THE EFFECTS OF STROBE LIGHT AND SOUND BEHAVIORAL DETERRENT SYSTEMS ON IMPINGEMENT OF AQUATIC ORGANISMS AT PLANT BARRY, ALABAMA

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Jeffery K. Baker

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VITA

Jeffery K. Baker was born in Cullman, Alabama on June 7, 1977. He grew up in Northern Alabama and graduated with an advanced diploma from Fairview High School in Cullman, Alabama. Following this, he attended the University of Alabama where he pursued a double major in Marine Science/Biology. Jeffery graduated from the University of Alabama cum laude with a Bachelors of Science in 2001. After receiving his undergraduate degree he worked two years as an observer biologist for the National Marine Fisheries Service and two years as an aquarium specialist for the University of Southern Mississippi. He then began his graduate degree as a research assistant in Fisheries and Allied Aquacultures at Auburn University. Jeffery finished his degree requirements for a Masters of Science in Fisheries and Allied Aquacultures in August 2008.

THESIS ABSTRACT

THE EFFECTS OF STROBE LIGHT AND SOUND BEHAVIORAL DETERRENT SYSTEMS ON IMPINGEMENT OF AQUATIC ORGANISMS AT PLANT BARRY, ALABAMA

Jeffery Kelley Baker

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A hybrid and a sonic deterrent system were both evaluated for their effectiveness to repel fish from becoming impinged in a cooling water intake structure located at Plant Barry (Mobile River, Mobile County, Alabama). The hybrid deterrent system combined strobe lights (300 flashes per minute), sonic sound frequencies (0.4 – 4.0 kHz), and ultrasonic sound frequencies (120 – 130 kHz). The sonic deterrent consisted of random tones at 0.4, 0.63, 1.00, 2.50, and 3.15 kHz. Evaluation of the hybrid deterrent system began 1 May 2006 and ended 6 October 2006. Evaluation of the low frequency sound burst deterrent began 15 November 2006 and ended on 22 December 2006. The sound and light was projected into the forebay of the cooling water intake structure.

Effectiveness of the deterrent systems was determined by monitoring impingement numbers.

Fish representing 26 taxa were captured during the study. For total fish impingement and for individual fish and non-fish species with sufficient numbers, a split-plot analysis was performed on the sequential treatment (deterrent on) and control (deterrent off) sampling events within each weekly test period. Temporal and environmental variables were considered and accounted for through paired evaluations during individual weeks. The split-plot analysis for the paired treatment evaluation of the total combined and the individual species show that there were no significant reductions in impingement while either deterrent system was in operation. The results of the Hybrid and Sonic fish deterrent testing demonstrated that none of the behavioral stimuli evaluated (sonic sound, ultrasonic sound or strobe lights) were capable of reducing the impingement of freshwater organisms at Plant Barry.

ACKNOWLEDGMENTS

I would like to give a special thanks to Jeff Terhune and Bill Garrett for their guidance and support during this project. As one of my committee members, I would also like to thank Russell Wright for his participation and advisement. I give a special thanks to all those who supported me and helped with the field work during this study, especially Justin Mitchell, Bill Shaw, John Ponstein, and Larry Craft. I thank all the faculty, staff, and fellow graduate students at the Department of Fisheries and Allied Aquacultures for their patience and help along the way. I thank Steve Amaral, Chuck Coutant, Elgin Perry and Art Popper for their reviews of this document. I would also like to express my appreciation for the support and funding of this project from Alabama Power Company's Environmental Affairs Department, Electric Power Research Institute, and Alden Engineering.

Computer software used: Microsoft Word 2003, Microsoft Excel 2003, and SPSS v. 15.0

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1 INTRODUCTION

Steam electric generating power facilities produce the majority of electricity used in the United States. A large percentage of these power plants use a once-through cooling water process. Water is withdrawn from a body of water, such as a river or reservoir, pumped through condensers to provide cooling and condensation of waste steam by heat exchange, and then discharged back into the same or a nearby water body (Veil 2002). Water is withdrawn through cooling water intake structures (CWISs) which include pump houses and rotating screens. Water being withdrawn through these CWISs to cool the facilities' condensers carries living organisms and debris into the intake structure where objects larger than the screen mesh are impinged (or pressed against the screens). This prevents those objects from reaching the condenser tubes, which could cause the tubes to become blocked. Objects smaller than the screen mesh, such as larval fish, pass through the screens and are considered to be entrained in the cooling water system before being discharged to a receiving water body (Hadderingh 1979; U.S. EPA 2002). The blockage of condenser tubing reduces power plant generation capacity and efficiency and, if excessive, may lead to shutting down a boiler.

There is concern that adverse environmental impacts may result if aquatic organisms enter the CWIS and become impinged or entrained (Lohner et al. 2000). Impingement occurs when larger organisms are retained on the traveling water screens located at the entrance of the intake structure (Dey 2002; Lohner et al. 2000). Organisms being impinged may be subject to gill compression leading to suffocation and other mechanical damage such as scale loss or skin lacerations (Hadderingh 1979). However, a recent study has shown that a significant number of impinged fish may have pre-existing diseases that may have made them susceptible to impingement (Baker et al. 2007). In addition, impinged organisms are often removed from the screens and discarded at facilities that are not equipped with fish return structures. Entrainment takes place when smaller aquatic organisms such as fish eggs, juvenile fish, fish larvae or shellfish larvae pass through the intake screens and enter the cooling-water circuit. Most of these organisms will pass through the condenser and exit at the cooling water discharge (Hadderingh 1979; Lohner et al. 2000; U.S. EPA 1977). Within the cooling water systems, these organisms are subject to physical and thermal stresses (U.S. EPA 1977).

Due to the concerns over the potential effects of impingement and entrainment losses, the Clean Water Act (CWA) Section 316(b) requires that the U.S. Environmental Protection Agency (U.S. EPA) regulate the location, design, construction and capacity of CWISs so that the structures reflect the best technology available (BTA) for minimizing adverse environmental impact (U.S. EPA 1977; Super 2002). Under CWA Section 316(b), the EPA categorizes power plants into one of three phases, with corresponding rules associated with each phase. The rules for each phase are based on the size and age of the facility, as well as whether it is classified as a steam electric generating facility. Specifically, the Phase II Rule applies to existing facilities that, as their primary activity, generate electric power, withdraw ≥189.3 million liters (50 million gallons) per day, and use 25% or more of that water for cooling purposes. The 2004 Phase II rule requires existing facilities to reduce impingement mortality by 80 to 95% from a calculated baseline where the impingement mortality would hypothetically occur if the facility had a shoreline near-surface intake with a standard 9.5 mm (0.4 in.) mesh traveling screen (U.S. EPA 2004). However, facilities that use closed-cycle cooling are considered to have the best technology available (BTA) for minimizing impingement (U.S. EPA 2004) and entrainment. Also, facilities that have through-screen design velocities of ≤ 0.5 fps are considered to have BTA for impingement only. In addition, the Phase II Rule requires facilities located on the Great Lakes, tidal estuaries, or small rivers where power plant cooling water withdraw > 5% of the mean annual flow to reduce the number of entrained aquatic organisms by 60 to 90% from a calculated baseline (U.S. EPA 2004). Approximately one-third of the existing power plants in the U.S. subject to the Phase II rule withdraw cooling water from freshwater reservoirs or large rivers. These power plants will only be subject to impingement reduction evaluations (Federal Register 2002).

On 25 January 2007 the Second U.S. Circuit Court of Appeals remanded several provisions of the Phase II Rule back to the U.S. EPA (Riverkeeper, Inc. v. U.S. EPA, No. 04-6692, 2d Cir. 25 Jan. 2007). As a result, the U.S. EPA suspended the entire rule (Federal Register 2007) and is in the process of rewriting it to comply with the Second Circuit's decision. Undoubtedly, the revised Phase II rule will establish "best technology available to minimize adverse environmental impact" whenever it is promulgated.

The Phase II rule has other requirements which include conducting environmental impact studies and other studies for any technology that may mitigate or reduce impingement. However, given the multitude of environmental variables that may affect the rates of impingement, the ability to quantify impingement or entrainment rates is challenging. Factors that may play a role in these rates include temporal variations, episodic events, water quality, and hydrological and biological factors including fish health. Accounting for these factors must be considered when evaluating the effectiveness of any potential mitigating technology that may reduce impingement.

Attempts to reduce impingement rates have included the development of exclusion devices that can be grouped in one of two categories: physical and behavioral. Physical devices typically surround an intake structure and physically block the entrance into the CWIS. However, physical barriers, such as traveling water screens, have limitations which include occlusion due to the selection of small mesh sizes (Mueller et al. 2001). Behavioral devices, on the other hand, are designed to act upon the fish's senses with the intention of inducing an avoidance response.

Research has shown that unnatural stimuli such as strobe lights tend to repel fish whereas other stimuli including constant light sources are attractants. (Coutant 2001b; Nemeth and Anderson 1992; Wickham 1973). The use of strobe lights and sound devices covering a broad range of frequencies (infrasonic, sonic, and ultrasonic) to manipulate the movement of fish has been well documented (Coutant 2001a). However, studies evaluating the use of sound in combination with lights as a hybrid deterrent have been limited. In addition, studies on the use of light or sound deterrents in an attempt to modify the behavior of an entire community of fish at CWISs are not well documented. The overall objective of this study was to evaluate the efficacy of a full-scale underwater strobe light and sound system as a behavioral deterrent to reduce the impingement rates at Plant Barry in south Alabama located along the Mobile River. The effectiveness of the strobe lights and sound deterrents were determined through the evaluation of traveling screen impingement.

2 LITERATURE REVIEW

Many studies have evaluated the use of behavioral deterrent devices in attempts to modify fish movements. A number of laboratory and field studies have begun to evaluate the applicability of using either light or sound as behavioral deterrents for fish. However, few studies have evaluated the potential for combining these deterrents into a “hybrid” (light and sound) behavioral deterrent system. Popper and Carlson (1998) suggest that the combined use of light and sound stimuli to modify fish behavior may yield the most promising results. The application of light and sound behavioral deterrents relies on the avoidance responses produced when fish perceive signals emitted from the devices through the senses of sight and hearing. However, the physiology and behavior of fish must be known before attempting to use a particular stimulus to elicit a response.

2.1 Light and Sound Detection in Fish

Fish have a variety of sensory capabilities that enable them to detect a wide range of external stimuli. Fish react to these stimuli with an assortment of behavioral responses. However, fish may be limited in their ability to detect the full range of signals within a given stimulus. For example, fish may not detect all flash rates emitted from a strobe light deterrent or all sound frequencies emitted from an acoustic behavioral deterrent. The signals that a particular species of fish is able to detect can be limited by the fish’s receptors or the signal transmission properties of the environment (Tavolga et al. 1981, Ali and Klyne 1985, Popper and Carlson 1998, Barton 2007). Fish have also demonstrated a preference for certain signals within the full range of possible signals produced by a sensory stimulus (Sager 1985).

2.1.1 Light Detection

Fish exhibit a wide degree of sight capabilities that reflect the different habitats, taxa and life stages that exist among these organisms. The efficiency of the eye to detect light is determined by the number, disposition, and types of visual cells; connection of the cells to the optic neurons; mechanisms for adjusting to different water qualities; and effectiveness of the tapetum lucidum (Baron 2007). The tapetum lucidum is a structure composed of reflective guanine crystals that enhances visual sensitivity under low light conditions (Barton 2007). Sight capabilities depend on rods and cones located in the retina. Rods function in dim light, whereas cones are adapted to function in brighter light and are responsible for color vision. There are at least two classes of cones responsible for color vision, with each sensitive to different portions of the electromagnetic spectrum (Hawryshyn 1998). Refer to Figure 1 for a representation of a fish eye, showing the relationships of its parts.

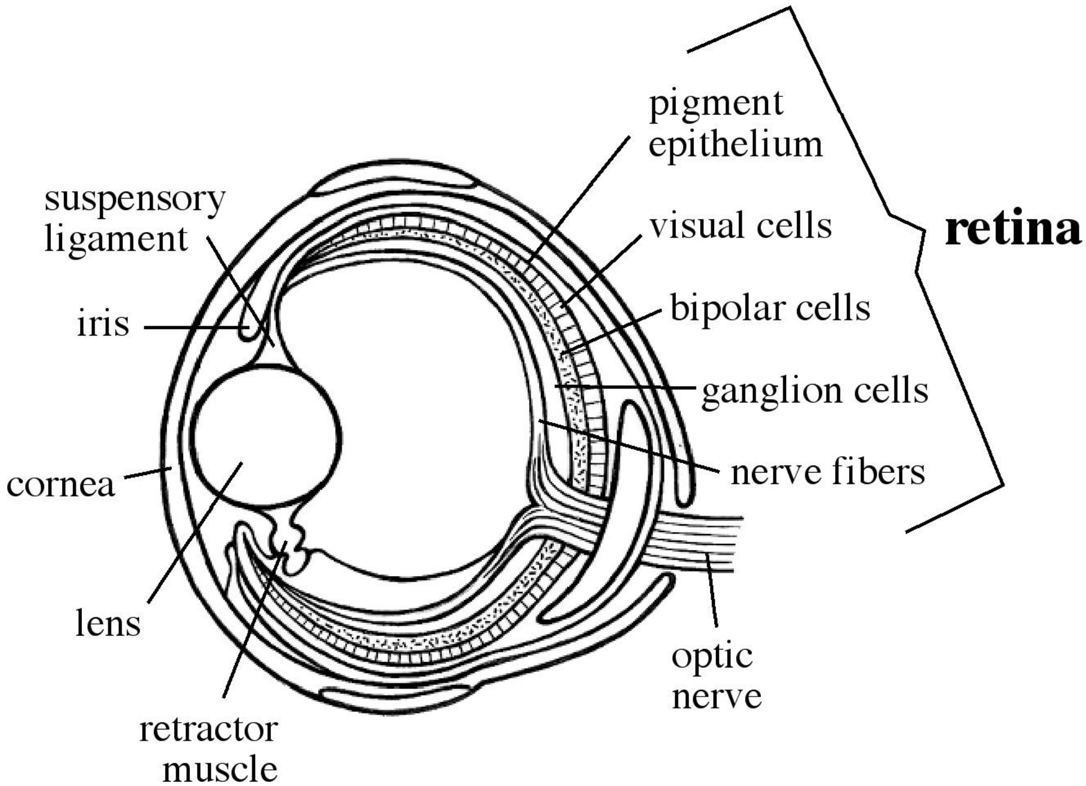


Figure 1. Cross-sectional view of a fish eye, showing the relationships of its parts. (Redrawn form Barton 2007.)

Vision is particularly critical to fish that live in clear, well-lit waters. Fish living in these waters rely more on the sense of sight compared to those living in a light-deprived habitat. Fish living in dimly-lit habitats rely primarily on olfactory senses, mechanosensory, or electrosensory lateral line systems (Barton 2007). Sensitivity to light also varies by species and life stage. Boehlert (1978, 1979) concluded that larvae and juvenile splitnose rockfish *Sebastes diploproa* stay near the surface for about a year before migrating to deeper water. As the fish move to deeper waters their retinas adapt to diminishing light conditions by decreasing cone density while increasing rod density. In addition, photo- and light-sensitive pigment ratios located on rods and cones may change with different life stages in anadromous fishes, with a resultant shift in spectral sensitivities. In observations of the sea lamprey *Petromyzon marinus* and white perch *Morone americana*, changes in pigmentation may maximize the visual capacities of these fish to changing environments (Ali and Klyne 1985).

The difference in eye size relative to body size appears to be related to the importance of vision, with species more dependent on sight having larger eyes (Beukema 1968). Pankhurst (1989) also found that fishes of different ecological niches or habitats had varying visual abilities based on differences among photoreceptors and eye morphology. Nocturnally active species lacked the visual acuity of diurnal species; however, nocturnal species had better sensitivity to light. Herbivores had smaller eyes than carnivores relative to their body size, whereas, planktivores and nocturnal species had relatively large eyes.

The ability of fish to detect a flashing (or strobe) light source may be explained through a phenomenon known as flicker fusion frequency (FFF). A transient retinal stimulus, such as a strobe light, is not extinguished immediately after cessation of the stimulus. The transient retinal stimulus persists for a short interval depending on the state of adaptation of the eye and the intensity of the stimulus. FFF occurs when the ability to distinguish separate flashes in a flashing light source ceases (Ali and Klyne 1985). Beyond FFF the sequential flashes of a strobe light would appear as a continuous light source. Little is known of FFF in fish; however, Patrick et al. (1982) reported that American eels responded to strobe lights flashing at a rate as high as 1090 flashes per minute.

2.1.2 Sound Detection

Fish are generally grouped as being either "hearing specialists" or "hearing generalists" based on the presence or absence of specialized structures that enhance sensitivity to sound. Fish perceive sound through the octavolateralis system that detects, extracts, and processes information from both hydrodynamic and acoustic components of the sound fields (Popper and Carlson 1998). This system consists of the auditory, equilibrium, and lateral line systems which use the hair cell for sensory reception (Schellart and Wubbles 1998). The inner ear of fishes function primarily in balance and sound reception via stimulation of hair cells by the otolith, while the lateral line system functions as a mechanoreceptor through detection of particle displacement of water and to pressure via direct stimulation of hair cells and associated structures (Barton 2007). The lateral line functions best in the zone nearest the sound source at frequencies < 200 Hz within a few body lengths of the fish (Carlson 1994; Popper and Platt 1993; Kalmijn 1988, 1989). Refer to Figure 2 for a visual representation of the octavolateralis system components.

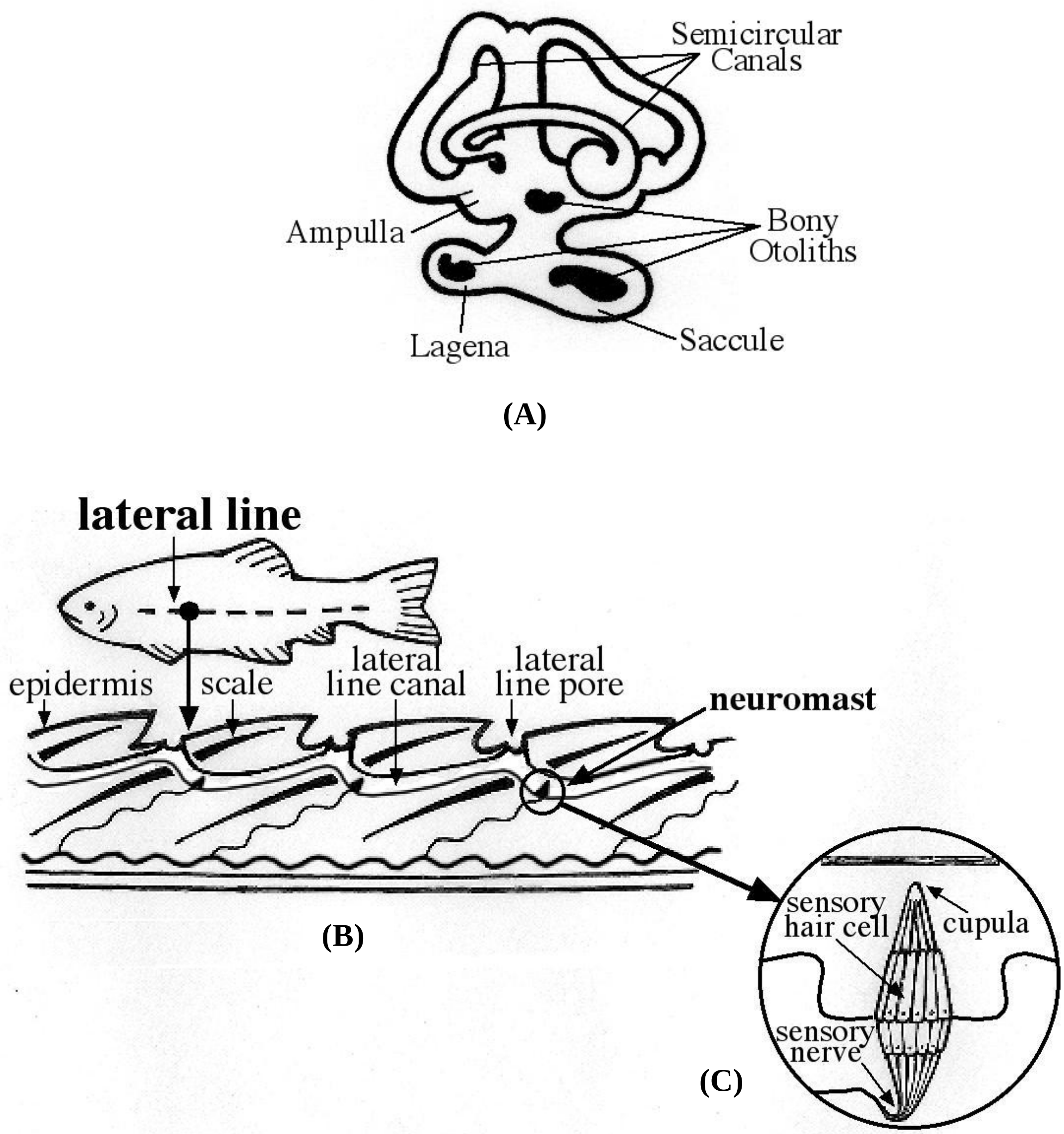


Figure 2. Components of the octavolateralis system in teleost fish. (A) The inner ear, similar to most vertebrates, contains three semicircular canals (equilibrium function) and an acoustic labyrinth with three sacs, each with a small dense bony otolith. (B) Cross-sectional view of the lateral line on the trunk of a cyprinid showing the distribution and innervation of neuromast receptors and the location of pores that connect the canal to the external environment. (C) The neuromast is composed of sensory hair cells, support cells, and innervating sensory neurons. (Redrawn from Helfman et al. 1997.)

The differences in hearing between species can result from the variability of size, shape, and orientation of their otoliths working in concert with the epithelium (Popper et. al 1992; Popper and Platt 1993). Hearing specialists can detect sounds by sensing both compression waves and particle displacement. They also have advantages in all areas of hearing including localizations of sound sources; detection of a wider range of frequencies; and higher sensitivity than fish without these structures (Alexander 1962; Allen et al. 1967; Blaxter et al. 1981; van Bergeijk 1967). Hearing specialists include Otophysans (catfishes and minnows) which have a series of bones called Weberian ossicles that physically connect the rostral end of the swimbladder to the fluid system of the inner ear (Alexander 1962; van Bergeijk 1967; Popper and Coombs 1980) (Figure 3). Members of the family Clupeidae (herrings and shads) have called prootic auditory bullae that are divided by a membrane into a gas-filled segment connected to the swim bladder and fluid-filled segment connected to the inner ear and head lateral line (Allen et al. 1976; Blaxter et al. 1981) (Figure 4). Perciformes (perches and basses) have a swimbladder attached to the skull adjacent to the inner ear (Platt and Popper 1981).

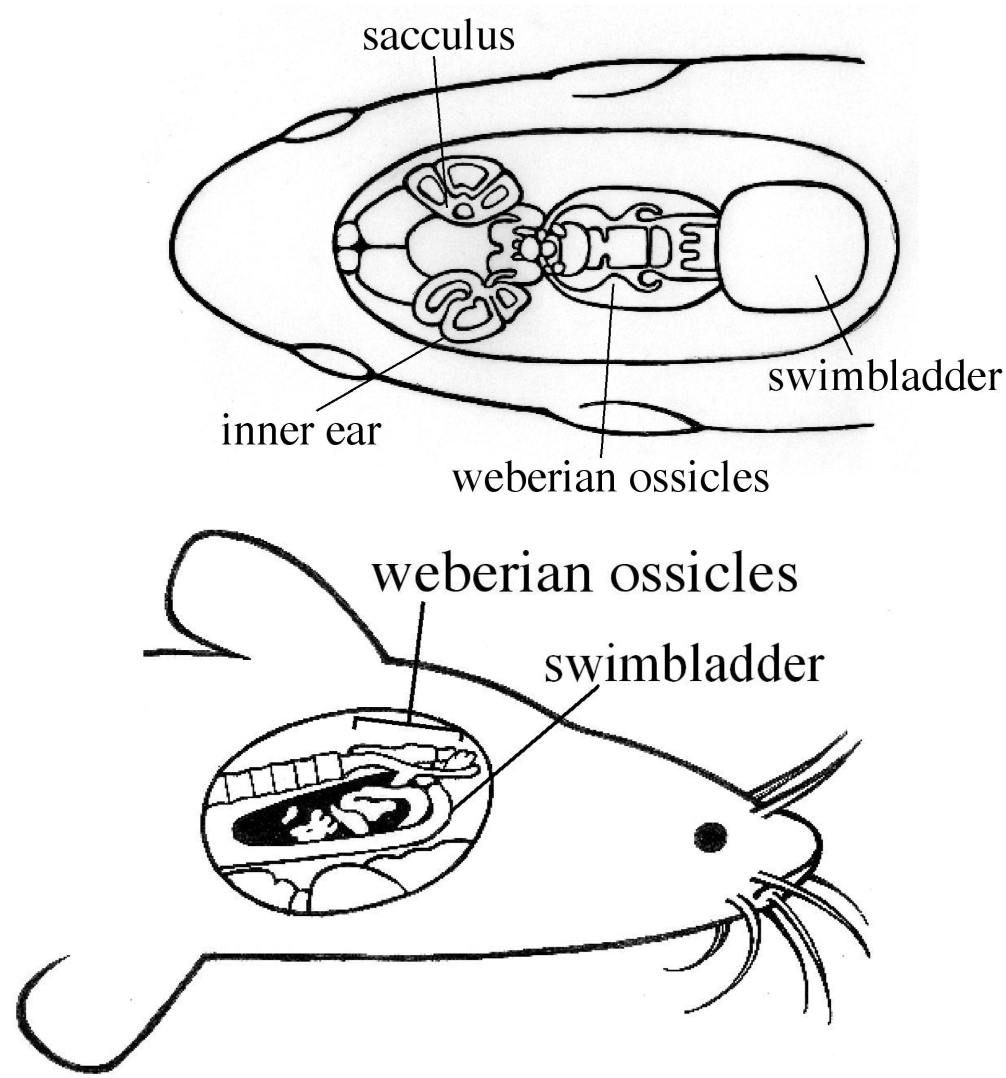


Figure 3. (top) Cyprinids have a series of bones called Weberian ossicles that acoustically couple the swimbladder with fluids of the inner ear bones. The swimbladder serves as primary transducer in receiving sound, transmitting vibrations to the Weberian ossicles and then to the sacculus of the inner ear. (bottom) Dissected side view of a catfish showing linkage from the swim bladder (opened) to the first series of Weberian ossicles. (Redrawn from Tavolga 1965.)

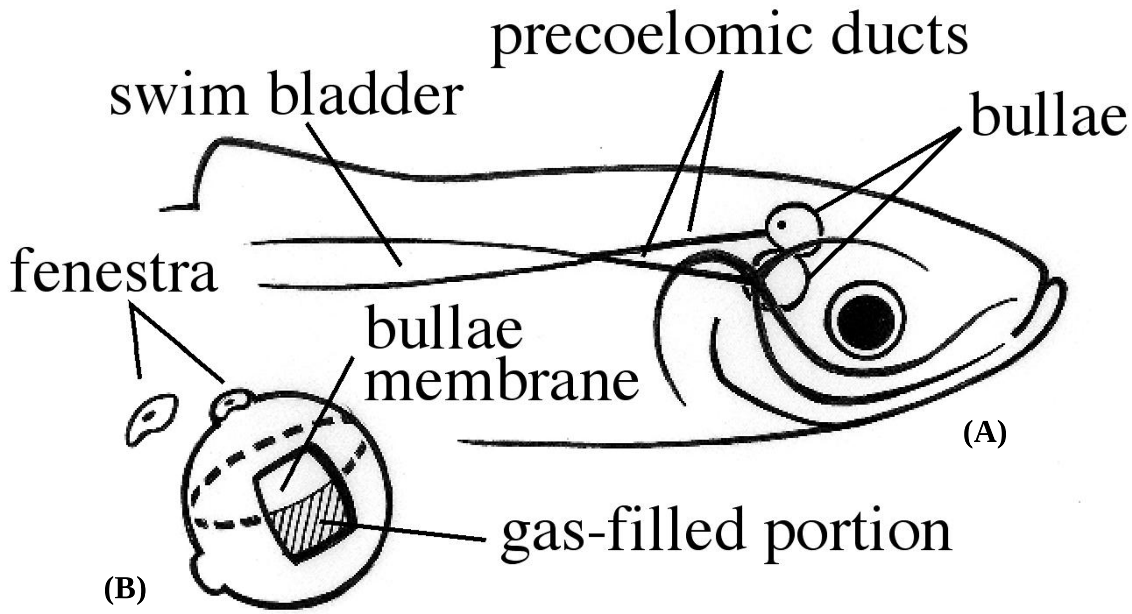


Figure 4. Features of the clupeid acousticolateralis system include bullae (pressure-displacement converters), hydrodynamical connections between the ear and lateral line, and gas connections between the bullae and swimbladder which allow adaptation to depth. (A) Position of two bullae, lateral line canals, and connections between bullae and swim bladder. (B) Bulla and its fenestra, elastic thread not shown. (Redrawn from Tavolga et al. (eds) 1981.)

Hearing generalists are fish without specialized swimbladders or other mediating structures that enhance sound reception and the ability to hear at extended distances from a sound source. They can only detect limited sound amplitudes and tend to have a comparatively narrow range of sound frequencies that they can sense. (Popper and Platt 1993; Carlson 1994; Popper and Carlson 1998; Barton 2007).

When referencing fish hearing the literature categorizes sound frequencies within three ranges:

- infrasound (infrasonic) <100 Hz
- low frequency (sonic) 100 Hz - 20 kHz, human hearing limits
- high frequency (ultrasound or ultrasonic) >20 kHz

The variability in the range of frequencies over which fish can hear has been shown through many hearing threshold studies. Several methods have been developed to study fish hearing. These methods include cardiac conditioning and the auditory brainstem response (ABR) (Otis et al. 1957, Kenyon et al. 1998). The cardiac conditioning method proposed by Otis et al. (1957) is a classical conditioning method that has commonly been used with fish. This method uses a mild electric shock applied shortly after a sound burst. Electrodes attached to the body of the fish detect a conditioned change in cardiac rhythm. The heart misses a beat when the sound is heard. However, when the sound is not heard, the heart rate remains the same until the shock arrives. ABR is a recent approach to measure fish hearing that is less stressful to the test subject (Kenyon et al. 1998).

Yan (2001) used ABR to conclude that goldfish *Carassius auratus* can hear up to 4 kHz, with best hearing frequency between 500 and 800 Hz. Other cyprinid species including common carp *Cyprinus carpio*, bighead carp *Aristichthys nobilis*, and silver carp *Hypophthalmichthys molitrix* have also been shown to have adequate hearing at frequencies up to approximately 3 kHz when tested through the ABR approach (Kojima et al. 2005; Lovell et al. 2006). Common carp was also tested through avoidance conditioning procedures (Popper 1972). Fathead minnow *Pimephales promelas* was reported to have adequate hearing at frequencies up to approximately 4 kHz when tested through the ABR approach (Sholik and Yan 2001). A study using ABR showed that Black drum *Pogonias cromis* can detect frequencies from <100 to 800 Hz, with greatest sensitivity <500 Hz (Ramcharitar and Popper 2004). Wolffe (1968) demonstrated that pike perch *Lucioperca sandra* can detect frequencies up to 800Hz through electric shock training. American shad *Alosa sapidissima* have the greatest sensitivity to sounds between 200 and 800 Hz, but also had sensitivity to ultrasonic frequencies with an upper limit at approximately 180 kHz (Mann et al. 1997). They used a classical conditioning technique in which the fish learned to reduce their heart rate when they detected a sound. It has been suggested that the detection of ultrasonic frequencies by *Alosa* involve the utricle of the inner ear (Mann et al. 2001; Higgs et al. 2004; Popper et al. 2004). Another clupeid, the gulf menhaden *Brevoortia patronus*, was also shown to be sensitive to ultrasonic frequencies from 40 to 80 kHz when tested through the ABR approach (Mann et al. 2001). However, other clupeids such as bay anchovy *Anchoa mitchilli*, scaled sardine *Harengula jaguana*, and Spanish sardine *Sardinella aurita* were only sensitive to sonic frequencies, with bay anchovy being able to detect sounds up to 4 kHz. It has been suggested that Atlantic cod *Gadus morhua* have the ability to detect ultrasonic frequencies (Astrup and Mohl 1993). In general, fish have optimal hearing capabilities within the infrasonic and sonic regions from <20 Hz up to approximately 700 Hz (Platt and Popper 1981; Sand et al. 2001).

Fish perceive synthetic loud noises as unnatural and these noises produce an avoidance response (Coutant 2001b). Sounds made by fish predators, such as marine mammals, have also been used to effectively induce avoidance responses (McKinley et al. 1987). The ability of fish to detect these alarming sounds is generally expressed as a minimal detectable level or threshold. The minimum threshold is often defined through trial studies as the sound pressure level to which the fish will respond on a specified proportion of presentations. The absolute hearing threshold is not necessarily fixed for a given species under predefined background noise conditions. Rather, the hearing threshold may change with age and physiological state (Hawkins 1981).

Knowledge of the frequency ranges fish are able to hear, along with minimum sound pressure levels (SPLs) at which fish can detect these frequencies is important when choosing frequencies especially when being used as a behavioral deterring methodology. In addition to identifying what fish can hear, previous sound deterrent studies can also provide valuable insight into which sound systems would prove successful at deterring a given suite of species in a particular set of environmental conditions. Hearing capabilities for fish species or representative fish species which occur at a specific location may be represented in graphical format. These graphs can then be overlaid with frequencies and SPLs to be used as a fish deterrent at these locations. Figures 5-11 present the hearing thresholds for American shad, clupeids, bay anchovies, cyprinids, ictalurids, bluegill *Lepomis macrochirus* and sciaenids.

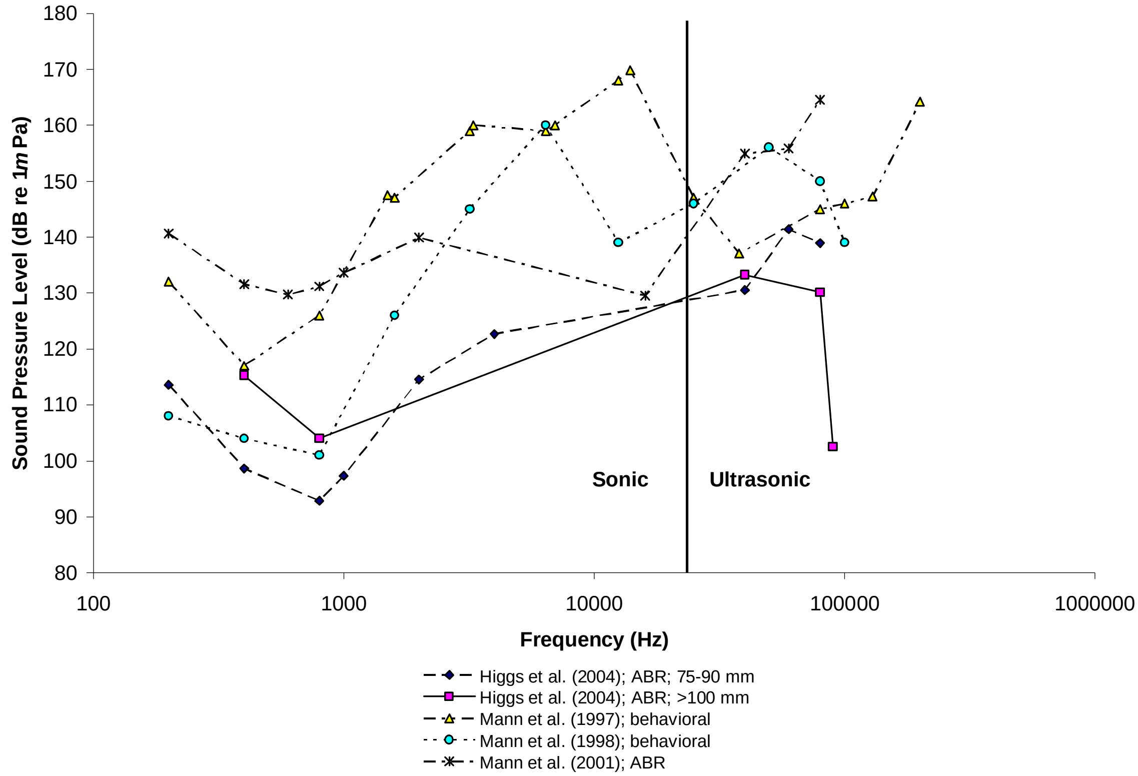


Figure 5. Hearing thresholds for American shad *Alosa sapidissima*.

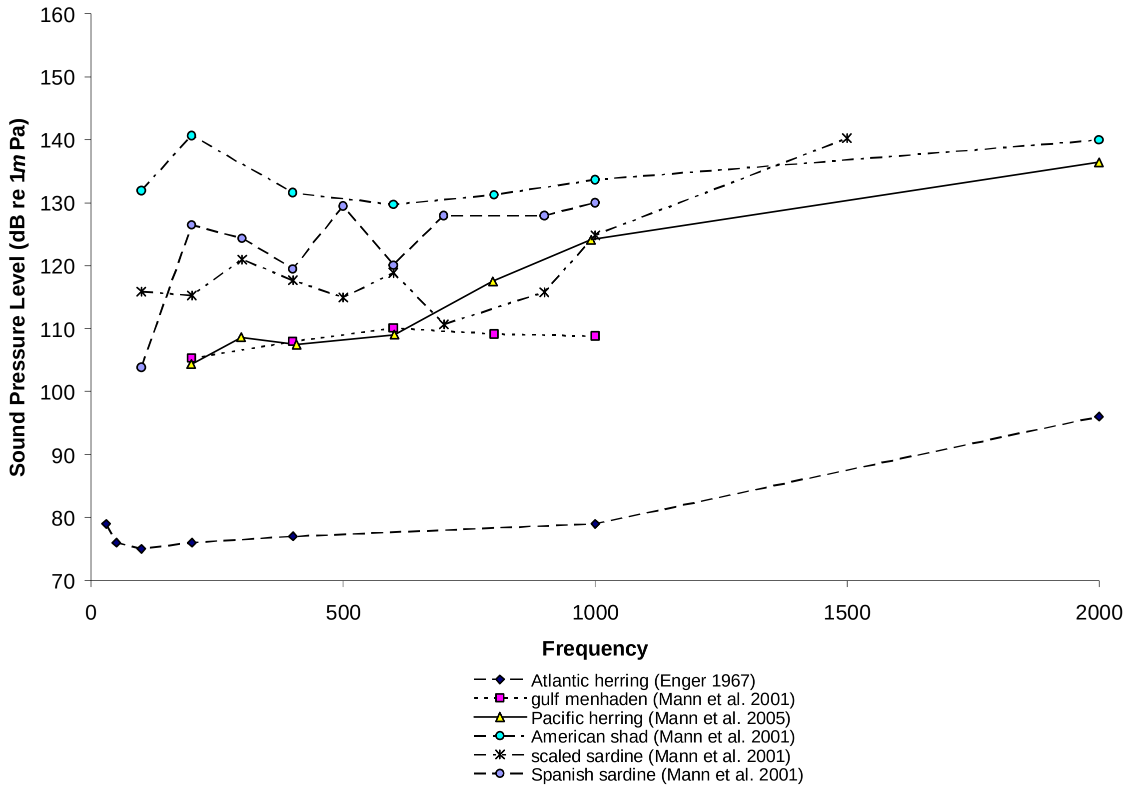


Figure 6. Hearing thresholds for six clupeid species: Atlantic herring *Clupea harengus* (Enger 1967) and Pacific herring *Clupea pallasii* (Mann et al. 2005), and gulf menhaden *Brevoortia patronus*, American shad *Alosa sapidissima*, scaled sardine *Harengula jaguana*, and Spanish sardine *Sardinella aurita* (Mann et al. 2001).

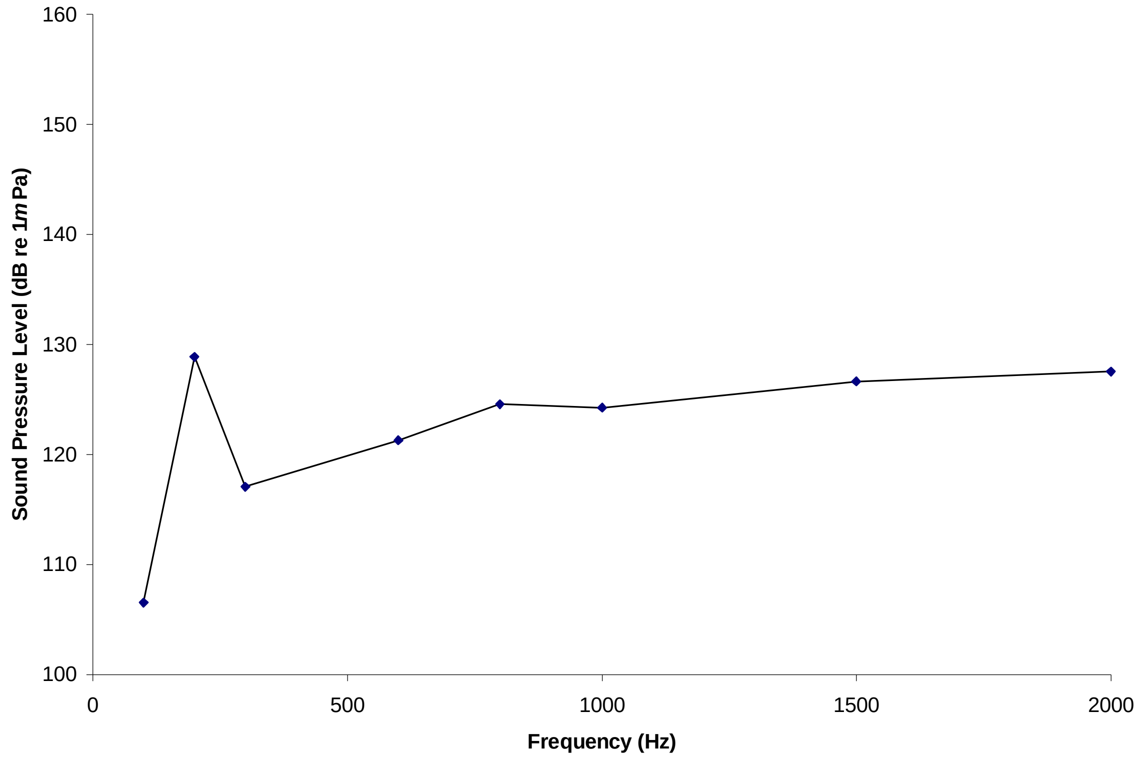


Figure 7. Hearing thresholds for bay anchovy *Anchoa mitchilli* (Mann et al. 2001).

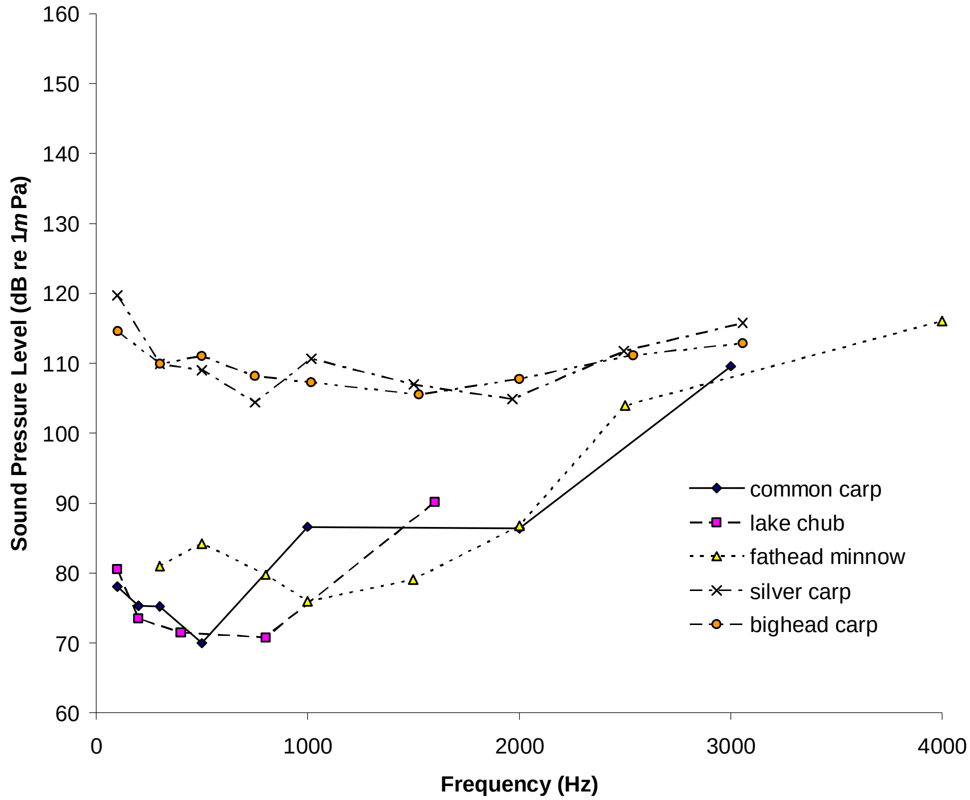


Figure 8. Hearing thresholds for five cyprinid species: common carp *Cyprinus carpio* (Kojima et al. 2005), lake chub *Couesius plumbeus* (Popper et al. 2005), fathead minnow *Pimephales promelas* (Sholik and Yan 2002), and silver carp *Hypophthalmichthys molitrix* and bighead carp *Aristichthys nobilis* (Lovell et al. 2005).

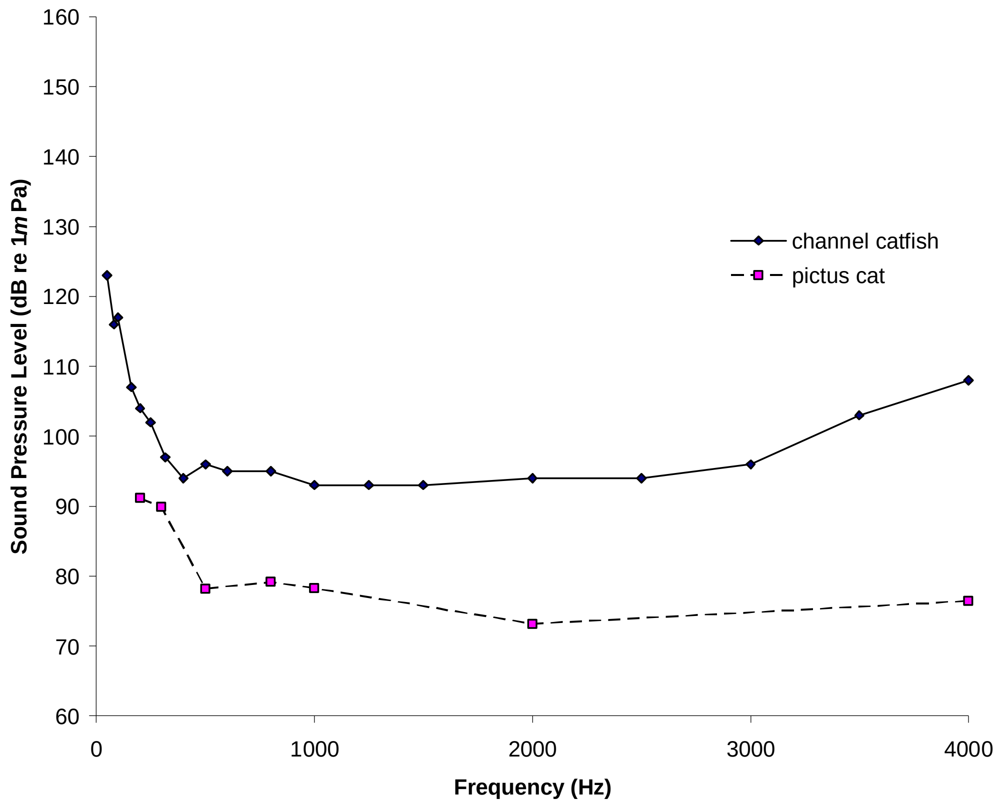


Figure 9. Hearing thresholds for two catfish species: channel catfish *Ictalurus punctatus* (Fay and Popper 1975) and pictus cat *Pimelodus ornatus* (Amoser and Ladich 2003).

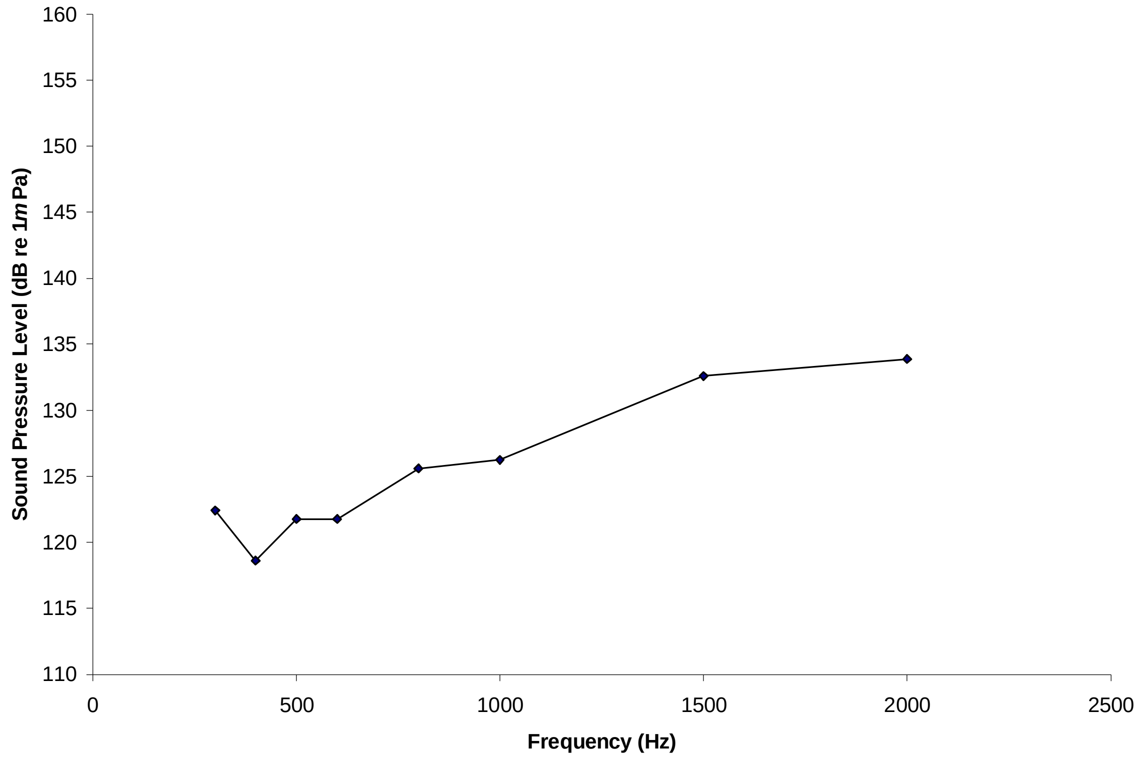


Figure 10. Hearing thresholds for bluegill *Lepomis macrochirus* (Sholik and Yan 2002).

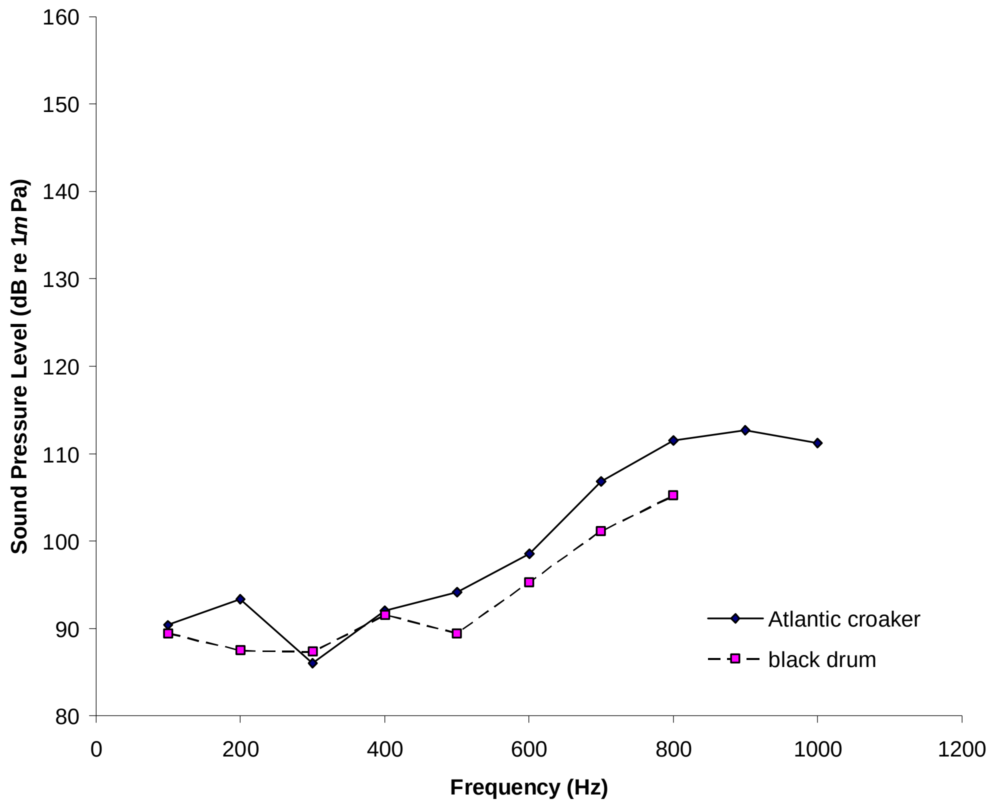


Figure 11. Hearing thresholds for two sciaenid species: Atlantic croaker *Micropogonias undulatus* and black drum *Pogonia cromus* (Ramcharitar and Popper 2004).

Fish hearing is most acute in the infrasonic and sonic ranges of 0-1000 Hz where ambient and manmade noise levels are highest (Urick 1967). Background noise in this range is also ubiquitous in the underwater environments near power plants (Anderson et al. 1989). The detection of sound in the infrasonic and sonic regions is important for the survival of the fish and may be produced by approaching predators or prey; the alarming body motion of a startled neighbor; the vocalizations of conspecifics; and other similar sources (Anderson et al. 1989; Urick 1967). Detection of sound may not be limited by sensitivity but by the level of background noise in the environment. Several studies have concluded that background noise has a masking effect that limits the detection of sounds. When fish are presented with a sound in a noisy environment, such as in the vicinity of a power plant, the threshold for hearing the sound depends on the intensity of environmental noise. Sound must be at least 10 dB above background noise to be detected (Tavolgo 1967, 1974; Buerkle 1968; Coombs and Fay 1989). Although, limited data exist on a variety of fish species and the effect of a continuous background noise source on fish hearing. Background noise must be taken into consideration and measured before an appropriate sound deterrent is selected for a given location. The sound deterrent must transmit sound at SPLs sufficiently greater than background noise levels in order to be detectable by fish in the surrounding area.

2.2 Overview of Deterrent Systems

2.2.1 Light Deterrents

Strobe lights have been successful in altering the behavior of fishes and are the most widely used underwater light system for fish deterrent purposes (Popper and Carlson 1998; EPRI 1999; Bullen and Carlson 2003). Strobe lights used in behavioral deterrent studies have similar operating criteria across manufacturers. Most strobe lights tested are high intensity; have the highest energy output in the violet-blue-green regions (400-570 nm) of the spectrum; and are set at flash rates of 300 flashes/minute or higher (Coutant 2001a; EPRI 2004). However, the intended performance of a strobe light can be affected by environmental conditions (turbidity, ambient light), target species, life stage, and physiological state (Anderson 1988; Fernald 1988; Nemeth and Anderson 1992; Amaral et al 1998; Mueller et al. 2001). Flashing and constant-intensity light may affect the target species by acting as an attractant in some instances while repelling fish in others cases. In general, strobe lights have been shown to repel fish (Patrick 1982a, 1982b; Patrick et al. 1982, 1985; Sager et al. 1987; Coutant 2001a), whereas constant lighting may produce either an attraction or repulsion (Wickham 1973; Nemeth and Anderson 1992; Taft et al. 2001). Fish perceive strobe lights as unnatural and exhibit an avoidance response (Coutant 2001b). A comprehensive review of strobe light behavioral guidance studies arranged by species is given in Appendix 1

2.2.1.1 Laboratory Studies Using Light

A number of controlled laboratory studies have been performed to determine the behavioral responses of fish exposed to strobe or constant light sources and the findings are mixed. Strobe lights have been shown to be effective in eliciting a response from a wide variety of species (Taft et al. 2001), and have been proven more effective at repelling fish than a continuous light source (Coutant 2001a). Jahn and Herbinson (2000) investigated light attraction of northern anchovy *Engraulis mordax*, white croaker *Genyonemus lineatus*, and Pacific sardine *Sardinops sagax*. They used a Y-shaped flume in which batches of fish were given a choice between exiting on a lighted (steady or strobed) side or a dark side. Although results were inconclusive for Pacific sardines, a steady light source was reported to be ineffective at producing either an attraction or aversion; however, use of a strobe light repelled white croaker. Northern anchovy showed both an attraction and repulsion to strobe light. PSEG (2003) reported similar ambiguous results when strobe lights were used to produce a behavioral response in weakfish *Cynoscion regalis*. Weakfish in their flume study showed little behavioral change for trials with only strobe light and were possibly attracted.

Several other controlled laboratory studies have used strobe light in attempts to modify fish behavior. Konigson et al. (2002) examined the behavior of whitefish *Coregonus lavaretus* exposed to strobe lights. The fish responded by turning away from the strobe light and increasing their swimming speed. A study evaluating gizzard shad *Dorosoma cepedianum*, hybrid striped bass *Morone chrysops-saxatilis*, largemouth bass *Micropterus salmoides*, bluegill *Lepomis macrochirus*, walleye *Sander vitreus*, and channel catfish *Ictalurus punctatus* using strobe lights resulted in all species, except largemouth bass, demonstrating some level of avoidance (EPRI 1990). Walleye exhibited the strongest avoidance response. Atlantic menhaden *Brevoortia tyrannus*, spot *Leiostomus xanthurus*, and white perch *Morone americana* exhibited some level of avoidance to strobe light. Their strengths of avoidance varied with turbidity conditions, often increasing at higher turbidity levels, which is perplexing because increased turbidity minimizes light transmission (McInnich and Hocutt 1987; Sager et al. 2000). McInnich and Hocutt (1987) suggested that the increased avoidance associated at higher tubidity levels may have been associated with increased light scattering within the near field. In a study evaluating two different illumination levels, European eels *Anguilla anguilla* avoided strobe lights with increasingly higher illumination levels (Hadderingh and Smythe 1997). Patrick et al. (2001) demonstrated that American eels *Anguilla rostrata* could also be repelled by a strobe light, regardless of flash rate (66-1090 flashes/min). Juvenile American eel avoidance was immediate whereas adults responded by exhibiting marked avoidance only after several minutes exposure to the strobe light source. Mueller et al. (2001) tested the use of strobe lights to induce avoidance movements in several salmonid species. Wild chinook salmon *Oncorhynchus tshawytscha* demonstrated avoidance movements in 60% of the tests; hatchery reared chinook salmon showed avoidance in 50% of the tests; rainbow trout *Oncorhynchus mykiss* showed avoidance in 80% of the tests; and brook trout *Salvelinus fontinalis* showed none to slight avoidance. Other studies involving salmonids have demonstrated some level of avoidance to strobe light, with the types of behavioral reactions varying with ambient light conditions (Puckett and Anderson 1987; EPRI 1990; Nemeth and Anderson 1992).

2.2.1.2 Controlled Field Studies Using Light

Attempts to modify fish behavior in controlled field studies have shown varying results dependent upon the species under investigation. Konigson et al. (2002) examined the behavior of whitefish *Corigonus lavaretus* enclosed in net pens exposed to strobe lights. Fish were observed to increase their swimming speed and their distance from the light source. Ploskey and Johnson (2001) evaluated avoidance of juvenile coho salmon *Oncorhynchus kisutch* and chinook salmon in net pens with lights mounted 1 m outside the pen. Avoidance response was estimated to be 80-100%. Amaral et al. (2001) used various behavioral stimuli in studies with cages conducted in the forebay of the Roza Dam irrigation diverson on the Yakima River, Washington. Smallmouth bass

Micropterus dolomieu and yearling chinook salmon displayed avoidance responses to strobe light at night by rapidly moving to the end of the cage opposite the active strobe lights.

2.2.1.3 Uncontrolled Field Studies Using Light

A study at Sanders Generating Station on the St. Lawrence River used strobe lights to effectively repel upstream migrating American eels. It was estimated that 65-92% of the eels were repelled (Patrick et al. 1982; Patrick et al. 2001). At Four Mile Dam in Michigan, entrainment of bullhead catfish *Ameiurus spp*. and shiner *Cyprinidae* were lower at dusk and dawn when the strobe lights were in operation (McCauley et al. 1996).

The use of strobe lights to modify the movements of salmonids has shown positive results. Johnson et al. (2001) used strobe lights to reduce juvenile salmon spp. densities by 87-96% in front of a filling culvert at the Hiram M. Chittenden Locks, Seattle, Washington. Brown (1999) reported that strobe lights were effective in repelling sockeye salmon *Oncorhynchus nerka* and land locked kokanee salmon *O. nerka*. Kokanee salmon demonstrated that response distance was positively correlated with water clarity. Maiolie et al. (2001) also demonstrated that strobe lights could be used to repel free-ranging kokanee salmon in the pelagic region of northern lakes. Densities of kokanee were reduced by 72-100% near the strobe lights in two Idaho lakes (Spirit Lake and Lake Pend Oreille).

Mixed results have been obtained when using strobe lights to deter clupeids. American shad *Alosa sapidissima* and alewife *A. pseudoharengus* had negligible responses to strobe lights, and in some cases it appeared to be an attractant (Patrick et al.

1988a; EPRI 1990). However, some studies have demonstrated that American shad and alewife can be repelled by strobe lights (Patrick 1982b; Patrick et al. 1985; EPRI 1992).

Mixed results have also been obtained when trying to deter an entire community of fish. Studies at Milliken Station, New York, resulted in some species being attracted to strobe lights while others were repelled. Additionally responses varied by season and fish age (Ichthyological Assoc.1994, 1997). Ability to reduce impingement of most anadromous species at Roseton Generating Station, Newburgh, New York was accomplished with strobe lights alone or in combination with a sound generating device and an air bubble “curtain”. Greater reductions were observed when devices were used in combination (EPRI 1988). Another study found freshwater species abundance near Ludington Pumped Storage Project (Ludington, Michigan) were significantly lower during periods when the strobe lights were operating compared to periods when the lights were off (EPRI 1990). In contrast, the use of strobe lights to reduce entrainment of riverine fish species at White Rapids Hydroelectric Project (Marinette, Wisconsin) was not detectable (Michaud and Taft 1999).

2.2.2 Sound Deterrents

The use of sound as a fish deterrent may be desirable over other methods. Nester et al. (1992) lists several advantages such as: 1) many fish are startled by sound 2) short-range propagation is minimally affected by turbidity and 3) sounds can be used during both day and night. Sound can also travel long distances, high rates of speed, and in all directions through water (Popper and Carlson 1998). Sound is used by fish to sense and respond to potential hazards in their environment (Carlson 1994; Bullen and Carlson

2003). Acoustic deterrents using infrasonic and sonic frequencies could potentially be used for a multi-species repulsion system, given that most fish are sensitive to sound in these ranges (Sand et al. 2001). A comprehensive review of acoustical behavioral guidance studies arranged by species is given in Appendix 2.

2.2.2.1 Laboratory Studies Using Sound

Controlled laboratory studies have been explored using sound as a fish deterrent for several species. Black drum *Pogonias cromis* placed in concrete raceways avoided infrasonic frequencies in the range of 10-100 Hz by moving to the opposite end of the tanks (Brown et al. 2006). In a study using a 10 Hz infrasonic frequency, avoidance responses were observed in chinook salmon (40-45 mm) within cages placed in a fiberglass tank (Mueller et al. 2001). Knudsen et al. (1997) also used an infrasonic frequency at 10 Hz, within circular tanks, to cause flight and avoidance responses in juvenile chinook salmon and rainbow trout. Karlsen et al. (2004) concluded that juvenile roach *Rutilus rutilus* demonstrated escape responses to 6.7 Hz infrasonic frequencies due to similar particle acceleration and compression produced by an approaching predator. Sonic frequencies of 100-3,000 Hz were used in flume studies to produce avoidance behavior in bay anchovy, Atlantic croaker *Micropogonias undulatus*, and weakfish (PSEG 2003). The authors also observed avoidance of blueback herring *Alosa aestivalis* to ultrasonic frequencies ranging from 80 to 120 kHz.

2.2.2.2 Controlled Field Studies Using Sound

Sound has been shown to be a feasible fish deterrent option in controlled field studies. Black drum stocked in ponds demonstrated an avoidance displacement when exposed to pure tones of infrasonic frequencies in the range of 10 to 60 Hz (Brown et al. 2006). The response of riverine fishes to sound signals was evaluated during cage tests conducted at the Kingsford Hydroelectric Project on the Menominee River in Wisconsin. It was shown that rainbow trout avoided frequencies of 6 kHz; walleye avoided frequencies between .6 to 3 kHz; yellow perch *Perca flavescens* avoided frequencies between .7 to 2 kHz; and largemouth bass avoided frequencies between .3 to 5.5 kHz (EPRI 1998b; Winchell et al. 1997; Michaud and Taft 1999). Holand and Walso used a 30 Hz infrasonic sound barrier to repel cod within a net pen at a tidal pool in Sommaroyhamn, Norway. Caged northern pikeminnow *Ptychocheilus oregonensis* strongly avoided infrasonic frequencies at <50 Hz at the forebay of the Roza Dam irrigation diversion, Washington (Amaral et al. 2001).

2.2.2.3 Uncontrolled Field Studies Using Sound

In natural systems, sound deterrent systems have demonstrated that fish movement and behavior can be manipulated using infrasonic, sonic, and ultrasonic frequencies. Sonny et al. (2006) used an infrasonic frequency of 16 Hz in a cyprinid dominated lake in Norway. Results showed that the numbers of cyprinid fishes entering a nuclear power plant's CWIS were significantly reduced. In addition, the cyprinids failed to show significant habituation to the deterrent. The authors concluded that the degree of avoidance was negatively correlated with water velocity entering the CWIS. European silver eels migrating downstream were significantly deterred from an acoustic fish fence operating at <35 Hz (Sand et al. 2001). PSEG (2005) used frequencies ranging from 100 Hz – 120 kHz in open water tests near the CWIS at Salem Generating Station, New

Jersey. The authors reported avoidance responses in blueback herring, American shad, Atlantic menhaden, bay anchovy, and Atlantic silverside *Menidia menidia*.

Other field studies also have shown that sound can be used to modify fish behavior, with frequencies being species specific. Studies have demonstrated that Atlantic salmon have optimum sensitivity around 200 Hz (Hawkins and Johnstone 1978). However, they have been shown to avoid an infrasonic frequency of 10 Hz, but not at sonic frequencies in the 150 Hz range (Knudsen et al. 1994). Maes et al. (2004) used sound in the infrasonic and sonic range of 20-600 Hz to reduce the numbers of clupeids from entering the CWIS at the Doel Nuclear Power Plant (Antwerp, Belgium). Atlantic herring *Clupea harengus* and sprat *Sprattus sprattus* were reduced from entering the CWIS by 94.7% and 87.9%, respectively. These authors also demonstrated a significant reduction in 7 other species or taxa including white bream *Abramis bjoerkna* (40.1%), smelt *Osmerus eperlanus* (53.5%), European seabass *Dicentrarchus labrax* (75.6%), European perch *Perca fluviatilis* (51.2%), common sole *Solea solea* (46.6%), flounder *Platichthys flesus* (37.7%), and gobies *Pomatoschistus spp.* (46.1%).

Some freshwater clupeids in the genus *Alosa*, on the other hand, are sensitive to ultrasonic frequencies in the range of 80-150 kHz and elicit avoidance responses to these frequencies (Dunning et al. 1992; Nestler et al. 1992; PSEG 2003). Alewife impingement was reduced by 80% using ultrasonic frequencies (122-128 kHz) at James A. FitzPatrick Nuclear Power Plant on Lake Ontario (Ross et al. 1996). At the Annapolis Tidal Generating Station, Nova Scotia, Canada, ultrasonic frequencies between 122 and 128 kHz were used to reduce American shad passage through turbines by 42% and alewife by 48% (Gibson and Myers 2002). On the Wye River in Wales, twaite shad *Alosa fallax*

fallax displayed avoidance behavior to sound transmitted at 200 kHz, but not at 420 kHz (Gregory and Clabburn 2003).

2.2.3 Hybrid Deterrents

Behavioral deterrent systems have generally been used separately in past studies to reduce impingement. These studies typically involve a single or limited number of target species. With sensory perception and stimulation varying among species, it can be presumed that a “multi-sensory” approach where different technologies are combined will deter a greater number of fish species and a wider range of size classes under a more diverse set of environmental and site conditions than any singular barrier could (Coutant 2001b; Patrick et al. 2006). Coutant (2001b) suggests using a combination of attraction (i.e., turbulent attraction flows, mercury lights) and repulsion (i.e., strobe lights, sound) techniques to take better advantage of fish sensory capabilities. For example, a deterrent could be applied in the vicinity of an intake and an attraction applied to a bypass. However, an attraction/repulsion behavioral guidance system would likely be designed for a narrow range of species, because what repels or attracts one species may not produce the same response in other species. On the other hand, using a combination of behavioral deterrent devices has resulted in a greater ability to repel a single species of fish and a greater diversity of fish than using either deterrent device alone (Patrick et al. 1985, 2006; EPRI 1988; McCauley et al. 1996). For a hybrid behavioral deterrent to be successful, as with any single deterrent, it will most likely depend on the primary fish species to be protected and local hydraulic and environmental conditions. Refer to Appendix 3 for a comprehensive review of hybrid behavioral guidance studies arranged by species.

2.2.3.1 Laboratory Studies Using Hybrid Deterrents

Laboratory studies have shown encouraging results when using a combination of deterrent devices to repel fish. It was demonstrated that a strobe light used to illuminate an air bubble curtain barrier could effectively deter alewife greater than the air bubble curtain used alone. The hybrid strobe light and air bubble deterrent ranged in effectiveness from 90 to 98%. This was up from the 38 to 73% effectiveness observed when using the air bubble curtain alone (Patrick et al. 1985). McIninch and Hocutt (1987) reported similar results for spot, Atlantic menhaden, and white perch to strobe light, an air bubble curtain, and a combined strobe light/air bubble curtain barrier. All tests, except for spot, indicated an increased avoidance to the hybrid strobe light/air bubble deterrent than either deterrent alone.

Patrick et al. (2006) conducted a study using strobe light, sound, and a combined strobe light/sound deterrent to repel pelagic (alwife, gizzard shad, and shiner minnows) and demersal (brown bullhead and white sucker) species. The hybrid strobe light/sound deterrent effectively repelled all species tested greater than any deterrent alone. A species specific response was observed with sound and/or strobes having a greater ability to repel certain species over others. For example, the sound system was more effective at repelling pelagic species (80% effective) over demersal (15 and 64% effective for brown bullhead and white sucker respectively) species. On average the strobe light deterrent outperformed the sound deterrent as a multiple species repellant.

2.2.3.2 Field Studies Using Hybrid Deterrents

The effectiveness of hybrid behavioral deterrents in the field has varied. Regardless of effectiveness, combining deterrents generally demonstrates a greater ability to repel fish than deterrents used alone. Combining strobe light and air bubble barriers have shown promising results. McCauley et al. (1996) used a strobe light/air bubble barrier to effectively reduce turbine entrainment at Four Mile Dam in northern Michigan. Strobe lights with and without air bubbles significantly reduced the number of fish passing through the turbine. During combined strobe light/air bubble studies fish passage was reduced, on average, by 81% across all species and sampling periods, while a 77% reduction was seen when strobe lights were used alone. At Roseton Generating Station, Hudson River, New York, a combined strobe light/air bubble deterrent was more effective at lowering clupeids (American shad, blueback herring) and white perch impingement than either deterrent used alone (EPRI 1988). In this study the authors also used a pneumatic gun and when combined with strobe light, resulted in highest overall reductions in total fish impingement. However, no combination of deterrents or a deterrent used alone was an effective behavioral barrier for all fish species under all conditions. The results showed that when all three deterrents were used in combination it tended to attract fish.

A study conducted at Pickering Generating Station, Lake Ontario, Canada also tested strobe light, pneumatic gun, and an air bubble curtain (Ontario Hydro and LMS 1989). The pneumatic gun when combined with the air bubble curtain, resulted in highest overall reduction in alwife dominated impingement. However, the reduction was similar to the pneumatic gun alone. Strobe light and bubble curtain combination was more effective at reducing impingement rates than either deterrent alone. Combining strobe light with the pneumatic gun increased the ability of strobe light to reduce impingement, but decreased the effectiveness of the pneumatic gun when compared to its use alone.

Mckinley and Patrick (1988) tested strobe lights, a popper, a hammer, and an air bubble curtain for their ability to repel outmigrating sockeye salmon smolts at Seton Hydroelectric Station, British Columbia, Canada. Combining strobe lights with the popper resulted in the highest amount of deterring effectiveness. However, the effectiveness of the combined deterrent was only about 2 percentage points greater than when using the popper alone. Combining strobe lights with the air bubble curtain resulted in low effectiveness (about 11%). The combination, however, proved to be more effective than using the air bubble curtain alone. Another study testing the effectiveness of behavioral deterrent on salmonids was conducted at Puntledge Generating Station, Vancouver, British Columbia (Bengeyfield and Smith 1989). The combined use of a fish hammer, a strobe light, and a steel chain failed to repel outmigrating coho salmon smolt from approaching the intake.

2.3 Possible Factors Influencing Effectiveness of Deterrents

Knowing the varying degrees of light and sound sensitivity among fish, factors such as species, age, physiological condition and environmental conditions may influence the overall effectiveness of underwater strobe lights and sound as a fish deterrent (Popper and Carlson 1998). Because the environment where deterrents are used is rarely static, deterrents can be influenced by a variety of diurnal, seasonal, and periodic events. These periods of change can behaviorally and physically alter the way fish respond to deterrents and, thus, their effectiveness. Other influential factors altering the effectiveness of deterrents are likely the same as those that may affect impingement rates. These factors include temperature, time of day, wind action, dissolved oxygen, turbidity, water velocity, habitat type, life stage, overall health, disease prevalence, and spawning events. Characteristics of the deterrents themselves such as flash rate for strobe lights and frequency and pressure levels for sound are also important factors influencing the effectiveness of the deterrent systems.

Turbidity and diurnal light cycles are dominant factors that could influence the efficacy of an underwater strobe light deterrent (McIninch and Hocutt 1987; EPRI 1994). Turbidity is defined as an optical property of water wherein suspended and dissolved materials such as clay, silt, small organic and inorganic matter, plankton, and other microscopic organisms cause light to be scattered and absorbed, thereby influencing light attenuation (APHA et al. 1980). Increasing turbidity would diminish the strobe light effectiveness by reducing light transmission. However, McInnich and Hocutt (1987) found their test species demonstrated increased avoidance to strobe light with increasing turbidity. Their findings could be attributed to increased light scattering within the area closest to the strobe lights, which resulted in the observed increase in avoidance. Diurnal factors also influence the effectiveness of using strobe lights in water (EPRI 1994). Background illumination during the day often dilutes light from the stimulus, making it less effective; however, the ambient light is lower at night resulting in greater strobe light efficacy (EPRI 1994). However, Johnson et al. (2005) noted that fish numbers increased with decreasing distance to the strobe lights, but fish near the lights exhibited avoidance responses. They postulated that fish may be foraging on invertebrate prey species attracted to the strobe lights.

Low temperatures or a reduction in temperatures may reduce the efficiency of sound as a fish deterrent. Alewives move into deeper water after spawning (Scott and Crossman 1973) and those remaining in shallow water after temperatures reach 13ºC or above are generally in poor condition (reduced body weight in comparison with length) rendering them less responsive to ultrasonic frequencies and thus reducing the effectiveness of the sound deterrent system (Ross et al. 1993; Ross et al. 1996). Alewifes are also in poor condition, due to lack of feeding and loss of equilibrium, during and immediately after an unusually cold winter (O'Gorman and Schneider 1986). Cold temperatures adversely affect other clupeid species as well. Studies conducted with threadfin shad at southeastern power plants has shown significant increases in impingement rates as the temperature drops below 15°C (Griffith and Tomljanovich 1975; Loar et al. 1978; McLean et al. 1985). Cooler temperatures also cause other temperate water species to be more sluggish and have reduced swimming ability (Griffith and Tomljanovich 1975; Grimes 1975; Hoyt 1979). Low temperatures have been shown to cause a loss of equilibrium, disorientation, and mortality in juvenile freshwater drum *Aplodinotus grunniens* (Bodensteiner and Lewis 1992). With reduced swimming abilities, alewife and other species loose the capacity to effectively avoid behavioral deterrents and thus, reduce the deterrent's efficiency.

Wind and wind-induced effects are strongly correlated to fish impingement (Lifton and Storr 1978). When the fetch of a lake is large, wind can have significant effects on fish location. Lifton and Storr (1978) concluded that fish could be passively moved by wind-created currents toward intake structures leading to increased impingement rates. They also concluded that turbidity increased with increasing wind action and caused fish to be at higher risk to impingement due to decreased visibility.

Impingement also tends to vary inversely with dissolved oxygen (DO) concentrations (Lewis and Seegart 2000). Decreases in DO concentration generally stimulate fish to search for higher concentrations in adjacent areas. The search for higher concentrations of DO may expose fish to other variables such as low temperatures or cause them to be displaced closer to the CWIS (Bodensteiner and Lewis 1992). Fish with reduced physical conditions resulting from low DO or low temperature stress may become subjected to suboptimal conditions rendering them incapable of producing the desired avoidance reactions, causing the deterrent system to become less effective (Bodensteiner and Lewis 1992; Knights et al. 1995).

Species-specific behavioral responses to strobe light flash rate and sound frequencies can determine how effective a deterrent will be for a given location and targeted species or suite of species. For example, the greatest avoidance to strobe lights was shown to be above 300 flashes per minute (Sager et al. 2000). Flash rates below 200 per minute were found to be significantly less effective than higher flash rates (Patrick 1982a). Given the wide range of hearing capabilities among species, appropriate sound frequencies should also be considered when choosing sound as a deterrent. In addition, sufficiently elevated SPLs are necessary to cause a deterrent response at these appropriate sound frequencies.

2.4 Evaluation of Behavioral Responses to Deterrent Systems

The effectiveness of behavioral technologies has been evaluated through a variety of methods in the field and laboratory settings. Passive techniques are generally used to monitor fish in a laboratory setting. However, in the field fish may be monitored both passively (e.g. hydroacoustics) and actively (e.g. impingement rate).

2.4.1 Laboratory Evaluations

The majority of behavioral guidance literature indicates that visual observations and video cameras are the primary methods for evaluation under laboratory conditions, with visual observations being most prevalent. A study conducted by Konigson et al. (2002) used an infra-red (IR) lamp and an IR-camera to film the reactions of whitefish to strobe lights without the interference of another visible light source for filming purposes. The IR-lamp radiated infrared light beams, which were invisible. The IR-camera was sensitive to that radiation and enabled the authors to film in the dark. Mueller et al. (2001) used high-resolution monochrome cameras with a wide-angle lens connected to an 8-mm camcorder to document and record the underwater movement of juvenile salmonids and char in response to infrasonic frequencies and strobe lights.

2.4.2 Field Evaluations

Field studies have taken advantage of hydroacoustic technology to passively evaluate the movements of fish. Ross et al. (1993) determined the effect of an ultrasonic behavioral deterrent on alwife *Alosa pseudoharengus* densities near the CWIS at the James A. FitzPatrick Nuclear Power Plant, Oswego, New York. The authors used a hydroacoustic system that included a 420 kHz echo sounder, two transducers, and a computerized echo counter. Sonny et al. (2006) used a Simrad EY60 echosounder with a composite 7º split-beam 200 kHz transducer to monitor the response of fishes to infrasonic frequencies at the intake of Tihange Nuclear Power Plant on the Meuse River in Belgium. Maiolie et al. (2001) used a Simrad EY500 split-beam scientific echosounder with a 120 kHz transducer to document the reponse of kokanee salmon to strobe lights at Dworshak Dam on the Clearwater River in northern Idaho. A split-beam echosounder was used to determine the effect of sonic frequencies on fish densities at the Hiram M. Chittenden Navigation Locks in Seattle, Washington (Goetz et al. 2001).

It is possible that hydroacoustic equipment could affect fish behaviors if the frequencies being transmitted fall within the hearing range of the fish species being studied. The hydroacoustic frequencies used in the previously mentioned studies were outside the upper hearing ranges of the fish species of interest (<380 Hz for salmon (Hawkins and Johnstone 1978) and up to a possible 180 kHz for alwife (Mann et al. 1997)). Hydroacoustic equipment used for fisheries assessment has not shown avoidance responses by fish primarily because the hydroacoustic frequencies commonly used (30 – 200 kHz) are outside the hearing capabilities of most fish (Simmonds and MacLennan 2005). However, hydroacoustic operating frequencies should be considered when monitoring species sensitive to ultrasonic frequencies that have overlapping hearing ranges.

The accuracy and precision of hydroacoustic equipment has been validated through many field studies. Correlation between net catches and hydroacoustics indicate that hydroacoustic equipment can reliably be used under most conditions to determine fish densities. Net catch estimates were highly correlated to hydroacoustic estimates of smolt passage through hydropower dams in the Columbia River basin (Ransom et al. 1996). Purse seine estimates also correlated well with hydroacoustic estimates of rainbow trout and cutthroat trout in several lakes and reservoirs in Wyoming (Yule 2000). Ploskey and Carlson (1999) found hydroacoustic counts of guided fish were significantly correlated with concurrent gatewell dipnet catches when testing the efficiency of submersible bar screens at John Day Dam on the Columbia River. Hydroacoustic counts of unguided fish were significantly correlated with fyke-net catches; however, hydroacoustic sampling underestimated both guided and unguided fish passage relative to netting estimates.

The use of hydroacoustic target strengths (TS) to calculate fish lengths has been well documented (Simmonds and MacLennan 2005). The size of the swimbladder, which is proportional to fish size and depth, is recognized as having the most important effect on fish TS. Foote (1980) studied the TS produced by fish with a swimbladder compared to those without a swimbladder. He found that more than 90% of the backscattered energy comes from the swimbladder. Other studies have also shown that most of the backscattered energy can be attributed to gas-filled structures in fish and other organisms. (Furusawa 1988; Mukai and Iida 1996; Simmonds and MacLennan 2005). TSs are also dependent on the depth of a fish, because depth can influence the size of a fish's swimbladder. The swimbladder is subject to Boyle's Law. The pressure water exerts at depth can reduce the size of a fish's swimbladder by compression; however, the swimmbladder expands as water pressure decreases when the fish ascends. The TS produced by physostomous fish (those fish that have a connection between the swimbladder and gut) is shown to be more dependent on depth because they typically lack a gas-secreting mechanism (Gunderson 1993; Simmonds and MacLennan 2005). Most TS experiments are expressed in terms of the body length L using the equation:

$$TS = m \log L + b$$

where m and b are constants for a given species. m is generally between 18 and 30, often close to 20. Physostomous fish have an m which is consistently close to 20. The length L normally denotes the total length of the fish, measured from the front of the head to the tip of the caudal fin (Simmonds and MacLennan 2005).

The predominant method of actively evaluating the effectiveness of behavioral technologies at power production facilities has been through impingement rate measurements. When measuring impingement rates, fish are first collected from the intake screening device, usually a rotational screen. The fish are then physically counted and/or examined to the researcher's specifications. After measurements have been taken, the fish can be either returned to a safe location in its environment, health permitting, or discarded.

The overall objective of this study was to evaluate the efficacy of an underwater hybrid (sound and light) behavioral deterrent system. This deterrent system was evaluated as a mitigating technology to reduce impingement rates to comply with previously required EPA performance standards under Section 316(b) of the Clean Water Act. The effectiveness of the strobe lights and sounds were determined through traveling screen impingement rates.

3 METHODS

This field study evaluated the effectiveness of a hybrid (light and sound) and sonic (sound only) deterrent system at Plant Barry from the spring to the winter of 2006. Only one of the two CWISs evaluated was equipped with the deterrent systems. The types of sound signals and strobe light flash rates were chosen based on the responses of representative fish species that exist in the literature along with the advice of other researchers. Impingement sampling was used to determine the effectiveness of these deterrent systems. Various environmental parameters were also monitored to ensure that these variables were not interfering with the evaluation of the deterrent systems.

3.1 Site Description

Barry Steam Plant (Plant Barry), which is owned and operated by Alabama Power Company, has a nominal rating of approximately 2,625 MW. Five coal-fired units (Units 1-5) can generate up to 1,525 MW and use once-through cooling water. Additionally, Plant Barry has two combined cycle electric generating units (Units 6-7) with a heat recovery steam generator. These combined cycle units use closed-cycle cooling and have a combined nominal rating of approximately 1,100 MW. The plant is located near Bucks, Alabama on the Mobile River (Mobile County, AL) approximately 49 km upstream from the confluence of the river with the Gulf of Mexico (Figure 12). The Mobile River at this location is fresh water; however river stage is influenced by tidal fluctuations.

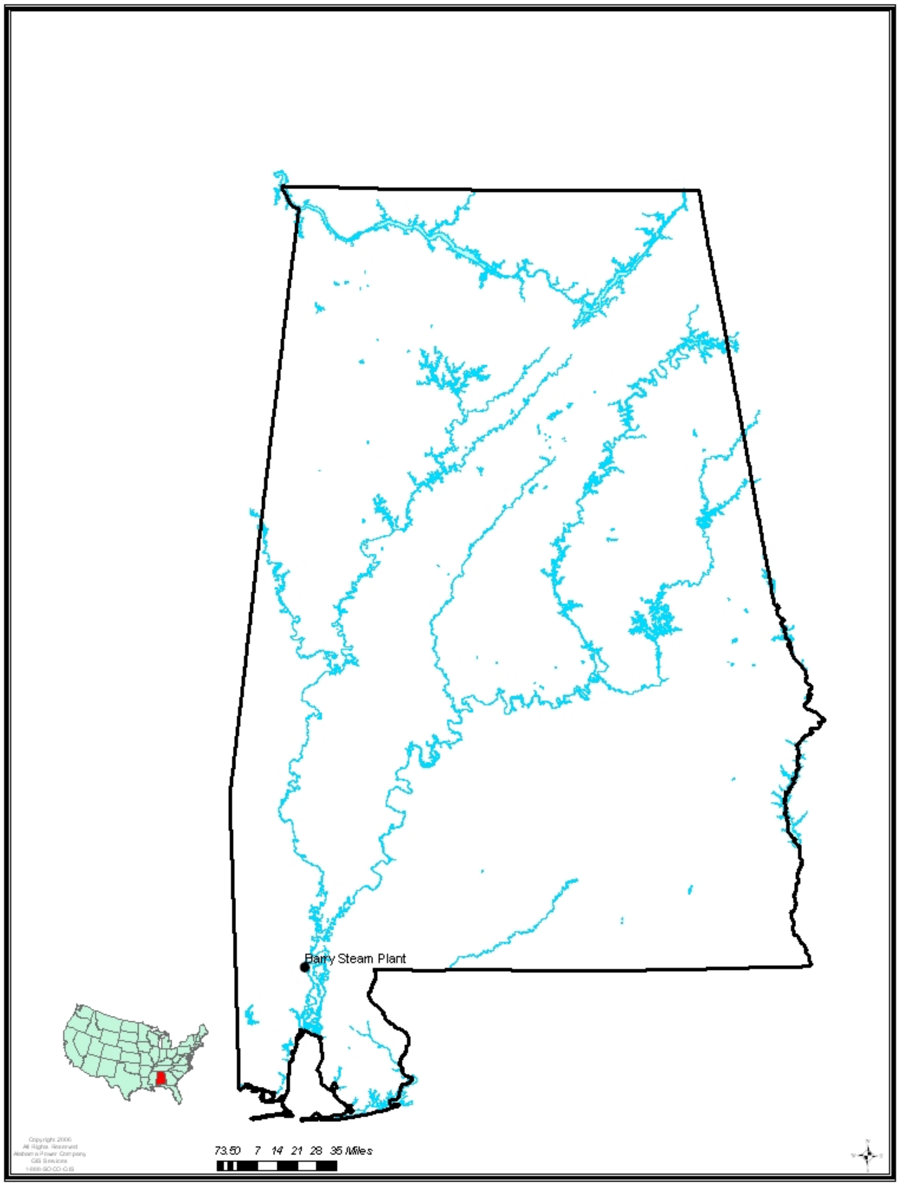


Figure 12. Map of Alabama showing Plant Barry located on the Mobile River near Bucks, Alabama.

3.1.1 Description of CWISs

Two CWISs, one for Units 1-3 and one for Units 4-5, are used to withdraw cooling and service water for the five coal-fired units and makeup water for the two combined cycle generating units. Both CWISs are located within a man-made barge canal that is perpendicular to the main river channel and separated by <61 m (Figure 13). At low flow and low tide the canal has a depth of 5 m, and the Mobile River at the junction with the intake canal has a depth of 13 m and a width of 198 m.

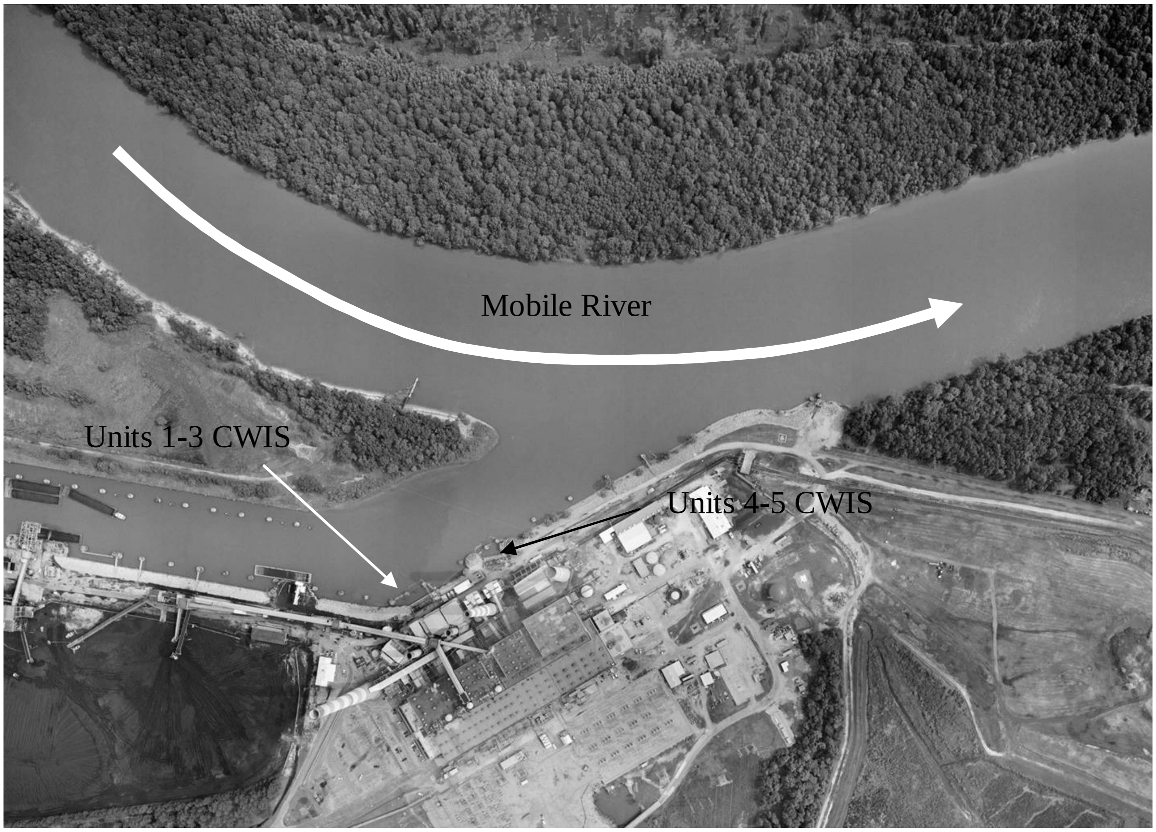


Figure 13. Aerial view of Plant Barry near Bucks, Alabama. Two separate cooling water intake structures (CWIS), one for Units 1-3 and one for Units 4-5 are located inside a man-made barge canal.

Both CWISs are equipped with floating debris buffers, trash racks, and traveling screens to remove the high volume of debris from the Mobile River (Figure 14). The debris buffer consists of a series of floating pontoon structures with vertical rods extending to a depth of 2 m and spaced 20 cm apart. The pontoons are located about 6.1 m upstream of the trash racks. Six traveling screen bays for the Units 1-3 CWIS and five traveling screen bays for the Units 4-5 CWIS are located immediately downstream of the trash racks (Figure 14). Each screen bay is approximately 3.4 m wide and houses a stainless steel trash rack with 8.9 cm x 2.1 cm bars and spaced 10.2 cm on-center with 8 cm clear openings. The trash racks are cleaned on a daily to weekly frequency depending on the extent of debris blockage. Each traveling screen is 3.0 m wide with a 9.5 mm screen mesh opening. The design through-screen velocity using normal water surface elevation of 0.6 m above mean sea level (msl) is approximately 0.5 m/s and 0.6 m/s for Units 1-3 and Units 4-5, respectively. A high pressure front spray wash system is used to remove fish and debris from the screens. This wash water then flows down a concrete sluiceway into a basket which collects the debris for disposal. At full load, Units 1-3 withdraw 1.772 x 10^6 liters/day (l/d) and Units 4-5 withdraw 2.532 x 10^6 l/d of cooling water from the intake canal. Water passes through the trash rack and into the plant via the intake structure underflow opening. Screened cooling water for each CWIS then flows into an intake tunnel that conveys water via circulating water pumps to the condensers for cooling.

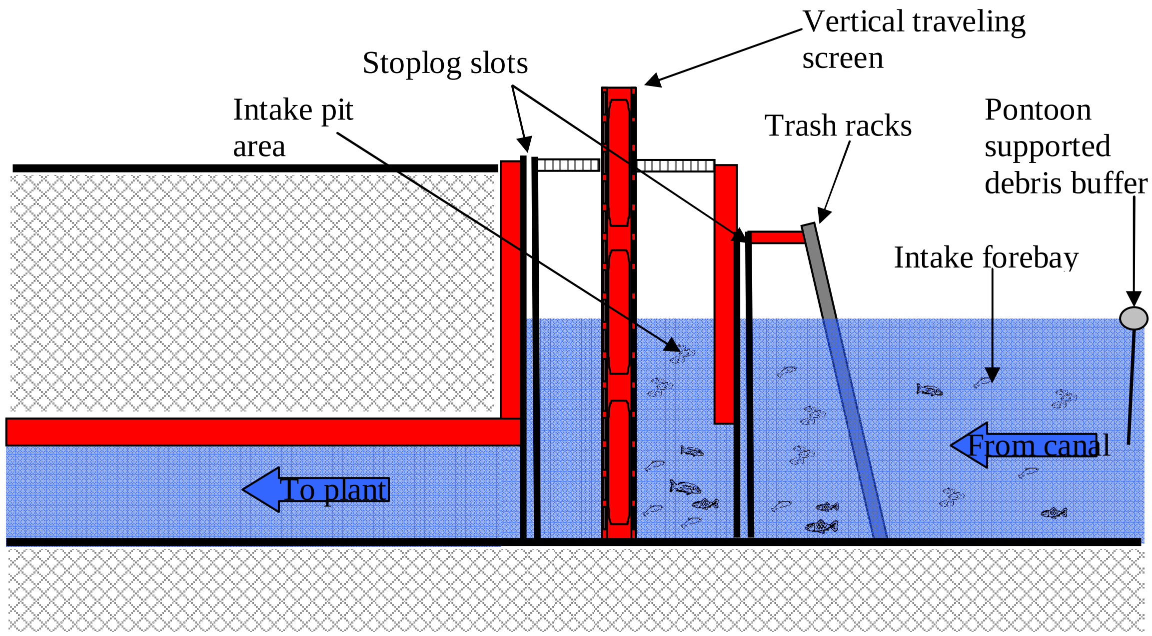


Figure 14. General schematic of the cooling water intake structures (CWISs) at Plant Barry.

3.2 Description and Installation of Light and Sound Deterrents

Strobe light and sound deterrent systems were deployed only at the Units 4-5 CWIS which Units 1-3 CWIS serving as a spatial control. The study was also divided into two phases to evaluate two separate deterrent systems:

(1) The hybrid deterrent which combined the use of strobe lights, sonic and ultrasonic sound frequencies was conducted from May 15 - November 14, 2006.

(2) The sonic deterrent which used low frequency sound bursts as the only deterrent was conducted over a shorter period of time from November 15 - December 22, 2006.

3.2.1 Light Deterrent

The type of strobe lights and the selected flash rates used in the hybrid deterrent system were based on available light response literature for the species that are commonly impinged at Plant Barry. Operational restraints limited the placement of the lights to the area immediately downstream and behind the trash racks. The number and placement of lights were based on the estimated transmission of light through the water.

3.2.1.1 Strobe Light and Flash Rate Selection

The predominant species impinged at Plant Barry were two Clupeidae species - threadfin shad *Dorosoma petenense* and gizzard shad; two Ictaluridae species - blue catfish *Ictalurus furcatus* and channel catfish; one Sciaenidae species - freshwater drum, one Engraulidae species – bay anchovy and one Soleidae species – hogchoker *Trinectes maculatus*. A review of the strobe light deterrent literature which reported flash rates revealed that of the predominant species found at Plant Barry, strobe lights have been tested on only gizzard shad, hogchocker, bay anchovy and channel catfish (Table 1). Appendixes 1 and 3, respectively, reference all of the light and hybrid (including light) deterrent studies.

Table 1. Summary of studies which evaluated the responses of gizzard shad, channel catfish, bay anchovy, and hogchoker to various strobe light flash rates.

Species	Reference	Type of Study	Avoidance Response	Flash Rate (flashes/min)
Gizzard Shad	Matousek et al. (1988)	Field	Yes, only effective at dawn	200
Gizzard Shad	Patrick (1980a)	Lab	Yes	unknown
Gizzard Shad	Patrick et al. (1980b)	Lab	Yes	>800
Gizzard Shad	Patrick et al. (1985)	Lab	Yes	300
Channel Catfish	EPRI (1990)	Lab	Yes	300
Bay Anchovy		Field	Yes, only effective during the day	200
Hogchoker	Matousek et al. (1988)	Field	Yes, effective both during the day and night	200
Flash rate avoidance response range reported from the literature				200 to >800
Flash rate used at Plant Barry				300
Flash head model used at Plant Barry: 30 Flash Technology Beacon (FTB) 920 strobe light systems with 13,000 effective lumens.				

The strobe light flash head model and flash rate for the hybrid deterrent evaluation were both chosen based upon resulting avoidance reactions produced by previous strobe light deterrent studies which used similar equipment. A flash rate of 300 flashes per minute was chosen for Plant Barry (EPRI 1990; Matousek et al. 1988; Patrick 1980a ; Patrick et al. 1980b, 1985). These studies used flash head models and flash rates that were successful at deterring several species similar to those which occur at Plant Barry.

3.2.1.2 Strobe Light System Components, Installation and Operation

The placement of strobe lights was designed to illuminate the water column in the vicinity of the trash racks. Based on historical turbidity values and secchi disk readings from the Mobile River, it was estimated that light penetration thru the water column would be approximately 3 feet in all directions at a turbidity reading of 50 NTU and approximately 5 feet at 20 NTU. Therefore, the strobe lights were spaced within 6 feet of each other. With turbidity readings around 50 NTU, the light spacing would have resulted in total coverage at the entrance into the CWIS.

To achieve this coverage across all trash racks, 30 Flash Technology Beacon (FTB) 920 strobe light systems (Flash Technology, Franklin, TN) were installed on Units 4-5. Similar strobe light systems produced avoidance responses in 5 studies using 4 species presented in Table 1. Each system consisted of a flash-head and power converter. Six flash-heads were mounted on each of 5 metal frames (Figure 15), one frame for each intake bay placed in the stoplog slots immediately upstream from the traveling screens

(Figure 16). The flash-heads used a horizontal beam spread of 360º, vertical beam spread of 100º, effective lumen value of 13,000 lumens, and 840 volt-amperes (VA).

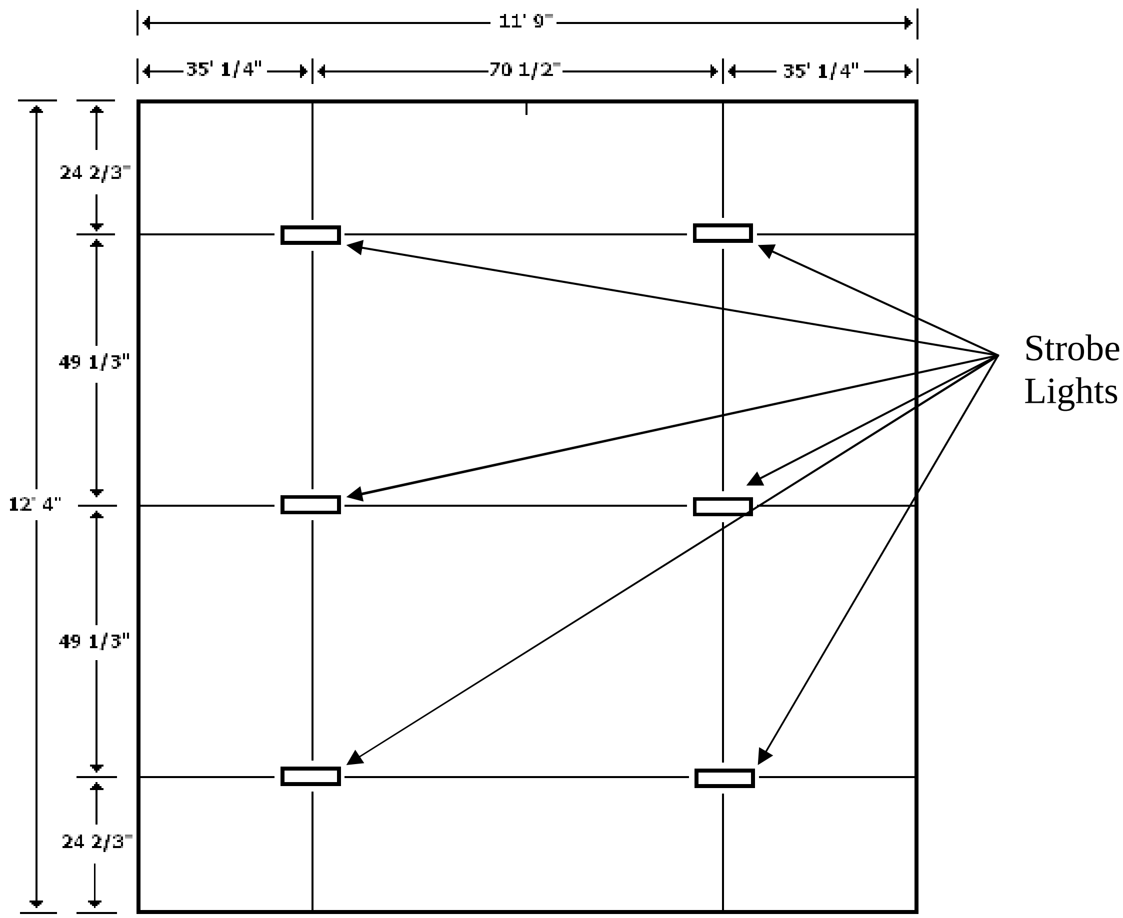


Figure 15. Configuration and location of strobe lights mounted on a metal frame showing placement of strobe lights in each intake screen bay.

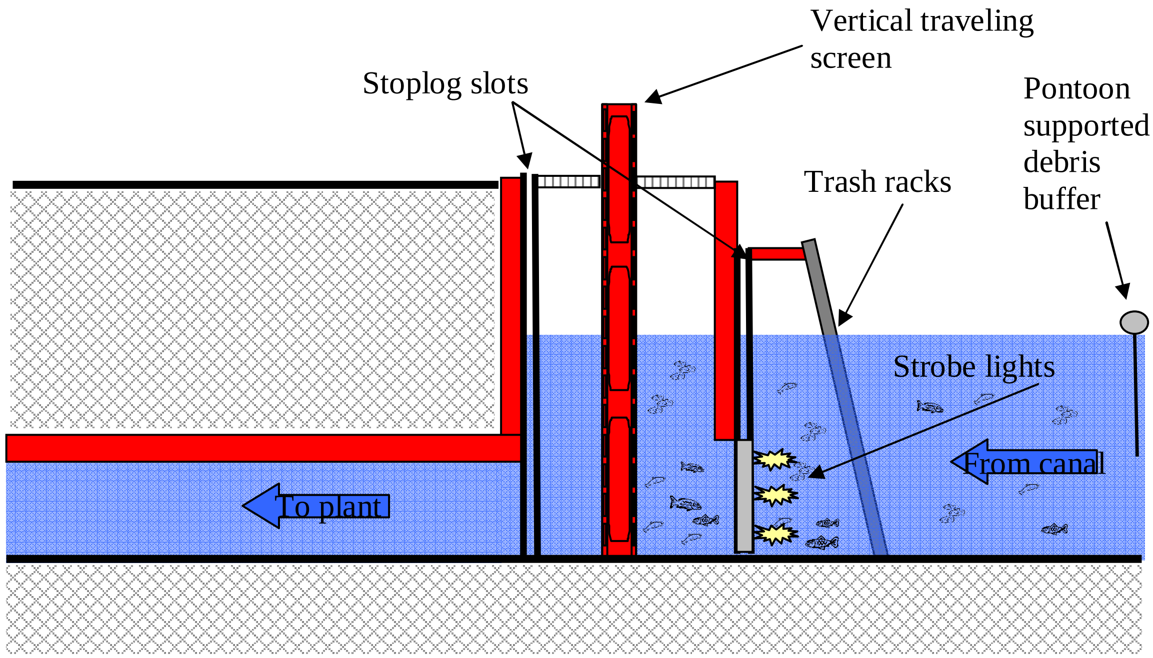


Figure 16. Locations of the strobe light frames within the stoplog slots of Units 4-5 CWIS.

A Flash Technology Controller 190 system (Flash Technology, Franklin, TN) provided control, monitoring and synchronization for the strobe light deterrent system. Visual display from the controller provided real time data on the operation of each flash-head and power converter. Prior to each impingement sample, the operational status of each flash-head was verified and recorded. Maintenance records throughout the study were also recorded to document system and individual component reliability.

3.2.2 Sound Deterrent

Sonic and ultrasonic sound frequencies and target sound pressure levels (SPL) were selected based on available information from previous sound deterrent studies. Acoustic modeling of the sound transmissions for selected underwater signals was conducted by Alden Research Laboratory, Inc. (Alden) and Scientific Solutions, Inc. (SSI). This initial modeling dictated the numbers and placements of the transducers selected for transmitting sonic and ultrasonic signals. The sound field was also mapped to confirm the operation of the sound deterrent systems before and during both of the deterrent studies.

3.2.2.1 Sound Frequency and Pressure Level Selection

Deterrent response data for many of the species commonly impinged on the Plant Barry intake screens are limited or not available. A review of the sound deterrent literature which reports the frequencies and SPLs reveal that sound has been tested on only two of the predominant species found at Plant Barry (Table 2). Appendixes 2 and 3, respectively, reference all of the sound and hybrid deterrent studies.

Table 2. Summary of studies which evaluated the avoidance responses of gizzard shad and bay anchovy to various frequencies and sound pressure levels (SPL).

Reference	Species	Type of Study	Avoidance Response	Frequency (Hz)		SPL (dB)	
				Min	Max	Min	Max
Negative Responses							
Consolidated Edison (1994)	Gizzard Shad	Field	No	122,000	128,000	170	>170
	Bay Anchovy	Field & Cage	No	122,000	128,000	170	>170
Positive Responses							
PSEG (2005)*	Bay Anchovy	Field	Yes, all frequencies used simultaneously	120,000	120,000	154	170
				100,000	100,000	153	167
				90,000	90,000	154	163
				80,000	80,000	147	159
				100	500	72	134
				500	3,000	110	124
Taft et al. (1996)	Bay Anchovy	Cage	Yes	100	5,000	154	unknown
Taft and Brown (1997)	Bay Anchovy	Cage	Yes	100	5,000	154	unknown
McKinley et al. (1987)	Bay Anchovy	unknown	Yes	300	900	unknown	unknown
PSEG (2003)	Bay Anchovy	Lab	Yes	100	3,000	80	136
Positive ultrasonic response ranges from the literature				**80,000**	**120,000**	**147**	**170**
Positive sonic response ranges from the literature				**100**	**5,000**	**72**	**136**
Ultrasonic sound levels modeled				**120,000**	**130,000**	**138**	**138**
Sonic sound levels modeled				**400**	**3,000**	**154**	**154**
Sound systems used at Plant Barry: Lubell Labs Inc. Model LL-9162 transducers with QSC power amplifiers and International Transducer Corporation Model 3406 transducers with a Instruments L6 amplifier.							

* same ultrasonic transducers as used in this study at Plant Barry

* It has been reported that only genus Alosa respond to frequencies over 80,000 Hz (Mann et al.1997)

Hybrid Deterrent Signals. Based on the information gathered, the following sound frequencies and pressure levels were selected for evaluation during the hybrid deterrent testing:

- Sonic sound frequency: band-limited random noise between 400 and 3,000 Hz
- Ultrasonic frequency: band-limited random noise between 120 and 130 kHz

Sound signals within both frequency ranges were transmitted with a repetition rate of one second (i.e., duty cycle of 33%) with source levels for the sonic and ultrasonic signals at approximately 154 and 146 dB re 1 µPa, respectively.

Sonic Deterrent Signals. During sonic deterrent testing, the ultrasonic signals were dropped and the sonic signals were modified to comprise the following:

- Tone burst frequencies of 400, 630, 1000, 1600, 2500, and 3150 Hz.

Each burst was 100 milliseconds with 50 milliseconds between bursts. The entire sequence of tone bursts (i.e., all frequencies) was transmitted at a 1.5 second repetition rate and the sequence of frequencies was varied with source levels at approximately 178 dB re 1 µPa.

3.2.2.2 Acoustic Modeling for Placement of Transducers

The acoustic modeling was conducted to develop an optimal configuration for the three sonic and five ultrasonic transducers within the Unit 4-5 intake forebay based on specified minimum sound pressure levels (SPLs) (Carlson 1994). Sound pressure level contours were developed using idealized computational models for an underwater sonic transmitting system operating between 400 – 4000 Hz and an ultrasonic transmitting system operating between 120 – 130 kHz.

For the modeling effort, three omni-directional sonic transducers (Lubell Labs Model LL-9162 or LL-916 and NRL Model J-11) were positioned at various locations in the forebay one foot above the bottom. A uniform water depth of 17 ft was used for all initial modeling work. The received levels at each computational field point included the contribution due to the direct path from each transducer as well as the contribution due to the first surface bounce. The frequency type used for the computations was band-limited white noise, flat across frequency from 400 – 4000 Hz. For the computations, this frequency interval was divided into 30 sub-bands. The contribution of each sub-band to the overall in-band received SPL was calculated at the center frequency of each sub-interval as the coherent sum of the direct path and surface reflected path.

Based on hearing capabilities of abundant species at Plant Barry or of similar species (see hearing thresholds data presented in Section 2.1.2), the criterion for the sonic signals was to have SPLs exceeding 130 dB throughout the forebay. The predicted sonic frequency SPLs for the initial configuration appeared to be relatively uniform at approximately -10 dB from the assumed source level of 180 dB, except for "hot spots" in the vicinity of the transducers. Based on deployment considerations (e.g., accessibility and positioning above substrate), the final configuration consisted of one transducer being located at either end of the intake trash racks and one positioned on the middle dolphin pier at the forebay entrance (Figure 17). Each of these transducers was located 0.3 m above the bottom. Additional modeling with this arrangement confirmed that relative uniformity and minimum SPL criteria was achieved.

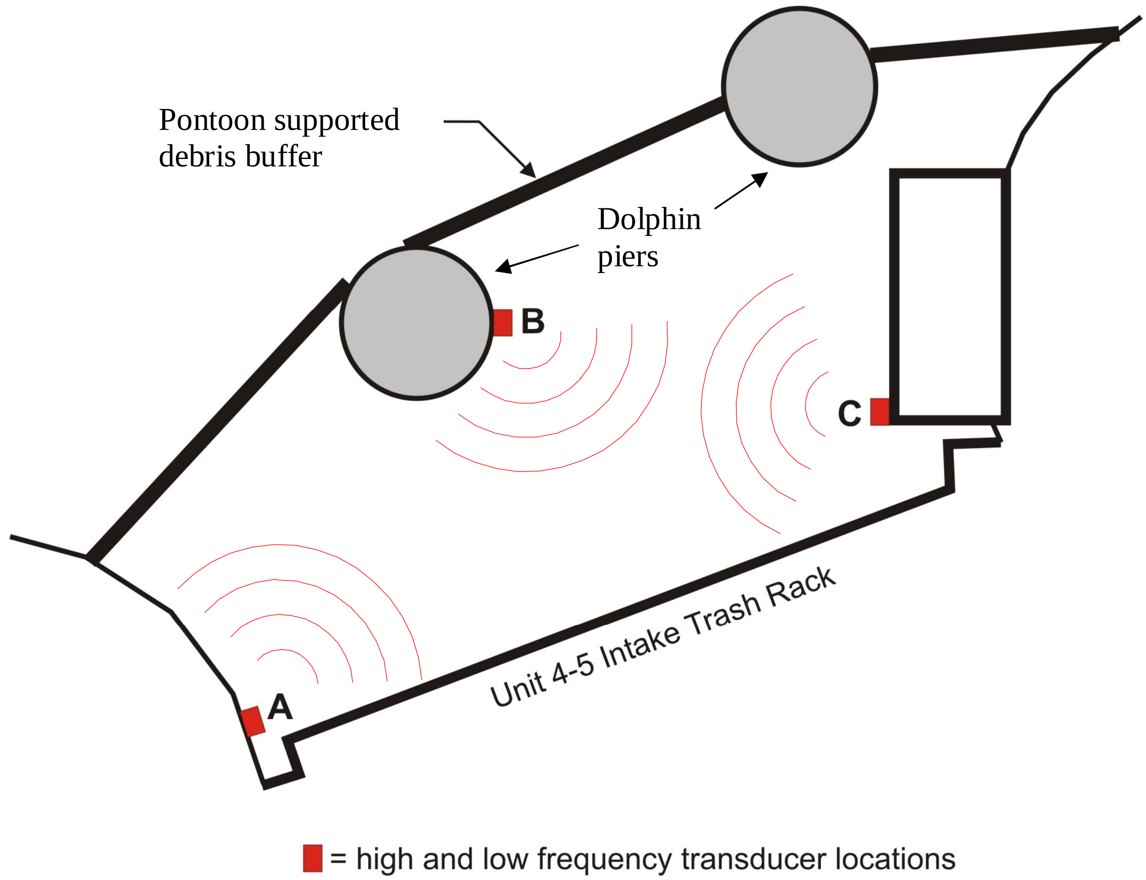


Figure 17. Locations of the 3 sonic and 5 ultrasonic sound frequency transducers inside the intake forebay of the Units 4-5 CWIS. One sonic and two ultrasonic transducers are located on each side of the intake structure (A and C). Location B is equipped with only one sonic and one ultrasonic transducer.

The ultrasonic transducer system was designed based on the ITC Model 3046, which are directive sources. The nominal beamwidth for these transducers is 45°. In the frequency range of interest (120 – 130 kHz) the actual beamwidth is slightly less than this. Recommended mounting locations and orientation for the transducers were developed by selecting an initial distribution based on practical considerations (number of transducers, utilization of existing equipment, ease of mounting, rigidity of mounting, non-interference with trash rake traverse, etc.) and then iteratively refining the distribution based on model results to achieve a uniform SPL distribution throughout the forebay. The final configuration consisted of two transducers on each end of the CWIS (same location as sonic units) and one on the middle dolphin pier (Figure 17). All transducers were positioned to transmit horizontally across the forebay. The overall in-band received SPL at each computational field point was computed as the in-coherent sum of the direct path contribution from each of the five ultrasonic transducers, accounting for the beam radiation pattern and for propagation losses due to spherical spreading.

3.2.2.3 Sound System Components, Installation and Operation

The primary components of the sonic sound system were three Lubell Labs, Inc. Model LL-9162 transducers and three QSC power amplifiers. The ultrasonic sound system was comprised of five International Transducer Corporation (ITC) Model 3406 transducers and an Instruments L6 amplifier.

The placement of the sonic and ultrasonic transducers followed the modeling results whereby a sound field was produced within the intake forebay, between the pontoon supported debris buffer and the trash racks, with sound pressure levels sufficiently higher than background noise levels. The three sonic transducers were placed 0.3 m above the bottom while the five ultrasonic transducers were placed at a mid-water depth of 2.6 m (Figure 17). The transducers were driven by amplifiers and mounted within the intake forebay of CWIS Units 4-5.

3.2.2.4 Sound Field Measurements

Sound field measurements were recorded on three occasions to confirm proper operation of the system and to map that SPLs in the forebay to determine if minimum levels were sufficient for detection by fish and relative uniformity was being attained. Background noise levels were also measured to determine if sound deterrent SPLs were sufficiently high to avoid masking of the transmitted signals (i.e., signal-to-noise ratio was high).

Sound measurements were recorded with a Reson Model TC4013 hydrophone connected to an Iotech WaveBook/516E high-speed data acquisition system. An 8-pole Bessel low pass filter with a corner frequency of 200 kHz was used for anti-aliasing and buffering. A gain of 30 dB was used for all measurements.

3.3 Impingement and Environmental Monitoring

The effectiveness of the hybrid and sonic deterrent systems were evaluated through impingement monitoring. Various environmental factors were also monitored to determine if there may be possible effects on impingement rates between the hybrid or sonic deterrent operation status.

3.3.1 Impingement Monitoring

Impingement monitoring was performed during the operation of both deterrent systems. The sampling design allowed for quantification of the seasonal, diurnal and CWIS variability within and between deterrent operation status (on and off).

Impingement samples were collected from May 15 - December 22, 2006 at both intakes. Four 4-hour samples (morning, afternoon, evening and night) were collected within a 48 hour period (Table 3). The time periods for sampling are as follows:

- Morning (0600-1200 hrs)
- Afternoon (1200-1800 hrs)
- Evening (1800-0000 hrs)
- Night (0000-0600 hrs)

Table 3. Weekly schedule of deterrent system operation. Shaded samples represent active sampling (treatment or control). No impingement sampling was performed during times for unshaded areas.

	Day		Night	
Sunday	Acclimation Period – status change (turned on or left off)			
Monday	morning	afternoon	evening	night
Tuesday	morning	afternoon	evening	night
Wednesday	Acclimation Period – status change (turned on or left off)			
Thursday	morning	afternoon	evening	night
Friday	morning	afternoon	evening	night
Saturday	Rest Period (system off)			

All organisms collected during each sampling event were backwashed off the traveling screen into a 9.5 mm mesh sampling basket. Organisms were removed from the sampling basket, sorted, identified to species, enumerated, and weighed. Total count and weight were recorded for each species. Severely decayed animals were discarded and not included in the sample.

Impingement numbers and weights were standardized to 4-hours when sampling a collection period greater than or less than the targeted collection time. For example, if the collection period was only 3 hours and 45 minutes, a correction factor was applied to adjust the numbers and weights up to a 4 hour impingement rate. A screen adjustment factor was also applied to the number and weights of organisms to account for organisms not recovered from inoperable traveling screens. If cooling water was flowing through a screen that could not rotate due to mechanical failure, a correction factor was applied to account for organisms that were impinged but unable to be collected.

3.3.2 Environmental Monitoring

Water quality samples were collected at both intakes during each impingement sampling event. Water quality parameters recorded included: water temperature (ºC), pH, dissolved oxygen (mg/l), turbidity (ntu), and specific conductance (µS/cm). Water quality measurements were taken from surface water samples immediately upstream from the trash racks. Water in front of the CWIS was thoroughly mixed and assumed to be representative of the whole water column within the intake forebay area. A YSI 85 meter (Yellow Springs Instruments, YSI Incorporated, Yellow Springs, OH) was used to measure dissolved oxygen and temperature. A LaMotte 2020 (LaMotte Company, Chestertown, MD) was used to measure turbidity. A WTW 340i meter (Wissenschaftlich-Technishe Werkstatten GmbH, Weilheim, Germany) was used to measure specific conductance and pH.

River stage and discharge data were obtained from the USGS gage (02470629) located approximately 0.8 km upstream from the plant intake canal. In addition, the CWIS flow volume (m^3/s), CWIS through-screen flow velocity (m/s), and the number of circulating water pumps in operation were recorded for each collection period. River stage, amount of surface area of the screen, and the volume of water withdrawn from the CWIS were used to calculate the CWIS flow velocities.

3.4 Experimental Design and Statistical Analyses

The efficacy of the hybrid and sonic deterrent systems were based on the ability of these two systems to reduce impingement in the vicinity of the Units 4-5 CWIS. Differences in the various environmental parameters were evaluated to determine if these variables could be influencing impingement when evaluating the treatment effects. Both the hybrid and sonic deterrent systems were evaluated using the mixed procedure in SPSS (Version 15.0 for Windows, SPSS, Chicago, Illinois). Differences were considered significant at $P < 0.05$.

3.4.1 Impingement Analyses

The experimental design for determining the efficacy of impingement reduction for either the hybrid or sonic deterrent system is presented in Table 3. The treatment system (deterrents on) operated continuously for 72 hours followed by a control period (deterrents off) for 72 hours with the sequence alternating every week. Sampling was not conducted during the first 24 hours of each treatment. This time period was used to allow the fish to become acclimated to either the deterrent or the control. Therefore, sampling was conducted during a Monday – Tuesday or Thursday – Friday time period within each week. Sunday and Wednesday of each week were acclimation periods. The treatment periods were observed in 4 quarterly diel periods (morning, afternoon, evening and night).

The impingement data were analyzed using split-plot or repeated measures methods (Maceina et al. 1994). Random effects were adjusted by accounting for the interaction between treatments (deterrents on/off) and week of the year (temporal effects) whereby the effects of each CWIS are nested within each week (Treatment x Week (CWIS)). Because fish abundance and species composition in the vicinity of each CWIS at Plant Barry fluctuate week to week, the CWIS x Week sampling unit was considered the primary experimental unit of this sampling design. The CWIS x Week units were subdivided into 8 Treatment x Diel subunits (2 CWISs x 4 Diel periods). The 2 levels of CWIS creates the between units factor with week providing replication as a blocking factor. The deterrent Treatment x Diel period provides the within week treatment structure. The dependent variables for the analysis were computed as the natural log (n + 1) transformation of the impingement rates for the predominant species individually and for all species combined. In these analyses, there are two important factors to be considered:

1. The CWIS x Treatment interaction which assesses whether the deterrent treatment created a larger difference in impingement numbers at the treatment CWIS than was observed at the control CWIS.

2. The CWIS x Treatment x Diel interaction which assess whether the deterrent was more effective at reducing impingement during a particular time of day (morning, afternoon, evening and night) at the Units 4-5 CWIS.

3.4.2 Environmental Analyses

Physical and chemical water monitoring was performed concurrently with the fish impingement monitoring. Therefore, these parameters (water temperature, pH, dissolved oxygen, turbidity, specific conductance and CWIS through-screen velocity) were analyzed using the untransformed data in the same manner as the impingement results.

In these analyses the important factors to consider are:

1. The CWIS x Treatment interaction which assess whether differences in any of these environmental factors may be affecting or confounding the impingement results.

2. The CWIS x Treatment x Diel interaction which assess whether any differences in the environmental parameters may be affecting or confounding the impingement results.

4 RESULTS

The hybrid deterrent system, which combined the use of strobe lights, sonic (0.4 – 4.0 kHz) and ultrasonic sound frequencies (120 – 130 kHz), was deployed from May 15 - November 14, 2006 at the Units 4-5 CWIS. In addition, the sonic deterrent system, which only used intermittent sound frequencies (0.4, 0.63, 1.00, 2.50, and 3.15 kHz) was deployed from November 15 - December 22, 2006 at the Units 4-5 CWIS. Evaluations of these deterrent systems, using impingement rates, indicate that neither of these behavioral deterrent systems effectively reduced impingement rates for fish or invertebrates (*Macrobrachium spp.* and blue crabs *Callinectes sapidus*). There were no differences in the environmental factors between treatments (on or off) and therefore these factors did not interfere in the evaluation of either the hybrid or sonic deterrent systems.

4.1 Deterrent System Operational Results

The strobe lights were difficult to maintain throughout the hybrid deterrent evaluation; however, on average 88% of the lights were operational throughout this evaluation. Surveys of the sound field inside the intake forebay indicate that the targeted ultrasonic (hybrid deterrent system) and sonic frequencies (hybrid and sonic deterrent systems) along with the respective SPLs were achieved during both evaluations.

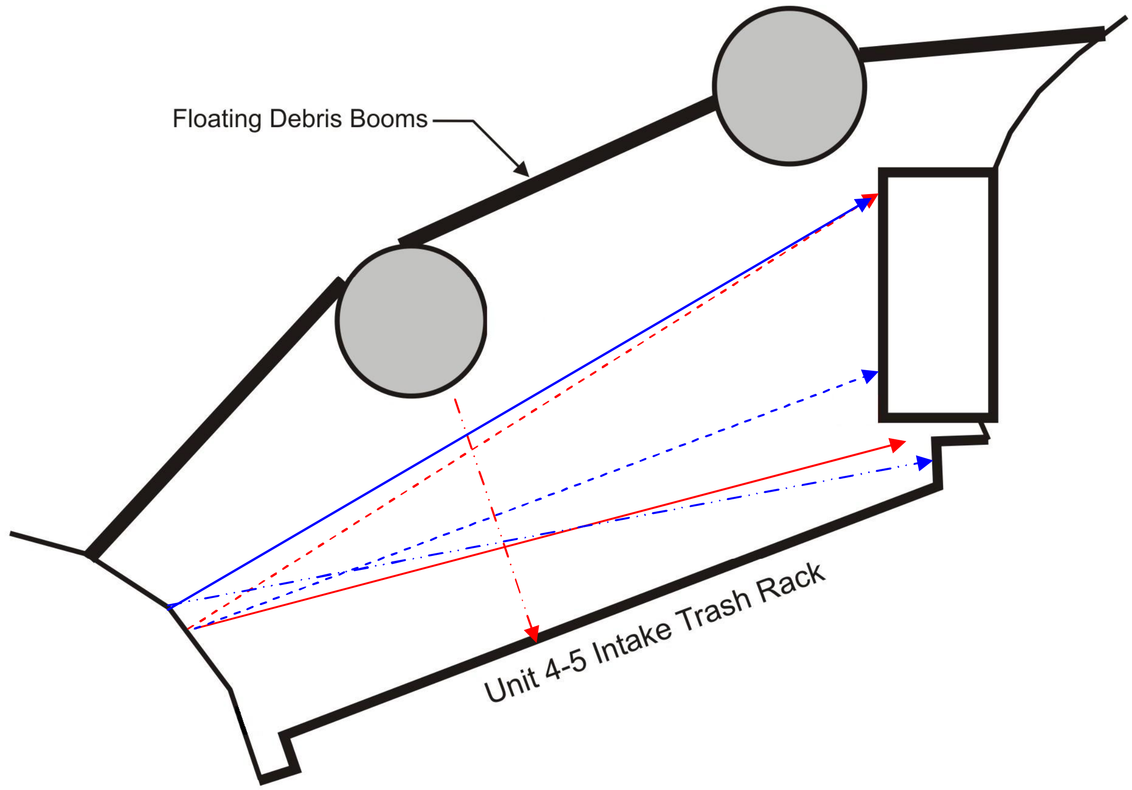
4.1.1 Strobe Light Operation Results

The strobe light portion of the hybrid deterrent system was very problematic and required intensive, unexpected maintenance on the strobe lights and on the power converters. Almost biweekly repair or replacement of flash-heads and power converters were required. Mid-way though the study, the manufacturer voluntarily exchanged and refurbished all 30 flash-heads due to various problems. Leading causes to strobe light failures include blown flash tubes, faulty transformers inside the flash-head and faulty underwater cable connectors. Failures associated with the power converters include transformer and capacitor failure, shorted discharge boards and blown fuses. The dependability of the strobe light system was recorded as percent operational flash-heads. The strobe light system dependability over the entire hybrid evaluation ranged from 73-100% with a mean of 88 %. However, 54% of the samples were collected with less than 10% non-operational flash-heads.

4.1.2 Sound Field Measurement Results

Sound field measurements were recorded prior to (April 26) and during (June 29) the hybrid deterrent evaluation. A third set of measurements were performed on November 14 shortly after the sonic deterrent evaluation was initiated. During each sound field mapping effort, the intake forebay area was gridded into transects (Figure 18). Individual sound measurements were taken at depths of 1.2, 2.4, and 3.7 m (depth permitting) at 1.5 m intervals along each transect. The sound survey data indicated sound pressure levels (SPL) of > 150 decibels at a reference level of 1 micro-Pascal (dB re 1μPa) for the sonic sound and around 140 dB re 1μPa for the ultrasonic sound. Recorded peak SPL values for the sonic sound were around 170 dB re 1μPa and around 160 dB re

1μPa for the ultrasonic sound. The results of the sound field measurements are summarized in Table 4.



1st Hybrid transect A — 2nd Hybrid transect A — Sonic transect A
1st Hybrid transect B — 2nd Hybrid transect B — Sonic transect B
1st Hybrid transect C — Sonic transect C

Figure 18. Sound field survey transects conducted in the forebay area of CWIS 4-5

Table 4. Mean minimum and maximum sound pressure levels (SPL) measured during the operation of the Hybrid and Sonic deterrent systems within the intake forebay.

Hybrid Deterrent Sound Pressure Levels (SPL)

		Depth (ft)	Sonic (band limited noise (400-3000 Hz))		Ultrasonic (band limited noise (120-130 kHz))	
			OA In-Band RMS SPL (dB re 1 μPa)	Peak SPL (dB re 1 μPa)	OA In-Band RMS SPL (dB re 1 μPa)	Peak SPL (dB re 1 μPa)
26-Apr	Mean	1.2 to 3.7	157.0	169.8	141.4	155.5
	Minimum		151.4	164.0	131.3	146.0
	Maximum		161.8	174.7	158.8	174.2
29-Jun	Mean	1.2 to 3.7	161.7	173.6	147.9	161.5
	Minimum		157.7	168.6	145.3	157.9
	Maximum		164.8	178.0	156.8	169.7

Sonic Deterrent Sound Pressure Levels (SPL)

		Depth (ft)	Sonic											
			OA In-Band RMS SPL (dB re 1 μPa)						Peak SPL (dB re 1 μPa)					
			400 (Hz)	630 (Hz)	1000 (Hz)	1600 (Hz)	2500 (Hz)	3150 (Hz)	400 (Hz)	630 (Hz)	1000 (Hz)	1600 (Hz)	2500 (Hz)	3150 (Hz)
14-Nov	Mean	1.2 to 3.7	147.2	158.5	168.5	160.8	159.5	153.8	156.3	165.4	174.3	167.2	165.6	160.7
	Minimum		135.3	141.2	153.3	147.0	144.6	139.9	149.6	154.7	164.2	158.6	157.3	151.0
	Maximum		161.4	171.8	187.1	178.6	175.2	170.0	169.9	177.4	190.7	182.7	178.8	174.5

4.2 Monitoring Results

4.2.1 Impingement Monitoring Results

Over 12,000 fish and 9,000 non-fish organisms were collected while evaluating the hybrid deterrent system. During the evaluation, 268 4-hour impingement samples were successfully obtained with approximately one-forth of the samples collected during each of the four CWIS-Treatment combinations. Only 5 samples were missing due to operational restraint within the split plot sample design. The split plot analyses of total fish numbers and numbers of predominant individuals by species clearly indicates that the hybrid deterrent system has little or no effect on the reduction of impinged fish at the Unit 4-5 CWIS.

Over 29,000 fish and 800 non-fish organisms were collected while evaluating the sonic deterrent system. During the evaluation of the sonic deterrent system, 73 4-hour impingement samples were successfully obtained with approximately one-forth of the samples collected during each of the four CWIS-Treatment combinations. Only 5 samples were missing due to operational restraint within the split plot sample design. The split-plot analysis of total fish numbers and numbers of predominant individuals by species clearly indicates that the sonic deterrent system also has little or no effect on the reduction of impinged fish at the Unit 4-5 CWIS.

The average impingement rates during the hybrid and sonic deterrent evaluations for fish and non-fish species are presented in Figures 19 and 20, respectively. There were 26 species of fish collected throughout both evaluations. Freshwater drum, blue catfish, threadfin shad and bay anchovies collectively contributed more than 5% toward the overall impingement while evaluating both deterrent systems. Hogchoker contributed to more than 5% of the impingement during the hybrid deterrent evaluation. Whereas, macrobrachium, corbicula and blue crabs were the predominant non-fish species, contributing more than 5% of the non-fish impingement while evaluating both deterrent systems.

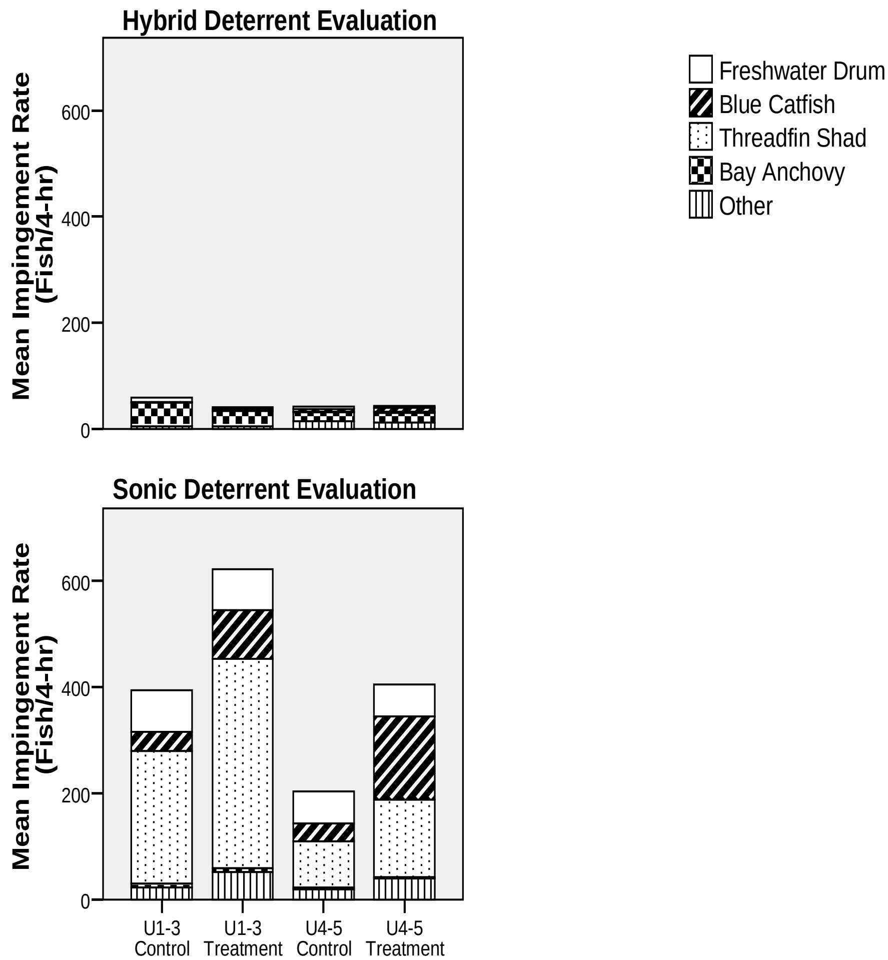


Figure 19. The mean number of fish impinged every 4 hours by species during the hybrid and sonic deterrent evaluations at Plant Barry, Alabama.

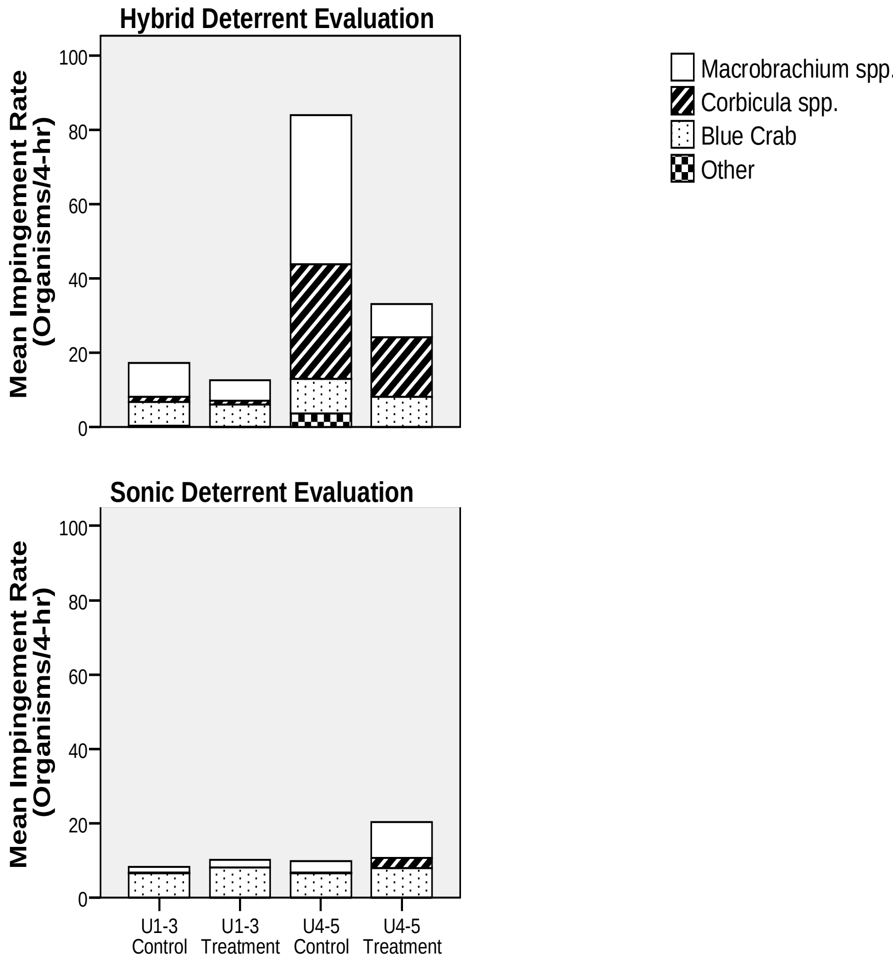


Figure 20. The mean number of non-fish organisms impinged every 4 hours by species during the hybrid and sonic deterrent evaluations at Plant Barry, Alabama..

The study sampling design allowed for a comparison of impingement rates when the deterrent system was on (treatment) or off (control) at both CWIS 1-3 (spatial control) and CWIS 4-5 (hybrid or sonic frequency pulse deterrent equipped). An evaluation of the overall impingement rates for all fish combined or for any of the predominant species impinged indicates that no meaningful reduction occurs when the deterrent systems operate in a hybrid mode or in a sonic mode.

The rates of impingement at both intakes were variable and yet followed a strong seasonal and diurnal trend (Figure 21 and 22). General rates of impingement were lower during the time frame of the hybrid deterrent system evaluation than when evaluating the sonic deterrent. In order to account for seasonal and diurnal variability the deterrent systems (hybrid or sonic) were evaluated on a weekly basis, whereby the two different treatments (on or off) would be paired and evaluated during individual weeks. The ability of the experimental design to account for temporal variability is obvious in Figure 21. In this Figure, the log-scale pairing of impingement rates clearly show close correlation between sample periods within each of the weeks while the deterrent systems were either on or off.

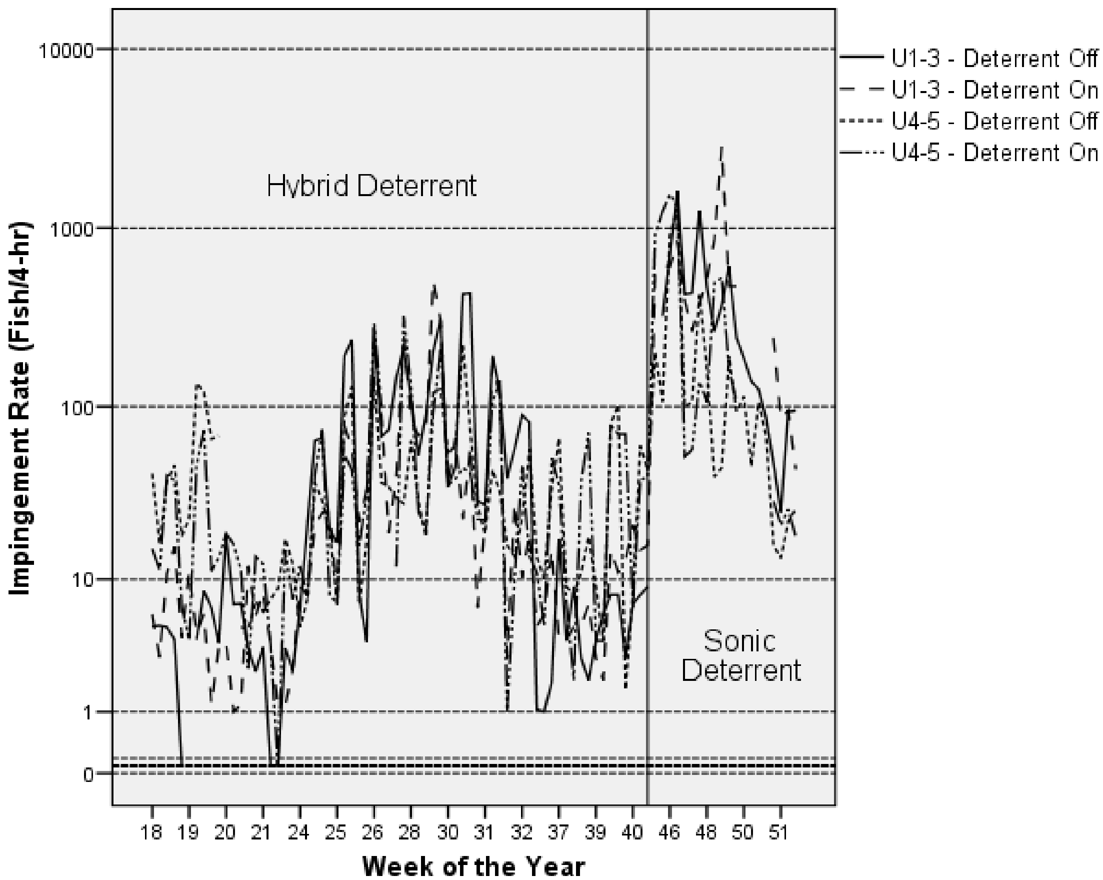


Figure 21. Measured impingement rates for all fish species combined during each 4-hr sample period during 2006.

The sampling design also allows for a pairwise comparison of impingement rates for the sequential treatment (deterrent on) and control (deterrent off) sampling events within each of the weekly test periods using a split plot analyses. Figure 22 presents the transformed means and 95% confidence intervals from the results of the MLE split plot analyses using SPSS Mixed (SPSS 2006).

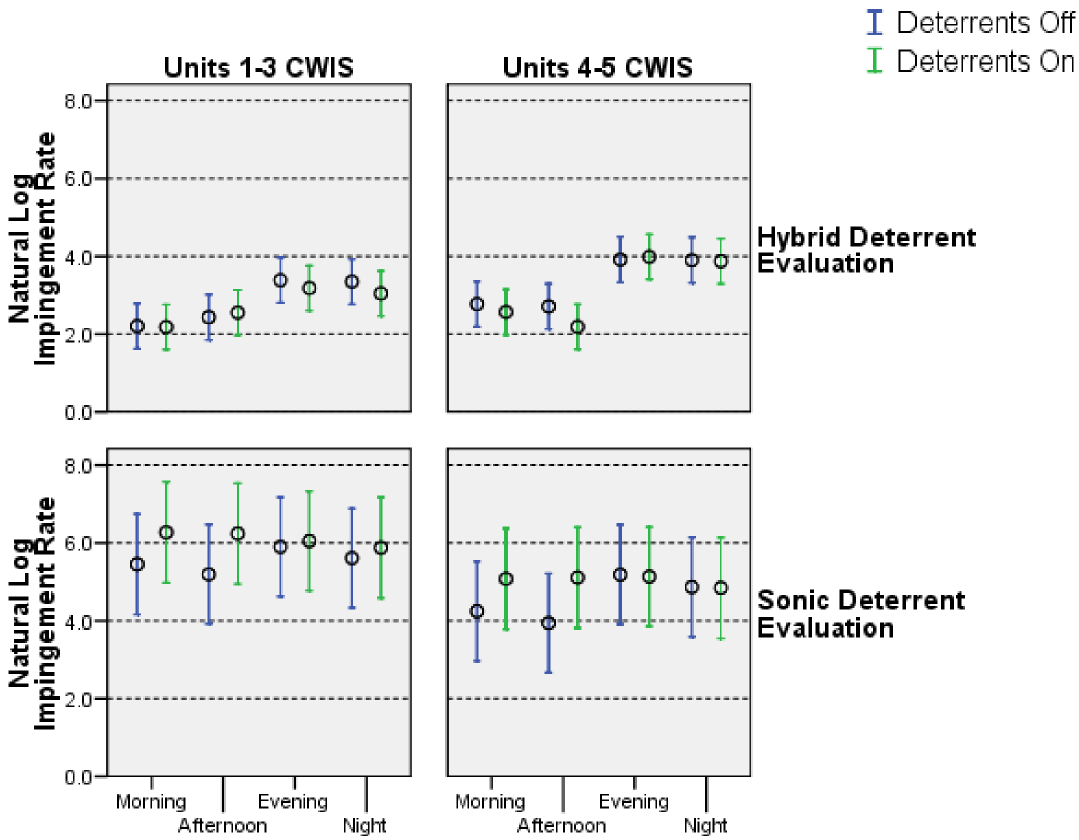


Figure 22. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean overall fish impingement numbers.

Table 5 presents the split plot impingement rate analyses for all of the combined fish species in log scale. Split plot analyses of the transformed (natural log) impingement rates found no significant reductions due to the operation of either the hybrid or sonic systems.

Marginal difference in impingement rates during the hybrid system evaluation existed between the two CWISs, whereby the Units 4-5 CWIS impinged more fish than the surrogate control Units 1-3 CWIS (p=0.066). However, the diel (samples: morning, afternoon, evening and night) effects were quite significant (p<0.0001) and were not consistent across the CWISs (p=0.003). The inconsistency of the diel effect between the two CWIS units is that there was a greater difference between day and night at the Units 4-5 CWIS than at the Units 1-3 CWIS, but at both CWISs, more fish were impinged during the evening and night periods. There is no evidence of a treatment effect that would indicate that the hybrid deterrent system may be modifying impingement at the Unit 4-5 CWIS and not at the surrogate control, Unit 1-3 CWIS (p=0.791). There is also no evidence suggesting that there was an increase in impingement due to a possible attraction of fish to the strobe lights used during the hybrid evaluation.

Significant differences (p= 0.021) in impingement rates between CWISs existed during the sonic evaluation, whereby Units 1-3 CWIS impinged more fish than the Units 4-5 CWIS. The main diel effect during the sonic evaluation was not as strong (p=0.106) as during the hybrid system evaluation (p<0.0001). Changing diel effects are likely associated with the time of year and the change in species of fish being impinged. The sonic evaluation was performed during the early winter whereas the hybrid system was evaluated throughout the warm season. As with the hybrid system, there is no evidence of a treatment effect that would indicate that the sonic deterrent system modifed impingement at the Unit 4-5 CWIS and not at the surrogate control, Unit 1-3 CWIS ($p=0.878$).

Table 5. Results of the MLE Split Plot analyses of the transformed (natural log) impingement rates using the SPSS Mixed procedure.

Type III Tests of Fixed Effects [a]

Deterrents	Source	Numerator df	Denominator df	F	Sig.
Hybrid Deterrent Evaluation	Intercept	1	16.009	201.352	.000
	INTAKE	1	15.875	3.908	.066
	TREATMENT	1	30.733	1.186	.285
	Sample	3	186.305	70.882	.000
	INTAKE * TREATMENT	1	30.733	.071	.791
	INTAKE * Sample	3	186.308	4.863	.003
	Sample * TREATMENT	3	186.321	.148	.931
	INTAKE * Sample * TREATMENT	3	186.322	2.002	.115
Low Frequency Sound Burst Evaluation	Intercept	1	4.035	132.885	.000
	INTAKE	1	4.143	13.083	.021
	TREATMENT	1	7.274	3.447	.104
	Sample	3	41.190	2.170	.106
	INTAKE * TREATMENT	1	7.190	.025	.878
	INTAKE * Sample	3	41.320	.625	.603
	Sample * TREATMENT	3	41.165	4.185	.011
	INTAKE * Sample * TREATMENT	3	41.315	.136	.938

a. Dependent Variable: ln_total_num.

Figures 23-29 present the transformed means and 95% confidence intervals from the results of the MLE split plot analyses for each of the predominant species using SPSS Mixed (SPSS 2006). Detailed split plot evaluations of log scale impingement rates for each of the predominant fish species (freshwater drum, blue catfish, threadfin shad, hogchoker and bay anchovy), revealed that there were no significant treatment effects at the species level for the hybrid ($p>0.490$) or sonic ($p>0.260$) CWIS x Treatment interactions. The same basic results were realized when evaluating the treatment effects for each of the predominant Mobile non-fish species (blue crab and macrobrachium) for the hybrid ($p>0.227$) or sonic ($p>0.738$) CWIS x Treatment interactions.

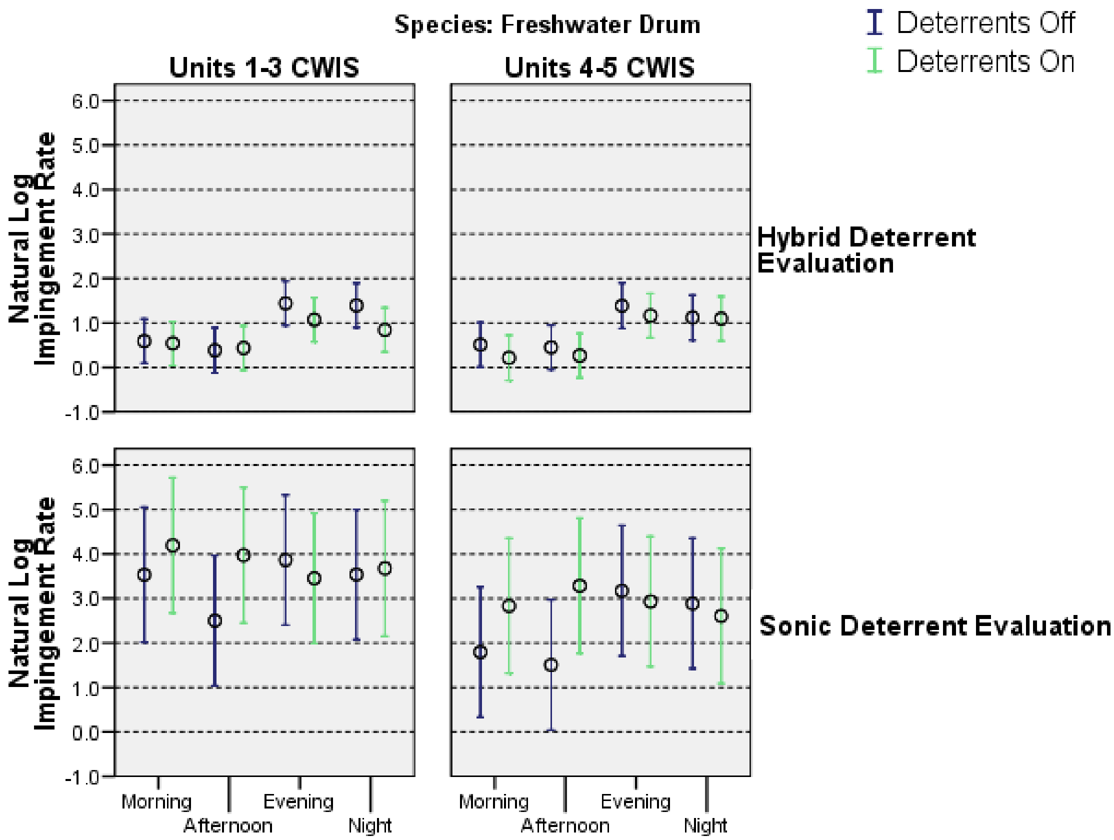


Figure 23. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for freshwater drum.

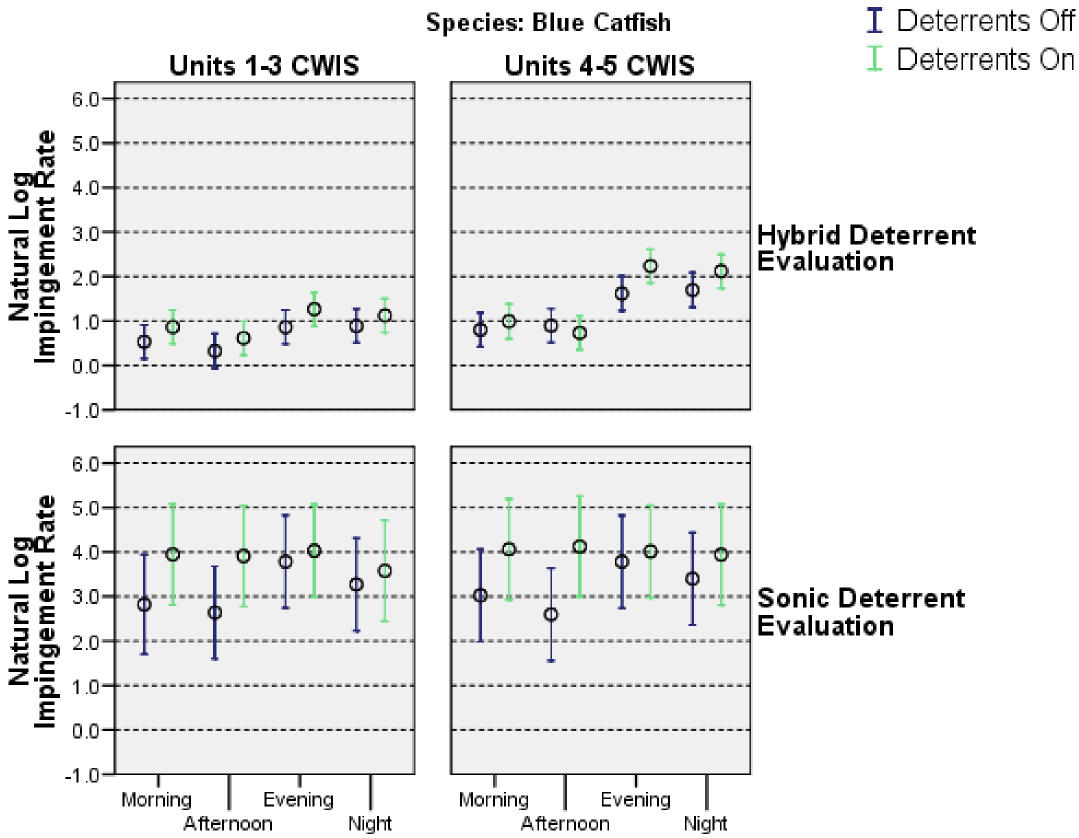


Figure 24. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for blue catfish.

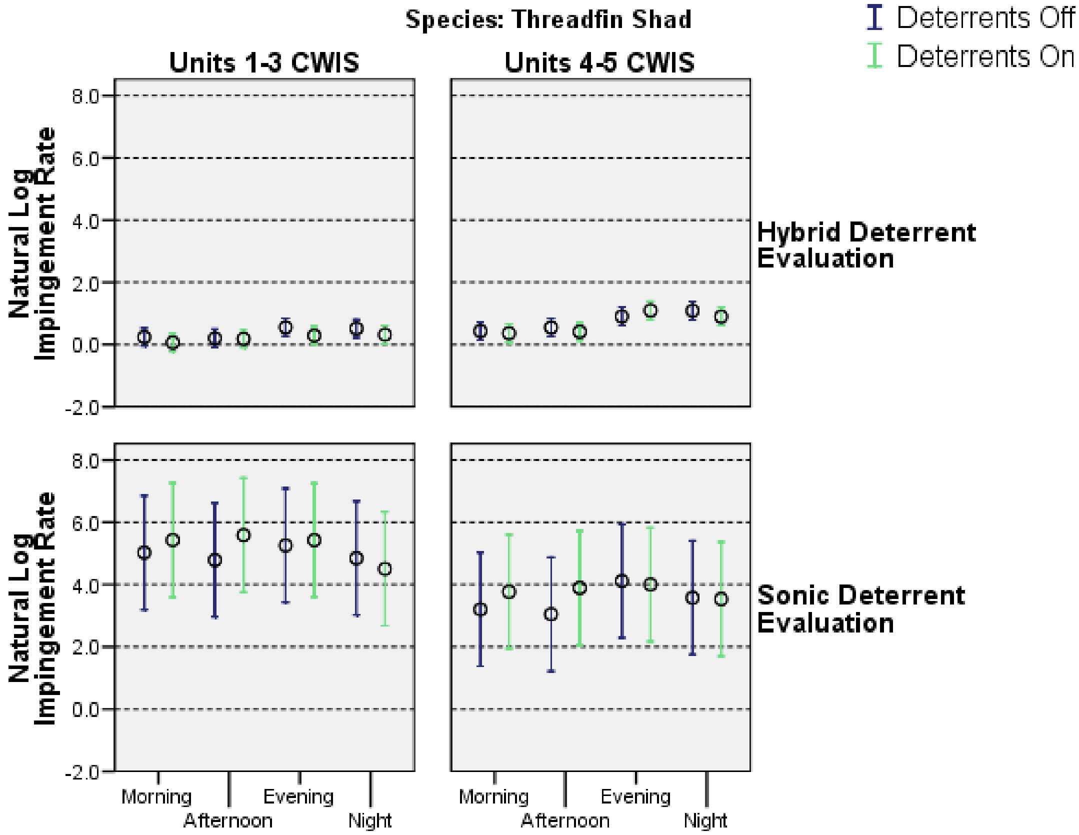


Figure 25. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for threadfin shad.

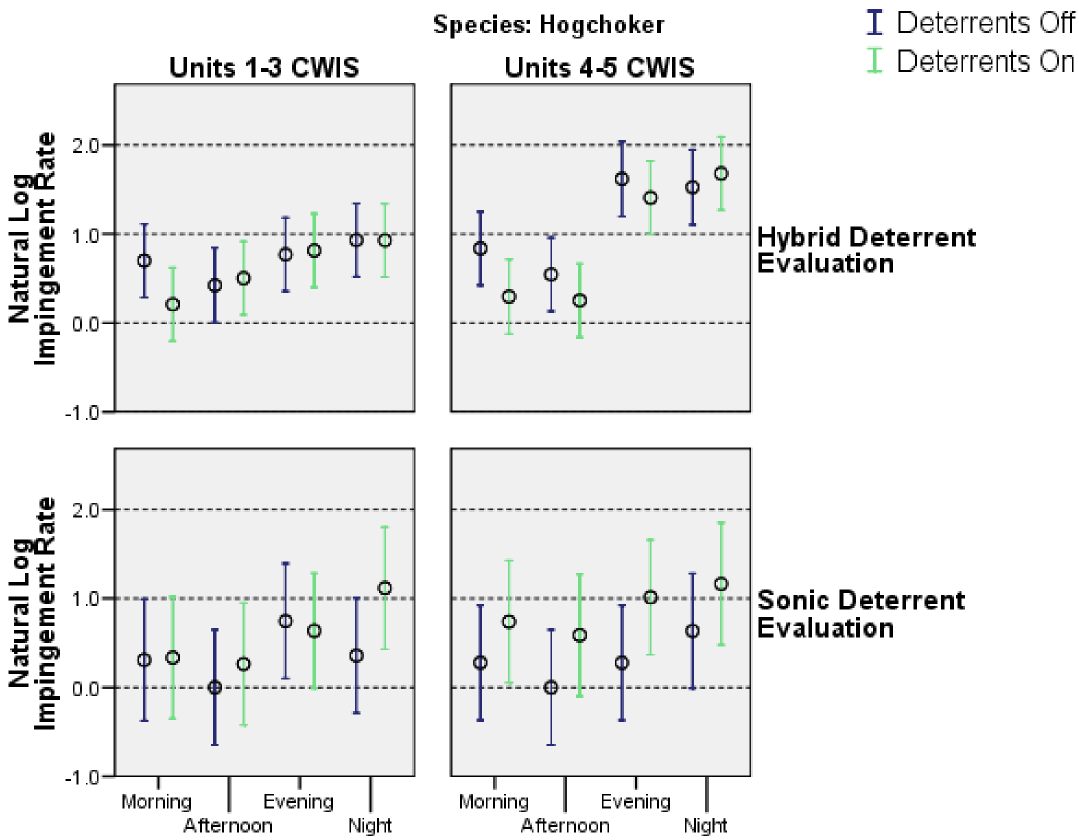


Figure 26. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for hogchoker.

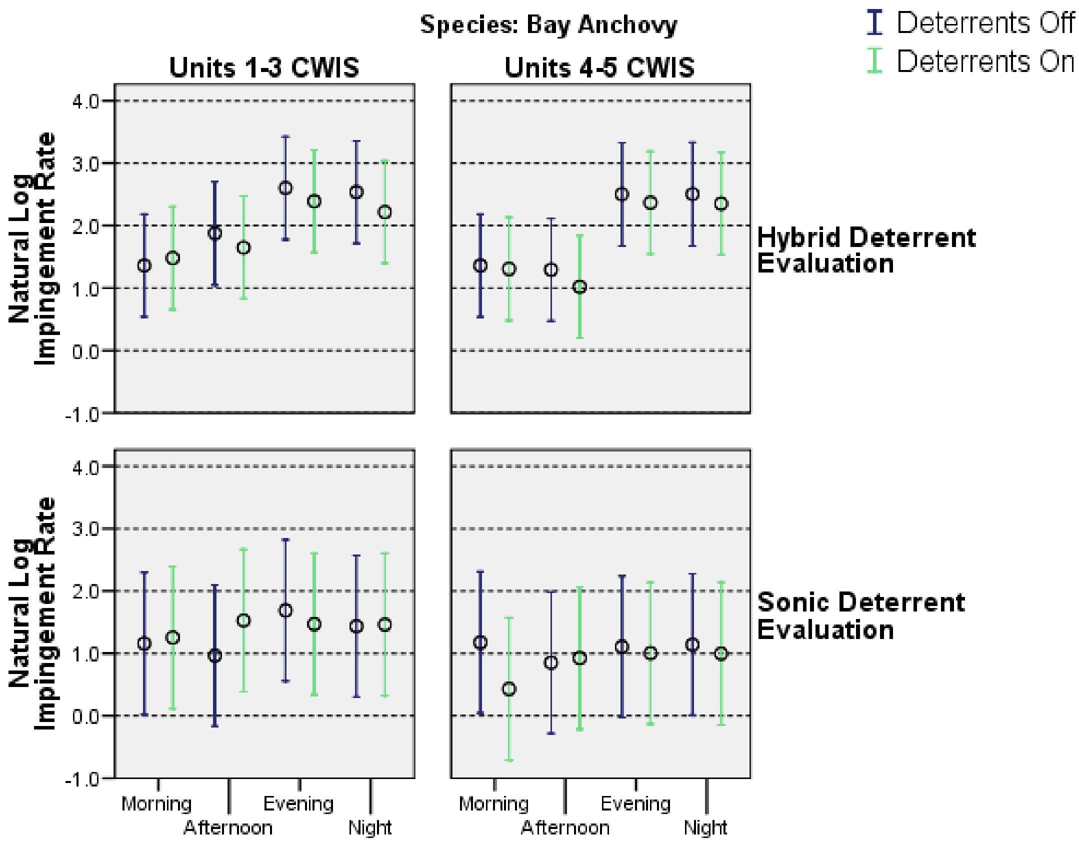


Figure 27. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for bay anchovy.

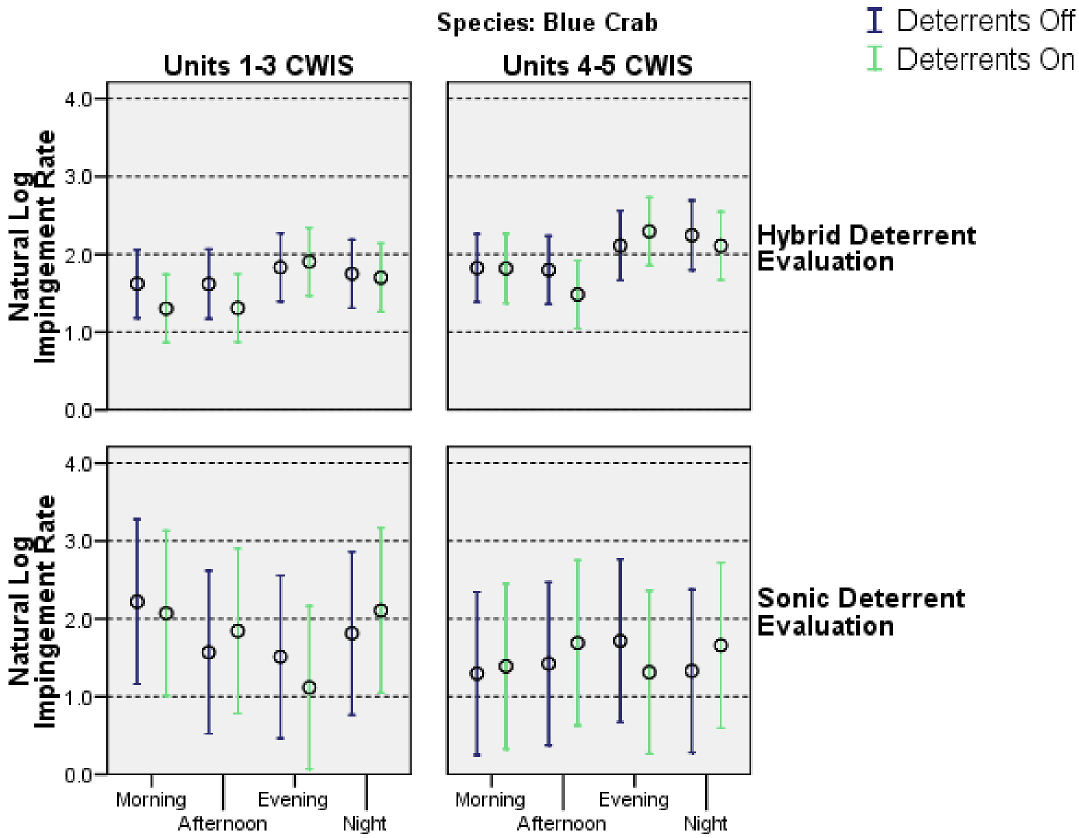


Figure 28. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for blue crab.

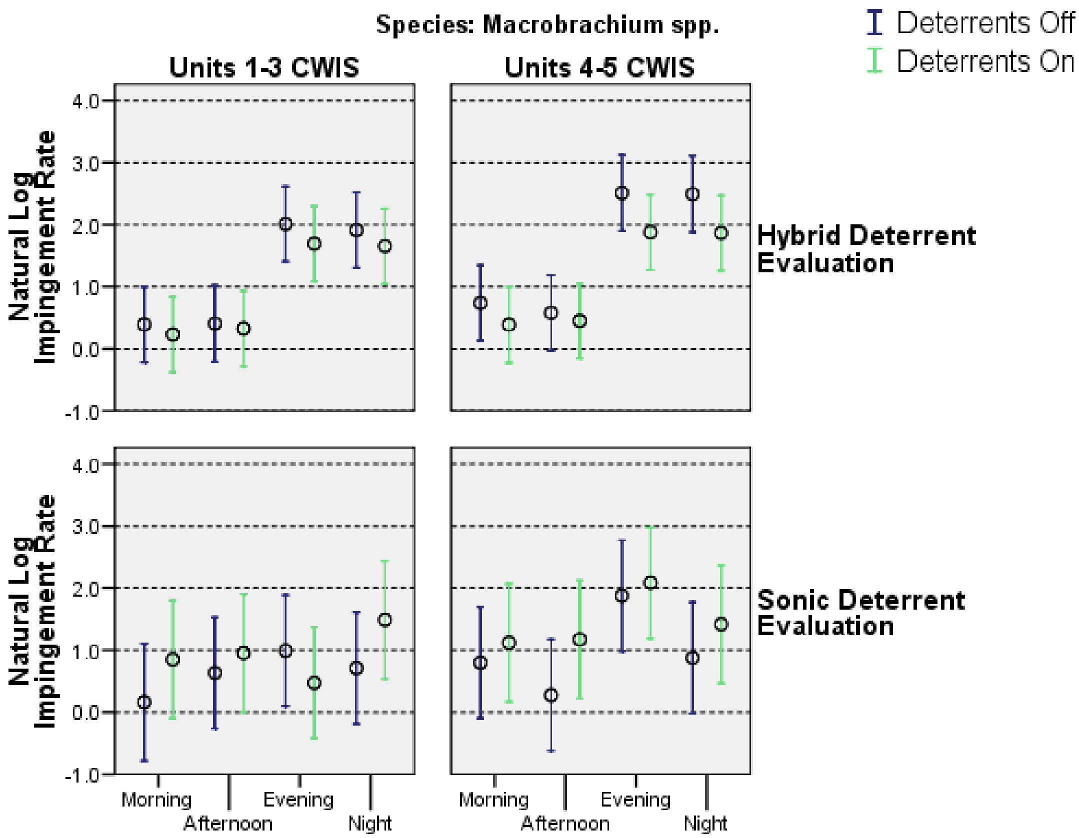


Figure 29. Split plot 95% confidence intervals for comparison of CWIS, diurnal, and treatment differences in mean impingement numbers for macrobrachium.

4.2.2 Water Quality and Environmental Monitoring Results

The effect of flow and water quality parameters on the numbers of fish being impinged or deterred was also considered when examining the effectiveness of the deterrent systems. None of these environmental parameters are considered to have had any meaningful effect on the impingement of fish while evaluating either the hybrid or sonic deterrent systems.

Pairwise comparisons of the marginal means for each of these parameters (using a Least Significant Difference) reveal that no significant differences in water temperature, dissolved oxygen or conductivity existed between treatments (Tables 6 and 7). Mean differences in pH were no greater than 0.162 pH units ($p>0.013$) for any of the CWIS x Diel comparisons.

Table 6. Mean, minimum, maximum and counts for various environmental parameters measurements collected during every impingement sampling event while evaluating the Hybrid deterrent system.

		Units 1-3 CWIS			Units 4-5 CWIS			Table Total
		Deterrents Off	Deterrents On	Group Total	Deterrents Off	Deterrents On	Group Total	Deterrents Off
Temp (C)	Mean	29.2	28.8	29.0	29.3	28.8	29.1	29.0
	Minimum	21.6	21.9	21.6	22.5	22.3	22.3	21.6
	Maximum	34.4	34.8	34.8	35.2	34.3	35.2	35.2
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
DO (mg/l)	Mean	7.36	7.31	7.33	7.41	7.33	7.37	7.35
	Minimum	5.94	6.07	5.94	6.01	6.17	6.01	5.94
	Maximum	9.39	8.52	9.39	9.22	8.56	9.22	9.39
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
pH (units)	Mean	7.34	7.32	7.33	7.33	7.30	7.32	7.32
	Minimum	6.99	6.81	6.81	6.91	6.97	6.91	6.81
	Maximum	7.83	7.77	7.83	7.74	7.75	7.75	7.83
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
Specific Conductance (microS/cm)	Mean	223.1	223.2	223.1	225.8	223.4	224.6	223.9
	Minimum	146.0	147.0	146.0	156.0	145.0	145.0	145.0
	Maximum	310.0	314.0	314.0	314.0	316.0	316.0	316.0
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
Turbidity (ntu)	Mean	19.9	26.2	23.1	20.0	15.7	17.8	20.5
	Minimum	5.2	5.1	5.1	4.5	5.2	4.5	4.5
	Maximum	117.9	663.0	663.0	124.3	57.1	124.3	663.0
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
CWIS Flow (cms)	Mean	193.50	191.66	192.58	315.04	315.43	315.24	253.45
	Minimum	83.32	111.09	83.32	289.46	315.43	289.46	83.32
	Maximum	220.56	220.56	220.56	315.43	315.43	315.43	315.43
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268
Through-Screen Velocity (mps)	Mean	.41	.41	.41	.69	.69	.69	.55
	Minimum	.13	.18	.13	.52	.53	.52	.13
	Maximum	.57	.55	.57	.87	.83	.87	.87
	N	N=67	N=68	N=135	N=66	N=67	N=133	N=268

Table 7. Mean, minimum, maximum and counts for various environmental parameters measurements collected during every impingement sampling event while evaluating the sonic deterrent system.

		Units 1-3 CWIS			Units 4-5 CWIS			Table Total
		Deterrents Off	Deterrents On	Group Total	Deterrents Off	Deterrents On	Group Total	Deterrents Off
Temp (C)	Mean	13.8	14.4	14.0	13.9	14.4	14.1	14.1
	Minimum	10.2	12.5	10.2	10.4	12.7	10.4	10.2
	Maximum	17.0	16.1	17.0	17.0	16.4	17.0	17.0
	N	N=19	N=16	N=35	N=20	N=16	N=36	N=71
DO (mg/l)	Mean	9.48	9.31	9.40	9.43	9.22	9.33	9.37
	Minimum	8.16	8.11	8.11	8.29	7.91	7.91	7.91
	Maximum	10.37	9.90	10.37	10.36	9.93	10.36	10.37
	N	N=19	N=16	N=35	N=20	N=16	N=36	N=71
pH (units)	Mean	7.22	7.25	7.23	7.24	7.25	7.25	7.24
	Minimum	6.96	7.15	6.96	7.04	7.09	7.04	6.96
	Maximum	7.42	7.38	7.42	7.45	7.40	7.45	7.45
	N	N=19	N=16	N=35	N=20	N=16	N=36	N=71
Specific Conductance (microS/cm)	Mean	194.7	189.8	192.5	195.6	189.4	192.9	192.7
	Minimum	173.0	174.0	173.0	173.0	173.0	173.0	173.0
	Maximum	216.0	210.0	216.0	217.0	209.0	217.0	217.0
	N	N=19	N=16	N=35	N=20	N=16	N=36	N=71
Turbidity (ntu)	Mean	16.7	24.0	20.1	16.3	25.8	20.5	20.3
	Minimum	11.0	10.0	10.0	9.5	9.8	9.5	9.5
	Maximum	43.4	56.4	56.4	46.3	66.1	66.1	66.1
	N	N=19	N=16	N=35	N=20	N=16	N=36	N=71
CWIS Flow (cms)	Mean	219.90	219.23	219.58	314.78	314.96	314.86	267.88
	Minimum	214.39	202.32	202.32	302.45	307.39	302.45	202.32
	Maximum	220.56	220.56	220.56	315.43	315.43	315.43	315.43
	N	N=19	N=17	N=36	N=20	N=17	N=37	N=73
Through-Screen Velocity (fps)	Mean	.52	.51	.52	.66	.66	.66	.59
	Minimum	.48	.46	.46	.59	.61	.59	.46
	Maximum	.57	.60	.60	.74	.74	.74	.74
	N	N=19	N=17	N=36	N=20	N=17	N=37	N=73

Overall, turbidity values averaged 20.5 and 20.3 ntu, respectively, for the hybrid and sonic deterrent evaluations (Tables 6 and 7). The strobe lights for the hybrid deterrent system were designed for a turbidity maximum of 50 ntu. The maximum turbidity value recorded for the Units 4-5 CWIS was 124.3 ntu while the hybrid deterrent (strobe light, sonic and ultrasonic deterrents) was off and 57.1 ntu while the hybrid deterrent was operating (Table 6). However, the pairwise comparison of the mean differences in turbidity at the Units 4-5 CWIS never exceeded 6 ntu between treatments and were not significant for each diel period ($p>0.691$) during the hybrid deterrent evaluation.

The differences in flow volume (cubic meters per second (cms)) or through-screen velocities (meters per second (mps)) between treatments are inconsequential compared to the typical flows and velocities that were calculated. Mean cooling water flows for the Units 1-3 CWIS were 193 and 219 cms during the hybrid and sonic deterrent evaluations, respectively. As expected the flows for the Units 4-5 CWIS were greater. The mean flows were 315 cms for both the hybrid and sonic deterrent evaluations. However, the pairwise comparisons of the flows for Units 1-3 CWIS never exceeded 7.32 cms between treatments for each of the diel periods ($p>0.032$). Mean differences for flows at the Units 4-5 CWIS were not significant and were calculated to be less than 8 cfs for each of the diel periods. The calculated CWIS flows are closely correlated with the calculated through-screen velocities. Mean through-screen velocities at the Units 1-3 CWIS were .41 mps for the hybrid and .52 mps for the sonic deterrent evaluation. The velocities were greater at the Units 4-5 CWIS with .69 mps during the hybrid and .66 mps during the sonic deterrent evaluation. Throughout both deterrent evaluations the mean treatment differences in the paired through-screen velocities never exceeded 0.09 fps ($p>0.023$).

5 DISCUSSION AND CONCLUSION

The results of the hybrid and sonic fish deterrent testing demonstrated that none of the behavioral stimuli evaluated (sonic sound, ultrasonic sound or strobe lights) were capable of reducing the impingement of freshwater organisms at Plant Barry. There is no evidence that the impinged total fish numbers or impinged individual species numbers were reduced when the deterrent systems were operating. Both deterrent systems operated as designed with the light and sound intensities equal to those which have been reported to stimulate responses in some of the same species of fish commonly impinged at Plant Barry. The evaluation of other environmental parameters which may have affected the results of this study has determined that these variables were consistent between the treatment periods (on or off) when evaluating the performance of the deterrent systems at the Plant Barry Units 4-5 CWIS. The impingement data set spanning over 30 weeks (341 individual samples) allowed for an analyses with a clear conclusion of no reduction in impingement rates with deterrents.

The deterrent system components operating at or near full capacity maintained the integrity of this system as a potential deterrent to the exposed fish community. Although the issues persisted with strobe light system maintenance, the time and attention given allowed relatively fast corrections to be made and minimized non-operational flash head time so that an average of 88% of the strobes were operational at 300 flashes/min throughout the Hybrid evaluation. Strobe light placement design was such that a solid wall of light should have been achieved in each of the CWIS openings (3 m x 3m) and extended at least 1.0 m in all directions. After comparing with actual test conditions of average turbidities of approximately 20 NTU (50 NTU design), the transmission of the strobe lights should have been 0.6 m greater than design (1.5 m in all direction). The Hybrid and Sonic behavioral deterrent systems operated properly at the following sound frequencies:

- Hybrid evaluation (sonic and ultrasonic sound with strobe lights)
    - sonic frequencies (band-limited random noise, 400-3000 Hz)
    - ultrasonic frequencies (band-limited random noise, 120-130 kHz)
- Sonic evaluation (sonic sound only)
    - sonic frequencies (tone burst of 400, 630, 1000, 1600, 2500, and 3150 Hz)

The sound pressure levels (SPLs) for the hybrid deterrent ranged from 157 to 161.7 dB for sonic frequencies and 141.4 to 147.9 dB for ultrasonic frequencies. The sonic deterrent SPLs ranged from approximately 150 to 170 dB for the 400 to 3,150 Hz frequency range. The SPLs of the hybrid and sonic deterrent evaluations should have been sufficient for fish entering the intake to detect the sound. However, the signal to noise ratio (SNR) appeared to be relatively low and may have been borderline for some species to adequately detect them above background noise levels. On the other hand, the tone bursts used during the sonic deterrent evaluation appear to have been considerably higher than background noise levels and would have been readily detectable by fish approaching the intake area.

Initial modeling showed that the predicted SPL contours for the ultrasonic sound frequency had some non-uniformity through the volume of the forebay, with higher levels at mid-water column than close to the bottom and surface boundaries, and at locations directly within the main lobe of a transducer than at locations within the nulls. The computations also show a region of low SPLs about 10 ft out from the intake trash racks. This occurred because this area is only ensonified by side lobe and backside energy from the transducers. The initial requirement established for the ultrasonic transmitting system was to achieve a uniform sound pressure level of 170 dB throughout the forebay. The modeling results indicated that it would be difficult to create an ultrasonic sound field with relatively uniform SPLs exceeding minimum criteria. However, previous studies have demonstrated that SPLs as low as 154 dB are sufficient for repelling members of the Clupeiformes (Table 2). The modeling results demonstrated that an ultrasonic sound system installed at Plant Barry could meet these minimum criteria.

Studies using flash head models and flash rates were successful at deterring several species similar to those which occur at Plant Barry. Previous strobe light deterrent studies with gizzard shad have shown avoidance responses to flash rates ranging from 200 to >800 flashes/min (EPRI 1990; Matousek et al. 1988; Patrick 1980a ; Patrick et al. 1980b, 1985). A review of strobe light deterrent studies involving other members of the family Clupeidae reported mixed results (Appendix 1). However, using flash rates of 300 flashes/min or greater generally resulted in avoidance of the strobe light deterrent.

The one study that used a strobe light with a flash rate of 300 flashes/min was effective at producing an avoidance response in channel catfish (EPRI 1990). However, other studies involving members of the family Ictaluridae (bullhead species *Ameiurus spp.*) have shown mixed results (GLEC 1994; McCauley et al. 1996; Patrick et al. 2006).

Strobe light deterrents have produced encouraging results when attempting to produce avoidance reactions in the family Sciaenidae. Six previous studies have shown that Sciaenid species avoided a strobe light deterrent, with the exception of a study involving weakfish. The strobe light flash rates that were evaluated ranged from 90 to 600 flashes/min, with all studies but one using flash rates at or above 300 flashes/min.

Little strobe light deterrent information is available on the Engraulidae and Soleidae families. Studies with members of the Engraulidae family have demonstrated mixed results; however, the one study conducted on a member (hogchoker) of the Soleidae family resulted in an avoidance reaction . The study performed by Matousek et al. (1988) involving bay anchovy and hogchoker was successful at deterring both species (Table 1). They evaluated a strobe light with a flash rate of 200 flashes/minute.

Sound frequencies and SPLs were chosen based primarily on previous sound deterrent studies and studies evaluating the hearing capabilities of the predominant species or similar species that are found at Plant Barry. The one study performed by Consolidated Edison (1994) involving gizzard shad failed to produce an avoidance response at the evaluated ultrasonic frequencies of 122-128 kHz (Table 2). Reviewing the literature for other species within the family Clupeidae showed that *Alosa* species have been repelled during lab and field studies with ultrasound (Appendix 2 and 3), while non-

Alosa species have demonstrated little or no avoidance to ultrasound and moderate or strong avoidance to sonic signals during field tests conducted in Europe (Maes et al. 2004). Because some members of the Clupeidae family (genus *Alosa*) have demonstrated strong avoidance to ultrasonic frequencies (> 80 kHz), an ultrasonic frequency was selected specifically as a potential deterrent for threadfin and gizzard shad for the Plant Barry hybrid deterrent evaluation. However, based on studies that have evaluated the hearing capabilities of several other clupeid species (Mann et al. 2001); information provided by Dr. Arthur Popper (personal communication); and previous sound deterrent studies (Appendix 2 and 3), it was concluded that non-Alosa clupeids, including threadfin and gizzard shad, are not able to detect ultrasound and therefore ultrasound was not evaluated during the Plant Barry sonic deterrent evaluation.

A review of the studies that measured the responses of bay anchovy to sound deterrents found that no responses to ultrasonic frequencies were observed during the Consolidated Edison study (1994). However, some type of response to sound was observed in a study which evaluated four ultrasonic frequencies ranging from 80 to 120 kHz and SPLs ranging from 147 to 170 dB. Sonic frequencies ranging from 100 to 5,000 Hz also produced avoidance responses in bay anchovies at SPLs ranging from 72 to 136 dB. Therefore, various sonic frequency ranges, similar to those evaluated by PSEG (2005), were evaluated during the Plant Barry hybrid and sonic deterrent studies.

Hearing threshold studies performed on channel catfish indicate that sonic frequencies ranging from 400 to 3,000 Hz should be detected if SPLs exceed 100 dB (Fay and Popper 1975). Assuming that channel catfish (which are also commonly impinged at Plant Barry) could serve as a surrogate for blue catfish, similar sonic frequencies with sufficient SPLs were used as a deterrent signal during the Plant Barry hybrid and sonic deterrent evaluations.

Sound deterrent responses have not been reported for freshwater drum. However, sound deterrents have produced encouraging results when attempting to produce avoidance reactions in the family Sciaenidae (Appendix 2 and 3). All of these previous studies have shown that Sciaenid species avoided sonic sound frequencies ranging from 100 to 5,000 Hz.

Hearing capabilities for several species that occur or are similar to those that occur at Plant Barry are presented in Figures 5-11. These figures demonstrate that the frequency ranges selected during the hybrid and sonic deterrent studies were assumed to be within the hearing capabilities of a number of frequently impinged species at Plant Barry based on a number of representative species. The figures also show that chosen sound frequencies were transmitted at sound pressure levels (SPLs) considerably higher than minimum hearing thresholds.

Environmental variables that appeared to have influence the overall impingement rates at Plant Barry were water temperature, dissolved oxygen, and time of day. The impingement rate increased with higher dissolved oxygen, lower temperatures, and during night-time hours. However, because there is no evidence of meaningful differences in any of the environmental parameters between the on and off treatment periods there is no reason to expect that these variables affected the proper evaluation of these deterrent systems.

Turbidity was an important design criterion governing the placement of the strobe lights. High turbidity greatly reduces the effective range of the strobe lights (Martin et al. 1991) due to the fact that increased turbidity minimizes light transmission. Occasionally, turbidity may have decreased the efficiency of the strobe light portion of the hybrid deterrent system. With turbidity reducing the effective distance of the strobe lights, the fish may not have been able to overcome the water velocity when finally able to detect the strobe lights. Water velocities toward the intake have been shown to lower the efficiency of behavioral barriers. Some fishes may detect the behavioral deterrents, however if the water velocities toward the intake exceed the fishes maximum swimming speed then they cannot necessarily escape and thus become impinged (Maes et al. 2004). At Plant Barry, the through-screen velocities for the CWIS equipped with the behavioral deterrents ranged from 0.52 to 0.87 mps. Studies with velocities in this range or lower have been associated with a reduction in the efficiency of behavioral deterrent devices (Sager et al. 2000; Pugh et al. 1970). It should be noted that there is no evidence to suggest that the strobe lights are attracting fish into the Units 4-5 CWIS. All statistical tests show that there were no significant ($p>0.05$) increases nor decreases in the impingement rates for these data.

Following a discussion of water velocities and turbidity effects, it is also important to note that previous studies of fish impinged at Plant Barry have documented relatively high rates of fish disease when compared to the control population. Diseased or weakened fish exposed to a deterrent may not react as a healthy fish would or even have the ability to avoid being impinged once in the hydraulic zone of influence (Baker 2007). This factor may have masked the true avoidance response by the healthy fish population. However, it was determined that the diseased fish population, although likely present, did not mask evidence of a deterrent avoidance response.

Based on impingement monitoring the use of sound and strobe lights as configured in this study was not effective at deterring a riverine fish community or fish species available in this section of the Mobile River and should not be considered as a solution for reducing impingement at Plant Barry. Mixed results in deterring fish have been reported in the literature when evaluating behavioral deterrent devices such as those reported in the literature review. From these mixed results, it can be concluded that there may be some other factors involved such as site-specific conditions or fish assemblages present or exposed. However, this test indicates both the hybrid and sonic deterrent systems with the strobe light and sound equipment and configurations tested could not be used as an effective technology option for reducing impingement at Plant Barry. As an apparent result, the deterrent systems evaluated in this report could not be selected as a viable technology option for complying with the 316(b) rule.

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APPENDICES

APPENDIX 1. A summarized literature review of strobe light behavioral studies arranged by species.

Family	Common Name	Scientific Name	Flash Head Model	Study Type	Flash Rates (fl/min)	Ambient Light Conditions	Temp (°C)	Approach Velocity (m/s)	Turbidity Conditions (NTU)	Movement type	Avoidance Response Observed	Site	Reference
Anguillidae	American eel	*Anguilla rostrata*	Tandy Electrionics	Field (Hydroelectric)	>800	24-hour testing	NR	NR	NR	deterrent	Yes	R. H. Saunders Generating Station (St. Lawrence River, Cornwall, Ontario, Canada)	Patrick et al. (1982, 2001)
	American eel	*Anguilla rostrata*	Tandy Electrionics	Laboratory (tank)	66, 200, 300, 450, 484, 748, 1090	night	NR	NR	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (1982, 2001)
	European eel	*Anguilla anguilla*	NR	Laboratory (flume)	600	NR	NR	0.11	NR	deterrent	Yes	Marine Biology Unit (Fawley, UK)	Haddering and Smythe (1997)
Catostomidae	white sucker	*Catostomus commersoni*	Flash Technology (FT) AGL 901	Field (CWIS)	300	day, dusk, night, dawn	NR	NR	NR	deterrent	Yes	Milliken Station	Ichthyological Assoc. (1994, 1997)

	white sucker	*Cataostomus commersoni*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
Centrarchidae	black crappie	*Pomoxis nigromaculatus*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	bluegill	*Lepomis macrochirus*	EG&G SS-122	Laboratory (raceway)	300	day	NR	0	NR	deterrent	Yes	University of Iowa	EPRI (1990)
	largemouth bass	*Micropterus salmoides*	FT AGL 900	Field (cage)	200, 300, 400, 500, 600	day, night	NR	NR	NR	deterrent	Yes	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)

	largemouth bass	*Micropterus salmoides*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	largemouth bass	*Micropterus salmoides*	EG&G SS-122	Laboratory (raceway)	300	day	NR	0	NR	deterrent	No	University of Iowa	EPRI (1990)
	pumpkinseed	*Lepomis gibbosus*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes (day), No (dusk), Yes (night), No (dawn)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
	smallmouth bass	*Micropterus dolomieui*	FT AGL 900	Field (cage)	200, 300, 400, 500, 600	day, night	NR	NR	NR	deterrent	No	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)

EPRI (1998a, 1998b) Michaud and Taft (1999)	Amaral et al. (1998)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)	EPRI (1988) Matousek et al. (1988)
White Rapids Hydroelectric Project (Menominee River, Wisconsin)	Roza Diversion Dam (Yakima River, Washington)	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Roseton Generating Station (Hudson River, New York)
No	Yes	No	No (for all light conditions)
deterrent	deterrent	deterrent	deterrent
3.92-9.34	3.3-6.8	NR	2.0-130
0.01-0.28	0.12	NR	NR
NR	NR	NR	6.0-32.0
24-hour testing	night	day, night	day, dusk, night, dawn
400	450	200, 300, 400, 500, 600	200
Field (Hydroelectric)	Field (cage)	Field (cage)	Field (CWIS)
FT AGL 900	NR	FT AGL 900	EG&G FA-107
Micropterus dolomieui	*Micropterus dolomieui*	*Lepomis spp.*	*Alosa pseudoharengus*
smallmouth bass	smallmouth bassCen	sunfish spp.	alewife
			Clupeidae

alewife	*Alosa pseudoharengus*	FT AGL 901	Field (CWIS)	300	day, dusk, night, dawn	NR	NR	NR	deterrent	Yes	Milliken Steam Electric Station (Cayuga Lake, Lansing, New York)	Ichthyological Assoc. (1994, 1997)
alewife	*Alosa pseudoharengus*	Lightomation SFF II, EG&G FA-107	Field (CWIS)	200	dusk, night, dawn	5.0-23.0	0.2-0.8	0.2-6.3	deterrent	Yes	Pickering Generating Station (Lake Ontario, Canada)	Hydro and LMS (1989)
alewife	*Alosa pseudoharengus*	generic	Field (Hydroelectric)	120	day, dusk	NR	0.5	NR	guidance	No	Fort Halifax Hydroelectric Station (Sebasticook River, Maine)	ECS and Lakside Eng. (1994)
alewife	*Alosa pseudoharengus*	FT	Laboratory (raceway)	NR	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)

Rodgers (1983) Rodgers and Patrick (1985)	EPRI (1988) Matousek et al. (1988)	Martin et al. (1991) EPRI (1990, 1992) Martin and Sullivan (1992)	EPRI (1990)
Ontario Hydro (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Roseton Generating Station (Hudson River, New York)	York Haven Hydroelectric Project (Susquehanna River, Pennsylvania)	Hadley Falls Hydroelectric Project (Connecticut River, Holyoke, Massachusetts)
Yes	No (day), No (dusk), Yes (night), No (dawn)	Yes	No
guidance	deterrent	deterrent	deterrent
NR	2.0-130	NR	NR
0.12-0.3	NR	0.1-1.0	NR
10.0-18.0	6.0-32.0	15.0-23.0	NR
NR	day, dusk, night, dawn	day, night	day
>200	200	300	300
Laboratory (tank)	Field (CWIS)	Field (Hydroelectric)	Field (Hydroelectric)
NR	EG&G FA-107	EG&G FA-107	NR
Alosa pseudoharengus	*Alosa sapidissima*	*Alosa sapidissima*	*Alosa sapidissima*
alewife	American shad	American shad	American shad

Atlantic menhaden	*Brevoortia tyrannus*	NR	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.3, 0.5	NR	deterrent	Yes	University of Maryland	Sager et al. (2000)
Atlantic menhaden	*Brevoortia tyrannus*	FT	Laboratory (tank)	300	Indoor lighting	NR	0.2	39.0-138	deterrent	Yes	University of Maryland	McInnich and Hocutt (1987)
Atlantic menhaden	*Brevoortia tyrannus*	Tandy Electrionics	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.5	NR	deterrent	Yes	Ontario Hydro and University of Maryland	Patrick et al. 1985
blueback herring	*Alosa aestivalis*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2.0-130	deterrent	No (for all light conditions)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
blueback herring	*Alosa aestivalis*	FT	Laboratory (flume)	300	dim overhead	8.8-11.0	0.08-0.12	<50	deterrent	Yes	Salem Generating Station (Lower Alloways Creek, New Jersey)	PSEG (2003)

EPRI (1988) Matousek et al. (1988)	Patrick et al. (2006)	Patrick et al. 1985	Patrick 1980b	Jahn and Herbinson (2000)
Roseton Generating Station (Hudson River, New York)	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Ontario Hydro and University of Maryland	Ontario Hydro	San Onofre Nuclear Generating Station (San Diego, California)
No (day), No (dusk), No (night), Yes (dawn)	Yes	Yes	Yes	Inconclusive
deterrent	deterrent	deterrent	deterrent	deterrent
2.0-130	NR	0, 1.0, 3.0	NR	NR
NR	0.1-0.5	0.11-0.32	0.15-0.32	0.5
6.0-32.0	NR	NR	7.0-9.5	NR
day, dusk, night, dawn	NR	day, night	dark	no light
200	NR	300	>800	90
Field (CWIS)	Laboratory (raceway)	Laboratory (tank)	Laboratory (tank)	Laboratory (flume)
EG&G FA-107	FT	Tandy Electrionics	NR	Realistic, Catalog number 423009A
Dorosoma cepedianum	*Dorosoma cepedianum*	*Dorosoma cepedianum*	*Dorosoma cepedianum*	*Sardinops sagax*
gizzard shad	gizzard shad	gizzard shad	gizzard shad	Pacific sardine

Cottidae	slimy sculpin	*Cottus cognatus*	FT AGL 901	Field (CWIS)	300	day, dusk, night, dawn	NR	NR	NR	deterrent	Yes	Milliken Steam Electric Station (Cayuga Lake, Lansing, New York)	Ichthyological Assoc. (1994, 1997)
Cyprinidae	common carp	*Cyprinus carpio*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	emerald shiner	*Notropis atherinoides*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	golden shiner	*Notemigonus crysoleucas*	FT AGL 4100	Field (Hydroelectric)	60 (1994), NR (1995)	day, dusk, night, dawn	NR	NR	NR	deterrent	No (day), Yes (dusk), Yes (night), Yes (dawn)	Four Mile Dam (Thunder Bay River, Michigan)	GLEC (1994) McCauley et al. (1996)

	northern pikeminnow	*Ptychocheilus oregonensis*	NR	Field (cage)	300	night	NR	0.12	3.3-6.6	deterrent	Yes	Roza Diversion Dam (Yakima River, Washington)	Amaral et al. (1998)
	northern pikeminnow	*Ptychocheilus oregonensis*	NR	Field (cage)	450	night	NR	0.12	3.3-6.7	deterrent	No	Roza Diversion Dam (Yakima River, Washington)	Amaral et al. (1998)
	spottail shiner	*Notropis hudsonius*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2.0-130	deterrent	No (day), No (dusk), Yes (night), No (dawn)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
Engraulidae	bay anchovy	*Anchoa mitchilli*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2.0-130	deterrent	Yes (day), No (dusk), No (night), No (dawn)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
	bay anchovy	*Anchoa mitchilli*	FT	Laboratory (flume)	300	dim overhead	22.3-22.8	0.08-0.12	<50	deterrent	No	Salem Generating Station (Lower Alloways Creek, New Jersey)	PSEG (2003)

	northern anchovy	*Engraulis mordax*	Realistic, Catalog number 423009A	Laboratory (flume)	90	no light	NR	0.5	NR	deterrent	Mixed	San Onofre Nuclear Generating Station (San Diego, California)	Jahn and Herbinson (2000)
Ictaluridae	brown bullhead	*Ameiurus nebulosus*	FT	Laboratory (raceway)	NR	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)
	bullhead catfish	*Ameiurus spp.*	FT AGL 4100	Field (Hydroelectric)	60 (1994), NR (1995)	day, dusk, night, dawn	NR	NR	NR	deterrent	No (day), Yes (dusk), Yes (night), Yes (dawn)	Four Mile Dam (Thunder Bay River, Michigan)	GLEC (1994) McCauley et al. (1996)
	channel catfish	*Ictalurus punctatus*	EG&G SS-122	Laboratory (raceway)	300	day, dark	NR	0	NR	deterrent	Yes	University of Iowa	EPRI (1990)
Moronidae	hybrid striped/white bass	*Morone chrysops x Morone saxatilis*	EG&G SS-122	Laboratory (raceway)	300	day	NR	0	NR	deterrent	Yes	University of Iowa	EPRI (1990)

	striped bass	*Morone saxatilis*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No (for all light conditions)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
	white perch	*Morone americana*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No (day), Yes (dusk), Yes (night), No (dawn)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)
	white perch	*Morone americana*	NR	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.3, 0.5	NR	deterrent	Yes	University of Maryland	Sager et al. (2000)
	white perch	*Morone americana*	FT	Laboratory (tank)	300	Indoor lighting	NR	0.2	39-138	deterrent	Yes	University of Maryland	McInnich and Hocutt (1987)
	white perch	*Morone americana*	Tandy Electrionics	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.5	NR	deterrent	Yes	Ontario Hydro and University of Maryland	Patrick et al. 1985

Osmeridae	rainbow smelt	*Osmerus mordax*	NR	Laboratory (tank)	>200	NR	10.0-18.0	0.12-0.3	NR	guidance	Yes	Ontario Hydro (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Rodgers (1983) Rodgers and Patrick (1985)
Percidae	logperch	*Percina caprodes*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	walleye	*Sander vitreus*	FT AGL 900	Field (cage)	200, 300, 400, 500, 600	day, night	NR	NR	NR	deterrent	Yes	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
	walleye	*Sander vitreus*	FT AGL 900	Field (Hydroelectric)	400	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids	EPRI (1998a, 1998b) Michaud and Taft (1999)
	walleye	*Sander vitreus*	EG&G SS-122	Laboratory (raceway)	300	day	NR	0	NR	deterrent	Yes	University of Iowa	EPRI (1990)

Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)	Ichthyological Assoc. (1994, 1997)	EPRI (1998a, 1998b) Michaud and Taft (1999)	Rodgers (1983) Rodgers and Patrick (1985)
Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Milliken Steam Electric Station (Cayuga Lake, Lansing, New York)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	Ontario Hydro (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)
Yes	Yes	No	Yes
deterrent	deterrent	deterrent	guidance
NR	NR	3.92-9.34	NR
NR	NR	0.01-0.28	0.12-0.3
NR	NR	NR	10.0-18.0
day, night	day, dusk, night, dawn	24-hour testing	NR
200, 300, 400, 500, 600	300	400	>200
Field (cage)	Field (CWIS)	Field (Hydroelectric)	Laboratory (tank)
FT AGL 900	FT AGL 901	FT AGL 900	NR
Perca flavescens	*Perca flavescens*	*Pera flavescens*	*Perca flavescens*
yellow perch	yellow perch	yellow perch	yellow perch

Ichthyological Assoc. (1994, 1997)	Georgia-Pacific Corp. (1989, 1990) Great Northern Paper (1995, 1998) Brown (1997)	NDT and Lakeside Eng. (1995)	Puckett and Anderson (1987) Nemeth (1989) EPRI (1990) Nemeth and Anderson (1992)
Milliken Steam Electric Station (Cayuga Lake, Lansing, New York)	Mattaceunk Hydroelectric Project (Penobscot River, Maine)	Rolfe Canal Hydroelectric Project (Contocook River, New Hampshire)	University of Washington
Yes	No	No	Yes
deterrent	guidance	guidance	deterrent
NR	NR	NR	NR
NR	NR	NR	0
NR	NR	NR	NR
day, dusk, night, dawn	24-hour testing	24-hour testing	dark
300	200 (1998-89), NR (1993-98)	300	100
Field (CWIS)	Field (Hydroelectric)	Field (Hydroelectric)	Laboratory (raceway)
FT AGL 901	FT AGL 4100	NR	EG&G SS-122
Percopsis omiscomaycus	*Salmo salar*	*Salmo salar*	*Salmo salar*
trout perch	Atlantic salmon	Atlantic salmon	Atlantic salmon
Percomsidae	Salmonidae		

Mueller et al. (2001)	Pacific Northwest National Laboratory (Richland, Washington)	No	deterrent	NR	NR	14	day	300	Laboratory (tank, net pen)	FT AGL 901	*Salvelinus fontinalis*	brook trout	
Ploskey and Johnson (1998, 2001) Ploskey et al. (1998)	Hiram M. Chittenden Locks (Seattle, Washington)	Yes	guidance	1	NR	NR	day	300	Field (cage)	FT	*Oncorhynchus tshawytscha*	Chinook salmon	
Amaral et al. (1998)	Roza Diversion Dam (Yakima River, Washington)	Yes	deterrent	3.3-6.5	0.12	NR	day, dusk, night	300, 450	Field (cage)	NR	*Oncorhynchus tshawytscha*	Chinook salmon	
Johnson and Ploskey (1998)	McNary Dam (Columbia River, Umatilla, Oregon)	Yes	deterrent	NR	NR	NR	NR	150, 200	Field (Hydroelectric)	FT AGL Series	*Oncorhynchus tshawytscha*	Chinook salmon	
Anderson et al. (1988)	Rocky Reach Dam (Columbia River, Washington)	No	guidance	NR	NR	NR	day, night	NR	Field (Hydroelectric)	NR	*Oncorhynchus tshawytscha*	Chinook salmon	

Puckett and Anderson (1987) Nemeth (1989) EPRI (1990) Nemeth and Anderson (1992)	**Mueller et al. (2001)**	**Ploskey and Johnson (1998, 2001) Ploskey et al. (1998)**	**Bengeyfield and Smith (1989)**
University of Washington	**Pacific Northwest National Laboratory (Richland, Washington)**	**Hiram M. Chittenden Locks (Seattle, Washington)**	**Puntledge**
Yes (for both light conditions)	**Yes**	**Yes**	**No**
deterrent	**deterrent**	**guidance**	**guidance**
NR	**NR**	**1**	**NR**
0	**NR**	**NR**	**NR**
NR	**14**	**NR**	**NR**
day, dark	**day**	**day**	**day, night**
100 (dark), 300 (day)	**300**	**300**	**60**
Laboratory (raceway)	**Laboratory (tank, net pen)**	**Field (cage)**	**Field (Hydroelectric)**
EG&G SS-122	**FT AGL 901**	**FT**	**NR**
Oncorhynchus tshawytscha	***Oncorhynchus tshawytscha***	***Oncorhynchus kisutch***	***Oncorhynchus kisutch***
Chinook salmon	**Chinook salmon**	**coho salmon**	**coho salmon**

Puckett and Anderson (1987) Nemeth (1989) EPRI (1990) Nemeth and Anderson (1992)	**Johnson et al. (2001)**	**Brown (2000)**	**Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)**	**Rodgers (1983) Rodgers and Patrick (1985)**
University of Washington	**Hiram M. Chittenden Locks (Seattle, Washington)**	**Dworshak Dam (North fork of the Clearwater River, Orofino, Idaho)**	**Kingsford Hydroelectric Project (Menominee River, Wisconsin)**	**Ontario Hydro**
Yes (for both light conditions)	**Yes**	**Yes**	**No**	**Yes**
deterrent	**guidance**	**deterrent**	**deterrent**	**guidance**
NR	**1.0-1.4**	**NR**	**NR**	**NR**
0	**0.1-1.7**	**NR**	**NR**	**0.12-0.3**
NR	**NR**	**NR**	**NR**	**10.0-18.0**
day, dark	**day**	**day, night**	**day, night**	**NR**
100 (dark), 300 (day)	**300**	**300, 360, 450**	**200, 300, 400, 500, 600**	**>200**
Laboratory (raceway)	**Field (Lock)**	**Field (open water lake)**	**Field (cage)**	**Laboratory (tank)**
EG&G SS-122	**FT AGL 901**	**NR**	**FT AGL 900**	**NR**
Oncorhynchus kisutch	***Oncorhynchus spp.***	***Oncorhynchus nerka***	***Oncorhynchus mykiss***	***Oncorhynchu s mykiss***
coho salmon	**juvenile salmon spp.**	**kokanee salmon**	**rainbow trout**	**rainbow trout**

Mueller et al. (2001)	McKinley and Patrick (1988)	Puckett and Anderson (1987) Nemeth (1989) EPRI (1990) Nemeth and Anderson (1992)	Konigson et al. (2002)	Konigson et al. (2002)
Pacific Northwest National Laboratory (Richland, Washington)	Seton Creek (near Lillooet, British Columbia, Canada)	University of Washington	Birko Island (on the Swedish Baltic Sea coast)	Saimaa Fisheries Research and Aquaculture Station (eastern Finland)
Yes	Yes	Yes (day), dark (inconsistent)	Yes	Yes
deterrent	guidance	deterrent	deterrent	deterrent
NR	NR	NR	NR	NR
NR	NR	0	NR	NR
14	NR	NR	NR	NR
day	dusk, night	day, dark	night	no light
300	>200	100 (dark), 300 (day)	180	180
Laboratory (tank, net pen)	Field (Hydroelectric)	Laboratory (raceway)	Field (net fence)	Laboratory (tank)
FT AGL 901	Lightomation SFF	EG&G SS-122	Velleman strobo 20	Velleman strobo 21
Oncorhynchus mykiss	*Oncorhynchus nerka*	*Oncorhynchus mykiss*	*Coregonus lavaretus*	*Coregonus lavaretus*
rainbow trout	sockey salmon	steelhead trout	whitefish	whitefish

Sciaenidae	Atlantic croaker	*Micropogonias undulatus*	FT	Laboratory (flume)	300	dim overhead	6.9-10.2	0.08-0.12	<50	deterrent	Yes	Salem Generating Station (Lower Alloways Creek, New Jersey)	PSEG (2003)
	spot	*Leiostomus xanthurus*	NR	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.3, 0.5	NR	deterrent	Yes	University of Maryland	Sager et al. (2000)
	spot	*Leiostomus xanthurus*	FT	Laboratory (tank)	300	Indoor lighting	NR	0.2	39-140	deterrent	Yes	University of Maryland	McInnich and Hocutt (1987)
	spot	*Leiostomus xanthurus*	Tandy Electrionics	Laboratory (tank)	300, 600	day, night	NR	0.2, 0.5	NR	deterrent	Yes	Ontario Hydro and University of Maryland	Patrick et al. 1985
	weakfish	*Cynoscion regalis*	FT	Laboratory (flume)	300, 360, 450	dim overhead	17.2-20.4	0.08-0.12	<50	deterrent	No	Salem Generating Station (Lower Alloways Creek, New Jersey)	PSEG (2003)

	white croaker	*Genyonemus lineatus*	Realistic, Catalog number 423009A	Laboratory (flume)	90	no light	NR	0.5	NR	deterrent	Yes	San Onofre Nuclear Generating Station (San Diego, California)	Jahn and Herbinson (2000)
Soleidae	hogchoker	*Trinectes maculatus*	EG&G FA-107	Field (CWIS)	200	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes (day), No (dusk), Yes (night), Yes (dawn)	Roseton Generating Station (Hudson River, New York)	EPRI (1988) Matousek et al. (1988)

APPENDIX 2. A summarized literature review of sound behavioral studies arranged by species.

Family	Common Name	Scientific Name	Acoustic System	Study Type	Ambient Light Conditions	Temp (°C)	Approach Velocity (m/s)	Turbidity (NTU)	Movement type	Frequencies Evaluated	Avoidance Response Observed	Site	Reference
Anguillidae	American eel	*Anguilla rostrata*	ITC model 3406 transducers	Field (Hydroelectric)	day, night	NR	0.68	NR	deterrent/ guidance	122-128 kHz	No	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Gibson and Myers 2002
	American eel	*Anguilla rostrata*	NR	Laboratory (tank)	NR	NR	NR	NR	guidance	<1,000 Hz	No (eels were attracted	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2001)
	European eel	*Anguilla anguilla*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	No	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
	European eel	*Anguilla anguilla*	piston	Field (open water)	NR	NR	0.9-1.3	NR	deterrent	<20 Hz	Yes	River Imsa	Sand et al. (2001)

Gibson and Myers 2002	PSEG (2005)	EPRI (1998a, 1998b) Michaud and Taft (1999)	EPRI (1998a, 1998b) Michaud and Taft (1999)
Annapolis Tidal Generating Station (Nova Scotia, Canada)	Salem Generating Station (Delaware River Estuary)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)
No	Yes	No	No
122-128 kHz	100-400 Hz, 500-3,000 Hz, 80-120 kHz	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz
deterrent/ guidance	deterrent	deterrent	deterrent
NR	15.6-147.0	3.92-9.34	3.92-9.34
0.68	NR	0.01-0.28	0.01-0.28
NR	7.6-30.9	NR	NR
day, night	daylight	24 hour	24 hour
Field (Hydroelectric)	Field (Open water)	Field (Hydroelectric)	Field (Hydroelectric)
ITC model 3406 transducers	ITC model 3406 transducer	U.S. Navy G34 transducers	U.S. Navy G34 transducers
Menidia menidia	*Menidia menidia*	*Cataostomus commersoni*	*Pomoxis nigromaculatus*
Atlantic Silverside	Atlantic Silverside	white sucker	black crappie
Atherinopsidae		Catostomidae	Centrarchidae

Patrick et al. (1988b) McKinley et al. (1987)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)	EPRI (1998a, 1998b) Michaud and Taft (1999)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
Lennox Generating Station	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	Kingsford Hydroelectric Project (Menominee River, Wisconsin)
No	No	No	Yes
27 Hz, 64 Hz, 99 Hz, 153 Hz	100-6400 Hz	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	100-6400 Hz
deterrent	deterrent	deterrent	deterrent
NR	NR	3.92-9.34	NR
NR	NR	0.01-0.28	NR
NR	NR	NR	NR
NR	day, night	24 hour	day, night
Field (forebay)	Field (cage)	Field (Hydroelectric)	Field (cage)
fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	U.S. Navy G34 transducers	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I
Pomoxis nigromaculatus	*Pomoxis nigromaculatus*	*Micropterus salmoides*	*Micropterus salmoides*
black crappie	black crappie	largemouth bass	largemouth bass

Winchell et al. (1997) EPRI (1998a, 1998b)	**Patrick et al. (1988b) McKinley et al. (1987)**	**Patrick et al. (1988b) McKinley et al. (1987)**
Kingsford Hydroelectric Project (Menominee River, Wisconsin)	**Lennox Generating Station**	**Lennox Generating Station**
No	**No**	**No**
5-60 Hz	**27 Hz, 64 Hz, 99 Hz, 153 Hz**	**27 Hz, 64 Hz, 99 Hz, 153 Hz**
deterrent	**deterrent**	**deterrent**
NR	**NR**	**NR**
NR	**NR**	**NR**
NR	**NR**	**NR**
day, night	**NR**	**NR**
Field (cage)	**Field (forebay)**	**Field (forebay)**
transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	**fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer**	**fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer**
Micropterus salmoides	***Lepomis gibbosus***	***Ambloplites rupestris***
largemouth bass	**pumpkinseed**	**rock bass**

EPRI (1998a, 1998b) Michaud and Taft (1999)	**Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)**	**Winchell et al. (1997) EPRI (1998a, 1998b)**	**Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)**
White Rapids Hydroelectric Project (Menominee River, Wisconsin)	**Kingsford Hydroelectric Project (Menominee River, Wisconsin)**	**Kingsford Hydroelectric Project (Menominee River, Wisconsin)**	**Kingsford Hydroelectric Project (Menominee River, Wisconsin)**
No	**Yes**	**No**	**Yes**
673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	**100-6400 Hz**	**5-60 Hz**	**100-6400 Hz**
deterrent	**deterrent**	**deterrent**	**deterrent**
3.92-9.34	**NR**	**NR**	**NR**
0.01-0.28	**NR**	**NR**	**NR**
NR	**NR**	**NR**	**NR**
24 hour	**day, night**	**day, night**	**day, night**
Field (Hydroelectric)	**Field (cage)**	**Field (cage)**	**Field (cage)**
U.S. Navy G34 transducers	**transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I**	**transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I**	**transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I**
Micropterus dolomieui	***Micropterus dolomieui***	***Micropterus dolomieui***	***Lepomis spp.***
smallmouth bass	**smallmouth bass**	**smallmouth bass**	**sunfish spp.**

Winchell et al. (1997) EPRI (1998a, 1998b)	Gibson and Myers 2002	Taft et al. (1996) Taft and Brown (1997)	Ross et al. (1993) Ross et (1996)
Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Salem Generating Station (Delaware River Estuary)	James A. Fitzpatrick Nuclear Power Plant (Lake Ontario near Oswego, New York)
No	Yes	Yes	Yes
5-60 Hz	122-128 kHz	121.8 kHz	122-128 kHz
deterrent	deterrent/ guidance	deterrent	deterrent
NR	NR	NR	NR
NR	0.68	NR	<0.4
NR	NR	NR	6.0-23.0
day, night	day, night	day, dusk, night, dawn	24 hour
Field (cage)	Field (Hydroelectric)	Field (cage)	Field (CWIS)
transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	ITC model 3406 transducers	transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I	narrow and wide-beam ultrasonic transducers
Lepomis spp.	*Alosa pseudoharengus*	*Alosa pseudoharengus*	*Alosa pseudoharengus*
sunfish spp.	alewife	alewife	alewife
	Clupeidae		

Dunning et al. (1992)	NDT et al. (1997)	Consolidated Edison (1994)	ECS and Lakside Eng. (1994)	Consolidated Edison (1994)
flooded rock quarry (near Verplanck, New York)	Pejepscot Hydroelectric Project (Androscoggin River, Maine)	Arthur Kill Generating Station (Staten Island, New York)	Fort Halifax	Arthur Kill Generating Station (Staten Island, New York)
Yes	Yes	Yes	No	Yes (>120 kHz)
110 Hz, 125 Hz, 117-133 kHz	120 kHz	122-128 kHz	4 kHz	18-198 kHz
deterrent	deterrent/ guidance	deterrent	guidance	deterrent
NR	NR	NR	NR	NR
NR	NR	NR	0.5	NR
13.0-14.0	NR	NR	NR	NR
day, night	NR	24 hour	day, dusk	day, night
Field (cage)	Field (Hydroelectric)	Field (CWIS)	Field (Hydroelectric)	Field (cage)
ITC model 3003 transducer	ultrasonic transducers	narrow and wide-beam ultrasonic transducers	an underwater alert system	directional ultrasonic transducers
Alosa pseudoharengus	*Alosa pseudoharengus*	*Alosa pseudoharengus*	*Alosa pseudoharengus*	*Alosa pseudoharengus*
alewife	alewife	alewife	alewife	alewife

ECS and Lakside Eng. (1994)	Patrick et al. (1988b) McKinley et al. (1987)	NYPA et al. (1991)
Fort Halifax	Lennox Generating Station (Bay of Quinte, Lake Ontario, Canada)	flooded rock quarry (near Verplanck, New York)
Yes	No	Yes (>110 kHz)
192 kHz	27 Hz, 64 Hz, 99 Hz	<100-1,000 Hz, 110-150 kHz
guidance	deterrent	deterrent
NR	NR	NR
0.5	NR	NR
NR	NR	NR
day, dusk	NR	day, night
Field (Hydroelectric)	Field (forebay)	Field (cage)
a fishfinder/depthsounder hydroacoustic system	fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer	HLF-6 sonic transducer
Alosa pseudoharengus	*Alosa pseudoharengus*	*Alosa pseudoharengus*
alewife	alewife	alewife

Patrick et al. (1988b) McKinley et al. (1987)	**Gibson and Myers 2002**	**PSEG (2005)**	**Consolidated Edison (1994)**
Lennox Generating Station (Bay of Quinte, Lake Ontario, Canada)	**Annapolis Tidal Generating Station (Nova Scotia, Canada)**	**Salem Generating Station (Delaware River Estuary)**	**Arthur Kill Generating Station (Staten Island, New York)**
Yes	**Yes**	**Yes**	**Yes**
153 Hz	**122-128 kHz**	**100-400 Hz, 500-3,000 Hz, 80-120 kHz**	**122-128 kHz**
deterrent	**deterrent/ guidance**	**deterrent**	**deterrent**
NR	**NR**	**15.6-147.0**	**NR**
NR	**0.68**	**NR**	**NR**
NR	**NR**	**7.6-30.9**	**NR**
NR	**day, night**	**daylight**	**24 hour**
Field (forebay)	**Field (Hydroelectric)**	**Field (Open water)**	**Field (CWIS)**
fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer	**ITC model 3406 transducers**	**ITC model 3406 transducer**	**narrow and wide-beam ultrasonic transducers**
Alosa pseudoharengus	***Alosa sapidissima***	***Alosa sapidissima***	***Alosa sapidissima***
alewife	**American shad**	**American shad**	**American shad**

Taft et al. (1996) Taft and Brown (1997)	RMC and Sonalysts (1993)	SWETS (1994)
Salem Generating Station (Delaware River Estuary)	Vernon Hydroelectric Project (on the Connecticut River in Hinsdale, New Hampshire and Vernon, Vermont)	York Haven Hydroelectric Project (Susquehanna River, Pennsylvania)
Yes	Yes	Yes
121.8 kHz	125 kHz	120-125 kHz
deterrent	deterrent/ guidance	deterrent
NR	NR	NR
NR	NR	NR
NR	NR	NR
day, dusk, night, dawn	NR	NR
Field (cage)	Field (Hydroelectric)	Field (Hydroelectric)
transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I	ultrasonic transducer	narrow and wide-beam ultrasonic transducers
Alosa sapidissima	*Alosa sapidissima*	*Alosa sapidissima*
American shad	American shad	American shad

RMC and Sonalysts (1993)	Kynard and O'Leary (1990)	Gibson and Myers 2002	Consolidated Edison (1994)
Vernon Hydroelectric Project (on the Connecticut River in Hinsdale, New Hampshire and Vernon, Vermont)	Hadley Falls Hydroelectric Project (Connecticut River, Holyoke, Massachusetts)	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Arthur Kill Generating Station (Staten Island, New York)
Yes	Yes	No	No
100-150 kHz	161.9 kHz	122-128 kHz	122-128 kHz
deterrent	deterrent	deterrent/ guidance	deterrent
NR	NR	NR	NR
NR	NR	0.68	NR
NR	NR	NR	NR
NR	NR	day, night	24 hour
Field (cage)	Field (Hydroelectric)	Field (Hydroelectric)	Field (CWIS)
ultrasonic transducer	Wesmar SS-165 scanning sonar	ITC model 3406 transducers	narrow and wide-beam ultrasonic transducers
Alosa sapidissima	*Alosa sapidissima*	*Clupea harengus harengus*	*Clupea harengus harengus*
American shad	American shad	Atlantic herring	Atlantic herring

Maes et al. (2004)	PSEG (2005)	Gibson and Myers 2002	Consolidated Edison (1994)	PSEG (2003)
Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Salem Generating Station (Delaware River Estuary)	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Arthur Kill Generating Station (Staten Island, New York)	Salem Generating Station (Delaware River Estuary)
Yes	Yes	No	Yes	Yes
20-600 Hz	100-400 Hz, 500-3,000 Hz, 80-120 kHz	122-128 kHz	122-128 kHz	80-120 kHz
deterrent	deterrent	deterrent/ guidance	deterrent	deterrent
NR	15.6-147.0	NR	NR	<50
<0.52	NR	0.68	NR	0.08-0.12
NR	7.6-30.9	NR	NR	8.8-11.0
24 hour	daylight	day, night	24 hour	dim overhead
Field (CWIS)	Field (Open water)	Field (Hydroelectric)	Field (CWIS)	Laboratory (flume)
FGS Mk II 30-600 sound projectors	ITC model 3406 transducer	ITC model 3406 transducers	narrow and wide-beam ultrasonic transducers	U.S. Navy J-11 and ITC model 3406 transducers
Clupea harengus harengus	*Brevoortia tyrannus*	*Alosa aestivalis*	*Alosa aestivalis*	*Alosa aestivalis*
Atlantic herring	Atlantic menhaden	blueback herring	blueback herring	blueback herring

PSEG (2005)	**Ross (1999)**	**Ross (1999)**	**Pickens (1992) Nestler et al. (1995) Nestler et al. (1998) Schillt and Ploskey (1997)**
Salem Generating Station (Delaware River Estuary)	**Crescent Hydroelectric Poject (Mohawk River, New York)**	**Visher Ferry Hydroelectric Poject (Mohawk River, New York)**	**Richard B. Russell Pumped Storage Project (Savannah River, South Carolina and Georgia)**
Yes	**Yes**	**Yes**	**Yes (118-130 kHz)**
100-400 Hz, 500-3,000 Hz, 80-120 kHz	**122-128 kHz**	**122-128 kHz**	**<1,000 Hz, 80-150 kHz, 420 kHz**
deterrent	**guidance**	**guidance**	**deterrent**
15.6-147.0	**NR**	**NR**	**NR**
NR	**NR**	**NR**	**NR**
7.6-30.9	**NR**	**NR**	**NR**
daylight	**NR**	**NR**	**day, night**
Field (Open water)	**Field (Hydroelectric)**	**Field (Hydroelectric)**	**Field (Hydroelectric)**
ITC model 3406 transducer	**ultrasonic transducers**	**ultrasonic transducers**	**ultrasonic transducers**
Alosa aestivalis	***Alosa aestivalis***	***Alosa aestivalis***	***Alosa aestivalis***
blueback herring	**blueback herring**	**blueback herring**	**blueback herring**

Pickens (1992) Nestler et al. (1995) Nestler et al. (1998) Schillt and Ploskey (1997)	Taft et al. (1996) Taft and Brown (1997)	Maes et al. (2004)	Consolidated Edison (1994)
Richard B. Russell Lake (South Carolina and Georgia)	Salem Generating Station (Delaware River Estuary)	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Arthur Kill Generating Station (Staten Island, New York)
Yes (110-140 kHz)	Yes	Yes	No
<1,000 Hz, 80-150 kHz, 420 kHz	121.8 kHz	20-600 Hz	122-128 kHz
deterrent	deterrent	deterrent	deterrent
NR	NR	NR	NR
NR	NR	<0.52	NR
NR	NR	NR	NR
day, night	day, dusk, night, dawn	24 hour	24 hour
Field (net pen)	Field (cage)	Field (CWIS)	Field (CWIS)
sonic and ultrasonic transducers	transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I	FGS Mk II 30-600 sound projectors	narrow and wide-beam ultrasonic transducers
Alosa aestivalis	*Alosa aestivalis*	*Sprattus sprattus*	*Dorosoma cepedianum*
blueback herring	blueback herring	European sprat	gizzard shad

Sonny et al. (2006)	Sonny et al. (2006)	Sonny et al. (2006)	EPRI (1998a, 1998b) Michaud and Taft (1999)	EPRI (1998a, 1998b) Michaud and Taft (1999)
Tihange Nuclear Power Plant (River Meuse, Belgium)	Lake Borrevann (Norway)	Tihange Nuclear Power Plant (River Meuse, Belgium)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	White Rapids Hydroelectric Project (Menominee River, Wisconsin)
Yes	Yes	Yes	No	No
16 Hz	16 Hz	16 Hz	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz
deterrent	deterrent	deterrent	deterrent	deterrent
NR	NR	NR	3.92-9.34	3.92-9.34
0.05-0.28	NR	0.05-0.28	0.01-0.28	0.01-0.28
5	8, 15	5	NR	NR
day, dusk, night	day, dusk, night	day, dusk, night	24 hour	24 hour
Field (CWIS)	Field (open water)	Field (CWIS)	Field (Hydroelectric)	Field (Hydroelectric)
particle motion generator (PMG)	particle motion generator (PMG)	particle motion generator (PMG)	U.S. Navy G34 transducers	U.S. Navy G34 transducers
Alburnus alburnus	*Alburnus alburnus*	*Abramis brama*	*Cyprinus carpio*	*Notropis atherinoides*
bleak	bleak	common bream	common carp	emerald shiner
Cyprinidae				

	golden shiner	*Notemigonus crysoleucas*	fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer	Field (forebay)	NR	NR	NR	NR	deterrent	27 Hz, 64 Hz, 99 Hz, 153 Hz	No	Lennox Generating Station (Bay of Quinte, Lake Ontario, Canada)	Patrick et al. (1988b) McKinley et al. (1987)
	golden shiner	*Notemigonus crysoleucas*	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	Field (cage)	day, night	NR	NR	NR	deterrent	100-6400 Hz	No	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
	golden shiner	*Notemigonus crysoleucas*	HLF-6 sonic transducer	Field (cage)	day, night	NR	NR	NR	deterrent	<100-1,000 Hz, 110-150 kHz	No	flooded rock quarry (near Verplanck, New York)	NYPA et al. (1991)
	northern pikeminnow	*Ptychocheilus oregonensis*	particle motion generator (PMG)	Field (cage)	night	NR	0.12	3.3-6.8	deterrent	10-50 Hz	Yes	Roza Diversion Dam (Yakima River, Washington)	Amaral et al. (1998, 2001)

roach	*Rutilus rutilus*	particle motion generator (PMG)	Field (open water)	day, dusk, night	8, 15	NR	NR	deterrent	16 Hz	Yes	Lake Borrevann (Norway)	Sonny et al. (2006)
roach	*Rutilus rutilus*	particle motion generator (PMG)	Field (CWIS)	day, dusk, night	5	0.05-0.28	NR	deterrent	16 Hz	Yes	Tihange Nuclear Power Plant (River Meuse, Belgium)	Sonny et al. (2006)
rudd	*Scardinius erythrophthala mus*	particle motion generator (PMG)	Field (open water)	day, dusk, night	8, 15	NR	NR	deterrent	16 Hz	Yes	Lake Borrevann (Norway)	Sonny et al. (2006)
spottail shiner	*Notropis hudsonius*	HLF-6 sonic transducer	Field (cage)	day, night	NR	NR	NR	deterrent	<100-1,000 Hz, 110-150 kHz	No	flooded rock quarry (near Verplanck, New York)	NYPA et al. (1991)
white bream	*Abramis bjoerkna*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)

PSEG (2005)	Consolidated Edison (1994)	Taft et al. (1996) Taft and Brown (1997)	McKinley et al. (1987)	Consolidated Edison (1994)
Salem Generating Station (Delaware River Estuary)	Arthur Kill Generating Station (Staten Island, New York)	Salem Generating Station (Delaware River Estuary)	Manimota Bay (Japan)	Arthur Kill Generating Station (Staten Island, New York)
Yes	No	Yes	Yes	No
100-400 Hz, 500-3,000 Hz, 80-120 kHz	122-128 kHz	100-5,000 Hz	300-900 Hz (taped marine mammal sounds)	75-500 Hz, 18-198 kHz
deterrent	deterrent	deterrent	deterrent	deterrent
15.6-147.0	NR	NR	NR	NR
NR	NR	NR	NR	NR
7.6-30.9	NR	NR	NR	NR
daylight	24 hour	day, dusk, night, dawn	NR	day, night
Field (Open water)	Field (CWIS)	Field (cage)	Field (open water)	Field (cage)
ITC model 3406 transducer	narrow and wide-beam ultrasonic transducers	transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I	underwater speakers	omni-directional sonic and directional ultrasonic transcucers
Anchoa mitchilli	*Anchoa mitchilli*	*Anchoa mitchilli*	*Anchoa mitchilli*	*Anchoa mitchilli*
bay anchovy	bay anchovy	bay anchovy	bay anchovy	bay anchovy
Engraulidae				

PSEG (2003)	**NYPA et al. (1991)**	**Holand and Walso (1988)**	**Gibson and Myers 2002**	**Maes et al. (2004)**
Salem Generating Station (Delaware River Estuary)	**flooded rock quarry (near Verplanck, New York)**	**Sommaroyh amn, Norway**	**Annapolis Tidal Generating Station (Nova Scotia, Canada)**	**Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)**
Yes	**No**	**Yes**	**No**	**No**
100-3,000 Hz	**<100-1,000 Hz, 110-150 kHz**	**30 Hz**	**122-128 kHz**	**20-600 Hz**
deterrent	**deterrent**	**deterrent**	**deterrent/ guidance**	**deterrent**
<50	**NR**	**NR**	**NR**	**NR**
0.08-0.12	**NR**	**NR**	**0.68**	**<0.52**
8.8-11.0	**NR**	**NR**	**NR**	**NR**
dim overhead	**day, night**	**24 hour**	**day, night**	**24 hour**
Laboratory (flume)	**Field (cage)**	**Field (net pen)**	**Field (Hydroelectric)**	**Field (CWIS)**
U.S. Navy J-11 transducers	**HLF-6 sonic transducer**	**sonic transducer**	**ITC model 3406 transducers**	**FGS Mk II 30-600 sound projectors**
Anchoa mitchilli	***Microgadus tomcod***	***Gaus spp.***	***Gasterosteus wheatlandi***	***Pungitius pungitius***
bay anchovy	**Atlantic tomcod**	**cod**	**blackspotted stickleback**	**ninespine stickleback**
	Gadidae		**Gasterosteidae**	

	three-spined stickleback	*Gasterosteus aculeatus*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	No	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
Gobiidae	goby spp.	*Pomatoschistus spp.*	FGS Mk II 30-600 sound projectors	Field (CWIS)	26 hour	NR	<0.54	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
Ictaluridae	bullhead catfish	*Ameiurus spp.*	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	Field (cage)	day, night	NR	NR	NR	deterrent	100-6400 Hz	Yes	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
Moronidae	European seabass	*Dicentrarchus labrax*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)

NYPA et al. (1991)	**PSEG (2005)**	**NYPA et al. (1991)**	**PSEG (2005)**	**Maes et al. (2004)**
flooded rock quarry (near Verplanck, New York)	**Salem Generating Station (Delaware River Estuary)**	**flooded rock quarry (near Verplanck, New York)**	**Salem Generating Station (Delaware River Estuary)**	**Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)**
Yes	**No**	**Yes**	**No**	**No**
<100-1,000 Hz	**100-400 Hz, 500-3,000 Hz, 80-120 kHz**	**<100-1,000 Hz**	**100-400 Hz, 500-3,000 Hz, 80-120 kHz**	**20-600 Hz**
deterrent	**deterrent**	**deterrent**	**deterrent**	**deterrent**
NR	**15.6-147.0**	**NR**	**15.6-147.0**	**NR**
NR	**NR**	**NR**	**NR**	**<0.55**
NR	**7.6-30.9**	**NR**	**7.6-30.9**	**NR**
day, night	**daylight**	**day, night**	**daylight**	**27 hour**
Field (cage)	**Field (Open water)**	**Field (cage)**	**Field (Open water)**	**Field (CWIS)**
HLF-6 sonic transducer	**ITC model 3406 transducer**	**HLF-6 sonic transducer**	**ITC model 3406 transducer**	**FGS Mk II 30-600 sound projectors**
Morone saxatilis	***Morone saxatilis***	***Morone americana***	***Morone americana***	***Liza ramada***
striped bass	**striped bass**	**white perch**	**white perch**	**thinlip mullet**
				Mugilidae

Osmeridae	European smelt	*Osmerus eperlanus*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
Percidae	European perch	*Perca fluviatilis*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
	logperch	*Percina caprodes*	U.S. Navy G34 transducers	Field (Hydroelectric)	24 hour	NR	0.01-0.28	3.92-9.34	deterrent	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	pike-perch	*Stizostedion lucioperca*	FGS Mk II 30-600 sound projectors	Field (CWIS)	24 hour	NR	<0.52	NR	deterrent	20-600 Hz	No	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)

walleye	*Sander vitreus*	U.S. Navy G34 transducers	Field (Hydroelectric)	24 hour	NR	0.01-0.28	3.92-9.34	deterrent	673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	No	White Rapids Hydroelectric Project	EPRI (1998a, 1998b) Michaud and Taft (1999)
walleye	*Sander vitreus*	U.S. Navy J-11 transducer	Labortatory (raceway)	NR	NR	NR	NR	deterrent	100-1,000 Hz	No	Tionesta State Fish Hatchery	Smith and Anderson (1984)
walleye	*Sander vitreus*	U.S. Navy G34 transducer	Field (Hydroelectric)	NR	NR	NR	NR	deterrent	100-1,000 Hz	No	Allegheny Reservoir (Pennsylvania and Nev York)	Smith and Anderson (1984)
walleye	*Sander vitreus*	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	Field (cage)	day, night	NR	NR	NR	deterrent	100-6400 Hz	Yes	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
walleye	*Sander vitreus*	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	Field (cage)	day, night	NR	NR	NR	deterrent	5-60 Hz	No	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Winchell et al. (1997) EPRI (1998a, 1998b)

EPRI (1998a, 1998b) Michaud and Taft (1999)	Patrick et al. (1988b) McKinley et al. (1987)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)
White Rapids Hydroelectric Project (Menominee River, Wisconsin)	Lennox Generating Station	Kingsford Hydroelectric Project (Menominee River, Wisconsin)
No	No	Yes
673 Hz, 2000 Hz, 2990 Hz, 5500 Hz	27 Hz, 64 Hz, 99 Hz, 153 Hz	100-6400 Hz
deterrent	deterrent	deterrent
3.92-9.34	NR	NR
0.01-0.28	NR	NR
NR	NR	NR
24 hour	NR	day, night
Field (Hydroelectric)	Field (forebay)	Field (cage)
U.S. Navy G34 transducers	fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I
Pera flavescens	*Pera flavescens*	*Pera flavescens*
yellow perch	yellow perch	yellow perch

Winchell et al. (1997) EPRI (1998a, 1998b)	**Maes et al. (2004)**	**Gibson and Myers 2002**	**Maes et al. (2004)**
Kingsford Hydroelectric Project (Menominee River, Wisconsin)	**Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)**	**Annapolis Tidal Generating Station (Nova Scotia, Canada)**	**Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)**
No	**No**	**No**	**No**
5-60 Hz	**20-600 Hz**	**122-128 kHz**	**20-600 Hz**
deterrent	**deterrent**	**deterrent/ guidance**	**deterrent**
NR	**NR**	**NR**	**NR**
NR	**<0.57**	**0.68**	**<0.52**
NR	**NR**	**NR**	**NR**
day, night	**29 hour**	**day, night**	**24 hour**
Field (cage)	**Field (CWIS)**	**Field (Hydroelectric)**	**Field (CWIS)**
transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	**FGS Mk II 30-600 sound projectors**	**ITC model 3406 transducers**	**FGS Mk II 30-600 sound projectors**
Pera flavescens	***Lampetra fluviatilis***	***Urophycis spp.***	***Limanda limanda***
yellow perch	**European river lamprey**	**hake**	**dab**
	Petromyzontidae	**Phycidae**	**Pleuronectidae**

Maes et al. (2004)	PSEG (2005)	Nedwell and Turnpenny (1997)	Knudsen et al. (1992)	Knudsen et al. (1994)	Sand et al. (2001)
Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Generating Station (Delaware River	Fawley Aquatic Research Station	University of Oslo	Sandvikselven River (Norway)	University of Oslo
Yes	No	Yes	No	Yes	Yes (<10)
20-600 Hz	100-400 Hz, 500-3,000 Hz, 80-120 kHz	NR	150 Hz	10 Hz	5-10 Hz, 150 Hz
deterrent	deterrent	guidance	deterrent	deterrent	deterrent
NR	15.6-147.0	NR	NR	NR	NR
<0.52	NR	NR	NR	NR	NR
NR	7.6-30.9	NR	NR	NR	NR
24 hour	daylight	NR	NR	NR	NR
Field (CWIS)	Field (Open water)	Field	Laboratory (pool)	Field (Hydroelectric)	Laboratory (pool)
FGS Mk II 30-600 sound projectors	ITC model 3406 transducer	NR	transducer	piston	piston
Platichthys flesus	*Pomatomus saltatrix*	*Salmo salar*	*Salmo salar*	*Salmo salar*	*Salmo salar*
flounder	bluefish	Atlantic salmon	Atlantic salmon	Atlantic salmon	Atlantic salmon
	Pomatomidae	Salmonidae			

Knudsen et al. (1992, 1994)	Mueller et al. (2001)	Goetz et al. (2001)	Ploskey et al. (2000)	Ploskey et al. (2000)
University of Oslo	Pacific Northwest National Laboratory (Richland, Washington)	Hiram M. Chittenden Locks (Seattle, Washington)	Bonneville Dam (Comumbia River, Oregon)	Bonneville Dam (Comumbia River, Oregon)
Yes	No	No	No	No
10 Hz	10-14 Hz	300 Hz, 400 Hz	300 Hz, 400 Hz	300 Hz, 400 Hz
deterrent	deterrent	guidance	guidance	guidance
NR	NR	NR	NR	NR
NR	NR	<0.25	0.65	0.65
NR	14	NR	NR	NR
NR	day	day, dusk, dawn	24 hour	24 hour
Laboratory (tank)	Laboratory (tank, net pen)	Field (lock)	Field (Hydroelectric)	Field (net pen)
piston	piston	EESCO model 220 transducers	Argotech model 215 transducers	Argotech model 215 transducers
Salmo salar	*Salvelinus fontinalis*	*Oncorhynchus tshawytscha*	*Oncorhynchus tshawytscha*	*Oncorhynchus tshawytscha*
Atlantic salmon	brook trout	Chinook salmon	Chinook salmon	Chinook salmon

Ploskey et al. (1998)	Loeffelman et al. (1991) Klinect et al. (1992)	Loeffelman et al. (1991) Klinect et al. (1992)	Hanson Environmental (1993) SL&DMWA and Hanson (1996) Hanson et al. (1997)
Hiram M. Chittenden Locks (Seattle, Washington)	Berrien Springs Hydroelectric Project (St. Joseph River, southwestern Michigan)	Buchanan Hydro Plant (St. Joseph River, southwestern Michigan)	Georgiana Slough (Sacramento River, California)
No	No	Yes	Mixed
300 Hz, 400 Hz	100-1,000 Hz	100-1,000 Hz	300 Hz, 400 Hz
guidance	guidance	guidance	deterrent
1	NR	NR	NR
NR	NR	NR	NR
NR	NR	NR	NR
day	NR	NR	24 hour
Field (cage)	Field (Hydroelectric)	Field (Hydroelectric)	Field (slough)
particle motion generator (PMG) and piston	Argotech model 220 transducers	Argotech model 220 transducers	Argotech model 215 transducers
Oncorhynchus tshawytscha	*Oncorhynchus tshawytscha*	*Oncorhynchus tshawytscha*	*Oncorhynchus tshawytscha*
Chinook salmon	Chinook salmon	Chinook salmon	Chinook salmon

Cramer et al. (1993)	**Mueller et al. (2001)**	**Mueller et al. (1998)**	**Amaral et al. (1998)**
Wilkins Slough Pumping Station (Sacramento River, California)	**Pacific Northwest National Laboratory (Richland, Washington)**	**Pacific Northwest National Laboratory (Richland, Washington)**	**Roza Diversion Dam (Yakima River, Washington)**
inconclusive	**Yes**	**No**	**No**
301 Hz, 400 Hz	**10-14 Hz**	**150 Hz, 180 Hz, 200 Hz**	**10-50 Hz**
deterrent	**deterrent**	**deterrent**	**deterrent**
NR	**NR**	**NR**	**3.3-6.8**
NR	**NR**	**NR**	**0.12**
NR	**14**	**NR**	**NR**
NR	**day**	**NR**	**night**
Field (slough)	**Laboratory (tank, net pen)**	**Laboratory (tank)**	**Field (cage)**
Argotech sonic transducers	**piston**	**EESCO model 215 transducer**	**particle motion generator (PMG)**
Oncorhynchus tshawytscha	***Oncorhynchus tshawytscha***	***Oncorhynchus tshawytscha***	***Oncorhynchus tshawytscha***
Chinook salmon	**Chinook salmon**	**Chinook salmon**	**Chinook salmon**

Ploskey et al. (1998)	Knudsen et al. (1997)	Goetz et al. (2001)	Ploskey et al. (2000)	Ploskey et al. (2000)
Hiram M. Chittenden Locks (Seattle, Washington)	Oregon State University	Hiram M. Chittenden Locks (Seattle, Washington)	Bonneville Dam (Comumbia River, Oregon)	Bonneville Dam (Comumbia River, Oregon)
Yes (10 Hz piston)	Yes	No	No	No
10-30 Hz	10 Hz	300 Hz, 400 Hz	300 Hz, 400 Hz	300 Hz, 400 Hz
guidance	deterrent	guidance	guidance	guidance
1	NR	NR	NR	NR
NR	NR	<0.25	0.65	0.65
NR	10	NR	NR	NR
day	NR	day, dusk, dawn	24 hour	24 hour
Field (cage)	Laboratory (tank)	Field (lock)	Field (Hydroelectric)	Field (net pen)
particle motion generator (PMG) and piston	piston	EESCO model 220 transducers	Argotech model 215 transducers	Argotech model 215 transducers
Oncorhynchus tshawytscha	*Oncorhynchus tshawytscha*	*Oncorhynchus kisutch*	*Oncorhynchus kisutch*	*Oncorhynchus kisutch*
Chinook salmon	Chinook salmon	coho salmon	coho salmon	coho salmon

Ploskey et al. (1998)	Ploskey et al. (1998)	Winchell et al. (1997) EPRI (1998a, 1998b) Michaud and Taft (1999)	Patrick et al. (1988b) McKinley et al. (1987)
Hiram M. Chittenden Locks (Seattle, Washington)	Hiram M. Chittenden Locks (Seattle, Washington)	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Lennox Generating Station
No	Yes (10 Hz piston)	Yes	No
300 Hz, 400 Hz	10-30 Hz	100-6400 Hz	27 Hz, 64 Hz, 99 Hz, 153 Hz
guidance	guidance	deterrent	deterrent
1	1	NR	NR
NR	NR	NR	NR
NR	NR	NR	NR
day	day	day, night	NR
Field (cage)	Field (cage)	Field (cage)	Field (forebay)
particle motion generator (PMG) and piston	particle motion generator (PMG) and piston	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	fish drone (sonic vigrations were used to excite a metallic structure at a selected resonance) and hammer
Oncorhynchus kisutch	*Oncorhynchus kisutch*	*Oncorhynchus mykiss*	*Oncorhynchus mykiss*
coho salmon	coho salmon	rainbow trout	rainbow trout

Mueller et al. (2001)	Mueller et al. (1998)	Winchell et al. (1997) EPRI (1998a, 1998b)	Knudsen et al. (1997)	Goetz et al. (2001)
Pacific Northwest National Laboratory (Richland, Washington)	Pacific Northwest National Laboratory (Richland, Washington)	Kingsford Hydroelectric Project (Menominee River, Wisconsin)	Oregon State University	Hiram M. Chittenden Locks (Seattle, Washington)
No	No	No	Yes	No
10-14 Hz	150 Hz, 180 Hz, 200 Hz	5-60 Hz	10 Hz	300 Hz, 400 Hz
deterrent	deterrent	deterrent	deterrent	guidance
NR	NR	NR	NR	NR
NR	NR	NR	NR	<0.25
14	NR	NR	10	NR
day	NR	day, night	NR	day, dusk, dawn
Laboratory (tank, net pen)	Laboratory (tank)	Field (cage)	Laboratory (tank)	Field (lock)
piston	EESCO model 215 transducer	transducer: Argotec Model 215; U.S. Navy J13, G34, F56, F33B, F33I	piston	EESCO model 220 transducers
Oncorhynchus mykiss	*Oncorhynchus mykiss*	*Oncorhynchus mykiss*	*Oncorhynchus mykiss*	*Oncorhynchus nerka*
rainbow trout	rainbow trout	rainbow trout	rainbow trout	sockey salmon

sockey salmon	*Oncorhynchus nerka*	Argotech model 215 transducers	Field (Hydroelectric)	24 hour	NR	0.65	NR	guidance	300 Hz, 400 Hz	No	Bonneville Dam (Comumbia River, Oregon)	Ploskey et al. (2000)
sockey salmon	*Oncorhynchus nerka*	Argotech model 215 transducers	Field (net pen)	24 hour	NR	0.65	NR	guidance	300 Hz, 400 Hz	No	Bonneville Dam (Comumbia River, Oregon)	Ploskey et al. (2000)
sockey salmon	*Oncorhynchus nerka*	particle motion generator (PMG) and piston	Field (cage)	day	NR	NR	1	guidance	300 Hz, 400 Hz	No	Hiram M. Chittenden Locks (Seattle, Washington)	Ploskey et al. (1998)
steelhead trout	*Oncorhynchus mykiss*	EESCO model 220 transducers	Field (lock)	day, dusk, dawn	NR	<0.25	NR	guidance	300 Hz, 400 Hz	No	Hiram M. Chittenden Locks (Seattle, Washington)	Goetz et al. (2001)
steelhead trout	*Oncorhynchus mykiss*	Argotech model 215 transducers	Field (Hydroelectric)	24 hour	NR	0.65	NR	guidance	300 Hz, 400 Hz	No	Bonneville Dam (Comumbia River, Oregon)	Ploskey et al. (2000)

Loeffelman et al. (1991) Klinect et al. (1992)	**Loeffelman et al. (1991) Klinect et al. (1992)**	**Taft et al. (1996) Taft and Brown (1997)**	**PSEG (2003)**
Berrien Springs Hydroelectric Project (St. Joseph River, southwestern Michigan)	**Buchanan Hydro Plant (St. Joseph River, southwestern Michigan)**	**Salem Generating Station (Delaware River Estuary)**	**Salem Generating Station (Delaware River Estuary)**
Yes	**Yes**	**Yes**	**Yes**
100-1,000 Hz	**100-1,000 Hz**	**100-5,000 Hz**	**100-3,000 Hz**
guidance	**guidance**	**deterrent**	**deterrent**
NR	**NR**	**NR**	**<50**
NR	**NR**	**NR**	**0.08-0.12**
NR	**NR**	**NR**	**8.8-11.0**
NR	**NR**	**day, dusk, night, dawn**	**dim overhead**
Field (Hydroelectric)	**Field (Hydroelectric)**	**Field (cage)**	**Laboratory (flume)**
Argotech model 220 transducers	**Argotech model 220 transducers**	**transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I**	**U.S. Navy J-11 transducers**
Oncorhynchus mykiss	***Oncorhynchus mykiss***	***Micropogonias undulatus***	***Micropogonias undulatus***
steelhead trout	**steelhead trout**	**Atlantic croaker**	**Atlantic croaker**
		Sciaenidae	

Brown et al. (2006)	**Brown et al. (2006)**	**Taft et al. (1996) Taft and Brown (1997)**	**PSEG (2003)**
Lyle St. Amant Marine Laboratory (Grand Terre Island, Louisiana)	**Lyle St. Amant Marine Laboratory (Grand Terre Island, Louisiana)**	**Salem Generating Station (Delaware River Estuary)**	**Salem Generating Station (Delaware River Estuary)**
Yes	**Yes**	**Yes**	**Yes**
10-100 Hz	**10-60 Hz**	**100-5,000 Hz**	**100-3,000 Hz**
deterrent	**deterrent**	**deterrent**	**deterrent**
NR	**NR**	**NR**	**<50**
NR	**NR**	**NR**	**0.08-0.12**
NR	**NR**	**NR**	**8.8-11.0**
NR	**NR**	**day, dusk, night, dawn**	**dim overhead**
Laboratory (raceway)	**Field (pond)**	**Field (cage)**	**Laboratory (flume)**
Argotech model 210 transducer	**Argotech model 210 nd 220 transducers**	**transducer: ITC model 3406; Argotec Model 215; U.S. Navy G34, F56, F33B, F33I**	**U.S. Navy J-11 transducers**
Pogonias cromis	***Pogonias cromis***	***Cynoscion regalis***	***Cynoscion regalis***
black drum	**black drum**	**weakfish**	**weakfish**

Scophthalmidae	Windowpane	*Scophthalmus aquosus*	ITC model 3406 transducers	Field (Hydroelectric)	day, night	NR	0.68	NR	deterrent/ guidance	122-128 kHz	No	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Gibson and Myers 2002
Soleidae	common sole	*Solea solea*	FGS Mk II 30-600 sound projectors	Field (CWIS)	25 hour	NR	<0.53	NR	deterrent	20-600 Hz	Yes	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)
Stromateidae	butterfish	*Peprilus triacanthus*	ITC model 3406 transducers	Field (Hydroelectric)	day, night	NR	0.68	NR	deterrent/ guidance	122-128 kHz	No	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Gibson and Myers 2002
Syngnathidae	Nilsson's pipefish	*Syngnathus rostellatus*	FGS Mk II 30-600 sound projectors	Field (CWIS)	28 hour	NR	<0.56	NR	deterrent	20-600 Hz	No	Doel Nuclear Power Plant (Scheldt Estuary, Doel, Belgium)	Maes et al. (2004)

	northern pipefish	*Syngnathus fuscus*	ITC model 3406 transducers	Field (Hydroelectric)	day, night	NR	0.68	NR	deterrent/ guidance	122-128 kHz	No	Annapolis Tidal Generating Station (Nova Scotia, Canada)	Gibson and Myers 2002

APPENDIX 3. A summarized literature review of hybrid behavioral studies arranged by species.

Family	Common Name	Scientific Name	Study Type	Behavior Deterrents Used	Ambient Light Conditions	Temp (°C)	Approach Velocity (m/s)	Turbidity Conditions (NTU)	Movement type	Avoidance Response Observed	Site	Reference
Catostomidae	white sucker	*Cataostomus commersoni*	Lab	Strobe light/ acoustic system	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)
	white sucker	*Cataostomus commersoni*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
Centrarchidae	black crappie	*Pomoxis nigromaculatus*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.34	3.92-9.40	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	largemouth bass	*Micropterus salmoides*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.32	3.92-9.38	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	smallmouth bass	*Micropterus dolomieui*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.33	3.92-9.39	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)

Clupeidae	alewife	*Alosa pseudoharengus*	Field	Pneumatic gun/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	alewife	*Alosa pseudoharengus*	Lab	Strobe light/air bubble curtain	day, night	NR	0.2, 0.5	NR	deterrent	Yes	Ontario Hydro and University of Maryland	Patrick et al. (1985)
	alewife	*Alosa pseudoharengus*	Field	Pneumatic gun/strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	alewife	*Alosa pseudoharengus*	Field	Strobe light/ pneumatic gun	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	alewife	*Alosa pseudoharengus*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	alewife	*Alosa pseudoharengus*	Field	Strobe light/air bubble curtain	dusk, night, dawn	5.0-23.0	0.2-0.8	0.2-6.3	deterrent	Yes	Pickering Generating Station (Lake Ontario, Canada)	Hydro and LMS (1989)

alewife	*Alosa pseudoharengus*	Field	Strobe light/ pneumatic gun	dusk, night, dawn	5.0-23.1	0.2-0.9	0.2-6.4	deterrent	Yes	Pickering Generating Station (Lake Ontario, Canada)	Hydro and LMS (1989)
alewife	*Alosa pseudoharengus*	Field	Pneumatic gun/strobe light/air bubble curtain	dusk, night, dawn	5.0-23.2	0.2-0.10	0.2-6.5	deterrent	Inconclusive	Pickering Generating Station (Lake Ontario, Canada)	Hydro and LMS (1989)
alewife	*Alosa pseudoharengus*	Field	Pneumatic gun/air bubble curtain	dusk, night, dawn	5.0-23.3	0.2-0.11	0.2-6.6	deterrent	Yes	Pickering Generating Station (Lake Ontario, Canada)	Hydro and LMS (1989)
alewife	*Alosa pseudoharengus*	Lab	Strobe light/acoustic system	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)
American shad	*Alosa sapidissima*	Field	Pneumatic gun/strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
American shad	*Alosa sapidissima*	Field	Pneumatic gun/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)

	American shad	*Alosa sapidissima*	Field	Strobe light/ pneumatic gun	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	American shad	*Alosa sapidissima*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	Atlantic menhaden	*Brevoortia tyrannus*	Lab	Strobe light/air bubble curtain	Indoor lighting	NR	0.2	39-138	deterrent	Yes	University of Maryland	McInnich and Hocutt (1987)
	blueback herring	*Alosa aestivalis*	Field	Pneumatic gun/strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	blueback herring	*Alosa aestivalis*	Field	Pneumatic gun/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	blueback herring	*Alosa aestivalis*	Field	Strobe light/ pneumatic gun	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	blueback herring	*Alosa aestivalis*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)

	gizzard shad	*Dorosoma cepedianum*	Lab	Strobe light/ acoustic system	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)
	gizzard shad	*Dorosoma cepedianum*	Lab	Strobe light/chain-net	simulated light and dark	NR	0.15-0.32	NR	deterrent	Yes	NR	Patrick (1980a)
Cyprinidae	bighead carp	*Hypophthalmichthys nobilis*	Lab	Pneumatic acoustic system/air bubble curtain	day	~10.9	no flow	NR	deterrent	Yes	NR	Taylor et al. 2005
	common carp	*Cyprinus carpio*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.29	3.92-9.35	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	emerald shiner	*Notropis atherinoides*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.28	3.92-9.34	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	golden shiner	*Notemigonus crysoleucas*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	NR	NR	NR	deterrent	Yes	Four Mile Dam (Thunder Bay River, Michigan)	McCauley et al. (1996)

Engraulidae	bay anchovy	*Anchoa mitchilli*	Field	Pneumatic gun/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	bay anchovy	*Anchoa mitchilli*	Field	Pneumatic gun/strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	bay anchovy	*Anchoa mitchilli*	Field	Strobe light/ pneumatic gun	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	bay anchovy	*Anchoa mitchilli*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
Ictaluridae	brown bullhead	*Ameiurus nebulosus*	Lab	Strobe light/sound system	NR	NR	0.1-0.5	NR	deterrent	Yes	Kinectrics (800 Kipling Ave, Toronto, Ontario, M8Z 6C4, Canada)	Patrick et al. (2006)
	bullhead catfish	*Ameiurus spp.*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	NR	NR	NR	deterrent	Yes	Four Mile Dam (Thunder Bay River, Michigan)	McCauley et al. (1996)
Moronidae	white perch	*Morone americana*	Field	Pneumatic gun/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)

	white perch	*Morone americana*	Lab	Strobe light/air bubble curtain	Indoor lighting	NR	0.2	39-138	deterrent	Yes	University of Maryland	McInnich and Hocutt (1987)
	white perch	*Morone americana*	Field	Pneumatic gun/strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	No	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	white perch	*Morone americana*	Field	Strobe light/ pneumatic gun	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
	white perch	*Morone americana*	Field	Strobe light/air bubble curtain	day, dusk, night, dawn	6.0-32.0	NR	2-130	deterrent	Yes	Roseton Generating Station (Hudson River, New York)	Matousek et al. (1988)
Percidae	logperch	*Percina caprodes*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.29	3.92-9.35	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)
	walleye	*Sander vitreus*	Field	Strobe light/sound system	24-hour testing	NR	0.01-0.31	3.92-9.37	deterrent	No	White Rapids Hydroelectric Project (Menominee River, Wisconsin)	EPRI (1998a, 1998b) Michaud and Taft (1999)

EPRI (1998a, 1998b) Michaud and Taft (1999)	**Welton et al (2002)**	**Bengeyfield and Smith (1989)**	**McKinley and Patrick (1988)**	**McKinley and Patrick (1988)**	**McInnich and Hocutt (1987)**
White Rapids Hydroelectric Project (Menominee River, Wisconsin)	**River Frome, UK**	**Puntledge Generating Station (Vancouver, British Columbia)**	**Seton Creek (near Lillooet, British Columbia, Canada)**	**Seton Creek (near Lillooet, British Columbia, Canada)**	**University of Maryland**
No	**Yes (predominantly at night)**	**No**	**Yes**	**Yes**	**Yes**
deterrent	**guidance**	**guidance**	**guidance**	**guidance**	**deterrent**
3.92-9.36	**NR**	**NR**	**NR**	**NR**	**39-138**
0.01-0.30	**~0.6**	**NR**	**NR**	**NR**	**0.2**
NR	**NR**	**NR**	**NR**	**NR**	**NR**
24-hour testing	**day, dusk, night, dawn**	**day, night**	**dusk, night**	**dusk, night**	**Indoor lighting**
Strobe light/sound system	**Pneumatic acoustic system/air bubble curtain**	**Strobe light/fish hammer/ steel chain**	**Strobe light/air bubble curtain**	**Strobe light/ popper**	**Strobe light/air bubble curtain**
Field	**Field**	**Field**	**Field**	**Field**	**Lab**
Pera flavescens	***Salmo salar***	***Oncorhynchus kisutch***	***Oncorhynchus nerka***	***Oncorhynchus nerka***	***Leiostomus xanthurus***
yellow perch	**Atlantic salmon**	**coho salmon**	**sockey salmon**	**sockey salmon**	**spot**
	Salmonidae				**Sciaenidae**