Underwater LED Light Guidance Devices

Requested by
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Executive Summary

Background

Caltrans is seeking information about underwater LED light guidance devices that could be used to improve the success of salmon and steelhead in migrating upstream of hydraulic grade control devices that are commonly used to improve fish passage at road-stream crossing barriers. These devices use LED or other types of light with specific color combinations, patterns or frequencies to either attract or repel fish. If effective, these devices could be used by Caltrans to attract salmon and steelhead to the entrance of fish access points such as ladders or other grade/velocity control devices, and repel resident or anadromous fish from work areas during construction activities.

To gather information for this Preliminary Investigation, CTC & Associates reviewed recently published domestic and international research and related resources that examine the use of underwater LED and other types of light to guide fish behavior. Contacts with selected experts and a review of commercially available light guidance devices supplemented the literature search results.

Summary of Findings

Literature Search Results

This report provides a sampling of recent research and related publications addressing the use of LED and other types of light to attract or repel different fish and fish families. A table, which begins on page 5, summarizes the publications highlighted in this Preliminary Investigation and is organized using the following categories:

Guidance Device

- LED light guidance (LED).
- Strobe light guidance (Strobe).
- Continuous, unspecified light guidance (Continuous).
- Other types of guidance devices (Other).

Note: Though some of the publications cited address the use of both LED and strobing lights, we present each publication only once in the table under a primary topic area.

Fish or Fish Family

- Multiple.
- Eel.
- Largemouth bass.
- Muskellunge.
- Rainbow smelt.
- Salmonid.
- Sturgeon.
- Walleye.

This table provides the publication title and year of publication; the type of guidance device; the fish or fish family examined in the research; a brief description of the research; and the page number where more detail about each publication can be found in the **Detailed Findings** section of this report. The table is organized by the type of guidance device and then by fish or fish family, beginning with the most recent research for each guidance device/fish category.

Consultation With Experts

We contacted four experts known to have experience with underwater LED light guidance devices.

Consulting Firms

We spoke with Paul Patrick, co-founder of ATET-Tech, Inc. (ATET), a Canadian environmental consulting company, and Doug Bradley, senior project scientist at LimnoTech, a Michigan environmental engineering and science firm, about fish light guidance devices generally and about modifications proposed for an ATET underwater light guidance device. Publications co-authored by Patrick that address the use of LED and other types of light to guide fish behavior are cited throughout this Preliminary Investigation.

Currently, ATET is working with LimnoTech to evaluate the modifications needed for programmability of ATET's light guidance device in the field, and for remote and portable applications. This evaluation is expected to produce the framework for a proof-of-concept underwater light guidance device that is portable, battery-powered and capable of being controlled remotely. Patrick and Bradley noted that if concept funding were available, it would allow for the immediate development of portable technologies for the ATET light guidance device.

University Researchers

We contacted two university researchers—Steven Cooke, director of Cooke Lab at Carleton University in Ottawa, Ontario, and Nann Fangue, director of Fangue Laboratory at University of California, Davis—by email to inquire about current research efforts and preliminary data that could be shared in advance of publication. Cooke reported that he had nothing to share in addition to the documents already published and the information available on his lab's web site. Cooke's recent publications examining the use of light and other guidance devices to guide fish behavior are cited throughout this Preliminary Investigation.

Fangue was unable to address our inquiry at the time of publication of this report and recommended that a follow-up contact be made after January 2019. Fangue's previous research has reviewed the effectiveness of underwater strobe lights in protecting juvenile Chinook salmon from entrainment into unscreened water-diversion pipes used for irrigation (see page 19). A project in progress that was conducted in collaboration with Cooke expands on Fangue's work with Chinook salmon and the use of LED light at diversion inlets to keep fish out. We were unable to identify an estimated publication date for Fangue's most recent findings at the time of publication of this report.

Commercial Light Guidance Products

Three commercial light guidance products are highlighted:

- ATET's light guidance device is described as using "red, green and blue LED light modules capable of producing different color combinations flashing at frequencies of 1 to

40 times per [second] to address species-specific responses of fish and other aquatic organisms."

- FishFlow Innovations, Inc., a company based in The Netherlands, has patented a fish deterrence device that uses strobe lights and consists of a number of glass-reinforced plastic or steel tubes containing LED lamps that shine outward through curved glass screens. The units are equipped with special lenses for better light projection.
- Fish Guidance Systems Ltd, a United Kingdom company, "offers a complete a range of behavioural systems for deflecting or guiding fish (including acoustic and light systems)." Among these systems is the Light Intensity Light Bar, which is typically used when fish need to be guided, when only a light system is required or on smaller intakes. The High Intensity Light Ring and Light Panel are used in larger applications, typically in conjunction with the company's sound projector.

Gaps in Findings

Nann Fangue, one the university researchers we contacted for this Preliminary Investigation, was unavailable to speak in detail about her most recent research efforts at the time of publication of this report. Future contacts may result in additional details about Fangue's ongoing research and future publications. Our contacts with ATET and LimnoTech indicated that ATET has not yet developed a proof-of-concept underwater light guidance device that is portable, battery-powered and capable of being controlled remotely. The availability of concept funding would allow for ATET's immediate development of portable technologies for its light guidance device.

Many of the researchers cited in this Preliminary Investigation have highlighted the need for additional field testing, including further research on site conditions and fish classes to determine how light and other guidance devices affect fish families and specific age classes of fish. Finally, there may be other commercially available light guidance devices similar to the three we cite in this report that may be of interest to Caltrans.

Next Steps

Moving forward, Caltrans could consider:

- Comparing and contrasting research findings by guidance device and fish or fish family to identify patterns or common themes for the fish of interest to Caltrans.
- Reviewing the types of fish guidance devices available commercially and used in research to determine those that might best fit Caltrans' needs.
- Consulting with ATET and LimnoTech to learn more about the possible development of a proof-of-concept portable light guidance device.
- Contacting Nann Fangue at University of California, Davis to learn more about her research and the future publication of research results.

Summary of Publications Cited by Guidance Device and Fish/Fish Family				
Publication (Year)	**Guidance Device**	**Fish or Fish Family**	**Description**	**For More Information**
Using an LED-Based Light to Guide Fish Behavior (2018)	LED	Multiple	Describes the LED light guidance device developed by ATET that uses red, green and blue light modules at different frequencies and in different combinations to guide fish behavior around hydroelectric power facility intakes.	10
Behavioural Guidance of Yellow-Stage American Eel *Anguilla rostrata* With a Light-Emitting Diode Device (2018)	LED	Eel	Uses a laboratory environment with a static water scenario to expose late, yellow-stage American eel to different colors and strobing frequencies of LED light. From the findings: • Eels entered the dark (control) side more often and for a longer duration compared to the illuminated side. • Blue light strobing at 30 Hz elicited the greatest initial avoidance response.	10
Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology (2017)	LED	Eel	Reviews the "world's primary and gray literature to evaluate one stimulus (light) and its potential for use in a downstream eel passage structure." Two types of lights—broad-spectrum white and narrow-spectrum blue—are recommended for testing because of eel-specific sensitivities.	11
The Behavioral Responses of a Warmwater Teleost to Different Spectra of Light-Emitting Diodes (2016)	LED	Largemouth bass	Tests the behavioral response of largemouth bass under 16 different LED color and light-pulse frequency combinations. Results suggest that colored light accompanied by light-pulse frequencies produced by LEDs can induce an avoidance response.	12
Behavioural Guidance of Chinook Salmon Smolts: The Variable Effects of LED Spectral Wavelength and Strobing Frequency (2018)	LED	Salmonid	Tests the movement and spatial response of fish to combinations of LED spectra (red, green, blue and white light) during the day and night, and strobing frequencies (constant and 2Hz) during the day. Primary result: Red light from the light guidance device had a moderate repulsive effect on Chinook smolts during the day but not during the night.	12
Characterization of Gatewell Orifice Lighting at the Bonneville Dam Second Powerhouse and Compendium of Research on Light Guidance with Juvenile Salmonids (2008)	LED	Salmonid	Presents general design guidelines for using artificial lighting to enhance the passage of juvenile salmonids into the collection channel at the Bonneville Dam second powerhouse. Recommends incorporating a ring of LEDs that would be recessed into the orifice opening.	13

Summary of Publications Cited by Guidance Device and Fish/Fish Family				
Publication (Year)	**Guidance Device**	**Fish or Fish Family**	**Description**	**For More Information**
Ontogeny of Light Avoidance in Juvenile Lake Sturgeon (2018)	LED	Sturgeon	Recommends for lake sturgeon moving at night: • Blue LED light strobing at 1 Hz for the attraction of the 1+ age class and white LED light strobing at 1 Hz for their repulsion. • Blue light or white light strobing at 1 Hz for repulsion of age 4+ fish.	13
Preferences of Age-0 White Sturgeon for Different Colours and Strobe Rates of LED Lights May Inform Behavioural Guidance Strategies (2018)	LED	Sturgeon	Exposes age-0 white sturgeon to light strobing at 1 Hz, 20 Hz or constant illumination with a range of colors (green, red and blue) under day and night conditions. From the findings: • Green light elicited the greatest rates of attraction overall. • More research is needed into how ambient light, light stimulus intensity, water flow, age, color and strobing rates might affect white sturgeon.	14
Group Behavioural Responses of Atlantic Salmon (*Salmo salar* L.) to Light, Infrasound and Sound Stimuli (2013)	LED, Other	Salmonid	Exposes sea-caged groups of 50 salmon to short-term exposure to visual or acoustic stimuli. In light experiments, fish were exposed to one of three intensities of blue LED light (high, medium and low) or no light (control). Light treatments reduced total echo-signal strength (indicative of swim bladder volume) after exposure to light.	20
Evaluating a Light-Louver System for Behavioural Guidance of Age-0 White Sturgeon (2017)	LED, Other	Sturgeon	Tests LED-based device equipped with adjustable wavelength and strobing output louver rack to assess behavior of age-0 white sturgeon through a bypass. Green light strobing at 20 Hz coupled with louver spacings of 10 or 20 cm achieved the highest rates of bypass usage (100% and 97%, respectively) under day and night conditions.	21
Stress Response and Avoidance Behavior of Fishes as Influenced by High-Frequency Strobe Lights (2007)	Strobe	Multiple	Examines the effects of strobe lights on plasma cortisol concentrations and avoidance behavior by evaluating five fish families. Direct observations of avoidance behavior revealed that largemouth bass, Chinook salmon and yellow perch were more sensitive to strobe lights than channel catfish and fathead minnow.	15
Behavioral Responses of Rainbow Smelt to In Situ Strobe Lights (2008)	Strobe	Rainbow smelt	Tests in situ strobe lights as a potential fish deterrent by examining avoidance and acclimation behaviors of rainbow smelt in Lake Oahe, South Dakota. Findings indicate strobe lights elicit behavioral avoidance and may aid in reducing entrainment losses through Oahe Dam.	15

Summary of Publications Cited by Guidance Device and Fish/Fish Family				
Publication (Year)	**Guidance Device**	**Fish or Fish Family**	**Description**	**For More Information**
Evaluation of Strobe Lights to Reduce Turbine Entrainment of Juvenile Steelhead (*Oncorhynchus mykiss*) at Cowlitz Falls Dam, Washington (2009)	Strobe	Salmonid	Conducts a radiotelemetry evaluation to determine if strobe lights could be used to decrease turbine entrainment of juvenile steelhead at Cowlitz Falls Dam, Washington. Results suggest that deployment location, exposure and flow are important variables that should be considered when evaluating strobe lights as a potential fish-deterring tool.	16
Chief Joseph Kokanee Enhancement Project: Strobe Light Deterrent Efficacy Test and Fish Behavior Determination at Grand Coulee Dam Third Powerplant Forebay (2005)	Strobe	Salmonid	Documents a four-year study to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee and rainbow trout at the entrance to the forebay of the third power plant at Grand Coulee Dam.	16
Efficacy of a Sensory Deterrent and Pipe Modifications in Decreasing Entrainment of Juvenile Green Sturgeon (*Acipenser medirostris*) at Unscreened Water Diversions (2014)	Strobe	Sturgeon	Tests a strobe light to determine its effectiveness in decreasing the entrainment of juvenile green sturgeon. Results indicate that strobe lights did not result in significant reductions in entrainment risk and did not alter the behavior of passing sturgeon. Researchers suggest considering the physiology, ecology and sensory capabilities of the fish when designing fish deterrents.	17
Laboratory Investigations on the Use of Strobe Lights and Bubble Curtains to Deter Dam Escapes of Age-0 Muskellunge (2014)	Strobe, Other	Muskellunge	Examines the effectiveness of a bubble curtain, strobe light and bubble curtain with strobe light barriers to deter muskellunge from escaping over spillways.	19
Can Behavioral Fish-Guidance Devices Protect Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) From Entrainment Into Unscreened Water-Diversion Pipes? (2014)	Strobe, Other	Salmonid	Tests entrainment susceptibility and behavior of juvenile Chinook salmon in a large-river-simulation flume. Entrainment increased by 61% (day) and 43% (night) when underwater strobe lights were active; decreased by 30% when using a metal vibrating (12 Hz) ring during the night; and was unaffected by velocity cap attachments.	19

Summary of Publications Cited by Guidance Device and Fish/Fish Family				
Publication (Year)	**Guidance Device**	**Fish or Fish Family**	**Description**	**For More Information**
Using a Non-Physical Behavioural Barrier to Alter Migration Routing of Juvenile Chinook Salmon in the Sacramento-San Joaquin River Delta (2014)	Strobe, Other	Salmonid	Evaluates a bioacoustic fish fence (BAFF) composed of strobe lights, sound and a bubble curtain that was intended to divert juvenile Chinook salmon away from a low-survival migration route that branches off the Sacramento River. Overall, 7.7% of the fish were entrained into Georgiana Slough when the BAFF was on, and 22.3% were entrained when the BAFF was off.	20
Laboratory Evaluation of a Bioacoustic Bubble Strobe Light Barrier for Reducing Walleye Escapement (2014)	Strobe, Other	Walleye	Evaluates the effectiveness of a bioacoustic bubble-strobe light barrier at reducing walleye escapement rates in reservoirs. Recommends evaluation of alternative nonphysical barriers for their potential to further increase retention of walleyes.	22
Effects of Light on the Behaviour of Brown Trout (*Salmo trutta*) Encountering Accelerating Flow: Application to Downstream Fish Passage (2012)	Continuous, Other	Salmonid	Assesses effects of a continuous light source on the downstream movement of brown trout as they encountered accelerating velocities created by a constricted channel in an experimental flume under three discharge regimes. Findings indicate that responsiveness (avoidance) can be enhanced when multimodal stimuli are presented.	21
Non-Physical Barriers to Deter Fish Movements (2012)	Multiple	Multiple	Examines the use and application of electrical, visual, acoustic, chemical and hydrological deterrence techniques that may be used to prevent fish movements. A table presents a summary of different nonphysical barriers that includes deployment conditions, advantages and disadvantages, and a representative citation showing each barrier type in use.	18
Sensory Deterrent Systems (2012)	Multiple	Multiple	Describes small- and large-scale deterrent systems, including the use of strobe lights.	18

Detailed Findings

Background

Caltrans is seeking information about underwater LED light guidance devices that could be used to improve the success of salmon and steelhead in migrating upstream of hydraulic grade control devices that are commonly used to improve fish passage at road-stream crossing barriers. These devices use LED or other types of light with specific color combinations, patterns or frequencies to either attract or repel fish. If effective, these devices could be used by Caltrans to:

- Attract salmon and steelhead to the entrance of fish access points such as ladders or other grade/velocity control devices to help improve the effectiveness of the device by increasing the fish's ability to locate the device more quickly, thereby reducing the effort or energy that the fish would spend trying to locate a path upstream.
- Repel resident or anadromous fish from work areas during construction activities such as isolation, dewatering and impact pile driving. Underwater LED devices that are effective in repelling fish from work areas will help Caltrans improve or achieve avoidance and minimization at a relatively low cost and without additional construction schedule disruptions.

A review of recent publicly available domestic and international literature identified publications in three topic areas:

- LED light guidance.
- Strobe light guidance.
- Light used with other barrier or guidance systems.

We also present the results of email and phone contacts with selected experts with experience in the use of underwater light guidance devices to attract or repel fish. Summaries of these contacts are followed by information about some of the commercial light guidance products currently available.

LED Light Guidance

The domestic and international research described below that examines the use of LED light to guide fish behavior is organized by the type of fish examined in the cited research, including:

- General fish behavior.
- Eel.
- Largemouth bass.
- Salmonid.
- Sturgeon.

General Fish Behavior

Note: The article cited below briefly describes an underwater light guidance device developed by ATET-Tech, Inc. (ATET), a Canadian environmental consulting company. Additional information about this device appears in **Consultation With Experts**, on page 23, and in **Commercial Light Guidance Products**, on page 26.

"Using an LED-Based Light to Guide Fish Behavior," Paul H. Patrick and A. Michael Sills, *Hydro Review,* Vol. 37, No. 5, June 2018.
https://www.hydroworld.com/articles/hr/print/volume-37/issue-5/articles/using-an-led-based-light-to-guide-fish-behavior.html
This brief article describes the LED light guidance device developed by ATET. The device uses red, green and blue light modules at different frequencies and in different combinations to guide fish behavior around hydroelectric power facility intakes. As the authors note, research results indicate different responses based on fish species and age. Next steps are summarized as the article concludes:

> The next steps are to evaluate the LGD [light guidance device] technology in the field; specifically to improve downstream fish movement away from turbines and toward a fish bypass. We also need to measure the spectral output of the LGD in the field, especially for different water bodies. In addition, LGD could be tested as an attractant to improve fish passage at upstream facilities. These tests will be necessary to understand the full usefulness of this tool.

Eel

"Behavioural Guidance of Yellow-Stage American Eel *Anguilla rostrata* With a Light-Emitting Diode Device," Chris K. Elvidge, Matthew I. Ford, Thomas C. Pratt, Karen E. Smokorowski, Michael Sills, Paul H. Patrick and Steven J. Cooke, *Endangered Species Research*, Vol. 35, pages 159-168, March 2018.
https://www.int-res.com/articles/esr2018/35/n035p159.pdf
Researchers exposed late, yellow-stage American eel to different colors and strobing frequencies of LED light and to unlit control trials in y-maze dichotomous choice tests. The research was completed in a laboratory environment using a static water scenario, and researchers noted that "[e]els tend to move downstream in the highest water velocities during

elevated spring discharges, and velocity can influence the effectiveness of light as a guidance tool, not only for eels but for other fish species as well." Highlighted below are some of the project's key findings:

- Eels demonstrated initial attraction toward the y-maze structure and entered the dark (control) side more often and for a longer duration compared to the illuminated side.
- Blue light strobing at 30 Hz elicited the greatest initial avoidance response, and eels spent less time on the light side with this treatment. Researchers recommend testing this setting under field conditions. As the researchers noted, "[t]he improved deterrence in our study at 30 Hz suggests that there may be guidance advantages to strobing light, in addition to other potential benefits including less attraction for other fishes and lower energy costs."
- Although the initial avoidance of all light settings attenuated over the 5-minute observations, this attenuation may be less relevant when eels are engaged in active migration, and LED lights may provide a viable means of guiding eels to safe outmigration paths.
- Future research on the use of LED lights should be scaled up and implemented under more natural settings.

Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology, 2017 Technical Report, Electric Power Research Institute, February 2017.
https://publicdownload.epri.com/PublicDownload.svc/product=000000003002009407/type=Product
Prepared by an "independent, nonprofit organization for public interest energy and environmental research," this report "reviews the world's primary and gray literature to evaluate one stimulus (light) and its potential for use in a downstream eel passage structure." This summary report is described as summarizing "all known work between 2007 and 2015," and also sought information from the "world's known eel research participants" to identify unpublished information for inclusion in the report. The executive summary, which begins on page 9 of the PDF, highlights the report's key findings:

- Multiple reports have shown that light is a stimulus that is likely to produce an effective behavioral eel guidance structure for the St. Lawrence River (Section 3.1.1.1).
- Three relevant studies have been completed since 2007, two of which show that LED strobe lights can be used as an effective silver eel guidance stimulus in field situations (Section 3.2).
- Two types of lights—broad-spectrum white and narrow-spectrum blue—are recommended for testing because of eel-specific sensitivities (Section 1.3.3).
- LED lights are recommended for further testing because they would be less expensive than xenon or other types of strobe lights, can incorporate UV anti-biofouling diodes to reduce cleaning requirements, can be operated in continuous or flashing mode, and their flash characteristics are highly flexible and could be programmed to vary within a 24-hour period or by season to improve visibility, reduce habituation and reduce effects on other fish species (Sections 3.2.5.3 and 3.3.7.5).

Readers are advised on how to apply the results described in the report, with the authors noting that "[t]his report identifies information gaps and existing information that can inform future research and development (R&D) activities to develop light-based behavioral eel guidance structures for the St. Lawrence River and other large rivers. The report also identifies limitations of light for eel guidance that may constrain application of light as a behavioral stimulus."

Largemouth Bass

"The Behavioral Responses of a Warmwater Teleost to Different Spectra of Light-Emitting Diodes," Brittany G. Sullivan, Alexander D.M. Wilson, Lee F.G. Gutowsky, Paul H. Patrick, Michael Sills and Steven J. Cooke, *North American Journal of Fisheries Management,* Vol. 36, No. 5, pages 1000-1005, October 2016.
Citation at https://afspubs.onlinelibrary.wiley.com/doi/abs/10.1080/02755947.2016.1141123
From the abstract: Freshwater ecosystems are threatened by a wide range of anthropogenic infrastructure related to hydropower, irrigation, municipal withdrawals and industrial cooling. Technology can be used to mitigate the loss of fish associated with such infrastructure by exploiting the sensory physiology of a species through stimuli designed to manipulate their natural behaviors (e.g., to attract or repel). Technologies used for behavioral guidance often incorporate light; however, previous studies investigating light devices have focused on mercury vapor bulbs and thus have been limited in their exploration of the broader light spectra. Innovations in light-emitting diode (LED) technology provide opportunities for manipulating light spectra (i.e., color) as well as light-pulse frequency. We tested the behavioral response of Largemouth Bass *Micropterus salmoides* under 16 different LED color and light-pulse frequency combinations as well as in a control in which no light was emitted. Red, orange, yellow and green were considered with four light-pulse frequencies (0, 120, 300 and 600 pulses/min). Using a large shallow arena, lateral fish movement in response to the light treatments was examined. Regardless of color or light-pulse frequency, fish were repelled by the light source. In contrast, when there was no light emitted, fish were evenly distributed throughout the arena. This work suggests that colored light accompanied with light-pulse frequencies produced by LEDs can induce an avoidance response in Largemouth Bass.

Salmonid

"Behavioural Guidance of Chinook Salmon Smolts: The Variable Effects of LED Spectral Wavelength and Strobing Frequency," Matthew J. Hansen, Dennis E. Cocherell, Steven J. Cooke, Paul H. Patrick, Michael Sills and Nann A. Fangue, *Conservation Physiology*, Vol. 6, No. 1, June 2018.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6016652/pdf/coy032.pdf
In the article's abstract, researchers noted that "[w]hilst there is some evidence that white light can be an effective deterrent for Chinook salmon smolts, the results have been mixed. There is a need to test the response of fish to different spectra and strobing frequencies to improve deterrent performance." Using a laboratory setting, researchers tested the "movement and spatial response of groups of four fish to combinations of light-emitting diode (LED) spectra (red, green, blue and white light) during the day and night, and strobing frequencies (constant and 2Hz) during the day, using innovative LED technology" intended as a guidance device for use in the field.

The article's discussion describes the project's most significant findings:

- The primary result is that the red light from the light guidance device had a moderate repulsive effect on Chinook smolts during the day but not during the night.
- While there was some evidence that the blue and green lights may attract the attention of Chinook smolts during the day (fish spent the highest amount of time closest to the light guidance device under these light treatments), there was no effect of different spectra during the night. More studies manipulating light intensity along with spectral frequency are needed.
- Strobing a spectrum at 2 Hz made no significant difference.

Characterization of Gatewell Orifice Lighting at the Bonneville Dam Second Powerhouse and Compendium of Research on Light Guidance with Juvenile Salmonids, R.P. Mueller and M.A. Simmons, Portland District, U.S. Army Corps of Engineers, September 2008.
https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-17210.pdf
From the overview:

> The goal of the study described in this report was to provide U.S. Army Corps of Engineers (USACE) biologists and engineers with general design guidelines for using artificial lighting to enhance the passage of juvenile salmonids into the collection channel at the Bonneville Dam second powerhouse (B2). The study was conducted during fall 2007 by researchers at the Pacific Northwest National Laboratory (PNNL) for the USACE Portland District.

The report's recommendations, which begin on page 3.1 of the report (page 40 of the PDF), include the following options for improving the lighting at the orifice entrances at the B2:

1. Incorporate a ring of LEDs that would be recessed into the orifice opening, thus eliminating the need for the light tubes. An automated cleaning system would also be required.
2. Incorporate the light source into the lens cap so that the cap and light housing is one waterproof unit. This would allow for all of the light to be directed into the light tube and eliminate the water scaling and debris-buildup issue, although water buildup could still pose a problem due to the splashing of water upward into the light tubes. Cleaning of the light and cap assembly also would be simplified.
3. Incorporate higher-intensity LED lamps. Several manufacture[r]s have developed high output LEDS which have been used in a variety of applications including automotive, flashlights, interior and exterior lighting and many industrial applications. These relatively new modules provide almost 50% more light (some up to 250 lux) than a standard 5-W LED bulb. The cool white version [has] an expected 50,000-hour lifespan and [has] peak wavelengths of 440 and 550 nm [nanometer, equal to one billionth of a meter].

The authors recommend testing to evaluate the effectiveness of modifications made to the existing system:

> Tests could be conducted in which tagged fish are released in the gatewell with a light on/off scenario and the OPE [orifice passage efficiency] evaluated. Different lighting could be used to test to determine if white light or light emitted within the peak action spectra of juvenile salmonids (blue-green region) is best for attracting fish near the orifice where the flow component is sufficient for entrainment into the collection channel.

Sturgeon

"Ontogeny of Light Avoidance in Juvenile Lake Sturgeon," Chris K. Elvidge, Connor H. Reid, Matthew I. Ford, Michael Sills, Paul H. Patrick, Dan Gibson, Stephanie Backhouse and Steven J. Cooke, *Journal of Applied Ichthyology*, October 2018 (online version of record before inclusion in an issue).
Citation at https://doi.org/10.1111/jai.13822
From the abstract: Hatchery-reared age 1+ and 4+ lake sturgeon (*Acipenser fulvescens*) were assayed to determine the effectiveness of coloured, strobing LED light guidance device (LGD) at achieving behavioural guidance for attraction or avoidance responses. Based on an initial y-maze dichotomous choice study in age 1+ fish during daytime, we selected green, blue, orange and full-spectrum white light, all strobing at 1 Hz, for further testing. During nighttime light guidance trials, age 1+ sturgeon demonstrated the fastest entries and greatest proportion

of entries to the cone of illumination in the experimental raceway when the LGD was producing blue light, and the lowest proportion of entries in response to orange light. Conversely, they also spent the greatest amounts of time under illumination during orange light trials. Blue light was associated with the greatest proportion and total numbers of complete passages through the illuminated zone, although passage rates through this area were observed during the unilluminated control trials. White light resulted in the least time spent in the illuminated zone, and the lowest rates of passage. Under the nighttime testing scenario, the age 4+ sturgeon, by contrast, demonstrated strong avoidance of blue light and white light. While their behaviour was negatively phototactic in general, orange light was the least repulsive. For the behavioural guidance of lake sturgeon moving at night, we recommend the use of blue light strobing at 1 Hz for the attraction of the 1+ age class and white light strobing at 1 Hz for their repulsion. For age 4+ fish, we recommend the use of blue light or white light strobing at 1 Hz for repulsion and caution that (a) light as a behavioural guidance tool appears most effective as a repulsive stimulus, and (b) further testing under both laboratory and field conditions are required.

"Preferences of Age-0 White Sturgeon for Different Colours and Strobe Rates of LED Lights May Inform Behavioural Guidance Strategies," Matthew I. Ford, Chris K. Elvidge, Dan Baker, Thomas C. Pratt, Karen E. Smokorowski, Michael Sills, Paul Patrick and Steven J. Cooke, *Environmental Biology of Fishes,* Vol. 101, No. 4, pages 667-674, 2018. https://www.fecpl.ca/wp-content/uploads/2017/12/10.1007_s10641-018-0727-1.pdf
Using a new programmable LED-based light guidance device, researchers exposed age-0 white sturgeon to light strobing at 1 Hz, 20 Hz or constant illumination with a range of colors (green, red and blue). Behavioral responses of the sturgeon were assessed using y-maze dichotomous choice tests under day and night conditions. The following findings are highlighted in the article abstract:

- Sturgeon demonstrated positive phototaxis (the movement toward or away from a source of light) under both day and night conditions, and approached the light guidance device more often when light was continuous or strobing at 20 Hz compared to strobing at 1 Hz.
- Green light elicited the greatest rates of attraction overall.
- The combination of strobing and color may help to protect imperiled fish from waterway development and serve as an effective form of mitigation at hydropower facilities and other human infrastructure where fish may be entrained or impinged.

The authors' discussion, which begins on page 671 or the article (page 7 of the PDF), addresses the need for additional research:

- More research is needed into how ambient light, light stimulus intensity, water flow, age, color and strobing rates might affect white sturgeon for field applications and conservation management, including how these light parameters influence other fish species that would encounter these devices to limit any negative impacts.
- The application of an LED-based light guidance device could significantly improve sturgeon survival and aid in management of populations at risk, particularly if used in combination with other physical (see Ford et al. 2017 for an evaluation of an integrated light-louver rack array system) or non-physical technologies.
- Additional benefits of using LED technology include stable output spectra, lower power requirements, lower operational costs, and possibilities of remote installations using alternative energy sources.

Strobe Light Guidance

The domestic and international research described below that examines the use of strobe lights to guide fish behavior is organized by the type of fish examined in the cited research, including:

- Multiple species.
- Rainbow smelt.
- Salmonid.
- Sturgeon.

Multiple Species

"Stress Response and Avoidance Behavior of Fishes as Influenced by High-Frequency Strobe Lights," Nathan S. Richards, Steven R. Chipps and Michael L. Brown, *North American Journal of Fisheries Management,* Vol. 27, No. 4, pages 1310-1315, November 2007.
Citation at https://afspubs.onlinelibrary.wiley.com/doi/pdf/10.1577/M06-239.1
From the abstract: We examined the effects of strobe lights on plasma cortisol concentrations and avoidance behavior across a broad range of fish taxa. Representative fish taxa from five families were evaluated and included: Centrarchidae (largemouth bass *Micropterus salmoides*), Cyprinidae (fathead minnow *Pimephales promelas*), Ictaluridae (channel catfish *Ictalurus punctatus*), Percidae (yellow perch *Perca flavescens*), and Salmonidae (Chinook salmon *Oncorhynchus tshawytscha*). Mean (±SE) plasma cortisol concentrations for channel catfish (89 ± 22 ng/mL), yellow perch (81 ± 39 ng/mL), and Chinook salmon (173 ± 27 ng/mL) increased significantly compared with those in control groups (50 ± 11, 3.0 ± 1.9, and 102 ± 35 ng/mL, respectively) after 1 h[our] of exposure to strobe lights. After 7 h of exposure, plasma cortisol levels were similar to those in control groups for all fish taxa. Fathead minnow showed no detectable response to strobe lights at either 1 or 7 h of exposure. Behavior experiments showed that the mean distance moved from the strobe light varied significantly between test and control fish and was highest for largemouth bass (mean distance after 1 h = 8.3 m), followed by Chinook salmon (7.3), yellow perch (7.3), and channel catfish (5.1). In contrast, avoidance behavior by fathead minnow exposed to strobe lights did not differ from that of controls. Although a significant increase in plasma cortisol level was useful for predicting an avoidance response, relative change in cortisol concentration was a poor indicator of sensitivity of individual fish taxa to strobe lights. Direct observations of avoidance behavior revealed that largemouth bass, Chinook salmon and yellow perch were more sensitive to strobe lights than channel catfish and fathead minnow. Lack of both a cortisol response and avoidance behavior by fathead minnow indicates low sensitivity of this species to strobe lights and warrants further investigation into the effectiveness of strobe lights on cyprinids [family of fish that includes fathead minnows].

Rainbow Smelt

"Behavioral Responses of Rainbow Smelt to In Situ Strobe Lights," Martin J. Hamel, Michael L. Brown and Steven R. Chipps, *North American Journal of Fisheries Management*, Volume 28, pages 394-401, 2008.
Citation at https://doi.org/10.1577/M06-254.1
From the abstract: We conducted in situ testing of strobe lights as a potential fish deterrent by examining avoidance and acclimation behaviors of rainbow smelt *Osmerus mordax* in Lake Oahe, South Dakota. Split-beam hydroacoustics were used to assess the effectiveness of the

deterrent system by comparing proximal densities of rainbow smelt before and after the device was activated. In summer 2005, strobe lights successfully repelled rainbow smelt to a minimum horizontal distance of 21 m[eters] at both 1 h and 4 h postactivation; the model AGL-FH 920 flashhead produced a light intensity of 6,585 lumens per flash. Similarly in 2004, a model AGL-FH 901 flashhead, which produced a light intensity of 2,634 lumens per flash, repelled rainbow smelt to a horizontal distance of 15 m. A comparison of strata 10 m above and below the strobe light system showed that rainbow smelt were vertically displaced to approximately 6 m. We conclude that strobe lights elicit behavioral avoidance by rainbow smelt and may provide an effective means for reducing entrainment losses through Oahe Dam.

Salmonid

"Evaluation of Strobe Lights to Reduce Turbine Entrainment of Juvenile Steelhead (*Oncorhynchus mykiss*) at Cowlitz Falls Dam, Washington," Tobias J. Kock, Scott D. Evans, Theresa L. Liedtke, Dennis W. Rondorf and Mike Kohn, *Northwest Science,* Vol. 83, No. 4, pages 308-314, 2009.
Citation at
https://www.researchgate.net/publication/258110292_Evaluation_of_Strobe_Lights_to_Reduce_Turbine_Entrainment_of_Juvenile_Steelhead_Oncorhynchus_mykiss_at_Cowlitz_Falls_Dam_Washington
From the abstract: We conducted a radiotelemetry evaluation to determine if strobe lights could be used to decrease turbine entrainment of juvenile steelhead (*Oncorhynchus mykiss*) at Cowlitz Falls Dam, Washington. We found that radio-tagged juvenile steelhead approached and entered two spillbays (one lighted, one unlighted) in equal proportions. However, the presence of strobe lights was associated with decreased spillbay residence time of juvenile steelhead and increased passage through induction slots (secondary turbine intakes located upstream of the ogee on the spillway). Mean residence time of tagged fish inside the lighted spillbay was 14 min[utes] compared to 62 min inside the unlighted spillbay. Radio-tagged steelhead passed through induction slots at a higher proportion in the lighted spillbay (55%) than in the unlighted spillbay (26%). Recent studies have suggested that strobe lights can induce torpor in juvenile salmonids. We believe that strobe light exposure affected fish in our study at a location where they were susceptible to high flows thereby reducing mean residence time and increasing the proportion of tagged fish entering induction slots in the lighted spillbay. Our results suggest that factors such as deployment location, exposure, and flow are important variables that should be considered when evaluating strobe lights as a potential fish-deterring management tool.

Chief Joseph Kokanee Enhancement Project: Strobe Light Deterrent Efficacy Test and Fish Behavior Determination at Grand Coulee Dam Third Powerplant Forebay, R.L. Johnson, M.A. Simmons, C.A. McKinstry, C.S. Simmons, C.B. Cook, R.S. Brown, D.K. Tano, S.L. Thorsten, D.M. Faber, R. LeCaire and S. Francis, Bonneville Power Administration, U.S. Department of Energy, February 2005.
https://www.osti.gov/servlets/purl/962012
From the summary: This report documents a four-year study to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee (*Oncorhynchus nerka kennerlyi*) and rainbow trout (*O. mykiss*) at the entrance to the forebay of the third powerplant at Grand Coulee Dam. The work was conducted for the Bonneville Power Administration, U.S. Department of Energy, by Pacific Northwest National Laboratory (PNNL) in conjunction with the Confederated Tribes of the Colville Reservation (Colville Confederated Tribes).

Sturgeon

"Efficacy of a Sensory Deterrent and Pipe Modifications in Decreasing Entrainment of Juvenile Green Sturgeon (*Acipenser medirostris*) at Unscreened Water Diversions,"
Jamilynn B. Poletto, Dennis E. Cocherell, Timothy D. Mussen, Ali Ercan, Hossein Bandeh, M. Levent Kavvas, Joseph J. Cech, Jr. and Nann A. Fangue, *Conservation Physiology*, Vol. 2, 2014.
https://academic.oup.com/conphys/article-pdf/2/1/cou056/945760/cou056.pdf
Researchers noted that many anadromous fish species are susceptible to entrainment into water diversions constructed to extract fresh water from a watershed for local urban, industrial and agricultural use. Many of these water diversions are unscreened. In this research, a strobe light was tested to determine its effectiveness in decreasing the entrainment of juvenile green sturgeon (mean mass ± SEM = 162.9 ± 4.0 g; mean fork length = 39.4 ± 0.3 cm) in a large (>500 kl) outdoor flume fitted with a water-diversion pipe 0.46 m in diameter. *From the article's discussion*:

> In contrast, the sensory deterrent tested (the use of strobe lights) did not result in significant reductions in entrainment risk and did not alter the behaviour of passing sturgeon. Therefore, we suggest that empirical investigations into the efficacy of fish-passage devices or sensory deterrents be completed for each target species prior to the implementation of such devices on water diversions. Our results suggest that affordable and effective fish deterrents can be designed when the physiology, ecology and sensory capabilities of the fish are considered.

Light Used With Other Barrier or Guidance Systems

The domestic and international research described below that examines the effectiveness of light used in conjunction with other barrier or guidance systems is organized by the type of fish examined in the cited research:

- Multiple species/multiple barrier systems.
- Muskellunge.
- Salmonid.
- Sturgeon.
- Walleye.

Multiple Species/Multiple Barrier Systems

Note: The two publications below describe multiple types of barrier systems, including light, and their application across multiple fish species.

"Non-Physical Barriers to Deter Fish Movements," Matthew R. Noatch and Cory D. Suski, *Environmental Review*, Vol. 20, pages 1-12, 2012.
http://fishlab.nres.illinois.edu/Reprints/Noatch_Suski_2012.pdf
The authors examine 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."

Table 1 on page 8 of the article presents a summary of different nonphysical barriers that could be implemented to deter the movement of fish. This table includes deployment conditions, advantages and disadvantages, and a representative citation showing each barrier type in use. Barrier types include electricity, strobe lights, sound, bubble curtains (a fence or curtain of bubbles emitted from air diffusers placed along the bottom perpendicular to the channel), water velocity, hypoxia (oxygen deficiency) and hypercapnia (excessive carbon dioxide), pheromones (secreted chemical odors that elicit a specific behavioral response from a member of the same species), chlorine and electromagnetism.

The authors recommend that future researchers focus on validating and optimizing deterrent strategies in controlled environments that allow for standardization, comparison and manipulation prior to field deployments. They also recommend additional effort to quantify deterrent effectiveness through methods such as biotelemetry or sonar in a laboratory or field setting to noninvasively monitor fish position or behavior during trials.

Sensory Deterrent Systems, U.S. Army Corps of Engineers, April 2012.
http://glmris.anl.gov/documents/docs/anscontrol/SensoryDeterrentSystems.pdf
This eight-page fact sheet addresses a range of sensory deterrent systems, including acoustic air bubble curtains, electrical barrier, underwater sound and underwater strobe lights. Included are descriptions of prior applications, a brief listing of relevant citations and an assessment of general effectiveness. *An example from the document*:

Underwater Strobe Lights – Strobe lights are a widely used type of lighting for fish control. Strobe lights produce flashes of light at rapid rates, depending on the target species and scale of the water body and light installation. Large scale systems commonly consist of four individual lights that flash at a rate of 450 flashes/minute, and have an approximate light intensity of 2634 lumens/flash. This type of system uses xenon gas tubes, which emit broad spectrum white light. Small scale systems can consist of an individual cylindrical strobe light (0.16 m length by 0.04 m diameter) with a flash rate of only 86 flashes/minute. Both systems have been shown to alter fish movements in both experimental and field settings for a variety of fish species.

Muskellunge

"Laboratory Investigations on the Use of Strobe Lights and Bubble Curtains to Deter Dam Escapes of Age-0 Muskellunge," Heather A. Stewart, Max H. Wolter and David H. Wahl, *North American Journal of Fisheries Management*, Vol. 34, No. 3, page 571-575, June 2014.
Citation at https://afspubs.onlinelibrary.wiley.com/doi/abs/10.1080/02755947.2014.892549
From the abstract: The movement of Muskellunge *Esox masquinongy* over a dam to leave a reservoir is known as dam escape. It is common in Midwestern U.S. reservoirs and has been as high as 25% of the adult population. A variety of barrier and guidance systems have been used to control fish movement, but the success of such barriers has been mixed and appears to be very species dependent. We examined the effectiveness of a simple, relatively low-power and low-cost bubble curtain, strobe light, and bubble curtain with strobe light barriers to deter Muskellunge from escaping over spillways. In 15 replicate trials of each treatment type conducted in a simulated spillway, age-0 Muskellunge were more likely to escape during daytime trials ($P < 0.01$), but the three barrier combinations did not reduce rates of escape. Light and bubble curtain barriers will likely not be effective in reducing spillway escapes by Muskellunge.

Salmonid

"Can Behavioral Fish-Guidance Devices Protect Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) from Entrainment Into Unscreened Water-Diversion Pipes?" Timothy D. Mussen, Oliver Patton, Dennis Cocherell, Ali Ercan, Hossein Bandeh, M. Levent Kavvas, Joseph J. Cech Jr. and Nann A. Fangue, *Canadian Journal of Fisheries and Aquatic Sciences,* Vol. 71, No. 8, pages 1209-1219, 2014.
Citation at http://dx.doi.org/10.1139/cjfas-2013-0601
From the abstract: Entrainment through water-diversion structures is a major passage challenge for fishes in watersheds worldwide. Behavioral guidance devices may be effective in passing fish by diversion inlets, thereby decreasing entrainment without reducing water-diversion rates, but data on their effectiveness is limited. In California's central valley, out-migrating Chinook salmon (*Oncorhynchus tshawytscha*) [is] a species at risk for entrainment through unscreened, small-scale water-diversion pipes. Therefore, we tested entrainment susceptibility and behavior of juvenile Chinook salmon in a large-river-simulation flume at a "river" velocity of 0.15 $m \cdot s^{-1}$ with a 0.46 m diameter pipe diverting water at 0.57 $m^3 \cdot s^{-1}$, during the day and night. Compared with control conditions (no fish deterrent devices present), mean fish entrainment increased by 61% (day) and 43% (night) when underwater strobe lights were active, decreased by 30% when using a metal vibrating (12 Hz) ring during the night, and was unaffected by velocity cap attachments.

"Using a Non-Physical Behavioural Barrier to Alter Migration Routing of Juvenile Chinook Salmon in the Sacramento-San Joaquin River Delta," R.W. Perry, J.G. Romine, N.S. Adams, A.R. Blake, J.R. Burau, S.V. Johnston and T.L. Liedtke, *River Research and Applications*, Vol. 30, No. 2, pages 192-203, February 2014.
https://www.researchgate.net/publication/263304251_Using_a_non-physical_behavioral_barrier_to_alter_migration_routing_of_juvenile_Chinook_salmon_in_the_Sacramento-San_Joaquin_River_Delta
Using the Sacramento–San Joaquin River Delta as the site for their research, this research team "evaluated a bio-acoustic fish fence (BAFF) composed of strobe lights, sound and a bubble curtain, which was intended to divert juvenile Chinook salmon (*Oncorhynchus tshawytscha*) away from Georgiana Slough, a low-survival migration route that branches off the Sacramento River." Researchers estimated individual entrainment probabilities from two-dimensional movement paths of juvenile salmon implanted with acoustic transmitters. Findings include:

- Overall, 7.7 percent of the fish were entrained into Georgiana Slough when the BAFF was on, and 22.3 percent were entrained when the BAFF was off.
- A number of other factors influenced BAFF performance. For example, BAFF effectiveness declined with increasing river discharge, likely due to increased water velocities that reduced the ability of fish to avoid being swept across the BAFF into Georgiana Slough.
- The BAFF reduced entrainment probability by up to 40 percentage points near the critical streakline. (A streakline is a particular point in space that has fluid moving past it, which in this case is each channel.)
- The effect of the BAFF declined moving in either direction away from the critical streakline.
- Careful monitoring in the field can aid in quantifying factors affecting performance of nonphysical barriers and provide critical information for their design and implementation.

"Group Behavioural Responses of Atlantic Salmon (*Salmo salar* L.) to Light, Infrasound and Sound Stimuli," Samantha Bui, Frode Oppedal, Øyvind J. Korsøen, Damien Sonny and Tim Dempster, *PLoS One,* Vol. 8, No. 5, May 2013.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3656933/pdf/pone.0063696.pdf
From the abstract: We examined the reactions of sea-caged groups of 50 salmon (1331±364 g) to short-term exposure to visual or acoustic stimuli. In light experiments, fish were exposed to one of three intensities of blue LED light (high, medium and low) or no light (control). Sound experiments included exposure to infrasound (12 Hz), a surface disturbance event, the combination of infrasound and surface disturbance, or no stimuli. Groups that experienced light, infrasound, and the combination of infrasound and surface disturbance treatments, elicited a marked change in vertical distribution, where fish dived to the bottom of the sea-cage for the duration of the stimulus. Light treatments, but not sound, also reduced the total echo-signal strength (indicative of swim bladder volume) after exposure to light, compared to pre-stimulus levels. Groups in infrasound and combination treatments showed increased swimming activity during stimulus application, with swimming speeds tripled compared to that of controls. In all light and sound treatments, fish returned to their pre-stimulus swimming depths and speeds once exposure had ceased. This work establishes consistent, short-term avoidance responses to these stimuli, and provides a basis for methods to guide fish for aquaculture applications, or create avoidance barriers for conservation purposes.

Note: The abstract for the research cited below does not specify the type of light when describing the use of a continuous light source to guide the behavior of brown trout moving downstream.

"Effects of Light on the Behaviour of Brown Trout (*Salmo trutta*) Encountering Accelerating Flow: Application to Downstream Fish Passage," Andrew S. Vowles and Paul S. Kemp, *Ecological Engineering,* Vol. 47, pages 247-253, October 2012.
Citation at https://doi.org/10.1016/j.ecoleng.2012.06.021
From the abstract: The influence of a continuous light source on the downstream movement of brown trout (*Salmo trutta*) as they encountered accelerating velocities created by a constricted channel in an experimental flume under three discharge regimes was assessed. It was predicted that: (1) in the absence of a light source, behavioural responses typical of downstream moving salmonids would be elicited on encountering velocity gradients, and that these responses would be initiated at some threshold spatial velocity gradient relative to body length and (2) light would act as an attractant and mask the deterrent effects of a velocity gradient and thus reduce delay. Typical avoidance behaviours, e.g. rheotactic switches in orientation or retreating upstream before re-approaching a velocity gradient, were common. The spatial velocity gradient threshold at which a response was initiated when dark was similar (ca. 0.4 cm s^{-1} cm^{-1}) independent of discharge. Fish responded farther upstream at a lower spatial velocity gradient threshold (ca. 0.2 cm s^{-1} cm^{-1}) in the presence of both mechanosensory and visual cues when light. Contrary to the second prediction, downstream movement was further delayed by the addition of a light stimulus. The findings support an alternate hypothesis, that responsiveness (avoidance) can be enhanced when multimodal stimuli are presented.

Highlights:

- The behaviour of downstream moving brown trout was assessed.
- When encountering accelerating flow, trout exhibited avoidance responses.
- Responses occurred at the same spatial velocity gradient irrespective of discharge.
- A light source was used to try and mask the deterrent [e]ffects of accelerating flow.
- Contrary to predictions delay was enhanced when encountering multimodal stimuli.

Sturgeon

"Evaluating a Light-Louver System for Behavioural Guidance of Age-0 White Sturgeon," M.I. Ford, C.K. Elvidge, D. Baker, T.C. Pratt, K.E. Smokorowski, P. Patrick, M. Sills and S.J. Cooke, *River Research and Applications*, Vol. 33, No. 8, pages 1286-1294, October 2017.
Citation at https://onlinelibrary.wiley.com/doi/10.1002/rra.3186
From the abstract: Water diversions for hydropower and other applications are some of the most disruptive alterations affecting fish populations in lotic [flowing water] systems. Although many different strategies have been developed to reduce lethal encounters with such infrastructure, few studies have evaluated different forms of behavioural guidance concurrently. Here, we combine an LED-based light guidance device (LGD) equipped with adjustable wavelength and strobing output with a reverse-configured louver rack to assess the effectiveness of this two-part behavioural guidance system on downstream movement through a bypass by age-0 white sturgeon (*Acipenser transmontanus*). Several combinations of LGD and louver settings were tested under both simulated day and night (low light) conditions in a laboratory setting. In the

absence of the LGD, louver slat spacings of 10 or 20 cm were most effective at achieving downstream bypasses with greater success rates (~ two-fold greater) under night conditions than under day conditions. Incorporating the LGD operating at the most attractive setting (green light strobing at 20 Hz) with the louver spacings of 10 or 20 cm achieved the highest rates of bypass usage (100% and 97%, respectively) under both day and night conditions while the control treatment (no LGD or louver) resulted in the lowest bypass rate (46%) among fish that moved downstream. Collectively, these results demonstrate that complementary cues can enhance the behavioural guidance of fishes and highlight the importance of continuing to explore the use of multiple strategies to mitigate entrainment for high priority fish species.

Walleye

"Laboratory Evaluation of a Bioacoustic Bubble Strobe Light Barrier for Reducing Walleye Escapement," Mark K. Flammang, Michael J. Weber and Megan D. Thul, *North American Journal of Fisheries Management*, Vol. 34, No. 5, pages 1047-1054, September 2014. Citation at https://www.tandfonline.com/doi/abs/10.1080/02755947.2014.943864
From the abstract: We conducted a laboratory experiment to evaluate the effectiveness of a bioacoustic bubble–strobe light barrier at reducing Walleye *Sander vitreus* escapement rates. We hypothesized that increasing the number and frequency of barrier stimuli would result in Walleyes approaching the barrier less frequently, reduced escapement, and increased amount of time before escapement occurred. Walleyes approached the barrier and were successfully deterred most often when lights were off and sound was on. Walleye escapement rates declined from 89.3% with the barrier off to 44.1% with low and medium sound, whereas up to 100% of the fish escaped with the addition of light. Mean time before escapement and time to 50% escapement increased with the use of sound, whereas fish escaped in less time when light was used as a deterrent. Most Walleyes escaped around sunset indicating that fish were most active during the crepuscular period. Despite reductions in escapement associated with sound–bubble barriers, we recommend that alternative nonphysical barriers be evaluated for their potential to further increase retention of Walleyes before installation of sound barrier deterrent systems in reservoirs.

Consultation With Experts

We contacted four experts known to have experience with underwater LED light guidance devices:

Consulting Firms

- Doug Bradley, Senior Project Scientist, LimnoTech.
- Paul Patrick, Co-founder, ATET-Tech, Inc.

University Researchers

- Steven J. Cooke, Director, Cooke Lab, Carleton University (Ottawa, Ontario).
- Nann Fangue, Director, Fangue Laboratory, University of California, Davis.

Below are summaries of our email exchanges or phone conversations with each person. Patrick, Cooke and Fangue have authored numerous publications in this topic area, and many of those recent publications are cited throughout this report. All three have collaborated on previous research and reported on research in progress that relates to Chinook salmon.

Consulting Firms

We spoke with Paul Patrick, co-founder of ATET, and Doug Bradley, senior project scientist at LimnoTech, about fish light guidance devices generally and the modifications proposed for an ATET underwater light guidance device.

Background

ATET, a Canadian environmental consulting company with a recently opened U.S. branch in Florida, is focused on fish conservation at industrial water intakes. The underwater LED light guidance device developed by ATET can be used alone or integrated with other fish-management applications as a fish attractant and/or deterrent technology. ATET is partnering with LimnoTech, a Michigan environmental engineering and science firm that specializes in customized field equipment for aquatic applications. ATET and LimnoTech are collaborating to develop light guidance device technology that can be used for field investigations at hydropower and other water user facilities and in portable applications.

ATET's web site describes its light guidance device technology as using "red, green and blue LED light modules capable of producing different color combinations flashing at frequencies of 1 to 40 times per [second] to address species-specific responses of fish and other aquatic organisms. Different controlled spectral/frequency and intensity combinations are controlled by user friendly software which have been demonstrated to be effective at either attracting or repelling juvenile fish such as Largemouth Bass and White Sturgeon."

The ATET light guidance device is currently designed to be used in a fixed position, most typically at hydroelectric plants, using 120-volt AC power and with a direct connection to a computer. ATET and LimnoTech are evaluating the changes needed to make the unit more portable to allow use as a handheld device in remote locations where ready access to power is not available and a continued computer connection is not practical.

Ongoing Research Related to Light Guidance Devices

A wide range of research over decades indicates that different types of light induce species-specific responses in fish. Researchers continue to investigate how different types of light at particular frequencies can either attract or repel particular aquatic species. As Patrick noted, research has produced a positive result for every species examined in connection with response to light—either the species is attracted or repelled. Differences can also occur by life stage within the same species. As an example, Patrick noted that adult sturgeon respond differently than juvenile sturgeon to the same light source. A light source at a particular frequency that strongly attracts juvenile sturgeon will repel the same sturgeon four years later. Further research is needed to know how particular species—and the size classes within that species—will respond to underwater light guidance devices.

As technology becomes more sophisticated, researchers can use software to adjust a guidance device's light frequency in the field to either attract or repel fish, as desired, adjusting to complex environmental conditions and sites with multiple target species and age classes. Conditions such as water flow, time of day, water quality and temperature affect the attraction and deterrent performance at a site for different target species. A database of research results that identifies species and age- and class-specific responses to light could assist practitioners in making the most effective use of light guidance devices to meet site-specific needs.

Patrick also commented on the use of strobe lighting as a fish guidance device. Research examining the impact of strobe lights on American eels found that a blue strobe light is just as effective as a white strobe light in guiding eel behavior in laboratory tests. However, the blue strobe light casts a softer light than the "harder" white light and is more appealing to humans, which could make the blue strobe easier for practitioners to work with in the field.

New Field Applications for the ATET Device

Many of the light guidance and other devices used to attract or repel fish have been developed for use in fixed locations. Experience with these fixed applications has indicated that any fish diversion device (light, sound or physical barrier) must be field-tested and fine-tuned to fit a site's environmental conditions and challenges, and the target species' requirements. To overcome field challenges among sites and to address a range of target species, guidance devices also need to be portable and adjustable in the field.

Currently, ATET is working with LimnoTech to evaluate the modifications needed for programmability of the ATET light guidance device in the field, and for remote and portable applications. This evaluation is expected to produce the framework for a proof-of-concept underwater light guidance device that is portable, battery-powered and capable of being controlled remotely. Patrick and Bradley noted that the availability of concept funding would allow for the immediate development of portable technologies for ATET's light guidance device.

Contacts

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University Researchers

Cooke Lab (Steven Cooke)

We contacted Steven Cooke, director of Cooke Lab at Carleton University, by email to inquire about current research efforts and preliminary data that could be shared in advance of publication. Cooke reported that he had nothing to share in addition to the documents already published and noted that he is collaborating with Nann Fangue's laboratory at University of California, Davis on research associated with Chinook salmon (see below). Cooke recommended a review of his web site to obtain further information. His recent publications examining the use of light and other guidance devices to guide fish behavior are cited throughout this Preliminary Investigation.

Contact

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Lab web site: https://www.fecpl.ca/

Fangue Laboratory (Nann Fangue)

We contacted Nann Fangue, director of Fangue Laboratory at University of California, Davis by email to inquire about her laboratory's recent and future research efforts. Fangue was unable to address our inquiry at the time of publication of this report and recommended that a follow-up contact be made after January 2019.

Fangue collaborated with Patrick and Cooke on a June 2018 article that examined the behavior of Chinook salmon smolts in response to LED lights (see page 12 of this report for the citation). Her previous research has reviewed the effectiveness of underwater strobe lights in protecting juvenile Chinook salmon from entrainment into unscreened water-diversion pipes used for irrigation (see page 19). A project in progress that was conducted in collaboration with Cooke expands on Fangue's later work with Chinook salmon and the use of LED light at diversion inlets to keep fish out. At the time of publication of this report, we were unable to identify an estimated publication date for Fangue's most recent findings.

Contact

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Lab web site: http://fanguelab.ucdavis.edu/

Commercial Light Guidance Products

Highlighted below are commercial light guidance products available from companies in Canada, the Netherlands and the United Kingdom.

ATET-Tech, Inc.

Our Services and Technologies, ATET-Tech, Inc., 2018.
http://www.atet-tech.com/our_services_and_technologies
From the web site:

> ATET-Tech is an environmental consulting company focused on fish conservation at industrial water intakes including once-th[r]ough-cooling, hydroelectric, irrigation, pulp & paper, and manufacturing. ATET-Tech has experience evaluating different fish protection systems especially related to cost-effectiveness, biofouling, and strengths/weaknesses in mitigation control. Technologies reviewed have included fish mitigation options such as acoustic and light systems, fish pumps, air bubble systems, fish return systems, fine mesh wedgewire screens, barrier nets, flow reduction methods and other approaches used at industrial plants.
>
> ATET has also developed a new underwater LED device (Light Guidance Device, LGD) for fish management applications which has been designed to work alone or integrated with different fish-conservation methods listed above. The device can also be used for research applications.

The web site offers information about ATET's collaborative efforts with researchers and other private companies to test its light guidance device. Information about recent publications associated with LED light guidance devices appears on the site's News page (see http://www.atet-tech.com/news-list).

FishFlow Innovations

Strobe Light Fish Deterrence, FishFlow Innovations, undated.
http://fishflowinnovations.nl/en/innovations/fish-deterrence/
This Netherlands company markets stroboscope (or strobe) lights that "are an effective fish deterrent that can be used at pumping stations, cooling water intakes, hydro power plants, et cetera. The patented fish deterrence using strobe lights consists of a number of GRP [glass-reinforced plastic] or steel tubes in which LED lamps are placed that shine outward through curved glass screens. Having the lamps inside the tubes protects them against water, damaging, weeds and algae growth. De [sic] LED units are equipped with special lenses for a better light projection."

The company's web site describes the product attributes:

- Widely applicable system.
- Low-energy LEDs.
- Ultra-bright light.
- Light amplification with special lenses.
- Very long life span.

- Simple to use and to maintain.
- Optional hoisting system to get the lamps in and out of the water.
- The amount of LED units is determined by the size of the inlet and the turbidity of the water.

Fish Guidance Systems Ltd

About Fish Guidance Systems, Fish Guidance Systems Ltd, 2015.
http://www.fish-guide.com/aboutus.html
From the web site: Preventing fish from entering water intakes is a common problem facing many users abstracting water from rivers, estuaries and the sea. This can include power stations, hydro electric stations, pulp & paper factories, refineries, and intakes for drinking water, flood relief, inland waterways, fish farming and irrigation schemes.

Fish protection has traditionally been achieved by using fine physical screens, but these have the associated problems of high capital and maintenance costs and may block easily, restricting water flow. Behavioural screens operate by using the natural response of fish to a stimulus to deflect the fish away from the stimulus. A number of behavioural systems have been tested and acoustic systems have been found to be the most effective.

The initial research conducted by FGS focused on the problem of using sound to guide fish and led to the development of the original acoustic equipment which has been continually refined to provide FGS's current systems.

FGS now offers a complete a range of behavioural systems for deflecting or guiding fish (including acoustic and light systems), and has successfully completed projects around the world through its network of local agents and representatives.

Related Resources:

High Intensity Light Systems, Fish Guidance Systems Ltd, 2015.
http://www.fish-guide.com/technical-lightsystem.html
From the web site: A number of different High Intensity Lights are available from FGS, depending upon the required application. The Light Intensity Light Bar is typically used when fish need to be guided, when only a light system is required, or on smaller intakes. The High Intensity Light Ring and Light Panel are used in larger applications, typically where the FGS 30-600 Sound Projector is installed.

HIL System: High Intensity Light System, Fish Guidance Systems Ltd, 2015.
http://www.fish-guide.com/light-system.html
From the web site: FGS provides a range of underwater High Intensity Light systems for deflecting eels from intakes, which can be used on their own or combined with acoustic systems, including the SPA [sound projector array] and the BAFF, to provide complete protection for all fish species.

If supplied separately the High Intensity Light systems are easily upgradeable at a later date to incorporate FGS's acoustic technology, which will enable the system to be future proof for anticipated forthcoming changes in legislation. The level of diagnostics and control over the system can be tailored to an individual client's requirements, with full control via the internet available if needed.

Contacts

CTC contacted the individuals below to gather information for this investigation.

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