels for passing vessels is not appropriate without accounting for distance from the source. However, the recordings of ambient conditions (lake and river) and rain can be compared to each other because the recordings were collected in the same way and the noise sources are uniformly distributed. The sound of rain measured at 1 m below the surface is generally 5 to 10 dB louder than that of the ambient Mississippi River background noise and 15 to 20 dB louder than that of the ambient lake background noise. The most powerful sounds

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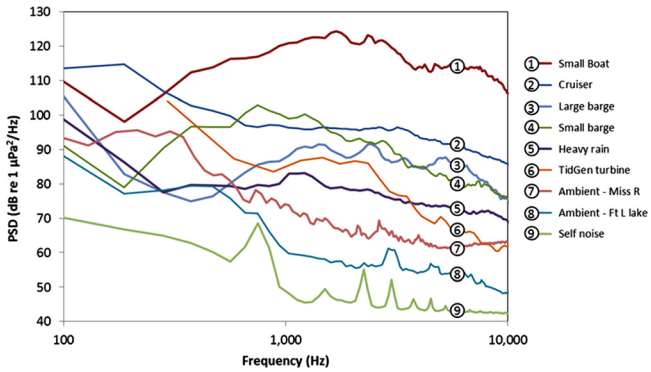

FIG. 2. (Color online) Power spectral densities (dB re 1 μPa^2/Hz) for eight sound sources (range): large barge train (230 m), small barge train (64 m), cabin cruiser (24 m), small work boat (8.5 m), heavy rain (1 m), ambient background in river environment (0 m), ambient background in lake environment (0 m), and the TidGen hydrokinetic turbine (21 m) and the recording equipment noise floor (self noise).

were emitted at frequencies below 200 Hz for all sources except for the small workboat (1688 Hz) and small barge train (750 Hz).

Because recordings of passing vessels were broken into smaller segments for analysis, the SPL_{rms} of each segment represents the sound arriving at the hydrophone from a particular distance. Time/distance series of SPL_{rms} for different sound sources allows for a comparison of the total sound produced among the different sources (Fig. 3). Lines for passing vessels generally have two legs, one as they approach and one as they move away from the hydrophone position. These two legs are not identical, apparently because sound from the engine and propeller do not emanate uniformly in all directions. For comparison, the SPL_{rms} of natural sound sources were also included: ambient or background in both a lake and river and heavy rain on the water surface. In addition, the single measurement from the TidGen turbine at 21 m was extrapolated to a range of distances using the spreading equations described earlier for comparison across a wider range. The estimated SPL_{rms} values for the TidGen turbine were higher than sound levels in the ambient environment including rain on the surface, but were substantially lower than the SPL_{rms} produced by boats and barge trains at all distances. The attenuation of sound with distance for the passing vessels was compared to that predicted by the two spreading equations, cylindrical and spherical, as indicated by the alternating 10 dB gray and white bands in Figs. 3(A) and 3(B), respectively. These bands were created by calculating the loss of sound from the source up to 500 m away from initial SPL_{rms} levels at the source (i.e., 1 m) of 180, 170, …, etc., to 110 dB.

IV. DISCUSSION

The sound sources measured in this study displayed a wide range of spectral variation and strength, and the anthropogenic sources contributed significantly to the ambient sounds that were present in underwater environments. The 10 dB bands in the two charts in Fig. 3 were included to facilitate comparison among sources. Of the two sound attenuation models depicted in Figs. 3(A) and 3(B) it appears

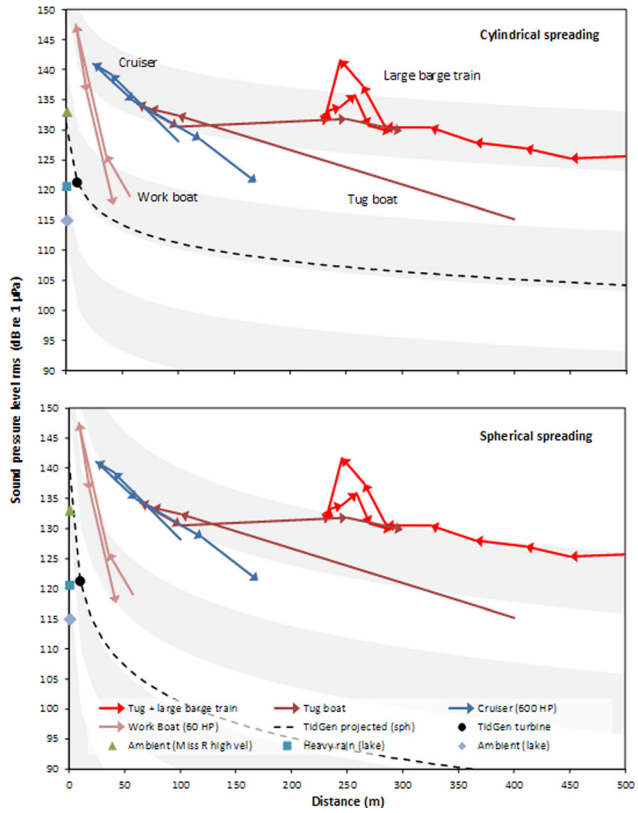

FIG. 3. (Color online) Rms of the SPL for a variety of sound sources relative to the distance from the source at which recordings were made. Alternating gray and white bands represent the predicted SPL range for sounds ranging from 180 to 110 dB (in 10 dB increments) at their source based on cylindrical spreading (top panel) and spherical spreading (bottom panel) models. The sound output of the TidGen turbine was extrapolated to 0 and 500 m from a single recording made at a distance of 21 m using the cylindrical and spherical spreading equations. Ambient river, ambient lake, and heavy rain were placed on the figure at a distance of 0 m, but these values represent measurements of sounds from a ubiquitous source without a specific location.

that the data for the different passing vessels fits the spherical model [Fig. 3(A)] better than the cylindrical [Fig. 3(B)] based on the amount of each vessel's track that is contained within a single band.

As expected, large vessels with large engines created the highest sound levels, and when compared to the sound created by an operating HK turbine were many times greater. At 21 m distance a small work boat creates sound that is roughly 10 dB stronger (or 10× greater because the decibel scale is logarithmic) than that measured at the TidGen turbine [see Fig. 3(B)]. The noise emitted from a cabin cruiser is at least 10× greater than the workboat over most of the range measured, and tug boats pushing large barge trains appear to be at about another 10× greater than that. Another way to interpret these results is that a large barge on the Mississippi River creates a louder sound at over 400 m distance than the single HK turbine does at 20 m distance. A rough estimate of barge traffic on the Mississippi River near Memphis, TN, based on an estimate of ~7800 barge trains per year for the Middle Mississippi River (United States Fish and Wildlife Service, 2004) suggests that a barge train passes a given spot on average once per hour. The barge train recorded on the Mississippi River in this study was a typical

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size for the middle Mississippi (a 15-barge train is considered the norm) and requires a tug of a round 5000 hp. Barge trains on the lower Mississippi may be as large as 40 barges and the associated tugboats may be powered with engines of up to 10 000 hp. Given the common occurrence of barges and other powered vessels on large rivers where HK devices are likely to be installed, the additional sounds produced by HK devices will likely be comparatively small.

To illustrate the extent of sound spreading from various sources relative to that produced by an HK turbine array within the confines of a large river setting, a noise map of a proposed Mississippi River HK deployment site was constructed using the SPL_{rms} values at different distances from each source (Fig. 4). The noise map represents a snapshot in time of the sounds emitted from three moving sources (a large barge train, a cabin cruiser, and a small workboat) and a stationary four-turbine HK array. This visual representation of areas of the river that will experience elevated noise levels (expressed as SPL_{rms}) clearly illustrates that the noise emitted from a small array of turbines is dwarfed by the noise from most boats that are common in the waterways being considered for HK development.

In recent years, there have been several studies that measured underwater sound from conventional and "silent" vessels (Ona *et al.*, 2007), estuarine ship traffic (van Walree *et al.*, 2007), construction (Greene *et al.*, 2008), tropical storms (Traer *et al.*, 2008), wind turbines (Tougaard *et al.*, 2009), wind (Poikonen and Madekivi, 2010), and ambient stream sounds (Lugli and Fine, 2007). On the other hand, very little work has been done on the cumulative effects of multiple sound sources emitting simultaneously. Because most HK projects propose deployment of multiple turbines at a site, understanding how sound emissions of arrays of turbines accumulate or interact will be important to understand before being able to assess potential environmental impacts of an array of HK devices.

Operational noise from generators, rotating equipment, and other moving parts of a HK unit may be similar to that emitted from offshore wind farms; however, the underwater noise created by a wind turbine is transmitted down through the pilings, whereas noises from HK devices are possibly greater because they are at least partially submerged. Wahlberg and Westerberg (2005) compared source level and underwater measurements of sounds from offshore windmills to information about the hearing capabilities of three species of fish: goldfish, Atlantic salmon, and cod. They predicted that these fish could detect offshore windmills at a maximum distance of possibly up to 25 km away, depending on wind speed, type and number of windmills, water depth, and substrate. However, they could find no evidence that the underwater sounds emitted by windmill operation would cause temporary or permanent hearing loss in these species, even at a distance of a few meters, although sound intensities might cause permanent avoidance within ranges of about 4 m.

The range of sound frequencies which fish are able to perceive differs greatly among species as does the sound pressure level that defines the hearing threshold across the frequency spectrum (Popper and Fay, 1993; Nedwell *et al.*, 2007; Ren *et al.*, 2012). Most tested fish species have little ability to detect sounds at frequencies higher than 1000 Hz, although the American shad are an exception with a range of hearing as high as 10 000 Hz. AAMI software was used to compare collected sound files to the hearing threshold of several fish species (Ren *et al.*, 2012). For the sounds recorded in this study, the noise produced by the movement of a tug with small barge train would be sensed by many fish species at a distance of 75 m [Fig. 5(A)]. On the other hand, the sound pressure levels produced during operation of a single TidGen HK turbine are below the hearing thresholds of most fish at a distance of 21 m [Fig. 5(B)].

Just because a sound can be perceived by a fish does not mean that there would be a response or that the response would necessarily be negative. Possible responses to the perceived sound may include altered behavior, e.g., attraction, avoidance, or interference with normal activities such as spawning and feeding (Nelson *et al.*, 2008). Ona *et al.* (2007) found that target fish reacted more strongly to a quiet vessel than to a more conventional noisier vessel, suggesting that reaction to foreign objects is complex and not always intuitive. Depending on circumstances, avoidance of noise may produce a positive outcome if it effectively removes fish from a dangerous situation (e.g., proximity to boat propellers or turbine rotors). Several studies have concluded that loud continuous noise can interfere with vocalizations and communications in several fish species (Vasconcelos *et al.*, 2007; Codarin *et al.*, 2009). Perhaps of greater impact than a behavioral response would be a physical or physiological response which has been demonstrated in many studies (Wysocki *et al.*, 2006; Graham and Cooke, 2008). If the intensity is great enough, hearing damage or mortality can occur. For example, fish kills have been reported in the vicinity of pile-driving activities (Longmuir and Lively, 2001; Caltrans, 2001). However, the results of the noise characterization presented here suggest that the noise emitted from an HK turbine is unlikely to result in physiological damage.

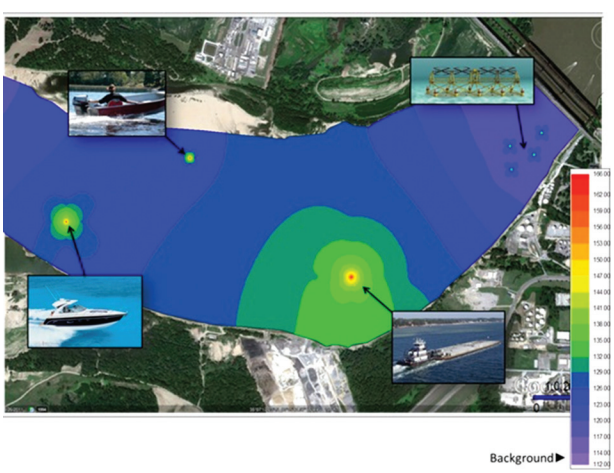

FIG. 4. Noise map of predicted sound levels (SPL_{rms}) surrounding four anthropogenic sound sources (hydrokinetic turbine, small workboat, cabin cruiser, and tug boat with barge train) superimposed arbitrarily on a section of the Mississippi River near Memphis, Tennessee, where hydrokinetic energy development has been proposed. Details of the four sound sources are provided in Table I.

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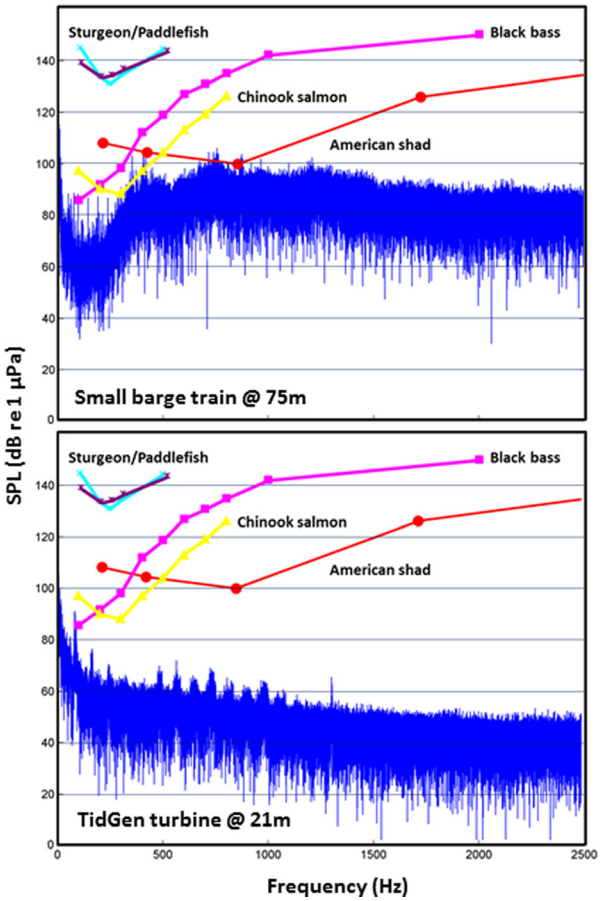

FIG. 5. (Color online) Comparison of hearing thresholds for five fish species (paddlefish [*Polyodon spathula*], lake sturgeon [*Acipenser fulvescens*], black bass [*Micropterus* sp.], Chinook salmon [*Oncorhynchus tshawytscha*], American shad [*Alosa sapidissima*]) and the frequency spectrum of sound recorded 75 m from a passing tugboat/barge (top panel) and 21 m from the TidGen hydrokinetic turbine (bottom panel). Original sources of the species-specific hearing thresholds are described in Ren *et al.* (2012). These thresholds were determined for pure tones and plotted against frequency to produce the audiogram. The SPL was in a band 1 Hz wide.

The results of this study suggest that the sounds produced by a single bottom-mounted HK turbine is significantly less than most of the other anthropogenic noise sources in rivers and bays. The predicted sound right at the TidGen turbine is either about the same as or only slightly louder (depending on which attenuation model is used) than the natural background noise in high velocity water. At a distance of 20 m the TidGen turbine is probably not even within the hearing range of most fish. It is unlikely that a single turbine will have any meaningful effect on the normal behavior of fish in the general area. The cumulative effect of tens or hundreds of turbines in an array on the other hand would produce sound over a larger area and with a greater cumulative sound.

Significant advances in understanding the effects of underwater sound on aquatic animals have been made in recent years as equipment for recording and analyzing sounds becomes more sophisticated, as the ability to measure physiological and behavioral responses becomes more advanced, and as concern grows about the ever-increasing barrage of sounds in the marine and freshwater environments. However, many questions still exist and critical cause-effect relationships are still unknown. Future research in this area should focus on a better understanding of the noise contribution and organismal response to other turbine designs and to an array of multiple turbines; further characterization of the variety of anthropogenic underwater sounds and how these sounds combine to produce a cumulative sound spectrum; establishing hearing thresholds for more species, but more importantly, response thresholds that relate certain levels of exposure to certain types of responses; field or mesocosm scale experiments on behavioral responses; and engineering mitigation technologies to minimize production of underwater noise and its environmental effects.

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