River Research and Applications

WILEY

REVIEW ARTICLE OPEN ACCESS

Reviewing the Potential for Behavioral Guidance to Improve Downstream Passage of Out-Migrating Anguillid Eels

M. E. Cole MacLeod[1] | Thomas C. Pratt[2] | Chris K. Elvidge[1] | Paul S. Kemp[3] | Steven J. Cooke[1]

[1]Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, Ontario, Canada | [2]Ecosystem Sciences Division, Fisheries and Oceans Canada, Sault Ste. Marie, Ontario, Canada | [3]International Centre for Ecohydraulics Research, Faculty of Engineering and Physical Science, University of Southampton, Southampton, UK

Correspondence: M. E. Cole MacLeod (colemacleod1@gmail.com)

Received: 31 January 2025 | **Revised:** 22 August 2025 | **Accepted:** 1 September 2025

Funding: This work was supported by the NSERC Alliance Grant to S.J.C.

Keywords: behavioral guidance | downstream passage | eel | fish guidance | fish passage | hydroelectric

ABSTRACT

Hydroelectric dams and their turbine infrastructure threaten out-migrating anguillid eels en route to marine spawning grounds. For decades, invested parties have attempted to guide eels away from turbines and toward safe passage routes. A subset of this work (hereafter behavioral guidance) has involved exploiting sensory biology (e.g., sight and hearing) to divert eels from areas of danger toward safe passage, including collection facilities for trap and transport. Here, we narratively review these efforts and interpret available information through an applied lens. We collated relevant literature and organized it based on behavioral guidance modalities of light, sound, hydrodynamics, and electricity. Combined (multimodal) approaches were categorized under the primary behavioral stimulus. With further research, light could have some degree of potential as a standalone method, but field evidence indicates it is more practically effective when paired with physical barriers. Sound alone may not be sufficient, but flume evidence indicates it can also increase the effectiveness of physical barriers. Current evidence to support manipulation of hydrodynamics as a means to alter eel behavior is limited, and responses may vary considerably according to the nature of the manipulation. Electrical fields can be hazardous to downstream-swimming eels, though they generally do elicit behavioral effects. Given our current understanding, it is apparent that multimodal approaches, particularly light and sound to augment physical barriers, are likely the most realistic for achieving reliable and effective behavioral guidance. Future research could refine knowledge in this area. It is important to continue to scale promising methods to the field to assess practical relevance.

1 | Introduction

For much of our existence, humans have exploited species' sensory biases (including our own; Roy and de Jong 2016) to incite behaviors deemed to be desirable. Relatively straightforward examples include uses of sound to repel pest animals (Gilsdorf et al. 2002), UV light and pheromones to trap or control insects (Shimoda and Honda 2013; Rizvi et al. 2021), and light to attract schooling fish and facilitate capture (Nguyen and Winger 2019). In practice, this use of nonphysical sensory stimuli to deter or attract a species can be broadly termed "behavioral guidance" (adapted from "nonphysical deterrence": Noatch and Suski 2012; precedent for "behavioral guidance": Kemp et al. 2012; Piper et al. 2015, 2019; Ford et al. 2017; Hansen et al. 2018; Elvidge et al. 2018; Holgate et al. 2023).

Behavioral guidance could also be useful for achieving more specialized environmental management goals (Laiolo 2010;

Sorensen and Johnson 2016; Elmer et al. 2021; Stoilova 2024). Some methods that target fishes include the use of electro-repulsive metals in fishing gear to reduce shark bycatch (Hutchinson et al. 2012); high-frequency sound to repel Alewife (*Alosa pseudoharengus*) from a water intake (Ross et al. 1993); and chemical attraction (Wagner et al. 2006) and electrical exclusion (Johnson et al. 2021) of invasive Sea Lamprey (*Petromyzon marinus*) around the Laurentian Great Lakes. Numerous behavioral guidance systems have been developed with the objective of improving fish passage outcomes at anthropogenic barriers such as hydroelectric infrastructure (EPRI 1998; Noatch and Suski 2012; Stoilova 2024), including for migratory species such as freshwater eels (Anguillidae, hereafter anguillid eels or eels).

Diadromous anguillid eels are particularly susceptible to obstructions on watersheds, given they may be required to pass these barriers multiple times to complete their life histories (Figure 1; Liermann et al. 2012; Cairns et al. 2013; Reid et al. 2019). In many cases, the upstream migrating elvers and young yellow eels are able to climb along the wetted zone at the edge of the structure if sufficient roughness elements are present, or may successfully negotiate it using specially designed eel passes if installed (Haro 2013; EPRI 2018; Vowles et al. 2017; Kerr et al. 2015). Yet, for downstream migrating late yellow and silver eels, facilitating passage remains a significant challenge at many sites (Hadderingh and Bruijs 2002; Versar, Inc 2009; Piper et al. 2013; EPRI 2018; Verhelst et al. 2018; Pratt et al. 2021). Observation of migratory obstruction and mortality of eels due to hydroelectric infrastructure is concurrent with sharp population declines in anguillid eel species worldwide (Liermann et al. 2012; Piper et al. 2013; Jacoby et al. 2015; Verhelst et al. 2018). Some of the most widely valued and studied of the 18 anguillid species (Teng et al. 2009), European Eel *Anguilla anguilla*, American Eel *A. rostrata*, and Japanese Eel *A. japonica*, are considered Critically Endangered, Endangered, and Endangered, respectively (Pike, Crook, et al. 2020; Pike, Kaifu, et al. 2020; Pike et al. 2023).

Physical structures (e.g., screens and bar racks) are often installed at hydroelectric stations, usually with the primary intent of stopping debris, and these may guide downstream-swimming fishes toward preferred passage routes (bypasses) by mechanically blocking their passage through less desirable routes (for a more thorough description of related fish protection strategies, see Schwevers and Adam 2019). This is less effective at larger facilities and in wider rivers, and maintenance of these structures can be problematic if they experience substantial biofouling and debris accumulation (EPRI 2018; Schwevers and Adam 2019; Bruijs 2021; Mensinger et al. 2021). Further issues specific to eel include their relatively poor burst swimming abilities (Bruijs and Durif 2009; Russon and Kemp 2011), preference for relatively fast water currents (Bruijs and Durif 2009; Piper et al. 2013), and elongate bodies (Calles et al. 2010). These traits presumably cause eels to be particularly vulnerable to entrainment in pumps or turbines; in numerous cases, eels exhibit the highest rates of mortality at hydroelectric stations of any fish species (Hadderingh and Bruijs 2002).

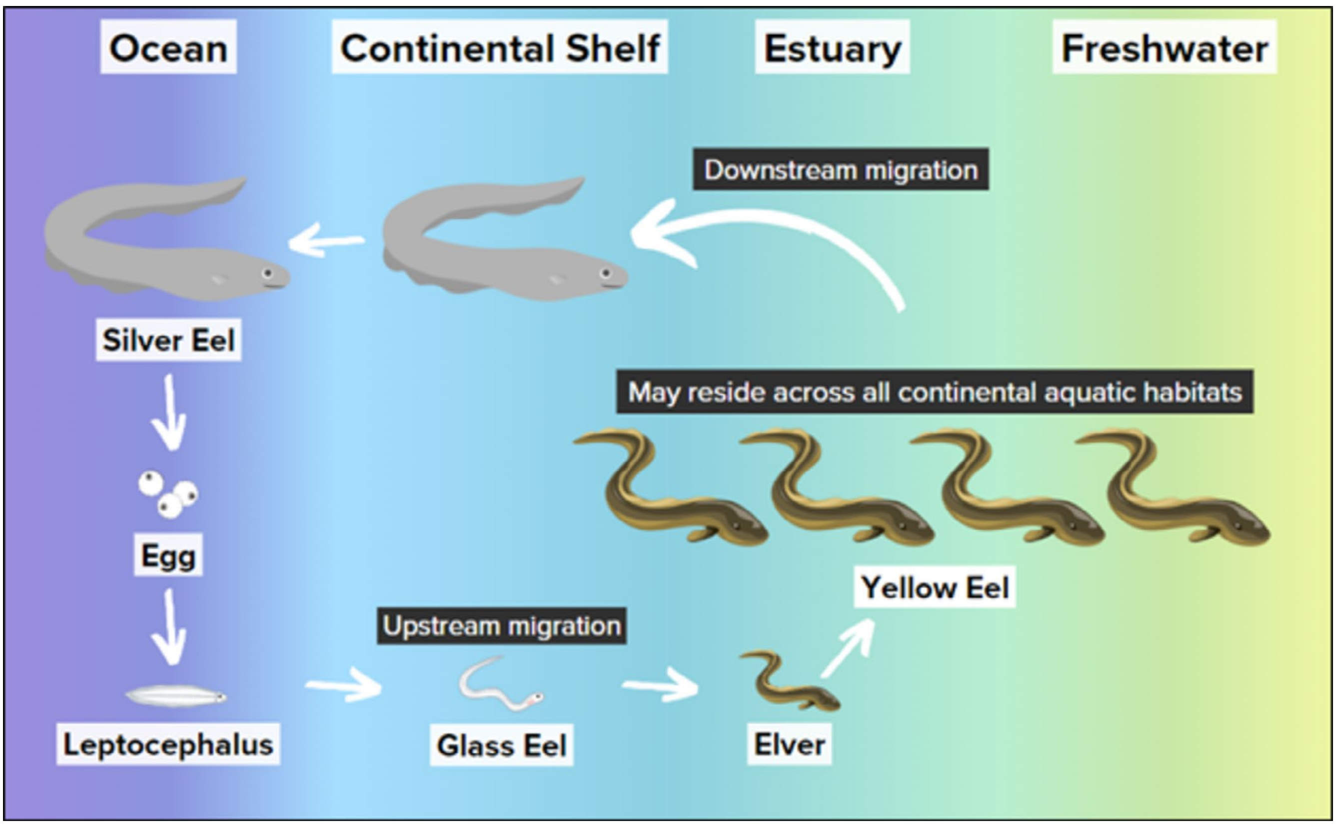

FIGURE 1 | The life cycle of anguillid eels (adapted from Cairns et al. 2013). Born in offshore marine areas, eel larvae and juveniles move toward continental shelves on ocean currents, where they reside in nearshore marine areas or further inland. In approximately 5–30 years, surviving individuals out-migrate and sexually mature, returning to their place of birth to reproduce and die. [Color figure can be viewed at wileyonlinelibrary.com]

In light of the challenges of using mechanical screening systems for eels, there is an interest in advancing behavioral solutions to manipulate their downstream movement trajectories either as a replacement for, or in combination with, physical screens (e.g., Hadderingh et al. 1999; Versar, Inc 2009; Piper et al. 2015, 2019; EPRI 2018; Elvidge et al. 2018; Popper et al. 2020; Pratt et al. 2021). Here, we aimed to summarize current knowledge based on an extensive review of the literature related to the behavioral guidance of mature anguillid eels. We focused on altering the movement of out-migrating eels away from hydroelectric infrastructure and toward collection points or safe passage. We rationalized the potential sensory modalities (light, sound, hydrodynamics, and electricity), summarized the relevant aspects of anguillid movement ecology and sensory biology, and provided a short overview regarding the underwater propagation of each stimulus. Each modality's potential for management-scale behavioral guidance was characterized using observational and experimental evidence. Studies that paired behavioral guidance with physical barriers (multimodal approaches) were categorized according to the primary sensory modality targeted in each experiment. Methods and results were sufficiently diverse to preclude quantitative analyses, so we embraced a narrative approach.

1.1 | Background

Eels respond to environmental cues such as hydrodynamics, light, and sound (Evans and Claiborne 2006; Trischitta et al. 2013) in different ways, depending on their life history stage and immediate behavioral priorities (Horodysky et al. 2022). While eels do not possess dedicated electrosensory anatomy (England and Robert 2022), their nervous system can be directly affected by electrical stimulation and they may respond involuntarily or due to discomfort (Cowx and Lamarque 1990; Sharber and Sharber Black 1999; Noatch and Suski 2012). Eels are also able to sense cues such as magnetism (Moore and Riley 2009; Durif et al. 2022), temperature, odor, and pressure (Evans and Claiborne 2006), but manipulation of these would be impractical under relevant field conditions, so they are not discussed further. For instance, chemicals in water are dominated by ambient hydrodynamics, and thus disperse unevenly and unpredictably in downstream flow (Allen et al. 2012). Here, we focus on light, sound, hydrodynamics, and electric fields as practical means for potentially altering the movement of downstream-swimming eels.

A few aspects of hydrodynamics are quite relevant to the development of a behavioral guidance system. At higher flow velocities, the effect of any stimulus may be dampened, and a greater intensity may be required to elicit a response (Hadderingh et al. 1999; Versar, Inc 2009; Putland and Mensinger 2019; Miller et al. 2021). Even if the stimulus intensity is great enough to induce the desired behavior, eels' responses may be physically limited when bulk flow velocity begins to compete with their burst swimming capacity (1.35–2.12 m/s; Russon and Kemp 2011), or if the stimulus is not detected at a sufficient distance to allow for the intended path adjustment in downstream flow, before the eel reaches a "point of no return" (Bruijs 2021). Eels also tend to avoid on- or in-water objects that create hydraulic disturbances (Piper et al. 2017), which could be a convenient multimodal effect depending on the design of a behavioral guidance system.

Light, sound, and electric fields each also present unique considerations in the development of a behavioral guidance system. High turbidity attenuates light, which can limit the distance at which fishes perceive and respond to it (Hamel et al. 2008; Putland and Mensinger 2019). Sound does not have this issue, but particularly wide or shallow channels may present an unsuitable acoustic field (Noatch and Suski 2012; Pratt et al. 2021). Furthermore, infrasonic signals can travel through or along channel beds and walls; depending on signal frequency, channel shape, and substrate composition, eels may detect this more strongly than through the water (Popper and Hastings 2009; Popper et al. 2020). Variability in water conductivity could be an important environmental consideration for a hypothetical electrical guidance system (Miller et al. 2021), and the hazardous nature of electricity should be kept in mind when designing experiments. Applicable to all modalities, ambient levels of the same or similar stimulus may decrease the relative intensity of the artificial signal compared to background levels; this is a particular concern at sites with light or noise pollution (Popper and Carlson 1998; Noatch and Suski 2012; Popper et al. 2020).

2 | Review Methods

Numerous searches across academic (e.g., Google Scholar and Web of Science), industry (Electric Power Research Institute), and common (Google) libraries were undertaken to locate relevant academic and grey (non-peer reviewed) literature. Relevant sources were also obtained through correspondence with subject matter experts and industry practitioners, and by "snowballing" from the references of known works (Table 1).

3 | Sensory Modalities

3.1 | Light

Considerable preliminary evidence indicates that light could be used to deter or guide anguillid eels. Many works regarding eel spatiotemporal ecology describe them as exhibiting a predominantly nocturnal out-migration, negative phototacticity, or as being generally more active at night or in darker areas (e.g., Smith and Saunders 1955; Helfman et al. 1983; Vøllestad et al. 1986; Stahl et al. 2023). Out-migrating eels also avoid artificial light in particular. For example, adding lights to one section of an eel weir reduced silver eel catches in nets near that section (Cullen and McCarthy 2000). In captive flume studies, downstream-swimming late yellow and silver stage eels have been deflected by fluorescent light (Hadderingh et al. 1999) and light-emitting diode (LED) illumination when offered a choice (Elvidge et al. 2018; Vowles and Kemp 2021). Elvidge et al. (2018) additionally considered light color and strobe rates. Blue (480 nm) LED light elicited the greatest avoidance, consistent with eel retinal cells' ontogenetic shift in physiological sensitivity (Pankhurst and Lythgoe 1983), followed by full-spectrum white light. In both cases, strobing (30 Hz) outperformed blinking (1 Hz) light.

TABLE 1 | Primary works investigating questions related to behavioral guidance of anguillid eels, from both academic and grey literature sources.

	Field		Laboratory/flume	
Sensory modality (*n* studies)	Published	Grey literature	Published	Grey literature
Light (*n* = 11)	Cullen and McCarthy (2000), Lenihan et al. (2025)	Hadderingh and Smythe (1997), McGrath et al. (2003), Bowen (2014), Kruitwagen (2014), Bruijis and Vriese (2013), EPRI (2024)	Hadderingh et al. (1999), Elvidge et al. (2018), Vowles and Kemp (2021)	
Sound (*n* = 6)	Piper et al. (2019), Deleau et al. (2020a)	Sand et al. (2000), Bau et al. (2011)	Deleau et al. (2020b)	EPRI (2016)
Hydrodynamics (*n* = 4)	Piper et al. (2015), Vowles et al. (2025)		Hadderingh et al. (1999)	EPRI (2016)
Electric fields (*n* = 4)	Hadderingh and Jansen (1990)	Versar, Inc (2009) (review; describes studies within), Life4Fish (2020)	Miller et al. (2021)	

Elvidge et al. (2018) therefore suggested that these colors and settings should be prioritized in field-scale evaluations of light guidance devices.

Field-scale light guidance tests often report promising results, but exist primarily in the grey literature (Hadderingh and Smythe 1997; McGrath et al. 2003; Kruitwagen 2014; Bruijis and Vriese 2013; Bowen 2014). Light, and more recently LEDs in particular have been reported to successfully guide or deter downstream-swimming mature eel from hydroelectric infrastructure on some occasions (Hadderingh and Smythe 1997; Bowen 2014; Kruitwagen 2014), but fail to do so on others, even when using the same equipment (Bruijis and Vriese 2013). In one case, submerged halogen lamps installed in the St. Lawrence River (North America) were designed to create a "wall of light" (McGrath et al. 2003). Substantial avoidance was observed, but issues with debris accumulation and impractical maintenance requirements discouraged the design as presented. Also, because the device formed a physical wall itself, eels still avoided the structure on control (lights off) nights. The extent of the light's effect on top of these hydrodynamic and physical barrier effects was not well-described, as results were based primarily on visual observation. The full results of many of these studies (i.e., Hadderingh and Smythe 1997; Kruitwagen 2014; Bruijis and Vriese 2013; Bowen 2014) were not accessible, so little more can be said, although it was proposed that the failure of the latter LED device may have been due to site-specific factors such as channel shape, turbidity, confounding environmental variables (e.g., turbulence and sound), and suboptimal placement of the lights (Bruijis and Vriese 2013).

A second study upstream of Iroquois Water Control Dam (at the same site as McGrath et al. 2003) used acoustic telemetry to describe in situ responses in greater detail than previous field studies (EPRI 2024). An above-water, rather than in-water, light guidance structure equipped with downward-facing white LEDs was deployed upstream of the dam at a 30° angle relative to the river axis. This configuration was designed to horizontally deflect eels toward one side of the river for collection and downstream transport, based on past telemetry data that clarified the major migratory trajectories used. Tagged migrant eels that swam near the illuminated guidance structure were not deflected as predicted; however, they did reduce their swimming speed and dive beneath the light field (EPRI 2024). Control eels also exhibited a much shallower dive, presumably due to hydrodynamic effects on the water's surface (Piper et al. 2017). These results suggest that in-water lighting may be more readily effective than above-water lighting, and more generally emphasize the importance of device configuration in eliciting the desired response.

Recently, the first published field study using strobing, broad-spectrum white LEDs observed an 80% deflection rate of out-migrating silver eels on the River Shannon (Lenihan et al. 2025). The lights were deployed in-water, 1.08 m apart, at a 45° angle relative to the river axis. Eels that were not guided were smaller than those that were, suggesting that larger eels were more capable of altering their migratory path to avoid the light array (Lenihan et al. 2025). As with McGrath et al. (2003), the authors note that the strong response observed was likely a combination of the eels being negatively phototactic as well as the hydrodynamic and physical effects associated with the light support structure.

Light appears to have potential as a behavioral guidance stimulus for out-migrating anguillid eels. Available evidence is cautiously encouraging, but there are currently few peer-reviewed field studies, and the methods and outcomes of the broader evidence base are quite varied, and in some cases, not readily accessible. Beneficial effects seem to be more readily obtained in a multimodal approach by pairing light with physical barriers, as demonstrated by Lenihan et al. (2025) and McGrath et al. (2003). Light has also enhanced physical barriers for other species, such as White Sturgeon *Acipenser transmontanus* (Ford et al. 2017) and Staghorn Sculpin *Leptocottus armattus* (Mussen and Cech 2018).

3.2 | Sound

The known auditory range of anguillids (< 1–300 Hz; Jerkø et al. 1989) is relatively narrow and of lower pitch compared to that of humans (20–20,000 Hz; Purves et al. 2001), but is comparable to other non-auditory "specialist" fishes (e.g., Gadids and Salmonids; Popper and Hawkins 2019). In eels, detection of the movement of water due to sound via the inner ear is understood to predominate until about 100 Hz (Jerkø et al. 1989). Between 100 and 300 Hz, direct detection of particle motion via the inner ear may be more difficult, and the reverberation of the swim bladder due to the pressure component of sound (analogous to the eardrum of mammals; Popper et al. 2019) may play an equal role (Jerkø et al. 1989). Unlike some other fish species, eels lack a specialized anatomy to facilitate this process, so this secondary signal probably attenuates significantly before it is detected by the inner ear (Popper et al. 2003; Ladich and Schulz-Mirbach 2016; Popper and Hawkins 2018). Thus, < 1–100 Hz, one-fifth of which is below the threshold for infrasound (< 20 Hz), may be anguillids' optimal hearing range. However, much of this information is uncertain, given recent evidence suggests audiogram measurements may not reflect optimal frequencies for behavioral responses (Holgate et al. 2023), and many other concerns have been raised regarding the validity of past aquatic audiological studies (Leighton et al. 2020). Relatively recent empirical work observed eels in a small flume exhibiting the greatest avoidance to three low-frequency signals (10, 50, and 100 Hz). Of these three, the strongest response was observed to 10 Hz and the weakest to 100 Hz,supporting the assertion that lower frequencies could be more effective for behavioral guidance (EPRI 2016).

Historically, laboratory and field experiments evaluating the efficacy of broadband (60–1000 Hz) and low-frequency sound as practically applicable behavioral guidance methods report poor to mixed outcomes (0%–57% reported success rate; Sand et al. 2000; Bau et al. 2011; Piper et al. 2019; Deleau et al. 2020a). Advances in acoustic field mapping and acoustic telemetry have enabled more detailed analyses in more recent experiments, generating observations that could guide a more focused approach. While infrasound was again shown to be ineffective as an outright deterrent in Piper et al. (2019), decreasing the number of eels that passed the sound source by only 28%, the authors were able to use in situ movement data to demonstrate that treatment eels did exhibit hesitance, erratic movement, and took more than two times as long to swim through the ensonified area than control eels. These results suggest that infrasound could remain useful as a secondary stimulus in a multimodal guidance system (Putland and Mensinger 2019; Pratt et al. 2021; Piper et al. 2019). This conclusion is consistent with Versar, Inc's (2009) supposition of an augmentative effect of vibrating moorings in the eel light guidance system described by McGrath et al. (2003), and with a study on Shiner Surfperch *Cymatogaster aggregata*, which demonstrated vibration can enhance the effectiveness of physical screens (Mussen and Cech 2018).

Infrasound does not presently appear to have been tested in a multimodal experiment. However, Deleau et al. (2020b) set out to determine whether either continuous broadband sound (60–1000 Hz) or a low-frequency (100 Hz) pulse could improve deflection of downstream swimming eels by a vertical bar screen toward a bypass in a flume. Responses to the acoustic signals were compared against control trials wherein there was a screen but no sound. Most eels in all trials reached the bypass, but fewer failed to be deflected during ensonified trials (three control; one in each sound trial). Both acoustic modalities caused eels to reach the bypass sooner than during the control trial, though the 100 Hz pulse had a greater effect. While Deleau et al.'s (2020b) methods, as described, successfully enhance the efficiency of the screen, infrasound may elicit a stronger response than higher frequencies under otherwise equivalent conditions (EPRI 2016), so it is possible that an even greater effect could be observed if a similar experiment were undertaken using infrasound.

Further investigation of sound as a secondary deterrent is warranted, but there are some obvious limitations. High ambient noise levels are common around generating stations, and existing infrastructure at some sites could interfere with eels' ability to detect the stimulus. Additionally, particularly shallow or wide rivers may present a challenging acoustic field, especially at lower frequencies (Noatch and Suski 2012; Pratt et al. 2021). Yet, if the predominant paths of out-migrating eels at the study site were determined in advance, it could be possible that a relatively small volume of the channel would need to be ensonified to affect a sufficient proportion of migrants (as in EPRI 2018). More studies with detailed quantifications of out-migrating eel responses to natural and anthropogenic sound are needed, particularly at varied sites with well-specified soundscapes (Popper et al. 2020).

3.3 | Hydrodynamics

Broadly, experimental evidence for hydrodynamic manipulation as a guidance mechanism is varied and inconclusive. One line of research is based upon the theorization of "sweeping flows" which may be able to guide eels toward one side of a channel (Coutant 2003), and a flume study that demonstrated that silver eels choose corridors of greater flow velocity (Hadderingh et al. 1999). In accordance with this evidence, EPRI (2016) attempted to use flow velocity enhancement in a flume to guide downstream-swimming eels toward a collection bin. However, they observed no evidence for guidance. These results were surprising given the high ambient flow velocity, and may have been an artifact of the study design (EPRI 2016). To date, this approach does not seem to have been tested in another experiment.

Rather than enhancing velocity, Piper et al. (2015) investigated how out-migrating eels respond to flow constriction and acceleration in the field. Eels rejected the constricted and accelerated site and took significantly longer to pass compared to control eels (though all did eventually pass). Vowles et al. (2025) further clarified the role of channel constriction (and subsequent flow acceleration); in addition to supporting the assertion that flow acceleration deters downstream-swimming eels, they also asserted that flow recirculation, a factor which is generally ignored, drove significantly more rejections. These observations suggest two things: First, it is important to limit acceleration and recirculation in any attractant-flow behavioral guidance system, or more generally, at the mouths of bypasses. Second, there is potential to use accelerated flow as a deterrent to drive eels toward more desirable routes, particularly in tandem with other modalities.

While more research is needed, it is plausible that manipulated hydrodynamics could behaviorally guide out-migrating eels under certain circumstances, given further clarification of parameters and responses. Observations by Piper et al. (2015) and Vowles et al. (2025) highlight the yet-unexplored potential for accelerated or recirculating flow as a deterrent in a multimodal guidance system. On very large rivers, especially those with strong ambient flow, it may simply be energetically and economically infeasible to modify the hydrodynamic regime enough to reliably affect the behavior of a useful proportion of out-migrating eels (Pratt et al. 2021). Thus, hydrodynamic manipulation, if supported by further research, may be limited in practice to relatively small channels with low to moderate flow velocity.

3.4 | Electric Fields

Electrical current directly stimulates the nerves of fishes, including eels, and most responses are likely to be either involuntary or because swimming too close causes discomfort (Cowx and Lamarque 1990; Sharber and Sharber Black 1999; Noatch and Suski 2012). There is a gradient of potential responses depending on device intensity and distance, ranging from discomfort and avoidance to induced positive galvanotaxis (i.e., electrofishing; Cowx and Lamarque 1990; Gabriel and Wendt 2003); onward to stunning, paralysis, musculoskeletal injury, or death (Noatch and Suski 2012).

Indeed, past research has demonstrated that electric fields can pose serious dangers to downstream-swimming eels. Hadderingh and Jansen (1990) described deleterious effects from early attempts to guide or deter eels with electric fields, and a study reviewed in Versar, Inc (2009) reported thousands of mortalities after an electrical deterrent immobilized out-migrating eels in high bulk flow, leading to mass impingement on an intake rack. Even if the eels were able to overcome the downstream flow velocity to escape the intake, they could not move back upstream without enduring more electrical shocks. Recent work by Life4Fish (2020) is more encouraging. Here, the installation of an electrical guidance device upriver of a hydroelectric station coincided with greater eel escapement and lower entrainment than in past years, but this report emphasized that bulk flow velocity was very low at this site, and there was minimal discussion regarding the broader implications of these findings. Furthermore, a published field evaluation of an electric guidance device is yet to exist.

One published flume experiment adds behavioral context to these observations by examining responses of mature eels to two electrical fields of different strengths across low and high flow velocities (Miller et al. 2021). A total of 74% of eels exhibited a response to the electrical field in low flow, compared to 31% in high flow. Of those that did respond under both hydrodynamic conditions, nearly twice as many chose to accelerate through the field compared to those that changed their trajectory. Yet, Miller et al. (2021) also found that electrical fields at low frequencies with short pulse widths reliably induce a twitch response in eels with little risk of tetany, suggesting these parameters could still be useful in a more subtle approach.

Available evidence suggests that electricity is inappropriate as a primary deterrent unless bulk flow velocity is minimal (Life4Fish 2020; Miller et al. 2021). However, variations in placement and parameters could have potential. For example, low-frequency, short-pulse electricity could possibly be used to "nudge" eels' swimming trajectories (Miller et al. 2021), or induced galvanotaxis (i.e., electrofishing) could be used at suitable collection sites to attract and/or narcotize out-migrating eels for downstream transport. Further experiments are warranted, but should be designed with caution and intention to avoid potentially severe negative effects on eels.

4 | Synthesis and Discussion

Behavioral guidance as a general approach is characterized by wide inter- and intra-specific variation based on a variety of factors, including sex, maturation status, and behavioral state (Putland and Mensinger 2019; Elmer et al. 2021). Here, available research was inconclusive regarding effective and practical methods for any single sensory modality, but multimodal approaches for light and sound have stronger support (e.g., McGrath et al. 2003; Deleau et al. 2020b; Lenihan et al. 2025; Figure 2). Flow acceleration or recirculation should be limited at preferred routes and may have potential as a deterrent in a multimodal system (Piper et al. 2015; Vowles et al. 2025), but this remains untested. Electrical fields represent considerable risk to an endangered species swimming downstream with ambient flow, but devices could be configured differently to more subtly guide swimming trajectories, either as a deterrent in very low-flow situations (Life4Fish 2020; Miller et al. 2021) or as an attractant/narcotic (akin to electrofishing) for collection and downstream transport post-guidance. Sound or light additions to existing physical barriers could be cost-effective relative to their potential benefit, especially compared to physical retrofits (Miller et al. 2022). This could garner immediate marginal gains to passage efficiency, whereby incremental advancements amount to meaningful improvement at a larger scale (Miller et al. 2022).

Overall, deterrence is more readily elicited, and perhaps more biologically realistic, than attraction. Hydrodynamic manipulation is the only method with any evidence for attracting eels via enhanced flow velocity, but high acceleration flows can also deter them. There is interest in attractant odors and sounds (Schmucker et al. 2017; Popper et al. 2020), but little progress has been made in these areas. This could be because silvering eels undergo extensive physiological and morphological changes over the course of their maturation and out-migration (Tesch and Thorpe 2003), and fishes interpret sensory stimuli in accordance with their behavioral state and life history stage (Horodysky et al. 2022). Thus, these individuals may not easily be attracted to anthropogenic cues, which are unlikely to be more biologically relevant than the prospect of reproducing before death. In contrast, acute bouts of avoidance due to unpleasant or noxious

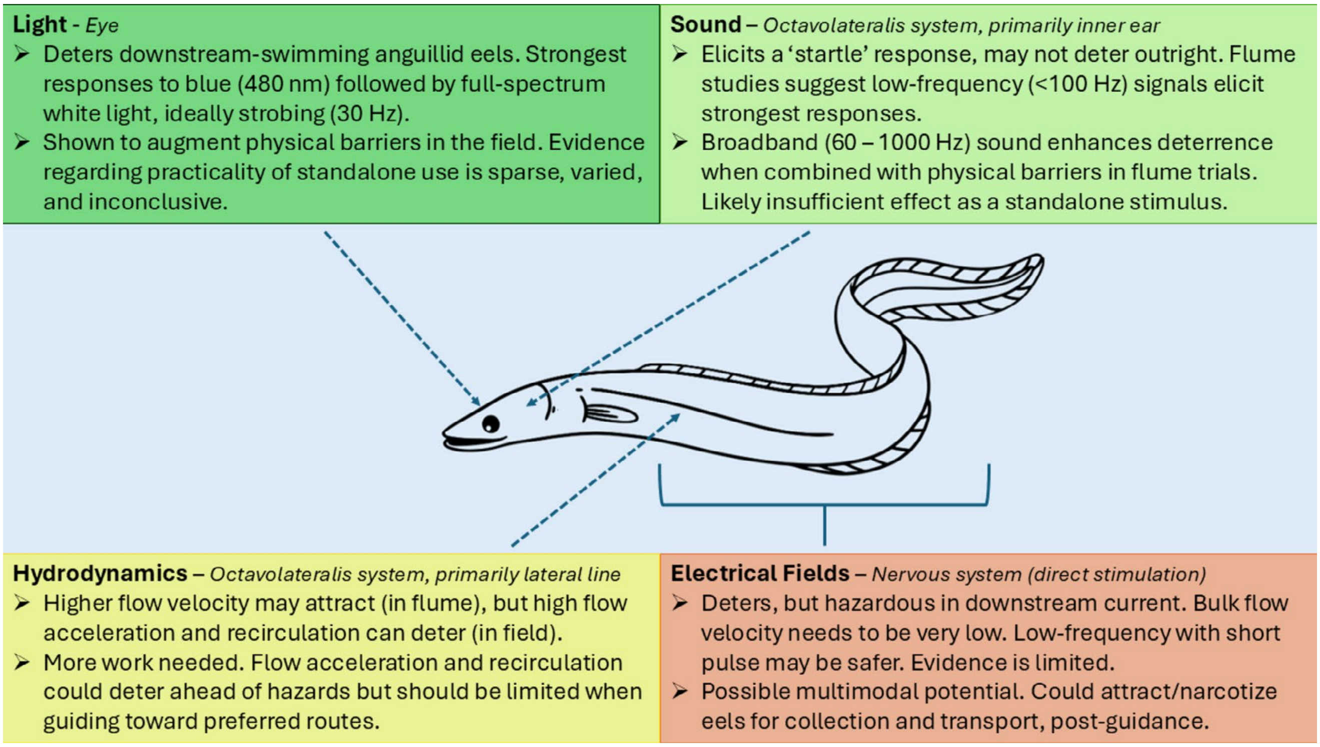

FIGURE 2 | Schematic diagram describing the feasibility of various stimuli for behaviorally guiding out-migrating anguillid eels. [Color figure can be viewed at wileyonlinelibrary.com]

stimuli may demand less relevance and thus could be easier to induce.

Acoustic telemetry, or ideally less invasive methods such as sonar, is a critical advancement for monitoring eel responses to stimuli. Pre-study monitoring allows for a baseline understanding of how eels naturally move through target sites, the importance of which is twofold. First, understanding preferred channels could dramatically decrease requisite coverage of a guidance device (e.g., methods in EPRI 2024). Second, these paths can be compared against experimental treatment and control data to not only isolate the effect of the stimulus, but also determine whether the structure itself has a meaningful hydraulic effect. In situ monitoring allows for detailed observation of behaviors in the field, rather than relying on outcomes alone, and has been used by many of the recent studies discussed here (Noatch and Suski 2012; EPRI 2018, 2024; Piper et al. 2013, 2015, 2017, 2019). Tracking wild fish also allows identification of peak migration periods, which is pertinent information for management-scale applications to maximize cost-effectiveness by limiting periods of deployment and to minimize collateral effects on non-target species.

Observational data must be accurate and represented in a useful manner to bolster interpretations and be more useful to future studies. Behavioral guidance sites and technologies need to be selected and developed based on detailed knowledge of site-specific characteristics (Noatch and Suski 2012), and there should be reliable pre-study estimates of the proposed stimulus intensity and coverage. Furthermore, it would be helpful to standardize terminology and protocols for measurements and reporting results to facilitate quantitative comparisons among studies (Popper et al. 2020). Some common issues include insufficient reporting of contextual data, poorly described responses, misrepresenting the magnitude of a response, variable and proprietary designs, poor stimulus mapping, and the use of improper metrics (Putland and Mensinger 2019; Popper et al. 2020).

Regarding practical benefits and advancements, behavioral guidance devices may be less permanent and can be temporarily deployed or remotely controlled to meet peak migration periods. LEDs in particular are promising components of light guidance systems as they are programmable to produce different colors, strobe rates, and intensities; can be adjusted while deployed; can incorporate UV anti-biofouling diodes; and are cheaper, more energy efficient, and have longer lifespans than alternative light sources (e.g., mercury, metal halide, and incandescent) that were used in earlier field tests (EPRI 2017). Growing recognition of the need to diversify from historically typical fish passage technologies (Silva et al. 2018) suggests behavioral guidance's importance may grow in the future (Elmer et al. 2021).

4.1 | Conclusion

Anguillid eels are a problematic taxon for fish passage, and species worldwide are endangered. Behavioral guidance strategies could improve survival outcomes during downstream eel passage through high-risk sites, including electrical generating stations. Here, we describe the functional principles of behavioral guidance, outline potential technologies, comment on the practicality of each, and recommend directions for future research. We also emphasize the importance of other efforts to mitigate out-migrating eel mortality, including innovations in fish-friendly turbines (e.g., Yang et al. 2018; Niño Del Río et al. 2023). We hope that this paper provides a useful starting point for hydropower proponents, regulators, and researchers interested in using behavioral guidance to reduce eel mortality.

Acknowledgments

This work was supported by an NSERC Alliance Grant to S.J.C. We are indebted to our partners—the Electric Power Research Institute, New York Power Authority, United States Fish and Wildlife Service, Ontario Ministry of Natural Resources, Ontario Power Generation, Hydro Quebec, Fisheries and Oceans Canada, and Québec Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

References

Allen, D. T., Y. Cohen, and I. R. Kaplan. 2012. *Intermedia Pollutant Transport: Modeling and Field Measurements*. Springer Science & Business Media.

Bau, F., J. Lafitte, P. Baran, M. Larinier, F. Travade, and E. H. De Oliveira. 2011. "Anguille et ouvrages: migration de dévalaison." Test d'un dispositif de répulsion à infrasons au droit de deux ouvrages hydroélectriques sur le Gave de Pau.

Bowen, M. D. 2014. "Strobe Light Diversion Effectiveness for European Eel." For the Thames Water Utilities Ltd. In, Turnpenny Horsfield Associates (THA) Report No. 606R0103. Ashurst, New Forest, UK.

Bruijis, M. C. M., and F. T. Vriese. 2013. "Workshop Fish Protection at Hydropower Stations in the River Meuse, the Netherlands, 2013." Workshop sponsor: Rijkswaterstaat, Ministerievan Infrastructuur en Milieu, Netherlands.

Bruijs, M. C. M. 2021. "Key Considerations for Developing Best-Practice Solutions for Safeguarding Downstream Fish Migration at Hydropower Facilities." Paper presented at IKSR-CIPR-ICBR Fish Experts Webinar: Fish Protection and Downstream Fish Migration at Large Hydropower Plants: Sharing Experiences and Knowledge. Online Webinar. September 15–16.

Bruijs, M. C. M., and C. M. F. Durif. 2009. "Silver Eel Migration and Behaviour." In *Spawning Migration of the European Eel: Reproduction Index, a Useful Tool for Conservation Management*, edited by G. van den Thillart, S. Dufour, and J. C. Rankin, 65–95. Springer Netherlands.

Cairns, D., G. Chaput, L. Poirier, et al. 2013. "Recovery Potential Assessment for the American Eel (*Anguilla Rostrata*) for Eastern Canada: Life History, Distribution, Reported Landings, Status Indicators, and Demographic Parameters."

Calles, O., I. C. Olsson, C. Comoglio, et al. 2010. "Size-Dependent Mortality of Migratory Silver Eels at a Hydropower Plant, and Implications for Escapement to the Sea." *Freshwater Biology* 55, no. 10: 2167–2180.

Coutant, C. C. 2003. "Induced Sweeping Flows at CWIS for Reducing Fish Impingement." In *EPA Proceedings Report. Symposium on Cooling Water Intake Technologies to Protect Aquatic Organisms*. EPA 625-C-05-002.

Cowx, I., and P. Lamarque. 1990. *Fishing With Electricity: Applications in Freshwater Fisheries Management*, 248. Fishing News Books.

Cullen, P., and T. McCarthy. 2000. "The Effects of Artificial Light on the Distribution of Catches of Silver Eel, *Anguilla anguilla* (L.), Across the Killaloe Eel Weir in the Lower River Shannon." *Biology and Environment: Proceedings of the Royal Irish Academy* 100B, no. 3: 165–169.

Deleau, M. J. C., P. R. White, G. Peirson, T. G. Leighton, and P. S. Kemp. 2020b. "Use of Acoustics to Enhance the Efficiency of Physical Screens Designed to Protect Downstream Moving European Eel (*Anguilla anguilla*)." *Fisheries Management and Ecology* 27, no. 1: 1–9.

Deleau, M., P. White, G. Peirson, T. Leighton, and P. Kemp. 2020a. "The Response of Anguilliform Fish to Underwater Sound Under an Experimental Setting." *River Research and Applications* 36, no. 3: 441–451.

Durif, C. M. F., H. H. Stockhausen, A. B. Skiftesvik, A. Cresci, D. Nyqvist, and H. I. Browman. 2022. "A Unifying Hypothesis for the Spawning Migrations of Temperate Anguillid Eels." *Fish and Fisheries* 23: 358–375.

Elmer, L. K., C. L. Madliger, D. T. Blumstein, et al. 2021. "Exploiting Common Senses: Sensory Ecology Meets Wildlife Conservation and Management." *Conservation Physiology* 9, no. 1: coab002.

Elvidge, C. K., M. I. Ford, T. C. Pratt, et al. 2018. "Behavioural Guidance of Yellow-Stage American Eel *Anguilla rostrata* With a Light-Emitting Diode Device." *Endangered Species Research* 35: 159–168.

England, S. J., and D. Robert. 2022. "The Ecology of Electricity and Electroreception." *Biological Reviews* 97, no. 1: 383–413.

EPRI. 1998. "Review of Downstream Fish Passage and Protection Technology Evaluations and Effectiveness." Electric Power Research Institute, Technical Report 111517.

EPRI. 2016. "Laboratory Studies of Eel Behavior in Response to Various Behavioral Cues." Electric Power Research Institute, Technical Report 3002009405.

EPRI. 2017. "Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology." Electric Power Research Institute, Technical Report 3002009407.

EPRI. 2018. *Eel Passage Research Center: 2013–2018 Synthesis Report*. Electric Power Research Institute.

EPRI. 2024. *River-Scale Evaluation of the Effects of a Floating LED Light Array on Swimming Trajectories of Outmigrating American Eel in the St. Lawrence River*. Electric Power Research Institute.

Evans, D. H., and J. B. Claiborne, eds. 2006. *The Physiology of Fishes*. 3rd ed. CRC, Taylor & Francis.

Ford, M. I., C. K. Elvidge, D. Baker, et al. 2017. "Evaluating a Light-Louver System for Behavioural Guidance of Age-0 White Sturgeon." *River Research and Applications* 33, no. 8: 1286–1294.

Gabriel, O., and T. Wendt. 2003. "Fishing Methods." In *The Eel*, 243–293. John Wiley & Sons, Ltd.

Gilsdorf, J. M., S. E. Hygnstrom, and K. C. VerCauteren. 2002. "Use of Frightening Devices in Wildlife Damage Management." *Integrated Pest Management Reviews* 7, no. 1: 29–45.

Hadderingh, R. H., and M. C. M. Bruijs. 2002. "Hydroelectric Power Stations and Fish Migration." *Tribune de l'Eau* 55, no. 619–620/5–6: 79–87.

Hadderingh, R., and H. Jansen. 1990. "Electric Fish Screen Experiments Under Laboratory and Field Conditions." In *Developments in Electric Fishing*, 266–280. Fishing News.

Hadderingh, R. H., and A. G. Smythe. 1997. "Deflecting Eels From Power Stations With Light." Paper presented at the "Fish Passage Workshop," Milwaukee, WI, May 6–8.

Hadderingh, R., G. Van Aerssen, R. De Beijer, and G. Van der Velde. 1999. "Reaction of Silver Eels to Artificial Light Sources and Water Currents: An Experimental Deflection Study." *Regulated Rivers: Research & Management* 15, no. 4: 365–371.

Hamel, M. J., M. L. Brown, and S. R. Chipps. 2008. "Behavioral Responses of Rainbow Smelt to In Situ Strobe Lights." *North American Journal of Fisheries Management* 28, no. 2: 394–401.

Hansen, M. J., D. E. Cocherell, S. J. Cooke, P. H. Patrick, M. Sills, and N. A. Fangue. 2018. "Behavioural Guidance of Chinook Salmon Smolts: The Variable Effects of LED Spectral Wavelength and Strobing Frequency." *Conservation Physiology* 6, no. 1: coy032.

Haro, A. J. 2013. *Proceedings of a Workshop on American Eel Passage Technologies*, 90. Atlantic States Marine Fisheries Commission.

Helfman, G. S., D. L. Stoneburner, E. L. Bozeman, P. A. Christian, and R. Whalen. 1983. "Ultrasonic Telemetry of American Eel Movements in a Tidal Creek." *Transactions of the American Fisheries Society* 112, no. 1: 105–110.

Holgate, A., P. R. White, T. G. Leighton, and P. S. Kemp. 2023. "Applying Appropriate Frequency Criteria to Advance Acoustic Behavioural Guidance Systems for Fish." *Scientific Reports* 13, no. 1: 8075.

Horodysky, A. Z., C. C. Schweitzer, and R. W. Brill. 2022. "Chapter 2—Applied Sensory Physiology and Behavior." In *Fish Physiology*, edited by S. J. Cooke, N. A. Fangue, A. P. Farrell, C. J. Brauner, and E. J. Eliason, 33–90. Academic Press.

Hutchinson, M., J. H. Wang, Y. Swimmer, et al. 2012. "The Effects of a Lanthanide Metal Alloy on Shark Catch Rates." *Fisheries Research* 131–133: 45–51.

Jacoby, D. M. P., J. M. Casselman, V. Crook, et al. 2015. "Synergistic Patterns of Threat and the Challenges Facing Global Anguillid Eel Conservation." *Global Ecology and Conservation* 4: 321–333.

Jerkø, H., I. Turunen-Rise, P. S. Enger, and O. Sand. 1989. "Hearing in the Eel (*Anguilla anguilla*)." *Journal of Comparative Physiology A* 165, no. 4: 455–459.

Johnson, N. S., B. Snow, T. Bruning, and A. Jubar. 2021. "A Seasonal Electric Barrier Blocks Invasive Adult Sea Lamprey (*Petromyzon marinus*) and Reduces Production of Larvae." *Journal of Great Lakes Research* 47: S310–S319.

Kemp, P. S., J. J. Anderson, and A. S. Vowles. 2012. "Quantifying Behaviour of Migratory Fish: Application of Signal Detection Theory to Fisheries Engineering." *Ecological Engineering* 41: 22–31.

Kerr, J. R., P. Karageorgopolous, and P. S. Kemp. 2015. "Efficacy of a Side-Mounted Vertically Oriented Bristle Pass for Improving Upstream Passage of European Eel (*Anguilla anguilla*) and River Lamprey (*Lampetra fluviatilis*) at an Experimental Crump Weir." *Ecological Engineering* 85: 121–131.

Kruitwagen, G. 2014. "Research at IJmuiden Lock Complex Provides Unique Insight in Fish guidance." In *International Fish Screening Techniques*, edited by A. W. H. Turnpenny and R. A. Horsfield. WITPress, Southampton.

Ladich, F., and T. Schulz-Mirbach. 2016. "Diversity in Fish Auditory Systems: One of the Riddles of Sensory Biology." *Frontiers in Ecology and Evolution* 4.

Laiolo, P. 2010. "The Emerging Significance of Bioacoustics in Animal Species Conservation." *Biological Conservation* 143, no. 7: 1635–1645.

Leighton, T. G., H. A. L. Currie, A. Holgate, et al. 2020. "Analogies in Contextualizing Human Response to Airborne Ultrasound and Fish Response to Acoustic Noise and Deterrents." *Proceedings of Meetings on Acoustics* 37, no. 1: 010014.

Lenihan, E. S., T. K. McCarthy, and C. Lawton. 2025. "Effectiveness of a Strobing Light System for Deflecting Downstream Migrating European Silver Eels (*Anguilla anguilla*)." *Fisheries Management and Ecology* 0: e12797.

Liermann, C. R., C. Nilsson, J. Robertson, and R. Y. Ng. 2012. "Implications of Dam Obstruction for Global Freshwater Fish Diversity." *Bioscience* 62, no. 6: 539–548.

Life4Fish. 2020. "Downstream Fish Migration Along the Low Meuse River: Monitoring of the Effectiveness of the Pilot Solutions." ProFish.

McGrath, K. J., S. Ault, and J. R. Skalski. 2003. "American Eel Light Avoidance Study." American Fisheries Society Meeting, Eel Symposium.

Mensinger, M. A., E. J. Blomberg, and J. D. Zydlewski. 2021. "The Consequences of Dam Passage for Downstream-Migrating American Eel in the Penobscot River, Maine." *Canadian Journal of Fisheries and Aquatic Sciences* 78, no. 8: 1181–1192.

Miller, M., J. de Bie, S. Sharkh, and P. Kemp. 2021. "Behavioural Response of Downstream Migrating European Eel (*Anguilla anguilla*) to Electric Fields Under Static and Flowing Water Conditions." *Ecological Engineering* 172: 106397.

Miller, M., S. Sharkh, and P. Kemp. 2022. "Response of Upstream Migrating Juvenile European Eel (*Anguilla anguilla*) to Electric Fields: Application of the Marginal Gains Concept to Fish Screening." *PLoS One* 17, no. 6: e0270573.

Moore, A., and W. D. Riley. 2009. "Magnetic Particles Associated With the Lateral Line of the European Eel *Anguilla anguilla*." *Journal of Fish Biology* 74, no. 7: 1629–1634.

Mussen, T. D., and J. J. Cech. 2018. "Assessing the Use of Vibrations and Strobe Lights at Fish Screens as Enhanced Deterrents for Two Estuarine Fishes." *Journal of Fish Biology* 95, no. 1: 238–246.

Nguyen, K. Q., and P. D. Winger. 2019. "Artificial Light in Commercial Industrialized Fishing Applications: A Review." *Reviews in Fisheries Science & Aquaculture* 27, no. 1: 106–126.

Niño Del Río, G. E., R. G. Ramirez Camacho, N. Manzanares Filho, W. De Oliveira, and T. M. Arispe Angulo. 2023. "A Methodology for Designing a Fish-Friendly Turbine Rotor Applied to High-Power Generation." *Journal of Applied Fluid Mechanics* 17, no. 1: 19–42.

Noatch, M. R., and C. D. Suski. 2012. "Non-Physical Barriers to Deter Fish Movements." *Environmental Reviews* 20, no. 1: 71–82.

Pankhurst, N. W., and J. N. Lythgoe. 1983. "Changes in Vision and Olfaction During Sexual Maturation in the European Eel *Anguilla anguilla* (L.)." *Journal of Fish Biology* 23, no. 2: 229–240.

Pike, C., J. Casselman, V. Crook, M.-B. DeLucia, and M. Gollock. 2023. *Anguilla Rostrata*. IUCN Red List of Threatened Species.

Pike, C., V. Crook, and M. Gollock. 2020. *Anguilla Anguilla*. IUCN Red List of Threatened Species.

Pike, C., K. Kaifu, V. Crook, D. Jacoby, and M. Gollock. 2020. *Anguilla Japonica*. IUCN Red List of Threatened Species.

Piper, A., C. Manes, F. Siniscalchi, A. Marion, R. Wright, and P. Kemp. 2015. "Response of Seaward-Migrating European Eel (*Anguilla anguilla*) to Manipulated Flow Fields." *Proceedings of the Royal Society B: Biological Sciences* 282, no. 1811: 20151098.

Piper, A., J. Svendsen, R. Wright, and P. Kemp. 2017. "Movement Patterns of Seaward Migrating European Eel (*Anguilla anguilla*) at a Complex of Riverine Barriers: Implications for Conservation." *Ecology of Freshwater Fish* 26, no. 1: 87–98.

Piper, A., P. White, R. Wright, T. Leighton, and P. Kemp. 2019. "Response of Seaward-Migrating European Eel (*Anguilla anguilla*) to an Infrasound Deterrent." *Ecological Engineering* 127: 480–486.

Piper, A., R. Wright, A. Walker, and P. Kemp. 2013. "Escapement, Route Choice, Barrier Passage and Entrainment of Seaward Migrating European Eel, *Anguilla anguilla*, Within a Highly Regulated Lowland River." *Ecological Engineering* 57: 88–96.

Popper, A. N., and T. J. Carlson. 1998. “Application of Sound and Other Stimuli to Control Fish Behavior.” *Transactions of the American Fisheries Society* 127, no. 5: 673–707.

Popper, A. N., R. R. Fay, C. Platt, and O. Sand. 2003. “Sound Detection Mechanisms and Capabilities of Teleost Fishes.” In *Sensory Processing in Aquatic Environments*, edited by S. P. Collin and N. J. Marshall, 3–38. Springer.

Popper, A. N., and M. C. Hastings. 2009. “The Effects of Anthropogenic Sources of Sound on Fishes.” *Journal of Fish Biology* 75, no. 3: 455–489.

Popper, A. N., and A. D. Hawkins. 2018. “The Importance of Particle Motion to Fishes and Invertebrates.” *Journal of the Acoustical Society of America* 143, no. 1: 470–488.

Popper, A. N., and A. D. Hawkins. 2019. “An Overview of Fish Bioacoustics and the Impacts of Anthropogenic Sounds on Fishes.” *Journal of Fish Biology* 94, no. 5: 692–713.

Popper, A. N., A. D. Hawkins, F. Jacobs, P. T. Jacobson, P. Johnson, and J. Krebs. 2020. “Use of Sound to Guide the Movement of Eels and Other Fishes Within Rivers: A Critical Review.” *Reviews in Fish Biology and Fisheries* 30, no. 4: 605–622.

Popper, A. N., A. D. Hawkins, O. Sand, and J. A. Sisneros. 2019. “Examining the Hearing Abilities of Fishes.” *Journal of the Acoustical Society of America* 146, no. 2: 948–955.

Pratt, T. C., D. R. Stanley, S. Schlueter, J. K. L. La Rose, A. Weinstock, and P. T. Jacobson. 2021. “Towards a Downstream Passage Solution for Out-Migrating American Eel (*Anguilla rostrata*) on the St. Lawrence River.” *Aquaculture and Fisheries* 6, no. 2: 151–168.

Purves, D., G. J. Augustine, D. Fitzpatrick, et al. 2001. “The Audible Spectrum.” In *Neuroscience*, 2nd ed. Sinauer Associates.

Putland, R. L., and A. F. Mensinger. 2019. “Acoustic Deterrents to Manage Fish Populations.” *Reviews in Fish Biology and Fisheries* 29, no. 4: 789–807.

Reid, A. J., A. K. Carlson, I. F. Creed, et al. 2019. “Emerging Threats and Persistent Conservation Challenges for Freshwater Biodiversity.” *Biological Reviews* 94, no. 3: 849–873.

Rizvi, S. A. H., J. George, G. V. P. Reddy, X. Zeng, and A. Guerrero. 2021. “Latest Developments in Insect Sex Pheromone Research and Its Application in Agricultural Pest Management.” *Insects* 12, no. 6: 484.

Ross, Q. E., D. J. Dunning, R. Thorne, J. K. Menezes, G. W. Tiller, and J. K. Watson. 1993. “Response of Alewives to High-Frequency Sound at a Power Plant Intake on Lake Ontario.” *North American Journal of Fisheries Management* 13, no. 2: 291–303.

Roy, E. A., and E. de Jong. 2016. “New Zealand Library Uses “Mosquito” Noise Device to Keep Youths Away.” *The Guardian*, September 8.

Russon, I. J., and P. S. Kemp. 2011. “Experimental Quantification of the Swimming Performance and Behaviour of Spawning Run River Lamprey *Lampetra fluviatilis* and European Eel *Anguilla anguilla*.” *Journal of Fish Biology* 78, no. 7: 1965–1975.

Sand, O., P. S. Enger, H. E. Karlsen, F. Knudsen, and T. Kvernstuen. 2000. “Avoidance Responses to Infrasound in Downstream Migrating European Silver Eels, *Anguilla anguilla*.” *Environmental Biology of Fishes* 57, no. 3: 327–336.

Schmucker, A. K., N. S. Johnson, H. S. Galbraith, and W. Li. 2017. “An Evaluation of Silver-Stage American Eel Conspecific Chemical Cueing During Outmigration.” *Environmental Biology of Fishes* 100, no. 7: 851–864.

Schwevers, U., and B. Adam. 2019. *Fish Protection Technologies and Fish Ways for Downstream Migration*, 279. Springer.

Sharber, N. G., and J. Sharber Black. 1999. “Epilepsy as a Unifying Principle in Electrofishing Theory: A Proposal.” *Transactions of the American Fisheries Society* 128, no. 4: 666–671.

Shimoda, M., and K. Honda. 2013. “Insect Reactions to Light and Its Applications to Pest Management.” *Applied Entomology and Zoology* 48, no. 4: 413–421.

Silva, A. T., M. C. Lucas, T. Castro-Santos, et al. 2018. “The Future of Fish Passage Science, Engineering, and Practice.” *Fish and Fisheries* 19, no. 2: 340–362.

Smith, M. W., and J. W. Saunders. 1955. “The American Eel in Certain Fresh Waters of the Maritime Provinces of Canada.” *Journal of the Fisheries Research Board of Canada* 12, no. 2: 238–269.

Sorensen, P. W., and N. S. Johnson. 2016. “Theory and Application of Semiochemicals in Nuisance Fish Control.” *Journal of Chemical Ecology* 42, no. 7: 698–715.

Stahl, A., S. M. Larocque, J. Gardner-Costa, et al. 2023. “Spatial Ecology of Translocated American Eel (*Anguilla rostrata*) in a Large Freshwater Lake.” *Animal Biotelemetry* 11, no. 1: 2.

Stoilova, V. 2024. “Behavioural Guidance Systems for Downstream Migrating Fish: A Mini-Review.” In *Advances in Hydraulic Research*, ISH 2023. GeoPlanet: Earth and Planetary Sciences, edited by M. B. Kalinowska, M. M. Mrokowska, and P. M. Rowiński. Springer.

Teng, H.-Y., Y.-S. Lin, and C.-S. Tzeng. 2009. “A New *Anguilla* Species and a Reanalysis of the Phylogeny of Freshwater Eels.” *Zoological Studies* 48, no. 6: 808–822.

Tesch, F. W., and J. E. Thorpe. 2003. *The Eel*. 3rd ed. Blackwell Science.

Trischitta, F., Y. Takei, and P. Sebert. 2013. *Eel Physiology*. Taylor & Francis Group.

Verhelst, P., D. Buysse, J. Reubens, et al. 2018. “Downstream Migration of European Eel (*Anguilla anguilla* L.) in an Anthropogenically Regulated Freshwater System: Implications for Management.” *Fisheries Research* 199: 252–262.

Versar, Inc. 2009. *Review of Technologies for Guiding, Capturing, Holding, Transporting, and Monitoring Outmigrating Eels*, 3472. Versar, Inc.

Vøllestad, L. A., B. Jonsson, N. A. Hvidsten, T. F. Næsje, Ø. Haraldstad, and J. Ruud-Hansen. 1986. “Environmental Factors Regulating the Seaward Migration of European Silver Eels (*Anguilla anguilla*).” *Canadian Journal of Fisheries and Aquatic Sciences* 43, no. 10: 1909–1916.

Vowles, A. S., A. M. Don, P. Karageorgopolous, and P. S. Kemp. 2017. “Passage of European Eel and River Lamprey at a Model Weir Provisioned With Studded Tiles.” *Journal of Ecohydraulics* 2, no. 2: 88–98.

Vowles, A. S., and P. S. Kemp. 2021. “Artificial Light at Night (ALAN) Affects the Downstream Movement Behaviour of the Critically Endangered European Eel, Anguilla Anguilla.” *Environmental Pollution* 274: 116585.

Vowles, A. S., P. Vezza, C. Manes, I. Garzia, and P. S. Kemp. 2025. “Response of Downstream Moving European Eel to Hydrodynamic Conditions Created by Channel Constrictions.” *Journal of Ecohydraulics*: 1–10.

Wagner, C. M., M. L. Jones, M. B. Twohey, and P. W. Sorensen. 2006. “A Field Test Verifies That Pheromones Can be Useful for Sea Lamprey (Petromyzon marinus) Control in the Great Lakes.” *Canadian Journal of Fisheries and Aquatic Sciences* 63, no. 3: 475–479.

Yang, C., Y. Zheng, Y. Zhang, and H. Luo. 2018. “A Review of Research on the Design of Fish-Friendly Hydraulic Turbines.” *Chinese Journal of Engineering Science* 20, no. 3: 96.