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Glen Canyon Dam Fish Escapement Options

Colorado River Storage Project
Upper Colorado Basin Region

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As water levels in Lake Powell on the Colorado River in Utah and Arizona are declining to historically low levels, the epilimnion where some non-native fish reside approaches the penstock intake elevations at Glen Canyon Dam. Non-native fish entrained through the penstocks threaten to compete with and/or predate the downstream native fish community, including threatened and endangered species. This study explores fish exclusion devices that may limit fish escapement from reservoirs through physical exclusion, behavioral exclusion, or by reducing downstream survival. Relevant example projects were identified, and alternatives were assessed in the context of preventing fish passage through Glen Canyon Dam. Applicability was based on scalability, effectiveness, operational impact and loss of power production, inspection and maintenance requirements, and recreational impact. There is no clear alternative that can fully eliminate non-native fish escapement from Glen Canyon Dam. Based on the review of applicable projects, a forebay barrier net or multi-stimulus barrier may be the most likely alternative to limit impacts to power production, operations, and recreation while maintaining a reasonable level of entrainment protection. Deeper water withdrawal through the river outlet works or installation of an energy dissipating valve on the penstock pipe will also likely limit passage of non-native fish, but considerable impacts to power production are expected. Preferred alternatives should be evaluated in greater detail to identify possible installation layouts and design features, anchoring strategies, anticipated efficacy, impacts to power production, implementation timeframe, and initial and ongoing costs.

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Contents

Executive Summary

Water levels in Lake Powell on the Colorado River in Utah and Arizona are declining to historically low levels due to the extended drought in the western United States. With a reduced water surface elevation, the epilimnion where some non-native fish reside approaches the penstock intake elevations at Glen Canyon Dam and the risk of fish entrainment increases. Non-native fish species threaten to compete with and/or predate the downstream native fish community, including threatened and endangered species such as Humpback Chub *Gila cypha* and Razorback Suckers *Xyrauchen texanus*.

This study explores fish exclusion devices that may limit fish escapement from reservoirs through physical exclusion, behavioral exclusion, or by reducing downstream survival. Relevant example projects were identified where fish escapement solutions have been installed or were considered for installation. Alternatives were assessed in the context of preventing fish passage through Glen Canyon Dam. Applicability was based on scalability to large lateral and vertical dimensions and large capacity withdrawal, effectiveness in excluding non-native fish populations, operational impact or loss of power production, inspection and maintenance requirements, and recreational impact.

In-reservoir options included physical barrier screens, barrier nets, air bubble curtains, underwater acoustic barriers, multi-stimulus barriers, carbon dioxide barriers, floating barriers, and electric barriers. At dam options included deeper water withdrawal, turbine mortality, and energy dissipating valves. Downstream removal options such as manual collection and removal through collection and sorting facilities and boat-based electrofishing and netting were also explored.

Preventing downstream movement of non-native fish from Lake Powell to the Colorado River downstream of Glen Canyon Dam is a difficult problem without a definitive solution. There is no clear alternative that can fully eliminate fish escapement. Based on the review of applicable projects, a forebay barrier net or multi-stimulus barrier may be the most likely alternative to limit impacts to power production, operations, and recreation while maintaining a reasonable level of entrainment protection. Deeper water withdrawal through the river outlet works will likely reduce fish entrainment, but water releases through the outlet works bypass the turbines and power production is currently not possible. Another option is installation of an energy dissipating valve on the penstock pipe to limit fish survival, but this device will impact power production by increasing headloss in the penstock pipe. Preferred alternatives should be evaluated in greater detail to identify possible installation layouts and design features, anchoring strategies, anticipated efficacy, impacts to power production, implementation timeframe, and initial and ongoing costs.

Introduction

Water levels in Lake Powell on the Colorado River in Utah and Arizona are declining to historically low levels due to the extended drought in the western United States. Glen Canyon Dam is a concrete arch structure with a structural height of 710 ft, a hydraulic height of 583 ft, and a crest length of 1,560 ft. Eight 15-ft-diameter steel penstocks are embedded in the dam for power production. The minimum water surface elevation for power operation is 3490 ft. The river outlet works, located near the left abutment, consist of two intake structures with trash racks, four 96-inch-diameter steel pipes, ring-follower guard gates, and hollow-jet valves for flow regulation. The centerline of each river outlet intake is 96 ft below the centerline of the penstock intakes.

With a reduced water surface elevation, the epilimnion where some non-native fish reside currently approaches the penstock intake elevations at Glen Canyon Dam and the risk of fish entrainment increases. The 2016 Long Term Experimental and Monitoring Plan Biological Opinion (U.S. Fish and Wildlife Service 2016) directed the Bureau of Reclamation (Reclamation) to pursue means of preventing the passage of deleterious invasive non-native fish through Glen Canyon Dam.

Above Glen Canyon Dam, the fish assemblage is mostly non-native sport fish (e.g., Smallmouth Bass *Micropterus dolomieu*, Striped Bass *Morone saxatilis*, Walleye *Sander vitreus*, Green Sunfish *Lepomis cyanellus*, Black Crappie *Pomoxis nigromaculatus*, Bluegill Sunfish *Lepomis macrochirus*, Channel Catfish *Ictalurus punctatus)* and below Glen Canyon Dam in Glen, Marble, and Grand Canyons, the fish assemblage consists of mostly native fish including the threatened Humpback Chub *Gila cypha* and endangered species Razorback Sucker *Xyrauchen texanus*. There is a Rainbow Trout *Oncorhynchus mykiss* fishery immediately below the dam that extends through Glen Canyon. A 2007-2009 hydroacoustic survey demonstrated there are non-native sport fish in the reservoir forebay that could become entrained in the penstocks when water is withdrawn from the epilimnion. Results of the hydroacoustic survey show that most sampled fish were found in the top 14 m (45.9 ft) of the water column for both light and dark periods with the first 4 m (13.1 ft) of water having the highest densities of fish (Bureau of Reclamation 2012). Forebay fish densities were highest during the summer months.

Downstream in Lees Ferry, Striped Bass and other non-native fish species have been detected during routine monitoring by the Grand Canyon Monitoring and Research Center (GCMRC) and Arizona Game and Fish Department (AZGFD), but water temperatures are now warm enough that there is risk of establishment. In July 2022, juvenile Smallmouth Bass were detected in the Colorado River below Glen Canyon Dam. These non-native fishes threaten to compete with and/or predate the downstream native fish community. The financial cost to Reclamation may be very high if long-term non-native fish eradication efforts are required.

Approach

The goal of this study is to explore fish exclusion devices and methodologies to restrict non-native fish in the reservoir from passing through Glen Canyon Dam powerplant and into the downstream river. This study includes a review of devices that may limit fish escapement from reservoirs through physical exclusion, behavioral exclusion, or by reducing survival. Literature was reviewed and subject matter experts were contacted in all of Reclamation's regions, along with other federal and state entities, to obtain best professional input on fish escapement strategies. Results from the 2020 Fish Protection Prize competition conducted by Reclamation and the Department of Energy Water Power Technologies Office and the 2019 Improving Fish Exclusion from Water Diversions and Intakes prize competition conducted by Reclamation were reviewed. Relevant example projects were identified where fish escapement solutions have been installed or were considered for installation by Reclamation or other entities.

Alternatives were assessed in the context of preventing fish passage through Glen Canyon Dam. Applicability was based on:

- Scalability to large lateral and vertical dimensions and large capacity withdrawal
- Effectiveness in excluding non-native fish populations, particularly mid-size fish
- No operational impact or loss of power production
- Inspection and maintenance requirements (including impacts by invasive mussels)
- Recreational impact

Considerations

Due to the urgency of the fish escapement problem, viable technologies should be field tested and commercially available rather than theoretical concepts that require significant development. Identified technologies should address longer-term solutions rather than stop-gap measures. The focus of the evaluation is on mid-size fish due to the possibility of this size class surviving passage through Francis turbines. It is likely that larger adult fish will be susceptible to turbine blade strikes and larval fish will be most susceptible to pressure change and shear stress. In addition, Lewis et al. (2022) report that small-bodied individuals tended to escape from reservoirs at higher rates than larger fish.

Inspection and maintenance requirements will be elevated due to the presence of invasive quagga mussels *Dreissena bugensis* in Lake Powell. Quagga mussel issues were first detected at the Glen Canyon powerplant in 2013. Mussels are considered a moderate problem at the powerplant. The most impacted components at the powerplant are Bailey valves, transformer cooling system, fixed wheel gates, and service station air compressors (Pucherelli et al. 2021). A 2019 study found rapid progression of mussel settlement on the penstock intake trashracks since a previous survey in 2017. Complete occlusion is not likely due to the large size of the trashrack openings, but extensive fouling has the potential to increase velocities and increase head loss.

Infrastructure installed at the dam face or in the reservoir forebay will be susceptible to biofouling by mussels. The highest densities of mussels are found near existing infrastructure and canyon walls. Settlement of mussels on installed infrastructure may result in occlusion of components that result in the device not working properly (e.g., clogging of air bubble lines) or adding weight to a system that exceeds design specifications or impedes performance. Application of commercially available silicone foul release coatings may limit mussel attachment on fish barriers installed in Lake Powell, although abrasion and gouge resistance needs to be assessed (Skaja 2012).

Colonial hydroid (*Cordylophora caspia, Pallas, 1771*) was found on settlement plates in Lake Powell in 2015. Colonial hydroid colonies have significant biofouling potential at hydropower facilities, including increasing maintenance and causing system failure (Pucherelli et al. 2016), and may be a biofouling concern for newly installed fish barrier infrastructure.

Local velocity is a factor in the design and effectiveness of fish exclusion technologies in the reservoir forebay. From a report on penstock withdrawal characteristics, near-field velocity measurements adjacent to the trashrack bars at the penstock centerline elevation for Unit 7 were 1.64 ft/s during a release of 3,600 ft^3/s (Vermeyen 2011). Velocity magnitudes decline to less than 0.4 ft/s at a distance of 20 ft from the operating intake at 3,600 ft^3/s. Far-field velocity measurements approximately 420 ft upstream of the dam face were less than 0.37 ft/s over a range of release flows (Vermeyen 2011).

Installation of a barrier components in the reservoir forebay may create infrastructure safety concerns. If part of a barrier system dislodges, it could block spillways or outlets or become entrained in penstocks. A Risk Analysis to identify potential impacts to dam safety may be required.

Review of Options

In-Reservoir Barrier Options

Physical Barrier Screens

Description

Physical barrier screens prevent the movement of fish into a diversion using a porous structure that allows water to flow through it while preventing objects larger than the opening size from moving through. There are many types of screens including vertical and horizontal flat plate screens, inclined screens, cylindrical and conical screens, Coanda screens, closed conduit screens (e.g., Eicher, Modular Inclined Screens (MIS)). Vertical wells and infiltration galleries (e.g., Ranney collector wells) can be used to withdraw water below the river bed. Rotating screens such as vertical or inclined traveling screens and cylindrical drum screens rotate to prevent debris from clogging the screen. Screens must have enough surface area to maintain low velocities through the screen to prevent fish from impinging on the screen face. Therefore, fish screens at large diversions or intakes can be very long.

The screen material is typically metal (e.g., woven wire, perforated plate, and profile bar) or engineered polymers. Screens are cleaned with automated traveling brushes, air burst, water jets, or manually raking the screen. Flow baffles or porosity boards (vertical louvers or perforated plate) designed to distribute diverted flow uniformly over the screen area can be located either behind the screen (flat screen panels) or inside the screen (cylindrical screen units). Recent research by a winner of the Fish Protection Prize was conducted to determine if a biometric-informed screen shape holds advantages for exclusion of larval fish and eggs (Benjamin Mater and Charles Coutant; https://americanmadechallenges.org/challenges/fishprotection/index.html).

Related Examples

The Interlake Tunnel Project is a proposed gravity water conveyance tunnel approximately 11,000 feet long connecting Nacimiento and San Antonio reservoirs in San Luis Obispo and Monterey Counties, respectively. A screened intake structure would be constructed to prevent White Bass *M. chrysops* from moving from Lake Nacimiento to San Antonio Reservoir. The screening system would be comprised of four cylindrical screen assemblies at a 1.75-mm screen opening. The proposed location of the intake structure would likely preclude the presence of eggs and larvae. A debris management system would require a debris boom across the intake structure, a trashrack with trash rake within the intake approach channel, and cylindrical screens with external and internal brushes.

At Willow Springs Lake in eastern Arizona, the Arizona Game and Fish Department is considering a fixed fish screen to prevent Smallmouth Bass and Green Sunfish escapement into Chevelon Canyon where several species of native fish reside, including listed Little Colorado Spinedace *Lepidomeda vittata*. Installation of a fish screen with 1/8-inch diameter holes is proposed to prevent downstream passage of nearly all fish except for small fry. The 40-ft-wide by 4-ft-tall fish screen would be installed downstream of the control structure in the spillway with operation up to a 25-year flow event. Annual mechanical removal efforts via boat electrofishing are currently conducted.

The Colorado Division of Parks and Wildlife operates a fish screen in Rifle Creek (Garfield County, Colorado) to prevent non-native fish in Rifle Gap Reservoir from entering the downstream Colorado River via Rifle Creek. The project aims to assist in recovery of listed species such as Humpback Chub, Razorback Sucker, Bonytail Chub *Gila elegans*, Colorado Pikeminnow *Ptychocheilus lucius*. The screening structure consists of a concrete structure with two 50-ft-long by 5-ft-wide Coanda screens. The two screens are constructed parallel to each other to minimize the overall structure size while maintaining a maximum flow capacity of 200 ft^3/s. Water is retained by a concrete barrier and pools up until it overtops the side of the concrete channel and flows down the angled screens. Most water passes through the screen with a mesh size of 3/32-inch opening. Larger objects such as fish and debris are collected in concrete troughs. Fish are sorted manually and selectively relocated. Debris must be removed manually from the screen by staff with a long-handled brush.

Fish protection alternatives were considered in 2011 to address fishery concerns in the Banks Lake Feeder Canal at the John W. Keys III Pump Generating Plant at Grand Coulee Dam (Svoboda 2011). Fish in Banks Lake tended to congregate in the feeder canal during pumping operations to feed when water is brought up from Franklin D. Roosevelt Lake by the pumping units. If the mode of operation quickly reversed from pumping to generating, fish were entrained through the feeder canal and into the generating units. Due to pressure changes within the pump-generator unit runners, a high level of mortality occurs. Species of interest in Banks Lake included Lake Whitefish *Coregonus clupeaformis*, Smallmouth Bass, Walleye, Rainbow Trout, Common Carp *Cyprinus carpio*, Kokanee Salmon *O. nerka*, and Yellow Perch *Perca flavescens*. A 357-ft-long bar rack with 1-inch spacing was proposed in the feeder canal for the exclusion of adult fish. Since water would flow in both directions in the feeder canal daily, areas of the screen clogged during generation were expected to dislodge when pumping resumed.

Applicability

Physical barrier screens in Lake Powell would need to be very large in horizontal extents for a flat plate screen, or would require a large number of cylindrical screens to meet the required discharge capacity. Fixed screens would not be possible with variable water surface elevations in the reservoir, so the system would need to be moveable and removable and be adjustable with water level. Although highly effective at reducing entrainment, physical barrier screens are susceptible to debris clogging and biofouling, including invasive mussel attachment. Screens must be inspected and cleaned regularly. Recreational impacts would be minimal because a physical barrier would be located within the forebay. Due to the capacity, extents, and variable water level, there is no identified practical application of physical barrier screens in the reservoir at Glen Canyon Dam.

Closed conduit screens (e.g., Eicher, Modular Inclined Screens (MIS)) could be used to generate impact mortality in fish passing through the penstock with a smaller screening footprint. However, the potential for screen clogging would be high and the subsequent increase in head loss at the turbine and subsequent negative impacts on power production limit practical application of this technology.

Barrier Nets

Description

A fish exclusion barrier net is installed to allow water to pass through while physically blocking the movement of fish larger than the net open area. Net open area is selected based on the size of the fish desired for exclusion while considering debris accumulation and cleaning requirements. Fish nets may include upstream floating booms to limit floating debris collection on the net. Nets can be installed and removed seasonally or left in place. Nets must be inspected regularly for integrity.

Related Examples

A fish exclusion barrier net was installed at Lovewell Dam by the Kansas Department of Wildlife, Parks, and Tourism. The purpose of the net was to reduce the loss of fish from the reservoir during periods of canal outlets works discharges and/or lower operational releases through the spillway. Due to concerns about installation of a fish exclusion barrier net upstream of dam components, the Bureau of Reclamation conducted a Risk Analysis in 2012 to review potential dam safety and operations and maintenance issues associated with the barrier net. The installation of the barrier was approved. A net with 0.25-inch aperture designed by Mackworth-Enviro Aquatic Barrier & Screening Solutions was designed to exclude juvenile and adult Walleye, Crappie *Pomoxis spp.*, and Gizzard Shad *Dorosoma cepedianum* (Mackworth Aquatic Environmental Systems 2012). The 430-ft-long, 21-ft-maximum height net successfully excluded fish during 3 years of operation, however, the flotation and netting deteriorated due to winter ice conditions and wind. To extend performance life, the barrier would have needed to be removed in September following the irrigation season and then reinstalled in April prior to first releases. Twice annual removal and reinstallation would have required significant personnel and resources. The barrier also caused unintended consequences to fish populations. About ninety-five percent of the retained fish were gizzard shad and overabundant numbers of gizzard shad in the reservoir competed with young sportfish for food resources.

A fish exclusion spillway net was installed in 1999 at Highline Lake near Loma, Colorado as part of the Upper Colorado River Endangered Fish Recovery Program's effort to keep non-native Smallmouth Bass and other non-native species from spilling out of the reservoir into the Colorado River where they prey on four native fish — Humpback Chub, Bonytail Chub, Colorado Pikeminnow, and Razorback Sucker. The Highline Lake spillway net is 363 feet wide, 19 feet deep, has a dry weight of 1,400 pounds, and mesh openings of 0.25 inches (Martinez 2001). It is fabricated of a high-tech sturdy polyethylene fiber called Dyneema, a material well suited for the net due to its resistance to abrasion, light degradation, and fatigue without special coverings or coatings (Martinez 2002). The net durability has resulted in the spillway net being left in place year-round, even during winter when the lake is frozen (Martinez 2001). Since the original installation in 1999, the Highline Lake spillway net has been replaced in 2006, 2014, and 2022. Colorado Parks and Wildlife conducts inspection and cleaning with a dive team at an annual cost of about $10,000-$20,000. The dive team conducts underwater inspections and cleanings approximately four-to-five times per year due to algal and debris buildup on the spillway net. Sampling efforts by the Colorado Parks and Wildlife show that the effectiveness of the net was favorable in controlling escapement of resident and stocked non-native fishes from the reservoir. Catch rates between the net and the spillway, however, were higher in 2021 and 2022 than previous years, likely due to net condition and canal surges that partially submerged the net (Upper Colorado River Endangered Fish Recovery Program 2022).

A similar fish exclusion spillway net was installed at Elkhead Reservoir near Craig, Colorado in 2016 as part of the Upper Colorado River Endangered Fish Recovery Program to prevent escapement of Northern Pike *Esox lucius* and Smallmouth Bass into the Yampa River. The Elkhead Reservoir net is 575-feet long and 30-feet deep and is also fabricated with the polyethylene fiber Dyneema. The net is fully exclusionary, extending from the reservoir bottom to the water surface and can remain effective for a spillway release of up to 2,000 ft^3/s. The $1.3M net was fabricated by Pacific Netting Products (www.craigdailypress.com/news/net-installation-begins-at-elkhead-reservoir/). It is secured to the reservoir bottom via anchors. A 2-foot diameter 800-foot long foam-filled debris boom with a 4-foot skirt extending beneath the water surface is situated upstream of the spillway net to reduce wave action and protect the net from large logs and other debris. The net is not removed seasonally. Colorado Parks and Wildlife conducts inspection and cleaning with a dive team at an annual cost of about $10,000-$20,000. Four underwater inspections and cleanings were completed in 2021 and four inspections and cleanings are expected in 2022. There are no Dreissenid mussels in Highline Reservoir and Elkhead Reservoir, so biofouling is limited to algal growth. The Elkhead Reservoir spillway net has no anticipated near-time replacement timeline. Sampling efforts show that the Elkhead Reservoir net is effective at substantially reducing escapement of non-native fish from the reservoir, but not eliminating it.

Floating nets near the spillway gates at Canyon Ferry Dam in Montana were considered by the Montana Fish, Wildlife, and Parks to prevent non-native stocked Walleye from passing over the spillway to the downstream blue ribbon trout stream. Floating nets were not installed due to dam safety concerns regarding the ability to sufficiently anchor the netting system and costs associated with the project.

Applicability
Fish exclusion nets have been installed at a few locations with some success. All identified projects with fish exclusion nets were fully exclusionary with the net extending from the reservoir bottom to the water surface. Due to fabrication, inspection, and anchoring requirements in the deep reservoir depths at Glen Canyon Dam, the fish exclusion net would need to be floating in about the upper 30-50 ft section of the water column. If an exclusion net were installed at the log boom location, the net would need to be approximately 1,000 ft long. Nets are installed in sections, so the length of the net is feasible but may produce notable installation and maintenance challenges.

For similar projects, fish exclusion nets were installed once and left in place. Due to the extensive length of the net barrier and no icing concern at Glen Canyon Dam, the net may be able to stay installed if biofouling can be managed and invasive mussels do not cause occlusion of the openings. Nets installed in other locations were inspected and cleaned several times per year to maintain effectiveness. If the net is left in place during years with higher water levels, maintenance may become difficult. One of the winners of the Fish Protection Prize is currently testing an additive to the manufacturing process to make underwater nets susceptible to inspection using sonar instruments, so that nets can be inspected in any water turbidity by boat (Prometheus Innovations, LLC; https://americanmadechallenges.org/challenges/fishprotection/index.html). This technology may improve future inspection and maintenance opportunities at fish nets.

Installation of a net upstream of a dam creates infrastructure safety concerns. If the net dislodges, it could block spillways or outlets or become entrained into penstocks. For the Lovewell Dam application, the Bureau of Reclamation conducted a Risk Analysis to identify potential impacts to dam safety and operations and maintenance. It is reasonable to expect that a similar assessment would be required for installation of a barrier net at Glen Canyon Dam.

Air Bubble Curtains and Underwater Acoustic Barriers

Description
Air bubble curtains are created when compressed air enters a linear air diffuser. The inner pressure releases bubbles through holes in the tubing line which forms a curtain of evenly dispersed bubbles. Air bubbles can be used for increasing oxygen, de-icing, debris collection, and sediment containment. In the context of fish deterrence, a continuous screen of bubbles in the water column creates an unnatural visual cue for fish to avoid. As a visual deterrent, air bubbles are limited by light penetration, especially due to turbidity. Air bubble curtains also produce ancillary acoustic and hydrodynamic fields that may deter fish.

Underwater acoustic barriers are sound-based behavioral deterrents. Fixed submerged sound projector arrays create sound waves at a certain frequency and amplitude to induce an avoidance response in fish. Bureau of Reclamation (2006) summarizes field application experience with sound systems from EPRI 1999.

Related Examples
Tennessee Valley Authority has been installing aeration systems in the southeast United States on hydropower projects since the 1970s. An oxygen diffuser system in the forebay of Tennessee Valley Authority's Douglas Dam near Knoxville, Tennessee was installed to increase dissolved oxygen levels (Mobley and Brock 1995). Although the purpose of the aeration system is not for fish

exclusion, the scale of the installation makes this project relevant to Lake Powell. Liquid oxygen is delivered by truck to an on-site bulk oxygen storage facility and gaseous oxygen is distributed to 12 miles of porous hoses attached to a frame. The hoses float approximately 20 ft above the reservoir bottom by using weights adjusted to match the bottom topography.

In 2002, a hypolimnetic oxygenation system was installed at Upper San Leandro Reservoir near Oakland, California to address algal blooms and taste and odor complaints (Mobley 2003). Similar to Tennessee Valley Authority aeration designs, the single-line diffuser extends 8,500 ft along the centerline of the reservoir with two sections of porous hose. Stainless steel cable attaches to anchors placed at the reservoir bottom with a buoyancy pipe connected to the porous hose. Pure gaseous oxygen is supplied by a 6,000-gallon storage tank onsite.

Laboratory research is being conducted on the use of oblique bubble screens as two-way dispersal barriers (Cupp et al. 2021). Oblique bubble screens are deployed across a channel at an angle to the flow (e.g., 45 degrees) to guide upstream-moving fish toward potential collection zones and to redirect downstream-moving particulates toward an active or passive collection point. After laboratory studies are complete, field tests are planned for 2023.

A winner of Reclamation's Improving Fish Exclusion from Water Diversions and Intakes prize competition (https://www.usbr.gov/research/challenges/fishexclusion.html) and finalist in the Fish Protection Prize suggested using air currents to direct larvae and eggs from intakes though physical attachment to bubbles (TWB Environmental Research and Consulting; https://americanmadechallenges.org/challenges/fishprotection/index.html).

A laboratory study conducted by Zielinski and Sorensen (2016) used a unidirectional bubble curtain to reduce passage of Silver Carp *Hypopthalmichthys molitrix*, Bighead Carp *H. nobilis*, and Common Carp. Passage was reduced in the experiment channel by 73–80% for all three carp species. The air bubble curtain produced sound between 100 and 1,000 Hz at 145 dB which was within the hearing range of the tested carp. A study by Zielinski et al. 2014 indicates that the addition of speaker arrays and lighting to an air bubble curtain created avoidance responses based on sound and fluid motion rather than visual cues. Researchers conclude that sound produced by the bubble curtains is most likely responsible for carp deterrence as bubble plumes efficiency can be limited by ambient light (Zielinski et al. 2014).

A study by Dennis et al. (2019) found that when an air curtain was coupled with sound, the combined stimulus was more effective in blocking Bighead Carp, Common Carp, and Largemouth Bass. They also concluded that response to behavioral sound barriers is species-specific and sound-specific, such that a proprietary sound was most effective in deterring carp, but not Largemouth Bass since they have less sensitive hearing than carp.

After successful pond studies, an experimental underwater acoustic deterrent system was tested in 2021 on the Mississippi River near Keokuk, Iowa in the downstream approach of lock no. 19 (Cupp et al. 2021). Studies are ongoing to determine the effectiveness of the 16 underwater transducers in deterring invasive carp.

The Brandon Road Interbasin Study is a complex plan by the U.S. Army Corps of Engineers Rock Island District to prevent upstream movement of invasive carp and other aquatic nuisance species into the Great Lakes from the Illinois Waterway. Engineering and design initiated in December

2020. Deterrence measures will be installed in sequence, such that species are exposed to one deterrent after another. Technologies to prevent the upstream passage of delirious species includes a flushing lock, engineered channel with electric barrier, underwater acoustic deterrent system, and air bubble curtain. Studies completed prior to construction will be used to define specific design parameters.

Applicability

The Tennessee Valley Authority installations show that there is precedent for very long aeration systems. Due to the significant water depth in Lake Powell, it is not feasible to install an air bubble curtain at the reservoir bed or to drive piles to fasten the air supply line. An air bubble curtain would need to be suspended by buoys with weights and/or bottom anchoring to prevent floating. If the air bubble curtain is installed at a specific depth from the surface, fish could move lower in water column to pass the behavioral curtain.

Air bubble curtains can create significant upwelling of the surrounding fluid which induces localized mixing. There may be implications to water temperatures or dissolved gas levels. The effectiveness of air bubbles in limiting non-native fish movement in Lake Powell is uncertain.

Underwater acoustic deterrents have shown promise for deterring invasive Carp since they have specialized hearing abilities (Popper 1972; Lovell et al. 2006). Sound systems have been inconsistent in generating fish exclusion and are more effective at some sites with certain fish species. Either independently, or in combination with an air bubble curtain, the effectiveness of acoustic deterrents in deterring non-native species of concern in Lake Powell is uncertain. Like the air bubble line, acoustic transducers would likely need to be suspended from the water surface rather than mounted at the reservoir bed.

Large-scale compressed gas injection for bubble barriers and underwater acoustic barriers require continuous energy to run using land-based infrastructure. Additional maintenance activities will be required such as dive inspections and cleaning. Infrastructure installed in the forebay may be susceptible to invasive mussel attachment, which may reduce the performance of the device.

Multi-Stimulus Barriers

Description

Multi-stimulus barriers use several types of behavioral deterrents in combination to create an avoidance response by fish. These multi-modal systems may incorporate an air bubble curtain, sound signals, and directional strobe light in a single barrier. Like air bubble and acoustic barriers, multi-stimulus barriers are installed on or near the bed of the water body. Applications have included exclusion at hydroelectric intakes, limiting passage of invasive fish, and guiding downstream-migrating fish away from diversions and canals.

Related Examples

A commercially-available Bioacoustic Fish Fence by Fish Guidance Systems was temporarily installed in the Sacramento River at Georgiana Slough in 2011 and 2012 to prevent downstream-migrating anadromous fish species including winter-run, spring-run, fall-run, and late fall-run Chinook Salmon *O. tshawytscha* and Steelhead *O. mykiss* from entering Georgiana Slough. The barrier was 630-ft-long with frames consisting of 600 sound projectors, 12 high-intensity modulated light bars, and perforated bubble pipe. The frame was attached to driven piles to adjust for the uneven bed contours with the bioacoustics fish fence situated approximately 12 ft below the high tide water level. During the 2011 study period, the Bioacoustic Fish Fence reduced the number of salmon smolts that would have been entrained by approximately two-thirds with 22.1% entrainment with the barrier off versus 7.4% entrainment with the barrier on (California Department of Water Resources 2012). High discharge was identified as an important predictor of fish behavioral response. High turbidity levels likely limited the use of visual cues created by the light intensity. The California Department of Water Resources plans to install and operate a Bioacoustic Fish Fence at the Georgiana Slough junction for 8 years from 2022 to 2030.

A Bioacoustic Fish Fence consisting of sound, bubbles, and high-intensity light-emitting diodes was also installed upstream of the divergence of the San Joaquin River and Old River in California in 2009 to deter anadromous juvenile salmonids from entering Old River (Bowen 2009). The barrier was 367 ft long at a 24-degree angle incident to the San Joaquin River. The barrier components were attached to a truss-style frame affixed to driven pilings.

In another installation, a BioAcoustic Fish Fence including sound, light, and bubbles was installed on the downstream side of Barkley Lock on the Cumberland River in Kentucky in 2020 to reduce movement of invasive carp through the lock chamber. The Bioacoustic Fish Fence will be installed as a three-year field study until fall 2023. Approximately 1,100 Silver Carp and 225 native fish were implanted with acoustic transmitters and an additional 1,500 transmitters are planned to be implanted later in the study, providing a robust data set to assess the efficacy of the barrier. Preliminary data show that the Bioacoustic Fish Fence is effective in reducing, but not eliminating, fish passage at the barrier location (U.S. Fish and Wildlife Service 2022).

Applicability

A multi-stimulus barrier may provide the best opportunity for behavioral deterrence due to the variety of stimuli. Multi-stimulus barriers are often fixed to the bed of the river or reservoir or attached to specially driven piles to support the weight of the components within the frame. No examples of multi-stimulus barriers suspended in the water column were identified, which would likely be required for an in-reservoir installation at Glen Canyon Dam. Like the air bubble or acoustic deterrent system, fish could move lower in the water column to pass a multi-stimulus behavioral barrier if it is suspended in the water column.

There are no impacts to operations or hydropower production with a multi-stimulus behavioral barrier. Multi-stimulus barriers increase maintenance requirements by requiring dive inspection and cleaning. Infrastructure installed in the forebay will be susceptible to invasive mussel attachment, which may reduce the performance of the device. Large-scale gas injection and sound modulation requires land-based infrastructure and continuous energy.

Carbon Dioxide Barrier

Description

Infusion of carbon dioxide into water has shown promise as a chemical fish deterrent. This type of system creates a non-physical means to reduce the movement of fish while not inhibiting river flow. Fish respond strongly to carbon dioxide by avoiding treated areas or becoming immobilized through narcosis. Carbon dioxide is nonselective to fish size and species. In 2019, carbon dioxide was registered with the U.S. Environmental Protection Agency as a pesticide for carp.

Related Examples

Research has been conducted on the use of carbon dioxide injection into navigation locks to deter invasive fish from swimming upstream while not impeding vessel passage or lock operation. Zolper et. al describe the performance of wall- and floor-based carbon dioxide-infused water injection manifolds in terms of mixing time, mixing homogeneity, injection efficiency, and operational power requirements at a concrete test pond in La Crosse, Wisconsin (2019) and at a navigational lock chamber on the Fox River near Kaukauna, Wisconsin (2022). Results show that mixing must extend to all regions of a lock to prevent passage of invasive carp. Study data can be used to guide design and improve performance of carbon dioxide infusion systems.

A study by Cupp et al. (2017) shows that carbon dioxide altered Silver Carp and Bighead Carp movement in outdoor ponds. In 2018, a field evaluation was completed to reduce fish abundance near culverts (Cupp et al. 2018). Fish abundance was 70-95% lower when target carbon dioxide concentrations of 100 mg/L could be achieved. In 2020, Cupp et al. completed a telemetry study to evaluate behavioral avoidance of invasive carp in a large U-shaped pond to carbon dioxide. On average, 58% of test fish were restricted in movement at 121 mg/L and 78% were restricted in movement at 213 mg/L.

The Tracy Fish Collection Facility in Tracy, California is exploring the use of carbon dioxide to remove adult and juvenile striped bass from the facility to reduce predation losses (Wu et al. in draft). In this application, dry ice is inserted into a confined channel. As striped bass move downstream to avoid the carbon dioxide, they are collected in holding tanks and removed from the facility.

Applicability

Carbon dioxide has shown some effectiveness in influencing fish movement in controlled environments in confined locations such as ponds and locks. In these environments, full mixing is required to all stagnation regions to prevent passage of invasive fish. Continued research is being conducted on direct gas injection systems that are designed for flowing water. No applications were identified where carbon dioxide was being injected in the form of a long barrier wall for fish deterrence in open water which is the most likely application at Glen Canyon Dam. Large-scale gas injection requires land-based infrastructure and continuous energy. This type of system could hang from a buoy line with weights or bottom anchors. Diffused gas may create upwelling of the surrounding fluid which induces localized mixing and elevated carbon dioxide levels will reduce the pH of the water. Carbon dioxide could also be injected directly upstream of the penstock trashracks. Vermeyen (2011) documented near-field velocity measurements adjacent to the trashrack bars at the penstock centerline elevation as 1.64 ft/s during a release of 3,600 ft^3/s. Fish that sense the barrier may be able to avoid entrainment, but narcotized fish would be drawn through the penstocks. Infrastructure in the reservoir forebay would typically be susceptible to invasive mussel impacts, but carbon dioxide has been shown to impede Dreissenid mussel attachment and survival (Waller et al. 2021) and may also impede Colonial hydroid biofouling (Brown et al. 2016).

Floating Barriers

Description

Floating barriers such as plates and curtains may be used to induce behavioral guidance. Since these barriers do not extend to the bed and may contain gaps at seams, they are not true physical barriers. These barriers are attached to floating buoys and extend some distance in the water column.

Related Examples

In 2014, a physical barrier called a Floating Fish Guidance Structure by Worthington Waterway Barriers was tested on the Sacramento River at Georgiana Slough as a guidance structure to prevent downstream-migrating anadromous fish species from entering Georgiana Slough. A typical Floating Fish Guidance Structure is made up of floating buoys that support vertically submerged solid metal plates which are designed to induce behavioral guidance. Separate plate sections are linked together and a flexible rubber material attached between the plates to prevent gaps. The Floating Fish Guidance Structure used at Georgiana Slough was about 361 ft long with steel sections 20 ft wide and 5 ft deep. A 10 ft panel depth was considered optimal, but could not be tested due to low water levels and a modeled panel submergence guidance of 50% depth. Study results show that the Floating Fish Guidance System was partially effective at reducing entrainment into Georgiana Slough with a five-percentage point reduction in entrainment at an intermediate discharge (California Department of Water Resources 2016).

Fixed submerged curtains have been used to control release flow temperatures at outlets and diversions to improve downstream fish habitat. Reclamation has installed flexible curtains at Whiskeytown Lake and Lewiston Reservoir in California for temperature control (Svoboda 2020). Specific application of fixed curtains to reducing fish movement could not be found.

Applicability

There is a buoy line installed in Lake Powell upstream of Glen Canyon Dam to prevent large floating objects from entering the forebay. It is possible that a floating barrier could be installed at or near the location of the buoy line, potentially with deeper panels deployed near the canyon walls to better contain littoral dwelling species such as Smallmouth Bass. There is no power requirement for floating barriers, so there is less ongoing operational cost. Floating barriers would require regular maintenance for inspection and repair. Floating barriers would be susceptible to fouling, particularly by invasive mussels and Colonial Hydroid, but functionality of the barriers may still be maintained even when fouled. Efficacy would be limited by fish swimming between gaps in the barrier or under the barrier. There would be no notable impacts to recreation due to installation in the forebay.

Electrical Barriers

Description

Electric barrier design typically involves submerging two or more metal electrodes in a fixed location and applying a voltage between them. When electrical current passes between the electrodes, an electrical field is formed in the water. Fish in contact with the electrical field may experience various responses such as avoidance, electrotaxis (forced swimming), electrotetanus (muscle contraction), electronarcosis (muscle relaxation or stunning), or death (U.S. Geological Survey 2001). Maximum power transfer to the fish occurs when the water conductivity is equal to the conductivity of the fish (approximately 115 µS/cm). When ambient water conductivity is higher, more current is required to transfer the same amount of power to the fish. Large fish are generally more susceptible to electrical fields than smaller fish because more power is transferred for a given voltage gradient (volts per unit distance) over the length of the fish (Reynolds 1996). Commercially available electric barriers can be installed with electrodes as vertical drops suspended from a cable, attached to pilings, attached to buoys at the water surface, or suspended mid-depth in the water column or electrodes can be flush-mounted on the river bottom in concrete.

Related Examples

In 2012, a vertically suspended electric fish barrier was installed by the Delta-Montrose Electric Association at the east end of South Canal to prevent downstream passage of Rainbow Trout and Brown Trout *Salmo trutta* from the Gunnison River into the South Canal Hydroelectric Plants. The vertical electrodes hang from an overhead cable for a total width of 74 ft, water depth of 16 ft, conductivity of 180 µs/cm and water velocities between 0.66-2.3 ft/s. Mark-recapture monitoring conducted by Colorado Parks and Wildlife show that 1.3% of tagged Rainbow and Brown Trout were recovered downstream of the barrier. Kowalski (n.d.) reports that the barrier was effective at limiting passage of larger fish, but not age 0, age 1, or age 2 trout.

Dozens of bottom-mounted electric barriers have been installed to limit upstream movement of fish. At Quilcene and Quinault National Fish Hatcheries in Washington and Eagle Creek National Fish Hatchery in Oregon, upstream-migrating salmon are blocked from upstream movement and diverted to the hatchery entrance. Electric barriers have also shown effectiveness in limiting the movement of invasive fish or the movement of fish into undesirable areas. Swink (1999) showed that an electric barrier greatly reduced the upstream migration of Sea Lamprey *Petromyzon marinus* in the Jordan River, Michigan with only 0-1.8% (95% confidence interval) passing. Only one of 130 Common Carp released below the electric barrier in the Chicago Sanitary and Ship Canal passed upstream of the electric barrier (Sparks et al. 2010). Barring power outages or low-flow conditions, electric barriers in the Central Arizona Project successfully prevented grass carp from migrating upstream in canals (Clarkson 2004).

A recent study by Meister et al. (2021) used an electrified bar rack to guide Spirlin *Alburnoides bipunctatus* and European Eel *Anguilla anguilla* to a bypass in a laboratory flume. Results showed that a wider electrified bar rack (51 mm clear spacing and 38 V pulsed direct current) produced similar protection efficiency to a bar rack with a smaller bar spacing (20 mm clear spacing). Various levels of injuries due to electrification were observed.

Applicability

Electric barriers could be considered for installation at several locations at Glen Canyon Dam including the reservoir forebay, at the penstock trashracks, and inside the penstocks. Due to the deep reservoir water depth, a forebay electric barrier would need to be surface mounted with vertically oriented electrodes in Lake Powell. The barrier length would need to be hundreds of feet long. Since electric barriers are size selective, the voltage gradient would need to be sufficiently high to produce an avoidance response in mid-sized fish, which may cause larger-bodied fish to respond in tetanus or narcosis and be entrained. Water conductivity measured at Wahweap in Lake Powell ranged from 897 to 1105 µS/cm in July 2022. Electric barriers must be set at a higher current to elicit a response from fish when the ambient water conductivity is greater than the approximate conductivity of fish (115 µS/cm). Electric fields can be disrupted by steel-hulled boats and power outages. An electric field generated in the reservoir would require constant power supply and land infrastructure. Worker safety precautions would be required in the forebay area. Alternately, the penstock trashrack bars could be electrified. Voltage gradient levels would need to be high enough between the 4-3/8-inch clear spacing to deter mid-sized fish at a distance where fish could avoid being drawn through the penstock intake. A velocity of 1.64 ft/s was measured adjacent to the trashrack bars (Vermeyen 2011). Larger-bodied fish that respond in tetanus or narcosis to an electrical field at the trashrack would be impinged on the trashrack or drawn through the penstocks.

An electrified section of pipe could be installed inside the powerplant to induce mortality in these fish prior to exit in the tailrace; however, the short exposure time may limit effectiveness.

Other In-Reservoir Barriers

Other types of in-reservoir physical barriers such as weirs, culverts, rock gabions, overshot and undershot gates, guide walls, and physical structures to create velocity barriers cannot be reasonably applied to deep reservoirs such as Lake Powell and will not be considered further. Other types of behavioral barriers include submerged velocity jets, flow alteration, olfactory stimulus, turbulence, infrasound, spaced louvers, hanging chains, chemicals, ozone, and pheromones; however, these technologies are unlikely to have high exclusion rates in the reservoir forebay. Underwater lights used independently would not have high efficacy during daylight hours. Seismic water gun arrays have been used to create concussive blasts that rupture fish swim bladders. Although the behavior of tested fish was altered, the method was not fully effective as a deterrent (Romine et al. 2015).

Several theoretical concepts identified during the 2020 Fish Protection Prize and the 2019 Improving Fish Exclusion from Water Diversions and Intakes prize competition were reviewed. Sound and light barriers based on sweeping chirp signals and looming darkness, cavitation barriers, floating barriers using the Coanda effect to separate fish from water, electromagnetic longitudinal wave barriers, fish entrainment reduction structures to guide bottom-oriented fish, and subsurface withdrawal systems were either still theoretical concepts or were not fully relevant to the application at Lake Powell (https://americanmadechallenges.org/challenges/fishprotection/index.html).

At Dam Options

Deeper Water Withdrawal

Description

The river outlet works, located near the left abutment of Glen Canyon Dam, consist of two intake structures with trash racks, four 96-inch-diameter steel pipes, ring-follower guard gates, and hollow-jet valves for flow regulation. The centerline of each river outlet intake is 96 ft below the centerline of the penstocks. Releasing water from deeper in the reservoir water column may prevent downstream passage of non-native fish that reside in the reservoir epilimnion.

Applicability

Results of a 2012 hydroacoustic survey show that most sampled fish were located in the top 14 m (45.9 ft) of the water column with the first 4 m (13.1 ft) of water having the highest densities of fish (Bureau of Reclamation 2012). Water releases through the outlet works may have benefits for preventing non-native fish from passing downstream. Any fish passing through the outlet works would encounter hollow-jet valves and high conduit velocities of approximately 50 ft/s (water velocity in penstock design is limited to 20 ft/s), which may limit downstream survival. Releasing water through the outlet works may increase periodic review maintenance activities but would have no recreational impact. Deeper water releases may also have benefits for passing cooler temperature flows downstream which may restrict establishment of non-native fish by inhibiting spawning of warmwater non-native species.

Water releases through the low-level river outlet works bypass the turbines. Power generation is not possible during river outlet works releases. Reclamation is currently conducting planning-level activities to identify potential concepts for hydropower generation at Glen Canyon Dam below the minimum power pool of elevation 3490 as a solution for potential drought relief. A recently completed Value Planning study (in draft, 2022) has identified several alternatives, including a bypass powerplant, a low-level power intake within the dead pool that connects to the existing powerplant penstocks, dead pool lake tap tunnel(s), and connection of outlet works conduits to the existing powerplant penstocks. Since a permanent solution to hydropower generation below minimum power pool may take more than 15 years (depending on the alternative selected for construction), other fish escapement solutions will be needed in the near-term.

Turbine Mortality

Description

Fish passing through turbines are susceptible to direct blade strikes, pressure changes that rupture the swim bladder, and shear stress that can result in descaling, stripping of the protective mucus coating, and tissue tearing. Mortality rates can depend on broad range of variables such as species, life stage, size, pressure differential, diameter of intake pipe and turbine, number of blades, size and shape of blades, speed of blades, fish passage location within turbine, intake velocity, and entrainment duration. Mortality can be immediate, or injuries sustained during entrainment can result in delayed mortality.

Related Examples

A systematic review by Algera et al. (2020) confirmed that turbines and spillways increase the risk of injury and/or mortality for downstream passing fish compared to controls. They also reported that Francis turbines resulted in a higher immediate mortality risk than Kaplan turbines relative to controls (Algera et al. 2020). Based on the supplementary meta-analysis data presented in Algera et al. 2020, the mean survival in Francis turbines is approximately 58.8% (for species other than eels), but survival values vary widely across species and size class.

Electric Power Research Institute (1992) summarizes data showing that maximum survival of fish passing through Francis turbines is achieved near peak unit efficiency, mortality increases with head on the turbine, and smaller fish tend to have lower mortality rates, although larval fish mortality was not evaluated.

Applicability

Fish entrained in the Glen Canyon Dam penstocks will pass through Francis turbines. Fish mortality due to turbine passage will reduce the number of non-native fish that survive passage downstream of Glen Canyon Dam, but some survival is expected. Utah State University researchers are deploying a Sensor Fish in 2022 to measure pressures, stresses, and velocities that live fish may experience when passing through the turbines at Glen Canyon Dam. Results will provide more information on the likely survival of fish through the turbines. A winner of the Fish Protection Prize is currently developing a technology to direct fish to streamlines in the low-velocity region near the turbine hub to minimize the likelihood of severe strike injury and mortality (Natel Energy; https://americanmadechallenges.org/challenges/fishprotection/index.html). In a reverse application, guidance to the areas of highest strike may increase mortality. Fish passage through the

Francis turbines has no operational, power, maintenance, or recreational impact. However, the effectiveness of turbine mortality as the sole fish exclusion technology will not meet project goals.

Energy Dissipating Valve

Description

Energy dissipating valves are used to control flow in water distribution and water treatment systems. Energy dissipating valves can be used on reservoir outlets for in-line pressure reduction, flow control, and energy dissipation of outflow water to minimize downstream scouring of the outlet structure and river bed. Commonly used in areas with a high pressure drop, the sleeve valve can discharge to the atmosphere, or to a submerged outlet downstream.

Related Examples

A Pratt energy dissipating sleeve-valve model 711 (Henry Pratt Company) was installed near the terminal end of the 48-inch-diameter reservoir discharge pipe at Ridges Basin Dam in Durango, Colorado (Bark et al. 2014). The sleeve valve consisted of opposing tapered nozzle holes at 0.63 inch diameter in a helical pattern. The purpose of the sleeve valve was to eliminate fish and fish embryo survival from Lake Nighthorse in the discharge water to limit negative impacts to downstream native fish.

During testing, fish were subjected to passage through the 0.63-inch holes of the energy dissipating valve. Survival of Fathead Minnow *Pimephales promelas* (post-larval to adult < 75 mm), Bluegill *Lepomis macrochirus* (age-0 < 50 mm), Largemouth Bass *Micropterus salmoides* (age-0 and age 1+ < 75 mm), and White Sucker *Catostomus commersonii* (age-0 < 75 mm and age-1+ at 75-125 mm) into the discharge water was completely eliminated at a discharge pressure of 62 psi and reduced to less than 1 percent at pressures equal to or greater than 50 psi. Rainbow Trout embryo survival (eyed stage 4 to 5 mm) was reduced to 12 percent at the maximum pressure tested of 71 psi, but intact eggs could not be destroyed at any of the reservoir elevations and pressures tested.

Applicability

Installation of an energy dissipating valve on the downstream penstock at Glen Canyon Dam will likely eliminate most fish survival. This type of technology would have some maintenance and cleaning requirements and no impact to recreation. However, installing an energy dissipating sleeve valve on the downstream penstocks will have impacts to power production due to increasing headloss in the penstock pipe. Calculations should be made to better quantify projected losses to power production with installation of an energy dissipating valve.

Other At Dam Options

It is possible that carbon dioxide or electricity could be applied at lethal dose inside penstocks, however this conceptual approach to inducing mortality has not been researched in a high-velocity in-pipe application. Dose concentration and retention time would need to be determined for flowing pipes and narcotized fish may survive passage. With carbon dioxide injection, there may be impacts to downstream water quality. In a similar type of application, ultraviolet treatment in cooling water systems have been studied at Davis Dam and Parker Dam to reduce settlement and increase mortality of larval quagga mussels (Pucherelli and Claudi 2017, Pucherelli et al. 2018).

Downstream Removal

Manual Collection and Removal

Description

Non-native fish that survive turbine passage at Glen Canyon Dam could be collected and manually removed from the Colorado River downstream of the dam. A physical or non-physical barrier could be installed to guide fish into a sorting facility such that undesirable fish can be removed. Picket barriers, inflatable weirs, louvers, and other physical barriers along with multi-stimulus behavioral barriers are possible river guidance system options. Alternately, non-native fish could be targeted for boat-based removal efforts through continuous electrofishing or netting.

Related Examples

Reclamation's Tracy Fish Collection Facility diverts and salvages fish from Sacramento-San Joaquin Delta water prior to export by the C.W. "Bill" Jones Pumping Plant to the southern San Joaquin Valley. The primary channel consists of a series of louvers, or vertically aligned metal slats, positioned at 1-inch spacing that creates turbulence that fish avoid. Fish move through one of four bypass pipes into a secondary channel where further dewatering occurs. Fish are collected in holding tanks and placed into trucks for transport away from the pumping plant.

Washington Department of Fish and Wildlife and the Confederated Tribes conduct targeted boat-based suppression efforts to slow the downstream movement of Northern Pike in the Columbia River Basin. The agencies target known spawning locations and remove Northern Pike with gillnets.

The Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program have conducted non-native fish removal for almost 30 years at an increasing scale and a current cost of up to $2 million per year based on annual workplans for each program (Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program 2022). While the number of non-native fish, including Northern Pike and Smallmouth Bass, have been reduced, which is beneficial to the native and endangered fishes, the elimination of non-native fish is not expected or possible (Martinez et al. 2014).

Applicability

The Colorado River is contained by steep canyon walls downstream of Glen Canyon Dam. Access to the river is available at Lees Ferry which is located approximately 15 miles downstream of Glen Canyon Dam. A river-spanning barrier would have significant impact on recreation. Effectiveness of barriers for guidance of downstream-moving fish is variable and would be impacted by boat passage. Fish collection would not be species-selective and all native and non-native fish would be collected for sorting. Sorting facilities would be labor and cost intensive since personnel would be required to operate them daily. Manual collection and removal with electrofishing or netting would also be labor and cost intensive. In the Upper Colorado River Basin, electrofishing removal efforts have been successful in reducing Smallmouth Bass densities, but in years when environmental conditions are favorable, population increases have the potential to overwhelm removal efforts (Breton et al. 2014).

Other Downstream Options

Fish entrainment outflow tests were conducted at Blue Mesa Reservoir in 1994-1996 (Mueller and Hiebert 1997). Sieve nets were installed in the stoplog slots directly at the penstock exit to collect fish that passed through the dam. The net installation was temporary during the duration of the test and was not intended for permanent application. Inducing mortality through physical impact on grates or energy dissipating blocks may reduce survival, but not for all size classes. Preventing downstream movement using engineered drop structures is not viable option at Glen Canyon Dam due to the river gradient.

Discussion

Preventing downstream movement of non-native fish from Lake Powell to the Colorado River downstream of Glen Canyon Dam is a difficult problem without a definitive solution. There is no clear alternative that can fully eliminate fish escapement without impact to operations, power production, maintenance, and recreation. Table 1 summarizes the assessment of alternatives based on applicability to Glen Canyon Dam.

In-reservoir barrier options are exclusion devices that block the downstream movement of fish into the dam. Physical barrier screens are the more effective way to prevent passage of fish, but installation of a full-scale physical barrier is not feasible at the vertical and horizontal scale of this reservoir application and cleaning requirements would be notable. Various floating barrier options (nets, solid plates, curtains) are more feasible in terms of scalability and some larger-scale installations exist in other locations, but these barriers will only limit passage in the upper water column for certain fish sizes and anchoring will be challenging. Behavioral barriers have advantages in terms of a more limited in-water footprint and flow impedance, but effectiveness by species is highly variable. Underwater acoustic barriers are most effective for hearing-specialist fish species such as carp. Response to air bubble barriers varies by species and is limited by visual cues. Multi-stimulus behavioral barrier may provide the highest likelihood of success due to the variety of stimulus. Although no examples of behavioral barriers suspended in the upper part of the water column were identified (aside from electrical barriers), it may be possible to design such a system for Lake Powell. Exclusion options on or near the trashracks are attractive in terms of targeting a more finite area, but trashrack-mounted technologies may not provide enough reduction in fish entrainment, particularly if fish are passively drawn through the trashracks (4-⅜ inch clear bar spacing) based on local velocity or fish are immobilized by the barrier and transported through the penstocks. For all reservoir forebay installations, colonization by invasive mussels and Colonial Hydroid will increase inspection and maintenance needs and may disrupt barrier performance if barrier components are occluded or weighed down. Benefits of in-reservoir technologies include limited impacts to power production and recreation.

Options located at the dam can limit passage or survival. Fish passing through the Francis turbines may experience immediate or delayed mortality. Although data is highly variable, studies show that some fish survival is expected. It is unlikely the turbine mortality will be fully effective as the sole solution to eliminate fish entrainment. Deeper water withdrawal through the river outlet works will likely reduce fish entrainment, but water releases through the outlet works would bypass the turbines and power production is currently not possible. Installation of an energy dissipating valve on the penstock pipe will limit fish survival, but this device will impact power production by increasing headloss in the penstock pipe. The effectiveness of applying carbon dioxide or electricity within the penstock at lethal dose to ensure mortality of fish that pass through is uncertain due to low exposure time in the flowing pipes. Downstream barriers would require ongoing manual labor to collect and sort fish and would cause significant disruption to recreation, depending on the location of the barrier. Continuous electrofishing or netting would be labor and cost intensive.

Based on the review of applicable projects, a forebay barrier net or multi-stimulus barrier may be the most likely alternative to limit impacts to power production, operations, and recreation while maintaining a reasonable level of entrainment protection. Deeper water withdrawal through the river outlet works or installation of an energy dissipating valve on the penstock pipe will also likely limit passage of non-native fish, but considerable impacts to power production are expected. Preferred alternatives should be evaluated in greater detail to identify possible installation layouts and design features, anchoring strategies, anticipated efficacy, impacts to power production, implementation timeframe, and initial and ongoing costs.

Table 1. Initial assessment of alternatives to limit non-native fish escapement at Glen Canyon Dam. Alternatives with limited applicability to Glen Canyon Dam are not summarized.

		Possible Application	Scalability	Effectiveness	Operational Impact and Loss of Power Production	Inspection and Maintenance Requirements	Recreational Impact
In-Reservoir Barriers	Physical Barrier Screens	Installed in forebay, at trashracks, or in closed conduit.	Large width and depth and large discharge capacity limit practical application of barrier screens.	High for fish larger than the opening size of the screen.	Trashrack screens and closed conduit screens would increase headloss due to debris clogging.	Susceptible to debris clogging and biofouling, including mussel attachment, and must be regularly inspected and cleaned.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
	In-Reservoir Net	Suspended from buoy line; independent installation across forebay.	There is precedent for fish exclusion nets at large widths and relevant depths due to modular layout, but anchoring would be a challenge.	Similar installations show that nets are effective at reducing entrainment for fish larger than the opening size, but not eliminating it.	Headloss across the net should be minimal. Infrastructure safety concerns should be addressed if the barrier dislodges.	Susceptible to debris clogging and biofouling, including mussel attachment, and must be regularly inspected and cleaned. Nets can be removed annually or left in place.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
	Air Bubbles	Suspended from buoy line; independent installation across forebay.	There is precedent for air bubble barriers at large widths and relevant depths due to modular layout, but anchoring or suspension would be a challenge.	Uncertain; varies by species and limited by visual cues. May reduce, but not eliminate entrainment.	Requires continuous energy to run. Infrastructure safety concerns should be addressed if the barrier dislodges.	Limited in-water infrastructure, but may be susceptible to some debris and biofouling impacts and must be occasionally inspected and cleaned.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.

		Possible Application	Scalability	Effectiveness	Operational Impact and Loss of Power Production	Inspection and Maintenance Requirements	Recreational Impact
In-Reservoir Barriers (cont.)	Underwater Acoustic Barriers	Suspended from buoy line; independent installation across forebay.	There is precedent for underwater acoustic barriers at large widths and relevant depths due to modular layout, but anchoring or suspension would be a challenge.	Uncertain; varies by species; most effective for hearing-specialist fish species. May reduce, but not eliminate entrainment.	Requires continuous energy to run. Infrastructure safety concerns should be addressed if the barrier dislodges.	Limited in-water infrastructure, but may be susceptible to some debris and biofouling impacts and must be occasionally inspected and cleaned.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
	Multi-Stimulus Barriers	Suspended from buoy line; independent installation across forebay.	There is precedent for multi-stimulus barriers at large widths and relevant depths due to modular layout, but anchoring or suspension would be a challenge.	May provide best opportunity for behavioral deterrence due to multi-stimulus approach. May reduce, but not eliminate entrainment.	Requires continuous energy to run. Infrastructure safety concerns should be addressed if the barrier dislodges.	Limited in-water infrastructure, but may be susceptible to some debris and biofouling impacts and must be occasionally inspected and cleaned.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
	Carbon Dioxide Barriers	Suspended from buoy line; independent installation across forebay; injection at trashracks to influence near-field entrainment; lethal dose injection within penstock.	No precedent for carbon dioxide injection barriers in open, flowing water.	Effective in influencing fish movement in controlled environments (ponds, locks). Near-field effectiveness could be limited by narcotized fish being drawn through penstocks.	Requires continuous energy to run. Infrastructure safety concerns should be addressed if the barrier dislodges.	Limited in-water infrastructure, but may be susceptible to some debris and biofouling impacts and must be occasionally inspected and cleaned. Biofouling may be less likely in the presence of carbon dioxide.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.

		Possible Application	Scalability	Effectiveness	Operational Impact and Loss of Power Production	Inspection and Maintenance Requirements	Recreational Impact
In-Reservoir Barriers (cont.)	Floating Barriers	Suspended from buoy line; independent installation across forebay.	There is precedent for floating-type barriers at large widths and relevant depths, but anchoring would be a challenge.	Uncertain. Not enough relevant examples identified.	No power requirement. Infrastructure safety concerns should be addressed if the barrier dislodges	Susceptible to debris clogging and biofouling, including mussel attachment, and must be regularly inspected and cleaned.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
	Electrical Barriers	Vertically suspended electrodes in forebay via cable; electrified trashrack bars; lethal application within penstock.	No precedent for required width and depth of forebay barrier.	Effectiveness is size selective such that larger fish receive greater impact. Near-field effectiveness could be limited by narcotized fish being drawn through penstocks.	Requires continuous energy to run. Worker safety precautions needed in the forebay. Infrastructure safety concerns need to be addressed if the barrier dislodges.	May be susceptible to some debris clogging and biofouling and must be regularly inspected. Electrified trashrack application may have less maintenance.	Minimal, since barrier would be installed in forebay area not accessible to boaters and anglers.
At Dam Options	Deeper Water Withdrawal	Release through low-level river outlet works.	No scalability concerns.	Water withdrawal below epilimnion will likely limit fish passage; conditions within conduit may limit survival.	No hydropower generation possible during outlet works releases; planning activities underway for future power generation below the minimum power pool.	Some periodic maintenance expected.	No recreational impact.

		Possible Application	Scalability	Effectiveness	Operational Impact and Loss of Power Production	Inspection and Maintenance Requirements	Recreational Impact
At Dam Options (cont.)	Turbine Mortality	Fish passage through Francis turbines will reduce fish survival.	Mortality increases with head on turbine.	Francis turbines have higher immediate mortality than Kaplan turbines; percent survival depends on a broad range of factors. Unlikely to induce mortality at a high enough rate to be used as the sole fish exclusion solution.	Fish passage through the turbines will have no impact on operations or power generation.	Minimal maintenance expected.	No recreational impact.
	Energy Dissipating Valve	Installed in downstream penstock.	Likely scalable.	High effectiveness likely.	Energy dissipating valves will increase headloss in the penstock pipes with impacts to power production.	Minimal maintenance expected.	No recreational impact.
Downstream Removal	Manual Collection and Removal through Sorting Facility	Physical or behavioral barrier installed across narrower section of river to guide all fish into a holding and sorting facility.	There is precedent for physical and behavioral barriers and collection and sorting facilities at large widths and relevant depths.	All fish will be collected; effectiveness is likely moderate and will be based on species and size class; effectiveness will depend on ability to keep barrier clean of debris	Requires daily operation of new collection and sorting facility downstream of the dam. Behavioral barriers will have continuous power requirements.	Susceptible to debris clogging and biofouling; behavioral barriers require less inspection and maintenance.	Significant recreational impact; barrier would require boat passage depending on installation location.
	Manual Collection and Removal through Electrofishing	Electrofishing or other active boat-based manual collection.	Large-scale electrofishing programs are in place.	Electrofishing can reduce densities, but favorable conditions for fish can overwhelm efforts.	Requires daily boat-based suppression efforts.	Minimal maintenance expected.	No recreational impact.

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