



January 2026
Study of Physical Data Gaps to Inform the Implementation
of Nur Rematriation Upstream of Shasta Dam
AB 211 Drought Grant Agreement Number – Q2396040)



Appendix R

Literature Review to Support and Inform Artificial Lighting for Fish Passage

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Prepared for

California Department of Fish
and Wildlife
P.O. Box 944209
Sacramento, California
94244-2090

Prepared by

Anchor QEA
33 New Montgomery Street
Suite 1210
San Francisco, California 94105

Prepared by

HDR Engineering, Inc.
4717 97th Street
Gig Harbor, Washington 98332

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ABBREVIATIONS

| | |
|-----------------------|--|
| ALAN | artificial lighting at night |
| Background Compendium | <i>Background Compendium and Design Criteria Report for the Feasibility of Volitional Fish Passage Above Keswick and Shasta Dams</i> |
| CDFW | California Department of Fish and Wildlife |
| Consultant Team | Anchor QEA, HDR Engineering, Inc.; U.S. Geological Survey; and QEDA Consulting, LLC |
| HDR | HDR Engineering, Inc. |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| Nomtipom Waywaket | Winnemem Wintu words for Sacramento River |
| Nur | Winnemem Wintu word for Chinook Salmon |
| QEDA | QEDA Consulting, LLC |
| USGS | U.S. Geological Survey |
| UV | ultraviolet |
| Winnemem Waywaket | Winnemem Wintu words for McCloud River |

1 Introduction

A team of engineering and fisheries science consultants consisting of Anchor QEA; HDR Engineering, Inc. (HDR); U.S. Geological Survey (USGS); and QEDA Consulting, LLC (QEDA) known herein as the "Consultant Team," has received funding from the California Department of Fish and Wildlife (CDFW) to implement studies to gather data, compile information, and identify data gaps related to physical and biological conditions in the Study Area. These studies will be referred to within this document as the "Project." The results of the Project will support an investigation of the feasibility of providing volitional passage for fish, particularly Chinook Salmon (*Oncorhynchus tshawytscha*), above Keswick and Shasta dams on the Nomtipom Waywaket (also known as the Sacramento River) and into the Winnemem Waywaket (also known as the McCloud River) in northern California. In this document, Chinook Salmon is used to generally describe the species because once connectivity is re-established through reintroduction, fish will adapt to the new environments and could display run timing consistent with multiple runs. It is inclusive of Nur, which the Winnemem Wintu Tribe uses for Chinook Salmon that have been raised by the Tribe. The formal, Evolutionarily Significant Unit (ESU)-specific name (e.g., Sacramento River winter-run Chinook Salmon) is used when discussing federal Endangered Species Act (ESA)-listed Chinook Salmon or steelhead (*O. mykiss*). This document is an appendix to the overarching report documenting the results of the Project, which is called the *Background Compendium and Design Criteria Report for the Feasibility of Volitional Fish Passage Above Keswick and Shasta Dams* (Background Compendium). This larger report contains additional background information for the Project and this document should be considered within this context.

The Project Study Area extends from the confluence of Cow Creek and the Nomtipom Waywaket and includes the Winnemem Waywaket from Shasta Reservoir to the McCloud Dam (Figure 1). It includes portions of the Winnemem Waywaket; the Nomtipom Waywaket, including Keswick and Shasta dams and reservoirs; Cow Creek; Little Cow Creek; and Dry Creek. These water bodies vary in hydrology, geomorphology, and water quality, with seasonal fluctuations in temperature and flow; these parameters are being measured during this Project to evaluate habitat suitability and passage for salmonids. Understanding these physical conditions is essential to evaluating the feasibility of restoring fish passage to historical spawning and rearing areas upstream of the dams.

This document provides results and synthesis of a comprehensive literature review on lighting influences and effects on migrating salmon (specifically Chinook Salmon). The information includes summaries of available literature, applicability of previous studies to fish migration pathways proposed as part of the Shasta Reintroduction Study, and application of guidelines and theory to lighting requirements in future fish passage alternatives. Information provided herein will be used to inform the conceptual design process and address relative uncertainties regarding efficacy of fishways present in long dark environments like tunnels. Results of the overall Project will be used to support a volitional passage feasibility study that will be reviewed by the salmon co-managers

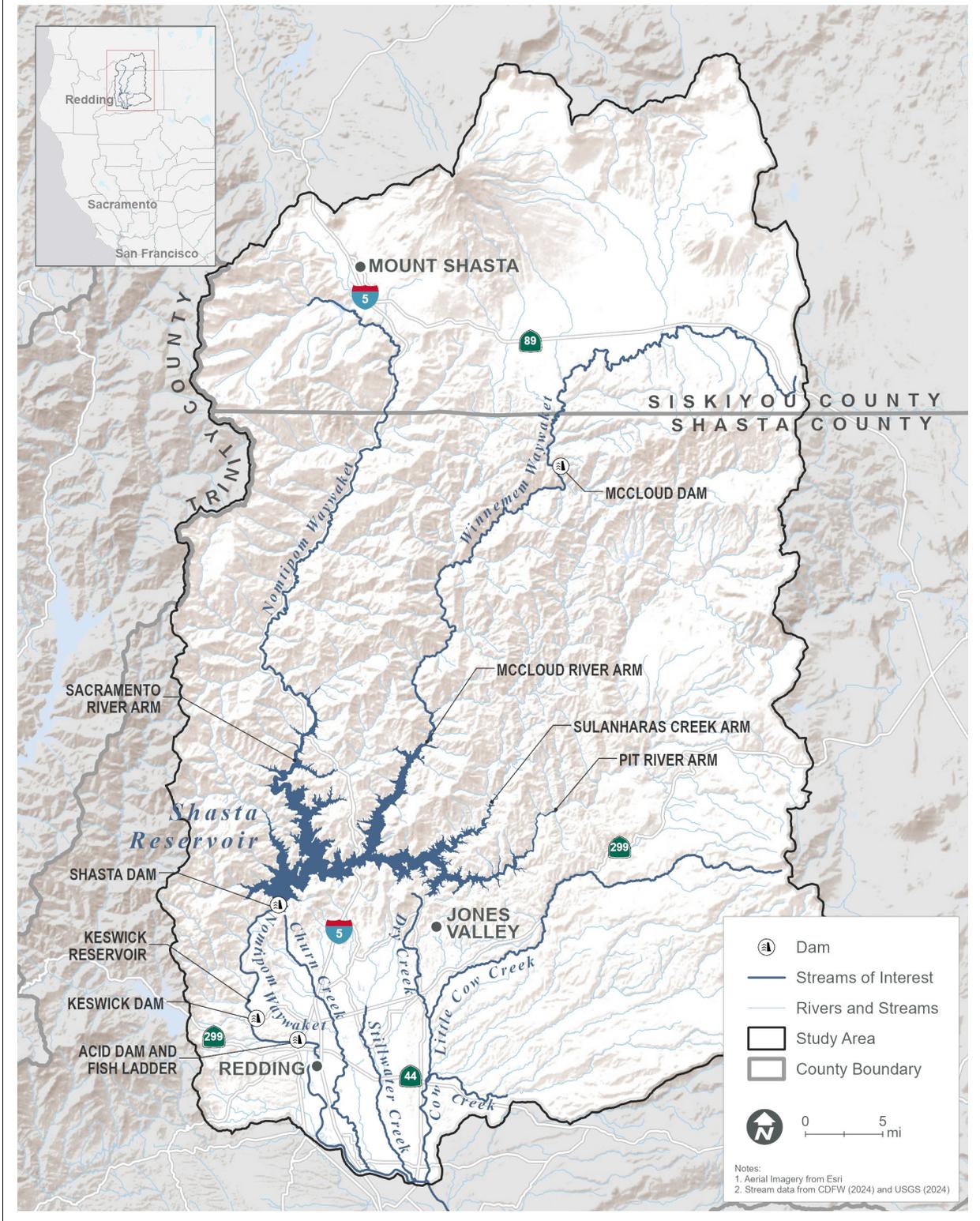
(Winnemem Wintu Tribe, CDFW, and National Marine Fisheries Service [NMFS]) and used to inform fish passage decisions.

The objectives of this document are to:

- Compile, and synthesize sources of information, literature, studies, and data regarding the influence of light on salmon migration behavior
- Summarize findings that help fill knowledge gaps regarding the behavior of salmon in ambient and artificially lit navigational pathways
- Identify applications and guidelines that can be used in the formulation and development of conceptual fish passage designs in long tunnels.

Readers should understand that on December 12, 2025, the Consultant Team received an email stating that the Winnemem Wintu Tribe does not endorse these reports (referring to the Background Compendium and appendices and *Alternatives Formulation and Evaluation Report* [Anchor QEA and HDR 2026]).

Figure 1
Study Area, Key Features, and Project Vicinity



2 Background

Light plays a fundamental role in the ecology and behavior of salmonids, shaping migration, predator avoidance, and foraging strategies. As salmonids encounter man-made structures such as culverts, dams, and long tunnels designed for passage, their ability to detect and respond to light becomes a critical design consideration. Research demonstrates that salmonids respond strongly to both the intensity and spectral composition of light, and in some instances, artificial illumination can delay migration, increase stress, or heighten predation risk (Schumann et al. 2025; Tabor et al. 2017; Vowles et al. 2014; Richards et al. 2007). It is important to understand lighting guidelines available in the best available science, including for salmonid visual physiology and behavioral responses to light, highlighting implications for artificial lighting in extended fishway conduits, such as with Alternative 1 shown in Figure 2.

Artificial illumination for fish passage systems has been reported to assist and improve the efficiency of fish passage to restore longitudinal riverine connectivity (NMFS 2023). Several research and case studies emphasize the need for a holistic approach towards designing a functional fishway, including all aspects of a fish's interaction with their environment. In a 2012 study, Vowles and Kemp argue that understanding the relationship between hydrodynamic cues and various environmental stimuli are critical towards implementing safe and successful lighting approaches (Vowles and Kemp 2012). However, there are mixed reviews on the effects of artificial light at night (ALAN), and fisheries researchers have often noted an increased effect of predation on smolt or juvenile salmonids when exposed to high light levels at night. Other research studies have posed that varying light levels can act as an attractant or a deterrent (Table 1).

Evidence from Mueller and Simmons (2008), Tetard et al. (2019), Vowles and Kemp (2012), and others shows that juvenile salmonids may be attracted to low-intensity lighting (~0.25 lux, equivalent to moonlight) but startled or deterred by intensities above 400 lux. For some species (e.g., Topeka shiner, fathead minnow), studies found no significant behavioral change in response to culvert lighting, highlighting the need for site-specific observation (Table 2).

NMFS (2023) states:

Ambient lighting should be provided throughout the fishway, and abrupt lighting changes should be avoided (Bell 1991). In enclosed systems, such as transport tunnels, provisions for artificial lighting should be included. In cases where artificial lighting is required, lighting in the blue-green spectral range should be provided. Artificial lighting should be designed to operate under all environmental conditions at the installation. These lighting criteria are based in part on laboratory studies where a majority of Chinook and sockeye salmon and steelhead entered the lighted orifice when given a choice

between a dark experimental orifice and a lighted control orifice where head was equal between the two orifices (Weaver et al. 1976).

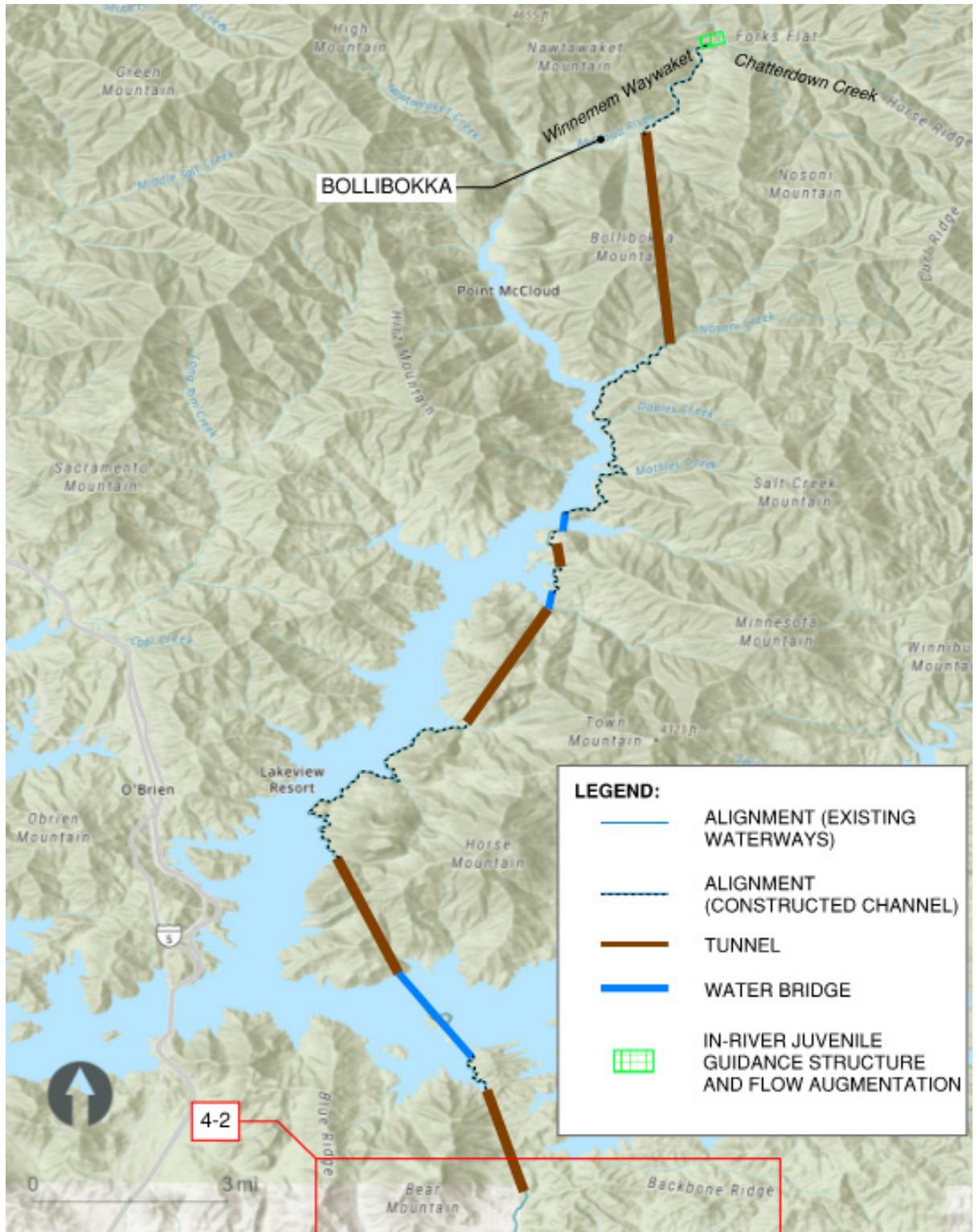
NMFS (2023) also recommends that “lighting conditions upstream of a bypass entrance should be ambient and extend downstream to the structure or device controlling bypass flow.”

Therefore, artificial lighting should be designed to mimic ambient light conditions, avoid high-intensity illumination, and minimize abrupt light transitions. In applications such as orifice or fishway entry lighting, night-time light levels should not exceed 0.25–3.3 lux, depending on target species and context, as recommended by field-tested studies (Mueller and Simmons 2008; Tetard et al, 2019; Vowles and Kemp 2012).

2.1 Fish Vision and Response to Light

Salmonids possess highly refined visual systems tuned to the variable light environments they encounter throughout their life cycle. Early physiological studies revealed multiple classes of cone photoreceptors sensitive to different parts of the light spectrum, enabling color vision and fine discrimination of ambient changes (Levine and MacNichol 1982).

Figure 2
Alternative 1: Passage Through Dry Creek, Constructed Channel Elements, Winnemem Waywaket



Bowmaker et al. 2008, Novales-Flamarique et al. 2016; Parkyn et al. 2008; Cheng et al. 2007; Hawryshyn et al. 2010). Browman et al. (1994) demonstrated that juvenile salmonids adjust photoreceptor function depending on habitat, while Hawryshyn (2010) emphasized the adaptive significance of shifts in spectral sensitivity during smoltification. Light not only mediates vision but also drives key ecological behaviors. Nemeth and Anderson (1992) observed that swimming performance and orientation are strongly modulated by illumination in their study on response of juvenile Coho Salmon (*O. kisutch*) and Chinook Salmon to both strobe and mercury lighting.

Like in research by Nemeth and Anderson (1992), behavioral evidence indicates that salmonids and other fish avoid abrupt transitions from light to dark or excessively illuminated conditions. Studies of culverts and small tunnels demonstrate hesitation or delay in passage where internal light levels were markedly lower than ambient river conditions (Axel et al. 2011; Kemp et al. 2008; Kemp et al. 2005; Richards et al. 2007). Similarly, Tabor et al. (2004, 2017, 2021) documented behavioral resistance at darkened passageways, among numerous other data points to support lighting as a catalyst to altered behavior, while Vowles et al. (2014) confirmed that juvenile Chinook Salmon exhibited higher rates of avoidance behavior when exposed to accelerating flows under light conditions when compared to dark, further exemplifying how visual cues amplify response to hydrodynamic stimuli. The results of Vowles et al. (2014) also suggest that artificial light enhances detection and reaction to velocity gradients, potentially increasing delay during downstream migration.

Brown (2000) discusses how strobe lighting systems developed by Flash Technology Corporation of America have shown promise in guiding fish away from high-risk areas like turbine intakes, especially for salmonid smolts. Extensive testing led to formal recommendations and permanent installations, demonstrating that strobe lighting can significantly reduce fatal fish entrainment under certain conditions.

Overall, the literature converges on three guiding principles: (1) provide light environments within tunnels that approximate natural daylight conditions, (2) avoid sharp light–dark contrasts across entrances and within passageways, and (3) consider the ecological risks of excessive illumination. These principles are essential for the design of long subterranean fishways (NMFS 2023).

2.2 Implications for Long Tunnels

Although most empirical studies focus on culverts, short fishways, or laboratory channels, their implications scale directly to the unique challenges of tunnels extending several miles. In such environments, ambient daylight cannot penetrate beyond the entrances, meaning the fish must pass through entirely dark or artificial light regimes. This raises concerns about fish orientation, delay, and stress over extended distances.

Work on culverts and short passage structures demonstrates that fish often hesitate at dark entrances and that delays can span hours to days if lighting is inadequate (NMFS 2023; Kemp et al. 2008; Mueller and Simmons 2008). Extrapolated to long tunnels, these delays could accumulate and compromise migration windows. The physiological consequences of prolonged dark passage may also be highly impactful. Elevated stress hormone levels have been recorded under mismatched light regimes (Congleton et al. 1988; Schumann et al. 2025; Richards et al. 2007).

Emerging studies suggest that spectral composition is as important as intensity. Hansen et al. (2018) and Jackson et al. (2024) found that certain wavelengths promote orientation (Chinook Salmon and Pacific Halibut, respectively), while others may suppress passage. Similarly, Schumann et al. (2025) emphasizes the need for artificial lighting that mimics ambient light, tuned to salmonid spectral sensitivity and circadian cycles. These findings echo earlier physiological work on photoreceptor function previously referenced.

Management guidelines are increasingly reflecting these principles. NMFS (2023) and highlight the need for gradual transitions, continuous illumination, and attention to wavelength, particularly in long confined structures. In the context of tunnels greater than 1 mile, this suggests designing lighting arrays that maintain uniform intensity throughout, emulate daylight spectra, and avoid over-illumination that could induce avoidance or predation risk (NMFS 2023).

3 Scope of Literature Review

Artificial lighting has been studied in a variety of aquatic and semi-aquatic contexts, though the body of work is fragmented across culverts, short tunnels, laboratory flumes, estuarine settings, and open-river migration studies. The literature on fish response to light in engineered passageways is relatively concentrated in smaller-scale or short-duration studies, with very few directly addressing the long, enclosed tunnel environments most relevant to Shasta Dam fish passage alternatives. Nevertheless, the collective findings from empirical experiments, applied case studies, and broader reviews provide important insight into the potential behavioral mechanisms, risks, and opportunities associated with light use in guiding and facilitating fish passage.

The scientific literature on fish responses to artificial lighting in passage systems has grown substantially over the past three decades, though the distribution of this work is uneven. Most of the passage-specific research has been conducted in culverts and short tunnels with additional insight from bypass and turbine avoidance studies. Laboratory studies, including controlled flume experiments provide detailed quantitative data on fish orientation, velocity, and attraction or avoidance responses under different light conditions. The broader ecological ALAN literature, though less passage-specific, extends this understanding by documenting species, and life-stage-specific variation in phototactic response, spectral sensitivity, and vulnerability to predation under illuminated conditions. Field-scale studies in long enclosed fishways are scarce, and virtually no studies have been conducted in tunnels approaching the length envisioned for the volitional passage around Keswick and Shasta dams alternatives.

3.1 Sources

Empirical studies were the focus of this review. Other resources, including several reviews and agency guidance documents, provide useful synthesis. These sources are particularly valuable for collating mechanisms of response attraction/avoidance, disorientation, and predation risk, and for linking lighting to outcomes such as migration delay or mortality.

Guidelines, Manuals, and Reports

- NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual (NMFS 2023)
- Technical Supplement 14N-Fish Passage and Screening Design (2007)
- Thomas, E. (2025). NOAA Fisheries Fish Passage Guidance and Criteria Engineering and Physical Sciences Branch NOAA Fisheries West Coast Region Salmonid Restoration Federation Fish Passage Design and Engineering Field School Why do we have Fish Passage Design Guidance Documents? <https://climatetoolbox.org/tool/Climate->
- California Department of Water Resources (2012) 2011 Georgiana Slough Non-Physical Barrier Performance Evaluation Project Report.

- NOAA Fisheries (2023). *Guidelines for Salmonid Passage at Stream Crossings in California*

Review Articles and Syntheses

- Alves, D. C., et al. (2019). Protocol for the assessment of mortality and injuries in fish larvae associated with their downstream passage through hydropower dams. *Reviews in Fish Biology and Fisheries*, 29(2), 501–512.
- Davies, T. W., et al. (2014). The nature, extent, and ecological implications of marine light pollution. *Frontiers in Ecology and the Environment*, 12(6), 347–355.
<https://doi.org/10.1890/130281>
- Harrison, P. M., & Silva, A. T. (2010). Upstream passage and entrainment of fish at hydropower dams: lessons learned from NSERC's (ResearchGate publication)

Attachment 1 summarizes each primary reference by species, life stage, light characteristics (intensity, spectrum, timing), observed behavioral response, and relevance to the Project.

4 Species-Specific Relevance

4.1 Target Species for Passage at Keswick and Shasta Dams

The effort to get fish above Keswick and Shasta Dams centers on historically extirpated winter-run Chinook Salmon, alongside the conservation of other runs of Chinook Salmon, steelhead (*O. mykiss* anadromous form), resident rainbow trout (*O. mykiss* resident form), and Pacific lamprey (*Entosphenus tridentatus*). Each of these taxa presents distinct ecological and sensory requirements. Chinook Salmon are the focal target because of their cultural significance to the Winnemem Wintu Tribe, federal listing, and recovery goals, but lighting strategies must be evaluated to avoid unintended passage barriers or physiological stress.

4.2 Empirical Evidence by Species

Light can influence fish behavior, orientation, and stress physiology across life stages. Within fish tunnels and conduits, ambient lighting conditions play a critical role in shaping passage success, particularly for salmonids. Experimental studies have shown that juvenile Chinook Salmon exhibit avoidance of abrupt light–dark transitions in flume environments, with elevated stress responses under brighter conditions. In contrast, low-intensity ambient lighting can facilitate smoother movement and reduce hesitation (Vowles et al., 2014).

Physiological research complements these behavioral observations. In controlled flume tests, plasma cortisol concentrations—a key indicator of stress—were significantly lower in Chinook Salmon smolts passing through completely darkened flumes compared to those exposed to partial daylight (Congleton et al., 1988). These findings suggest that reducing light intensity within tunnels may mitigate stress responses and improve passage efficiency. Steelhead, however, showed elevated cortisol levels regardless of lighting condition, with the highest increase observed in narrower baffled flumes. This indicates that while Chinook Salmon are more sensitive to light, steelhead may respond more strongly to hydraulic complexity.

Visual physiology studies further inform tunnel lighting design. Rainbow Trout, and steelhead possess polarization-sensitive vision, particularly in the ultraviolet (UV) and short-wavelength spectrum (Parkyn et al., 2003; Hawryshyn, 2010). These species can orient to polarized light fields, and trained individuals have demonstrated the ability to transfer this behavior to natural skylight conditions. During smoltification, UV-sensitive cones in the ventral retina undergo programmed cell death, reducing overhead polarization detection. However, UV cones persist in the dorso-temporal retina, allowing lateral detection of polarized cues. This suggests that tunnel lighting should avoid intense overhead sources and should favor lateral, diffuse illumination that mimics natural conditions.

Fish passage best available science reinforces the importance of ambient lighting. Silva et al. (2018) emphasize that successful passage requires minimizing delay and stress while maximizing approach, entry, and internal movement. Lighting interacts with hydraulic conditions and tunnel geometry to influence these outcomes. High-intensity or poorly placed lighting can act as a behavioral barrier, while ambient, spectrally appropriate lighting can enhance passage success. Moreover, the cumulative effects of lighting, flow acceleration, and tunnel design must be considered holistically to avoid unintended consequences such as fallback, disorientation, or ecological traps.

Taken together, the literature supports a key pattern: fish across taxa, including the target species for the Project, respond more favorably to gradual, ambient, and spectrally natural lighting than to abrupt or artificial illumination. Engineering applications should prioritize low-intensity, blue-green spectra and avoid sudden transitions to align with species-specific visual sensitivities and diel rhythms. This approach can reduce stress, improve orientation, and facilitate efficient migration through fish tunnels and conduits.

4.3 Applicability and Indirect Insights

In the absence of tunnel-specific empirical studies, indirect inference is necessary to evaluate implications for tunnels extending several miles.

Non-target species examined in the literature review are included because studies across taxa are informative and reveal diverse responses to lighting cues shaped by multiple variables including habitat, life stage, and behavioral ecology. These findings provide foundational insight into light-mediated movement and orientation necessary for evaluating fishway passage design and predicting species-specific outcomes. A broader dataset strengthens the ecological relevance of the review and supports hypothesis development for target species in data-limited contexts.

Culvert and weir studies demonstrate that salmonids in other basins benefit from low-intensity lighting continuity. Laboratory work on lamprey, zebrafish, and Asian carp confirms that abrupt contrasts are disruptive and that spectral sensitivity favors blue-green wavelengths. These findings justify applying ambient mimicry principles to Alternative 1 proposed volitional fish passage system.

4.4 Data Gaps

No studies have directly evaluated artificial lighting in long (approaching one mile and longer) tunnels. Data gaps include:

- **Longitudinal Lighting Effects:** Studies reviewed in this TM focus on short flumes or culverts. It is unknown how light exposure over many miles affects behavior, stress physiology, or migration timing.

- **Cumulative Stress and Fatigue:** While short-term cortisol responses have been measured, data on how prolonged exposure to artificial lighting, especially in enclosed, confined tunnels, affects cumulative stress, fatigue, and downstream migration success is lacking.
- **Behavioral Consistency Across Tunnel Zones:** It is unknown if fish maintain consistent movement patterns throughout a long tunnel or if lighting causes hesitation, fallback, or milling at certain points.
- **Integration with Hydraulic Conditions:** Lighting interacts with flow velocity, turbulence, and tunnel geometry. Integrated studies have not examined how lighting and hydraulics jointly affect passage success in long tunnels.
- **Post-Tunnel Outcomes:** Studies reviewed for this TM have not evaluated how lighting conditions within a tunnel affect fish once they exit—e.g., changes in orientation, predator avoidance, or spawning readiness.

5 Synthesis and Review

Fish, particularly juvenile salmonids, respond strongly to abrupt light, dark transitions, often hesitating or reversing course when encountering sudden changes in illumination. These behaviors can delay passage, increase energetic costs, and elevate stress. Conversely, ambient lighting, characterized by low-intensity, diffuse illumination that mimics natural conditions, has been shown to reduce hesitation and facilitate smoother movement through passage structures.

The physiological and behavioral sensitivity of fish to light is species and life-stage specific. Salmonids exhibit strong spectral preferences, with blue, green wavelengths aligning with their visual systems. Other species, such as lamprey, are less well studied, and their responses to artificial lighting in tunnel environments are largely unknown. This underscores the need for caution when extrapolating findings across taxa.

For long tunnels lighting should be designed as a neutral environmental feature, one that minimizes disruption and supports natural movement, mimicking natural ambient lighting (moonlight, starlight, diffuse sunlight). Artificial lighting schemes that rely on bright, directional, or strobe illumination risk creating ecological traps, altering predator-prey dynamics, or masking natural cues. Instead, the goal should be to make the tunnel “invisible” to fish by replicating the ambient light conditions they would encounter in open water or shaded stream corridors.

In summary, while direct empirical evidence for long tunnel lighting is limited, the collective findings from culvert, flume, and bypass studies provide a strong foundation for design principles. Ambient, spectrally appropriate lighting, applied consistently and without abrupt transitions, is the only strategy currently supported by the behavioral and physiological data. Future research should focus on filling critical gaps related to long-duration exposure, species-specific responses, and the integration of lighting and hydraulic conditions to ensure safe and effective passage through extended tunnel systems.

Table 1
Light Response of Target Fish Species

| Family | Species | Life Stage | Key Finding | Citation |
|------------|---|------------|---|---|
| Salmonidae | Coastal cutthroat trout; Mountain whitefish; Rainbow trout; winter-run steelhead; Brown trout | Juvenile | Context-dependent responses to artificial light in that they were often attracted to low-intensity light (<50 lux) but startled or avoided high-intensity light (>100 lux). Behavior included increased aggregation near illuminated structures, delayed migration, altered diel patterns, and elevated stress under continuous exposure. Studies also observed optimal swimming and welfare at moderate light levels | Mueller and Simmons, 2008; Tetard et al., 2019; Kemp et al., 2006; Liu et al., 2025; Tabor et al., 2004; Jensen 2023 |
| Salmonidae | Chinook Salmon, Coho, and Sockeye salmon | All | Light influenced movement or habitat selection in salmonids across life stages; (Sockeye Salmon)Avoidance of high-velocity acceleration zones under light may reflect stress or risk sensitivity; | Celedonia et al., 2007; Jensen, 2023; Kemp et al., 2006; Mueller and Simmons, 2008; Tabor et al., 2004; Tetard et al., 2019 |
| Salmonidae | Juvenile Salmonids | Smolt | Juvenile salmonids experienced delays or disrupted movement under artificial light exposure | Mueller and Simmons, 2008 |
| Salmonidae | Steelhead | Smolt | Higher passage under light; larger fish favored short weir under light | Kemp et al., 2006 |

Note:

Documented behavioral responses of key native fish species to artificial lighting or shaded conditions across various life stages. Findings are paraphrased for clarity and based on peer-reviewed and agency reports.

Table 2
Light Response of Non-Target Fish Species

| Family | Species | Life Stage | Key Finding | Citation |
|---------------|--|------------|--|---------------------|
| Anguillidae | European Eel (<i>Anguilla anguilla</i>) | Silver eel | Tended to avoid illuminated areas, possibly to reduce predation risk | Vega et al., 2024 |
| Centrarchidae | Carnivorous Fish (e.g., <i>Micropterus salmoides</i>) | Mixed | Carnivorous species had higher mean detection rate and relative read abundance under ALAN; <i>Micropterus salmoides</i> only detected under ALAN | Oyabu et al., 2024 |
| Cyprinidae | European Gudgeon (<i>Gobio gobio</i>) | Adult | Experienced delays or disrupted movement under artificial light exposure | Tarena et al., 2023 |

| Family | Species | Life Stage | Key Finding | Citation |
|------------|--|-------------------------|--|--|
| Cyprinidae | Italian Riffle Dace (<i>Telestes muticellus</i>) | Adult | Italian Riffle Dace (<i>Telestes muticellus</i>) showed no significant behavioral response to light or shade | Tarena et al., 2023 |
| Cyprinidae | <i>Schizothorax waltoni</i> | Adult | Preferred green > blue > red > yellow. Strong attraction to green and blue light, repulsion from red and yellow. Suggests green/blue for guidance to safe areas, red/yellow for deterrence | Xu et al., 2022 |
| Gadidae | Cod (<i>Gadus morhua</i>) | Juvenile | Light reduces upper codend entry only at night; No effect of illumination during the day | O'Neill et al., 2022 |
| Gadidae | Haddock (<i>Melanogrammus aeglefinus</i>) | Juvenile | Fewer enter upper codend under illumination and at night; Illumination and diel cycle reduce the proportion entering upper codend. Significant length interaction observed | O'Neill et al., 2022 |
| Salmonidae | Atlantic Salmon & European Eel | Fry; Migratory | Atlantic Salmon & European Eel experienced delays or disrupted movement under artificial light exposure. | Vega et al., 2024; Riley et al., 2013 |
| Salmonidae | Atlantic Salmon (<i>Salmo salar</i>) | Adult | Despite expectations, salmon successfully navigated a dark, low-velocity tunnel without lighting. Upstream migration confirmed via resistivity counter, even under sub-optimal hydraulic condition | Rogers and Cane, 1979 |
| Salmonidae | Atlantic Salmon (<i>Salmo salar</i>) | Smolt (Early Migration) | Reduced entry into lit bypass zone, but increased passage rate; Atlantic Salmon (<i>Salmo salar</i>) experienced delays or disrupted movement under artificial light exposure | Tétard et al., 2019; Vega et al., 2024 |
| Cyprinidae | Fathead Minnow; Topeka Shiner | Adult | No statistically significant trend in selection or movement through shaded vs unshaded areas | Kozarek et al., 2017 |
| Salmonidae | Sea Trout (<i>Salmo trutta</i>) | Adult | Sea trout successfully passed through the long, dark tunnel. Performance not improved by lighting; illumination deemed unnecessary | Rogers and Cane, 1979 |

Note:

Observed responses of non-target or related fish species to artificial lighting or shaded environments. Included for comparative context.

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