REVIEW / SYNTHÈSE

Non-physical barriers to deter fish movements

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Abstract: Anthropogenic modifications to aquatic ecosystems have altered connecting pathways within, and in some cases, between watersheds. Human structures, such as hydroelectric facilities, often impede fish migrations and may inflict heavy mortality on fish that become impinged or entrained. Conversely, an increase in connectivity between two waterways (e.g., through the construction of shipping canals, increased boat traffic) often results in an elevated risk of invasive species introductions. Non-physical barriers, which obstruct fish from an undesirable location without influencing the waterway, are one management approach to protecting valuable fish stocks and deterring biological invasions. Because many methods of behavioral deterrence have been employed against fish, there is a need to summarize and compare existing and developing technologies. This review details the use and application of electrical, visual, acoustic, chemical, and hydrological deterrence techniques that may be used to prevent fish movements. Site requirements are discussed, and a critical assessment of benefits and limitations to each technique are given. Because no single method of fish deterrence is "one size fits all", this review to non-physical fish barrier technology will benefit managers and researchers attempting to develop a best-fit strategy on a case-by-case basis.

Key words: invasive species, dispersal, electricity, movement, migration, fish.

Résumé : Les modifications anthropogènes aux écosystèmes aquatiques ont altéré les routes de communication à l'intérieur et, à l'occasion, entre des bassins versants. Les structures humaines, telles que les installations hydroélectriques, empêchent souvent les migrations des poissons et peuvent entrainer de fortes mortalités chez les poissons affectés ou entrainés. Réciproquement, une augmentation des liaisons entre deux voies d'eau (p. ex., par la construction de canaux pour les bateaux, l'augmentation du trafic maritime) entraîne souvent un risque élevé d'introduction d'espèces envahissantes. Les barrières non physiques obstruant le passage des poisons d'origine indésirable sans influencer la voie d'eau constituent une méthode d'aménagement pour protéger les réserves de poisson de valeur et décourager les invasions biologiques. Puisque plusieurs méthodes plusieurs méthodes de dissuasion comportementale ont été employées contre les poissons, il y a un besoin de résumer et de comparer les technologies existantes et en développement. Dans cette revue les auteurs relatent en détail l'utilisation et l'application de techniques de dissuasion électrique, visuelle, acoustique, chimique et hydrologique pouvant être utilisées pour empêcher les mouvements des poissons. On discute des besoins des sites, et on présente des évaluations critiques des bénéfices et des limitations, pour chaque technique. Parce qu'aucune méthode spécifique ne constitue une panacée pour la dissuasion, cette revue sur la technologie des barrières physiques pour les poissons sera utile aux aménagistes essayant de développer la meilleure stratégie appropriée sur une base cas par cas.

Mots-clés : espèces envahissantes, dispersion, électricité, mouvement, migration, poisson.

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Introduction

Barriers have been used for many years to deter animal movements and direct desirable species away from anthropogenic dangers. For instance, roads and vehicle traffic are well-recognized sources of mortality for wildlife, and also are known to limit animal dispersal (e.g., Forman and Alexander 1998; Clevenger et al. 2003; Gibbs and Shriver 2005). Along roads with a history of wildlife mortality, mitigation efforts, such as fences leading to culverts, have been used successfully to direct moving animals away from vehicles and minimize mortality (Dodd et al. 2004; Aresco 2005). Similarly, fish guidance systems have been used to direct the movements of commercially or recreationally valuable fish around facilities such has hydropower dams that can threaten their survival (Taft 2000). Salmon runs along the East and West Coasts are economically valuable, and often represent the culmination of large amounts of time and effort invested by hatchery and fish management programs (Naylor et al. 2003). It is therefore desirable, and often required by

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law, to reduce salmon mortality in an effort to maintain fishable stocks, and fish guidance systems have been successfully implemented to help achieve this goal (Anderson 1999).

Biological invasions as a consequence of human activities are a form of human-driven animal movement that can have serious constraints on ecological diversity and economic goals (Ricciardi and MacIsaac 2011). In many instances, introduced species, freed of the constraints of competition and predation, will expand rapidly and aggressively until their range covers the extent of environmental tolerances. Approximately 42% of the federally threatened or endangered species in the US are considered at risk primarily because of the influence of non-native species (Pimentel et al. 2005). Of the documented extinction cases where causes are understood, 54% were influenced to some degree by invasive species (Clavero and Garcia-Berthou 2005). A recent estimate of economic damages associated with non-indigenous species within the US totals just under USD$120 billion annually (Pimentel et al. 2005), and this figure continues to grow (Lodge et al. 2006). In addition, it is believed that global climate change may increase the rate of invasive species introductions (Hellmann et al. 2008; Rahel and Olden 2008). Though vital to modern economic interests, increased global commerce often functions as a pathway to help spread exotic species (Hulme 2009). As national economies become more globalized and international trade and tourism increases, it is possible that these processes will continue, resulting in the continued threat of unintentional movement of animals to novel locations.

The costs that arise due to the introduction of invasive species provide strong economic and ecological incentives for the prevention of new invasions. Lodge et al. (2006) recommend early prevention of exotic organisms from entering into new regions rather than attempting to remove invasives following introduction because many invasive species are nearly impossible to eradicate once established. Despite this, most actions to prevent biological invasions focus on population control efforts after establishment (Lodge et al. 2006). Precautionary actions geared towards preventing the establishment of non-native species have been suggested as a more cost-effective approach in the long term (Lodge et al. 2006; Finnoff et al. 2007). Therefore, there is a critical need for methods and technologies that stop the spread of exotic organisms through natural and human-mediated pathways. Barriers placed within known pathways to interfere in dispersal movements are one such method.

In the examples cited in the previous text, where movement barriers are implemented in an effort to achieve conservation goals, fish can be looked upon as a group of organisms that are an excellent model for successful implementation. Fish dispersion is constrained to a network of waterways, and dispersion routes of invasive fish species can often be predicted, and even potentially blocked (Kolar and Lodge 2002). Unlike most terrestrial fauna, fish movements may be deterred by both physical obstructions placed in waterways and non-physical cues that alter behavior.

One longstanding method of guiding or repelling fish movements is through the use of non-physical deterrent systems. Non-physical deterrence can be defined as “any stimulus or non-solid obstruction that discourages or prevents a selected species from passing through a target region.” The significance of non-physical deterrence systems as they relate to aquatic systems is that they typically do not constrain water flow or restrict navigation, and, in some cases, will allow movements of non-target organisms through the water column. Non-physical barriers become practical when physical alteration of a water way is detrimental to regional economic interests (e.g., the damming of a stream or closing of a ship canal) and when physical barriers are not effective at reducing mortality of a desirable species (e.g., fish becoming impinged on a water intake screen). Because non-physical fish barriers come in many varieties that vary in effectiveness with individual project circumstances and barrier characteristics, a guide to current fish deterrent techniques would benefit managers and researchers alike.

The objective of this review is to present a summary of non-physical barriers or fish deterrent concepts discussed in the literature or under development. We first provide an overview of each deterrent that introduces the biological reasoning behind its effectiveness, and basic engineering and implementation considerations. We then discuss known applications of its use, and follow each review with an assessment of applicability and recommendations regarding use. Finally, we present a comparison among the reviewed techniques, and address common themes and concerns that may be of value to project managers.

Electric barriers

Overview

For over 60 years, fishery managers have utilized electrical currents passing through water to conduct fish collections and perform non-lethal sampling (Reynolds 1996; Sharber and Black 1999). This technique of fish collection is possible because a portion of electrical energy applied to water is transferred to fish (Reynolds 1996). As a result of this energy transfer, electricity in water can lead to taxis (forced swimming), immobilization, and possibly trauma for fishes (Reynolds 1996). The effects of electricity on fish can vary by species (Dolan and Miranda 2003), water conductivity (Hill and Willis 1994), design and placement of electrodes (Copp 1989), type of electrical current, and direction of current (Bohlin et al. 1989). Electrical energy dissipates in water such that fish located greater distances from electricity sources are less likely to suffer trauma or taxis, and have the ability to avoid electric currents (Reynolds 1996). The size (volume) of a fish is an important factor dictating immobilization of fish by electricity, with smaller fish requiring a greater amount of power for immobilization than larger fish (Dolan and Miranda 2003), but even larvae and (or) juvenile fishes are sensitive to being influenced by electrical energy at certain voltage gradients (Henry et al. 2003). Fish barriers that use electricity consist of a series of metal anodes and cathodes in the water column. Electrical current passes through the water from an anode to a cathode creating an electric field in the vicinity of the barrier, and fish barriers that use electricity derive much of their effectiveness through behavioral avoidance of electrical fields (Katopodis et al. 1994).

Potential

Electric barriers have proven effective at preventing fish movement, particularly through constricted waterways. When used to stem the spread of fish, two major limitations must be considered. First, deactivation due to power outage, maintenance (or lack thereof), and human error precludes any single electric barrier from operating 100% of the time over prolonged deployments (Clarkson 2004). In situations where it is critical that no movements across a barrier occur, redundancies and integrated deterrence systems are recommended. Second, small fish may be unaffected by electric fields, resulting in size-elective effectiveness that might not meet all management goals (Reynolds 1996).

Applications

Over the past several decades, electrical barriers have garnered much attention as a means of preventing established populations of invasive fish from conducting spawning runs, or more importantly, expanding their ranges to new bodies of water. A historic example of electrical barrier use involved efforts to block sea lamprey (*Petromyzon marinus*) spawning runs within the Great Lakes tributaries (Katopodis et al. 1994). These original electric barriers were gradually phased out of use with the development of lampricide (3-trifluoromethyl-4-nitrophenol). However, growing concern over non-target effects of lampricide to other fish and aquatic macroinvertebrates, coupled with the development of more efficient and effective barrier technology, has renewed interest in electric barriers as a lamprey control method (Katopodis et al. 1994). Electrical barriers have also been implemented successfully for prevention of entrainment (Burrows 1957), estimation of harvest escapement (Palmisano and Burger 1988), and to contain potentially invasive fish within a segment of a water body (Bullen and Carlson 2003). More recently, there have been several examples of electrical barriers placed within shipping canals to prevent the introduction of invasive fish in adjoining water bodies. Several barriers have been placed in the Central Arizona Projects canals to prevent immigration of nonindigenous species into the Gila River from the Colorado River (Clarkson 2004). Several more are now active within the Chicago Sanitary and Shipping Canal (CSSC) to block immigration of invasive silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*) (referred to collectively as Asian carp) into the Great Lakes (Conover et al. 2007). Bullen and Carlson (2003) reported that an electric barrier was 98.7% effective in containing grass carp (*Ctenopharyngodon idella*) within a single bay of a lake.

Strobe lights

Overview

Ambient light levels are known to influence many facets of fish behavior, including orientation, location of food, communication between conspecifics, circadian movements, and avoidance of predators (Li and Maaswinkel 2007; Guthrie and Muntz 1993). Unlike most mammals, many teleosts lack a movable iris, and the response of their eyes to light level changes is often slow (Li and Maaswinkel 2007). Strobe lights introduce unnatural light levels relative to the ambient environment, having the ability to negatively impact fish behaviors and induce an avoidance response.

Potential

The reported effectiveness of strobe-light deterrent systems varies and appears to be driven by the life history of the target species, design and brightness of the lights, turbidity, and ambient light level (McIninch and Hocutt 1987; Johnson et al. 2005*a*; McLean 2008). While there is evidence to suggest that fish do not exhibit short-term habituation to sustained strobe light exposure (Hamel et al. 2008), studies to date do not suggest that strobe lights employed as a stand-alone method of deterrence could provide complete security in situations where total deterrence is the goal. Several studies report high (≥80%) reductions in numbers of fish approaching illuminated areas (Hamel et al. 2008). Others report <50% reductions, or an inability to meet fish deterrent goals through the use of strobe lights alone (Johnson et al. 2005*a*; Nemeth and Anderson 1992; McIninch and Hocutt 1987). Due to differences in species tested, site conditions, brightness of lights used, and method of reporting results, direct comparisons between studies are challenging. Differences in results can often be attributed to varying behavioral responses among fish, with some species showing distinct avoidance responses (Hamel et al. 2008), and others congregating in areas around lights (Johnson et al. 2005*a*). Several studies note a distinct ineffectiveness of strobe lights during daylight hours (Nemeth and Anderson 1992; Johnson et al. 2005*a*), and reduced effectiveness in highly turbid water (McIninch and Hocutt 1987). Strobe lights may be more effective when used as part of an integrated deterrence system. McIninch and Hocutt (1987), for example, suggest that strobe lights may be combined with other visual stimuli, such as air bubble barriers, for enhanced effectiveness.

Applications

Strobe lights have undergone more than 50 years of research as fish deterrent and (or) guidance systems (Brown 2000). To date, much of this research effort has focused on reducing mortality in Salmonid fishes, but other species are increasingly being used in strobe light research (Brown 2000). There are many examples of researchers and fish managers using strobe lights to reduce entrainment of commercially and recreationally valuable salmonids at hydroelectric dams including Oahe Dam, SD, and Grande Coulee Dam, WA (e.g., Johnson et al. 2005*a*; Hamel et al. 2008). Strobe light deterrence systems have also been implemented at lock and dam filling culverts and pumping stations that draw surface water (Brown 2000). Additional studies have been completed in holding tanks to test the reactions of different species and effects of ambient lighting and turbidity (Nemeth and Anderson 1992; McIninch and Hocutt 1987).

Acoustic fish deterrents (AFD)

Overview

When site conditions preclude the use of visual stimuli to induce fish avoidance behaviors, sound and pressure waves may be a viable alternative. All sound generated in water consists of pressure waves that may be detected by tiny hairs within the inner ear and (or) lateral line of fish (Bass and Lu 2007; Schilt 2007). Despite recent objections in the literature (see Popper and Fay 2011), fish have been broadly categorized as either "hearing generalists" or "hearing specialists", with specialists having an anatomical structure that connects the inner ear and a gas bubble (such as a swim bladder) to assist in transmitting sound waves to the inner ear. Generalists hear sounds below 1 KHz, whereas specialists are able to detect frequencies of up to several KHz (Schilt 2007).

Potential

Similar to visual deterrents, the reported effectiveness of sound as a fish deterrent has varied considerably (Maes et al. 2004), and the effectiveness of AFD systems can be influenced by bottom morphology, hydrology, and angle of sound waves (Katopodis et al. 1994). Low-frequency sound waves, though effective deterrents in some studies, propagate poorly in shallow water and across hard substrates (Popper and Carlson 1998). Successful treatment levels can occur in the ranges of acoustic sound (20 Hz to 20 kHz) and infrasound (0.01 to 20 Hz); some studies have also evaluated ultrasound, but have generally not been effective (Sonny et al. 2006). In addition to variation in frequency, sound intensity (amplitude) can be increased in an effort to induce avoidance behaviors (Haymes and Patrick 1986; Popper and Carlson 1998).

Applications

Most field applications of AFD systems are intended to meet goals similar to visual deterrents, such as reducing impingement and entrainment of fishes at hydropower facilities (Maes et al. 2004; Knudsen et al. 1997; Ross and Dunning 1993). Acoustic fish deterrents with varying frequencies and decibel levels have been successfully implemented as fish deterrents in several different situations (Lovell et al. 2006; Maes et al. 2004; Sonny et al. 2006), but the effectiveness of a given frequency is dependent on aforementioned site characteristics and species involved. In one successful application of a sound barrier, sound frequencies between 20 and 600 Hz were used to reduce impingement of many fish species by 60% at an estuary power plant (Maes et al. 2004). High-frequency sound (122–128 kHz) demonstrated 87% effectiveness in repelling alewives (*Alosa pseudoharengus*) from a water intake in Lake Ontario (Ross and Dunning 1993). Another experimental sound deterrent system used infrasound (16 Hz) to reduce cyprinid impingement by as much as 80% at a nuclear power plant (Sonny et al. 2006). Sound also has potential as a behavioral barrier within open channels where Knudsen et al. (1994) reported high effectiveness of infrasound in preventing salmon smolts from entering a river side channel. In a similar manner, an acoustic fish fence generating infrasound decreased catches of migrating European silver eels (*Anguilla anguilla*) by 57% in traps placed close to the sound source (Sand et al. 2000). Haymes and Patrick (1986) demonstrated that seismic devices could be modified to create “pneumatic poppers” that emit low-frequency, high-intensity sound and deter alewife (*Alosa pseudoharengus*) movements by 71%–99%. In the case of Asian carp, research has reported up to 95% reduction of passage of Asian carp when confronted with AFD devices (Pegg and Chick 2004).

Bubble curtains

Overview

An alternative visual cue that has received consideration as a fish deterrent is a fence or curtain of bubbles emitted from air diffusers placed along the bottom perpendicular to the channel. A continuous “screen” of bubbles in the water column provides an unnatural visual cue for fish to avoid. Bubble curtains are inherently limited in that they emit no light of their own, and may not be easily noticed from a distance. Light penetration, especially due to turbidity, is a major obstacle to their effectiveness (McIninch and Hocutt 1987).

Potential

Bubble curtains as a stand-alone fish barrier have limited potential. In most lotic systems, for example, periodic high water may decrease their visibility and (or) integrigy. However, bubble curtains display more potential for fish effectiveness when used as a component of an integrated deterrence system. When considering whether or not to include air diffusers as a component of an integrated system, site considerations are crucial, with turbidity, depth, and bottom geography being key considerations. One major design constraint in most bubble curtains is their inability to maintain equal air pressure across differing depths. Sites with a high degree of depth change across the cross section of a channel would therefore present unique engineering challenges.

Applications

While few successful field applications of bubble curtains exist (Taft 2000), several reports of experimental evaluations in a controlled laboratory setting hint at their potential. One study indicated that 70%–95% of observed baitfish (family Clupeidae) avoided air bubbles under adequate lighting (Patrick et al. 1985). Another study reported that roundfish (*Pollachius* spp. and *Labrus mixtus*) confined to enclosures would not cross a bubble barrier (Stewart 1981). Several studies indicate higher rates of deterrence when bubble barriers are paired with a source of supplementary illumination, such as strobe lights (Patrick et al. 1985; McIninch and Hocutt 1987), or sound (Welton et al. 2002). Pegg and Chick (2004) reported that an experimental barrier composed of a bubble curtain coupled with acoustic deterrents was 95% effective in confining the movements of Asian carp.

Velocity barriers

Overview

One particularly resourceful method of confining fish movements is to modify flow regimes within a stream or canal so that water velocities exceed the swimming ability of a targeted species. This is typically accomplished by constricting water flow through a culvert, chute, or flume, thereby increasing velocity. When confronted with moving water, all fish have inherent physiological limitations in their ability to move upstream against a current, and natural or artificial areas of high water velocity are known to function as boundaries to the upstream movements of riverine fishes (Haro et al. 2004).

Potential

Velocity barriers have the potential to selectively limit the movement of different fish species, impeding the swimming potential of an undesired species while passage of desirable fish species is maintained. When considering water velocity as a potential barrier to fish, it is important to recognize that a fish is limited both in its capacity to swim aerobically at sustained speeds, and anaerobically in short, but faster bursts (Hammer 1995; Haro et al. 2004). A successful velocity barrier must feature water velocities in excess of the target fish's aerobic swimming capacity or power output, and, ideally, a channel length greater than the distance it can cover in an anaerobic burst. Fortunately, a large number of publications detailing the results of swim performance quantification have been published since the 1960s (for a review, see Plaut 2001). To be considered, a site should ideally have a channel small enough to permit the construction of a chute or similar structure that increases flow rates. The watershed must also have sufficient water flow to permit operation of the barrier during periods of fish passage across various seasons. Velocity barriers will not have wide-scale application, but may help managers achieve project goals when a complete closure of passage to all fish species is not desired.

Applications

Although velocity barriers may be impractical at very large scales, several examples of smaller-scale velocity barriers exist. One experimental velocity barrier has been implemented in a Great Lakes tributary that functioned as spawning grounds for invasive sea lampreys, although reported effectiveness has only been 33% (Heinrich et al. 2003). The sea lamprey presents an ideal case study of how water velocities can selectively prevent the passage of a target species as they are weak swimmers relative to desirable salmonid species that spawn within the same tributaries (Katopodis et al. 1994). Another possible candidate species for velocity barrier control is the round goby (*Neogobius melanostomus*), which has a maximum swimming speed of 75 cm/s^{-1} (Hoover et al. 2003). Several laboratory studies have attempted to quantify and predict the effects of velocity barriers on fish movements; one such study found that voluntary maximum swimming distance decreases with velocity in six freshwater species (Haro et al. 2004). Models developed from these data can be used to predict swimming speeds across a range of velocities, and maximum swimming distance when swim speed and fatigue time are known (Castro-Santos 2005, 2006). Thus, effectiveness of a velocity barrier design can be estimated prior to construction.

Hypoxia and hypercapnia

Overview

Chemical toxicants have been used for many decades to exclude aquatic organisms from specific locations. Chlorine, for example, has a history of use as a defouling treatment to prevent biological build-up within power plant discharge pipes (Cherry et al. 1979; Giattina et al. 1981). Manipulations of dissolved oxygen and (or) carbon dioxide hold similar potential to act as chemical barriers to deter fish movements through the alteration of water chemistry. Oxygen availability has long been recognized as a limiting resource to many forms of aquatic life (Kramer 1987), and regions of hypoxic water have been reported to negatively influence fish distribution (Pihl et al. 1991; Maes et al. 1998; Hasler et al. 2009). Many publications report the ability of fish to detect and avoid low oxygen gradients (e.g., Whitmore et al. 1960; Miranda and Hodges 2000; Burleson et al. 2001), as well as high carbon dioxide (Perry and Gilmore 2002). Increasing the carbon dioxide concentration of ambient water would decrease the CO_2 gradient across the gill-water interface, thereby hampering respiration. An artificial zone of low oxygen or high CO_2 could hypothetically be created through the addition of nitrogen or carbon dioxide gas through diffusers, or by introduction of an agent which creates either condition through a chemical process (e.g., organic material that increases bacterial respiration). If a localized pocket of hypoxia or hypercapnia (>20 mg/L dissolved carbon dioxide) could be created at a narrow fish passageway, it could function as either a behavioral or physiological barrier to fish movement.

Potential

To ensure the establishment of an effective hypoxic/hypercapnic barrier, tolerance thresholds of target and non-target fish must first be quantified, ideally through laboratory investigations (e.g., Davis 1975). Additional research considering site and engineering constraints must be made; factors influencing design of a gas diffuser system include bottom topography, hydrological characteristics, storage of bulk gas supplies, and control of treatment levels. The most formidable obstacle to dissolved gas barriers is a lack of field testing and ecosystem-scale evaluation. In light of the other options presented in this paper, economic considerations must also be made before a full-scale barrier can be utilized as a management tool. It is also important to point out that the modification of abiotic variables may influence non-target fishes in addition to target species.

Despite the unknowns, hypoxic and hypercapnic barriers remain a concept worth further investigation. Whereas the effectiveness of an electrical barrier is size dependent, dissolved gas barriers have the potential to be effective across all sizes of fish once a particular threshold is reached (in the case of low dissolved oxygen, this would be approximately 1.5 mg/L; Whitmore et al. 1960; Miranda and Hodges 2000). Where it is critical that no nuisance species traverse the barrier, the treatment zone could be extended in length until it is hypothetically impossible for fish to pass without losing equilibrium along the way. Unlike other chemical additives that are known to repel fish, nitrogen and carbon dioxide are naturally occurring gases that, if used properly, would not persist within the water column for a prolonged period of time, or pose a toxicity threat to birds or mammals.

Applications

The concept of a poor water quality barrier has recently garnered consideration to prevent movements of invasive fishes between the Mississippi River Basin and the Great Lakes via the Chicago Sanitary and Shipping Canal. This canal is subject to episodes of hypoxia as a result of anthropogenic discharges. Schreier et al. (2008) suggested that supplemental aeration in the CSSC could be ceased to create a hypoxic zone to deter downstream movements of round goby. Currently, a study is ongoing to determine the feasibility of a gas bubble curtain that delivers either purified nitrogen or carbon dioxide to the water column (Suski et al. unpublished data).

Pheromones

Overview

Pheromones have been broadly defined as secreted chemical odors that elicit a specific behavioral response from a conspecific (Sorensen and Stacey 2004). In fish, pheromones are known to play important roles in reproduction and predator avoidance. Attraction pheromones are often excreted by a sexually receptive individual to draw in members of the opposite sex. Conversely, alarm pheromones, believed to be the chemical compound hypoxanthine-3-N-oxide, are often released when the skin of a fish becomes damaged, and function to trigger evasive responses from conspecifics (Brown et al. 2000; Sorensen and Stacey 2004).

Potential

As a potential chemical barrier, pheromones could be collected or synthesized and released into the water column. Similarly, alarm pheromones could be used to exclude fish from a particular location, whereas attraction pheromones could be used to aggregate fish away from a source of danger or closed passageway. Additional investigation into effectiveness, procurement, and deployment of pheromones against nuisance species must be made before pheromones can be considered as a permanent non-physical barrier. However, alarm pheromones have a more immediate potential as a temporary barrier during down time of permanent barrier systems.

Applications

While the use of pheromones to attract and trap organisms has been extensively studied and applied in insects (e.g., Burkholder and Ma 1985; Turchin and Odendaal 1996), sea lampreys are one example of this practice among fishes. Female sea lampreys have been successfully captured via the use of traps baited with sexually mature males excreting sex pheromones (Johnson et al. 2005*b*). More recently, traps baited with synthesized lamprey pheromones have been shown to lure in approximately 50% of marked female lampreys released downstream (Johnson et al. 2009). It has also been suggested that chemical cues affecting sea lamprey migration could be introduced to divert migrating lampreys into traps or areas where spawning is impossible (Wagner et al. 2006). Coupled with other control methods previously described, this pheromone-baited trapping constituted the “first attempt to use vertebrate pheromones as part of an integrated pest management strategy” (Wagner et al. 2006). Alarm pheromones have been documented in fishes such as common carp (Sorensen and Stacey 2004), suggesting a potential for these chemicals to act as a deterrent for conspecifics. A potential advantage to the use of alarm pheromones to direct movements is selectivity; heterospecifics may not react adversely to pheromone treatments. Recently, work has shown that chemicals emitted by decaying lampreys (a necromone) can elicit an avoidance behavior by migrating conspecifics, indicating the potential for these chemicals to divert migrating individuals away from targeted watersheds (Wagner et al. 2011).

Magnetic fields

Overview

Several groups of aquatic organisms, including cartilaginous fishes (sharks, rays), nonneopterygian bony fishes, and many amphibians (Northcutt et al. 1994) contain electroreceptive organs that are able to sense electric fields in the water. These electroreceptive organs are absent in most teleost fishes, but have been identified in sturgeon (*Scaphirhynchus platorynchus*) (Northcutt et al. 1994; Gibbs and Northcutt 2004).

Potential

The purpose of these electrosensory pores is to provide organisms an advantage in locating prey items. Strong magnetic fields, however, may over-stimulate these receptors, providing a deterrent or repellent that may be useful in directing organisms away from undesired locations.

Application

Current research in this area has focused largely on the use of magnetic fields to reduce incidental bycatch of elasmobranch fishes from commercial harvesting, demersal longlines, in particular, and results have been positive in many situations. Stoner and Kaimmer (2008), for example, showed that spiny dogfish (*Squalus acanthius*) attacked and consumed fewer baited hooks relative to control treatments when a cerium mischmetal was present near the bait. Similarly, O’Connell et al. (2010) showed that both the southern stingray (*Dasyatis americana*) and the nurse shark (*Ginglymostoma cirratum*), were repelled from baited areas containing magnets. Robbins et al. (2011), however, showed that social interactions such as conspecific density was a better predictor of whether or not Galapagos sharks (*Carcharhinus galapagensis*) would ingest a baited hood independent of the presence of a magnetic deterrent, suggesting that the efficacy of magnetic detterents may be somewhat species-specific.

Other chemicals

Overview

There are several examples of piscicides, broad application biocides, and species specific toxins that can be used as deterrents against aquatic organisms (Bettoli and Maceina 1996). Applications of fish toxicants may broadly qualify as non-physical barriers, if their application is restricted to a relatively small area vital to fish passage.

Potential

The use of chemical toxicants as a passage barrier entails many considerations and potential drawbacks, the most obvious of these are deleterious effects on non-target organisms. The release of toxins into the environment and their associated collateral damage to desirable organisms may cultivate a negative public perception of fisheries and natural resource management (Bettoli and Maceina 1996). Where toxicants may be potentially harmful to humans or domestic animals, public health concerns may override fishery goals.

To be considered as a barrier to fish movement, toxicants should generally be non-persistent and their application restricted to an area critical to passage of the target species.

When applying chemicals to water ways, the threat of nuisance species migrations must be weighed accordingly against the effects on non-target species and public support (Bettoli and Maceina 1996). The application of rotenone to the CSSC, for example, was carried out in light of the serious threat that Asian carp pose to the USD$7 billion commercial fishing industry in the Great Lakes (Buck et al. 2010).

Applications

One of the most published examples of a chemical deterrent is chlorine, which has been used as a biocide and defouling agent in cooling water discharges for many decades (Katz 1977; Giattina et al. 1981). Chlorine is a strong oxidizer that attacks the gill tissue of fish (Brungs 1973). Although lethal to fish in the proper dosage, sublethal chlorine gradients can be detected and avoided by numerous fish species (Brungs 1973; Heath 1977; Giattina et al. 1981; Wilde et al. 1983). Chlorine has seen continued use as a chemical barrier because it can be applied at effective rates that are non-toxic to mammals (Brungs 1973) and is non-persistent in natural systems. Chlorine degrades gradually in water; the length of its persistence depends upon sunlight, aeration, and the availability of nitrogenous compounds with that it forms more stable residuals (Katz 1977).

Lampricide (3-trifluoromethyl-4-nitrophenol) has been used extensively in the Great Lakes tributaries as a control measure to reduce sea lamprey spawning runs (Dermott and Spence 1984). These applications can be considered non-permanent chemical barriers to sea lampreys as they effectively inhibit the passage of adults to spawning grounds. Concern has arisen over the use of lampricide due to its effects on non-target species (Dermott and Spence 1984). Toxicity to non-target fish and invertebrates is known to vary with water pH, and by temperature and taxon (Dermott and Spence 1984).

A range of other fish toxicants have been considered for their potential to deter fish movments. These toxicants include rotenone, antimycin, and salicylanilide I, GD-174 (2-[digeranylamino]-ethanol) (Marking and Bills 1981; Dermott and Spence 1984; Chapman et al. 2003). Rotenone, for example, was recently applied to the CSSC in late 2009. This application of a broad-spectrum fish toxicant coincided with a period of maintenance to the aforementioned electric barrier placed in the CSSC to deter Asian carp immigration (Buck et al. 2010).

Conclusions

The use of non-physical barriers to deter fish movements can broadly be categorized as a "push–pull" strategy of behavioral manipulation using external stimuli that modify the abundance and distribution of target organisms (Cook et al. 2007). More specifically, a "push" strategy would include stimuli such as strobe lights, high-intensity sound or excessive current that repels individuals away from a targeted area. In contrast, a "pull" strategy would include attractive stimuli such as pheromones that concentrate organisms in a certain area, often facilitating targeted removal. To maximize effectiveness, deterrent systems that use "push–pull" strategies must first be based on a comprehensive, scientific understanding of the biology of the target organism, and the success of a non-physical barrier would be maximized with both "push" and "pull" strategies employed concurrently (Cook et al. 2007). Additionally, deterrence methods that differ in biological rationale (i.e., auditory, olfactory, chemosensory) may be coupled to increase the chances of avoidance and reduce the chance of acclimation to stimuli.

After examining the various options for non-physical deterrence of fish movements, several themes and considerations can be found across categories (Table 1). Non-solid deterrent systems share several fundamental strengths over the use of solid barriers. Most of the options discussed can be custom designed and effectively positioned within water ways without posing a restriction to navigation or impounding water flow. With a few exceptions, the various categories of non-physical barriers can be considered non-permanent. Treatments can therefore be timed to meet and repel movements of undesirable fish, while the option remains to deactivate the barrier and grant passage to other species. Non-physical deterrent systems may be removed or repositioned as management goals change, whereas the removal of solid barriers (i.e., dams, weirs) is sometimes undesirable due to the loss of revenue and services or costs (Whitelaw and MacMullan 2002). Several of the options reviewed display some potential for selective screening of fish by species or size through both behavioral and physiological mechanisms. In some cases, non-physical fish deterrent systems may be implemented where physical barriers are not possible. One example of such a situation would be water intakes located in a drainage with periodic heavy discharge carrying large amounts of debris; physical screens may become clogged with debris, and impingement of migrant fish may result in unacceptable levels of mortality.

The primary drawback to any non-solid fish barrier is the <100% long-term effectiveness associated with virtually every barrier system reviewed. Whereas fish cannot pass through solid concrete, temporary gaps in treatment may occur when using non-physical deterrence. Such gaps may be spatial, particularly during periods of high water, or temporal, such as during power outages. It is also important to recognize that, while some barriers are potentially harmful to persistent fish (e.g., chemical and electrical), others rely completely on behavior modification (e.g., visual and acoustic). An optimal barrier that relies on behavior modification will still be ineffective against organisms that are unable to "cooperate" such as larval or planktonic life stages transported by currents that cannot "choose" to leave an area. Therefore, implementation of non-physical barriers must be considered exclusively within the context of project goals. Where the primary goal is to reduce fish mortality at a hydroelectric facility, behavioral deterrents may be the best option. When complete restriction of an invasive species is needed, non-physical barriers may not succeed indefinitely.

In all examples of non-physical fish deterrence, site selection is crucial to the choice of barrier and design specifications of the chosen option. For these systems to be practically and financially viable, a constricted fish passageway should be considered. Such natural or artificial "choke points" minimize the expense of equipment and infrastructure while maximizing the likelihood of individual fish encountering negative stimuli. Beyond this, many factors should be quantified during initial site surveys. These include hydrol-

Table 1. Summary of different non-physical barriers that could be implemented to deter the movements of fishes. Also listed are deployment conditions where barriers are likely to be successful, advantages and disadvantages of different barrier types, and representative citation showing the barrier in use.

Barrier/Deterrent	Deployment conditions	Advantages	Disadvantages	Relevant citations
Electricity	Site with adequate power source; appropriate water conductivity	Flexible deployment, very effective against recruited fish	May not affect smaller fish	Bullen and Carlson 2003; Savino et al. 2001; Clarkson 2004
Strobe lights	Consistent low water turbidity	Less infrastructure, potentially lower cost	Lower effectiveness, especially in daytime	Johnson et al. 2005*a*; Hamel et al. 2008
Sound (AFD)	Site with adequate acoustic characteristics	Effective across a wide range of environmental conditions	Variable effectiveness; frequencies must be chosen per species	Maes et al. 2004; Sonny et al. 2006
Bubble curtains	Low water turbidity, relatively shallow water	Few as a stand-alone deterrent; may enhance other deterrents	Low effectiveness, may not work under all conditions	Patrick et al. 1985; Stewart 1981
Water velocity	Target species that is a weak swimmer; narrow channel with adequate water flow	Selectively excludes nuisance species	Major modification to channel; few sites meet criteria	Hoover et al. 2003; Katopodis et al. 1994
Hypoxia and hypercapnia	Relatively shallow water, space needed for bulk gas storage	Potential to exclude virtually all fish	Large investment of research time and capital	
Pheromones	Confined spaces and (or) short term application	Potential to selectively exclude particular fish	Time and effort to procure pheromones in bulk quantity	Little and Calfee 2006; Johnson et al. 2005*b*
Chlorine	Highly constricted deployment space	Potential to exclude virtually all fish	Deleterious to almost all aquatic fauna; negative public perception	Giattina et al. 1981; Wilde et al. 1983
Electromagnetism	Constricted areas, choke points	Cost effective, low environmental impact	May not work on all teleost fishes	Northcutt et al. 1994; Gibbs and Northcutt 2004

ogy, bottom topography, water turbidity, water chemistry, power grid access and characteristics, site access to personnel and maintenance crews, and site security. The cost of implementation is another consideration that must be investigated thoroughly prior to project initiation. Costs will vary across sites, projects, deterrent system and location, making detailed descriptions of financial considerations beyond the scope of this review. Other critical considerations include the life history of the targeted specie(s), and the native fish assemblage and ecology as many non-physical barriers are not species-specific and can impede movements of desirable species.

Future research needs in the area of non-physical fish deterrents can be divided into three areas: integration of barrier types/technologies, controlled laboratory deployments, and improved monitoring of barrier effectiveness. Currently, while a great deal of work has been done with the development of technologies to deter fish movements, a large portion of this work has been performed looking at the efficacy of single deterrent systems in isolation (e.g., strobe lights alone, bubble curtains alone, etc.). To improve effectiveness of barriers, minimize the likelihood of acclimation, and provide additional safety/redundancy, future work should attempt to integrate multiple deterrent systems concurrently. Pegg and Chick (2004), for example, used bubble curtains and acoustic deterrents in concert to deter movements of Asian carp, and reported an efficiency of 95%, and projects such as this with multiple barrier strategies used in concert should be performed. Similarly, much of the work that has been performed to date has been carried out in a field setting, often with little validation, testing or analyses under controlled laboratory conditions. Future studies, therefore, should work to validate and optimize deterrent strategies in controlled environments that allow for standardization, comparison and manipulation prior to field deployments. Such validation and testing prior to field deployment would improve effectiveness and provide improved confidence in the ability of deterrence systems to optimally deter fish. Finally, it is imperative that researchers invest additional effort into quantification of deterrent effectiveness. Technologies such as biotelemetry (Cooke et al. 2004) or sonar (Belcher et al. 2002) can be employed either in a laboratory or field setting to non-invasively monitor fish position or behavior during trials with deterrents to conclusively demonstrate barrier effectiveness.

In closing, results from this review emphasize that there is no one-size-fit-all solution to fish passage challenges. Ultimately, it is up to fishery managers and project shareholders to identify the ecological and financial goals of each fish passage project, and research and engineer case-specific solutions to meet these goals.

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