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Feasibility Study: using acoustic deterrents to prevent invasive bigheaded carp at Lock and Dam 5

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List of Abbreviations

ANOVA = analysis of variance

ATL = adaptive threshold level

BAFF = bio – acoustic fish fence

CFD = computational fluid dynamics

dB = decibels

EA = Environmental Assessment

EIS = Environmental Impact Statement

FFT = Fast Fourier Transformation

GISP = Global Invasive Species Program

GIS = Global Information Systems

H1 = Hydrophone 1 (upstream inside lock chamber)

H2 = Hydrophone 2 (downstream inside lock chamber)

H3 = Hydrophone 3 (near dam gates)

H4 = Hydrophone (downstream lock approach)

HP = horse power

Hz = Hertz

MATLAB = mathematical computer software

NEPA = National Environmental Policy Act

NR = not reported

Pa = Pascals

PAM = passive acoustic monitoring

PAL = particle acceleration level

PIT = passive integrated transponder

PSD = power spectral density

PTS = permanent threshold shift

RMS = root means squared

SD = standard deviation

SPD = spectral probability density

SPL = Sound pressure level

TL = total length

TTS = temporary threshold shift

USACE = United States Army Corps of Engineers

USGS = United States Geological Survey

1. Introduction

Invasive species have been linked to major ecological and economic impacts, because once free of the constraints of competition and predation in their native areas, they expand their range rapidly and aggressively, covering the extent of their environmental tolerance (Ricciardi and MacIsaac, 2011). Invasive species often transform the structure and species composition of an ecosystem by repressing or excluding native species, either directly by outcompeting them for resources or indirectly by changing the way nutrients are cycled through the system (McNeely *et al.*, 2001). No criteria have yet been agreed upon to constitute the minimum damage, spread or size of a population needed for a species to be considered invasive. However, it is clear that a very small number of individuals, representing a small fraction of the genetic variation of the species, can be enough to generate massive environmental and/or economic damage (Mack, 2000). The Global Invasive Species Program (GISP) stated that the fundamental objective in all cases of invasive species is to minimize the transfer of harmful organisms (McNeely et al., 2001).

The silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*), collectively referred to as bigheaded carp (Figure 1), were introduced to Arkansas from China in the 1970s (Kolar and Lodge, 2002; Pegg and Chick, 2004). Both species were stocked to consume algae and organic matter in wastewater effluent, or to improve water quality in aquaculture facilities (Dong *et al.*, 1992). Fish also were transported to the states of Illinois and Alabama for research during this time (Cremer and Smitherman, 1980). Accidental releases occurred for both species within a few years of their introduction, with silver carp found in the White River, Arkansas in 1974 and bighead carp appearing in the same location in 1981 (Freeze and Henderson, 1982). Successful reproduction of both species in the wild was documented in the US by the early 1990s (Burr *et al.*, 1996). Subsequently, both species became established in the Mississippi River by the 2000s (Pegg and Chick, 2004) and have been recorded to be moving north ever since (Kolar et al., 2007).

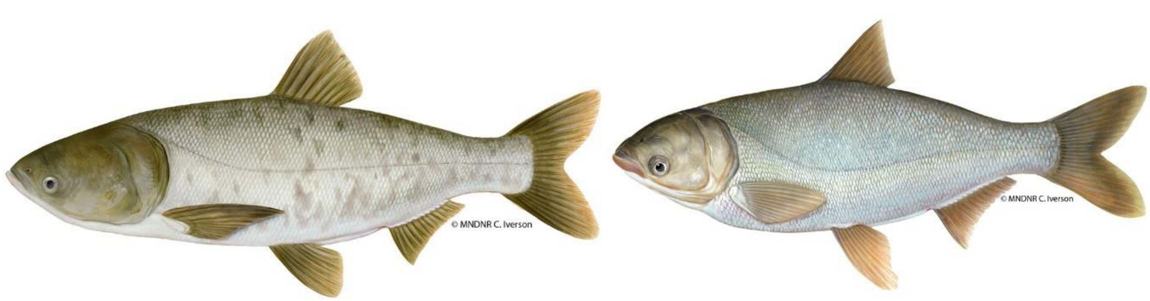

Figure 1: Scientific illustrations of bighead (left) and silver carp (right). (Images from Minnesota DNR).

The prevention of further range expansion by bigheaded carp throughout the Mississippi River basin and introduction into the Laurentian Great Lakes is a priority for fisheries management. Both species of invasive carp belong to the cypriniformes (an order of fishes comprised of carps and minnows), are planktivorous and could cause significant ecological damage via direct competition for food with native paddlefish (*Polydon spathula*), gizzard shad (*Dorosoma cepedianum*) and bigmouth buffalo (*Ictiobus cyprinellus)* (Irons et al., 2007; Sampson et al., 2009; Schrank et al., 2011; Solomon et al., 2016). Additionally, zooplankton community shifts associated with the introduction of bigheaded carps would impact lower trophic level organisms and early life history stages of native fishes (Xie and Yang, 2000; Cooke and Hill, 2010; Sass *et al.*, 2014). Silver carp also have the potential to threaten human safety and degrade recreational waterways due to their jumping abilities (Buck *et al.*, 2010).

In terms of economic impacts, both recreational and commercial fisheries of the Great Lakes and Mississippi River basin depend on fish populations that could be affected by invasive carp. The Great Lakes fisheries currently generate approximately $7 billion annually (Stern *et al.*, 2014), which could be decreased significantly if a breeding, bigheaded carp population became established. The Great Lakes is a complex ecosystem of different fish populations, among multiple water bodies, and of varying importance to user groups. Invasive bigheaded carp are likely to affect each lake and ecosystem differently because of the biological, chemical and physical conditions. Although the net effects are likely to be negative, it is also possible that the introduction of invasive bigheaded carp to the Great Lakes may lead to the development of a new commercial fishery (Stern *et al.*, 2014).

In the upper Mississippi river, from St. Louis, MO to Minneapolis, there are 29 locks and dams, that provide physical barriers to upstream fish migration. Yet, lock operation is necessary to maintain commercial boat traffic, providing a pathway for fish to migrate upstream past the dam. However, at the same time, locks provide a potential bottleneck that could be targeted for deterrents (Figure 2). The search for effective ways to deter upstream carp migration without physical intervention or causing harm to native fishes is a major challenge for fish management. Deterrents that exploit the diverse suite of sensory cues that fish use for guidance has been receiving increased attention in the past decade. Fishes detect light, chemical, magnetic, tactile and sound cues to navigate the aquatic environment. All these cues except sound dissipate quickly underwater, especially in turbid waters. Sound attenuates slowly, is highly directional and is not impeded by low light levels or water turbidity. Many species of fish also use sound as part of their behavioral repertoire and laboratory studies have shown invasive bigheaded carp consistently swim away from broadband sound (60 – 10,000 Hz) (≥ 150 dB re 1 μPa) (Vetter *et al.*, 2015; Murchy *et al.*, 2016).

Figure 2: Map of the 29 locks in the Upper Mississippi River. [Taken from Belby 2018].

1.1 Scope of Work

Lock and Dam 5, near Winona, Minnesota (Figure 3) was identified as a potential location for acoustic deterrents owing to the small number of fish north of the site, no evidence of an established spawning population upstream from the site and the minimal time the dam gates have been raised since 1980. The dam creates a physical barrier limiting fish passage, with relatively infrequent opportunities for the carp to migrate past the dam during open water conditions (Montenero *et al.*, 2018). Thus, fish passage appears to only be possible through the lock chamber. Therefore, a successful deterrent at this location would minimize the possibility of further upstream migration and lessen the threat of a breeding population being established.

This report is an assessment of the feasibility of implementing an effective invasive carp acoustic deterrent at Lock and Dam 5. The report integrates knowledge on the natural history, behavior and bioacoustics of invasive bigheaded carp and the efficacy of prior acoustic deterrents. The report is a compilation of data from laboratory studies, soundscape analysis in the field, literature reviews and interviews of state, federal and acoustic deterrent industry representatives (Figure 4). The information included in this report provides stakeholders with the most up to data information prior to making a final decision on installation at this site.

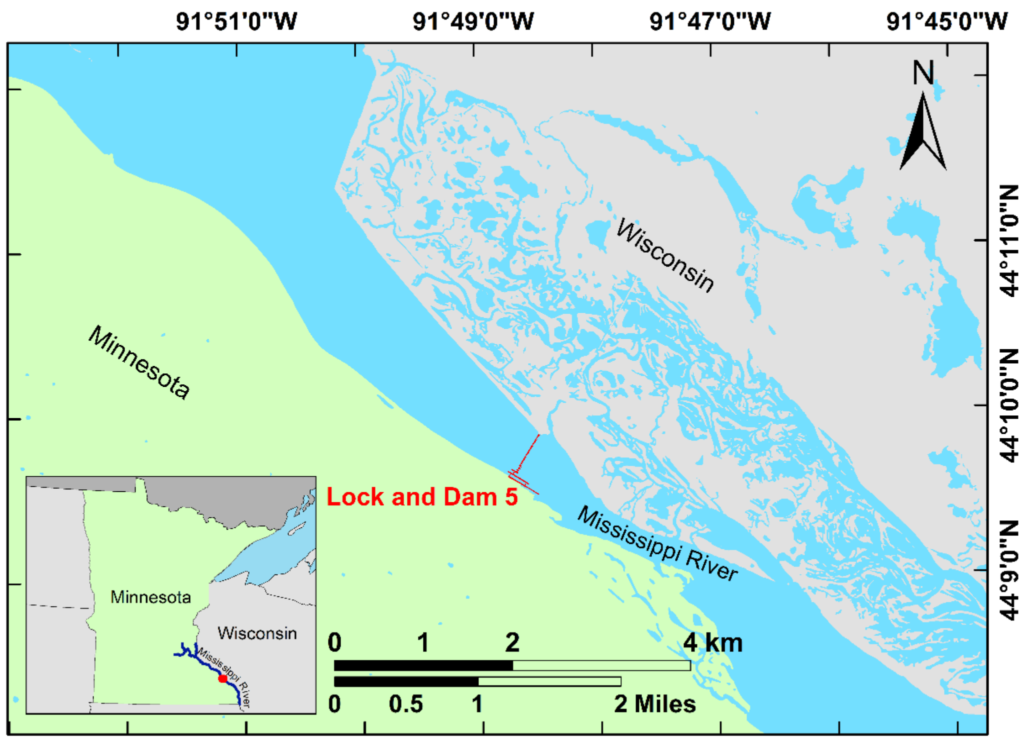

Figure 3: Map of Lock and Dam 5, near Winona, MN. Produced using ArcGIS with data provided by USACE and USGS. The dam consists of concrete structures 493 m (1619 ft) long with 6 roller gates and 28 tainter gates. The lock is 33.5 m (110 ft) wide by 182 m (600 ft) long.

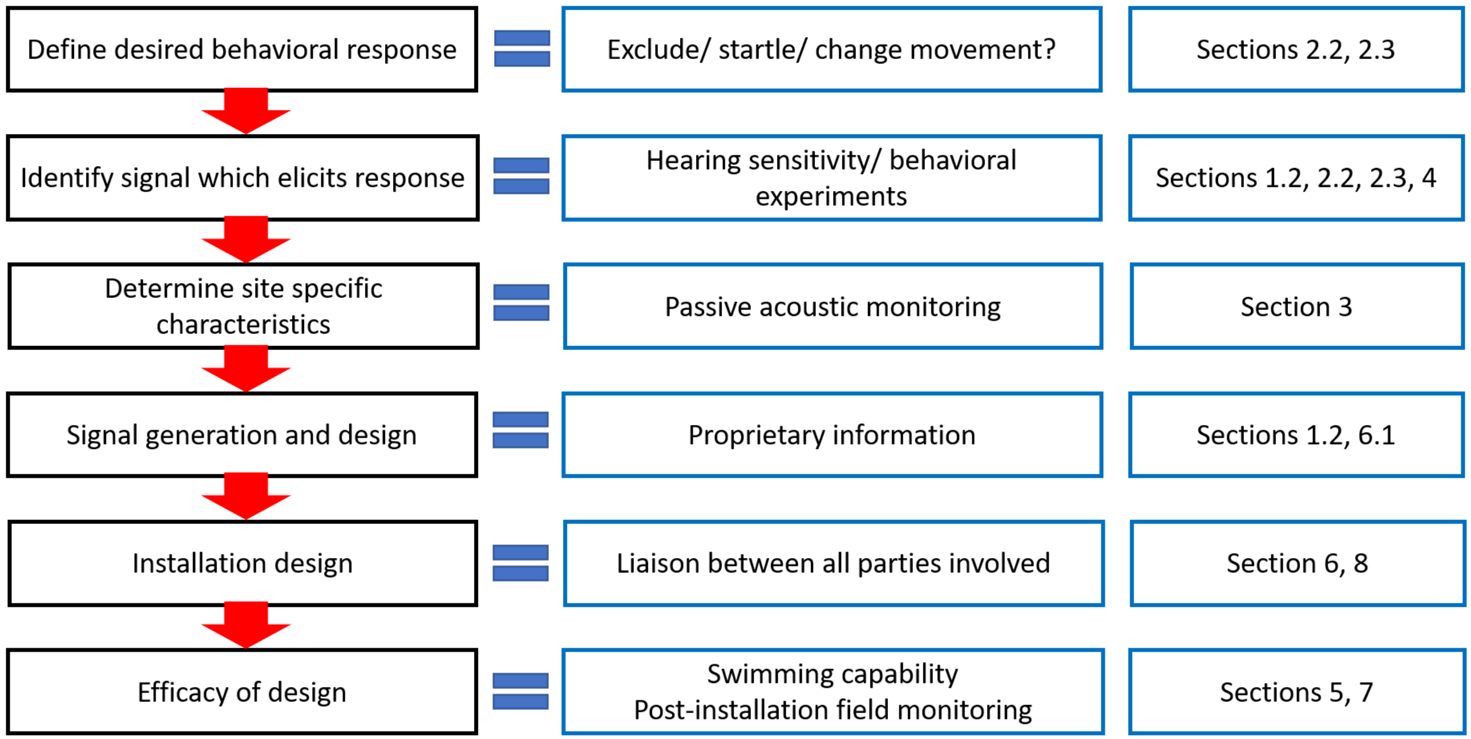

Figure 4: Flow chart outlining the steps for needed for acoustic deterrent for invasive bigheaded carp to be deployed. The left column outlines the steps needed for deterrent implementation following identification of the sensory system that will be targeted. The middle column outlines the information needed for identifying and assessing an acoustic deterrent. The right column outlines where this information can be found.

2. Underwater sound and fish hearing

2.1 Basics of underwater sound

Prior to any review of acoustic deterrents, understanding the physics of sound is critical when considering how animals detect sound in their natural environment. Sound is a waveform that travels through a medium accompanied by a transfer of energy (Urick, 1983). The waves consist of alternating pressure deviations, which cause localized regions of compression and rarefaction, resulting in *sound pressure*. Whereas, individual particles of the medium do not travel with the wave, but vibrate back and forth, causing *particle motion*.

Intensity, frequency and wavelength are the main parameters to describe the characteristics of sound:

- Sound intensity is the time averaged product of sound pressure and particle motion, to account for both magnitude and direction of sound energy. The greater the amplitude of vibrations of particles in the medium, the greater the rate at which energy is transported through it and the more intense the sound wave. Intensity is measured using the decibel (dB) scale. The logarithmic nature of the dB scale means that each 10 dB increase is a ten-fold increase in acoustic power. A 20-dB increase is then a 100-fold increase in power, and a 30-dB increase is a 1000-fold increase in power. However, a ten-fold increase in acoustic power does not mean that the sound is perceived as being ten times louder. Humans perceive a 10 dB increase in sound level as only a doubling of sound loudness, and a 10 dB decrease in sound level as a halving of sound loudness (DOSITS 2018).
- Frequency (f) is the number of times that an oscillation occurs in a specified time, usually the number of cycles per second, Hertz (Hz).
- Wavelength (λ) is defined as the distance between crests of a wave. Frequency, wavelength and speed of sound (c) are related by the formula $\lambda = c/f$ (Urick, 1983).

Sound also varies according to distance from the source, i.e. the vocalizing fish or an acoustic deterrent. Within approximately two wavelengths of the sound source, the near-field, the sound waves behave in a complex fashion and there is not a simple relationship between sound intensity and distance because sound pressure is not in phase with the particle motion component (Figure 5) (Higgs and Radford, 2016). The far field is defined as the area where the near field ends and extends to infinity. In the far field, particle motion is in phase with sound pressure, therefore the sound intensity decreases by approximately 6 dB for each doubling of distance from the source.

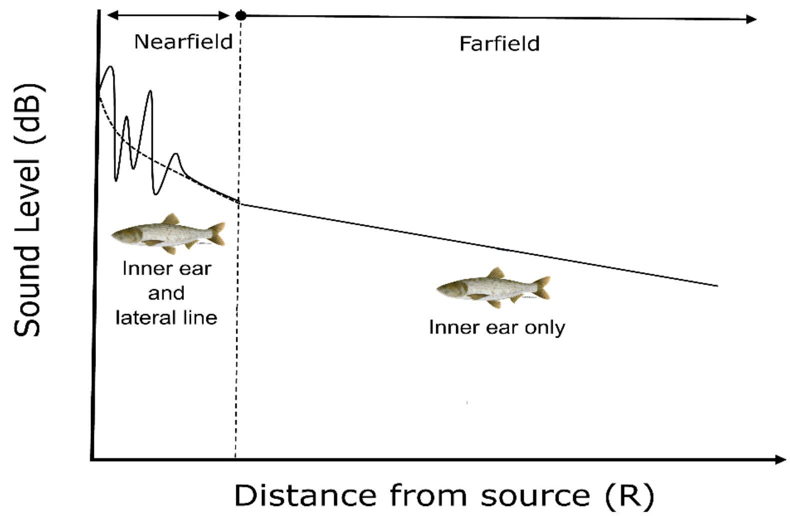

Figure 5: Sound level as a function of distance (R) for a representative source. Within the near field, there is not a simple relationship between sound level and distance from the source, whereas in the far field there is sound level decreases by approximately 6 dB per doubling of distance. (Image adapted from Higgs and Radford 2016).

2.2 Hearing sensitivity of carps

Importantly, the frequency range of any sound emitted from an acoustic deterrent must be within the target species' hearing sensitivity to be effective. Fish use the three otolith organs in their inner ears to detect particle motion, with the otoliths also functioning as accelerometers. (Fay and Popper, 1978; Hawkins, 1981).

Ostariophysi is the second largest superorder of fish, containing almost 8,000 species and 68% of freshwater species. Ostariophysans include characiformes (characins and allies), siluriformes (catfishes), gymnotiformes (electric eels and knifefish) as well as the cypriniformes (carps and minnows, catfishes, characins and knifefishes). Members of this group are important for sport fishing, the aquarium industry and research. They have several common characteristics including the Weberian ossicles, a series of bones that transmit sound pressure vibrations from the swimbladder to the inner ear (Figure 6). These bony ossicles amplify the vibrations and allow these fishes to perceive a greater range of auditory stimuli, both in terms of a wider frequency range and more sensitive hearing threshold than other fish species (Lovell *et al.*, 2006).

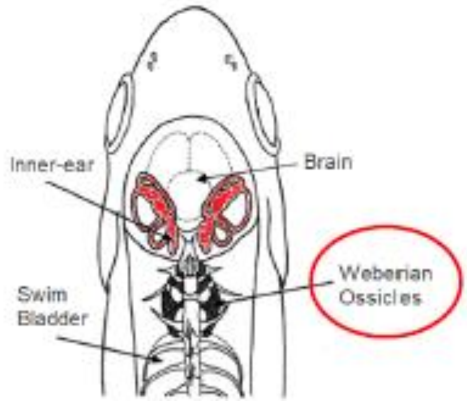

Figure 6: Illustration of the hearing system of cyprinidae (carps and minnows) with the Weberian ossicles connecting the swim bladder to the inner ear. (Image from Webb et al. 2009).

Ostariophysans, which include bigheaded carp are also capable of detecting both particle motion and sound pressure, the two components of underwater sound (Popper and Fay, 2011). Fishes that lack a swimbladder are thought to only be able to respond to the particle motion component of underwater sound and have limited hearing in comparison. One method to measure the hearing sensitivity of fishes for both components, is the auditory evoked potential (AEP) technique. This minimally invasive procedure records small electrical responses to a sound stimulus via electrodes placed on the skull (Paulraj *et al.*, 2015). Originally developed for mammals (Jeweet, 1970; Jeweet and Williston, 1971), the method has been adapted for fish and has been used in a variety of studies on fish hearing (Ladich and Fay, 2013). The technique is most effective in determining the range of frequencies a fish can detect and relative differences in auditory threshold to given frequencies observed between fish under similar conditions (Sisneros *et al.*, 2016). AEPs are also an advantageous technique because it is a minimally invasive procedure that allows repeated tests to be conducted, before and after exposure to noise (Maruska and Sisneros, 2016).

Recent investigations conduct by the Mensinger lab on the hearing of invasive carps indicate they can detect a frequency range of 0.1 to up to 5,000 Hz, with the most sensitive hearing at 500 Hz (Vetter *et al.*, 2018) (Figures 7 - 8). This is important to note because acoustic deterrents targeting bigheaded carp would need emit sound at frequencies within this range.

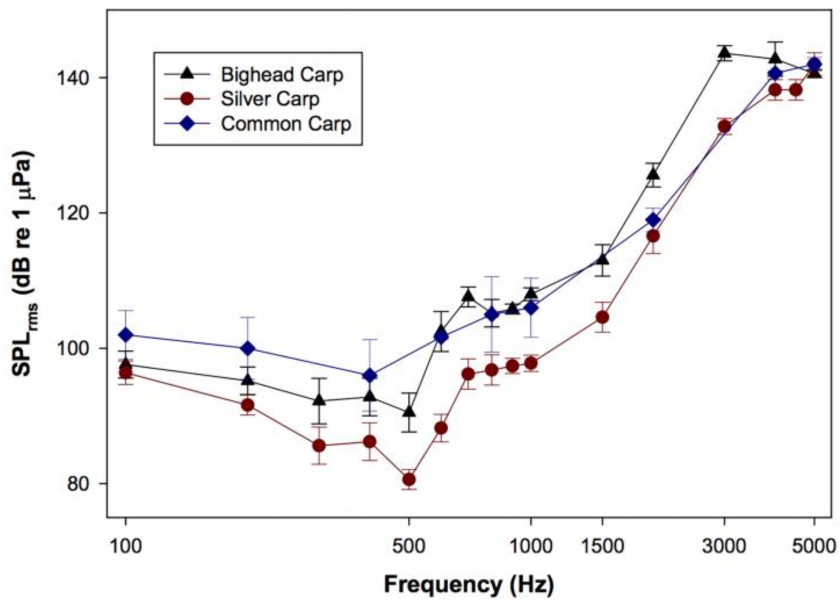

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Figure 7: Hearing sensitivities for bighead, silver and common carp. Each data point represents the minimum sound pressure level (SPL; dB re 1μPa SPL_{rms}) necessary to invoke a response at each frequency examined. Data plotted as mean ± SD. Silver carp had the lowest thresholds of the species examined [Taken from (Vetter *et al.*, 2018)].

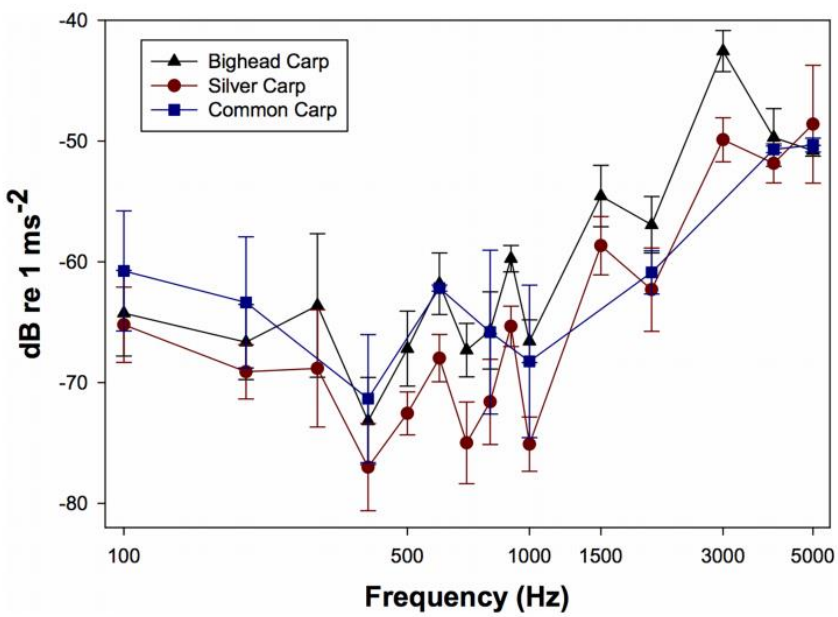


Figure 8: Particle acceleration thresholds (dB re 1 ms^{-2}) for the bighead, silver and common carp. Each threshold was derived using a tri-axial accelerometer and are reported as a combined vector of the x, y and z axes. Date are reported as mean ± SD [Taken from (Vetter *et al.*, 2018)].

Psychophysics and electrophysiology experiments provide evidence of the hearing sensitivities of fishes. However, current data is limited with only a few species of freshwater fish tested. Without this fundamental quantitative information further work on acoustic deterrents, especially their impact on native non-target fish, can only be speculative. To date, for invasive bigheaded carp, auditory evoked potentials have been performed on juvenile silver and bighead carp, total length 145 ± 34.0 mm and 161.9 ± 53.2 mm (mean ± SD) respectively (Vetter *et al.*, 2018; Nissen *et al.*, (in review)). Information on the hearing sensitivity of adult carp and larval fish is unknown and should be investigated to ensure the acoustic deterrents put in place are effective for all life stages of invasive bigheaded carp.

2.3 Hearing sensitivity of non - target species

The hearing sensitivity of non-target species, including fish, birds and mammals for any proposed deterrent location should be determined prior to installation, to optimize the sound frequencies that will be effective against bigheaded carp and minimize any detrimental effect to non-target species. The Upper Mississippi River supports over 30 fish species, including migratory species that need to traverse the lock and dam systems for successful survival and reproduction (Wilcox *et al.*, 2004). Minnesota is also resident to 78 mammals, 22 amphibians, 31 reptiles and 428 bird species (Minnesota DNR 2018) that may be impacted by the construction and operational phases of an acoustic deterrent. However, the hearing range of only a few native fishes (Figure 9), bird and mammal species (Figure 10) have been investigated. Sometimes hearing ranges may be extrapolated from laboratory studies of other closely related species. However, caution should be exercised because comparing hearing sensitivities between laboratories is not recommended based on different apparatus and tank sizes used (Sisneros *et al.*, 2016; Popper and Hawkins, 2018). Future experiments should test all fish species that would exposed to sound emitted from an acoustic deterrent using the same methodology and apparatus to allow the most accurate direct comparison between species.

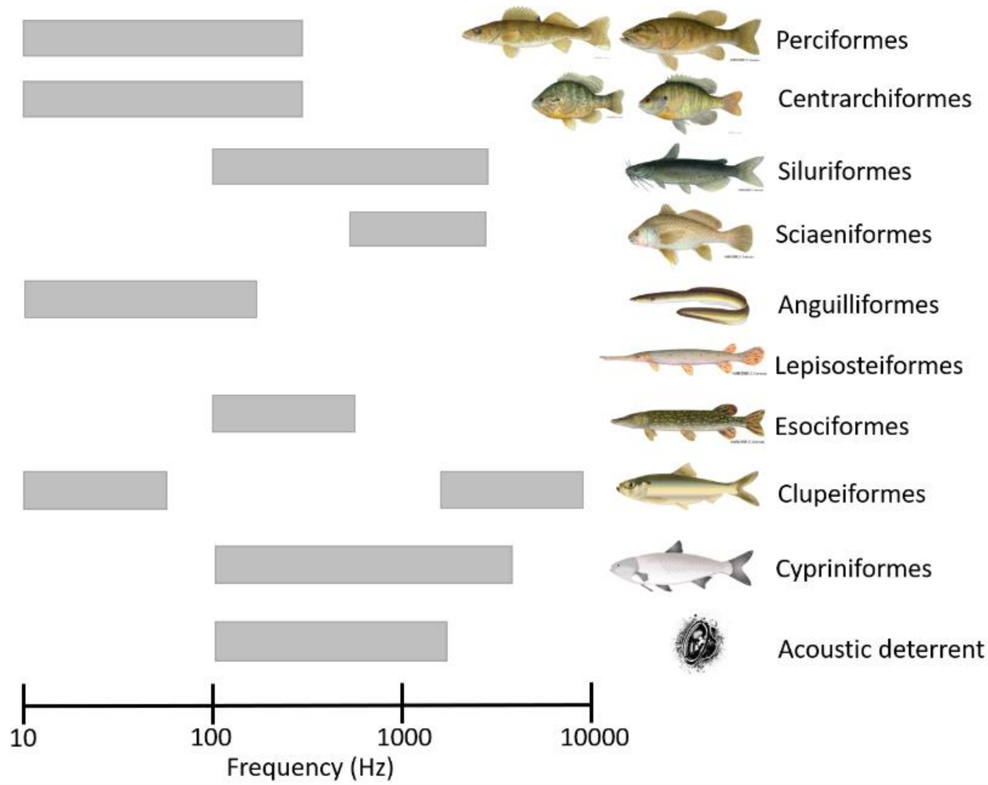


Figure 9: The general hearing range of other fish groups found in the Upper Mississippi River Basin. Perciformes including walleye and smallmouth bass, based on data extrapolated from troutperch (Mann *et al.*, 2007), centrachiformes including bluegill and pumpkinseed sunfish (Wysocki and Ladich, 2005), siluriformes such as channel catfish (Wysocki *et al.*, 2009a), sciaeniformes such as freshwater drum with data extrapolated from black drum (Ramcharitar *et al.*, 2006) anguillformes such as American eel (Jerkø *et al.*, 1989), lepisosteiformes such as longnose gar (unknown), esociformes such as northern pike (Mann *et al.*, 2007), clupeiformes such as gizzard shad with data extrapolated from American shad (Mann *et al.*, 1998), cypriniformes including silver and bighead carp (Vetter *et al.*, 2018) compared to the frequency range of acoustic deterrents (Table 2 and Supplementary Information Table 1).

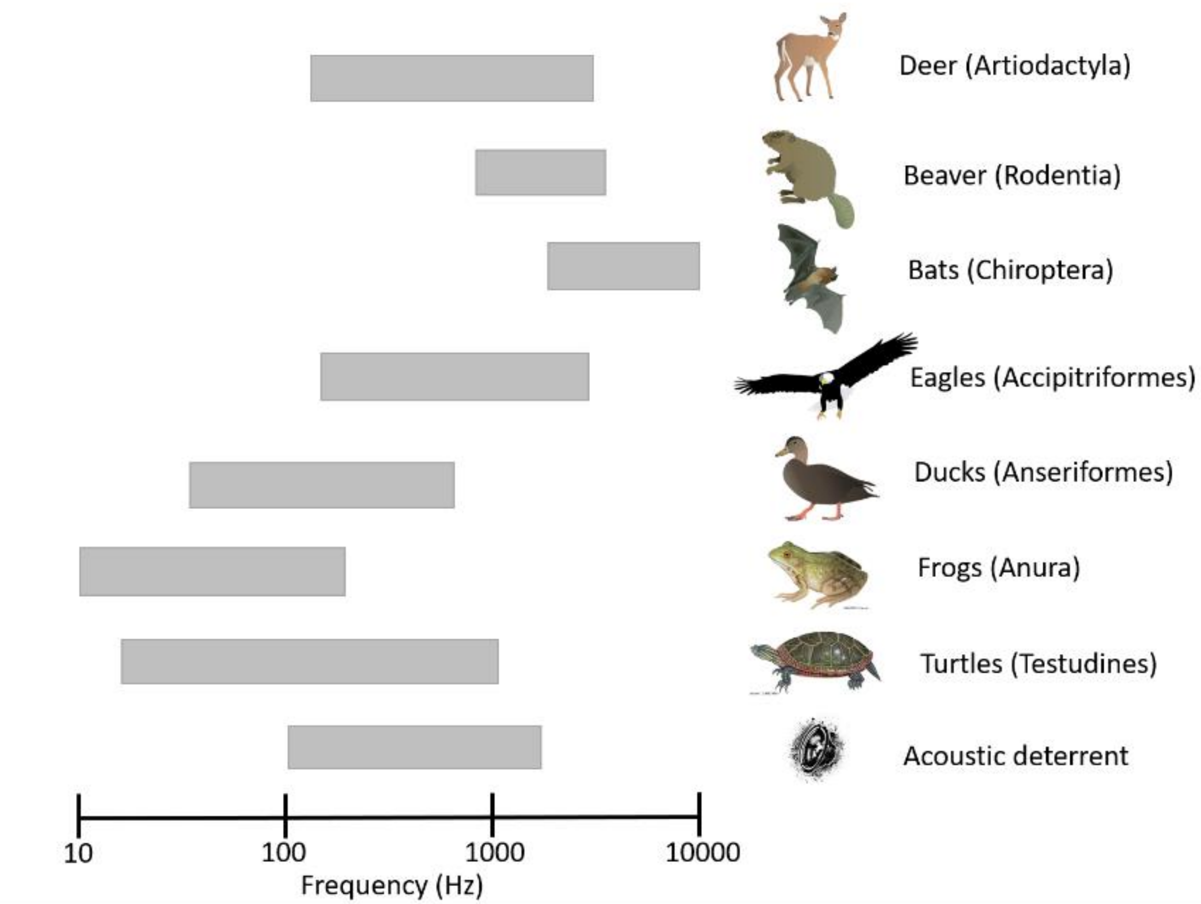


Figure 10: The hearing range of other fauna found in the Upper Mississippi River Basin, from top to bottom: deer, beavers, bats, eagles, ducks, frogs and turtles (Irwin *et al.*, 2014), and how it overlaps with the sound most commonly produced by acoustic deterrents (Table 2).

Previous studies have conducted AEPs on the following native species to the Upper Mississippi River (Supplementary Information):

- Fathead minnow (*Pimephales promelas*) (Figure S1) (Scholik and Yan, 2001)
- Channel catfish (*Ictalurus punctatus*) (Figure S2) (Wysocki *et al.*, 2009b)
- Paddlefish (*Polyodon spathula*) (Figure S3) (Lovell *et al.*, 2005)
- Lake sturgeon (*Acipenser fulvescens*) (Figure S3) (Lovell *et al.*, 2005)
- Northern pike (*Esox lucius*) (Figure S4) (Popper *et al.*, 2005; Mann *et al.*, 2007)
- American eel (*Anguilla rostrata*) (Figure S5) (Jerkø *et al.*, 1989)

The behavioral response of fishes to sound, which is often considered more sensitive than the AEP, yet significantly more time consuming, has been tested for 21 of Minnesota's native and invasive fish species over a limited number of frequencies. However, for most native and potential invasive fish species (n = 28) to the Upper Mississippi River hearing sensitivities remain unknown (Table 1) and conducting both behavioral experiments and auditory evoked potentials is recommended.

Table 1: Fish species found in Minnesota/Wisconsin rivers and lakes that may encounter acoustic deterrents. Whether each species has been tested for their response to sound via behavioral experiments or auditory evoked potentials is listed. If they are an otophysan fish, meaning they may have specialized auditory adaptations is also listed as they would likely be most impacted by a potential acoustic deterrent. In red invasive carp species.

Common name	Latin name	Response to sound tested?		Otophysan fish?
		AEPs	Behavioral experiment	
American eel	*Anguilla rostrata*	Yes [1]	Yes [2,3]	
Bighead carp	*Hypophthalmichthys nobilis*	Yes [4]	Yes [4]	Yes
Bigmouth buffalo	*Ictiobus cyprinellus*		Yes [5]	Yes
Black bullhead	*Ameiurus melas*			Yes
Black carp	*Mylopharyngodon piceus*	Yes [6]		Yes
Black crappie	*Pomoxis nigromaculatus*		Yes [7,8]	
Blackchin shiner	*Notropis heterodon*			
Bluegill	*Lepomis macrochirus*		Yes [5]	
Bluntnose minnow	*Pimephales notatus*			Yes
Bowfin	*Amia calva*			
Brook stickleback	*Culaea inconstans*			
Brown bullhead	*Ameiurus nebulosus*			Yes
Brown trout	*Salmo trutta*			
Burbot	*Lota*			
Central mudminnow	*Umbra limi*			Yes
Channel catfish	*Ictalurus punctatus*	Yes [9]	Yes [5]	Yes
Common shiner	*Luxilus cornutus*			
Creek chub	*Semotilus atromaculatus*			
Fathead minnow	*Pimephales promelas*	Yes [10]	Yes [5]	Yes
Flathead catfish	*Pylodictis olivaris*			Yes

Freshwater drum	*Aplodinotus grunniens*			
Golden redhorse	*Moxostoma erythrurum*			
Golden shiner	*Notemigonus crysoleucas*		Yes [7,8,11]	
Grass carp	*Ctenopharyngodon idella*		Yes [5]	Yes
Green sunfish	*Lepomis cyanellus*			
Gizzard shad	*Dorosoma cepedianum*		Yes [5]	
Johnny Darter	*Etheostoma nigrum*			
Lake sturgeon	*Acipenser fulvescens*	Yes [12]	Yes [5]	
Largemouth bass	*Micropterus salmoides*		Yes [7]	
Longnose gar	*Lepisosteus osseus*			
Mottled sculpin	*Cottus bairdii*			
Mummichog	*Fundulus heteroclitus*			
Muskellunge	*Esox masquinongy*			
Northern pike	*Esox Lucius*	Yes [13, 14]	Yes [5]	
Northern redbelly dace	*Chrosomus eos*			
Paddlefish	*Polyodon spathula*	Yes [12]		
Pumpkinseed	*Lepomis gibbosus*		Yes [8]	
River redhorse	*Moxostoma carinatum*			
Rock bass	*Ambloplites rupestris*			
Sauger	*Sander canadensis*			
Shorthead redhorse	*Moxostoma macrolepidotum*			
Silver carp	*Hypophthalmichthys molitrix*	Yes [4]	Yes [15]	Yes
Smallmouth bass	*Micropterus dolomieui*		Yes [7]	
Spottail minnow	*Notropis hudsonius*			Yes
Striped bass	*Morone saxatilis*		Yes [11, 16, 17]	
Tadpole madtom	*Noturus gyrinus*			
Walleye	*Sander vitreus*		Yes [5, 7, 18, 19]	
White sucker	*Catostomus commersoni*		Yes [7]	
Yellow bullhead	*Ameiurus natalis*			Yes
Yellow perch	*Perca flavescens*		Yes [7, 8]	

1. (Jerkø *et al.*, 1989)
2. (Patrick *et al.*, 2001)
3. (Gibson and Myers, 2002)
4. (Vetter *et al.*, 2018)
5. (Murchy, 2017)
6. (Nissen *et al.*, (in review))
7. ((EPRI). 1998)
8. (McKinley *et al.*, 1987)
9. (Wysocki *et al.*, 2009a)
10. (Scholik and Yan, 2001)
11. (New York Power Authority (NYPA) Inc, 1991)
12. (Lovell *et al.*, 2005)
13. (Mann *et al.*, 2007)
14. (Popper *et al.*, 2005)
15. (Vetter *et al.*, 2015)
16. (Public Service Enterprise Group (PSEG), 2005)
17. (Taft *et al.*, 1996)
18. (Flammang *et al.*, 2014)
19. (Smith and Anderson, 1984)

3. Acoustic deterrents

3.1 Design of acoustic deterrents

There are several different acoustic deterrent systems commercially available in Europe and North America. The basis of these systems is to passively deter fish and other aquatic animals (such as marine mammals) away from an area, with deterrents installed near potable water intakes, flood relief pumping stations, thermal and hydroelectric power plants. The major provider of these deterrents is Fish Guidance Systems, who have installed over 120 systems primarily to deflect migrating salmon and eel smolt, or to provide general screening for a broad spectrum of fishes (per comms. Lambert).

The two main types of acoustic deterrents are underwater speakers and bubble curtains (Figure 11). Underwater speakers produce an omni-directional field of sound, with the frequency and type of sound signal (pulses, tones or sweeps) chosen for the target species. The sound is then amplified (up to 210 dB re 1µPa) and projected underwater at various water depths, analogous to a domestic hi-fi system. In contrast bubble curtains are produced by injecting compressed air through a perforated tube laid on the bottom of the waterway: as the bubbles reach the surface and pop, the compressed air expands, thus creating a pressure wave, which is ultimately heard as a typical popping sound (Leighton and Walton, 1987). Bubble curtains use both sound and tactile cues to deter fishes from swimming through them.

Both underwater speakers and bubble curtains utilize fishes' ability to detect both the pressure and particle motion aspects of underwater sound. However, sound pressure decays rapidly from the source (Figure 5) to approximately 5% within 0.5 – 1 m from the bubble curtain depending on water flow, depth and equipment (Turnpenny and O'Keefe, 2005). Underwater speakers transmit sound over a wider distance while bubble curtains restrict sound to a narrow portion of the water column.

Underwater speakers can also be combined with a bubble curtain, to create a ensonified bubble curtain. This process is possible because the velocity of sound in aerated water differs from that in water or air (Welton *et al.*, 2002). The sound level inside an ensonified bubble curtain has been suggested to be as high as 170 dB re 1µPa, which can be considerably higher than the ambient soundscape, however the horizontal range is extremely limited.

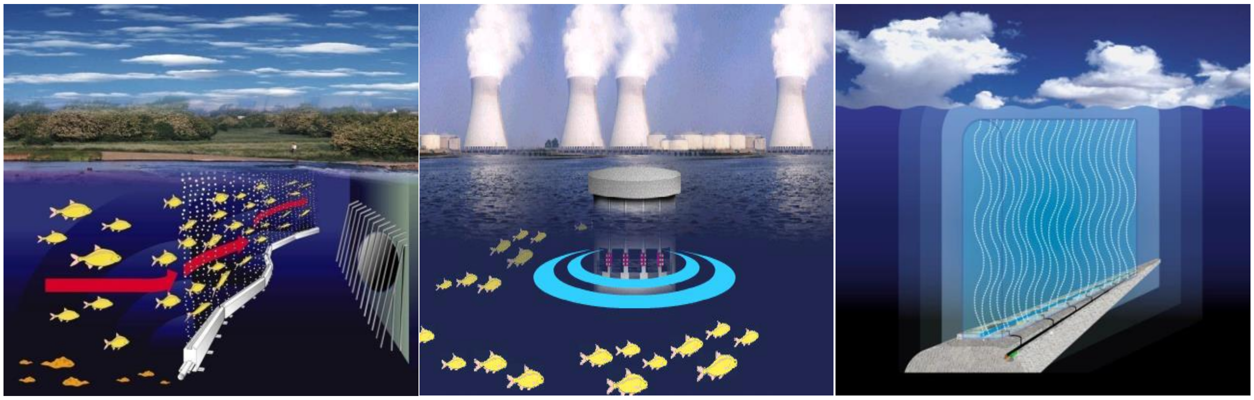


Figure 11: The different types of acoustic deterrents commercially available. From left to right, bubble curtains, speaker arrays or a hybrid system of both devices, an ensonified bubble curtain. (Images from Fish Guidance Systems).

Acoustic deterrents can also be broadly categorized according to human hearing abilities with emission frequencies classified as: infrasound (< 20 Hz), audible range (20 – 20,000 Hz) and ultrasound (> 20,000 Hz). The vast majority of fish species detect sound between 20 – 3,000 Hz (Hawkins, 1981). However, otophysans (including bigheaded carp) which possess specialized hearing capabilities can detect sound up to 6,000 to 7,000 Hz (Vetter *et al.*, 2018). Sound systems outside of fish hearing ranges would not be expected to be successful acoustic deterrents. A major challenge is that most of the information on specific frequencies used by companies selling acoustic deterrents is proprietary and so unavailable for scientists to independently test the claims of the manufacturer or to test undesirable side effects on non-target species. It is extremely important to know the specific frequencies and sound level produced by any proposed deterrent, as well as a thorough understanding of the biology and behavior of both targeted and not targeted species, to insure optimal deterrence and limit the effects to non-target species.

3.2 Costs and maintenance

The installation and operation of each site/ system are different, taking into consideration the number of units, length of array, additional parts purchased and the physical characteristics of each site. In terms of design, all types of acoustic deterrent are usually positioned at an angle to the flow, or in a loop around the intake or entrance to deflect approaching fish and guide them away (Turnpenny and O'Keefe, 2005). Most systems are also designed for continuous operation and may continue to operate even if there are issues with certain components. However, to optimize deterrence of target species, reduce potential habituation and lessen the effect on non-target species, deterrents should be timed to operate during peak movements of target fish (Noatch and Suski, 2012).

In terms of cost, underwater speakers are usually less expensive than a hybrid system that incorporates both speakers and a bubble curtain (per comms. Lambert). In general, acoustic deterrents from FGS are designed to be flexible to allow modifications to be made to the system over time and minimize restrictions to water flow or navigation (per comms Lambert).

During construction, a potential issue for onsite contractors would be balancing time for the system to be installed while keeping the lock available for navigation. Information on downtime for construction and during operation was not routinely reported in the literature. During operation, companies generally strive to keep the down time, due to equipment issues or maintenance during operation, to a minimum. However, power interruptions could pose an issue, as they do for any electrical system. Therefore, for an additional cost, back-up systems can be incorporated into a permanent system to prevent these problems (per comms. Lambert).

In terms of maintenance, planned outages are incorporated into any system. Speakers require maintenance every 18 months, whereas a bubble curtain would require more regular servicing for the compressor (based on the number of hours continuously run). Lights can also be incorporated in any system as an additional sensory cue. High intensity lights can be supplied so that they are self-cleaning, but if easily accessible, it is recommended they are cleaned on a regular basis, typically every 6 – 8 weeks (per comms. Lambert).

Managers must liaise with all parties involved to ascertain which system to choose based on the budget/timeline as well as efficacy and target range needed.

4. <u>Literature Review</u>

A literature review of acoustic deterrents was conducted to provide managers and researchers with information to consider their potential effectiveness. The review was divided into four sections. 1) literature review parameters; 2) use of acoustic deterrents for cyprinids; 3) prior efficacy of acoustic deterrents; and 4) future research for acoustic deterrents.

4.1 Review methodology

The literature search was conducted using ISI Web of Science and Google Scholar web sites with the following terminology or key words employed for the search: “acoustic deterrents fish”, “fish guidance”, “fish deterrence”, “non-physical barrier fish”, “acoustic barrier fish” and all combinations of these words. A total of 89 published texts (including 39 peer reviewed journal articles, 44 technical reports, 3 book sections and 3 theses between Jan 1900 – July 2018) were found that included the direct application of acoustics to alter the behavior or movement of fishes.

Information was collated on:

- fish species
- fish age (juvenile or adult)
- fish size (total length and weight)
- location
- laboratory or field setting
- ambient sound pressure level (dB re 1µPa)
- type and number of acoustic devices used
- source level of each device (dB re 1µPa)

- frequency range of sound emitted (Hz)
- duration/duty cycle of sound emitted (s)
- qualitative response to acoustic device
- quantitative efficacy of acoustic device (% change from control)
- whether any habituation was observed

Any information missing from the text was considered not reported.
For full tables of information collated, see the supplementary information.

4.2 Acoustic deterrents and cyprinids (carp)

All studies involving acoustics deterrents on bigheaded carp have been conducted in the US (Supplementary Info. Table S1), with publications found in the literature since 2005. However, additional research has been conducted in Europe targeting native cyprinids using acoustic deterrents as a behavioral barrier (Figure 12, Supplementary Table S1). These research efforts provide additional comparisons to the work conducted on invasive bigheaded carp.

A technical report published in 1994 provided some of the first field evidence that an acoustic deterrent could be successful in deterring cyprinids. Five cyprinid species were investigated: roach (*Rutilus rutilus*), common bleak (*Alburnus alburnus*), common bream (*Abramis brama*), common dace (*Leuciscus leuciscus*) and chub (*L. cephalus*) with a 68 – 88% deterrent rate around a cooling water inlet in the UK (Wood et al. 1994). However, the frequency range and source level used was not reported, owing to the proprietary nature of the equipment owed by FGS, and the results were never peer reviewed which is considered the standard for studies to be considered scientifically valid. Field tests in Belgium (River Schelde estuary) also showed positive results for an underwater speaker produced by FGS emitting 20 – 600 Hz sound. Total fish impingement was reduced by 60%, for non-cyprinid species including perch, herring and sprat. However, the avoidance response was lower for the only cyprinid in this system, white bream (*A. bjoerkna*), although, numbers drawn into the inlet were still significantly reduced (a 40.1 % decrease) and numbers of other cyprinids in the vicinity were rather low (Maes *et al.*, 2004).

Following this work, a preliminary field test was conducted in Lake Borrevann, Norway, to determine if infrasound was an effective deterrent for three species of cyprinids: rudd (*Scardinius erythrophthalamus*), roach and common bleak. Acute avoidance responses at a distance up to 10 m from a 16 Hz infrasound projector were revealed by echo-sounding the environment for fish movements. Additionally, there was a reduction of individual fishes entering an intake canal during on-periods of infrasound (16 Hz) of greater than 80% at a distance between 0 -12 m from the projectors used (two symmetrical pistons in an air-filled cylinder) and at 54 m away there was a significant reduction of 48% observed. Habituation was not evident during these tests, conducted every hour over one overnight period (Sonny *et al.*, 2006).

More recently a study in Portugal used a sine sweep up to 2,000 Hz and intermittent 140 Hz tone to deter two endemic cyprinid species Northern straight mouth nase (*Pseudochondrostoma duriese*) and Iberian barbel (*Luciobarbus bocagei*) (Jesus *et al.*, 2018) in laboratory tanks, with the eventual goal of using this for water intakes. The two species exhibited a strong repulsive response to the sweep (> 80 %) but did not response to the pure tone (only 14% of individuals were deterred). The differential behavior was suggested to relate to the acoustic sensitivity of cyprinids to detect higher frequencies. However, the sweep-up signal varied greatly in amplitude across the frequency range tested (< 2,000 Hz) due to non-linearity of the speaker, meaning that the sound level used as a deterrent was unknown. Additionally, all experiments were conducted in raceway tanks (9 m long, 0.9 m wide and 0.6 m deep) and authors noted a certain part of the tank was preferred by fish but did not expand further as to why (Jesus *et al.*, 2018).

Figure 12: Map of where acoustic deterrents have been used for cyprinids (carps, minnows and catfish) worldwide. Locations taken from the studies in literature review (Table 2).

Despite the variability of response of native cyprinids to acoustic deterrents in Europe, research has been conducted by the Mensinger and Sorensen labs at the University of Minnesota to determine whether acoustic deterrents could be a possible tool for fish deterrence of invasive carp species (Table 2).

Outside ponds divided into two halves by a barrier with a 1 m channel opening (USGS facility in Lacrosse, WI) were used to determine if sound could stop fish moving from one side of the pond. Results showed that bigheaded carp, swam slowly throughout the pond in loose schools and crossed the barrier every three to five minutes. However, during periods of sound projection from the underwater speakers near the opening (SPL 155 dB re 1µPa @ 1m) fish schools turned away and did not cross the barrier (Figure 13). Both bigheaded species as well as mixed schools had a significant decrease in the number of successful crossing attempts when challenged with sound, with repulsion rates of 82.4% for bighead carp, 93.7% for silver carp and 92.2% for the mixed group (Murchy, 2016). The use of acoustics to deter cyprinids therefore showed promise from small scale and short-term laboratory studies. For example, bigheaded carp exhibit a clear change in swimming behavior away from the sound source (Vetter *et al.*, 2015; Murchy, 2016; Vetter *et al.*, 2017). Thus, not only could sound deter bigheaded carp, it could be used to herd these fishes into an area, which could facilitate their capture.

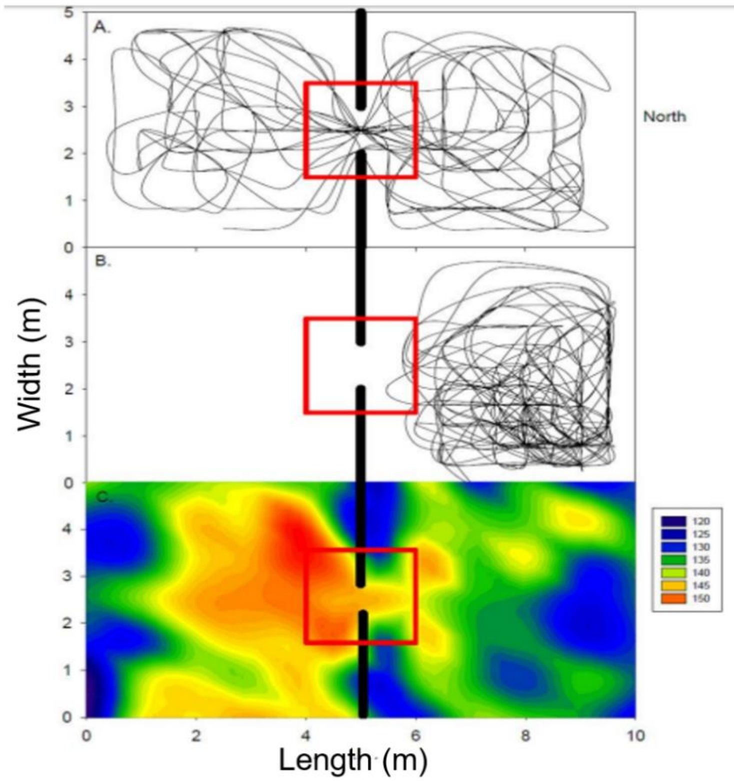


Figure 13: Overhead view of an experimental pond used to test acoustic deterrents (5 m x 10 m). The red box indicates the reaction zone with the corners of the box representing speaker locations. The location of the fish school was determined every five seconds, the x, y coordinates plotted and connected with lines. Top) speakers inactive; Middle) speakers activated when fish entered reaction zone; Bottom) Sound map of pond with color-bar indicating sound intensity level dB re 1μPa @ 1m when the speaker was activated. [Taken from (Murchy, 2016)].

Work conducted at the Sorensen lab has focused more on the use of bubble curtains to effectively inhibit the movement of carp species (including common, silver and bighead). For example, trials using common carp (*Cyprinus carpio*) showed that graded and coarse bubble curtains reduced passage across the curtain by 75 – 85% in both up and down stream directions (Table 2). Concurrent acoustic field measurements also revealed that the bubble curtains generated sound at approximately 200 Hz and 130 dB re 1μPa. Further testing combining bubble curtains with speaker arrays and strobe lights suggested that carp avoidance of the bubble curtain was due to both sound and fluid motion rather than sound only (Zielinski *et al.*, 2014). However, extrapolating results from a proxy species such as common carp to bigheaded carp is difficult due to different behavior, feeding mechanism and natural history.

Moving forward, the Sorensen lab conducted a similar study on both common and bigheaded carp species. The bubble curtain in that study reduced passage of all species through the experimental channel by 73 – 80%, while producing sound between 100 – 1,000 Hz at 145 dB re 1μPa. Common carp were diverted to an unblocked channel, while the bigheaded carp species reduced overall swimming activity suggesting a slightly greater overall sensitivity (Zielinski and Sorensen, 2016). However, physical limitations of the experimental tank inflow systems prevented behavioral testing at water velocities greater than 5 cm/s which do replicate natural conditions.

Studies to determine the basic sensory abilities of fishes and behavioral responses are best done in the laboratory, under controlled conditions. Yet, laboratory experiments cannot encompass all variables and it is difficult to extrapolate behavior, such as the movement of fish held in small tanks (Popper and Hastings, 2009), to full scale application. Additionally, fish behavior can differ dramatically from indoor and outdoor tanks. It is suggested that preliminary testing be conducted in large, outdoor ponds that can better replicate environmental conditions. Field studies should also be incorporated into the scientific evaluations of a technology's ability to meet desired effectiveness, either at the proposed site or at a site that is considered representative of expected applications.

In 2005, a proprietary system, termed the bioacoustics fish fence (BAFF) which is an ensonified bubble curtain, repelled up to 90% of passage attempts by bighead carp in a shallow concrete channel over a short time period (Taylor *et al.*, 2005). This result suggested that bighead carp exhibited an elevated sensitivity to the BAFF system because the frequencies used were within the hearing sensitivity of the species. It was also suggested that additional tailoring of the BAFF might provide opportunities for native species with less sensitive or lower frequency auditory capabilities to move through the barrier unimpeded (Taylor *et al.*, 2005). Following this study, the Illinois Natural History Survey conducted field trials using a system that incorporated a bubble curtain, speaker and strobe lights to deter bigheaded carp. Initial trials using a 20 – 500 Hz signal yielded only moderate performance, with 56% of initial approaches being successfully repelled. The signal was subsequently replaced by a 20 – 2,000 Hz signal, which increased deflection efficiency to 95% (Ruebush *et al.*, 2012). This study indicated that acoustic deterrents may work under certain field conditions however, there were several issues with this study and it was never replicated to correct these issues. For example, there was no mechanism to monitor fish interactions with the barrier and it was possible that fish moved downstream and did not challenge the barrier during the time of the study which was acknowledged by the authors of the study (Ruebush *et al.*, 2012). This highlights that all past evaluations and applications of similar devices, including failures or shortcomings should be fully disclosed to justify using a certain technology.

The Sorensen lab have also conducted field tests following their laboratory studies, to evaluate how bubble curtains would perform during natural flow regimes. Bubble curtains were tested in Kohlman Creek, Maplewood, MN, USA and fish movement monitored using a PIT antenna system (Zielinski and Sorensen, 2015). The efficacy of the bubble curtain to block downstream movement was 59 ± 14% and upstream was 16 ± 11%. Although these efficacies were somewhat less than the 75 – 85% observed in the laboratory, it was suggested the lower efficacy may be acceptable in areas with reduction, not total elimination of movement is the primary goal (Zielinski and Sorensen, 2015).

Table 2: Information gathered about previous studies conducted on invasive carp and different types of acoustic deterrent. NR denotes when the information was not reported in the literature.

Reference	Common name	Juvenile / adult	Type of acoustic deterrent (number used)	SPL (dB re 1µPa)	Ambient sound (dB re 1µPa)	Frequency range (Hz)	Efficacy	Habituation	Lab / field
Pegg and Chick 2004	Bighead carp	NR	NR	NR	NR	20 - 2,000	NR	NR	NR
Zielinski *et al.* 2017	Bighead carp	juvenile	Underwater speakers (4)	150	80	150 - 2,000	6.8	Y	Lab
Taylor *et al.* 2005	Bighead carp	NR	Hybrid system	NR	NR	20 - 500	56	NR	Lab
Zielinski *et al.* 2017	Bighead carp	NR	Bubble curtains (2)	145	105	100 - 1,000	75	NR	Lab
Murchy *et al.* 2016	Bighead carp	juvenile	Underwater speakers (2)	< 150	NR	60 - 10,000	83.4	NR	Lab
Murchy *et al.* 2017	Bighead carp	juvenile	Underwater speakers (2)	155	NR	60 - 10,000	93.7	NR	Lab
Vetter *et al.* 2017	Bighead carp	juvenile	Underwater speakers (2)	120 - 155	NR	500 - 2,000	93.7	N	Lab
Ruebush *et al.* 2012	Bighead carp	NR	Underwater speakers (16)	NR	NR	500 - 2,000	95	NR	Field
Taylor *et al.* 2005	Bighead carp	NR	Hybrid system	NR	NR	20 - 2,000	95	NR	Lab
Vetter *et al.* 2015	Silver carp	juvenile	Underwater speakers (2)	150	NR	500 - 2,000	NR	Y	Lab
Vetter *et al.* 2017	Silver carp	juvenile	Underwater speakers (2)	144 - 166	110	200 - 10,000	NR	NR	Lab
Zielinski *et al.* 2017	Silver carp	juvenile	Underwater speakers (4)	150	80	150 - 2,000	5.7	Y	Lab
Zielinski *et al.* 2017	Silver carp	juvenile	Bubble curtains (2)	145	105	100 - 1,000	75	NR	Lab
Murchy *et al.* 2017	Silver carp	juvenile	Underwater speakers (2)	155	NR	60 - 10,000	82.4	NR	Lab
Ruebush *et al.* 2012	Silver carp	NR	Underwater speakers (16)	NR	NR	500 - 2,000	95	NR	Field

Table 3: Information gathered about the size and weight of invasive carp used in previous studies and the types of acoustic deterrent. NR denotes when the information was not reported in the literature.

Reference	Common name	Juvenile / adult	Mass (g)	Total length (mm)	Acoustic deterrent used
Pegg and Chick 2004	Bighead carp	NR	NR	NR	NR
Taylor *et al.*2005	Bighead carp	NR	NR	600 - 676	Hybrid system
Ruebush *et al.* 2012	Bighead carp	NR	NR	465 - 790	Underwater speakers
Murchy *et al.* 2016	Bighead carp	juvenile	NR	180 - 240	Underwater speakers
Zielinski *et al.* 2017	Bighead carp	juvenile	16 - 48	118 - 160	Underwater speakers
Zielinski *et al.* 2017	Bighead carp	NR	112 - 318	236 - 324	Bubble curtains
Murchy *et al.* 2017	Bighead carp	juvenile	NR	180 - 240	Underwater speakers
Vetter *et al.* 2017	Bighead carp	juvenile	89.1 - 113.7	204.3 - 219.7	Underwater speakers
Ruebush *et al.* 2012	Silver carp	NR	NR	141 - 795	Underwater speakers
Vetter *et al.* 2015	Silver carp	juvenile	NR	180 - 240	Underwater speakers
Vetter *et al.* 2017	Silver carp	juvenile	NR	180 - 240	Underwater speakers
Zielinski *et al.* 2017	Silver carp	juvenile	179 - 161	202 - 272	Underwater speakers
Murchy *et al.* 2017	Silver carp	juvenile	NR	180 - 240	Underwater speakers

4.3 Prior efficacy of acoustic deterrents

Acoustic deterrents have demonstrated positive results when used to target fishes with moderate to high hearing sensitives, such as clupeids (herrings and shads), cyprinids (carps and minnows) and salmonids (salmon) because they have specialized hearing anatomy and fully developed swimbladders (Hawkins, 1981). Whereas, species with poorly developed or no swim bladder like most benthic species including pleuronectids (flatfish), were only deterred using high sound level (Maes *et al.*, 2004) which may not be ecologically feasible (Figure 14).

The primary drawback to any acoustic deterrent is the less than 100 % long term success associated with every system reviewed, with bigheaded carp efficacy ranging from 5.7 – 95% (Table 2). While behavioral screens cannot be expected to achieve a complete barrier to fish movement such as physical barriers (i.e. dams), the level of efficacy reported in the literature varies substantially, with results ranging from failure in controlling behavior, to positive demonstrations that a few species might be manageable under very specific conditions. One of the biggest challenges facing managers, is not only the wide variability in efficacy reported, but the absence of quantitative methodology or results. For example, due to the propriety nature of commercial deterrents, it is impossible for third parties to recreate the results which goes against the gold standard of reproducibility in science. Additionally, most studies only provide a qualitative positive or negative description, so comparison between studies as well as recommendations of a certain system are difficult.

There is also a lack of standardization among the terminology and methods used to describe acoustic and behavioral research, which leads to unnecessary ambiguity and impedes effective communication between scientists, regulators and other stakeholders. Many of the studies found on the use of sound to deter or guide fish movements were from the “grey literature” and thereby lack many important methodological details such as frequency range, sound pressure level, particle motion data or type of equipment. In many cases this is because the material and data are proprietary. However, the frequent lack of data, as evident in Table 2, make it impossible to fully evaluate the effectiveness of the techniques. Inventors, manufacturers and sales representatives have a vested interest in the sale of their technology and may be considered biased in their claims or product effectiveness. Fishery managers and other industry professionals therefore need to greet new approaches to safe fish passage or diversion with caution.

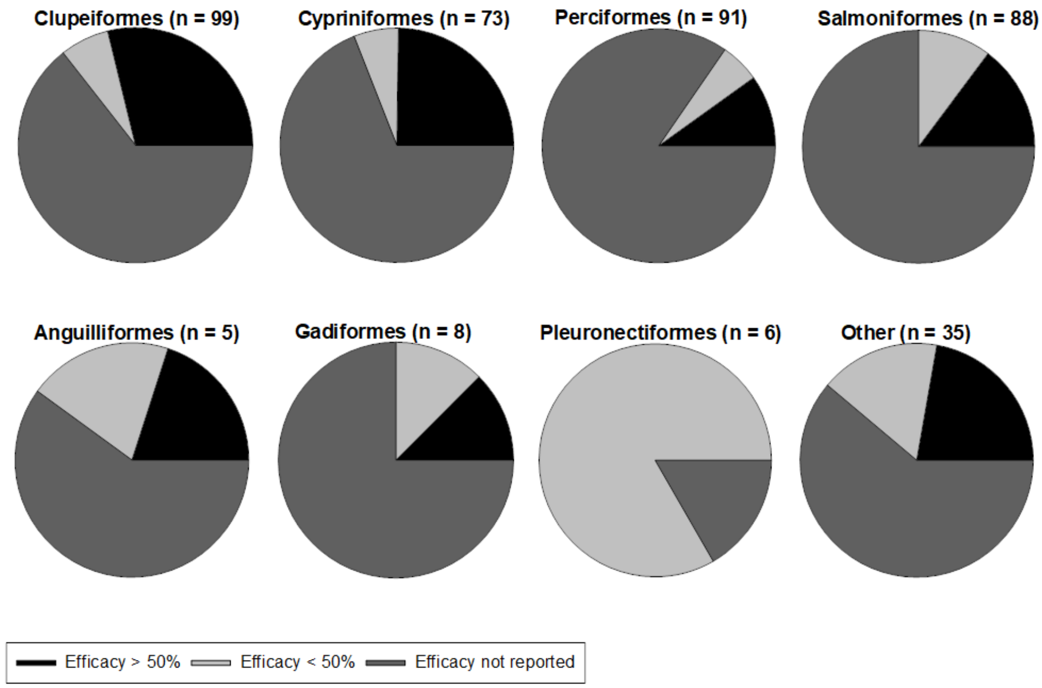


Figure 14: The efficacy of acoustic deterrents for 8 different fish groups: clupeiformes (herring and shads), cypriniformes (carps and minnows), perciformes (perches), salmoniformes (salmon), anguilliformes (eels), gadiiformes (cod and hakes), pleuronectiformes (flatfish) and any other. The efficacy is broken down into three categories as stated in the literature for each fish group: efficacy > 50% (black; meaning fish passage reduced by at least 50%), efficacy < 50% (light grey; meaning fish passage reduced by < 50%) and not reported (dark grey).

In general, for efficient operation, an acoustic deterrent must transmit sound at a sufficient sound pressure level (SPL) to be detectable by fish in the surrounding area and cause the desired attraction or avoidance response (Turnpenny and Nedwell, 2003). For most fishes, the minimum detectable level or threshold, at which there is a 50% probability of a response is generally considered to be at least 10 dB above ambient soundscape (Tavolga, 1967; Buerkle, 1968; Tavolga, 1971). Models should be used to predict received sound pressure levels (units of dB re 1 μPa) for any given geometry of sound sources, taking account environmental conditions and bathymetry of a proposed location to insure that both surface and bottom reflections are considered in the final system design. Baseline acoustic recordings of any proposed location also need to be collected and models validated before any acoustic deterrent is selected.

In summary, only a small number of technologies are currently considered by the industry to be effective and/ or acceptable to the various agencies charged with fisheries management. Future scientific research, technology innovation and evaluation of field prototypes is expected to improve the efficacy of acoustic deterrents. Although, the failure of acoustic methods in various scientific trials highlights that currently it is not an easy or universally suitable technology (Turnpenny *et al.*, 1993; Goetz *et al.*, 2015).

The most common reasons for failure of an acoustic deterrent were the following:

- Ambient sound not considered
- Unusual propagation patterns caused by interference
- Excessive water velocities
- Water temperature, turbidity or light conditions different to lab conditions
- Sound outside the hearing range of target fish
- Ineffective signal types (pure tones versus broadband)
- Inadequate sound pressure levels
- Disruption of signal or tactile cue because of ship traffic
- Failure to provide a clear diversion area.
- Extrapolating the behavior of one species (i.e. common carp) as a proxy for distant related bigheaded carp

4.4 Habituation

A major concern of using acoustic deterrents to prevent invasive fish passage is that fish will habituate to the sound stimulus and deterrence will diminish over time. Most animals will gradually habituate to non-threatening or constant stimuli. For example, if one taps a fish tank, all the fish will startle during the first contact but will eventually ignore repeated stimuli. As bigheaded carp deterrence will need to be deployed into the foreseeable future, the challenge is not only to optimize the deterrent rate but also minimize potential habituation to sound that would decrease the effectiveness of the technology.

In most of the literature reviewed, habituation was not addressed or reported (Figure 15). Many of the studies were also relatively brief in time and had a low number of trial numbers, which makes it difficult to evaluate long term success. For example, the work conducted by Taylor et al. 2005 only analysed data from three replicates over a three-day period. Recapture rates for the study conducted by Ruebush at al. 2012 were also very low, making it difficult to assess the long-term success rate of either study.

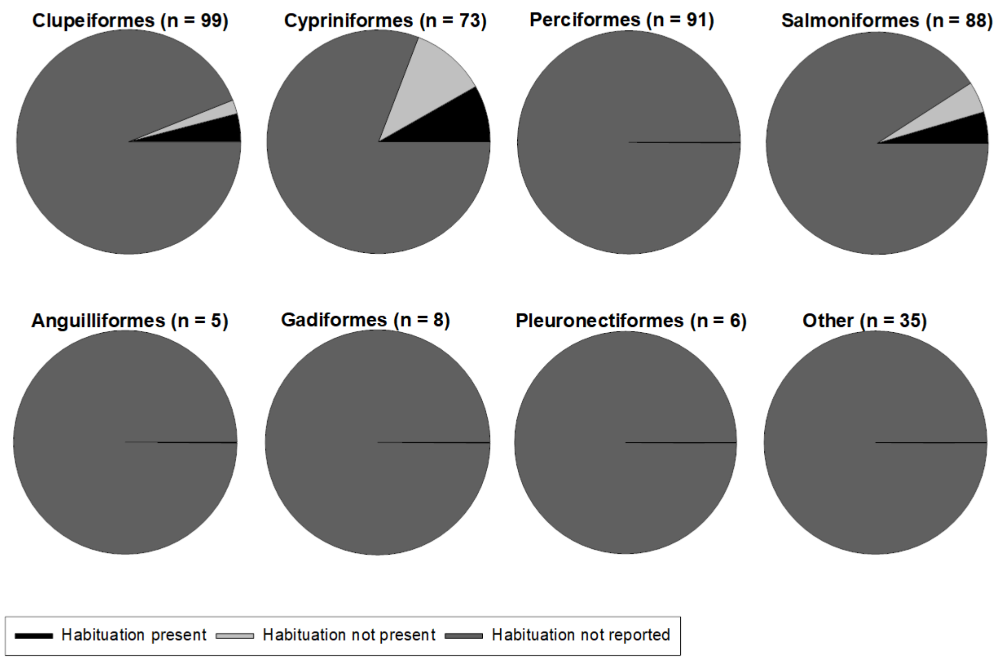


Figure 15: Whether habituation was noted when acoustic deterrents were used to deter 8 different fish groups: clupeiformes (herring and shads), cypriniformes (carps and minnows), perciformes (perches), salmoniformes (salmon), anguilliformes (eels), gadiiformes (cod and hakes), pleuronectiformes (flatfish) and any other. Habituation is broken down into three categories as stated in the literature for each fish group: present (black), not present (light grey) and not reported (dark grey).

To test whether bigheaded carp habituate to sound, the phonotaxis response of silver carp was investigated by broadcasting pure tones (500 – 2,000 Hz) and broadband sound (outboard motor sound) to fish confined in outdoor concrete ponds (Vetter *et al.*, 2015). Silver carp consistently reacted to the complex sound, exhibiting negative phonotaxis with fish directed away up to 37 times when the sound was alternated between opposite ends of the tank (Figure 16). However, fish habituated quickly to the pure tones, reacting to only 5% of those presentations and never showed more than 2 consecutive responses (Figure 16) (Vetter *et al.*, 2015) which demonstrated that not only the frequency range but type of signal used must be evaluated prior to installation. Despite bighead and silver carp not showing short term habituation to the exposure of broadband sound, an increase in tolerance over longer exposure periods should not be excluded (Nedelec *et al.*, 2016). For example, habituation must be considered with resident fish populations, where the fish may be in contact with the sound for extended periods and therefore develop a tolerance (Rankin *et al.*, 2009). Studies to address longer term habituation were initiated at the USGS in LaCrosse and the results are currently being analysed (Brey, personal communication).

At a Lock and Dam structure, the most logical placement of acoustic deterrents is in or near the downstream opening of the lock chamber. Such a deterrent could be extremely effective if it causes sufficient sensory overload or discomfort that single challenges are sufficient to deter the fish for extended time periods. However, persistent attempts may result in the fish becoming habituated to the sound and crossing the barrier. The motivation for carp to continue to migrate upstream is unknown although it may be related to spawning or resource acquisition. Acoustic deterrents would potentially work best where fish are not continually exposed but rather are exposed during specific times (Knudsen *et al.*, 1992), such as when the lock gates are open or when fish are migrating, which would reduce the chance of habituation. Further research is needed, especially with highly motivated fish to test the efficacy of barriers. At the Central Environmental Research Center, feeding fish (i.e. motivated) were initially deterred by relative modest intensity sound. However, they eventually habituated suggesting the sound intensity was insufficient to cause permanent repulsion (per comms. Calfee).

For longer term effectiveness, it has been suggested that the deterrent signals be altered on a regular basis, at least once per day (Turnpenny and Nedwell, 2003). Signal generators with multi signal capability may be used for this purpose. However, no studies exist quantifying the effectiveness of signal alternation or its effect on reducing habituation. This is vital information and an area that needs additional research.

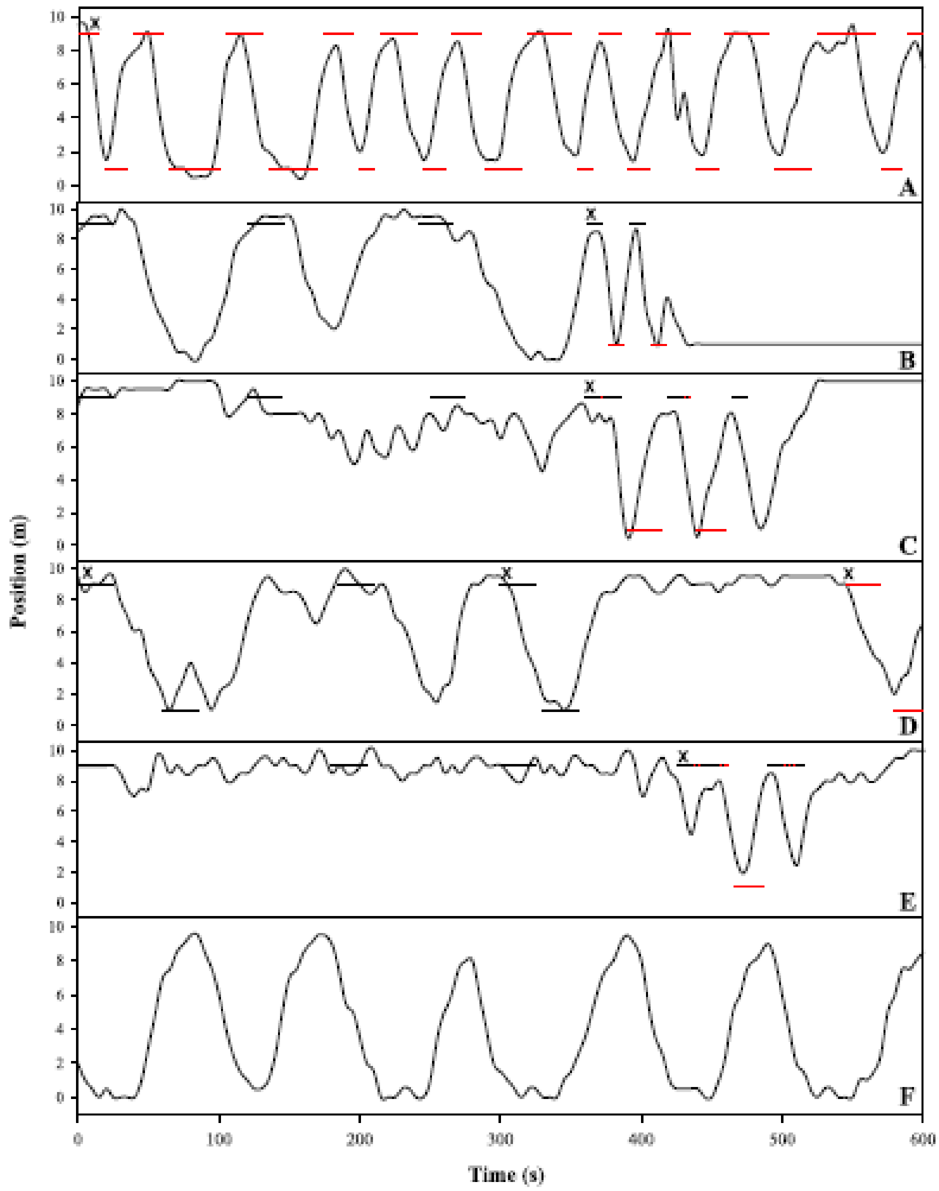


Figure 16: Positions of a school of bighead carp in relation to a speaker source placed at either end of an experimental tank (5 m x 10 m). Solid lines above and below each fish position indicate the location and duration of the sound stimulus. A) Broadband sound; B) 500 Hz pure tone; C) 1,000 Hz pure tone; D) 1,500 Hz pure tone; E) 2,000 Hz pure tone; F) control with no sound. [Taken from (Vetter *et al.*, 2017)].

5. Long-term soundscape of Lock and Dam 5

The soundscape of an area is the combination of sounds (abiotic and biotic) that arise in an environment and how these sounds effect the physical and behavioral characteristics of organisms living in that environment (Pijanowski *et al.*, 2011). Most soundscape studies have been conducted in the marine environment and there is limited knowledge regarding inland freshwater lakes and rivers. Therefore, a major aim of this project was to understand the general soundscape around Lock and Dam 5 in terms of both temporal and spatial patterns prior to any future installation of acoustic deterrents.

5.1 Acoustic methodology

Acoustic data were collected at four recording stations at Lock and Dam 5, near Winona, MN during the ice-free months that corresponded with peak navigation use. Deployment dates were from 30th October – 25th November 2017 and 20th April – 10th September 2018 (Table 4). At Lock and Dam 5, the one active lock chamber is 182.9 m (600 ft) long x 33.5 m (110 ft) wide x 5.5 m (18 ft) deep. Two recording stations were positioned inside the lock chamber and two outside (one on the downstream approach channel and the other on the outside wall of the lock on the dam side) to encompass the route vessels navigate as well as the route invasive carp may take to pass upstream (Figure 17).

Omnidirectional hydrophones (ST202 Ocean Instruments, NZ) were placed in the lock ladder wells to prevent damage to the equipment during vessel passage. All recording apparatus (hydrophone, battery, recorder and timer) were attached 3 m above the lock floor inside the ladder well. The water level inside the lock is controlled by miter gates located at the up and down stream end of the chamber and a system of low level valves and tunnels. During vessel passage, the two recording stations inside the chamber (H1 and H2) were exposed to differential water depths as the chamber was filled and emptied during vessel passage (Figure 18). However, at all depths spherical spreading of sound was assumed to occur, owing to interactions between the water surface and lock floor. Hydrophones at H3 and H4 (Figure 17) were attached between 0.5 – 2.5 m above the river bottom dependent on river depth which varied over the deployment period between 1 – 3 m (5 – 10 ft).

All hydrophones were programmed to sample continuously at 24,000 Hz (equating to an upper frequency limit of 12,000 Hz), for the duration of each deployment, with recordings saved continuously as one-minute files. Louder sound files require more memory, therefore during a couple of deployments, the hydrophone ran out of memory. During the third summer deployment (Table 4) at H1 and H3 the hydrophone also stopped recording for unknown reasons. In total, 12,330 hours of sound were recorded at Lock and Dam 5 combining data from all four listening stations (Table 4), at least 90% of the time.

All hydrophones had a -3dB frequency response of 10 – 72,000 Hz. Self-noise of all recording devices was less than 34 dB/ $\sqrt{\text{Hz}}$ re 1µPa above 2,000 Hz (Ocean Instruments NZ). All hydrophones were calibrated using a piston phone (Bruel & Kjaer) with a 1,000 Hz tone. Calibration tones were also included at the beginning of every recording to ensure the acoustic recorder did not affect independence of recordings. All acoustic data were analysed using MATLAB (version 2014b) and custom written scripts.

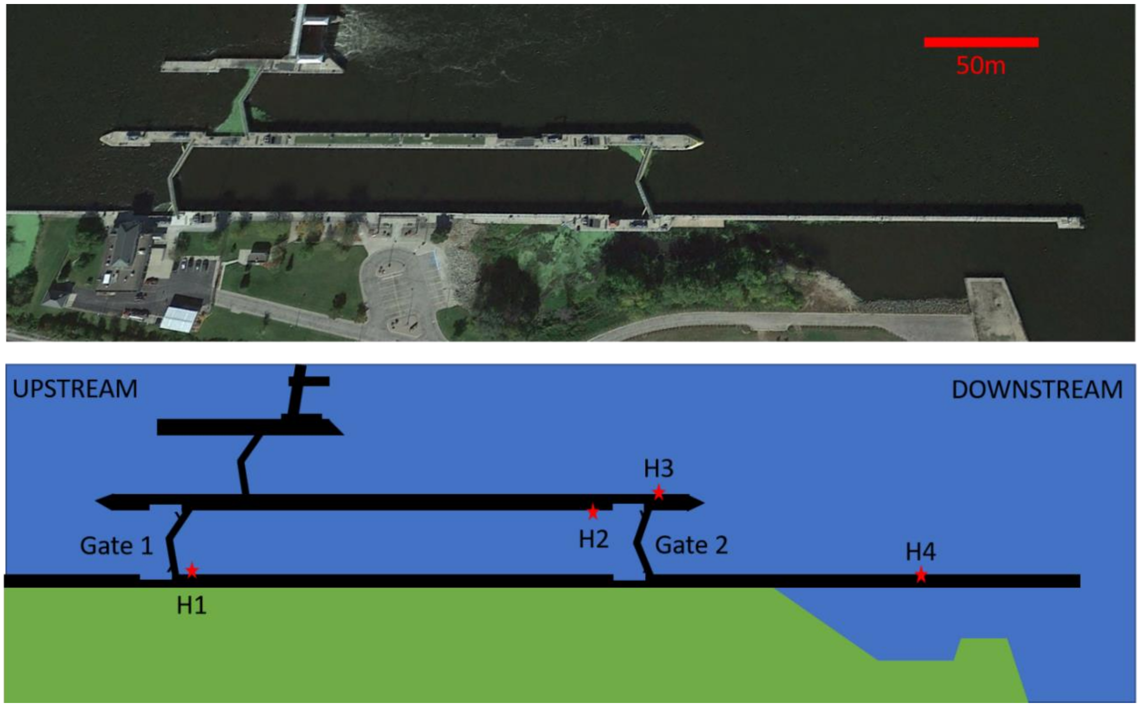


Figure 17: The top panel shows an aerial photograph of Lock and Dam 5. The bottom panel shows a schematic of the location of the four recording stations (H1 - H4) were positioned inside and outside of the lock chamber.

Table 4: Deployment schedule for the four listening stations at the Lock and Dam 5. H3 and H4 were only deployed during summer 2018.

		Deployment Number	Start date	End date	Days missing	Number of files
H1	**Fall 2017**	F1	Oct 30	Oct 31		2122
		F2	Nov 03	Nov 17		20160
		F3	Nov 17	Nov 27		14580
	Summer 2018	S1	Apr 20	May 14		34314
		S2	May 15	May 19		5168
		S3	Jun 12	Jul 06	23	34708
		S4	Jul 11	Aug 04	4	43580
		S5	Aug 07	Aug 31	2	34570
					TOTAL	**189202**
H2	**Fall 2017**	F1	Oct 30	Nov 03		6300
		F2	Nov 03	Nov 17		20340
		F3	Nov 17	Nov 25		11520
	Summer 2018	S1	Apr 20	May 14		34318
		S2	May 15	Jun 11		38852
		S3	Jun 12	Jul 10		40064
		S4	Jul 11	Aug 06		37832
		S5	Aug 07	Sep 10		48990
					TOTAL	**238216**
H3	**Summer 2017**	S1	Apr 20	May 14		34278
		S2	May 15	May 24		13446
		S3	Jun 12	Jul 10	18	40210
		S4	Jul 11	Aug 06		37836
		S5	Aug 07	Sep 07		44628
					TOTAL	**170398**
H4	**Summer 2018**	S1	Apr 20	May 14		34318
		S2	May 15	Jun 10		37866
		S3	Jun 12	Jul 10	1	40248
		S4	Jul 11	Aug 06		37838
		S5	Aug 07	Sep 08		45744
					TOTAL	**196014**

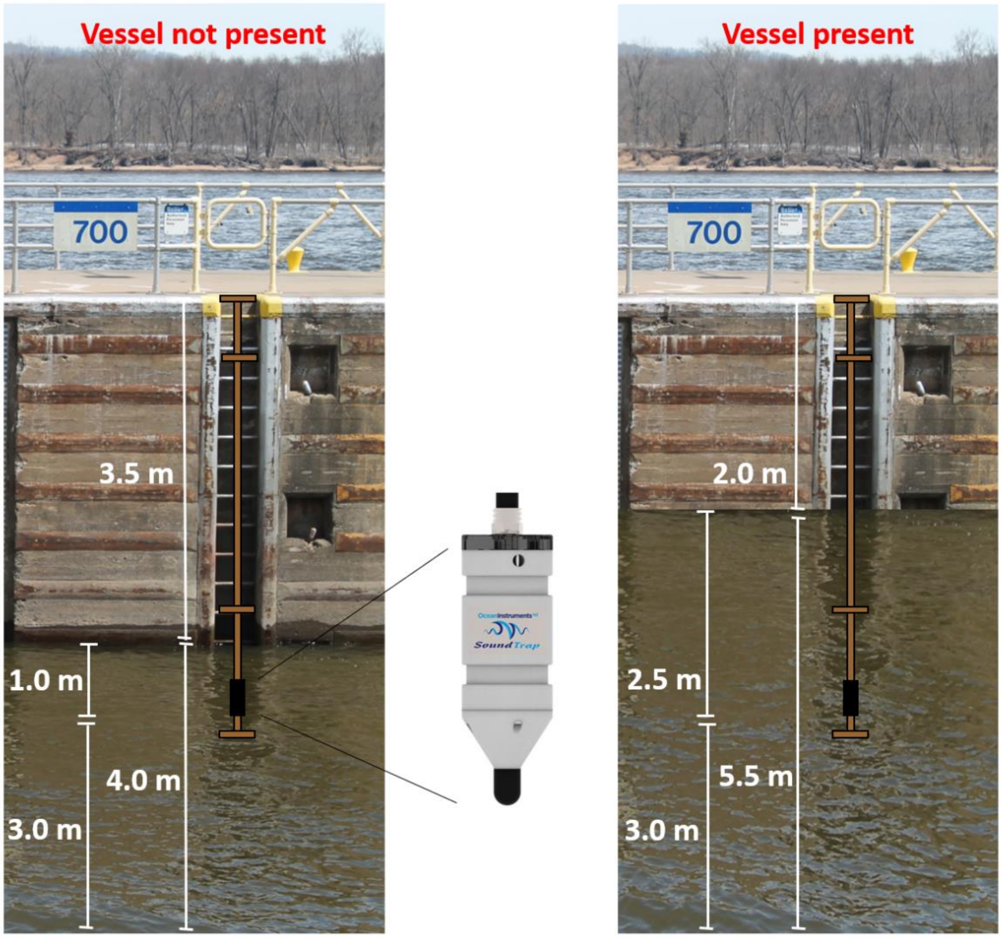


Figure 18: Schematic showing how hydrophone was positioned inside a ladder well. Left shows when no vessel in present and the lock is at its minimum water level and right when a vessel is passing through the lock. Photo of hydrophone (Ocean Instruments NZ).

1) **To determine if sound level varied over time** (section 5.2), four quantitative measures were calculated for every minute over the deployment period: broadband (10 -12,000 Hz) median, 95th and 5th percentile sound pressure level (SPL) as well as root-mean-square (RMS) SPL.
2) **To determine if sound level was affected by season or listening station** (section 5.2), RMS SPL at each listening station was analyzed statistically using a two-way ANOVA.
3) **To determine if sound level is affected by water velocity** (section 5.4), RMS SPL at each listening station was analyzed before, during and after the dam gates were opened.
4) **To determine if sound level varied with frequency** (section 5.5), RMS SPL and power spectral density (PSD) were calculated for all recordings. PSDs were calculated using a fast Fourier transformation (FFT) of each minute of recording,

creating 1 Hz frequency resolution and applying a 1 sec Hanning window with 50% overlap. To evaluate data quality, spectral probability density (SPD) was also calculated between 10 – 12,000 Hz (Merchant *et al.*, 2015). This measure shows the modal structure and outlying data in the underlying distribution, which is helpful when interpreting averages and percentiles.

5) **To determine if vessel passage numbers/ time changed over time** (section 5.6), the shipping log was used to compare vessel passages according to day of the week and season.

6) **To determine if sound level was affected by vessel passage** (section 5.8), an adaptive threshold level (ATL) was used to determine the relative SPL when a vessel is passing through the lock versus the general background soundscape.

[The ATL works on the assumption that the minimum recorded SPL over a given period is representative of background sound within that period. The threshold adapts to long term variations in the broadband SPL while distinguishing short term relatively high amplitude events (Merchant *et al.*, 2015). This method is considered preferable to a fixed threshold, which would be insensitive to temporal and spatial variability (Putland *et al.*, 2017). All broadband SPLs were then calculated in 20-minute bins as per the method established by Merchant et al. 2012.]

7) **To determine if sound level was affected by type of vessel** (section 5.8), broadband SPL was assessed between recreational and commercial vessel passages versus the general background soundscape (when the lock had no vessels passing through).

8) **To determine if sound level was affected by commercial vessel metrics** (section 5.6), broadband SPL was compared to length (m), breadth (m), draft (m) and gross tonnage using Pearson's product correlation.

5.2 Spatial/temporal variability

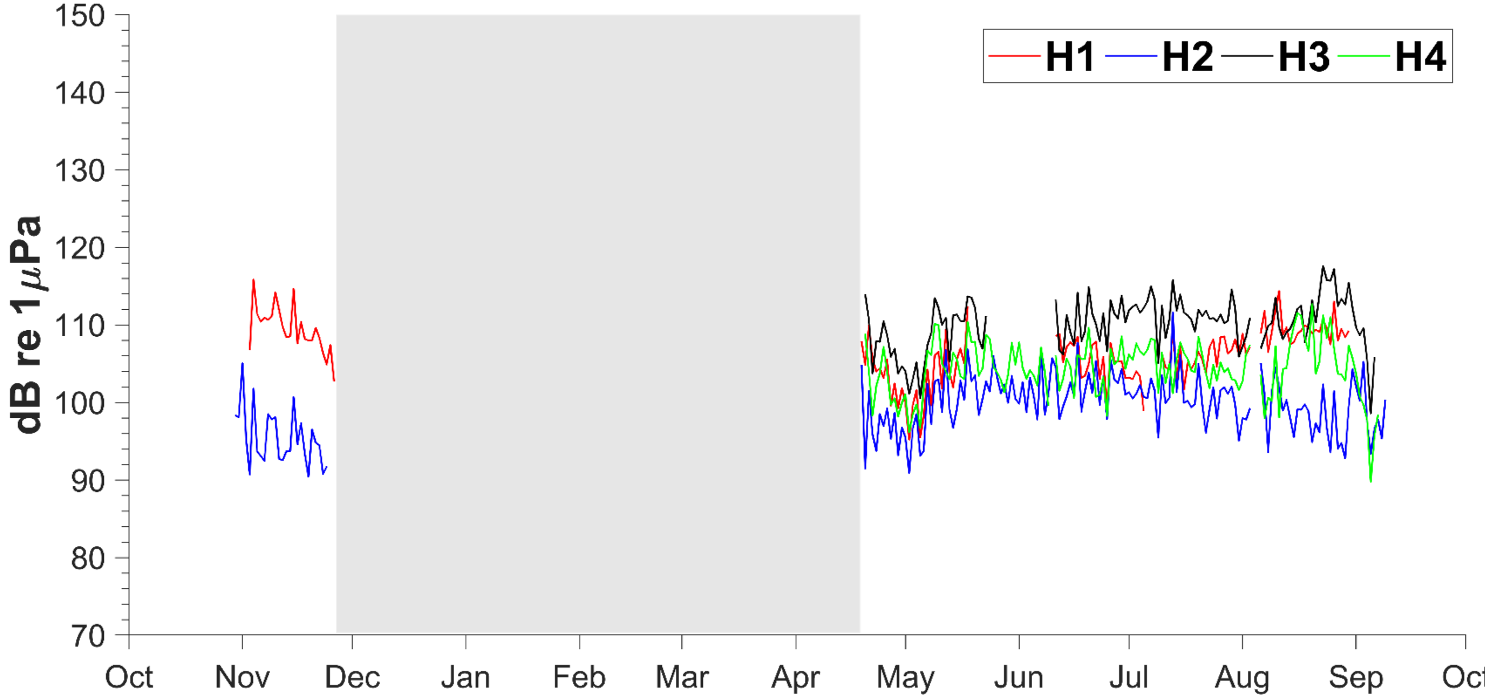


Figure 19: Root-means-squared (RMS) broadband sound pressure level (SPL) between 200 – 5000 Hz for the four listening stations throughout the deployment period. Each listening station is represented by a different colored line and the grey box shows when the recording stations were not present at Lock and Dam 5. For 2018, two additional hydrophones were deployed.

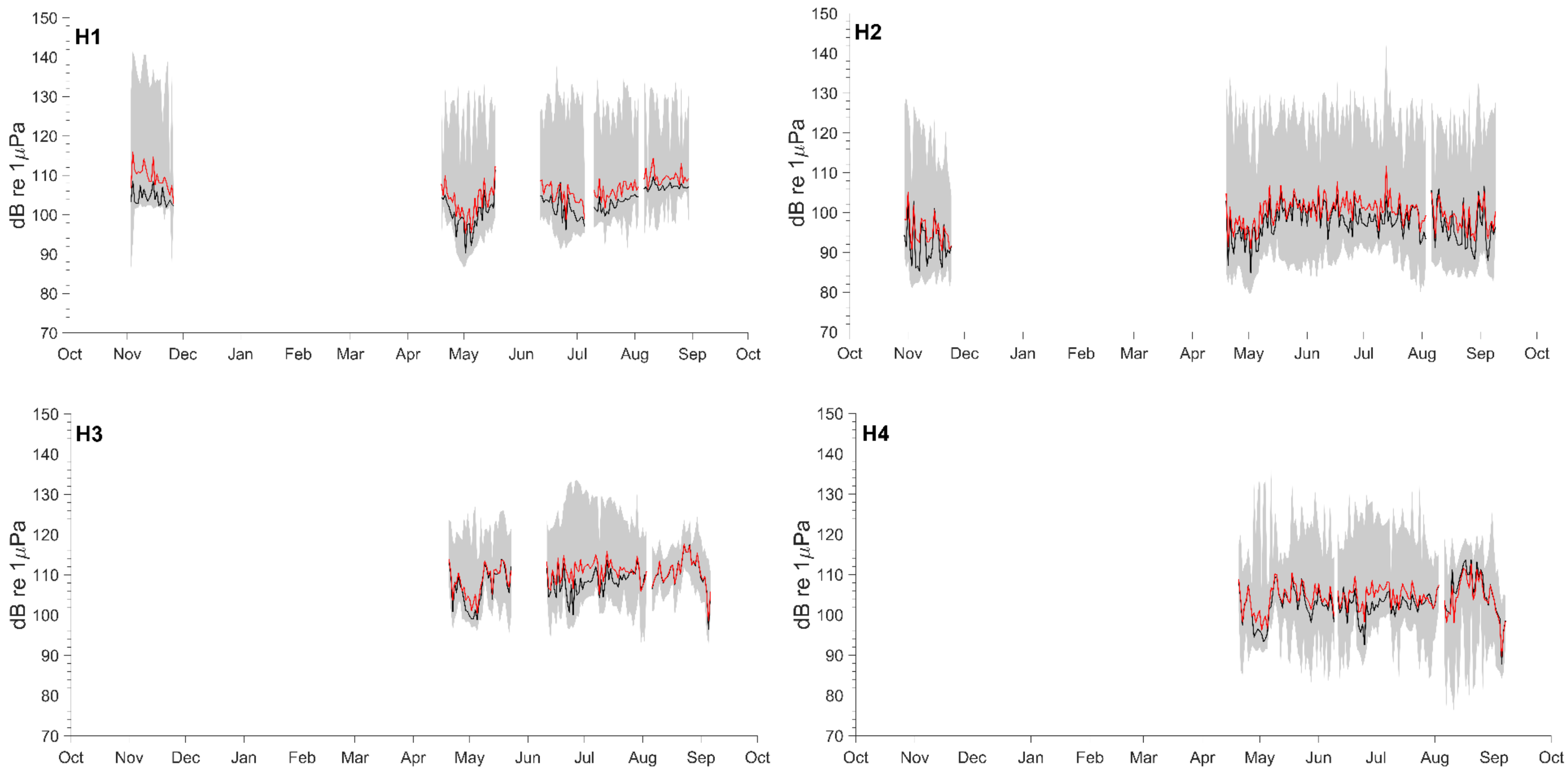


Figure 20: Daily broadband sound pressure level (SPL) between 200 – 5000 Hz. Red represents root means squared SPL, black represents median SPL, grey boundaries represent 95% and 5% SPL.

Statistics of temporal/spatial differences

A two-way ANOVA was performed to determine if there was a difference in the daily RMS broadband SPL (200-5000 Hz) owing to listening station (H1, H2, H3, H4) or season (fall, spring, summer). The RMS SPL data passed normality (Shapiro-Wilk P = 0.196) and equal variance tests (Brown-Forsythe P = 0.501).

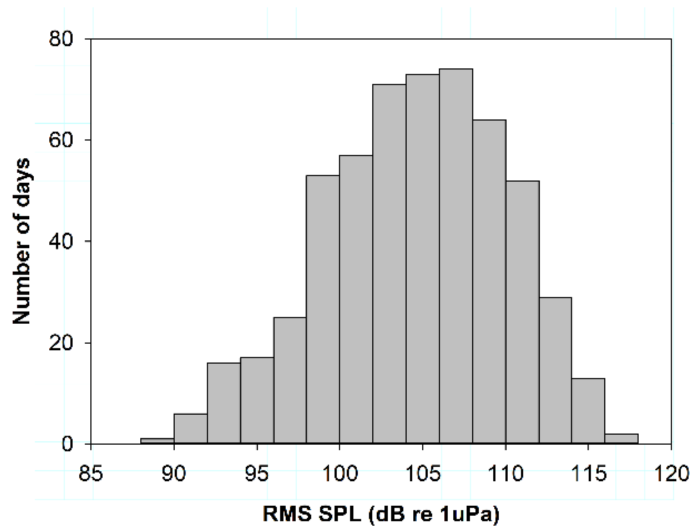


Figure 21: Histogram of daily RMS broadband SPL (200-5000 Hz) data, bin size (2 dB).

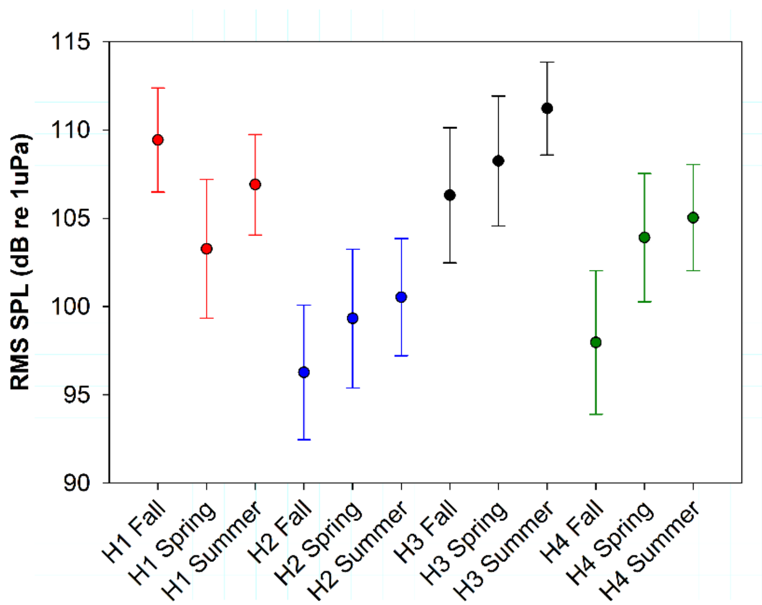


Figure 22: RMS broadband SPL (200-5000 Hz) (mean ± 1 SD) according to listening station (H1, H2, H3, H4) and season (fall September – November, spring March – May, summer June – August).

Both season and listening station were found to cause significant differences for the RMS SPL at Lock and Dam 5 (Table 5). Spring was defined as March – May, summer as June – August and fall as September – November. Summer has the highest daily RMS SPL (105.9 ± 0.2 dB re 1μPa), compared to spring (103.7 ± 0.3 dB re 1μPa) and fall (102.4 ± 0.5 dB re 1μPa). The listening station outside the lock on the dam side (H3) had the highest daily RMS SPL (108.6 ± 0.5 dB re 1μPa) followed by those inside the lock chamber (H1 and H2) (106.5 ± 0.3 dB re 1μPa). The quietest station H4 was along the lock approach (98.7 ± 0.3 dB re 1μPa).

Table 5: Results of two-way ANOVA performed on RMS SPL (200-5000 Hz) for season and listening station.

Source of Variation	DF	F	P
Season	2	35.919	<0.001
Listening Station	3	157.521	<0.001
Season x Listening Station	6	998.221	166.370

5.3 Abiotic sounds

Abiotic sounds including the weather or water movement can alter the soundscape (Urick, 1983). For example, thunderstorms can temporarily increase the mid frequency (200 – 1,000 Hz) sound pressure level by 30 dB or more (Tacconi, 1981). However, during the deployment periods (Table 3) weather did not alter the sound recorded. During the winter months, heavy snowfall would be expected to increase the soundscape of the area because of the percussive effect of snow hitting either the water surface or ice cover. The highest rainfall (snow) at Lock and Dam 5 occurred on 22nd December 2017 (Figure 23), however all listening stations had already been removed from the water owing to ice cover.

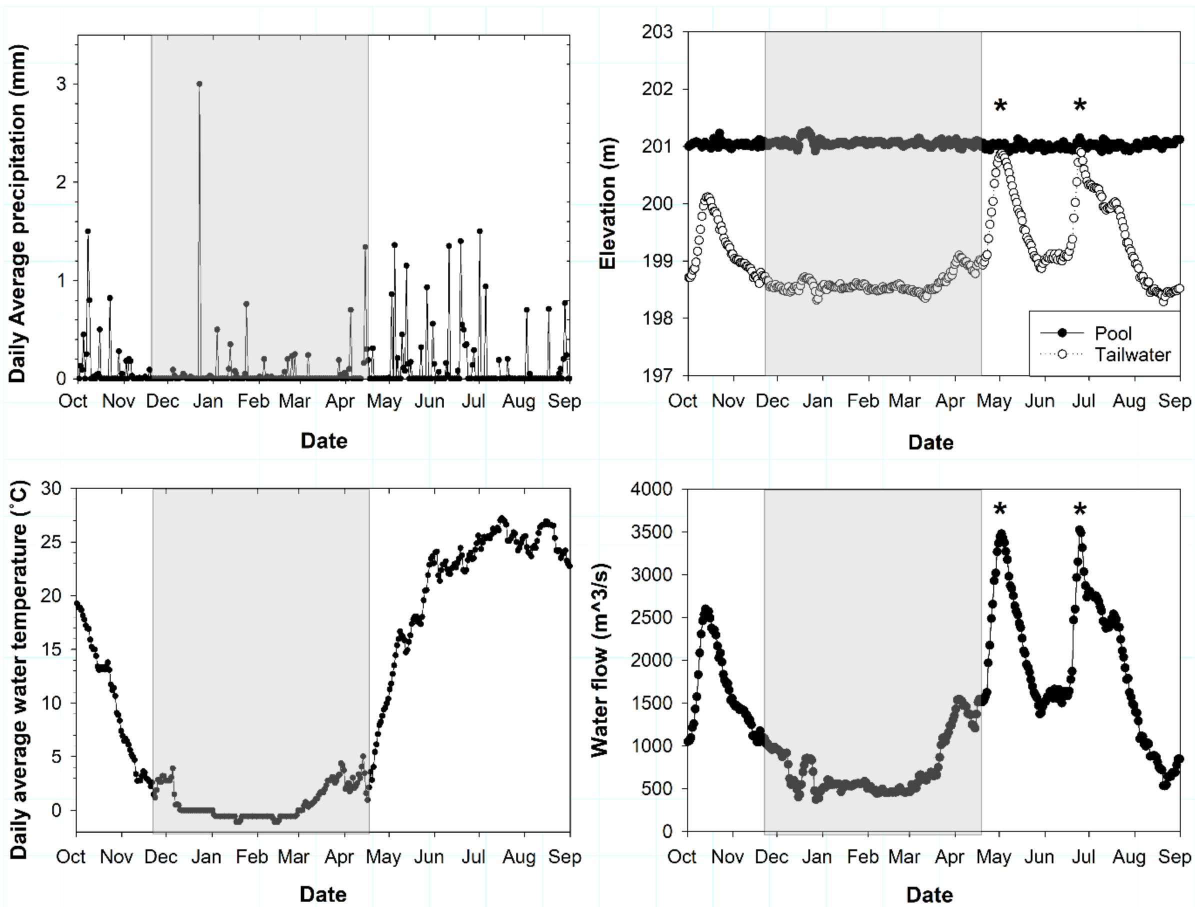


Figure 23: Metrics taken from USACE records between 1st October 2017 and 1st September 2018. Top left; Daily average precipitation (mm). Top right; Water elevation (m). Bottom left; Daily average water temperature (˚C) and bottom left; water flow (m^3/s). Asterisks indicate when the tailwater exceeded poolwater.

5.4 Effect of dam gates being raised on SPL

Following heavy rainfall or snowmelt, a dam's tainter gates may have to be raised owing to high poolwater and increased water flow pass the lock approach (per. comms USACE). At Lock and Dam 5, the gates are rarely out of the water because the dam has one of the highest bearing loads in the Mississippi River (per comms. USACE). However, during this study, the gates were raised once (between 2nd – 3rd May 2018). Broadband SPL (50 – 12,000 Hz) was monitored during this time because if sound levels increase proportional to the increased water flow it could make acoustic deterrents less effective due to masking. When the gates were opened, the broadband SPL recorded at listening station 4 (outside the lock chamber) showed a significant increase (average SPL >120 dB re 1µPa) compared to recordings before and after (average SPL <110 dB re 1µPa), when the gates were closed (Figure 24). The SPL increased within the hearing range of the carp (100 – 6,000 Hz) when the gates were opened (Figure 25). However, the increase was over a short time (~ 4 hours) (Figure 23).

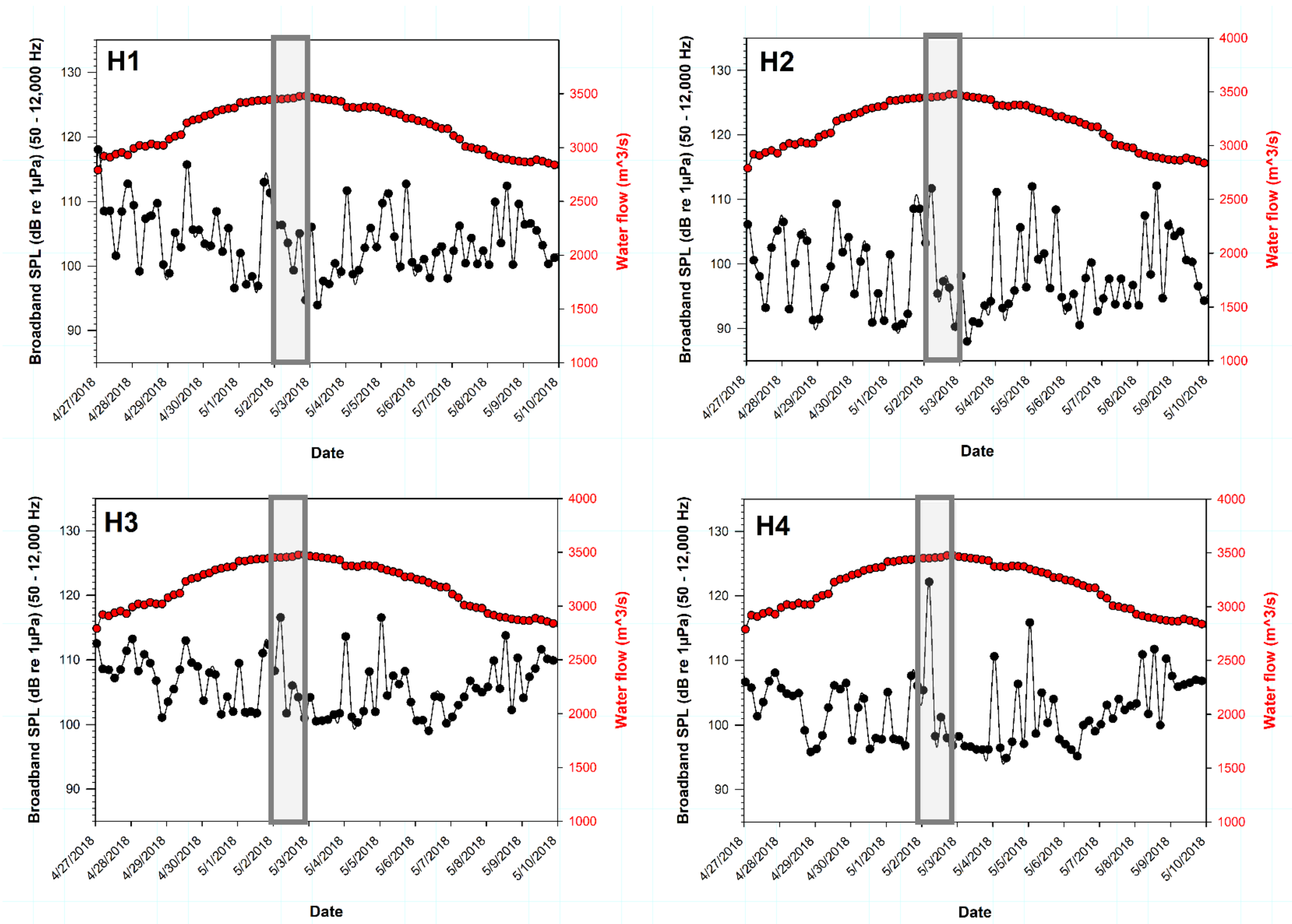


Figure 24: Broadband sound pressure level (SPL) between 50 – 12,000 Hz (dB re 1µPa), shown by the black lines, and water flow (m^3/s), shown by the red lines, averaged over 4-hour time periods at the four listening stations (H1 – H4). The grey box depicts 2nd May 2018 when gates were opened.

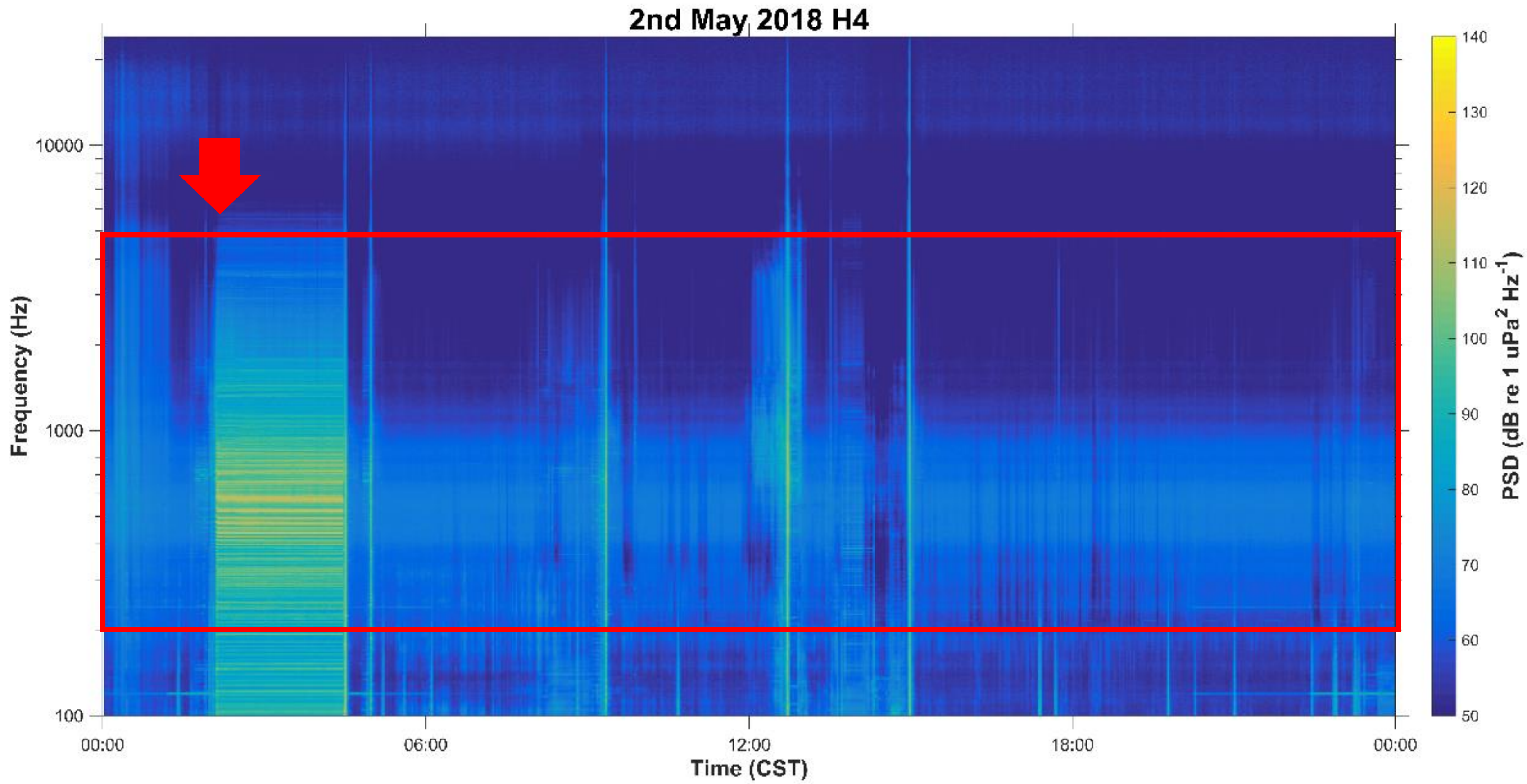


Figure 25: Spectrogram of sound data at listening station H4 at Lock and Dam 5 on 2nd May 2018 when the tainter gates were opened. The color bar represents power spectral density (dB re 1μPa^2/ Hz). The red box represents the hearing range of invasive bigheaded carp. The red arrow shows when the gates were opened.

5.5 Frequency (Hz) distribution of SPL over the deployment period

The power spectrum of a time series describes the distribution of power into frequency components. When the energy of the signal is concentrated around a finite time interval, especially if its total energy is finite, one may compute the power spectral density considering the entire time of recording.

Conventional methods of analyzing the frequency distribution of a sound recording include power spectral density, to show temporal variation or percentiles to summarize frequency content. However, spectral probability density is a more statistical approach of temporal data, which requires a large sample size, and reveals modal behavior, outliers, tonal components and the system noise floor (Merchant *et al.*, 2013). The long-term passive monitoring dataset at Lock and Dam 5 yielded >730,000 minutes of recording, making it ideal for this statistical analysis.

Spectral probability density of the recordings taken at Lock and Dam 5 showed a normal distribution, with limited evidence of multi-modality. Median background sound levels ranged from 50 – 70 dB re 1μPa^2/Hz across the frequency range 10 – 12,000 Hz (Figure 26). The RMS SPL at all listening stations was higher as it takes into consideration the continuous noise spectrum at the location, therefore it ranged between 80 – 110 dB re 1μPa^2/Hz between 10 – 1,000 Hz, and < 80 dB re 1μPa^2/Hz at frequencies > 1,000 Hz (Figure 26).

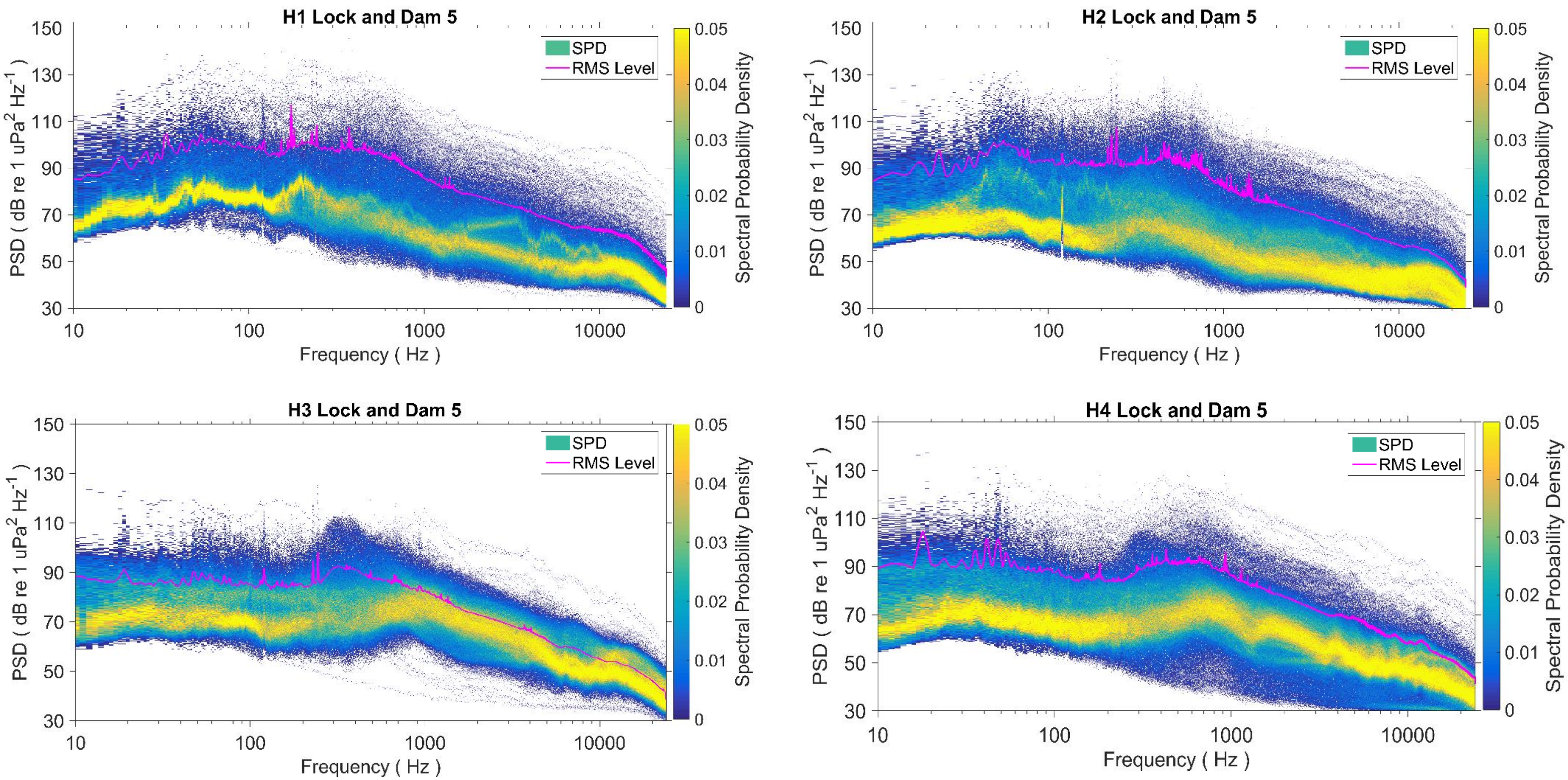


Figure 26: RMS level (pink line) of the power spectral density (PSD) as well as spectral probability density (SPD) (color-bar) for all deployments at each of the four listening stations: H1 (top left), H2 (top right), H3 (bottom left) and H4 (bottom right).

5.6 Vessel information

Besides abiotic sounds in the environment, there is also the dominant sound produced by human activity to consider. Records of vessel activity through Lock and Dam 5, were collected from the USACE to assess if there was a difference between the number of passes through the lock over time and the associated sound produced.
During this study two types of vessels transited up and downstream through the lock.

- Recreational vessels are defined as motorized boats used for fishing and leisure and passenger ferries.
- Commercial vessels are defined as industrial barges propelled by motorized boats referred to as tugs or tow boats. Barge "trains" ranged from 3 to 18 barges. When barge number exceeded 9, lock navigation was accomplished by performing a double lockage. During a double lockage, the first set of barges (up to 9) are disconnected and put through the lock chamber. Since these barges are no longer connected to a towboat, they are pulled through using a tow-haulage (cable and hoist system). After the barges are locked through, the second lockage includes the tow boat and remaining barges. In this case, barge propulsion was accomplished by the tow boat. The barge train was then "reconstituted" near the up or downstream opening. Thus, in addition to the propulsion sounds from the towboat, sound is produced from the barges as they interact with the water, as well as idling sound when the towboat is static, plus machinery noises from the opening of the gates and the land-based tow station and water flow.

For this study, a vessel passage was defined as the time from when the first set of gates opened, up or downstream until when the last set of gates closed (Figure 27). This time was extended for commercial vessels that were undergoing a double lockage.

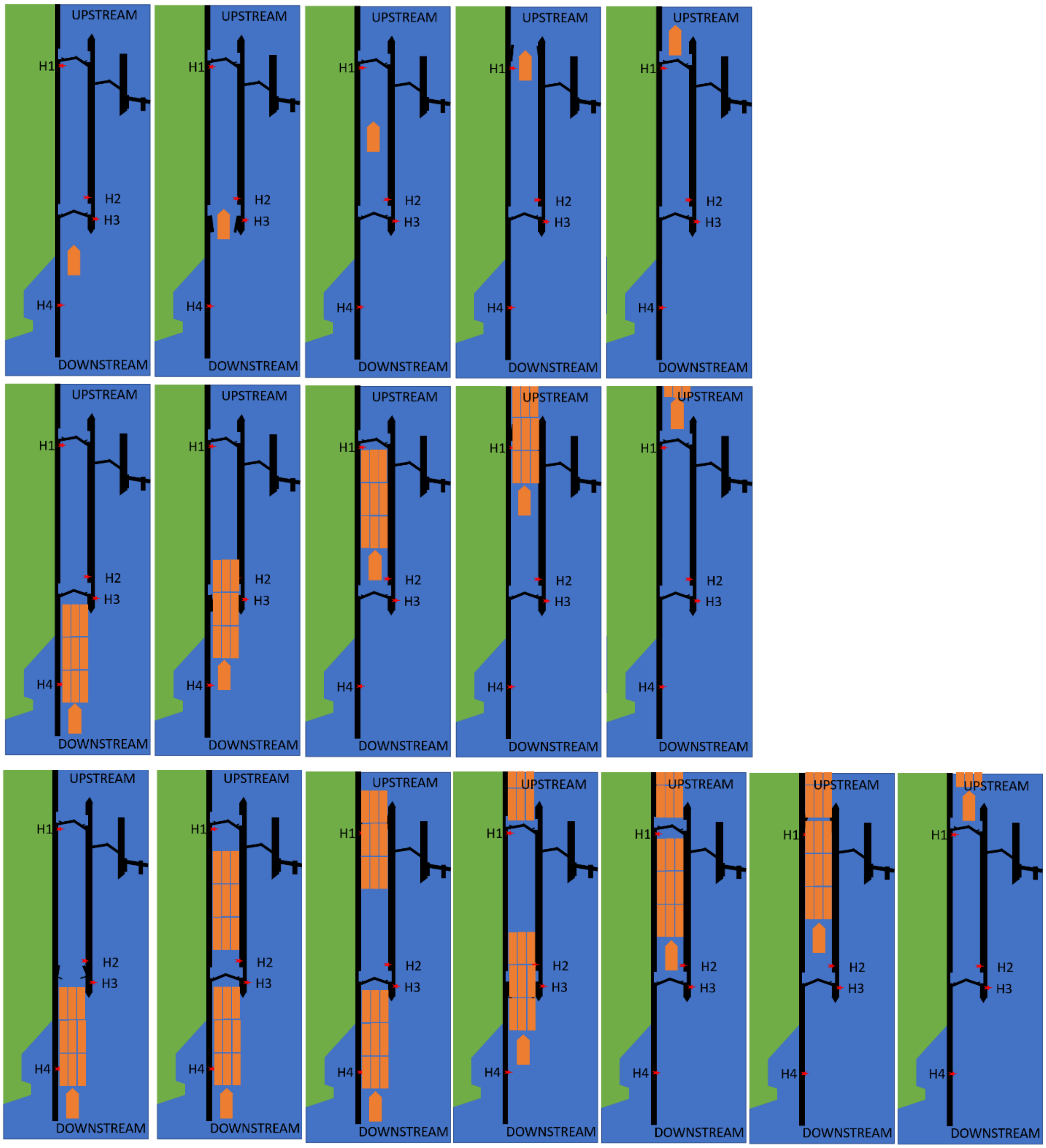


Figure 27: Schematic showing top: a recreational vessel passing through the lock; middle: a six-barge commercial vessel passing through the lock; bottom: a twelve-barge commercial vessel conducting a double lock passage.

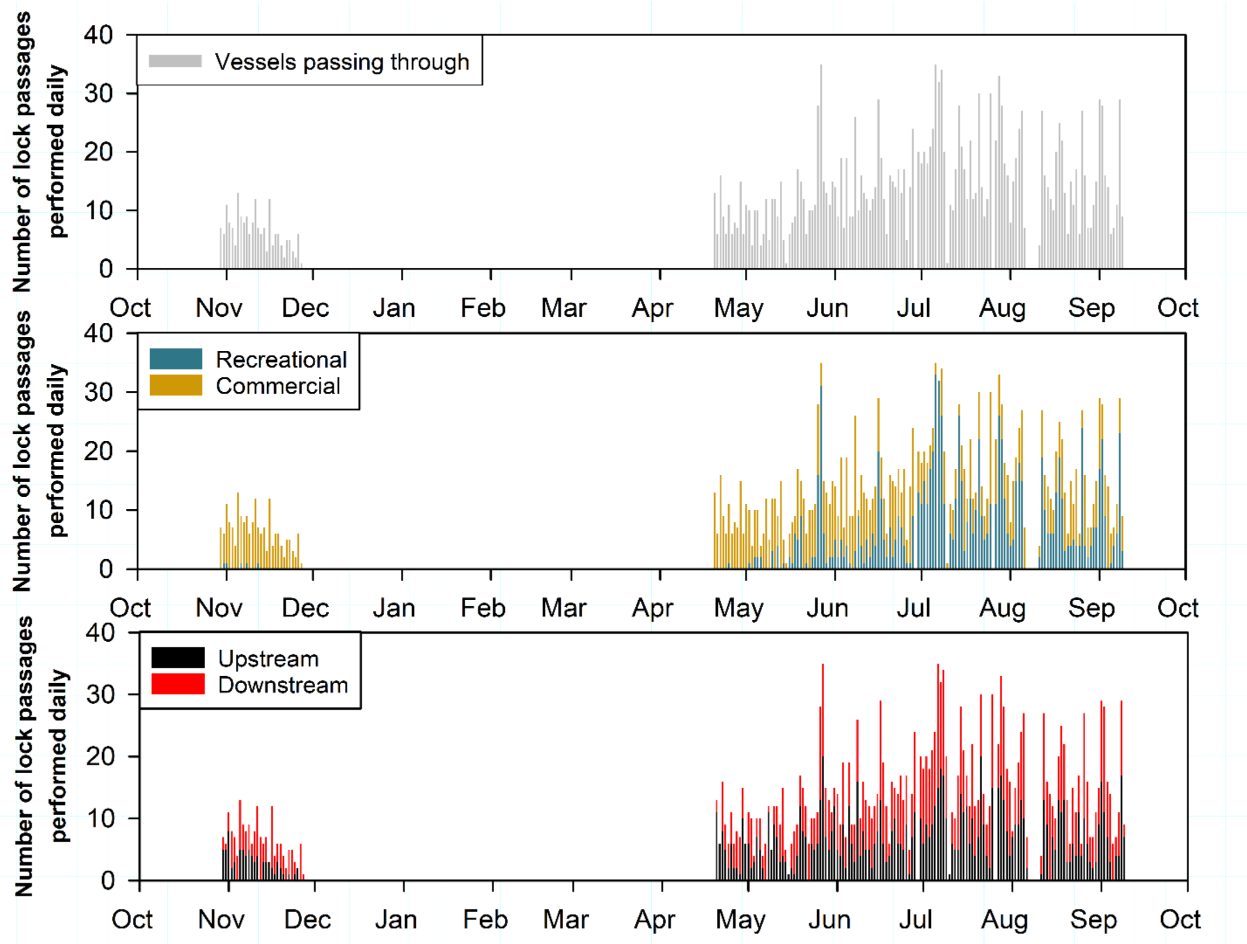


Figure 28: Daily number of lock passages over the deployment period: (top) total number of lock passages performed daily (middle) recreational and commercial vessels, (bottom) upstream and downstream information.

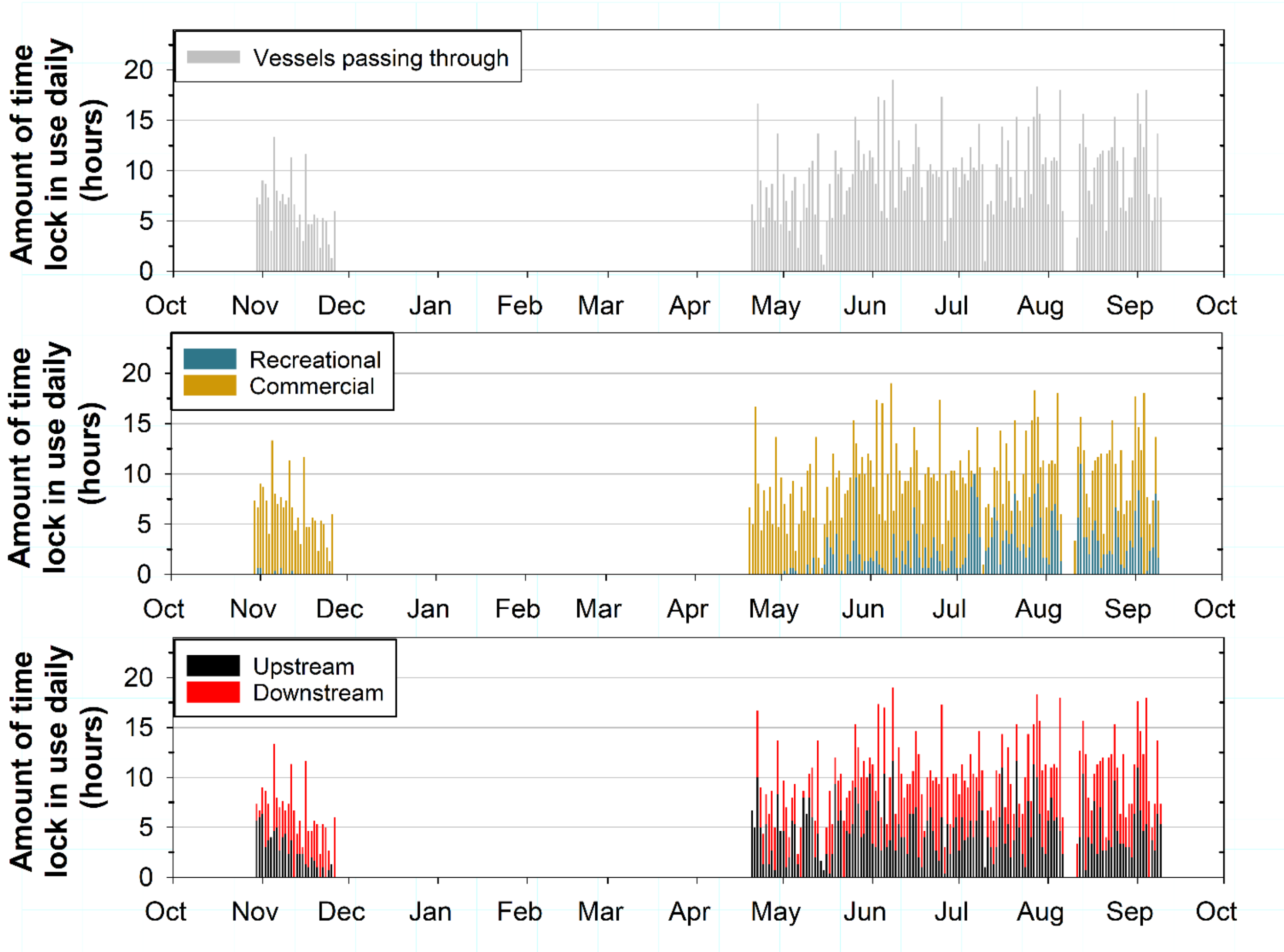


Figure 29: Amount of time (hours) for the daily: (top) total number of lock passages performed daily (middle) recreational and commercial vessels, (bottom) upstream and downstream information.

Table 6: Average daily number of lock passages according to recreational/commercial vessels or downstream/upstream movement.

Day of the week	Recreational vessels		Commercial vessels		Upstream		Downstream	
	Average daily number of passes	Total number of passes	Average daily number of passes	Total number of passes	Average daily number of passes	Total number of passes	Average daily number of passes	Total number of passes
Monday	6	92	8	189	6	131	6	150
Tuesday	4	58	7	156	4	88	6	126
Wednesday	4	84	8	178	6	131	6	131
Thursday	6	83	7	163	6	116	6	130
Friday	9	138	8	184	7	168	7	154
Saturday	14	269	7	157	9	217	9	209
Sunday	13	249	8	205	9	207	10	247

Commercial vessels had an average passage time (time from arrival to departure at lock chamber) of 53 ± 29 minutes (mean ± SD).

Recreational vessels had an average passage time of 12 ± 7 minutes (mean ± SD).

The navigational lock at Lock and Dam 5 is used for both up and down stream passage of boat traffic multiple times per day (between 4 - 7 times each way per day).

The key to any deterrent is to prevent egress into the lock chamber while the downstream gates are open. The gates open well before (up to 20 minutes prior) commercial vessels are at the gates extending the amount of time an acoustic deterrent is needed. Maintaining the lower (downstream) gates closed until needed for commercial barge transits would help minimize the time available for carp to swim into the lock chamber.

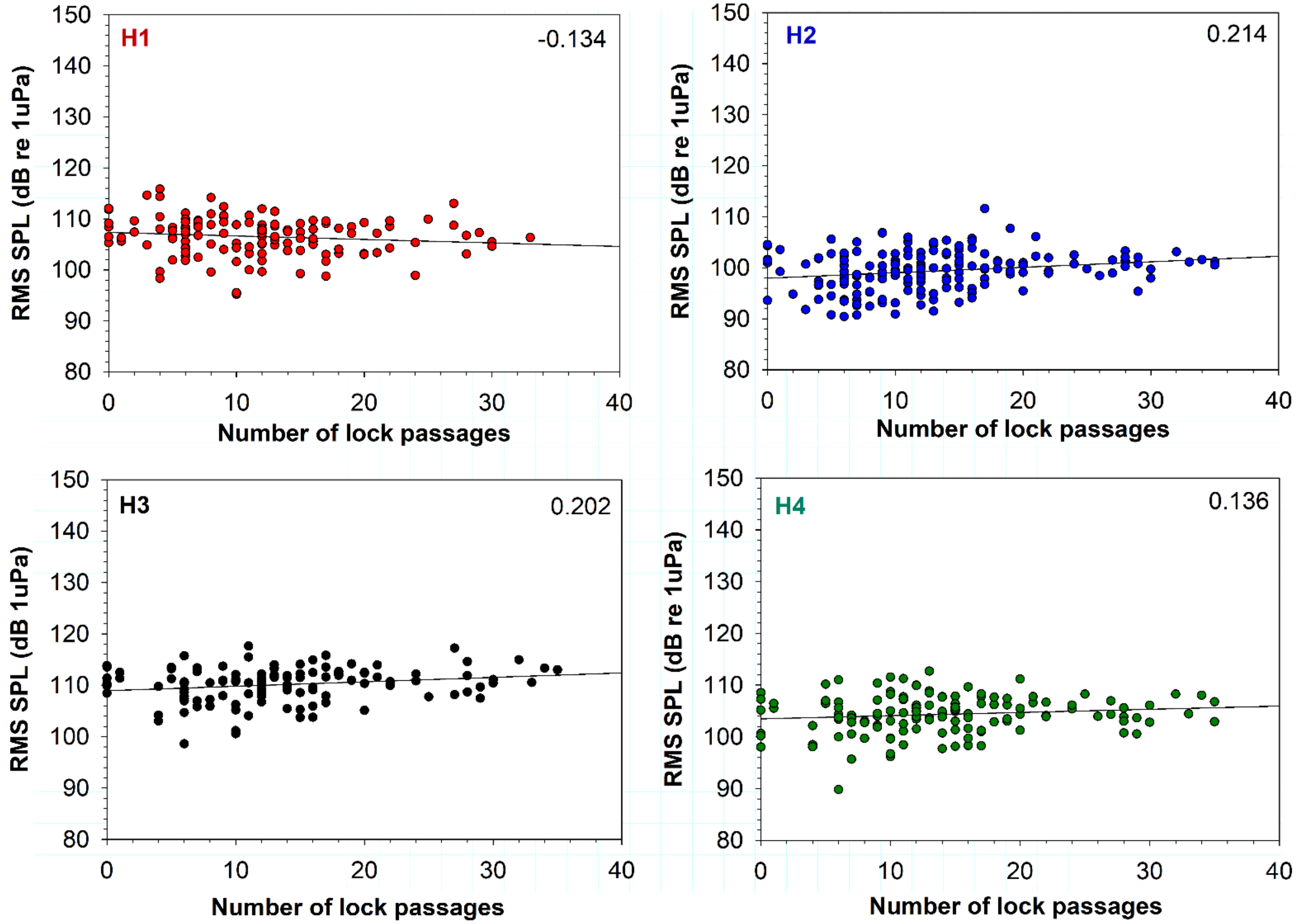


Figure 30: Daily RMS SPL (dB re 1µPa) between 200-5000 Hz compared to the daily number of lock passages. The Pearson's Product Correlation Coefficient is shown in the top right corner of each subplot.

5.7 Effect of vessel passage on daily soundscape - Regular week day

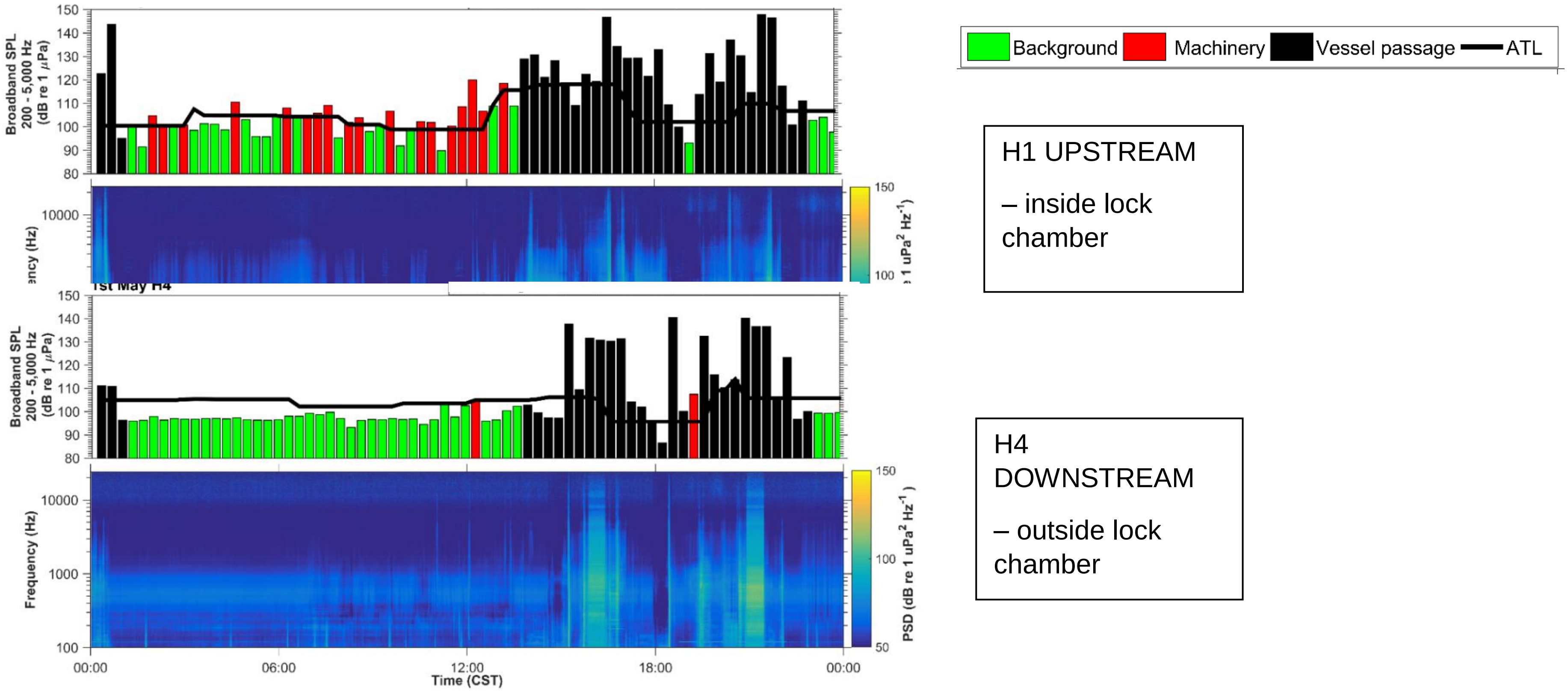


Figure 31: Spectrograms and broadband SPL (20 - 5,000 Hz) for H1 (inside lock chamber) and H4 (outside lock chamber) for Tuesday 1st May 2018 when 11 lock passages (all commercial, 6 up and 5 downstream) occurred totalling 9.6 hours the lock had vessels passing through. Intermittent refers to when machinery was in action at the lock and dam. Lock in use refers to both commercial and recreational vessel passages. ATL refers to the adaptive threshold level which is 9 dB above the average broadband sound. Broadband SPL is split into 20-minute bins.

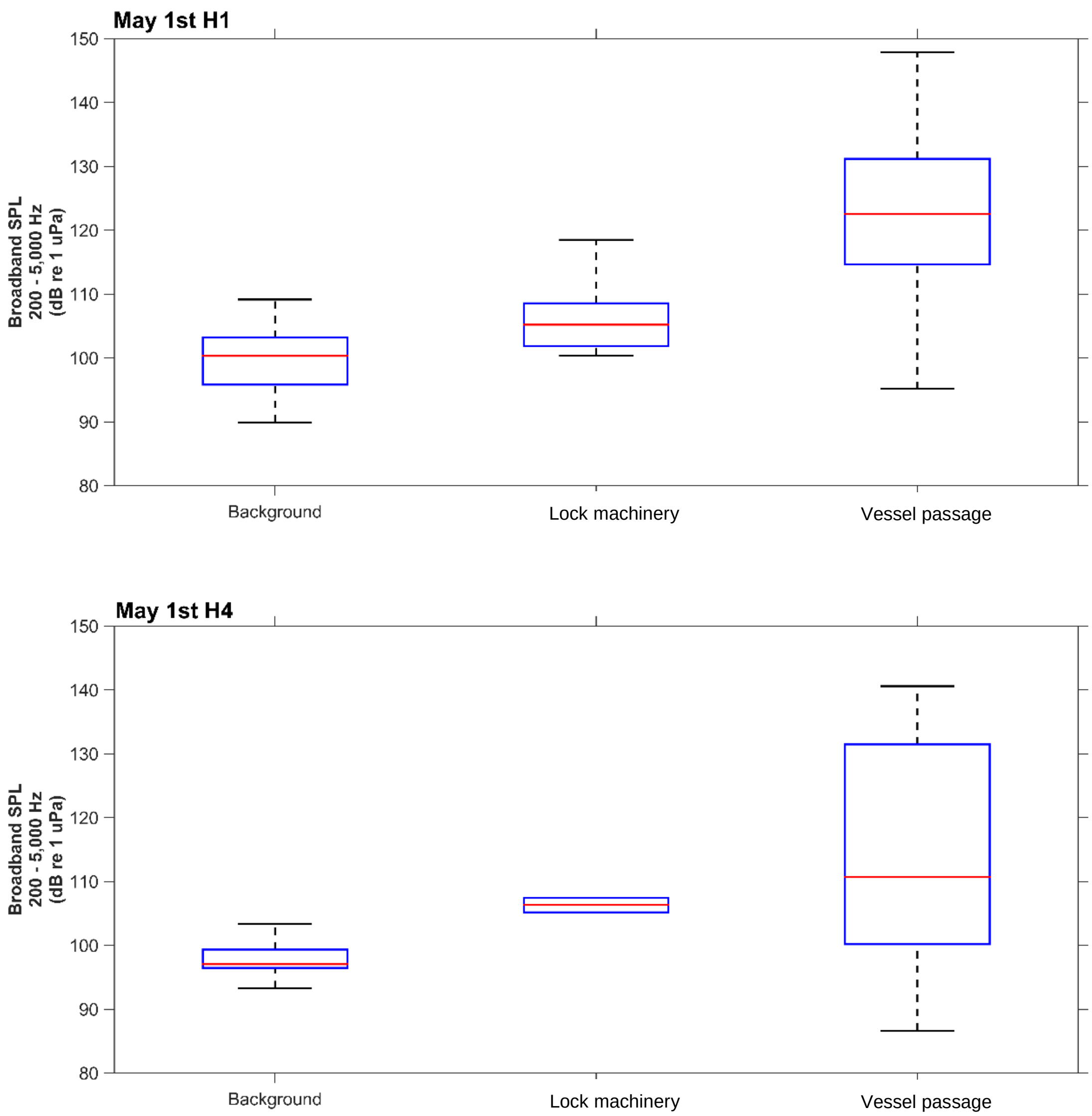


Figure 32: Difference in broadband SPL (200 – 5,000 Hz) for recordings taken at H1 and H4 on Tuesday 1st May 2018 categorized as background when lock had no vessels passing through, when lock machinery was in use, and when a vessel was passing through.

Weekend with a high number of recreational traffic passages

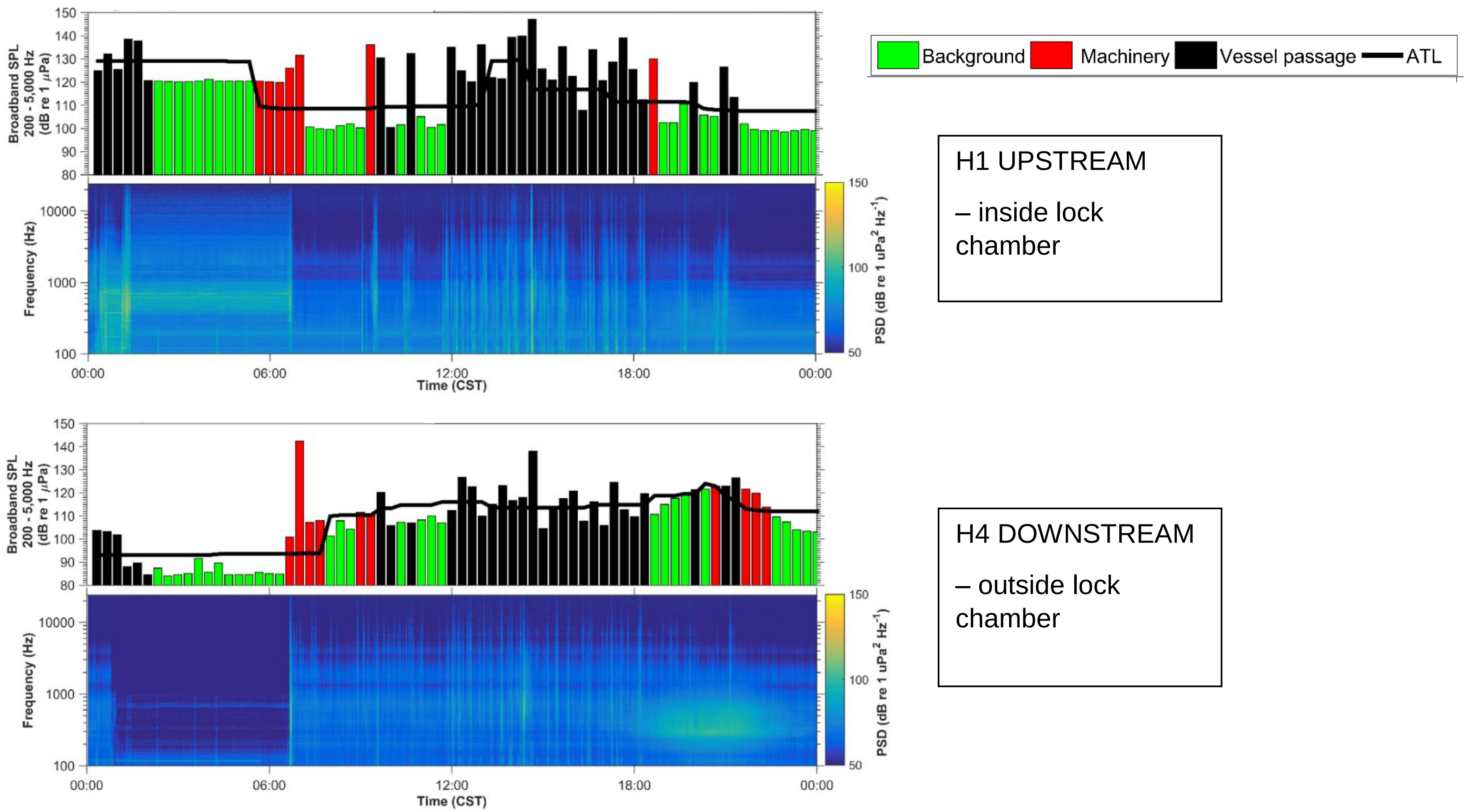


Figure 33: Spectrograms and broadband SPL (20 - 5,000 Hz) for H1 (inside lock chamber) and H4 (outside lock chamber) for Saturday 14th July 2018 when 28 lock passages occurred totalling 9.3 hours the lock had vessels passing through. Intermittent refers to when machinery was in action at the lock and dam. Lock in use refers to both commercial and recreational vessel passages. ATL refers to the adaptive threshold level which is 9 dB above the average broadband sound. Broadband SPL is split into 20-minute bins.

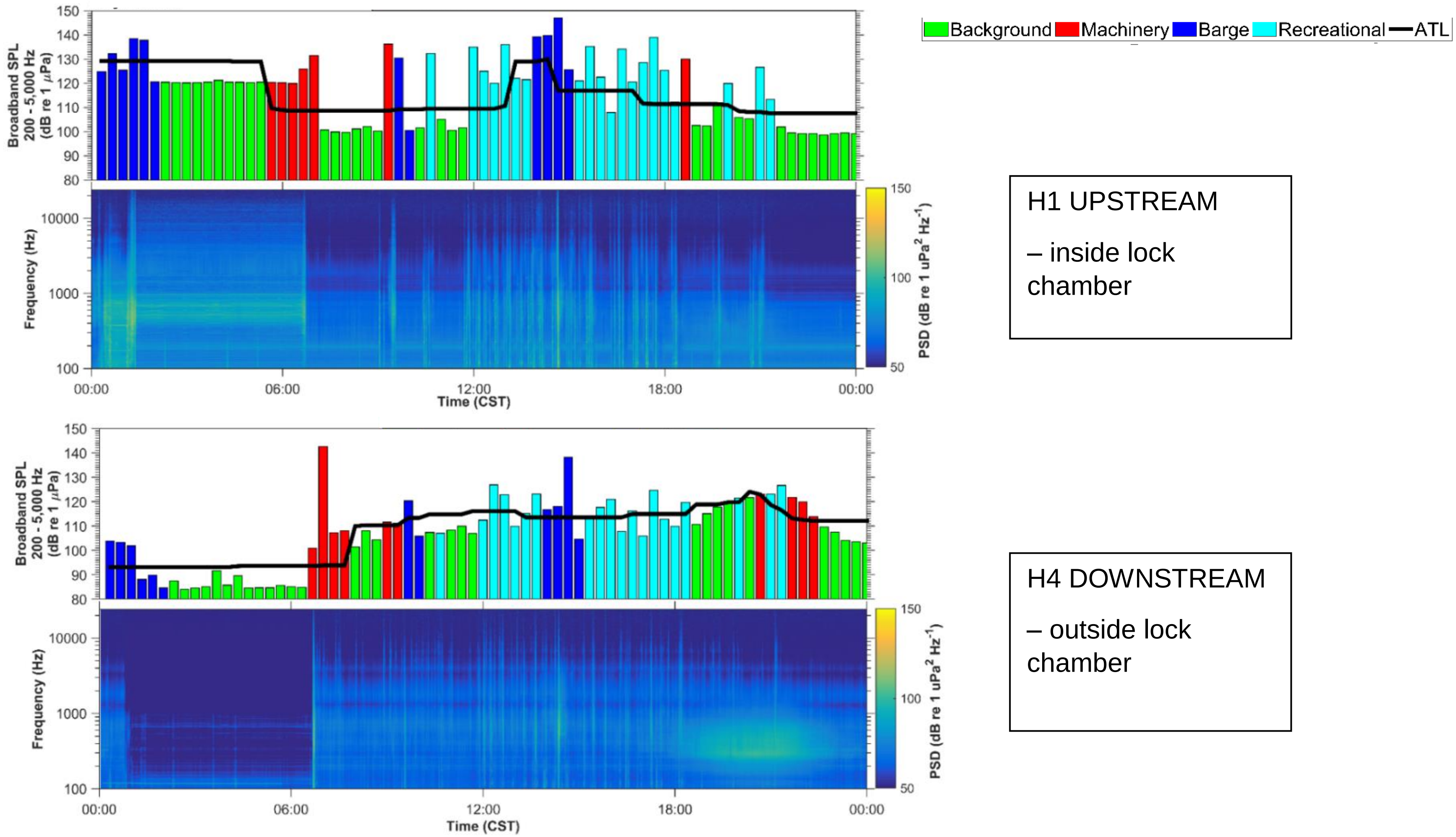


Figure 34: Spectrograms and Broadband SPL (20 - 5,000 Hz) for H1 (inside lock chamber) and H4 (outside lock chamber) for Saturday 14th July 2018 when 28 lock passages occurred totalling 9.3 hours the lock had vessels passing through. Time lock had vessels passing through is broken down occurring to type of vessel (2 commercial and 26 recreational lock passages, 14 up and 14 downstream). Intermittent refers to when machinery was in action at the lock and dam. ATL refers to the adaptive threshold level which is 9 dB above the average broadband sound. Broadband SPL is split into 20-minute bins.

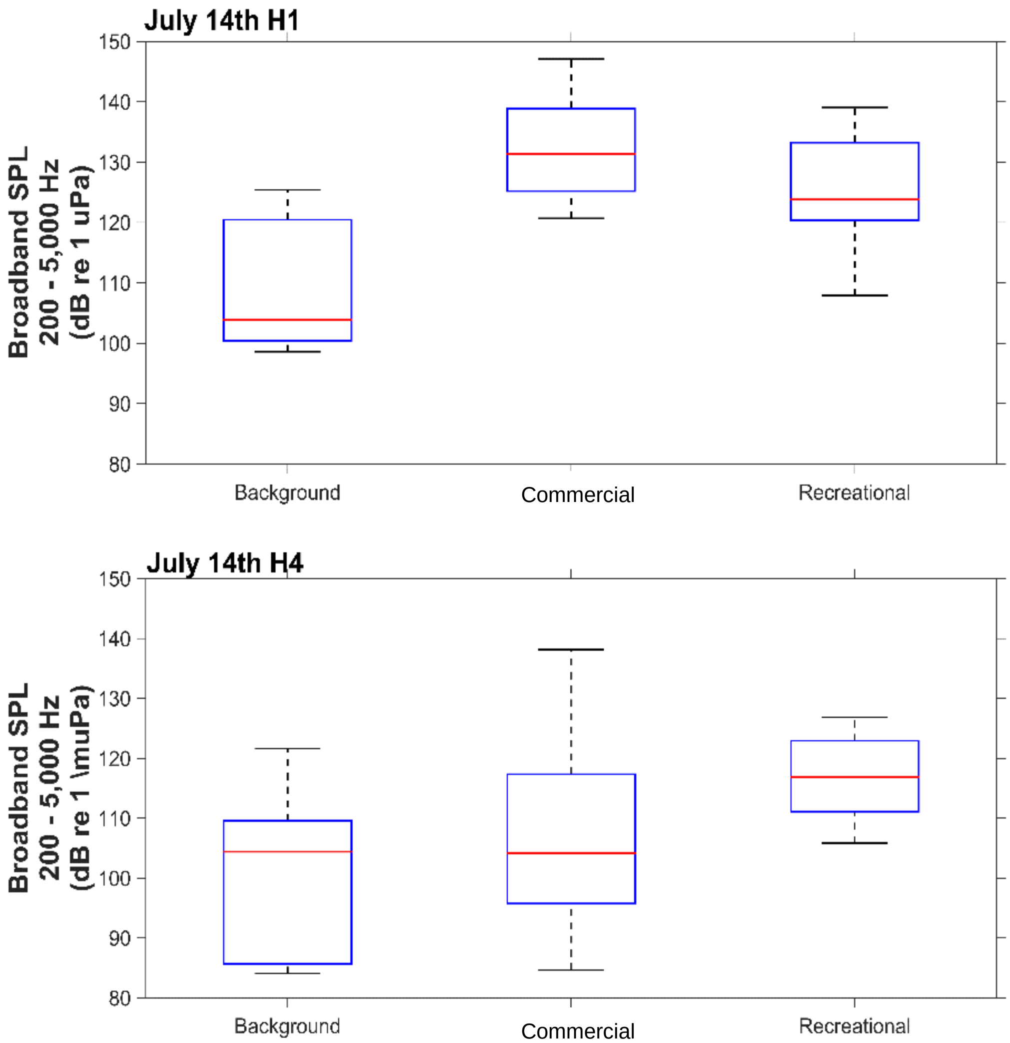


Figure 35: Difference in broadband SPL (200 – 5,000 Hz) for recordings taken at H1 and H4 on Saturday 14th July 2018, categorized as background when lock had no vessels passing through, commercial lock passages and recreational lock passages.

5.8 Effect of vessel passage during total deployment

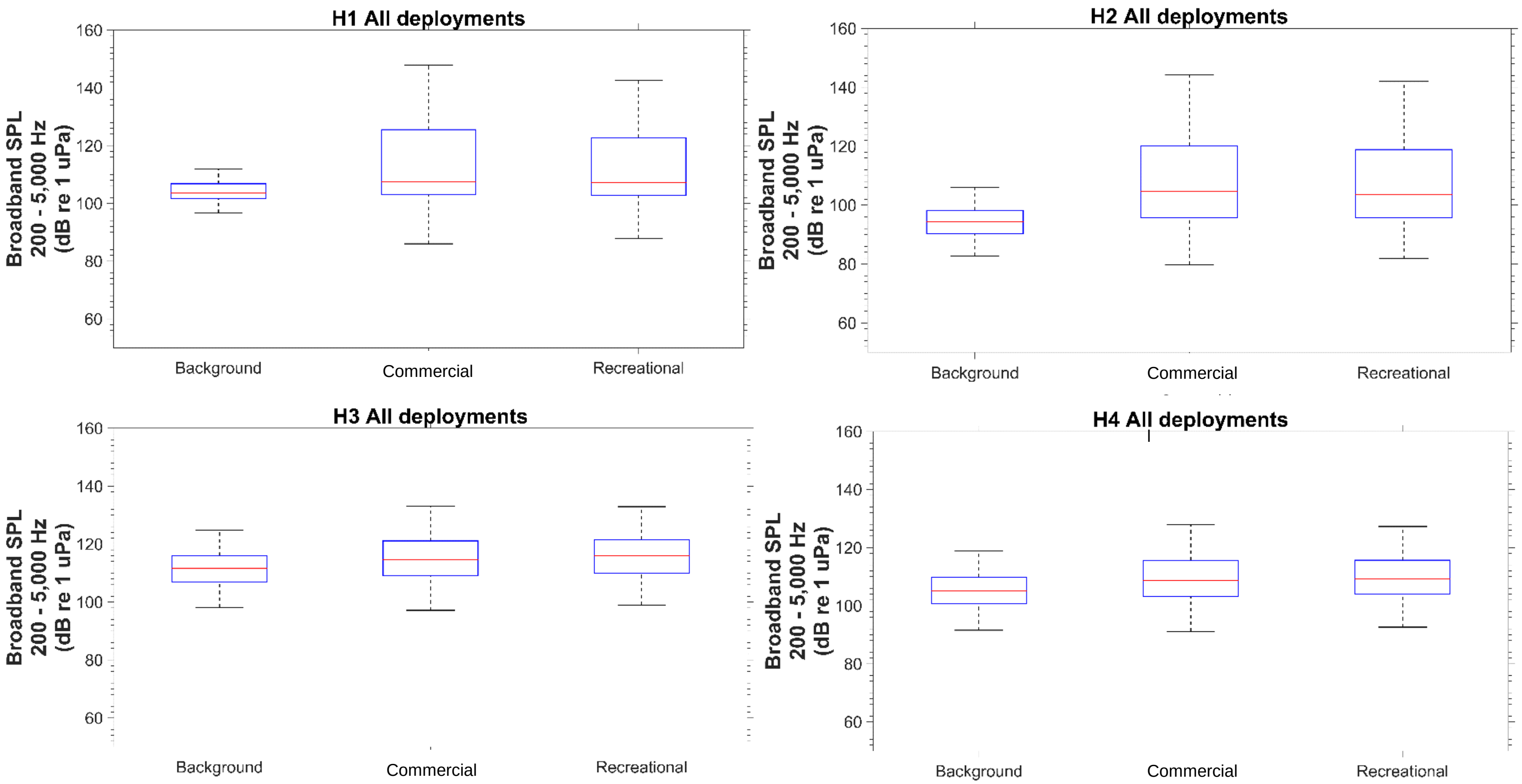


Figure 36: Difference in broadband SPL (200 – 5,000 Hz) for all recordings at H1 (top left), H2 (top right), H3 (bottom left) and H4 (bottom right). Categories are background when the lock had no vessels passing through, commercial and recreational lock passages.

Over the total deployment period (fall 2017 – fall 2018), broadband SPL (200 – 5,000 Hz) was shown to increase when the lock had vessels passing through at all listening stations (Figure 30). Inside the lock chamber (H1, H2) commercial vessel passages increased the median SPL by up to 10.2 dB, and recreational passages up to 9.1 dB. Whereas outside the lock chamber (H3, H4), commercial passages increased the SPL by up to 3.6 dB and recreational passages by up to 4.2 dB (Figures 31 – 36). Currently sound at the lock follows a gradient, with louder sound upstream inside the lock compared to downstream on the approach (Figure 36). Therefore, any bigheaded carp swimming upstream during a vessel passage is currently faced with ever increasing sound and therefore any acoustic deterrents would have to account for this by exceeding the highest current SPL. The gradient could be cause by reflections of sound off the lock chamber walls during the entrance/exit of the lock passage.

The broadband SPLs for both commercial and recreational passages also have a wide range. Commercial passages ranged from 76.5 – 154.4 dB and recreational passages from 77.8 – 156.6 dB. This range takes into consideration all sound files recorded between the arrival time and departure time of a vessel, which could also include a waiting period whereby the vessel remains idle or turns its engines off at the lock approach.

Previous studies have also shown a relationship between sound produced by commercial vessel passages and the length of the individual vessel (Figure 37). To test whether vessel metrics had any effect on the SPL, a Pearson's product correlation was performed between broadband SPL and length, breadth, draft and gross tonnage. Data from the 117 commercial vessels that passed through the lock during the deployment period was available from the USACE.

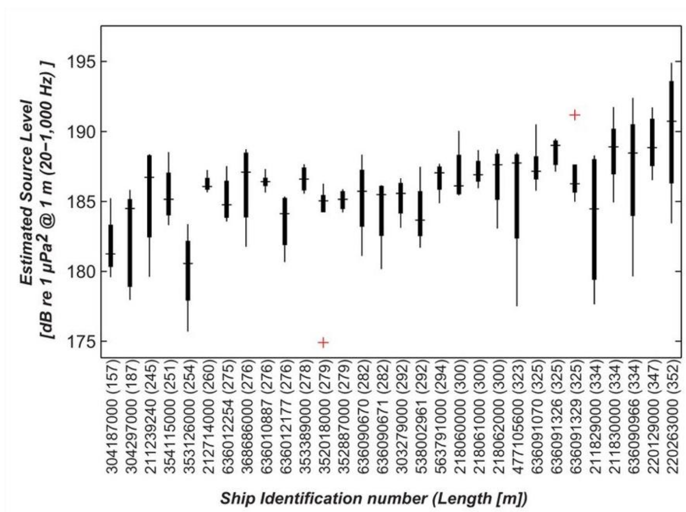


Figure 37: Sound produced (dB re 1μPa^2) versus the length (m) from ships that transited on four or more different occasions past a hydrophone array in Southern California [Taken from (McKenna *et al.*, 2013)].

Table 7: Information about the 117 commercial vessels recorded during the deployment period (MarineTraffic.com). All statistics given as the mean ± 1 standard deviation.

	Length (m)	Width (m)	Draught (m)
Commercial vessels	40.4 ± 10.7	12.3 ± 3.1	2.9 ± 0.7

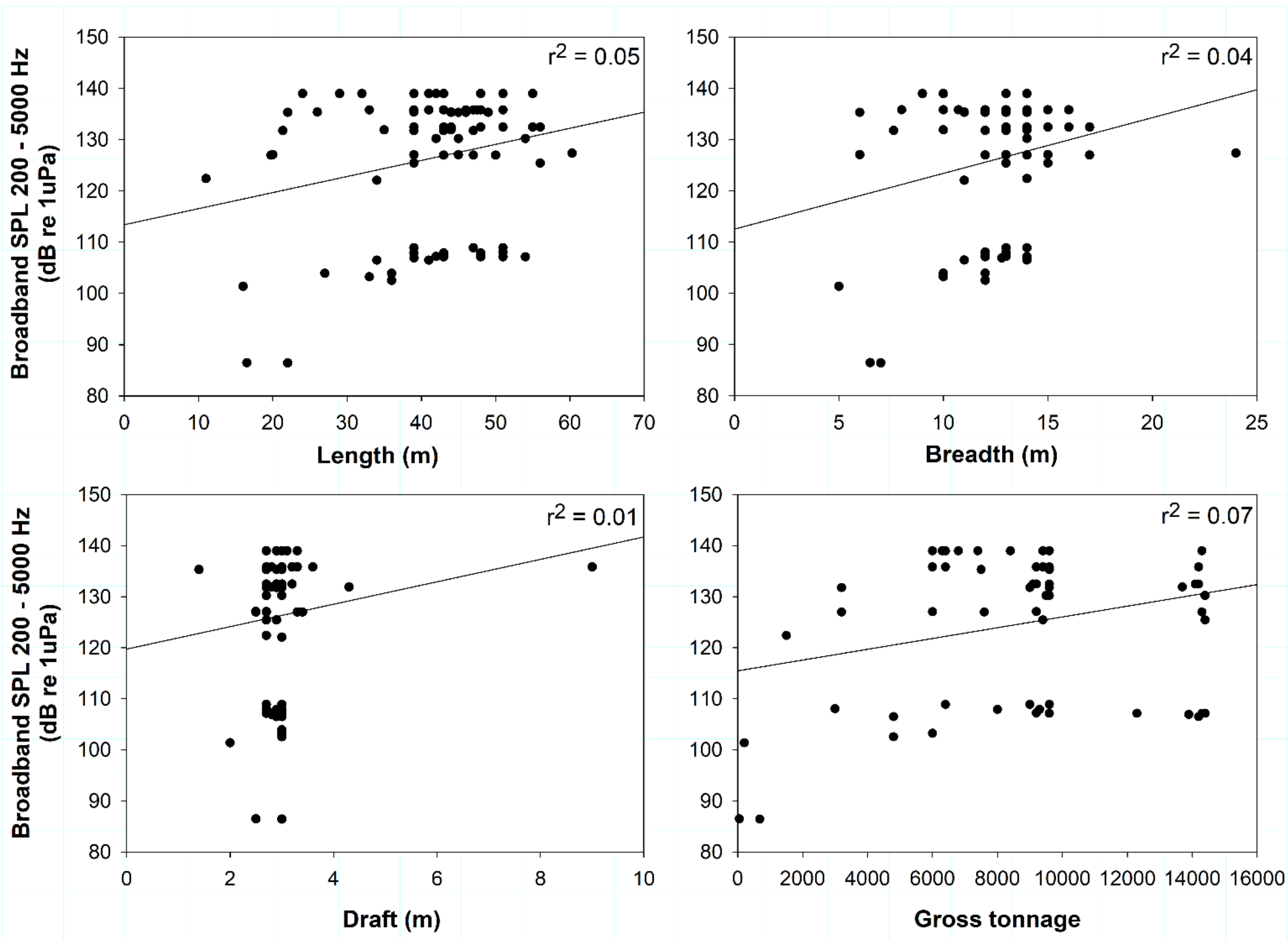


Figure 38: Comparing metrics for commercial vessels (taken from the shipping log at Lock and Dam 5) against the broadband SPL between 200 – 5,000 Hz.

There was no significant correlation between the broadband SPL between 200 – 5,000 Hz and length, breadth, draft or gross tonnage of the vessels over the deployment period (Figure 38). The speed as the vessel approached the lock chamber may explain the bimodal distribution of the SPL data (Figure 38). However, speeds were not able to be interpolated from AIS (automatic identification ship tracking data) for each transit owing to quick decrease and increase of speed as a vessel enters/exits the lock chamber.

Analyzing only one individual vessel at a time did show an increase in broadband SPL between 200 – 5,000 Hz as gross tonnage increased (Figure 39). A similar trend was seen for every passing commercial vessel on record.

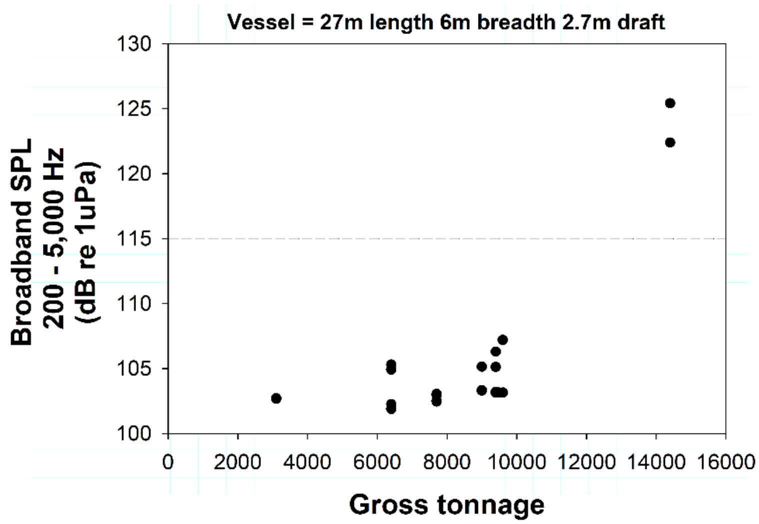


Figure 39: Broadband SPL for one individual commercial vessel (length 27 m, breadth 6 m, draft 2.7 m) that passed through Lock and Dam 5 carrying different gross tonnages.

5.9 Soundscape of Lock and Dam 5 Summary

The following summary is broken down to answer the questions put forth in section 5.1 of this technical report:

1) Background sound level (RMS SPL) changed over time according to the season (Section 5.2), with a significant difference between summer, spring and fall recordings. Therefore, any acoustic deterrent would need to account for the increase of approximately 3 dB during summer.
2) Background sound level (RMS SPL) was significantly different between listening stations. The highest SPLs were recorded on the outside of the lock chamber, near the dam (H3), followed by inside the lock chamber (H1-H2) and the lock approach (H4).
3) Background sound level (broadband SPL) significantly increased following the dam gates being raised by approximately 10 dB (Section 5.3). Any acoustic deterrent would need to account for this increase as it could make acoustic deterrents less effective owing to masking of the acoustic deterrent by background sound.
4) Sound level (broadband SPL) was highest between 100 – 1,000 Hz at all listening stations (Section 5.2). To have a greater difference between background SPL and acoustic deterrent SPL it would be suggested to use an acoustic deterrent emitting frequencies > 1,000 Hz.

5) Section 5.6 - The average daily number of transits by commercial vessels was 8, which was independent of the day of the week or season. Passages occurred any time of the day or night with average passage time of 53 ± 29 minutes (defined as the time from first set of gates being opened, upstream or downstream, to the last set of gates being closed).

   Gates were often opened well before vessels were in the vicinity of the gates. These extended openings would require acoustic deterrents to be operational throughout the duration of the open downstream gates.

   The average daily number of recreational vessels was 6 on weekday and 14 at the weekend, with no statistically significant seasonal difference during hydrophone deployment. Recreational vessels transited individually, without other recreational or commercial vessels. Recreational vessels had a passage time of 12 ± 7 minutes, so acoustic deterrents could be active for a shorter duration than during commercial passages. Recreational passages also only occurred during the daytime between 6 am and 9 pm (CST).

6) The total daily number of lock passages did not significantly alter the daily average SPL recorded (Section 5.7). However, individual vessel passages did significantly alter background SPL by up to 50 dB. Machinery at the gates and inside the lock chamber also significantly increased the SPL recorded by hydrophones within the lock chamber (Section 5.7). Hydrophones outside the lock chamber (H3, H4) were not affected by machinery noise.

7) Sound level significantly increased in the lock approach (H4) and lock chamber (H1, H2) during both recreational and commercial vessel passages (Section 5.8). The significant increase occurred within the hearing range of invasive carp and the frequency range of a proposed acoustic deterrent. Therefore, any acoustic deterrent would need to account for the increased sound during a vessel passage when the lock is susceptible to fish passage.

8) Sound level was not significantly affected by the length, breadth, draft or gross tonnage of the vessel passing through the lock (Section 5.8). However, when an individual vessel with multiple passages was analysed there was an increase in the broadband SPL recorded and gross tonnage (Section 5.8). National and international recommendations to reduce the sound level produced by vessels underwater include changing propeller design and reducing vessel speeds (McKenna *et al.*, 2013).

6. Linking carp hearing to Lock and Dam 5 soundscape

Increasing inputs of anthropogenic (i.e. man-made) sound have been suggested to cause homogenisation or fragmentation of the soundscape. Acoustic deterrents may also affect non-target species if played continuously or at key times, such as during migrations or mating season. In this section, whether current sound levels at Lock and Dam 5 could be detected by bigheaded carp will be determined, and the effect of noise exposure on hearing sensitivity discussed.

6.1 Methodology

To determine the difference in sound, during and between vessel transits and its relationship to bigheaded carp hearing, the relative dB was estimated using the broadband SPL (200 – 5,000 Hz) from the hydrophone recordings (Section 5) and hearing sensitivity (sound pressure) measured by (Vetter *et al.*, 2018) for bighead and silver carp (Section 2.2).

6.2 Results

At Lock and Dam 5, the sound level was higher between 200 – 1,000 Hz (<150 dB re 1μPa) than > 1,000 Hz (<130 dB re 1μPa) when both a commercial or recreational vessel passed through the lock chamber (Figure 40). The sound level was also higher at H1 inside the lock chamber compared to H4 on the lock approach, especially for frequencies < 1,000 Hz.

For bighead carp, the relative SPL exceeded 0 dB, suggesting sound can be detected, at frequencies < 1,500 Hz (inside red box Figure 41) when the lock was being used for vessel passages (commercial and recreational) compared to only at frequencies < 500 Hz when a vessel passage was not occurring (Figure 41).

For silver carp, the relative SPL exceeded 0 dB, suggesting sound can be detected, at frequencies < 2,500 Hz (inside red box Figure 42) when the lock was being used for vessel passages (commercial and recreational) compared to only at frequencies < 1,000 Hz when a vessel passage was not occurring (Figure 42), reflecting the greater hearing sensitivity of silver compared to bighead carp (Vetter *et al.*, 2018).

Both carp species are capable of detecting vessel passages at frequencies < 2,000 Hz (Figures 41, 42). Therefore, perhaps to have a greater difference between background SPL and acoustic deterrent SPL it would be suggested to use frequencies > 1,000 Hz for an acoustic deterrent signal.

The same technique can be applied to determine what frequencies, native, non-target species can detect and subsequently, at what sound levels and frequencies emitted from acoustic deterrents they can potentially be impacted. However, very few MN native fishes have had their hearing frequencies and thresholds quantified (Section 2.3).

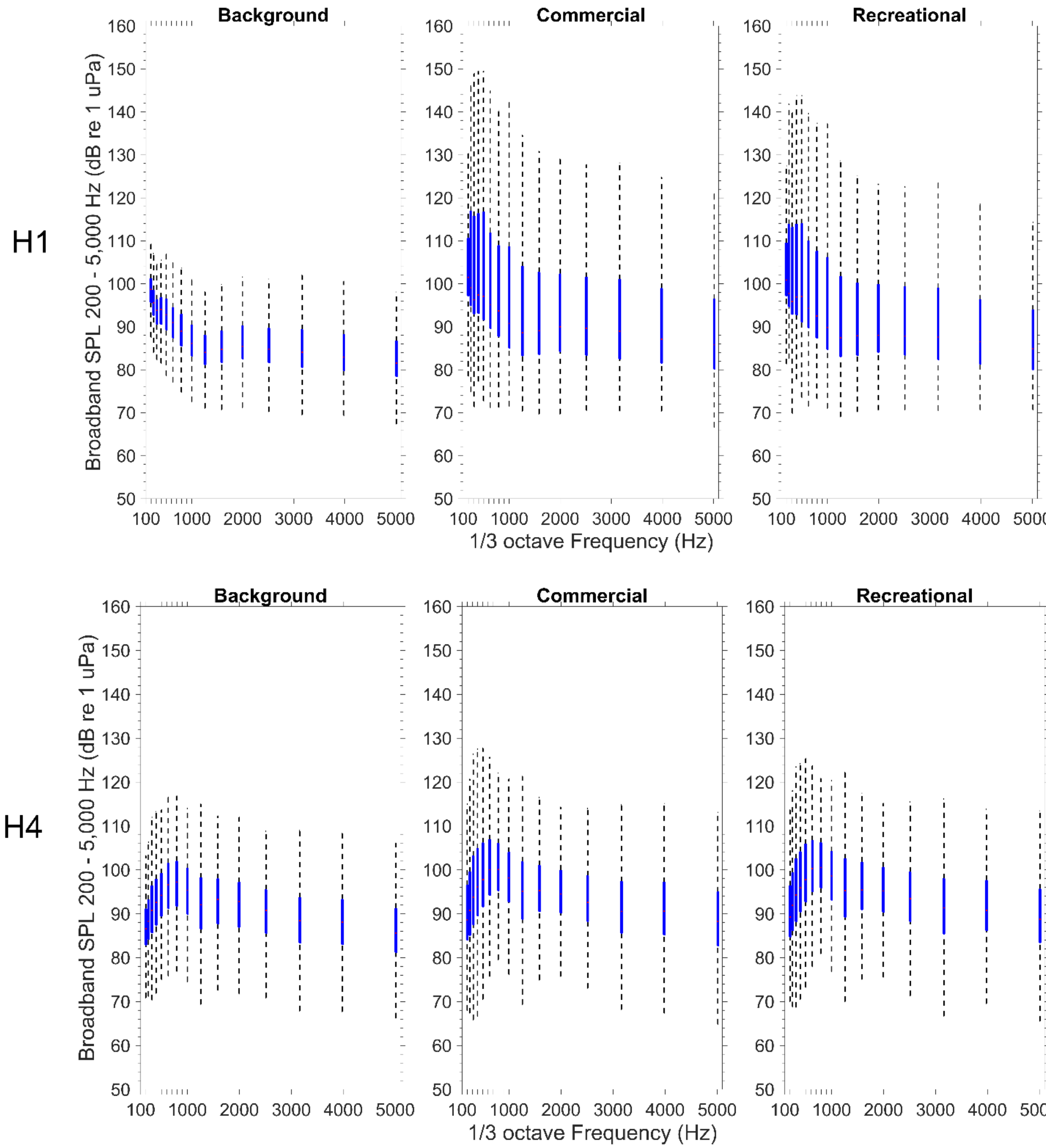


Figure 40: Boxplots of broadband SPL (dB re 1µPa) between 100 – 5,000 Hz at Lock and Dam 5 during background (no vessel passage) (left), commercial vessel passage (middle) and recreational vessel passage (right). Top three figures are taken from H1 inside the lock chamber and bottom three figures are taken from H4 outside the lock chamber.

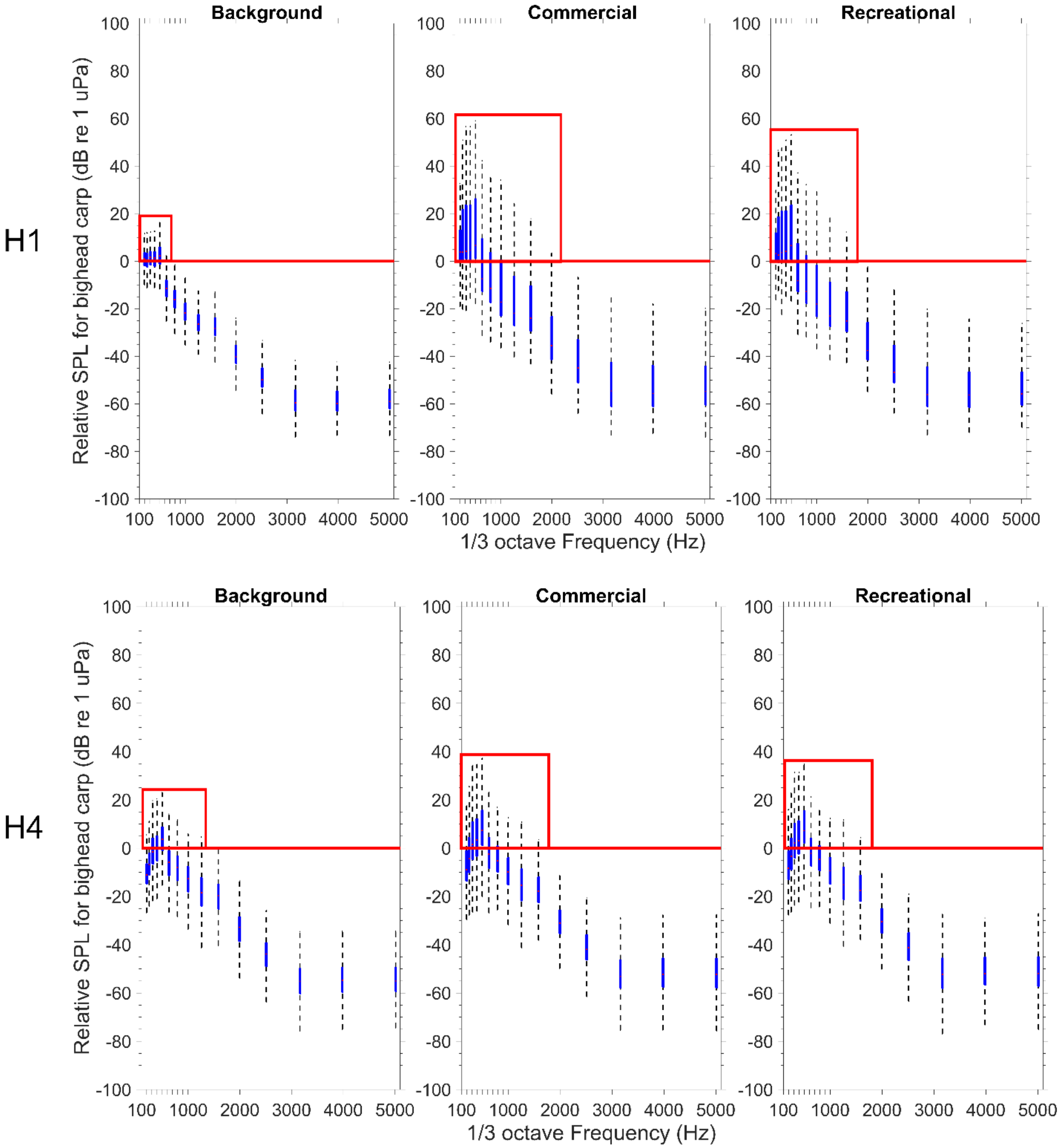


Figure 41: Relative SPL (dB re 1µPa) for bighead carp between 100 – 5,000 Hz at Lock and Dam 5 during background (no vessel passage) (left), commercial vessel passage (middle) and recreational vessel passage (right). Top three figures are taken from H1 inside the lock chamber and bottom three figures are taken from H4 outside the lock chamber. Bighead carp hearing thresholds taken from (Vetter *et al.*, 2018). Above red line at 0 dB shows frequencies sound could be detected by bigheaded carp.

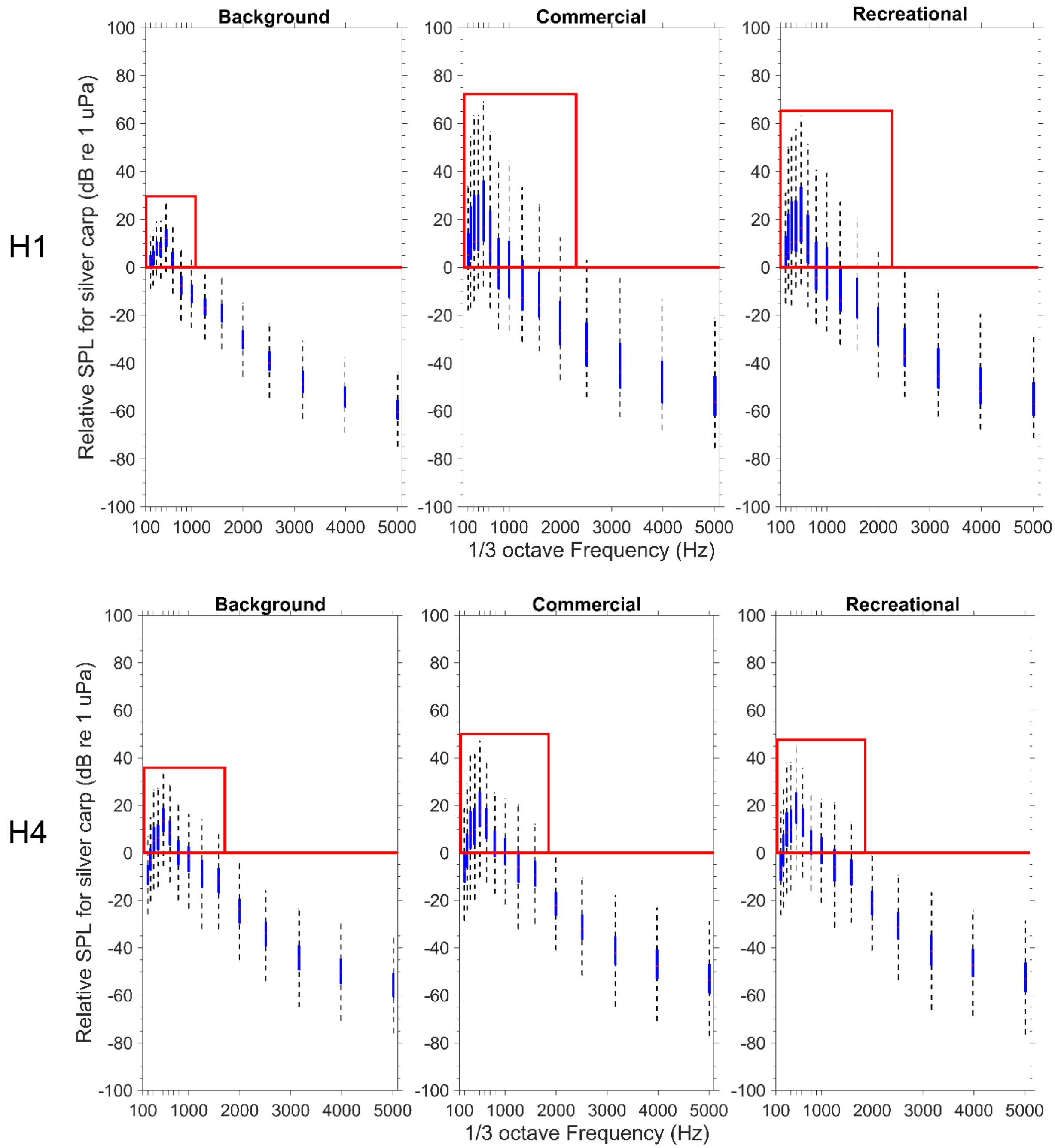


Figure 42: Relative SPL (dB re 1μPa) for silver carp between 100 – 5,000 Hz at Lock and Dam 5 during background (no vessel passage) (left), commercial vessel passage (middle) and recreational vessel passage (right). Top three figures are taken from H1 inside the lock chamber and bottom three figures are taken from H4 outside the lock chamber. Bighead carp hearing thresholds taken from (Vetter *et al.*, 2018). Above red line at 0 dB shows frequencies sound could be detected by silver carp.

6.3 Effect of noise on hearing sensitivity of fishes

Fish have exhibited both negative and positive responses to sound, yet there is still a paucity of data on the effects of anthropogenic sound especially in regard to acoustic deterrents on fish hearing and behavior. For an acoustic deterrent to be effective, the sound pressure level emitted needs to be above the hearing sensitivity for any target species, yet not at too high a level to be detrimental to fish hearing.

Temporary threshold shift (TTS) occurs when the hair cells of the inner ear are fatigued, yielding an increase in auditory threshold. The auditory evoked potential technique has been useful to study TTS because fish can be measured repeatedly to investigate the degree and recovery over relatively short time periods. Different noise types have been used including background noise, broadband (white) noise and pure tones (Ladich and Fay, 2013).

Recent experiments determined the hearing sensitivity of bigheaded carps before and after exposure to high intensity (SPL >150 dB re 1µPa, PAL >8 dB re 1 ms^{-2}) broadband sound (60 – 10,000 Hz), that matched the signal that had successfully been used as a deterrent for invasive carp (Murchy, 2017). Preliminary results suggest that silver and bighead carp experience TTS following 30 minute and 24 hour sound exposure (Nissen et al. under review). For both species and exposure periods, the largest magnitude TTS was observed between 400 – 2,000 Hz, suggesting acoustic deterrents using these frequencies have greater chance of causing hearing loss (Figure 43, 44).

Based on the field studies at Lock and Dam 5, carp are already receiving sound above their hearing range from vessel activity (Figures 41, 42). Throughout the deployment period at Lock and Dam 5 (fall 2017 – fall 2018), each recreational passage lasted 12 ± 7 minutes (mean ± SD), slightly below the 30 minute sound exposure conducted in the recent experiment, however, each commercial vessel passage lasted on average 53 ± 29 minutes (mean ± SD), exceeding sound exposure duration [Nissen *et al.* (in review)]. Therefore, during individual vessel passages if carp were present and did not swim away or were trapped in the lock or impinged under the barge's bows, they may suffer TTS. A change in hearing sensitivity, because of TTS, has implications for bigheaded carps because it reduces their ability to communicate or assess their environment. Subsequently, any acoustic deterrent will become less effective if fish suffering from TTS can no longer detect the sound and swim away.

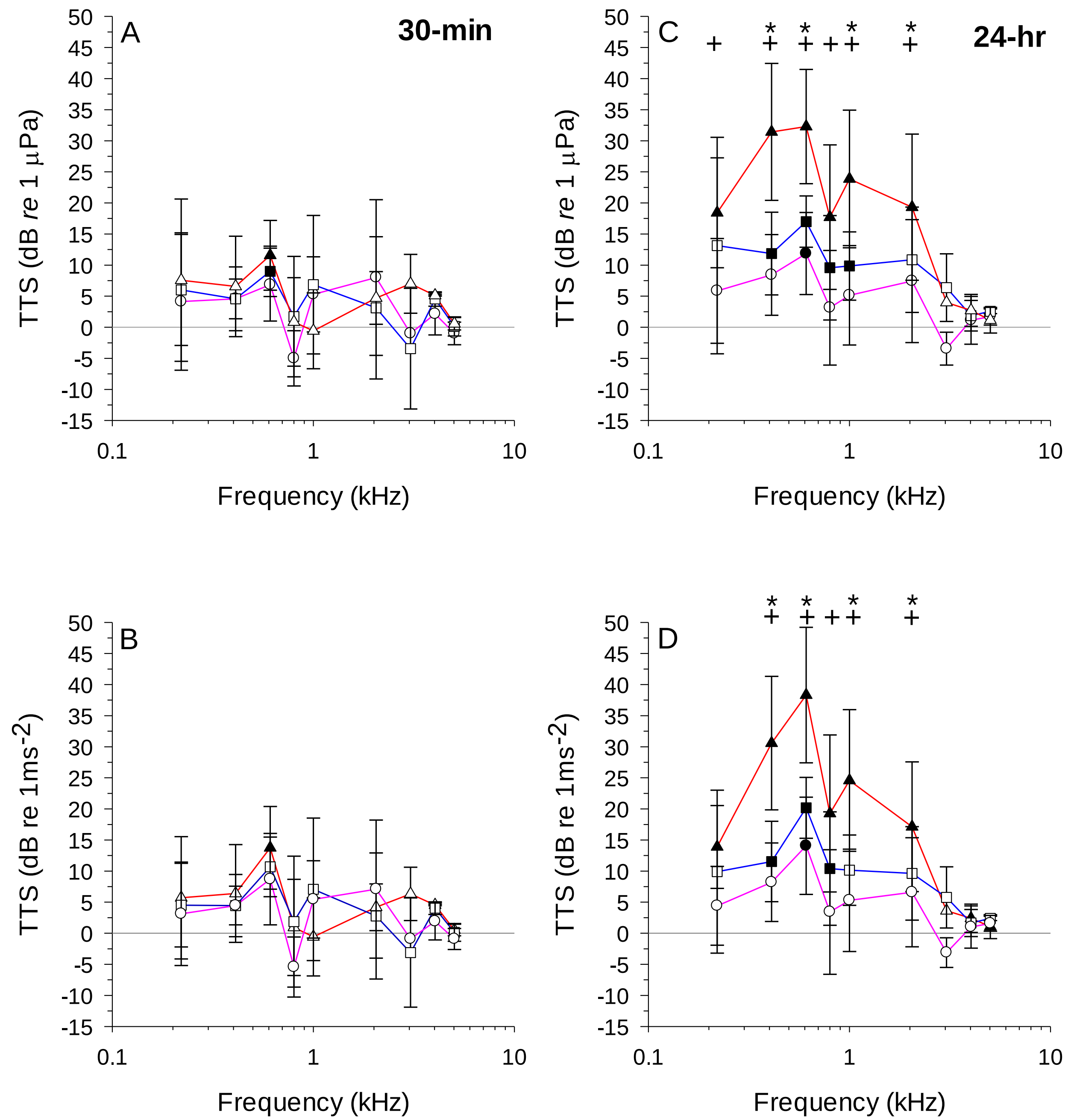


Figure 43: Silver carp mean auditory SPL (A, C) and PAL (B, D) threshold shifts following 30-min (A, B) and 24-hr (C, D) noise exposure and 0-hr (red triangle), 48-hr (blue square), and 96-hr (pink circle) recovery periods. Filled symbols indicate a significant difference (Holm-Šidák, $p<0.05$) from baseline thresholds (gray reference line). Asterisks indicate a significant difference (Holm-Šidák, $p<0.05$) between thresholds following 0-hr and 48-hr recovery periods. Crosses indicate a significant difference (Holm-Šidák, $p<0.05$) between thresholds following 0-hr and 96-hr recovery periods. [Taken from Nissen et al. 2018 (in review)].

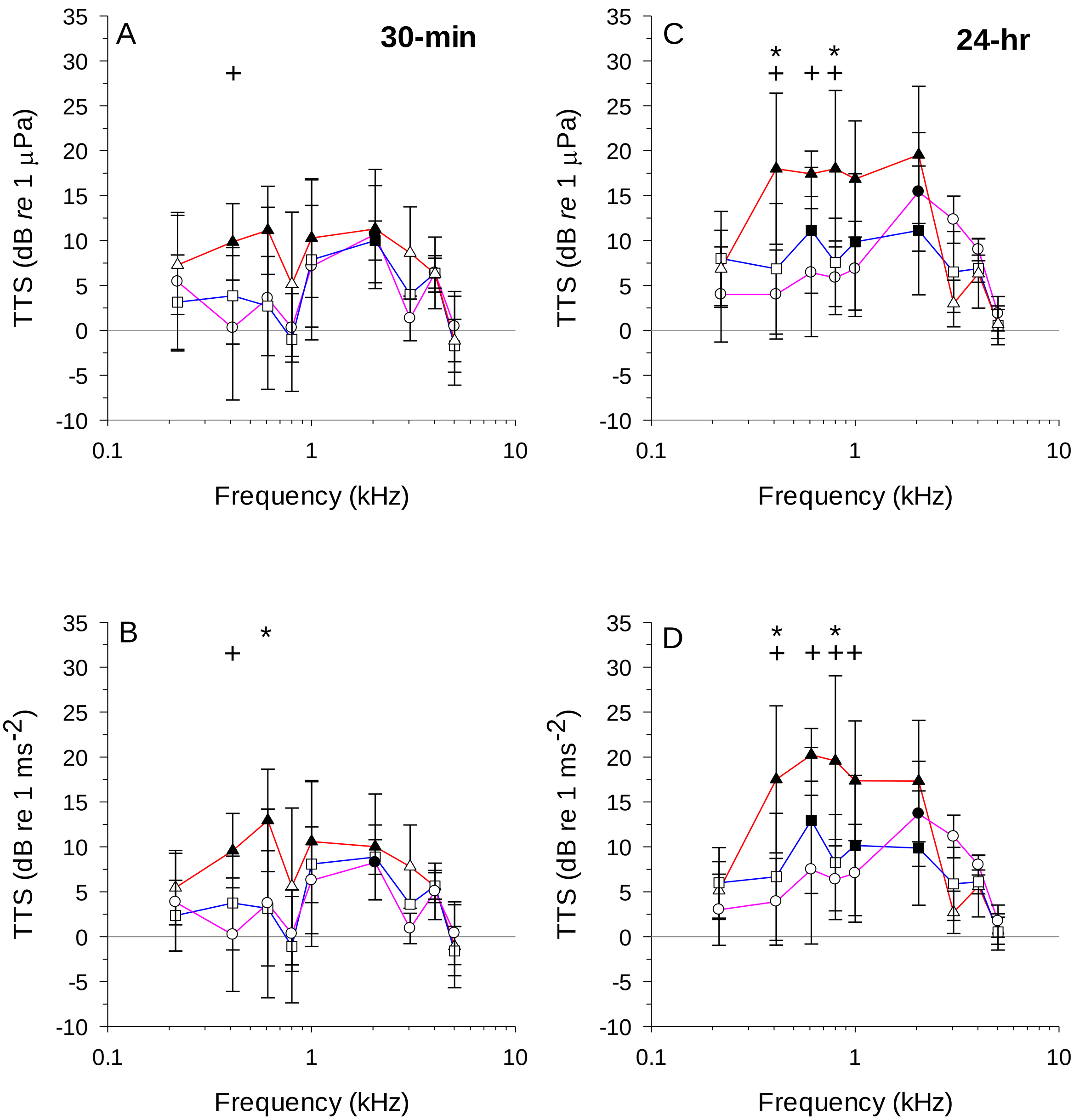


Figure 44: Bighead carp mean auditory SPL (A, C) and PAL (B, D) threshold shifts following 30-min (A, B) and 24-hr (C, D) noise exposure measured after 0-hr (red triangle), 48-hr (blue square), and 96-hr (pink circle) recovery periods. Filled symbols indicate a significant difference (Holm-Šidák, p<0.05) from baseline thresholds (gray reference line). Asterisks indicate a significant difference (Holm-Šidák, p<0.05) between thresholds following 0-hr and 48-hr recovery periods. Crosses indicate a significant difference (Holm-Šidák, p<0.05) between thresholds following 0-hr and 96-hr recovery periods. [Taken from Nissen et al. 2018 (in review)].

Native fishes have also been found to undergo TTS. For example, fathead minnows (*Pimephales promelas*) were exposed to broadband noise (300 – 4,000 Hz) at 142 dB re 1µPa for 1 – 24 hours. Following exposure, fish showed significantly higher threshold compared to the control baseline sensitivity (Figure 45) (Scholik and Yan, 2001). In comparison, when bluegill (*Lepomis macrochirus*) were exposed to the same broadband noise (300 – 4,000 Hz) at 142 dB re 1µPa for 24 hours, there was minimal effect on hearing sensitivity (Scholik and Yan, 2002b).

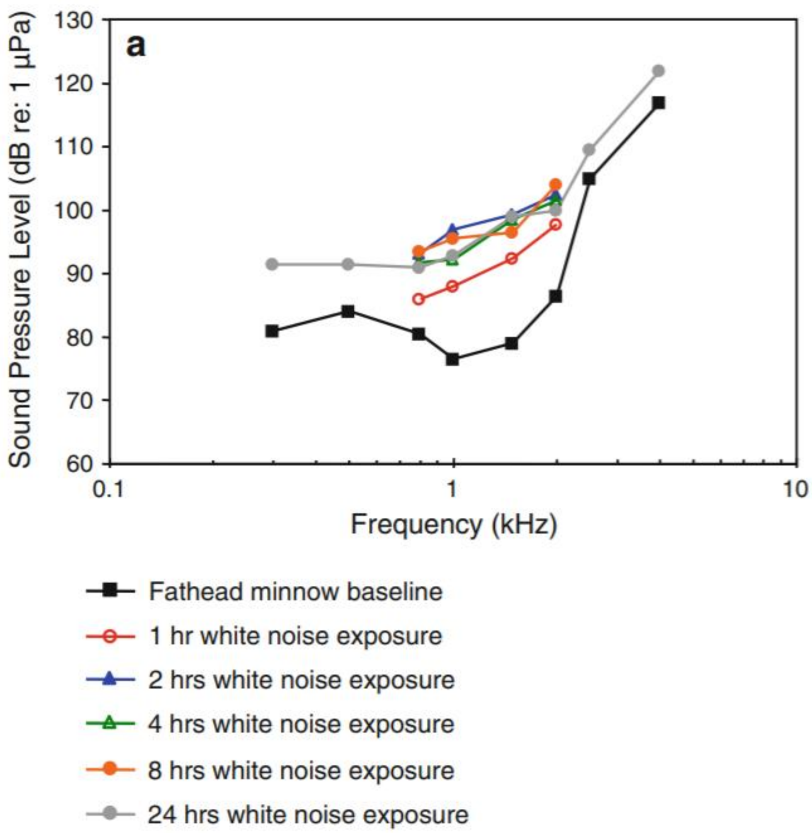


Figure 45: Hearing sensitivity of fathead minnow *Pimephales promelas* before and after exposure to broadband noise at 142 dB re 1µPa. [Taken from (Scholik and Yan, 2002a)].

Whether fish would remain near high intensity sound fields long enough to cause TTS remains to be determined. At a lock system, high intensity sounds could be produced by vessel passages, machinery and proposed acoustic deterrent. The duration of sound exposure from vessel passages and machinery depends on the number and type of vessel passages each day. Whereas duration of sound exposure from an acoustic deterrent depends on the deterrent design and installation parameters. If an acoustic deterrent is switched on prior to a vessel passage, sound exposure would last from minutes to hours depending on the vessel type, gross tonnage the vessel is carrying and vessel speed. Another option is for any proposed acoustic deterrent to be set to loop continuously, yet duration of TTS is correlated to exposure duration (Nissen et al. under review).

Much of the research on hearing sensitivity has been performed at sound pressure levels well below what is more than likely needed in the field. This is due to health and safety concerns that continual long duration loud exposure in human occupied laboratories can cause harm to researchers. Typically, laboratory speakers have an upper limit of 150 dB and higher sound pressure levels can make the recording electrodes unstable to record AEPs. Although approximately 97% of the sound is attenuated at the air/water interface, when sound pressure levels are increased above 150 dB, depending on the depth of the source (acoustic deterrent), sound can be transmitted into the air. Loud acoustic deterrents may therefore impact land and water based personnel at lock and dams. Previous attempts at constructing an acoustic deterrent at Lock and Dam 8 deployed speakers that generated over 200 dB re 1µPa (per comms. Sorensen) and FGS has indicated that sound pressure levels in its bioacoustic fish fence (BAFF) can reach 170 dB re 1µPa. Laboratory studies have yet to approach sound pressure levels exceeding 150 dB re 1µPa, meaning the effect on both aquatic and terrestrial animals is unknown. However, as hearing damage is correlated with both sound pressure levels and duration, it is expected that brief exposure at high intensity sound levels may cause greater damage than longer exposure at moderate intensities.

Furthermore, limited research has been conducted on the recovery of carp hearing following TTS. In other species, it has been found that once source of TTS ceases, normal hearing sensitivity returns over time as inner ear hair cells can be repaired or replaced. For example, goldfish took between 3 - 14 days to fully recover to control hearing sensitivity after exposure to 21 days of aquaculture noise (170 dB re 1µPa 100 – 10,000 Hz) (Smith *et al.*, 2004). In another study, goldfish hearing threshold returned to baseline levels within 3 days, whereas catfish (*Ictalurus punctatus*) experienced greater and prolonged TTS that remained above baseline levels for over 14 days after exposure. These experiments highlight that the recovery of TTS is both species specific and depends on the sound exposure level. Therefore, it is important to study the effect on bighead and silver carp with respect to the sound exposure level proposed for acoustic deterrents (>150 dB re 1µPa). Hair cells of the inner ear of bighead and silver carp exposed to 150 dB re 1µPa broadband sound are currently being examined for hearing damage and subsequent repair following recovery periods (24 - 96 hours). This work is being carried out at Western Kentucky University in Dr. Michael Smith's laboratory.

The chances of TTS occurring also increases the higher the sound level and the longer the duration of the source (Hastings *et al.*, 1996) with repeated exposure to TTS expected to result in permanent threshold shift (PTS). PTS is a consequence of the death of the sensory hair cells in the ear, damage to the innervating auditory nerve fibres or damage to other tissues in the auditory pathways, such as the swim bladder. If PTS occurs near an acoustic deterrent, it would be expected that the fish would no longer respond and would swim pass the barrier. Unlike mammals, teleost fish can regenerate sensory hair cells however, they require extended time to recover. Most terrestrial mammals including humans cannot regenerate their hair cells and care must be taken to insure that potentially damaging sound is not transmitted into the air.

In addition to fishes, the effects of acoustic deterrents, on other aquatic life must be considered. Over the last 25 years that Fish Guidance Systems has been installing systems they have not found any adverse impacts to birds or mammals (per comms. Lambert) however, there has been no published papers or third party evaluation of these claims. Quantitative behavioral and physiological research on the effect of exposure to acoustic deterrents on both target and non-target fish, birds or mammals (Figures 9,10) around the proposed location, Lock and Dam 5, is essential before acoustic deterrents can be implemented.

7. <u>Swimming ability of target fish</u>

For an acoustic deterrent be effective, the stimulus must be strong enough to repel fish at a range where they are not at risk of being involuntarily drawn in by the strength of the water current, due to insufficient swimming ability. Equally, it must be weak enough to avoid the risk of injuring the fish or removing non-target fish completely from the vicinity, which may impact commercial fishing or alter natural patterns of fish migration in rivers.

In terms of invasive bigheaded carp movement, there are the 29 lock and dam systems in the Upper Mississippi River which create a physical barrier to fish movement and provide excellent candidates for the deployment of acoustic deterrents. When the tainter gates are in the closed position the most logical egress would be through the lock chamber absent of any wetlands where carp can circumnavigate the lock and dam complex. Therefore, the lock chamber is the logical implementation point for acoustic deterrents. Although, if the tainter gates are raised, it raises the possibility that fish could swim through the dam complex. Lock and dams have different rates and frequencies of when these gates are open. Lock and Dam 5 is particularly suitable for an acoustic deterrent as the dams are rarely raised to create free river conditions and therefore the major egress would be fish migration through the lock chamber. Additionally, the berm on the Wisconsin side of the river appears to be of sufficient height to prevent overflow in all but the most catastrophic floods.

However, there are several issues that preclude recommending an acoustic barrier at LD5 and the following sections will go into each of the following in more detail:

- Swimming capability of bigheaded carp in free river conditions
- Potential for carp to swim through the dam gates
- Potential for carp to jump over the barrier
- Potential for carp to swim through flooded areas
- Potential for carp to swim through culverts and other bypass channels

7.1 Swimming ability of carp

Occasionally, when the gates have to be raised there is concern invasive carp may be able to pass under the dam despite high flow rates. Information on carp swimming is therefore needed to evaluate whether individuals can surpass high flow rates caused by open dam conditions.

In general, body shape, size and developmental stage are key factors in determining swimming capability, with larger fish having a greater swimming ability (Beamish 1978). Fast swimming fish tend to have streamline, torpedo shaped (fusiform) bodies, such as tuna and salmon. The maximum burst speed a fish can achieve amounts to approximately 10 - 12 fish lengths per second for salmonids, cyprinids and percids (Jens, 1997). However, the performance capability of the fish weakens with prolonged durations (Bainbridge, 1960) and the sustained swimming speed of cyprinids, percids and salmonids is reduced to 5 body lengths per second (Jens, 1997). Conversely, larval stage and juveniles of some species, while capable of active swimming often have poor swimming ability and rely upon tidal currents for transportation (Haro and Castro-Santos, 2012). Therefore, in strong or accelerating water velocity fields, the lack of swimming ability, or swimming fatigue in small fish may prevent it from responding to a stimulus even if it attempts to do so (DWA., 2005).

Both species of invasive carp have fusiform flexible bodies, narrow peduncles and moderately high forked caudal fins (Figure 1), which suggests they are capable of extended high-speed movements. During acoustic telemetry studies (in the carp's native range of China), sub - adult carp [360 – 460 mm (TL)] were found to be able to exceed 3 m/s, although overall swimming speed averaged < 0.35 m/s (Konagaya and Cai, 1987; 1989) and juvenile carp (93.3 mm TL ± 19.5 SD) were displaced by water velocities averaging 0.25 m/s ± 3.8 SD (Layher and Ralston, 1997).

The first laboratory study to assess the swimming ability of invasive carp in the United States was conducted by Hoover et al. in 2012. To quantify swimming performance the authors investigated rheotaxis (the percentage of fish that orientated head first into flow), endurance (time to fatigue at test water velocity) and behavior (modes of locomotion exhibited by the fish) by placing fish (33 – 334 mm TL) in a tank (juveniles in a 100 L Blazka swim tunnel and subadults in a 1200 L Brett swim tunnel). The main findings were that ~ 90% of fish were rheotaxic and demonstrated a maximum sustained swim speed ranging from 0.2 – 0.8 m/s depending on size. Burst swimming speed for bighead carp was also 0.4 m/s faster than silver carp in sub-adults (Table 8). Bighead carp have a larger head, a wider body and a shorter ventral keel than silver carp. However, they also have larger pectoral fins as adults (Soin and Sukhanova, 1972), which may compensate for the greater drag experienced by their larger bodies (Schofield *et al.*, 2005; Hoover *et al.*, 2016b). The major pitfall of this laboratory experiment was that fish were collected from the field or at aquaculture facilities by seining and transported to the laboratory which may have caused stress or damage to the animals. Therefore, to minimize transport and the need for acclimatization, wild caught bighead and silver carp, ranging from 560 – 920 mm TL, 1.7 – 8.3 kg were tested for endurance swimming using a mobile single velocity swim tunnel (Hoover *et al.*, 2016a) that could be transported to the field. Thirteen silver carp and one bighead carp were tested using this approach. For silver carp, prolonged swimming (0.63 – 4.63 min) averaged 1.09 m/s and burst swimming (0.05 – 0.47 min) averaged 1.37 m/s. The maximum predicted burst speed was stated as 1.9 body lengths per second (BLS) or 1.51 m/s. For the bighead carp tested, the endurance was comparable, but slightly lower than that of silver carp (2.62 vs 4.63 minutes)(Hoover *et al.*, 2016a). This study was positive in allowing field evaluation of endurance swimming to provide a benchmark for invasive carp swimming speed capabilities. However, it should not be taken to represent the maximum swimming speed of the fishes. Recently captured fish should not be used for maximum swim speed studies due to the stress involved in capturing and handling the fish, which would lead to increased cortisol levels and muscle fatigue. The integument of bigheaded carp is also easily damaged by handling resulting in haemorrhaging and damage to the mucous coat, which will decrease hydrodynamics in swimming fish. Thus, this data should be considered conservative and represent swimming speeds that these fish can sustain.

Figure 46: The mobile swim tunnel used to evaluate bighead and silver carp swimming endurance at a single velocity. Inflow was located on the left side and outflow was located on the right side with a collimator grid blocking the outflow entrance. [Taken from (Hoover *et al.*, 2016a)].

Table 8: Summary of results of the swimming ability of bighead and silver carp from a laboratory. [Table adapted from (Hoover *et al.*, 2012) and field experiment (Hoover *et al.*, 2016a)].

		Sustained swimming speed 200 min (m/s)		**Prolonged swimming speed 1 min (m/s)**		**Burst swimming speed 0.1 min (m/s)**	
		Bighead carp	**Silver carp**	**Bighead carp**	**Silver carp**	**Bighead carp**	**Silver carp**
Laboratory	**Small juveniles***	0.20	n/a	0.34	n/a	0.56	n/a
	Large juveniles**	0.60	0.60	0.64	0.62	0.86	0.77
	Sub-adults***	0.80	0.50	1.10	0.73	1.66	1.28
Field	**Adults******	n/a	n/a	n/a	1.09 – 1.23	n/a	1.37 – 1.51

*Small juveniles range was 36 – 69 mm for bighead carp (n = 56)
**Large juveniles range was 72 – 106 mm for bighead (n = 32) and 85 – 116 mm for silver carp (n = 33)
***Sub-adults range was 250 – 334 mm for bighead (n = 48) and 141 – 288 mm for silver carp (n = 45)
**** Adult range was 560 – 920 mm for bighead (n = 1) and silver carp (n = 13)

Table 9: Comparison of bighead and silver carp swimming speeds to other native fishes found in the Upper Mississippi River Basin [Table adapted from (Peake *et al.*, 1997; Peake *et al.*, 2000; Hoover *et al.*, 2017)].

Fish species	Reference	Sustained swimming speed 200 min (m/s)	Prolonged swimming speed 1 min (m/s)	Burst swimming speed 0.1 min (m/s)
Bighead carp	(Hoover *et al.*, 2017)	0.20 – 0.80	0.34 – 1.10	0.56 – 1.66
Silver carp	(Hoover *et al.*, 2017)	0.50 – 0.60	0.62 – 1.23	0.77 – 1.51
Lake sturgeon	(Peake *et al.*, 1997)	0.20 - 030	0.10 – 0.80	0.50 – 1.80
Walleye	(Peake *et al.*, 2000)	0.30 – 0.73	0.43 – 1.14	1.60 – 2.60

Comparing the swimming capability of invasive carp to native fishes found in the Upper Mississippi River Basin showed that bighead and silver carp swimming speed exceeded lake sturgeon (*Acipenser fulvescens*) and walleye (*Stizostedion vitreum*) for sustained and prolonged swimming (Peake *et al.*, 1997; Peake *et al.*, 2000) (Table 9). However, burst swimming speeds documented for carp using the flume tunnel method were very low in comparison to other fusiform fishes, such as salmon (10 BLS) (Videler and Wardle, 1991a), so their ability to pass a man-made structure remains uncertain. For the swim tunnel method, the low swimming speeds recorded may be explained by the flume tunnel pitfalls:

1) The fish tested were of a ranging size and weight. The author stated that to analyze burst and gliding, a technique used by some pelagic fishes to increase endurance, is virtually impossible for a large fish confined in a swim tunnel (Hoover *et al.*, 2016b).
2) Water inside the tank was warm (>26˚C) owing to the time of testing (24 – 26 September). Water temperature at Lock and Dam 5 (Section 5.2) only exceeded 25˚C during August and September 2018. The swimming ability of fishes has been found to differ according to the environmental temperature, therefore it would be suggested that the swimming ability of bighead and silver carp be tested in cooler waters.
3) Riverine water where the individual fish originated from was hypoxic which could have impacted fish physiology. Despite the fact water in the tank was regulating aerated to maintain normoxia, it could be suggested that fish used in the experiment were not of good body condition owing to exposure to hypoxic conditions prior to testing.
4) Temperature, pH, turbidity and dissolved oxygen varied during the swimming tests according to time of day. Any future swimming tests should aim to minimize differences in environmental variables to prevent any confounding factors in the results.

5) Swimming performance is influenced by a complex suite of factors including reproductive condition and prior exposure to flow (Beamish, 1978; Videler and Wardle, 1991b). Yet, after experiments were conducted, the fish were released so the age and sex of the tested fish remained unknown. In future studies a proportion of the fish would need to be evaluated for age and sex.

7.2 Potential for carp to swim through dam gates

Dams already appear to impede upstream passage of invasive carp by producing high velocities and potentially harmful turbulence immediately downstream of the gates. Taking a swimming speed of 1.00 TL/s for bighead and 1.25 TL/s for silver carp, Zielinski *et al.* 2018 modelled whether individual fish would be able to swim through the dam. The model simulated fish paths based on a rules-set aimed at fish swimming as far upstream as possible before complete exhaustion by selecting the path of least fatigue. The model also generated fish with unique swimming performance metrics and total length based off both laboratory and field measurements. Information about behavioral tendencies was absent because while both environmental stimuli and physiological traits of certain species are well understood in laboratory studies; fish behavior in situ is inherently difficult to obtain and unavailable for invasive carp.

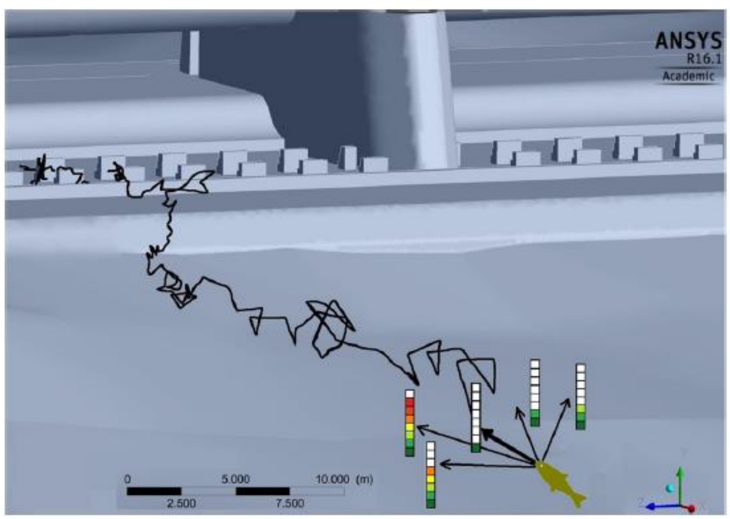


Figure 47: Schematic of a fish placed into the model. Vertical bars indicate relative fatigue related to swimming to each neighbouring noise, with the fish selecting the lowest fatigue path (bold arrow). [Taken from (Zielinski *et al.*, 2018)].

The advanced computational fluid dynamics (CFD) model of the velocity fields in and around dam gates also allowed recommendations to be made to the USACE about gate position to optimize velocities field to stop carp upstream movement, minimize scour and allow lake sturgeon passage (Zielinski *et al.*, 2018). The USACE confirmed that their office is considering all recommendations. The alterations to gate operating procedures could be utilized at Lock and Dam 5 to also reduce passage of invasive carp, at least at certain times of the year. Geometrical features at Lock and Dam 8 (where the CFD model was based) are similar to Lock and Dam 5 (Table 10). Such modifications could be implemented quickly, at little to no cost, and seemingly would not interfere with the navigational function of the lock and dam (Zielinski *et al.*, 2018). Regardless, there is always the possibility for fish to pass a lock and dam by swimming through the navigational lock chamber, hence why behavioral deterrents, such as sound projectors as being considered. These swimming speeds are also much less than reported for burst swimming of jumping carp. Salmon navigate cascading waterfalls by repeated leaping which produces less drag and allows them to cover greater distance in rapidly flowing water. It is possible that silver carp use this strategy which will be discussed in the next section.

Table 10: Comparison between Lock and Dam 8 (where the CFD model was based) and 5 (where acoustic deterrents are proposed for this study). Information was gathered from USACE databases.

Feature	Lock and Dam 8	Lock and Dam 5
Pool Elevation	631 ft	660 ft
Length of moveable dam	934.5 ft	493.5 m (1619 ft)
Size of tainter gates	35 x 15 ft	35 ft x 15 ft
Number of tainter gates	10	28
Size of roller gates	80 ft x 20 ft	60 ft x 20 ft
Number of roller gates	5	6

7.3 Potential for carp to jump over acoustic barrier

The goal of locating acoustic deterrents outside the lock chamber is to elicit a desired response from the target fish, in this case to change direction. However, silver carp are well known to exhibit jumping behavior and jump over barriers such as nets very easily. Therefore, there is warranted concern that if an acoustic deterrent, such as an ensonified bubble curtain is deployed, the silver carp will simply jump over the system rather than changing direction.

Recent research showed that broadband sound (60 – 10,000 Hz) recorded from an outboard motor (100 hp at 32 km/hr) or played from speakers mounted on a slow moving boat (3 – 6 km/hr) elicits jumping behavior in wild fish (Vetter and Mensinger, 2016). This was the first study to show that wild silver carp response to sound independent of stimulation from moving watercraft. Sound pressure also appeared to influence the jumping pattern (Vetter *et al.*, 2015) played broadband sound at 150 dB re 1μPa (at the source) which did not elicit jumping, whereas the same stimulus played at 170 dB re 1μPa (3 m from the speaker) successfully elicited jumping (Vetter and Mensinger, 2016). This is the reported SPL for the BAFF and therefore contact with the bubble curtain may elicit jumping.

Table 11: Burst swim speed estimates measured from videography for silver carp jumping in four locations [Table adapted from (Parsons *et al.*, 2016)].

Location	n	Burst swim speed (m/s)	Speed (BLS)	Size (mean TL mm)
Wabash River	7	5.30 ± 0.61	8.16 ± 0.60	650 ± 28.1
Illinois River	5	8.12 ± 0.64	10.45 ± 1.45	777 ± 61.1
Middle Mississippi River	8	8.39	11.3	743
Upper Mississippi River	7	8.13	10.94	743

Whether the water flow through the dam could prevent jumping behavior also needs to be investigated. Using videography in the field, the burst speed of 27 jumping silver carp was estimated between 5.30 – 8.39 m/s, equivalent to 8.16 – 11.30 body lengths per second in four separate locations (Table 11). These swimming speeds are well above the burst speeds reported during swim tunnel experiments (Section 5.1), suggesting the use of a swim tunnel failed to maximize fish swim speed or the fish were compromised. These higher estimations therefore need to be factored into swimming models as fish may be able to alter their swimming through open tainter gates.

Additionally, the species was estimated to leap up to 2.24 m out of the water and cover a horizontal distance of 2.81 – 5.82 m (Parsons *et al.*, 2016). It was therefore suggested that silver carp jumping would be restricted by water velocities > 10 m/s and vertical drops > 3m. However, caution in the using the estimations was noted by the authors of this study, owing to how season, body condition, reproductive state, prior experiences of the fish and environmental conditions all influence physiological state and thus swimming speeds (Parsons *et al.*, 2016). The video was also recorded at 30 frames per second. Moving forward, high speed videography (up to 500 frames per second) could be used to quantify the jumping behavior of silver carp in both lab and field settings. In addition to direct estimates of burst swim speeds, measurements of angle, height and duration of any given leap at a high resolution could be used to determine an additional estimate of swimming speed.

7.4 Potential for carp to swim behind a vessel entering the lock chamber

Acoustic deterrents, such as ensonified bubble curtains, would seem less effective in a waterway that sustains the degree of commercial vessel traffic that Lock and Dam 5 receives. The level of sound produced by a transiting vessel can increase the background SPL by up to 50 dB, which could mask the sound produced by an acoustic deterrent and render it less effective. Additionally, because the position of the barrier is proposed where vessels enter the lock chamber, passing vessels will physically disrupt any bubble curtain. A continuous wall of bubbles from the substrate to surface is necessary for the bubble curtain to be effective as the bubbles contain the sound to a thin segment of the water column and any disruption to the bubbles would negate the effectiveness of the barrier. While the lock approach is offset from the main river flow, there is still the possibility of river currents or wind generated waves degrading the surface integrity of the curtain. Additionally, bow waves and vessel wakes will generate substantial surface current that may disperse the bubbles. Loaded barges, especially those with heavy gross tonnages, have significant draft and will disrupt the bubble curtain throughout the water column. There are already issues with entrainment of bigheaded carp in the bow region of barges and it is unlikely that once the curtain is disrupted by the first barge of a “train”, that the deterrent will be effective in dispersing these fish. Furthermore, barge trains are long and when multiple passages through the lock are required, a bubble curtain may be rendered ineffective for extended periods of time by barges docked in the approach channel awaiting passage. If the bubble curtain is moved out of this staging area, then it would be impacted by river conditions. Importantly, the use of bubble curtains in high vessel traffic areas has not been evaluated in the peer review literature. At a minimum, the sound field disruption caused by barge transit needs to be determined prior to deploying bubble curtains in the field.

7.5 Flooding and bypass channels

Invasive carp could potentially move upstream past a lock and dam structure via side tributaries or wetlands of the Mississippi River, particularly during or after a flooding event. The greatest flooding event in the historical record in Winona (where Lock and Dam 5 is located) occurred from mid-April to early-May in 1965. The crest from this flood reached 6.33 m (20.77 ft) and for 26 days the river flooding exceeded the moderate flood stage (> 4.57 m, >15 ft) (National Oceanic and Atmospheric Administration). Flooding occurred due to significant late season snowfall, and the succeeding snowmelt combined with heavy rainfall in early spring led to a rapid rise in water level in the Mississippi River (National Oceanic and Atmospheric Administration). This flooding increased tributary levels within the wetlands to the north of Lock and Dam 5. Other minor flooding events have occurred since 1965, with the most recent in September 2018 (Winona News), that would also increase potential carp habitat to in the wetlands bordering Lock and Dam 5. However, the dyke road along the Mississippi river from the dam towards Buffalo City, which borders the adjacent wetlands state park and is managed by USACE was not breached owing to its height over > 10m. Therefore, as no flooding event in recent history has breached the dyke road, Lock and Dam 5 does provide a sufficient bottleneck in at least the main channel of the river during high water events.

However, a potential bypass channel for invasive carp was identified during this study in the wetlands on the Wisconsin side of the river. There is a three-tunnel culvert to the north west of Lock and Dam 5 (Figure 49). While it is unlikely that water levels would be high enough that invasive carp would swim over the dyke road and enter the upstream waters of the Mississippi River following flooding conditions, the wetlands offer a viable bypass option at most times. The culverts are each 2 m in diameter and 40 m in length and do provide an alternative bypass. Overhead views of the area show clear channels that would provide direct access to the culverts for any fish and flow rates in the wetlands are much lower than in the main channel, providing little impediment for fish of even modest swimming abilities.

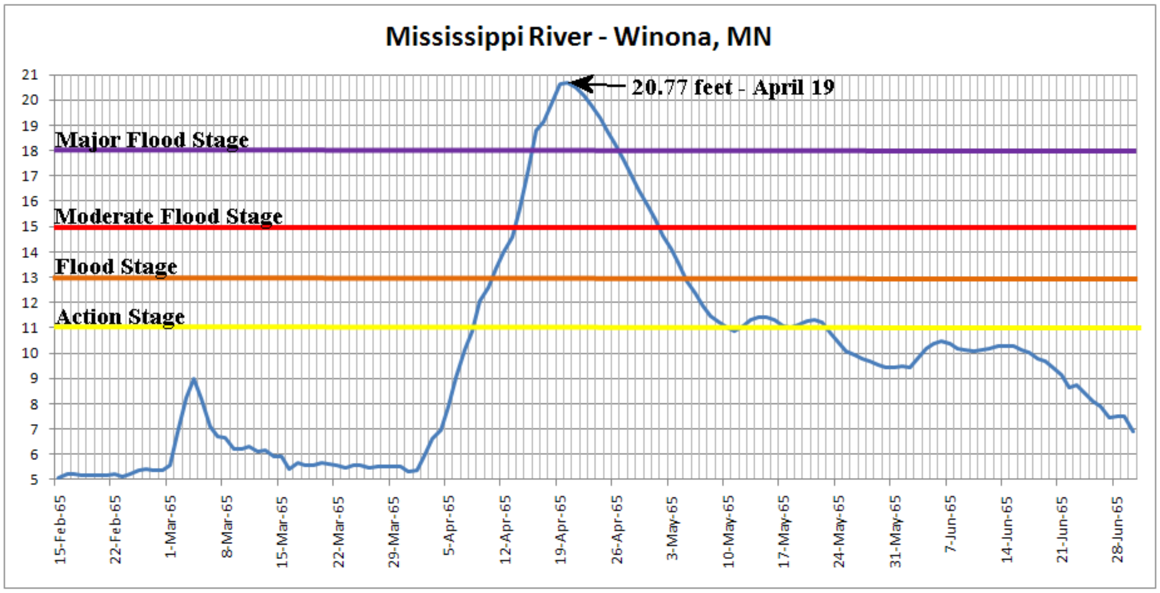


Figure 48: Hydrograph constructed from 8 am river stages at Winona, MN. (Image from National Oceanic and Atmospheric Administration database).

Figure 49: Map of Lock and Dam 5 showing the location of the culvert to the northwest.

To investigate whether invasive carp would be able to swim through the culvert and gain access to upstream waters, the flow rate at the downstream opening of each tunnel was measured using a flowmeter (Marsh McBirney Flo-Mate 2000). Measurements were taken in April (when the culvert was partially open), in June and August (when the culvert was fully opened) and at three water depths (bottom, middle and upper portion of the culvert (Figure 50).

Figure 50: Photographs of the three tunnels of the culvert, in April the culverts were exposed (left) and in August they were submerged (right) showing the difference in water depth.

Table 12: Water flow measurements taken at a culvert close to Lock and Dam 5.

Date	Water depth (m)	Average water flow (m/s)		
		Upper water column	Mid water column	Bottom water column
6th April 2018	0.6	0.08	0.05	0.04
11th June 2018	1	2.58	2.73	2.48
10th August 2018	2	0.61	0.73	0.52

Based on carp swimming speeds (Hoover *et al.*, 2017), bigheaded carp could easily exceed the flow rates measured in the culvert during April and August. Additionally, these water velocities are probably the maximum current that fish would experience throughout most of the wetlands and therefore it is predicted that they can reach the culverts throughout most of the year and swim through them during low water flow (< 0.8 m/s).

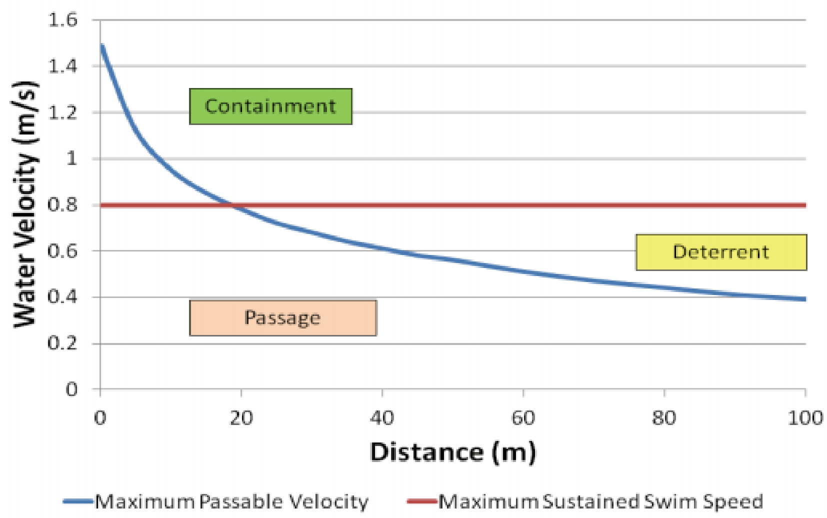


Figure 51: Maximum passable water velocities for sub-adult bighead carp swimming at maximum sustained speed (red line) and at prolonged and burst speeds (blue line). For distances > 19 m, water velocities > 0.8 m/s will exceed the swimming capability of the fish and so will cause deterrence. Whereas, water velocities < 0.8 m/s are within the swimming capabilities of the fish and will enable fish passage. [Taken from (Hoover *et al.*, 2012)].

It is possible the individual would be able to swim against the current. However, the distance the carp would need to swim to pass upstream also needs to be considered. The following equation is used to predict the maximum velocity that can be traversed by fish moving at various distances through culverts, canals or any other waterway:

$V_f = V_s - (D / E_{vs})$

Where V_f = ambient water velocity, V_s = swimming speed of the fish, D = distance travelled and E_{vs} = endurance at that swimming speed.

Using the relationship between distance and water velocity, established by (Hoover *et al.*, 2012) (Figure 51), it is suggested that carp would be able to pass through the culvert at least during April and August and other times when the flow rate was less than 0.8 m/s (Hoover *et al.*, 2012). In terms of preventing carp swimming through, the three-tunnel culvert does have gates that can be raised depending on water levels in the wetlands, but they are never fully closed. Therefore, recommendations must be that the gates on the upstream side of the tunnel are lowered on a more regular basis, to create a smaller diameter culvert to elevate flow and decrease the chance of fish passage. This would need to be done particularly during the spring and fall months when water flow is lower.

Any installation of an acoustic deterrent will need to factor in a solution to this alternative route. For example, if the screens were lowered it may be able to deter large adult carp however this will result in increased maintenance to keep the screens clear of debris. Whereas, if moving gates is not possible, a physical or behavioral barrier would be needed to prevent invasive carp from moving through the culvert upstream.

8. Interviews

8.1 Interview with Fish Guidance Systems

Fish Guidance Systems (the leading consultancy for acoustic deterrents) were approached for comments regarding the installation of acoustic deterrents for invasive carp and the potential for a Lock and Dam 5 system. The two main products of FGS are sound projector arrays (SPAs) and bio-acoustic fish fences (BAFFs), which utilize underwater speakers and a combination of speakers and bubble curtains respectively. Below are the questions asked and answers provided by David Lambert (Managing Director for FGS):

1. **Where are your devices currently in place? And where they have been used for invasive species.**

   "Our systems have been installed at a number of different sites in North and South America, Europe, Asia and Oceania. In total we have installed over 120 systems. Primarily they are installed to deflect migrating salmon smolt and eels, or to provide general screening for a broad spectrum of fish species. There have been a number of trials to assess our systems for bigheaded Carp, including the work carried out by Mark Pegg and Blake Ruebush. We are currently working with other groups regarding the deployment of our systems for invasive species in the US and elsewhere, but currently those projects are protected by non-disclosure agreements. We trust we will be able to release details of those projects in due course."

2. **Where has the efficacy of FGS systems been stated?**

   "There have been a number of summary reports reviewing the different options for screening against invasive species, which can be found on the internet. They include the FishPro Report 'Feasibility Study to Limit the Invasion of Asian Carp into the Upper Mississippi River Basin', dated 15 March 2004 for Minnesota DNR and also the BARR Report 'USACE Lock and Dam 1 – Asian Carp Deterrence Alternatives', dated 4 January 2013. Both reports concluded the BAFF available from FGS is the preferred solution. Other reports are available, including that from the State of California Department of Water Resources, prepared after they assessed BAFF systems at both Head of Old River and Georgiana Slough (in California) for migrating smolt (salmonids). The final report was released in March 2015 – 'Engineering Solutions to Further Reduce Diversion of Emigrating Juvenile Salmonids to the Interior and Southern Delta and Reduce Exposure to CVP and SWP Export Facilities'."

   All these reports are included in the literature review conducted in Section 2.

3. **Is there information on the habituation of invasive carp to acoustic barriers?**

   "I am not aware of the papers produced by USGS, but Dr. Peter Sorensen's research has demonstrated the habituation of bigheaded carp to non-FGS barriers, and no habituation to the BAFF. However, those results are not yet published, but I understand that they have been submitted for publication, and so assume they will be published soon."

4. **Is there any information on the impacts on non-target species, such as fish, birds or mammals?**

"Over the last 25 years that FGS has been installing systems we are not aware of any adverse impacts on birds or mammals."

5. **Has there been any concerns or situations where the acoustic barriers have impacted navigation?**

"One of the main advantages of the BAFF is that it is a non-physical barrier, and so provides the required deterrent, but also enables boats to pass through the barrier. This happened at Georgiana Slough (California); I saw I saw boats passing through the system, and we are not aware of any adverse impacts or comments from those vessels. We are all aware that there are comments being raised that the navigation industry may object to the systems being proposed on the 'Mississippi'. I trust the navigation community will come to realize that there is no significant impact on vessels using the locks once they start to encounter the systems that are going to be installed at Lock and Dam 19 and at Barkley Dam. It may come down to experience, but I trust providing information before the installations will help alleviate any fears that are being created."

6. **In your installation of acoustic barriers, what are the most common challenges/obstacles (i.e. power supply) that on-site contractors may have to overcome?**

"The overriding challenge is acceptance of the technology. It took 14 years from the first FishPro report for a system to finally be installed. As far as challenges/obstacles for on-site contractors, we will have to wait and see, as lessons will be learnt from the installation of the systems at Lock and Dam 19 and at Barkley Lock. My suspicion is the main issue will be balancing access time for the system to be installed and yet also keeping the lock available for vessels that want to use it. I will be able to report back on this once the systems have been installed."

7. **What are typical construction and operation costs? For example, if the DNR would like to place a barrier on Lock and Dam 5 could you provide a ballpark of the costs.**

"The estimates in the previous review reports have been on the conservative side, I can provide budget costs for the hardware relatively easily, but as with my comments above, the installation and operation costs are just being worked through. However, every site / system is different."

8. **What are typical operation versus down time due to equipment issues, power interruptions or adverse water/weather conditions?**

"The systems are designed for continuous operation and can continue to operate even if there are issues with particular components. Obviously, power interruptions could pose an issue, as they do for any electrical system. If required, backup systems can be incorporated into a permanent system to prevent these problems. "

9. **How often do acoustic barriers need maintenance?**

- The Sound Projector proposed for Barkley will be an upgraded unit, that will require maintenance only once every 18 months.
- The compressor for the bubble curtain / BAFF requires regular servicing, albeit that compressor servicing is based upon hours run, and the servicing will be more regular than every 18 months.
- High Intensity Lights can be supplied so that they are self-cleaning, but they take very little time to clean if accessible and so generally are cleaned on a regular basis, typically every 6-8 weeks.

10. **Is there potential for modifications or upgrades to the system over time?**

"FGS systems are constantly being improved and updated, as noted above regarding the Sound Projectors. So yes, there is the potential for modifications and upgrades to the system over time."

8.2 Interview with USGS

Individuals from the USGS (United States Geological Survey) were interviewed in regard to potential implementation of acoustic deterrents for invasive bigheaded carps. The following is a compilation of the general questions and responses. The responses should be considered as general consensus to these questions and not attributed to any one individual and are not to be construed as official USGS policy.

1. **What are some concerns regarding the use of acoustic deterrents?**

   In general, there is broad support for continuing to investigate the feasibility of acoustic deterrents. Preliminary studies have shown promise however, the majority of studies have been conducted in relatively small ponds. Extrapolating these results to larger field sites is challenging and decisions should be based on quantitative assessment of well-designed scientific studies. Other concerns included how carp may habituate to an acoustic stimuli and the impact of acoustic deterrents on non-target species.

2. **What kind of deterrent (underwater speakers, bubble curtains or both) do you think is best situated for use at a lock and dam?**

   There were several concerns regarding the potential installation of the bubble curtain because of the prodigious jumping ability of the silver carp especially when it senses a barrier, such as a net, in front of it, would seem to negate the effectiveness of the bubble curtain. Also, the curtain will be placed in the path of relatively long vessels (i.e. multiple barges). There was concern that up to this point, the dispersion of the curtain by both the physical presence of the barge and resultant flow field had not been considered. Additionally, as small carp are known to take up residence near the bow of the barge, it is unclear how the bubble curtain would displace these fish. There was also mention of navigation challenges although it was thought that this would be more for the Army Corps of Engineers to address.

3. **At which lock and dam, do you think an acoustic deterrent would be best placed if implemented?**

   There was strong consensus that initial barriers should be installed only where sufficient numbers of invasive carp already exist to be able to properly test the efficacy of the barrier. Placing a barrier initially at Lock and Dam 5 or Lock and Dam 8 was not seen to be the best use of barrier technology as insufficient numbers of invasive carp are found in the vicinity.

4. **Do you have any concerns regarding the cost and maintenance of an acoustic deterrent?**

   It was felt that this area needs further discussion by all parties involved. These barriers have not been installed routinely at the openings of locks so maintenance, upkeep and running the barrier was considered a concern but may be outside of USGS responsibility. Good communication between state and federal parties is imperative.

5. **What kinds of further research do you suggest is needed before implementation?**

   The impact of acoustic deterrents on non-target species as well as the reactions of all stages of the carp's live history were highlighted as key areas for further research. Suggestions also included doing a longer-term study on fish habituation and testing motivated versus non-motivated fish. Additionally, modelling or testing the effect on vessel transit through the bubble curtain was suggested.

6. **If an acoustic deterrent was implemented, what recommendations would you make to test its efficacy?**

   There was strong consensus that evaluation of any installed acoustic deterrent must be completed by an independent party (i.e. not the manufacturer of the deterrent or any party funded or associated with the manufacturer of the deterrent) to avoid conflict of interest. The constant reference to proprietary "sound" in the literature makes it extremely difficult for independent entities to test the efficacy of these barriers and while it is understood that companies have the right to protect their intellectual property rights, it prevents government and/or scientific agencies from properly evaluating or recommending their product. Greater transparency in this area would lead to better deterrents while still protecting the ability of the company to manufacture and install their products. Furthermore, the only way to truly field test the barrier, is to place it in a location were sufficient number of invasive carp reside and tagged (i.e. acoustic tags) so their reaction to the deterrent can be quantified.

8.3 Discussion with USACE

The USACE maintains the 29 lock and dam structures of the Mississippi River for navigation. The USACE has managed them for decades using simple operating rules and approaches that maintain minimal downstream velocity and minimize scour. In terms of the installation of any acoustic deterrent, USACE would need to be consulted to ensure that any proposed barrier does not interfere with or constitute a hazard to navigation and Section 408 approval requirements followed.

Individuals from the USACE were interviewed in regard to potential implementation of acoustic deterrents at Lock and Dam 5. The main concerns were:

- would the system work?
- who would be conducting the installation and maintenance of the system?
- how often maintenance would be needed?
- health and safety regarding the estimated sound level to be emitted by the system?

9. Future recommendations

In terms of designing and deploying an acoustic deterrent the following needs to be considered:

9.1 Set level of efficacy

The level of efficacy needs to be clearly set by fish managers and shareholders before researching, engineering and deploying case specific solution, to meet their goals. For example, when the primary goal is to reduce fish mortality at a hydroelectric facility or cooling water intake, behavioral deterrents may be the best option as any reduction is deemed a positive result. However, when restriction of an invasive species is needed, acoustic barriers need to perform at a much higher success rate as even a low percentage of transgression can lead to a breeding population past the deterrent.

A top priority in assessing the level of efficacy for any acoustic deterrent, is only studies which have provided full transparency of design, acoustic parameters and success rate be included. At a very minimum the frequency range and source level needs to be reported to assess that the sound produced can be detected by the target species and the impact to non-target species is minimized. Additionally, only peer reviewed literature by independent parties should be considered because it provides an unbiased assessment of the efficacy of the deterrents.

9.2 Effectiveness post deployment

While there often is a desire to do “something” in response to invasive species, it is not a good use of time and money to deploy a structure that cannot be tested. There are extremely low numbers of invasive bigheaded carp surrounding Lock and Dam 5 (or Lock and Dam 8). This technology has never been tested against invasive carp at this scale and therefore due to the low numbers of fish, it will be impossible to verify its effectiveness. Initial trials of this technology need to transpire in areas that contain invasive carp so careful, controlled studies can be used to determine the deterrent's success in preventing the upstream migration of invasive fish. Furthermore, technological advances such as acoustic telemetry (Cooke *et al.*, 2004), sonar (Arnett *et al.*, 2013) or passive integrated transponder (PIT) tags (O'Donnell and Letcher, 2017) can be employed to non-invasively monitor fish position or behavior during both preliminary and prolonged trials to conclusively demonstrate deterrent effectiveness.

9.3 Habituation

A major concern of acoustic deterrents is the unknown effect of long term habituation in reducing the efficacy of any proposed system. Short term exposure to broadband sound showed little evidence of habituation in bighead and silver carp species, however if a system was implemented and emitted a sound stimulus frequently it is unknown whether carp would become accustomed to it. Longer term, repeated exposure studies should be conducted to follow on from the work conducted by Vetter et al. 2017.

9.4 Hearing damage

Temporary threshold shifts in hearing sensitivity due to even brief noise exposure can dramatically lessen the efficacy of any acoustic deterrent. Therefore, additional research is needed on the effect of sound exposure to fish hearing. Acoustic deterrents need to be optimized for maximum efficacy that produce minimal hearing damage.

9.5 Motivation

There is very limited research into the movement patterns of bigheaded carp and the motivation behind their movements. It is often challenging to recreate the driving forces that spurn upstream migration in laboratory settings. Feeding studies are one way to examine motivated fish, however many long migrations are catalyzed for reproduction. Tracking wild fish movements is one way to determine if there are critical times during the year when fish are motivated to swim upstream. This is vital information as it may allow acoustic deterrents to be operated only during specific periods that would optimize their success while reducing habituation.

9.6 Impact on native species

A major gap in the current research is effects of acoustic deterrents on non-target fish including native fishes. There is very limited literature on the hearing ability of native fishes in the Mississippi River and even less on how these species behave around acoustic deterrents (either underwater speakers or bubble curtains). Without this information, it is difficult to assess the potential impacts on native fish hearing.

Currently, the hearing sensitivities of 42 species found within Minnesota and Wisconsin rivers and lakes (84 % of all fish species listed on MN DNR website) are unknown, therefore research using auditory evoked potentials is recommended. Once the hearing of these species is known the potential for acoustic deterrents to cause hearing damage can be determined. Sublethal effects such as a reduction in hearing sensitivity can lead to fish being unable to detect predators or prey and result in reduced populations. For example, introducing sound into the environment around a lock and dam could potentially distract or detrimentally change behavioral performance (Purser and Radford, 2011) resulting in a reduction in prey capture. Furthermore, native species could be displaced or elect to avoid the habitat permanently in response to introduced sound which could be detrimental to the local ecology or economy (Hawkins and Popper, 2017).

9.6 Lock openings

A major challenge in preventing invasive species dispersal at lock and dams is that each lock opening increases the chance of an individual/or group of fish moving upstream. Recreational vessels passed through Lock and Dam 5 an average of 4 times each day with total passage taking 12 ± 7 minutes (Section 5.6).

One way to reduce the opportunity for carp dispersal is to limit the number of lock openings for recreational vessels to certain times (i.e. on the hour) or when sufficient numbers are queued to reduce the number of openings. This is already done at certain drawbridges to reduce disruption to ground transportation and a similar schedule could be used for the lock and dam system without impacting commercial shipping. Another problem identified during passive acoustic monitoring at Lock and Dam 5 was that the gates would often open up to 20 minutes prior to the vessel actually passing through the lock. Maintaining the lower (downstream) gates closed until needed for commercial barge transits would help minimize the time available for carp to swim into the lock chamber. If done correctly, this should have no impact on commercial traffic while minimizing the time gates are open. However, this may impact the workload of shore-based personnel and increase maintenance required if the gates are opened and closed more often, so this would need to be considered by USACE prior to implementation.

10. National Environmental Policy Act (NEPA)

The National Environmental Policy Act (NEPA) of 1969 requires federal agencies, including the United States Army Corps of Engineers (USACE) to consider the potential environmental impacts of their proposed actions and any reasonable alternatives before undertaking action.

As such, an environmental assessment (EA) or an environmental impact statement (EIS) needs to be conducted before any proposed acoustic deterrent is awarded a construction contract.

> An EA is a concise document that serves to provide sufficient information to determine whether the project will have significant effects on the environment and thus require an EIS (USACE 2018). It includes information on:
>
> 1. Proposed action
> 2. Alternatives
> 3. Environmental setting
> 4. Environmental impacts

5. Status of environmental compliance
6. List of agencies consulted

An EIS must be prepared if the proposed action will have significant impacts on the human environment. A draft is prepared first and then published to obtain comments from the public and government agencies. For more information on this process please see extensive reviews conducted by the USACE (Hagerty, 2005).

At Lock and Dam 5, the effect of acoustic deterrents on native fish species needs to be considered. The effect on any species whose hearing overlaps the sound produced by any deterrent needs to be assessed to determine how they would response physically and behaviorally. The significance of impacts also needs to be determined for the context and intensity.

Once the impact on native species is known, the NEPA lists 5 hierarchical actions to address mitigation:

1. Avoid the impact
2. Minimize the impact
3. Rectify the impact
4. Reduce the impact
5. Compensate for the impact

Overall, the NEPA is seeking to create balance and synergy among human development and natural systems. However, the NEPA does not require agencies to take the environmentally preferable action; it only requires them to consider the effects of their actions.

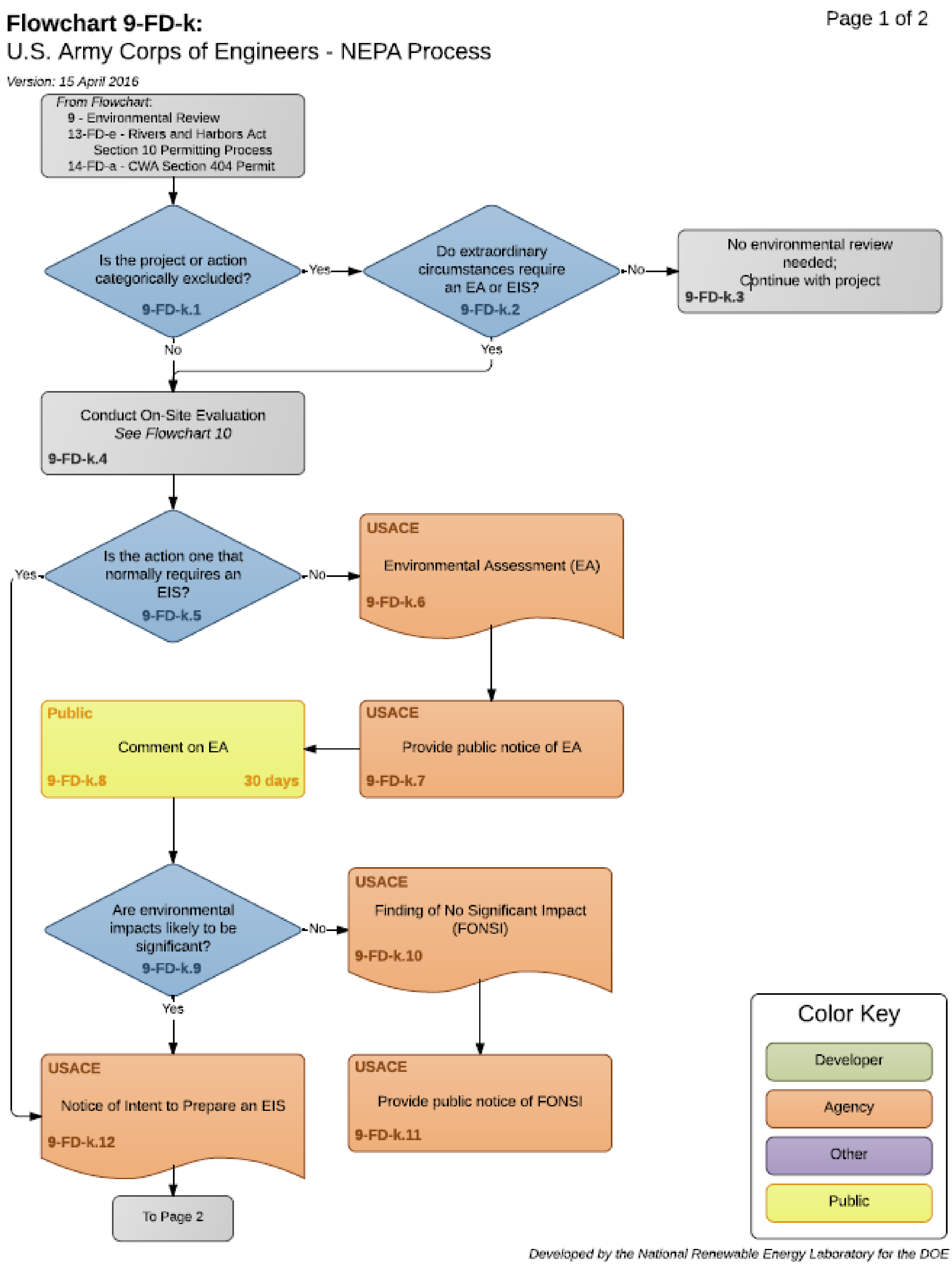


Figure 52: Page 1 - Flowchart illustrating the procedures used by the USACE to ensure compliance with NEPA. (Taken from USACE).

Flowchart 9-FD-k (continued):
U.S. Army Corps of Engineers - NEPA Process

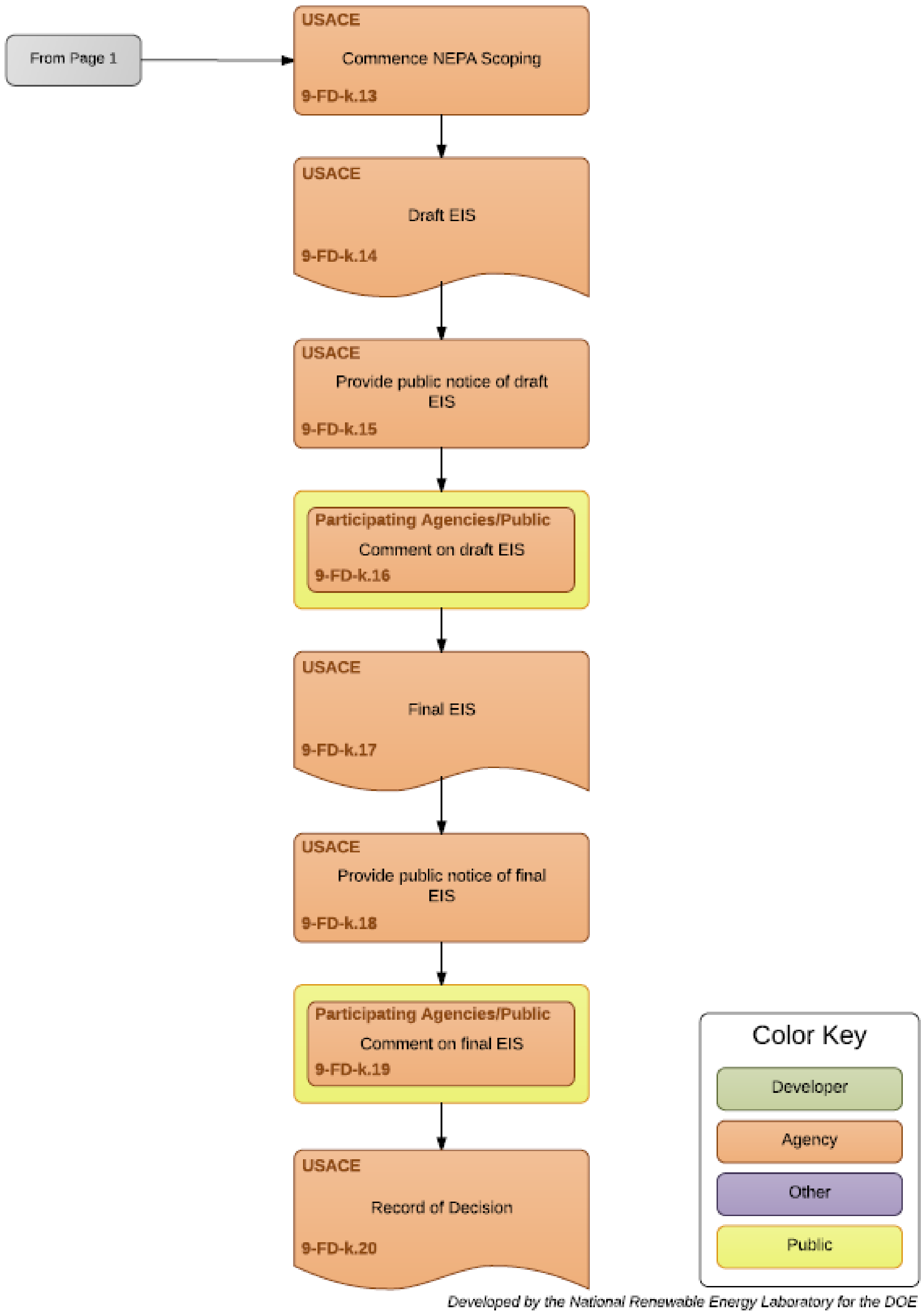


Figure 53: Page 2 - Flowchart illustrating the procedures used by the USACE to ensure compliance with NEPA. (Taken from USACE).

11. Overall Recommendation

The deployment of an acoustic deterrent is not recommended at Lock and Dam 5 or at similar sites in Minnesota. The major concerns are summarized below:

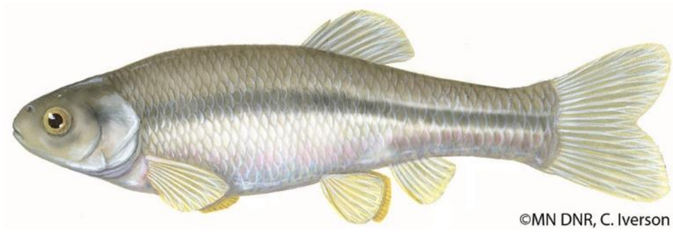
1) There are insufficient numbers of invasive bigheaded carp in Minnesota to justify the expenses of an acoustic deterrent that has not and cannot be tested for efficacy against bigheaded carp in MN waters given the current carp population. Carp have already migrated upstream past Lock and Dam 5. If the upstream population did not exist, it would be easier to test the effectiveness of the proposal deterrent. However, given the extremely low-density population and the prohibition against adding invasive species into the wild, there are insufficient bigheaded carp to tag and test the deterrent efficiently. Using common carp as a proxy species is not scientifically justified as they have completing different behavior, feeding mechanism and life histories and are not comparable to bigheaded carp.
2) The second issue with the potential deployment is that an ensonified bubble curtain will be continuously disrupted by barges either transiting into the lock chamber or those waiting outside the lock chamber for transit. A bubble curtain entrained with sound from a speaker works by creating a sharp gradient of sound to repel fish. Once the bubble curtain is interrupted the sound is no longer contained and the sharp gradient that works as a deterrent is eliminated. Additionally, silver carp may be able to jump over this type of barrier rendering it useless.
3) At Lock and Dam 5, the adjacent wetlands already provide an alternative upstream path around the lock and dam and this bypass would need to be assessed prior to the deploying an acoustic deterrent.
4) The use of an ensonified bubble curtain has not been tested in lock and dam systems that are impacted by the frequency and size of commercial vessels that transits the Mississippi River. Vessel transits as well as vessels awaiting access to the lock may also disrupt the bubble curtain and reduce its effectiveness. An alternative strategy could be ensonification of the entire lock chamber and establish a sound gradient to deter fish from entering the lock. The sound pressure level would be highest at the upstream gates and lowest in the approach channel. Fish that are trying to move upstream would encounter every increasing sound levels and be deterred to retreat from the lock chamber.

12. Supplementary Information

Table S1: Information gathered about previous studies conducted on non-invasive carp and different types of acoustic deterrent. NR denotes when the information was not reported in the literature.

Reference	Common name	Juvenile / adult	Type of acoustic deterrent (number used)	SPL (dB re 1µPa)	Ambient sound (dB re 1µPa)	Frequency range (Hz)	Efficacy	Habituation	Lab / field
Murchy *et al.* 2017	Bigmouth buffalo	NR	Underwater speakers (2)	135 - 140	NR	60 - 1,000	NR	NR	Lab
Wood *et al.* 1994	Chub	NR	Underwater speakers (6)	NR	NR	NR	88	NR	Field
Wood *et al.* 1994	Common bleak	NR	Underwater speakers (6)	NR	NR	NR	72	NR	Field
Sonny *et al.* 2006	Common bleak	NR	NR	NR	NR	NR	80	NR	Field
Sonny *et al.* 2006	Common bleak	NR	Particle motion generator	NR	NR	16	NR	NR	Field
Wood *et al.* 1994	Common bream	NR	Underwater speakers (6)	NR	NR	NR	74	NR	Field
Sonny *et al.* 2006	Common bream	NR	NR	NR	NR	NR	80	NR	Field
Zielinski *et al.* 2017	Common carp	juvenile	Underwater speakers (4)	150	80	150 - 2,000	6.5	Y	Lab
Zielinski *et al.* 2015	Common carp	juvenile	Underwater speakers	150	NR	100 - 2,000	57	NR	Field
Zielinski *et al.* 2017	Common carp	juvenile	Bubble curtains (2)	145	105	100 - 1,000	75	NR	Lab
Zielinski *et al.* 2014	Common carp	NR	Bubble curtains (2)	130	NR	200	80	NR	Lab
Zielinski *et al.* 2014	Common carp	NR	Underwater speakers (2)	130	NR	100 - 300	80	NR	Lab
Zielinski *et al.* 2014	Common carp	NR	Bubble curtains (2)	130	NR	200	80	NR	Lab
Murchy *et al.* 2016	Common carp	juvenile	Underwater speakers (2)	< 150	NR	60 - 10,000	90	NR	Lab
Dennis 2017	Common carp	NR	NR	NR	NR	10 - 1,000	NR	Y	Lab
Dennis 2017	Common carp	NR	NR	NR	NR	1,000 - 10,000	NR	NR	Lab
EPRI 1998	Common carp	NR	Underwater speakers	NR	NR	2,000	NR	NR	Field
EPRI 1998	Common carp	NR	Underwater speakers	NR	NR	2,990	NR	NR	Field
EPRI 1998	Common carp	NR	Underwater speakers	NR	NR	673	NR	NR	Field
EPRI 1998	Common carp	NR	Underwater speakers	NR	NR	5,500	NR	NR	Field
Murchy *et al.* 2017	Common carp	NR	Underwater speakers (2)	135 - 140	NR	60 - 1,000	NR	NR	Lab
Wood *et al.* 1994	Common dace	NR	Underwater speakers (6)	NR	NR	NR	76	NR	Field
Sonny *et al.* 2006	Common nase	NR	NR	NR	NR	NR	80	NR	Field
FGS Report 1996	Cyprinids	NR	Hybrid system (1)	NR	NR	20 - 500	92	NR	Field
EPRI 1998	Emerald shiner	NR	Underwater speakers	NR	NR	5,500	NR	NR	Field

EPRI 1998	Emerald shiner	NR	Underwater speakers	NR	NR	673	NR	NR	Field
EPRI 1998	Emerald shiner	NR	Underwater speakers	NR	NR	2,000	NR	NR	Field
EPRI 1998	Emerald shiner	NR	Underwater speakers	NR	NR	2,990	NR	NR	Field
Murchy *et al.* 2017	Fathead minnow	NR	Underwater speakers (2)	135 - 140	NR	60 - 1,000	NR	NR	Lab
ESEERCO 1991	Golden shiner	NR	NR	NR	NR	NR	NR	NR	NR
McKinley *et al.* 1987	Golden shiner	NR	Particle motion generator	NR	NR	99	NR	NR	Field
McKinley *et al.* 1987	Golden shiner	NR	Particle motion generator	NR	NR	27	NR	NR	Field
McKinley *et al.* 1987	Golden shiner	NR	Particle motion generator	NR	NR	63	NR	NR	Field
McKinley *et al.* 1987	Golden shiner	NR	Particle motion generator	NR	NR	153	NR	NR	Field
NYPA *et al.* 1991	Golden shiner	NR	Underwater speakers	NR	NR	100 - 1,000	NR	NR	Field
NYPA *et al.* 1991	Golden shiner	NR	Underwater speakers	NR	NR	110,000 - 150,000	NR	NR	Field
Witchell *et al.* 1997	Golden shiner	NR	Underwater speakers	NR	NR	100 - 6,400	NR	NR	Field
Murchy *et al.* 2017	Grass carp	NR	Underwater speakers (2)	135 - 140	NR	60 - 1,000	NR	NR	Lab
Jesus *et al.* 2018	Iberian barbel	NR	Underwater speakers	140	NR	140	15.9	N	Lab
Jesus *et al.* 2018	Iberian barbel	NR	Underwater speakers	140	NR	2,000	95.9	N	Lab
Jesus *et al.* 2018	Northern straight mouth nase	NR	Underwater speakers	140	NR	140	30.7	N	Lab
Jesus *et al.* 2018	Northern straight mouth nase	NR	Underwater speakers	140	NR	2,000	87.9	N	Lab
Wood *et al.* 1994	Roach	NR	Underwater speakers (6)	NR	NR	NR	68	NR	Field
Sonny *et al.* 2006	Roach	NR	NR	NR	NR	NR	80	NR	Field
Sonny *et al.* 2006	Roach	NR	Particle motion generator (2)	NR	NR	16	NR	N	Field
Sonny *et al.* 2006	Rudd	NR	Particle motion generator (2)	NR	NR	16	NR	N	Field
Mussen 2009	Sacramento splittail	adult	Particle motion generator	NR	NR	NR	NR	NR	Lab
ESEERCO 1991	Spottail shiner	NR	NR	NR	NR	NR	NR	NR	NR
NYPA *et al.* 1991	Spottail shiner	NR	Underwater speakers	NR	NR	110,000 - 150,000	NR	NR	Field
NYPA *et al.* 1991	Spottail shiner	NR	Underwater speakers	NR	NR	100 - 1,000	NR	NR	Field
FGS Report 1996	White bream	NR	Hybrid system (1)	NR	NR	20 - 500	40.1	NR	Field
Maes *et al.* 2004	White bream	NR	Underwater speakers (20)	172	110	20 - 600	40.1	NR	Field
EPRI 1998	White sucker	NR	Underwater speakers	NR	NR	673	NR	NR	Field
EPRI 1998	White sucker	NR	Underwater speakers	NR	NR	2,000	NR	NR	Field
EPRI 1998	White sucker	NR	Underwater speakers	NR	NR	2,990	NR	NR	Field
EPRI 1998	White sucker	NR	Underwater speakers	NR	NR	5,500	NR	NR	Field



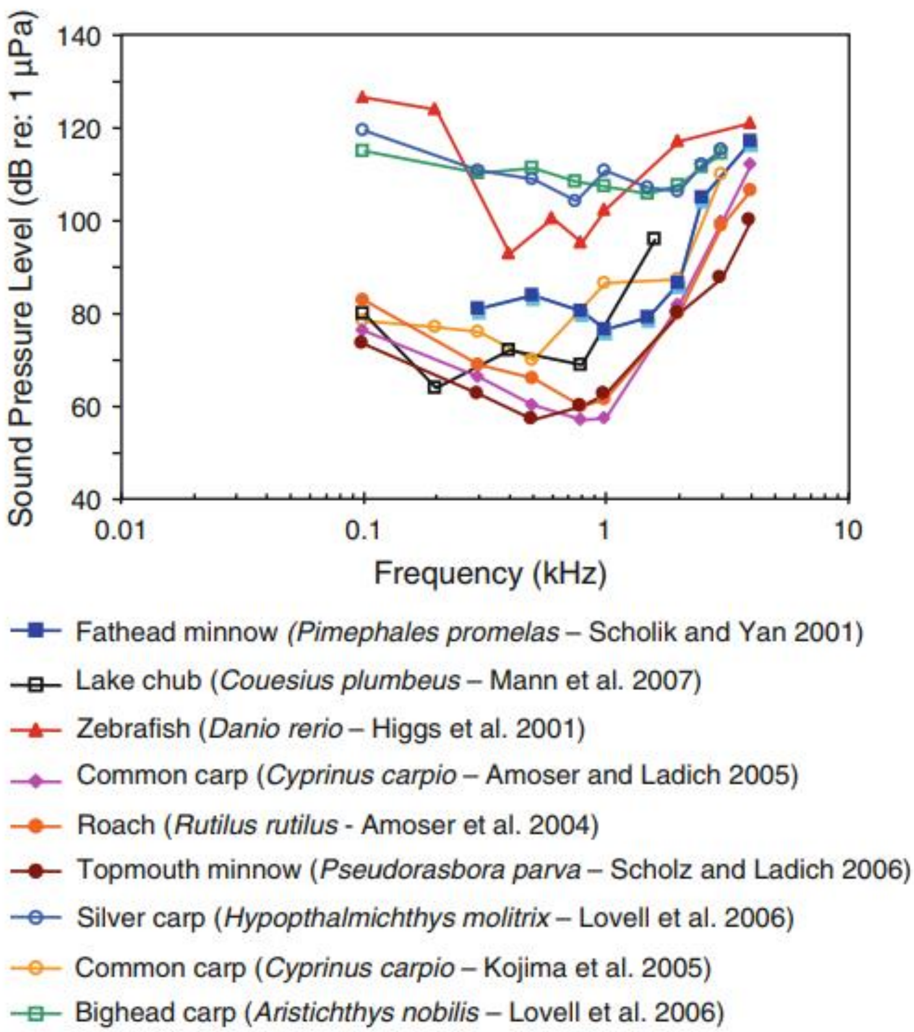


Figure S1: Hearing sensitivities for eight representatives of the Cypriniformes, including the fathead minnow (*Pimephales promelas*) shown in dark blue versus silver carp (*Hypophthalmichthys molitrix*) shown in light blue and bighead carp (*Hypophthalmichthys nobilis*) shown in light green [Adapted from (Ladich and Fay, 2013)].

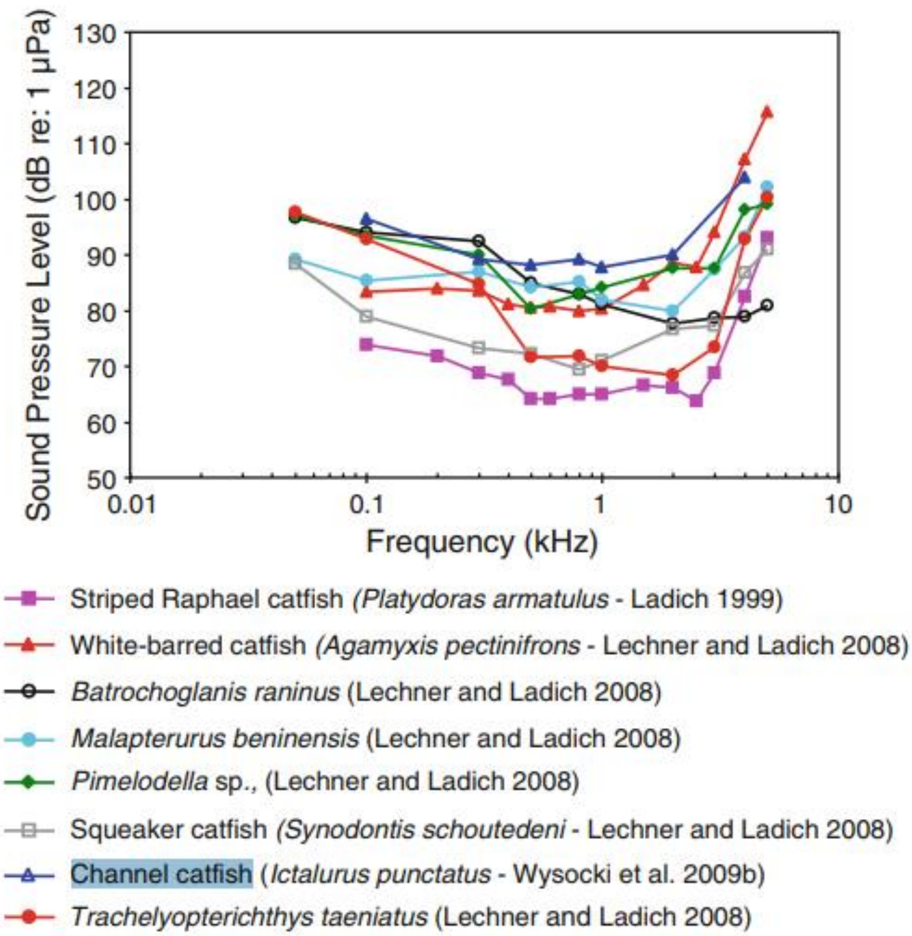


Figure S2: Hearing sensitivities for eight representatives of the Siluriformes, including the channel catfish (*Ictalurus punctatus*) shown in dark blue [Adapted from (Ladich and Fay, 2013)].

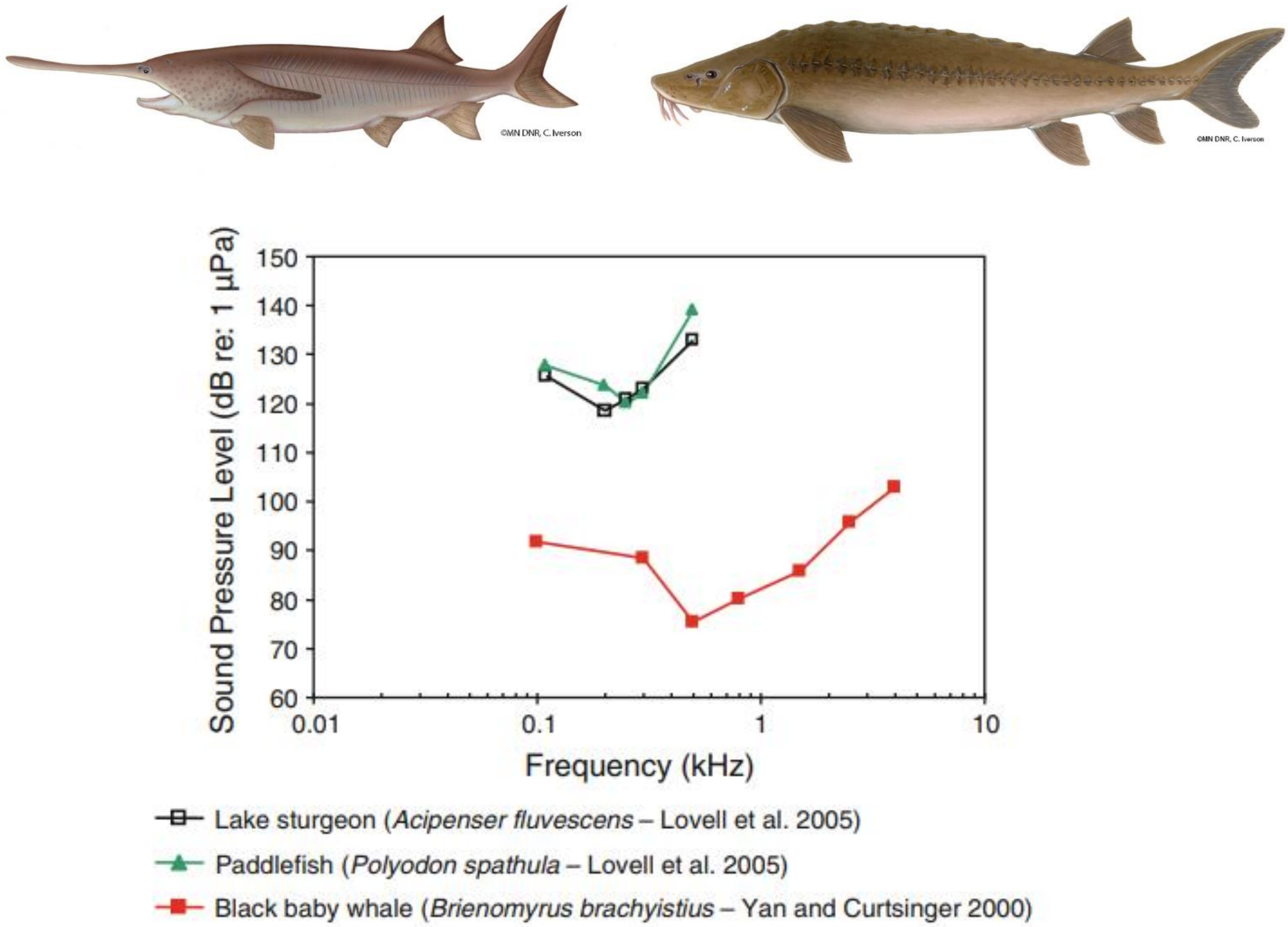


Figure S3: Hearing sensitivities for the paddlefish (*Polyodon spathula*) shown in green and lake sturgeon (*Acipenser fluvescens*) shown in black [Adapted from (Ladich and Fay, 2013)].

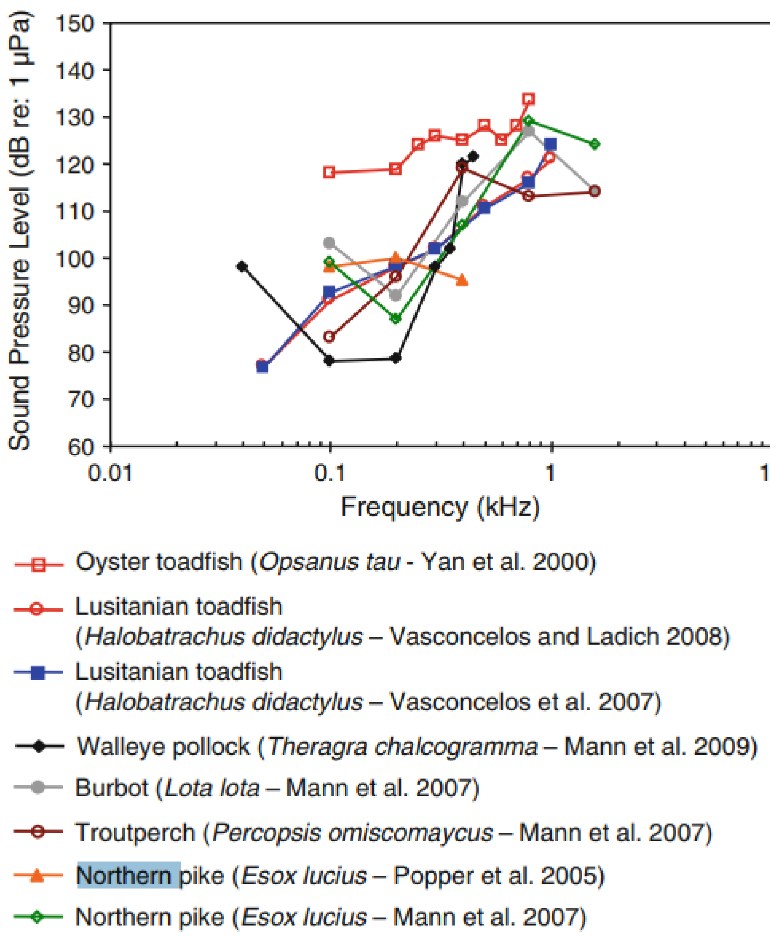


Figure S4: Hearing sensitivity for the northern pike (*Esox lucius*) shown in orange and green [Adapted from (Ladich and Fay, 2013)].

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