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Characterization of Gatewell Orifice Lighting at the Bonneville Dam Second Powerhouse and Compendium of Research on Light Guidance with Juvenile Salmonids

FINAL REPORT

RP Mueller
MA Simmons

September 2008

Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The study described in this report was conducted by the Pacific Northwest National Laboratory (PNNL) to provide biologist and engineers of the U.S. Army Corps of Engineers (USACE) with general design guidelines for using artificial lighting to enhance the passage of juvenile salmonids into the collection channel at the Bonneville Dam second powerhouse, managed by the USACE Portland District. The work comprised three primary objectives. The first was to review and synthesize all relevant studies in which artificial light was evaluated in a field or laboratory setting for its potential to guide fish at passage barriers within juvenile salmonid outmigration corridors. The second objective was to conduct a field study at the Bonneville Dam second powerhouse to evaluate the output levels of two artificial light sources at one orifice entrance within Gatewell 12. The third objective was to compare, in a laboratory setting, the performance of three light sources in terms of light intensity values.

PNNL reviewed 36 sources in the published gray and peer-reviewed literature and prepared a synopsis that includes the study objectives, species and life stage, experimental conditions, type of lighting used, and a summary of the results. We found that artificial lighting has been used in two general applications: 1) as a means to induce avoidance behavior by altering the fishes' swimming pathway and 2) as a guidance or attraction avenue to assist fish in locating safe passage routes. The literature review indicated that several factors play a combined role in the fishes' ability to safely navigate passage barriers. These factors include genetic makeup (species and subspecies), life stage, season, time of day, light levels, presence of predators, distance to cover, water temperature, group size, noise regime, and water current.

Our review determined that juvenile salmonids can be attracted to illuminated regions during nocturnal periods and can perceive light levels down to approximately 0.25 lux or 10^{-2} ft-c, equivalent to the light produced by moonlight. At the other end of the spectrum, we found that juvenile salmonids generally avoid or are startled when exposed to more intense light levels that correspond to daylight conditions or near 400 lux ($10^{-1.5}$ ft-c). To guide fish through manmade structures using artificial lights requires an understanding of the types of illumination and the nature of salmonid light perception. To respond to a light source, the fish visual system must be able to respond to the appropriate wavelengths that correspond to peaks in the spectral response of the photo receptors in the eye. Studies that have examined the use of artificial light to guide salmonids safely through migration barriers such as hydroelectric dams show measurable differences in juvenile responses to both the quantity and quality of the light stimulus. Our literature review concluded that any fish passage guidance structure must be based on an understanding of fish behavior and environmental and hydraulic conditions at the specific location.

Our field study at the Bonneville Dam second powerhouse (B2) found the existing lighting conditions at the orifice tubes in the downstream migration channel to be less than ideal to illuminate the entrance of the orifice. Based on our review of the lighting studies, a minimum luminance value of approximately 200–300 lux is needed at the orifice entrance. While some studies, in controlled laboratory experiments, have shown that this light intensity could possibly startle test fish (if exposure is sudden), light intensity values are expected to decrease rapidly within a short distance from the orifice. High water turbidity present for much of the spring outmigration period in the Columbia River also would play a role in decreasing light intensity at the orifice.

Field measurements of light intensity from light-emitting diode (LED) light bulbs at a single orifice in Gatewell 12 were low, at approximately 0.1 lux with a water-scaled lens. Light output for a 90-W halogen light with a water-scaled lens was 0.25 lux at the opening. When the water-scaled lens was exchanged for a new lens, the readings increased to 0.6 lux for the LEDs and 3.25 lux for the halogen light. For comparison, 1 lux is the amount of light produced by moonlight at high altitude, and 10 lux is the intensity of a candle at a distance of 1 ft. The halogen lights were far more effective at producing illumination near the orifice regions and outward to approximately 16 in. on axis with the opening, where the values were similar to the ambient light background measurements. The LEDs were less effective at illuminating the region; this was especially evident when the water-scaled lens was used. Both light sources produced light levels below effective minimum luminance values noted in the literature.

The laboratory tests were conducted at the PNNL Aquatic Research Laboratory in Richland, Washington. We measured the light output from halogen spotlights and mercury vapor lamps as well as the LED lamps currently in use at the B2. Our results using a water-scaled glass lens showed that the light loss for the halogen and the aqua green LED lamp was 5–6 times higher than the loss with a clean lens. Output from a mercury vapor lamp when the water-scaled lens cap was placed at the light face was reduced by only a factor of two. The drawback to using the mercury vapor and the halogen lamps is the amount of heat produced by the lens (250°F for the mercury vapor and 143°F for the halogen) and the reduced bulb life as compared to the LEDs.

Based on our study, some options for improving the lighting at the orifice entrances at the B2 include the following:

- Incorporate a ring of LEDs that would be recessed into the orifice opening, thus eliminating the need for the light tubes. An automated cleaning system also would be required.
- Incorporate the light source into the lens cap so that the cap and light housing is one waterproof unit. This would allow for all of the light to be directed into the light tube and eliminate the water scaling and debris-buildup issue, although water buildup still could pose a problem due to the splashing of water upward into the light tubes. Cleaning of the light and cap assembly also would be simplified.
- Use a white emitted light source that has a minimum luminance value of approximately 200–300 lux near the immediate orifice entrance.
- Incorporate higher-intensity LED lamps. Several manufactures have developed high-output LEDS that have been used in a variety of applications, including automobiles, flashlights, and residential and industrial interior and exterior lighting. These relatively new modules provide almost 50% more light (some up to 250 lux) than a standard 5-W LED bulb. Models of the cool white version have an expected 50,000-hour lifespan and have peak wavelengths of 440 and 550 nanometers.

To evaluate the effectiveness of any modification to the existing system, tests could be conducted in which tagged fish are released in the gatewell with a light-on/light-off scenario and the orifice passage efficiency evaluated. Different lighting sources could be tested to determine if white light or light emitted within the peak action spectra of juvenile salmonids (blue-green region) is best for attracting fish near the orifice where the flow component is sufficient for entrainment into the collection channel.

Acknowledgments

Funding for this project was provided by the U.S. Army Corps of Engineers (USACE), Portland District. Dennis Schwartz was the technical contracting officer, and Jonathan Rerecich and Tammy Mackey from the USACE helped coordinate work at Bonneville Dam. We thank Shon Zimmerman, Pacific Northwest National Laboratory (PNNL) Bonneville Field Office, for his assistance with the field study. Dr. Richard Brown, PNNL, served as the technical peer reviewer for this report.

Contents

Figures

Tables

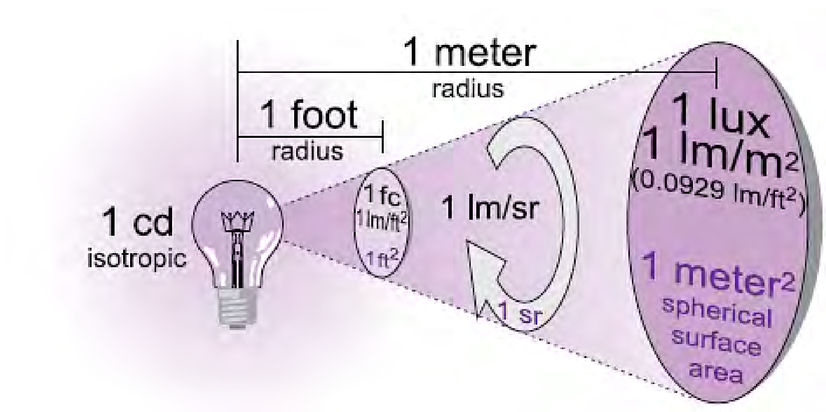
Abbreviations and Acronyms

B2	Bonneville Dam second powerhouse
cd	candela
cfs	cubic feet per second
deg	degree(s)
DSM	downstream migration (channel)
EPRI	Electric Power Research Institute
ft	foot, feet
ft-c	foot-candle(s)
in.	inch(es)
lb	pound(s)
LED	light-emitting diode
m	meter(s)
mm	millimeter(s)
nm	nanometer(s)
NTU	nephelometric turbidity unit(s)
OPE	orifice passage efficiency
PAR	photosynthetically active radiation
PIT	passive integrated transponder
PNNL	Pacific Northwest National Laboratory
USACE	U.S. Army Corps of Engineers
UV	ultraviolet
W	watt(s)

Glossary of
Light Measurement Terminology

candela The unit of luminous intensity. One candela is defined as the luminous intensity of 1/600,000 square meter of projected area of a blackbody radiator operating at the temperature of solidification of platinum under pressure of 101,325 newtons per square meter.

foot-candle A measure of light intensity; the amount of light received by 1 square foot of a surface that is 1 foot from a point source of light equivalent to one candle of a certain type (see illustration).



Irradiance (from http://www.intl-lighttech.com/services/light-measurement-handbook)

end foot-candle End foot-candle measurements are based on the focused light beam only. The spherical energy or surrounding light output is not captured by or reflected back to the surface of the foot-candle light meter. End foot-candle is the focal light beam measurement from point A to point B at a 1-foot distance.

lumen A unit of light flow or luminous flux. The lumen rating of a lamp is a measure of the total light output of the lamp. The most common measurement of light output (or luminous flux) is the lumen. That is, 1000 lumens, concentrated into an areas of 1 square meter, lights up that square meter with an illuminance of 1000 lux. The same 1000 lumens spread out over 10 square meters produce only 100 lux.

end lumens End lumens measurements are based on a spot of light only. The spherical energy or surrounding light output is not captured by or reflected back to the surface of the lumen light meter. End lumens is the light measurement from point A to point B at a 1-foot distance.

luminance Luminous flux (light output); the quantity of light that leaves the lamp, measured in lumens. Lamps are rated in both initial and mean lumens:

- Initial lumens indicate how much light is produced once the lamp has stabilized; for fluorescent and high-intensity discharge lamps, this is typically 100 hours.
- Mean lumens indicate the average light output over the lamp's rated life, which reflects the gradual deterioration of performance due to the rigors of continued operation; for fluorescent lamps, this is usually determined at 40% of rated life.

illuminance The intensity or degree to which something is illuminated as measured in lux or foot-candles.

lux The metric unit of measure for illuminance of a surface. One lux is equal to 1 lumen per square meter. One lux equals 0.0929 foot-candle.

light level Light intensity measured on a plane at a specific location is called illuminance. Illuminance is measured in foot-candles, which are workplane lumens per square foot.

efficacy of a light source The total light output of a light source divided by the total power input. Efficacy is expressed in lumens per watt.

radiance How much energy is released from a specific light source.

watt The unit of measuring electrical power. Wattage does not relate to the light output level. It defines the rate of energy consumption by an electrical device when it is in operation. The energy cost of operating an electrical device is calculated as its wattage time in hours of use.

Overview

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

The specific objectives for this study were to

1. Review and synthesize existing lighting data for juvenile salmonid attraction and deterrence and how the data are used at fish bypass facilities.
2. Evaluate current B2 orifice lighting conditions with both light-emitting diode (LED) and halogen lighting sources.
3. Conduct laboratory tests to measure the light output of halogen spotlights and mercury vapor lamps as well as the LED lamps currently in use at the B2 orifices.
4. Provide the USACE with recommendations as to what lighting intensity, source, and configuration would improve fish passage at the B2 orifices.

In this report, Chapter 1 provides PNNL's synthesis of the relevant literature related to light and fish guidance for both field and laboratory studies. Chapter 2 presents a description of the PNNL field measurements of light levels at one B2 orifice through which fish must pass to reach the fish collection channel. Two light types were evaluated—LED lights and halogen spotlights. Additional measurements with mercury lamps were made at the PNNL Aquatic Research Laboratory in Richland, Washington, to determine baseline intensity of the current lighting. Recommendations based on the study are offered in Chapter 3. An Appendix presents a tabulated synopsis of literature reviewed as part of this study.

Chapter 1

Compendium of Research on Using Artificial Light To Guide Juvenile Salmonids – Field and Laboratory Studies

Mary Ann Simmons and Robert P. Mueller

Introduction

The objective of this task was to review the available literature on the response of juvenile salmonids to light, specifically to lights used as guidance at hydroelectric facilities. We further focused the review on non-strobe light sources such as incandescent and mercury vapor lights. The Appendix to this report provides a synopsis of the literature reviewed in table format.

Reviews of the response of fish to lights have found a range of responses, from no response to attraction and repulsion. Factors affecting the response appear to be species, age, previous light exposure, and light source.

Table 1.1 contains a list of species studied in the reviewed sources. Two common names are listed for *Oncorhynchus nerka* and *O. mykiss*; the first is the anadromous species, the second the freshwater counterpart. Figure 1.1 shows the various developmental stages for anadromous Pacific salmon species. Juvenile salmon encompass the alevin, parr, and smolt stages.

Figure 1.2 illustrates the range in the lighting spectrum; Figure 1.3 shows the color spectrum associated with visible light. Table 1.2 includes the most common light units reported in the literature—foot-candles (ft-c) and lux—as well as examples of the amount of visual light these represent. Another unit of light, microeinsteins, is used to describe electromagnetic radiation and cannot be converted easily to lux without knowing the spectral distribution of the light source.

Table 1.1. Common and scientific names for Pacific Northwest salmon and trout used in light studies

Common Name	Scientific Name
Chinook	*Oncorhynchus tshawytscha*
Sockeye/Kokanee	*Oncorhynchus nerka*
Steelhead/Rainbow trout	*Oncorhynchus mykiss*
Coho	*Oncorhynchus kisutch*
Chum	*Oncorhynchus keta*
Pink	*Oncorhynchus gorbuscha*
Cutthroat trout	*Oncorhynchus clarkii*
Brook char	*Salvelinus fontinalis*

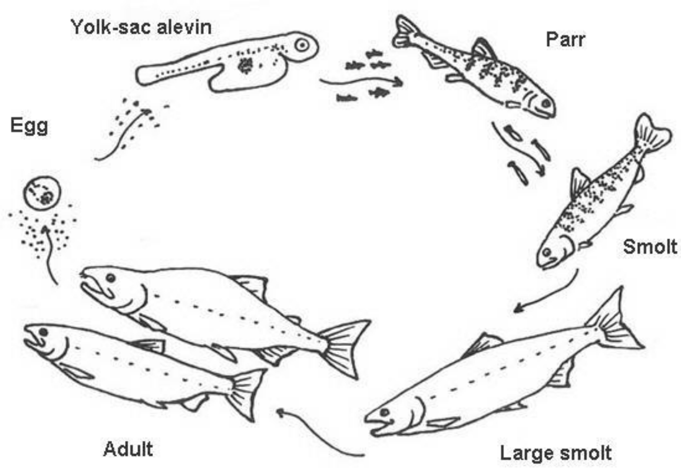


Figure 1.1. Life cycle of anadromous Pacific salmon showing major developmental stages. Illustration © Vancouver Aquarium Marine Science Centre (http://www.vanaqua.org/ salmontales/english); reproduced with permission.

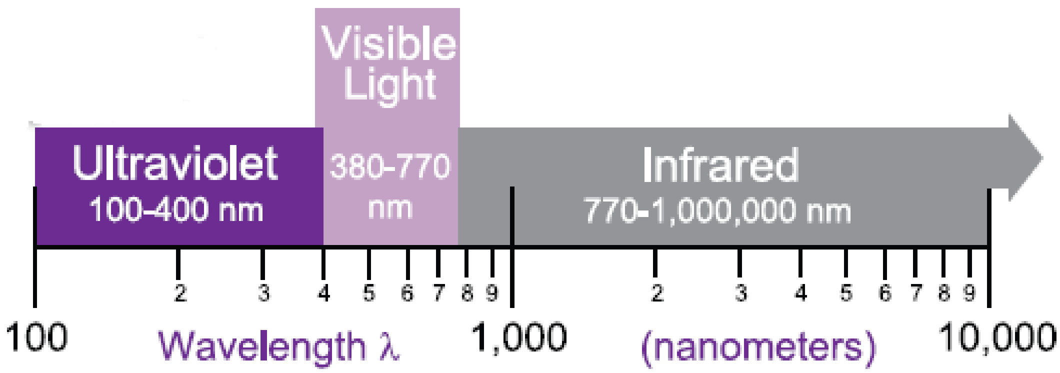


Figure 1.2. Entire light spectrum (from *The Light Measurement Handbook*, http://www.intl-light.com)

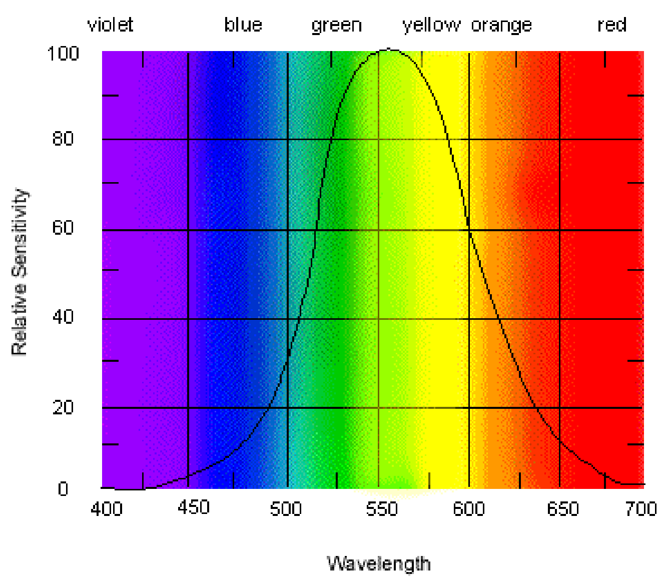


Figure 1.3. Visible color light spectrum and associated wavelengths (nanometers)

Table 1.2. Light levels in lux and foot-candles for various levels of daylight (http://en.wikipedia.org/wiki/Daylight)

Example	Lux	Foot-Candles
Starlight	0.00005	4.65E-06
Moonless overcast night sky	0.0001	9.26E-06
Moonless clear night sky	0.001	0.0000929
Quarter moon	0.01	0.000929
Full moon on a clear night	0.25	0.0232
Moonlight	<1	0.0929
Sunrise or sunset on a clear day	400	37.2
Sunlight on an average day (min)	32,000	2973
Sunlight on an average day (max)	100,000	9290
Conversion: 1 foot-candle = 10.764 lux.		

The range of the visible light spectrum perceivable by the human eye encompasses wavelengths from 380 to 770 nanometers (nm). Many species of fish have visual sensitivities into the shorter wavelengths of the ultraviolet (UV) range starting at approximately 350 nm (Bowman et al. 1993) (Figure 1.4).

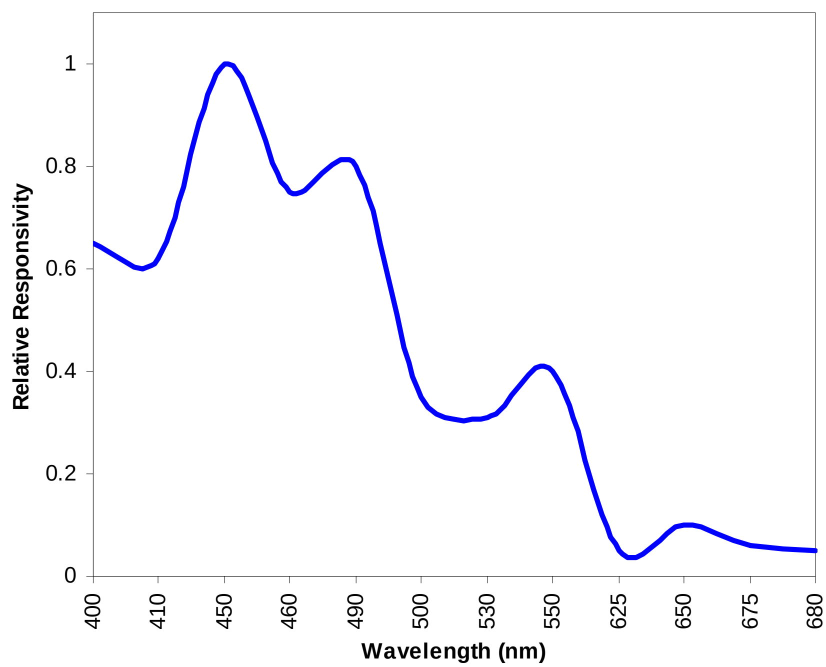


Figure 1.4. Average action spectra of six juvenile rainbow trout in a controlled laboratory experiment (Douglas 1983)

Our review first includes a discussion of behavior of juvenile salmonids with respect to ambient light levels, followed by a description of studies on the physiology of the fish's eye and the response to light stimulus. The next two sections of this chapter discuss results of laboratory and field studies of the response of fish to lights.

Juvenile Salmonid Fish Behavior

The response of fish to light is dictated by a number of factors, including species, age, the light source, and previous exposure to light. Our main focus of this review was on anadromous Pacific salmonids that, after a varying amount of time in freshwater, migrate to the ocean and must pass around or through numerous dams. The collective physiological changes occurring as the salmon goes from freshwater to seawater are termed *smoltification*. Behaviorally, in preparation for downstream migration, the juvenile fish must leave in-shore or bottom habitats for the open water. Photoperiod has been linked to smoltification. The length of the photoperiod appears to influence plasma levels of thyroxine and cortisol, hematocrit levels, condition factor (length–weight relationship) and the hepatosomatic index (Hoffnagle and Fivizzani 1998). Both chum and coho salmon were found to prefer open water to shaded areas after exposure to elevated thyroid levels (Iwata 1995).

The behavioral response to light (both ambient and artificial) by juvenile salmonids varies with species and age. The alevins of Chinook salmon are initially negatively phototactic (Beauchamp et al. 1983) and migrate downward into the gravel. After yolk absorption, the fish emerge during nocturnal periods as free-swimming fry. Juvenile steelhead are primarily bottom feeders, occur in areas with the highest stream cover (Pauley et al. 1986), and tend to be quiescent at night (Simenstad et al. 1999). Sockeye fry are extremely light-sensitive and remain hidden under stones and debris during the day, emerging at dusk (Pauley et al. 1989). Pink and chum salmon show nocturnal activity and are either negatively phototaxic (Simenstad et al. 1999) or positively phototaxic (Hoar et al. 1957), depending on the light level. Juvenile coho salmon (74–104 mm) exhibit a strong cover-seeking reaction when exposed to full ambient daylight, while juvenile Chinook salmon (79–115 mm) appear unresponsive to light stimuli (Nemeth and Anderson 1992).

A multiyear monitoring study of juvenile fall Chinook salmon implanted with passive integrated transponder (PIT) tags migrating down the Snake River found shoreline collections of fish declined abruptly when the fish reached 60 mm fork length (Connor et al. 2003). Fish then moved offshore and began the downstream migration. A study at McNary Dam found that nearly 80% of migrating fall Chinook salmon smolts chose an uncovered channel versus a covered channel when presented with the choice (Kemp et al. 2005). These results provide additional evidence for a change in behavior associated with smoltification and subsequent downstream migration.

The diel movement and vertical distribution of migrating smolts of Chinook salmon, steelhead, and sockeye salmon at The Dalles and McNary dams on the Columbia River were evaluated in 1960 and 1961 (Long 1968). Results showed that more fish were caught at night compared to the numbers caught in the daytime. All catches were made at turbine intakes. In a study of residence time in the fish passage system at McNary Dam, most fish (juvenile Chinook salmon and steelhead) passed from the gatewell to the collection channel during the evening, regardless of the time they were released (i.e., midday vs. evening) (Beeman and Maule 2001). Evidence suggests that migration begins as light intensity falls below the cone threshold (Simenstad et al. 1999). At this light level, the fish is unable to maintain position in relation to a given reference point.

Schilt (2007) reviewed fish passage and protection at hydropower dams. In the Columbia River basin, he found juvenile salmon passage follows a diel trend, with deep passage through turbines and spill bays occurring in late evenings and early mornings, while shallow passage through surface routes occurs during daylight hours. He also noted that light-based behavioral guidance systems are limited by turbidity and habituation.

Small fish avoid lights generally because of predation (Nemeth and Anderson 1992; Tabor et al. 2004). Tabor et al. (2004) in a series of laboratory and field experiments found downstream migration by sockeye fry was hindered by lights (maximum 10.8 lux), and the fish were then more vulnerable to predation by sculpin.

Visual Systems

Guiding fish through manmade structures using artificial lights requires an understanding of the types of illumination and the nature of salmonid light perception. For fish to respond to a light source, their visual system must be able to respond to the appropriate wavelengths that correspond to peaks in the spectral response of the photo receptors in the eye. Research suggests that the increase in the number of cones as the eye of juvenile fish grows larger leads to greater sensitivity and improved resolution of an image (Northmore et al. 1978; Fernald 1988). These developmental changes are important and provide for the ability to migrate at progressively lower light intensities. In addition, the spectral response of the eye differs within species and life stage of the fish (Fernald 1988). Studies that have examined the use of artificial light to guide salmonids safely through migration barriers such as hydroelectric dams show measurable differences in juvenile responses to both the quantity and quality of the light stimulus. Juvenile salmonids have specific sensitivity in the blue and green wavelengths; most freshwater teleosts have three cone pigments that absorb at their maximum around 455, 530, and 625 nm (Loew and Lythgoe 1978). The action spectra of juvenile rainbow trout peaks at approximately 450 nm (Figure 1.4).

The following studies examined the spectral sensitivity of Pacific salmon to visible and UV spectra. Several studies looked at species differences, and others investigated mortality related to light exposure.

The visual system of salmonids contains both rhodopsin and porphyropsin visual pigments (Alexander et al. 1994). Rhodopsin is associated with shorter wavelength spectral sensitivity, while porphyropsin is associated with longer wavelengths. Retina with equal mixtures of the two pigments will have intermediate spectral sensitivities. A study of coho salmon through the smoltification process found the proportion of these two visual pigments shifted from a porphyropsin-dominated visual pigment in pre-smolts to a rhodopsin-dominated retina in the smolt stage (Alexander et al. 1994). The shift in visual pigments was hypothesized to allow the fish better visual acuity in the marine environment, which allows for the passage of shorter wavelengths than do the freshwater habitats.

An extensive study of the structure of the eye in response to different light levels was conducted by Ali (1959). Four species of salmon (sockeye, chum, pink, and coho) were studied, from alevin through smolt stage. Physical changes in the eye as well as schooling and feeding behavior were evaluated. Figure 1.5 illustrates the results in relation to known light levels. In general, schooling and feeding occur at light levels occurring at dawn and dusk that correlate to intensities of 10^{-1} for coho salmon. Times for cones and pigment to fully adapt to light or dark conditions were between 10 and 20 minutes, depending on species and life stage. The times for cones to fully adapt correlated well with maximum feeding rates. The study concluded that downstream movement of juvenile salmonids occurs as a result of their eyes being in a semi-dark adapted state for a short duration at dusk. The fish gradually lose their reference points and swim with the current while being displaced downstream.

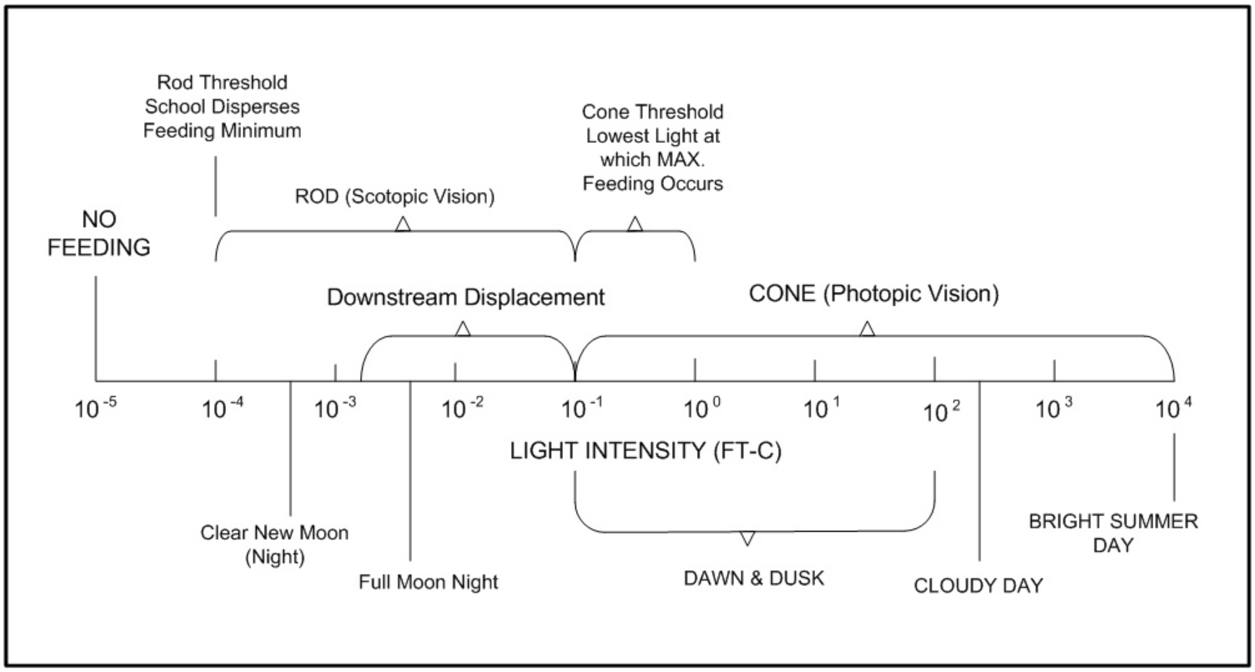


Figure 1.5. Response of juvenile Pacific salmon to various light intensities and the relationship to ambient light (Ali 1959, p. 987, Fig. 14; © *Canadian Journal of Zoology*; reproduced with permission)

A study of the photic environment of Lake Cowichan in British Columbia, Canada, found changes in both light intensity and spectral composition with depth and time of day (Novales-Flamarique et al. 1992). The spectral composition of surface layers had fairly equal proportions of UV, short, middle, and long wavelengths. Near the bottom, middle and long wavelengths dominated the spectra. Over the day, peaks in UV and blue light were noted prior to sunrise and immediately after sunset; the opposite occurred for long wavelengths. Similar changes in spectral composition may be evident also in large rivers such as the Columbia.

Parkyn and Hawryshyn (2000) found the spectral sensitivity in response to an increase in light differed among juvenile (parr) salmonid species. Specifically, the response was dominated by L- (long or red) and M- (medium or green) cone mechanisms in steelhead, rainbow, cutthroat trout, and brook char, while in kokanee the M-cone mechanism dominated. There were no species differences in the response to a decrease in light intensity. The differences noted for the light response may be linked to habitat; species with the L- and M-cone mechanisms inhabit streams and rivers, while kokanee is a lake species. Table 1.3 lists the maximum eye receptor cell response for rainbow trout, sockeye salmon, brown trout, and brook trout.

Table 1.3. Comparison of the maximum spectral sensitivity of the photopic mechanisms in salmonids (from Bowmaker and Knuz 1987; Parkyn and Hawryshyn 2000)

Species	Photopic Peak Cell Response (nm)
Rainbow trout	375, 440, 540, 580
Sockeye salmon	370, 440, 520, 590
Brown trout	355, 441, 535, 600
Brook char	370, 420, 540, 560

Novales-Flamarique (2000) examined the spectral sensitivity of sockeye salmon throughout its life history. No differences were found in the cone mechanisms related to short-, middle – and long-wavelength sensitivity over the life stages of these salmon. However, cones sensitive to UV wavelengths were found to disappear at the smolt stage and reappear in the adult. It was hypothesized that the UV cones improve prey contrast and that the loss of UV cones may be an accidental consequence of hormonal changes during smoltification. Similar results were noted for rainbow trout and steelhead (Deutschlander et al. 2001).

A test of foraging and prey-selection under polarized light by rainbow trout found prey were detected at greater distances under polarized light compared to unpolarized lights (Novales-Flamarique and Browman 2001). In another study, juvenile rainbow trout, steelhead, and brook trout were trained to orient relative to the axis of polarized light (Parkyn et al. 2003); however, untrained fish showed no orientation response.

The visual pigments and photoreceptor types in coho, chum, and Chinook salmon were examined relative to time of year and developmental stage (Novales-Flamarique 2005; Novales-Flamarique et al. 2006). All three species had visual pigments with maximum absorbance in the UV, blue, green, and red parts of the spectrum. However, fish in the alevin stage did not have blue visual pigments. All fish had rod photoreceptors with visual pigment in the 504- to 531-nm range. Temperature affected the peak absorption of the visual pigments during smoltification and appears to be linked to hormonal factors that vary with species, developmental stage, and environmental variables (Novales-Flamarique 2005).

One study looked at visual performance and physical changes in retinal morphology in sockeye and kokanee following exposure to strobe lights (Novales-Flamarique et al. 2006). Overall, there were no detectable changes after a 5-minute exposure to strobe lights; however, a 3-hour exposure resulted in mortality. Behaviorally, fish exposed to strobe lights showed an escape response to an overhead shadow.

In the review by Simenstad et al. (1999), the amount of time required for structural changes to occur in response to variations in light intensity varied with species and life stage. They report that 30 to 40 minutes were required for light-adapted chum and pink salmon to fully adapt to dark, while dark-adapted fry required 20 to 25 minutes to adapt to increases in light. During these periods, visual acuity ranged from periods of blindness to slightly diminished, depending upon the magnitude of the contrast in light intensity.

In summary, it appears juvenile Pacific salmon are most sensitive to the blue-green spectra characteristic of mercury vapor lights. There were few species differences in visual morphology or spectral sensitivity. The major life-history change involves the loss of UV sensitivity during smoltification, which returns in adult fish. Overall, juvenile salmon are able to discern the wavelengths found in ambient light.

Laboratory Studies

Early evaluations of the response of salmon species to light were conducted between 1959 and 1963 at the University of Washington (Fields 1966). The first tests were conducted in outdoor raceways using several species of young of the year salmon and steelhead. Tests conducted in both daytime and nighttime found fish preferred the darker side of the raceway. At night, fish avoided the artificially lighted side. In a separate study, juvenile salmon and steelhead (28 to 275 mm) were placed in an aquarium and exposed to a light gradient. All species of downstream migrating salmon were found to prefer the darker portion of the light gradient. However, the fry of some species exposed previously to light (e.g., hatchery Chinook salmon) were attracted to the light.

In another series of tests, fish were exposed to multiple levels of light, water depth, and velocity (Fields 1966). The levels of illumination were 0.31 and 40 ft-c and water velocities of 0.37 and 3.90 ft/sec. Results indicated that the fish generally avoided lighted areas, and fewer fish entered the lighted areas as the light intensity increased. However, velocity had a distinct effect on the response to light, with more fish found in lighted areas as the velocity increased. There was a species difference; steelhead were the most sensitive to light, and Chinook salmon the least.

Hoar et al. (1957) measured the attraction/avoidance response of several species of fry and smolt salmon (pink, coho, chum, and sockeye) to changing light levels. In the tests, fish had a choice of lighted or darkened areas within the aquarium. They were exposed to either increasing light levels (5 to 1000 ft-c) or constant illumination (500 ft-c). The changes from one light level to the next were abrupt, and the fish remained at that level for 10 minutes before the light level was increased or decreased. Light levels used in the exposure were generally less than maximum sunlight; values given in the report indicate 1000 ft-c corresponds to light levels between 0900 and 1000 hours (Pacific Standard Time) in May in Fort St. John, British Columbia. In no case was the response all or none; fish would pass between the light and dark areas of the tanks. In general, the response to light was dependent on the species and age (fry vs. smolt) of the fish. Chum and pink salmon fry showed a preference for light, while sockeye fry retreated to darker areas and coho fry appeared to be indifferent to moderately high light levels and inactive at low light levels. The smolt stage of both sockeye and coho salmon was associated with an increasing sensitivity to light.

Puckett and Anderson (1988) conducted laboratory tests on juvenile Chinook salmon (average length = 53 mm). The fish were exposed to an adaptation light (0.1 to 1 microeinstein/m^2/s) for 20 minutes, then exposed to a stimulus light; behavior was monitored for 2 minutes. The intensity of the stimulus light varied such that the ratio of the stimulus light to the adaptation light ranged from 0.005 to 100. Water was flowing during the experiments, but no measure of velocity was given. The study found that juvenile Chinook salmon were attracted to light, and the strength of the attraction was related to the ratio of intensity of stimulus to adaptation light. Maximum attraction was when the ratio was 1 and light levels were 0.5 microeinstein/m^2/s (which approximates moonlight). Attraction was less as either the stimulus light increased relative to the adaptation light or decreased relative to the adaptation light. Puckett and Anderson noted that when the stimulus light was brighter than the adaptation light, fish were attracted to the dim zone that bounded the intense light spot. When the ratio was 100, fish were observed to swim to the farthest reaches of the test flume.

The behavioral response of juvenile coho and Chinook salmon to mercury lights was evaluated under different pre-exposure light regimes (Nemeth and Anderson 1992). In these tests, fish were adapted to one of four conditions: normal daylight, normal nighttime, and reversed day and reversed night. For reversed day, the test raceway was darkened during the day, while for reversed night, the raceway was illuminated at night. Fish were then exposed for an hour to a mercury vapor light. Light intensity in the raceway varied from 100 microeinsteins/m^2/s at 1 m to near zero at 8 m; the raceway was 8.8 m long. Under ambient light adaptation, coho salmon hid during the day and swam actively at night when exposed to mercury lights. Under reversed adaptation, there was no clear response; approximately half of the fish were passive, while the other half were active (dark adapted during the day) or hiding (light adapted during the night). For Chinook salmon, there was no response to lights during the day under ambient lighting, while at night fish first actively swam toward the lights and then away. Under reversed adaptation, Chinook salmon swam actively when the mercury light was turned on. Mercury vapor lights emit in the blue-green range (450–550 nm) (Pauley et al. 1986).

A floating test platform in the Yakima River was used to evaluate the response of Chinook salmon smolts to drop lights (Amaral et al. 2001). The movement of fish with respect to the lights was video-taped under ambient daylight and dusk conditions. At night, additional low-level lights were used to facilitate the video recording. Test conditions involved 1- and 2-minute exposures to lights, separated by a rest period. In addition, the lights were either on continuously during the test or turned on/off every 1 or 15 seconds. Results indicated a weak avoidance, with fish generally moving less than 0.5 m further from the lights when they were on. The authors mentioned there was no startle response and only a few dramatic movements in response to the lights.

Kelly and Bothwell (2002) examined the response of juvenile coho salmon to UV radiation. In the experiments, an outdoor test enclosure was covered with two solar exclusion panels, creating a binary choice for the fish. The panels contained filters that allowed fish to be exposed to only photosynthetically active radiation (PAR; 400–700 nm), PAR plus UV-A (320–400 nm), PAR plus UV-A and UV-B (280–320 nm), and 50% PAR plus UV-A and UV-B. Results showed fish had a significant preference for the absence of UV radiation. This preference was not evident on cloudy days when solar intensity was half that under full summer sun. The avoidance of high light environments by juvenile salmonids has been linked to a predator avoidance response, but it also could be an avoidance of harmful UV radiation.

An experiment evaluating fish (smolts of coho, Chinook, and steelhead) response to a bypass system found that 70% to 90% of the fish preferred the side of the model constructed of clear Plexiglas (Wert 1988). When the Plexiglas was covered with opaque plastic, fish appeared to swim randomly within the model.

A laboratory test of juvenile salmonid response to strobe lights found that, after an initial escape response, fish were observed to maintain position or follow the penumbra (i.e., the edge between darkness and intense brightness of the strobe light) (Hays 1988). No light levels were given.

Douglas (1983) conducted laboratory tests on the corneas of rainbow trout that were exposed to 150-W tungsten light and a monochromatic light. He found the light output of the tungsten white light served as a broad-based band stimulus and tended to stimulate all types of visual receptors in juvenile rainbow trout. This study also showed that rainbow trout have the ability to distinguish color.

Field Studies

The University of Washington conducted field studies in addition to its laboratory work (Finger and Fields 1957; Fields et al. 1958; Fields 1966). These studies focused on using lights to guide fish downstream. In Minter Creek, a light barrier was tested and found to stop a large part of the downstream migration. In this situation, the lights repelled the fish; however, if the fish were exposed to lights in low-velocity areas (0.5 ft/s), then fish were attracted to the lights, albeit dim (0.015 ft-c). Tests at White River bypass again found fish avoided lights; the degree of avoidance was dependent on the turbidity. However, fish were attracted to a dim light (<0.015 ft-c) in both clear and turbid conditions. Also, light attraction was obtained if fish were allowed to adapt to the barrier lights in low-velocity areas.

The remaining studies conducted by the University of Washington (Fields 1966) were at the McNary and The Dalles dams. Most of the fish were Chinook salmon fry and smolts. Results from McNary Dam point to an interaction between three factors: flow velocity, light adaptation, and light intensity. In 1959, fish avoided a 200-W lamp placed in front of an intake structure. In 1963, fish appeared to not respond to the light (with either attraction or repulsion). The main difference between the two years was flow, with discharge in 1959 at 1150 cfs, while in 1963, discharge was 650 cfs. Fields indicates that avoidance of lights was associated with high velocities. He postulated that the fish's retina does not adapt fast enough at higher velocities, and the primary response is avoidance.

A study conducted at McNary Dam in 1969 (Marquette et al. 1970) evaluated the effect of light on passage of wild or naturally migrating coho, sockeye, and Chinook salmon, and steelhead trout smolts from gatewells through orifices into the collection channel. The effect of illumination was evaluated at both the gatewell and orifice; the gatewells were either covered or uncovered, while test conditions near the orifices included ambient lighting, electrical lights (150-W halogen flood lamp), and total darkness. The testing period ranged from 24 to 48 hours. For the 24-hour tests, the lowest retention in the gatewell—3% for sockeye, 7% for steelhead trout, 14% for coho, and 26% for Chinook salmon—was seen when the gatewell was dark and the orifice was lighted. For longer-term tests (36–48 hours) (all with a darkened gatewell), Chinook salmon showed a preference for a lighted orifice (~75% passage rate) while steelhead trout and sockeye salmon showed no preference for the light condition at the orifice. The study recommended that all orifices be illuminated continuously with electric lights to help fish locate and pass through these structures.

Brett and MacKinnon (1953) tested the response of juvenile spring migrating salmon to a bubble curtain and lights in a canal that connected the Puntedge River in British Columbia to a powerhouse. The lights were three sealed-beam headlights that were either continuously on or flashing at a rate on 1/sec. Light intensity at the water surface was 3.5 ft-c. All experiments were conducted at night. Results indicated lights, either flashing or continuous, were effective in diverting approximately two-thirds of the fish from one side of the canal to the other.

Congleton and Wagner (1988) evaluated the stress response (i.e., plasma cortisol levels) in relation to light intensity (and flume design) for migrating smolts of Chinook salmon and steelhead. At night, plasma cortisol levels were higher for both species after passing through the flumes. During the day, Chinook salmon smolts passing though the darkened flumes had the lowest cortisol levels, lower even than the baseline. The highest plasma cortisol levels were associated with Chinook salmon going through uncovered corrugated flumes during the day. For steelhead tested during the day, plasma cortisol levels generally increased for fish passing through the flumes, regardless of the light levels in the flumes. The light levels during holding prior to testing were not given.

Studies at Wanapum Dam in 1989 tested the effectiveness of mercury lights to improve the passage of juvenile salmonids. The lights were installed on the pier noses and spillway gates to a depth of 3 to 6 m during the nighttime period and monitored with hydroacoustics. The study found no statistical differences in fish passage rates with the lights on or off. The authors suggest the results should be considered inconclusive, based on the short duration and limited illuminated region (Coutant 2001).

Discussion

Rainey (1985) reviewed various design features of juvenile bypass systems including light. He references Fields' results (1966) and concludes that avoidance by juvenile fish is based on visual response, touch, or perception of a change in hydraulic condition. Juvenile salmonids normally face upstream during outmigration, and most migration occurs at night (2000 to 2400 hours).

While the studies indicate a variable response to light, the most compelling studies by Hoar et al. (1957), Fields (1966), and Puckett and Anderson (1988) indicate the variability in response is probably due to light acclimation and the intensity of the light. Generally, fish appear to avoid or be startled by sudden exposure to intense light levels. Even studies that examined fish response to flows found fish attracted to lighted areas (Wert 1988).

Results of behavioral studies of the response to juvenile salmonids to light (non-strobe) range from no effect to attraction. As Hoar et al. (1957) noted, the response to moderate light intensities (i.e., less than full daylight) was never complete attraction or repulsion. Fish swam in and out of the light and, depending on species, age, and number of fish present, spent more or less time in the light.

Finally, Schilt (2007) indicates that "...with all behavioral methods it is important to be aware that the visual system and hearing and all of the other systems operate in concert within themselves and among each other and responses to a sound might be affected by light level, current, or any number of other sensory factors." The following factors have been identified as enhancing or limiting the response to stimuli: genetic makeup (species and subspecies), life stage, season, time of day, light levels, presence of predators, distance to cover, temperature, group size, noise regime, and current. He cautions that the development of an effective juvenile fish passage system must be based on an understanding of fish behavior.

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Chapter 2

Field and Laboratory Tests of Lights and Light Intensities with Reference to Use in Gatewell Orifice Structures at the Bonneville Dam Second Powerhouse

Robert P. Mueller

Background

The U.S. Army Corps of Engineers (USACE) has been using lighting associated with the orifice locations at all Columbia and Snake River projects. The basic location and lighting used varies from project to project, and no studies have been conducted to characterize the lighting environment or determine if the lighting systems are effective at improving fish passage. During the 2007 fish passage season, the halogen lights along the Bonneville Dam second powerhouse (B2) were replaced with light-emitting diodes (LEDs) for cost savings, lower heat output, and longer bulb life. A total of two lights are used per orifice opening. Units 15 through 18 have one orifice each, while units 11 through 14 have two orifices for each gatewell. The lights are easily accessed within the downstream migration (DSM) channel. The lights are operated 24 hours/day during the entire fish passage season (April 1–December 15). During the year, project biologists observed that the new lights had a much lower intensity and expressed concern that the lower intensity and the green hue produced by the lights may not be providing adequate light stimulus for fish in the gatewell to move to the regions where they could then be passed downstream via the smolt bypass system.

As downstream migrating fish encounter hydropower projects, they are initially screened from turbines and guided upward into the gatewell near the forebay (Figure 2.1). The objective of the initial phase of the fish collection and bypass system is to safely guide migrants via intake screen to swim into the gatewells and then exit into the collection channel via underwater orifices. The orifices are located near the upper portion of the water column and near the corners of each gatewell. Early work by K. L. Liscom, Bureau of Commercial Fisheries,[a] showed that more fish would enter the orifices at these locations. Once fish enter the gatewell, it is important that they do not reside in these areas for extended periods. Studies have shown that excess residency in this area can result in a variety of stresses, including those from delay and crowding (particularly in gatewells equipped with standard-length submersible traveling screens) and excessive descaling and injury (in gatewells equipped with extended-length submersible bar screens [Ferguson et al. 2005]). Assessments of orifice passage efficiency (OPE) have been conducted at several USACE projects using fin-clipped or PIT-tagged fish, with the percentage of fish leaving the gatewell in 24 hours constituting the OPE.

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[a] K. L. Liscom, *Development and Evaluation of an Orifice System for Removing Juvenile Salmonids from Turbine Intake Gatewells*. 1966 unpublished report, Fish Passage Research Program, Bureau of Commercial Fisheries, Seattle. Washington.

The regionally accepted minimum level for OPE with submersible traveling screens installed is 70%. However, because of the increased flows and higher turbulence in gatewells associated with extended-length bar screens, OPE levels approaching 90% are probably more appropriate for gatewells with these guidance devices (Ferguson et al. 2005). Studies at the B2 in 2001 using PIT-tagged fish showed an OPE of 94% to 97% for yearling Chinook salmon and near 100% for subyearling Chinook salmon (Monk et al. 2002).

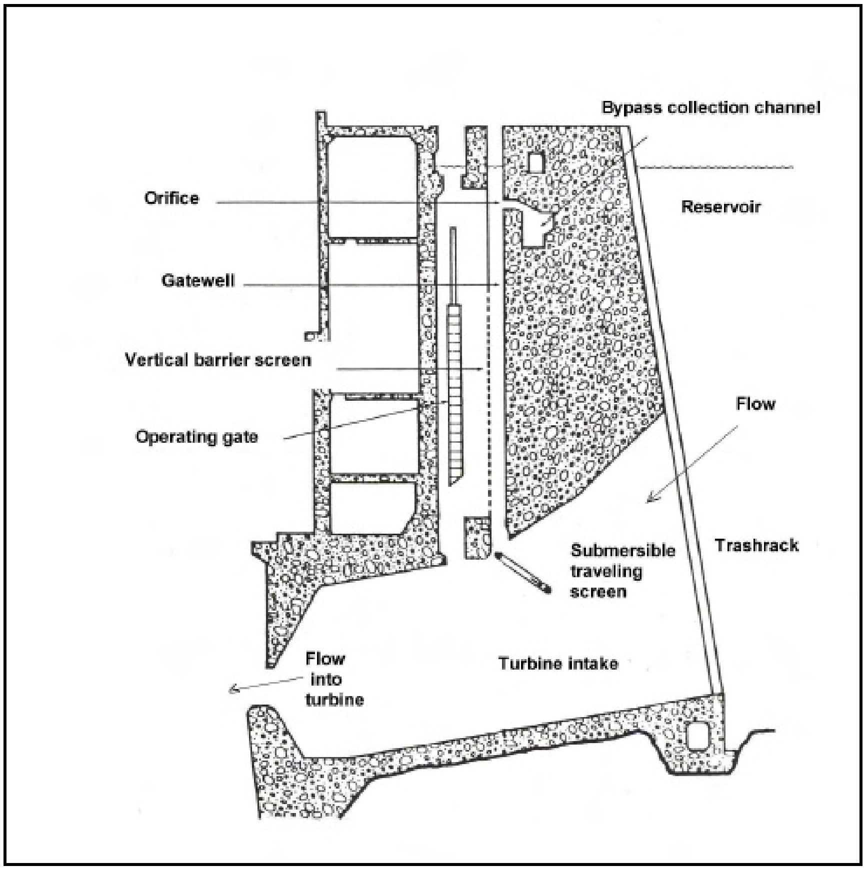

Figure 2.1. Cross section of a typical Columbia River hydroelectric project illustrating the mechanical bypass system

Methods

Field Study

Field measurements were made on October 31 and November 1, 2007, at the B2 in Gatewell 12A at the south orifice. A custom-made trolley was lowered to the orifice opening via a rope and pulley system attached to a framework that spanned the gatewell opening at the road deck. The trolley apparatus was constructed from 1-in.-square aluminum tubing approximately 3 ft by 7 ft, with 2-in.-diameter caster wheels attached at each end and 5-lb lead weights at the corners to facilitate submergence (Figure 2.2). An underwater camera with incorporated LED lights also was attached to the light sensor to verify the sensor location at the orifice opening. All measurements were made during the daylight hours, with the top of the gatewell completely covered with canvas and plastic tarpaulins to eliminate ambient light and simulate nighttime conditions. The orifice gate at the terminus of the orifice opening was closed during the light measurements. The water turbidity was measured in nephlometric turbidity units (NTU) with a LaMotte Model 2008 portable turbidimeter.

Figure 2.2. Support frame and weighted trolley used to deploy light sensor in Gatewell 12A

Four separate lighting conditions were evaluated. For conditions 1 and 2, the existing LED spot lamps were tested with the water-scaled and new (clean) lens caps, respectively. For conditions 3 and 4, 90-W halogen flood lights in the DSM channel were evaluated with the dirty and clean lens caps. All lamps were placed in a light receptacle with a heat shield and placed 1 to 2 in. from the lens cap (Figure 2.3).

Figure 2.3. Light-emitting diode light installed above light tube at Orifice 12A South

Light Sensor

A calibrated underwater high-gain luminance detector (International Light [IL] Model SHD033) was used along with an IL Model 1700 research radiometer/photometer. This sensor has a broad spatial response and is capable of detecting very low light levels. The sensor has a spectral range of 470 to 700 nm, with peak sensitivity at 555 nm. The light detector outputs the average light intensity in lux units. The sensor was mounted to the trolley frame and could be repositioned easily using a locking slide sleeve fastened to 1-in.-square aluminum tubing (Figure 2.4). Calibration marks were made on the framework to replicate sensor position for each series of measurements.

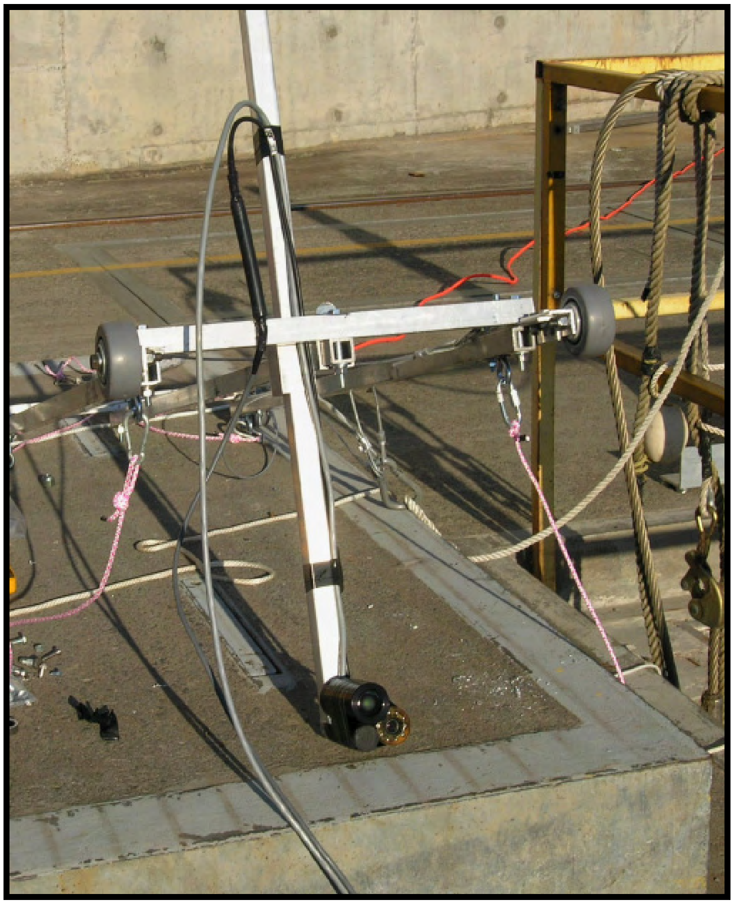

Figure 2.4. Light sensor attached to trolley with underwater camera for position verification

Light Types

Two light sources were tested in the field and in the laboratory. The LED lamps currently in use at the B2 collection channel are manufactured by LEDtronics, Inc. (Model R30). The lights used previously were a standard 90-W Phillips halogen PAR flood lamp. A typical halogen light spectrum peaks in the range of 650 to 950 nm (Figure 2.5). One LED flood lamp is installed for each orifice tube. The specifications for each of these light sources are listed in Table 2.1.

Orifice Layout

The B2 consists of eight turbine units, each with three screened gatewells open at the top and measuring 4.1 ft wide by 23 ft long by approximately 50 ft deep (water depth). The water elevation within the gatewell was at about 75 ft above mean sea level. There are two orifices in each gatewell at an elevation of 65 ft mean sea level, each measuring 12.5 in. in diameter (Figure 2.6). The south orifice is 36 in. from the end wall; the north orifice is centered at 16 in. from the end wall. The orifice extends 30 in. and terminates in the dewatering channel in the DSM channel at an elevation of 67 ft mean sea level. Each orifice has two light tubes, approximately 7 in. in diameter and 54 in. long, which are angled upward and terminate in the DSM channel (Figure 2.7). Each light tube has a glass lens that seals the upper end of the light tube. The exposed portion of the lens cap is subjected to the wet and damp environment of the DSM channel. This environment, in combination with the heat produced by the halogen light, causes water scale and debris buildup on the lens, greatly diminishing the clarity of the glass.

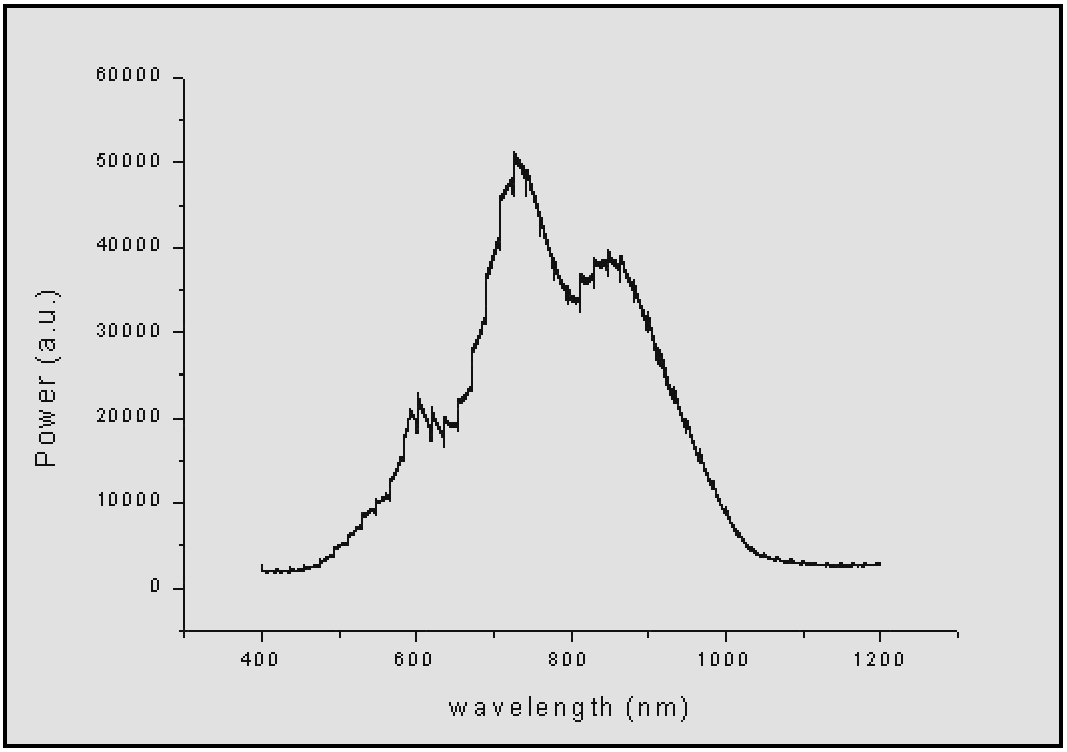

Figure 2.5. Halogen light spectrum

Table 2.1. Characteristics of light-emitting diode and halogen lights tested at B2 collection channel at Bonneville Dam in 2007

Model	Emitted Color	Intensity (lumens)	Total Foot-Candles	Bulb Beam Angle	Peak Wavelength (nm)	Bulb Life (hr)
Light-emitting diode						
R30-123-0AG-120AN	Aqua green	390	2091 cd	15 deg	525	100,000
Halogen						
Sylvania (90 W)	White	1350	n/a	25 deg flood	710	2000–3000

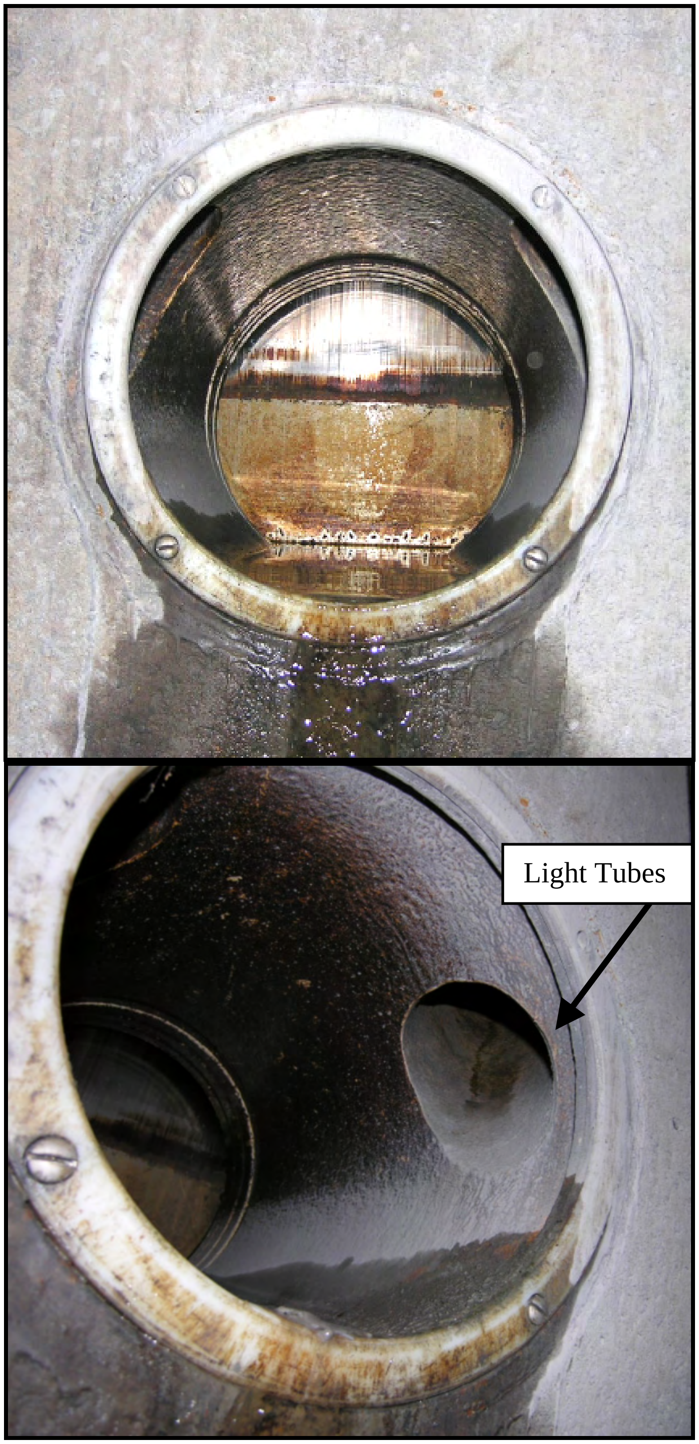

Figure 2.6. Dewatered closed orifice at north end of Gatewell 13B showing light tubes at orifice entrance

Figure 2.7. Top portion of light tubes in downstream migration channel with halogen lights installed

Results

Field Study

The water clarity was very good during the field measurement dates, with turbidity readings of 2.8 and 2.5 NTU and the Secchi disk reading of 7 ft at the Bonneville Dam forebay. Ambient light levels were measured in the covered gatewell with the light sensor pointed upward at the water surface and at 2- to 4-ft intervals down to 12 ft. The values were found to be fairly consistent and ranged from 0.32 to 0.5 lux (Figure 2.8). When the sensor was oriented to point north across the gatewell, the readings fell to 0.08 lux at a depth of 12 ft. A separate measurement of 12.8 lux was made at the deck level under the tarpaulins.

Orifice Lighting Characterization

Light intensity measurements for the LEDs with the sensor placed directly on axis with the orifice opening and just off the axis were generally very low. Only a slight improvement was noted when the dirty lenses were exchanged for the clean lenses (Figures 2.9 and 2.10). The highest value obtained with the LEDs was 0.65 lux at a distance of 2 in. from the opening. In comparison, the halogen lights produced the highest light level of 3.3 lux with the clean lens at the orifice opening, with a gradual loss of intensity out to a distance of 24 in. With a dirty (water-scaled) lens, the light intensity of the halogen was comparable to the LED light. When the sensor was 6 in. above the opening, the LED illumination output was slightly higher than when measured directly on axis (Figure 2.10). This small increase may be the result of light reflecting off the lower portion of the orifice and producing somewhat higher readings in this region (Figure 2.10). A small increase was observed also for the halogens.

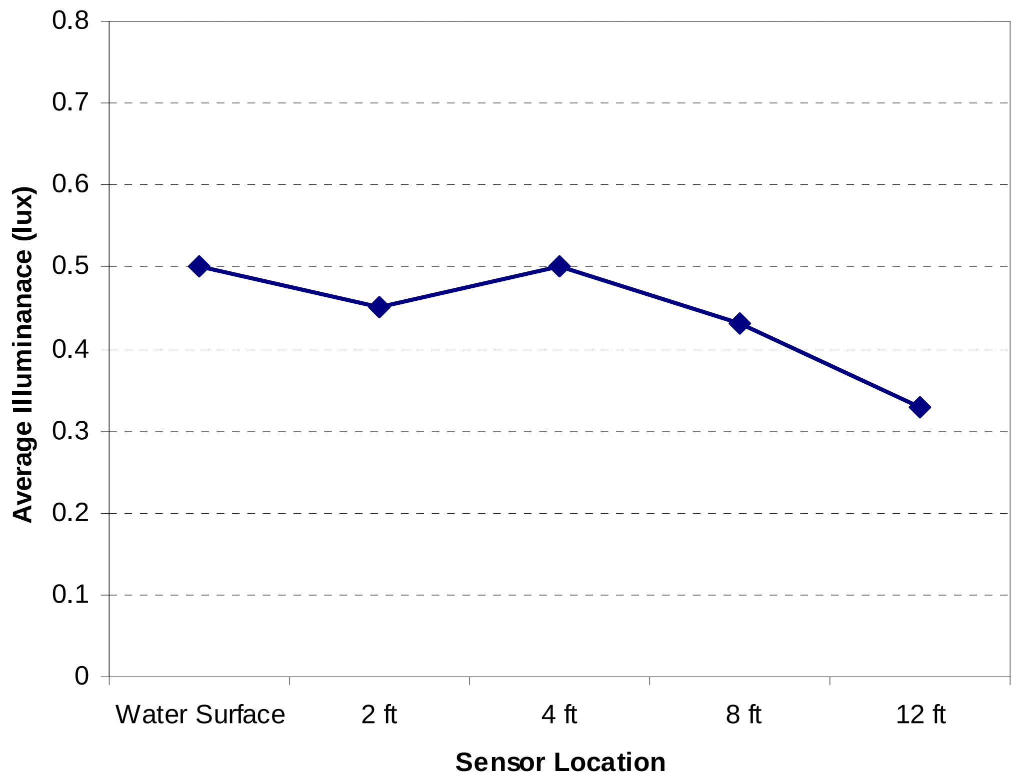

Figure 2.8. Ambient light levels measured within covered Gatewell 12A at various water depths

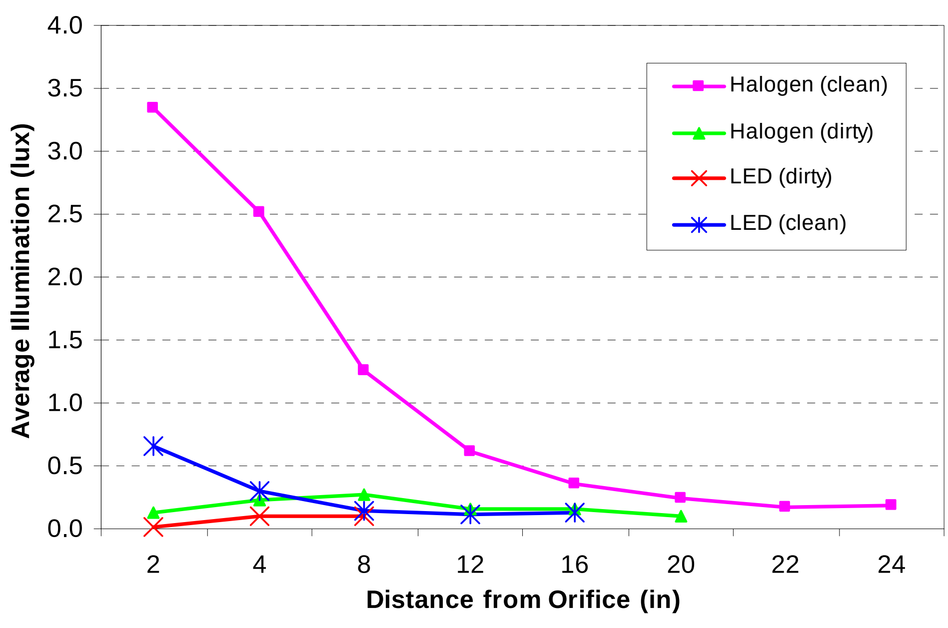

Figure 2.9. Light intensity measured at center of south orifice in Gatewell 12A for both light-emitting diode and halogen lamps using the clean and dirty lens caps

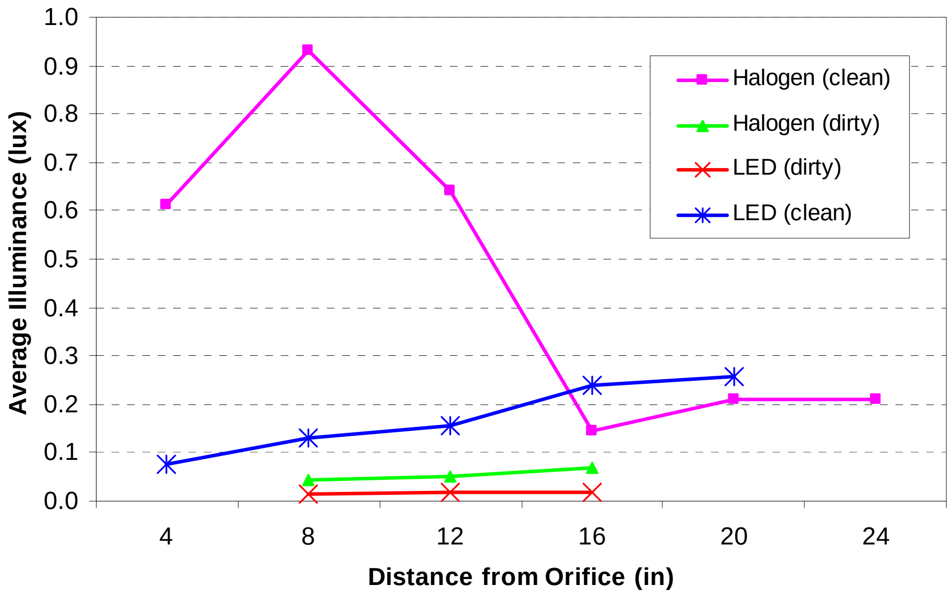

Figure 2.10. Light intensity measured 6 in. above top of south orifice in Gatewell 12A for both light-emitting diode and halogen lamps using the clean and dirty lens caps

Additional measurements were taken with the sensor placed 12 in. from the south part of the orifice and oriented toward the orifice opening. The illumination profile shows a general reduction in light intensity out to at a range of 24 in. for the halogen and 18 in. for the LEDs (Figure 2.11).

Laboratory Tests

Laboratory tests were conducted to determine the intensity of the halogen, aqua green LED lamp, and a mercury vapor lamp with a clean clear glass lens and a water-scaled lens retrieved from the dam and used for the entire fish passage season (Figure 2.12). In addition to the halogen and LED flood lamp, a 100-W mercury vapor bulb was tested. The bulb was powered using an external ballast. Measurements were taken in a darkened laboratory space on a bench top with the sensor placed on axis with the light at 54 in. The in-water measurements were taken using a small raceway in which the light was placed 30 in. above the water surface with the sensor placed at a depth of 15 in. using clear water.

The results show a substantial decrease in the output of the lamps when the water-scaled orifice tube lens cover was positioned at the light face (Table 2.2). The light loss was consistent for the LED and halogen lights, with a decrease in light intensity of 5 to 6 times. The light loss for the mercury lamp was only 2 times. Temperatures were taken at the face of each lamp to determine heat output. The resulting values were 143°F for the halogen, 74°F for the LED, and 250°F for the mercury vapor bulb.

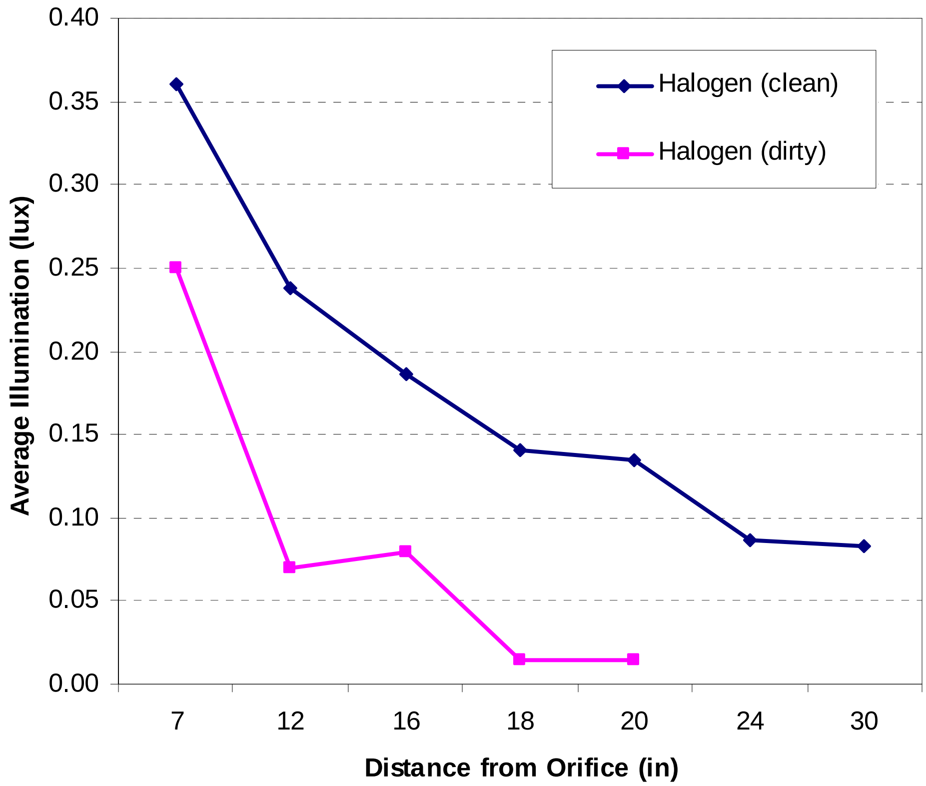

Figure 2.11. Light intensity with light sensor 12 in. from south end of orifice, sensor pointed toward north (toward orifice)

Table 2.2. Laboratory tests using three light sources in air and with light sensor in water using clean and water-scaled lens at light face (all values in lux)

Light Source	In Air (54-in. spacing)		
	Clean Lens Cover	Water-Scaled Lens Cover	Light Loss Factor
90-W halogen	1811	365	5x
Aqua green LED	347	59	6x
100-W mercury vapor	670	334	2x
	Lamp over Water (45-in. spacing with sensor 15 in. below water)		
	Clean Lens Cover	Water-Scaled Lens Cover	Light Loss Factor
90-W halogen	2200	430	5.1x
Aqua green LED	550	86	6.3x
100-W mercury vapor	699	370	1.9x

Figure 2.12. Water-scaled orifice tube lens cover (left); mercury vapor bulb with heat shield (right)

Discussion

Based on the field measurements at a single orifice in Gatewell 12, the existing light output from the LEDs in the immediate vicinity of the orifice opening was low, at approximately 0.1 lux with the dirty lens. Light output for the halogen light with the dirty lens was 0.25 lux at the opening. When the water-scaled lenses were exchanged for the clean ones, the readings rose to 0.6 lux for the LEDs and 3.25 lux for the halogen. For comparison, 1 lux is the amount of light produced by moon-light at high altitude, and 10 lux is the intensity of a candle at a distance of 1 ft. The halogen lights were far more effective at producing illumination near the orifice regions and outward to approximately 16 in. on axis with the opening where the values were similar to background measurements (ambient light). The LEDs were far less effective at producing an illuminated region; this was especially evident when the water-scaled lens was used. When the sensor was positioned 12 in. from one end of the orifice, light intensity for the halogen with the clean clear lens decreased by approximately a factor of 4, from 1.5 (on axis) to 0.35 lux at 7 in. from the opening.

Water turbidity will influence to a large degree the illumination capability of any artificial light source. Water turbidities during the bulk of the smolt outmigration in the spring would be expected to be 3–5 ft as measured with a Secchi disk. During the summer and fall, the water clarity generally improves to 6–7 ft. During the field tests at the B2 for this evaluation, the Secchi disk value was 7 ft. Generally, light at the longer wavelengths (red regions) would be better suited to penetrate the water than the shorter wavelengths, and white light produced by the halogen lamp would also be well suited for more turbid conditions.

The laboratory tests with the water-scaled lenses showed that the light loss for the halogen and the LEDs was 5–6 times in air and with the sensor placed in water. Output from the mercury vapor lamp when the water-scaled lens cap was placed at the light face was reduced by only a factor of two. The drawback to using the mercury vapor and the halogen is the amount of heat produced by the lens (250°F for the mercury vapor and 143°F for the halogen) and the reduced bulb life as compared to the LEDs.

References

Ferguson JW, GM Matthews, RL McComas, RF Absolon, DA Brege, MH Gessel, and LG Gilbreath. 2005. *Passage of Adult and Juvenile Salmonids through Federal Columbia River Power System Dams*. NOAA Technical Memorandum NMFS-NWFSC-64, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Monk BM, RF Absolon, BP Sandford, and JW Ferguson. 2002. *Evaluation of Intake Modifications at Bonneville Dam Second Powerhouse, 2001*. Fish Ecology Division, Northwest Fisheries Science Center, Seattle, Washington.

Chapter 3

Recommendations

Based on the information obtained from the literature search, juvenile salmonids can be attracted to illuminated regions during the nocturnal periods and can perceive light levels down to approximately 0.25 lux or 10^{-2} ft-c, which equates to the light produced by moonlight. At the other end of the spectrum, previous researchers found that juvenile salmonids generally avoid or are startled when exposed to more intense light levels that correspond to daylight conditions or near 400 lux ($10^{-1.5}$ ft-c). The existing conditions for lighting placed above the orifice tubes in the DSM channel have proved to be less than ideal for light to penetrate the light tube and illuminate the orifice region. Based on the review of previous studies, a minimum luminance value of approximately 200–300 lux should be produced at the immediate orifice entrance. While some studies have shown that this light intensity could possibly startle test fish (when suddenly exposed) in controlled laboratory experiments, the values are expected to become less intense within a short distance from the orifice. Also, the expected higher water turbidity during the bulk of the spring outmigration would limit the light intensity.

Based on our study, some options for improving the lighting at the orifice entrances at the B2 include the following:

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

To evaluate the effectiveness of any modification to the existing system, tests could be conducted in which tagged fish are released in the gatewell with a light on/off scenario and the OPE evaluated. Different lighting could be used to test to determine if white light or light emitted within the peak action spectra of juvenile salmonids (blue-green region) is best for attracting fish near the orifice where the flow component is sufficient for entrainment into the collection channel.

Appendix

Synopsis of Literature Reviewed

Appendix

Synopsis of Literature Reviewed

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Alexander G, R Sweeting, and B McKeown (1994)	Determine if the change from a visual system dominated by porphyropsin to one dominated by rhodopsin is one of the developmental processes of smoltification	Coho salmon	Juvenile (yearling)	Fish were reared in outdoor raceways; visual pigments were extracted over a 26-week period from January 21 through July 14.	Normal photoperiod	The proportion of the two visual pigments changed during smoltification, from porphyropsin-dominated in pre-smolts to rhodopsin-dominated in the smolt stage. Change can affect visual acuity.
Ali MA (1959)	Examination of the ontogeny of photomechanical and behavioral responses of different salmon species to light	Sockeye, coho, pink, and chum	Alevin through smolt	For adaptation rates (as measured by the thickness of the cones), fish were either left in total darkness or illuminated at 400 ft-c overnight; samples were taken between 1 and 70 min after exposure to light or darkness; other studies looked at feeding rates and schooling times after exposure to lights. Retinal response, feeding rates, and schooling behavior were studied under different light intensities.	Various: 10^{2}, 10^{1}, 10^{0}, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, and 400 ft-c	As the fish became older, time for light adaptation decreased. The time for dark adaptation increased with age. The retinal epithelial pigment for all fish, except late pink fry, had a latent period before the start of contraction in the dark. Species differences in retinal and behavioral response to light were noted.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Amaral SV, FC Winchell, and TN Pearsons (2001)	Determine if strobe light, drop light, and infrasound stimuli would divert migrating fish to a collection facility (Roza)	Chinook salmon, pikeminnow, smallmouth bass	Smolt	Exposure periods for the drop lights were 1 or 2 min; lights were either on continuously or switched on/off on a 1- or 15-sec interval. Fish were evaluated with a test channel positioned within the river. Tests were conducted during the day, dusk, and at night (at night, additional lights were used to observe fish).	None reported for 500-W SubSea light	Weak avoidance response noted to 1-min drop light test; at dusk and at night, fish moved farther away from the lights compared to the control by 0.3 and 0.13 m, respectively, for 1 sec on/off, 0.33 and 0.16 for the 15-sec on/off, and 0.06 and 0.5 m for continuous lights on. During the day, fish were slightly closer to the lights. For the 2-min treatment, there was slight movement away from the lights when they were on continuously at night. Most differences were <0.5 m.
Beauchamp DA, MF Shepard, and GB Pauley (1983)	The review is designed to provide a brief, comprehensive sketch of the biological characteristics and environmental requirements	Chinook salmon	All			
Beeman JW and AG Maule (2001)	Evaluate residence times within a portion of the fish collection system at McNary Dam	Chinook salmon and steelhead trout	Juvenile	Fish were radio-tagged and released individually into the gatewell during the daytime (1130 hours) and evening (2000 hours)	Ambient	Median gatewell residence times were 8.9 hr for Chinook and 3.2 hr for steelhead. Most fish passed through the gatewell to the collection channel during the evening, regardless of release time.
Brett JR and D MacKinnon (1953)	Evaluate the effectiveness of a bubble curtain and lights in deflecting fish	Chinook salmon	Under-yearling (average length = 58 mm)	In canal, fish were exposed to a bubble curtain and/or either continuously on or flashing lights. Fish were captured using paired nets; the nets were set between 8:30 and 9:30 p.m. and left in place for 3–4 hours.	3.5 ft-c at the water surface. Flash rate was 1/s.	More than two-thirds of the fish were deflected away from the lights; the flashing lights appeared to be more effective in diverting fish than the continuously on lights (74% vs. 68%). The bubble curtain did not appear to be effective in diverting fish.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Congleton JL and EJ Wagner (1988)	Determine plasma cortisol responses to passage through three prototype flumes that could be used to replace pressurized-pipe bypasses at dams on the Columbia and Snake rivers	Chinook salmon and steelhead trout	Smolt	Three flume designs (small baffled, large baffled, and unbaffled with corrugations) were tested under three conditions (nighttime, partly darkened in the daytime, completely darkened in daytime.	Partially darkened: 400–900 lux; completely darkened daytime: 1–4 lux	Plasma cortisol levels were higher at night for fish passing through the flumes. During the day, Chinook smolts going through the darkened flume had the lowest levels, while fish going through uncovered flumes had the highest levels. For steelhead, cortisol levels were highest during the day, regardless of light levels.
Connor WP, RK Steinhorst, and HL Burge (2003)	Describe the migrational behavior of fall Chinook salmon from shoreline rearing to migration down the Snake River. Analyze the effects of flow, temperature, initial tagging date, fork length, and distance traveled on migration rate.	Chinook salmon	Fry to smolt	Fish were captured between April and June/July and PIT-tagged. Tagged fish were released at capture sites; fish were recaptured using either beach seines or detected passing Lower Granite Dam.	Not applicable	Fall Chinook passes through four migrational phases: 1) discontinuous downstream dispersal along the shoreline; 2) abrupt and mostly continuous dispersal offshore; 3) passive, discontinuous downstream dispersal offshore; and 4) active and mostly continuous seaward migration.
Deutschlander ME, DK Greaves, TJ Haimberger, and CW Hawryshyn (2001)	Map the ultraviolet sensitivity topographically during smoltification	Rainbow and steelhead trout	Rainbow parr and steelhead smolt	Rainbow parr were exposed to thyroxine; steelhead smolts were assessed for ultraviolet sensitivity.	Spectral sensitivity was determined at increasing intensities of monochromatic light flashes for 12 wavelengths (350–650 nm).	Ultraviolet visual sensitivity appears to be reduced and possibly lost during smoltification in anadromous salmonids. Reduction in ultraviolet sensitivity occurs in the ventral retina.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Fields PE (1966)	Experiments at McNary and The Dalles dams looking at the behavioral response of juvenile salmon to light	Salmon (no species given) and steelhead	Downstream migrating	Lights were placed to guide fish toward or away from structures	No intensity measured, just wattage of light sources	Variable results, depending on placement of lights and flows, time of day, and season. In general, dark-adapted smolts avoided lights; fish that have previous exposure to light were attracted to light if the intensity of the light was reduced relative to the adaptation light. Velocity was the single most important factor affecting downstream migrants.
Fields PE, AK Murray, DE Johnson, and GL Finger (1958)	Evaluate the effect of ambient light conditions on the response to a light barrier	Silver (coho) salmon	Yearling (migratory size)	Environmental light intensities were paired with barrier light intensities. Each trial lasted 5 min, after which the position of the fish was noted (25 fish per test).	Environmental light intensity (ft-c): 0 to 60; barrier light levels: 10, 20, and 40 ft-c.	Dark-adapted fish tested under maximum contrast had the highest avoidance response; light adaptation reduced negative phototaxis.
Finger GL and PE Fields (1957)	Effectiveness of lights with respect to flow and turbidity	Silver (coho) and Chinook salmon	Yearling (migratory size)	Report covers several sets of experiments conducted in situ.	0, 75, and 300 W (no intensity given)	As turbidity increased the number of fish collected in the dark trap declined from 92% to 16% (run magnitude was also increasing) at night. During the day, fish appeared to be attracted to the 75-W trap and slightly repelled by the 300-W. A dim light (0.015 ft-c) attracted fish in both clear and very turbid water.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Hays SG (1988)	Study evaluated avoidance behavior near a submersible traveling screen at Rocky Reach Dam. A separate laboratory study was carried out to evaluate the use of strobe lights on salmon and steelhead behavior; results are summarized in this report.	Salmon (no species given) and steelhead			Strobe lights	The sudden appearance of a strobe light produced escape speeds of about 7 body lengths per second. However, fish were observed to maintain position or follow the penumbra (the edge of the beam where the intensity was less).
Hoar WS, MHA Keenleyside, and RG Goodall (1957)	Study the response of several species of salmonids to various light intensities	Pink, chum, coho, sockeye	Fry and smolt	Several sets of experiments were conducted. The first was conducted in an aquarium subdivided into an illuminated and a darkened half; lights were turned on and intensity increased in at 10-min intervals. In the second, fish were exposed to lights combined with water flow and turbulence. In a third experiment, fish were studied in a tall tank to look at vertical movement.	Light intensity varied from 10 to 1000 ft-c	In no case was the response all or none; after an initial startle response, fish would pass between the light and dark areas of the tank. Species differences were noted: chum and pink preferred the light, while sockeye fry retreated to darker areas and coho appeared indifferent to moderately high light levels. Differences were noted also between hatchery and wild salmon of the same species.
Hoffnagle TL and AJ Fivizzani, Jr. (1988)	Determine whether salmon can alter smoltification hormones in response to changes in photoperiod	Chinook salmon	Juvenile fall Chinook	Held between March 10 and June 3 under three light conditions: 24 hr light; 9 hr light–15 hr dark; and increasing photoperiod (from 10 hr light to 15.5 hr light at end)	Broad-spectrum fluorescent light 40 cm above the surface; light intensity at surface was 55 lux.	Natural photoperiod group had a more coordinated and complete smoltification based on highest mean and peak levels of both thyroxine and cortisol, greatest decrease in hepatosomatic index, greatest decrease in the condition factor, and least decrease in hematocrit.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Iwata M (1995)	Review of downstream migratory behavior and its relationship to cortisol and thyroid hormones	Chum and coho	Fry, smolt			Chum fry and coho smolts changed preference from shade to open water after exposure to thyroid hormones.
Kelly DJ and ML Bothwell (2002)	Determine if fish selectively avoid UV radiation and gauge the importance of UVA and UVB wavelengths in photo-avoidance behavior	Coho salmon	Alevin and pre-smolt	Outdoor, in-stream enclosures covered with different combinations of two solar exclusion panels; cloudless and cloudy days	4 solar exclusion panels: PAR (400–700 nm); PAR + UVA (320–400 nm); PAR + UVA + UVB (280–320 nm) and 50% (PAR + UVA + UVB)	Under sunny conditions, coho alevins showed significant preference for PAR and 50% (PAR+ UVA+UVB), and juvenile coho showed significant preference for the absence of UV radiation. Under cloudy skies, juvenile coho showed no preference for any of the treatments.
Kemp PS, MH Gessel, and JG Williams (2005)	Assess the capability of fall Chinook salmon smolts to recognize and avoid or choose areas with overhead cover during downstream migration	Chinook salmon	Smolt	Experimental flume at McNary Dam; overhead drop lighting illuminated the flume, while a cover positioned 0.65 m above the water surface provided shade along one-half.	None reported	Approximately 80% of the migrating smolts avoided the covered channel and selected the uncovered half.
Long CW (1968)	Determine the timing and distribution of fingerling salmon entering turbine intakes at The Dalles and McNary dams on the Columbia River	Chinook salmon and steelhead trout	Juvenile	Fyke nets were fished at the center intake of turbines at the ends and middle of the powerhouse at The Dalles and at intake C of Unit 12 at McNary. At The Dalles, nets were set to look at diel and vertical distributions, while at McNary, nets were set at night to look at the vertical distribution.	Not applicable	All age groups and species were more abundant at night than during the day; the I-group salmonids were significantly more plentiful (94% of the I-group Chinook and 85% of the I-group steelhead were caught at night. Vertically, most fish were caught in the top two of the six nets. The I-group Chinook and the I-group steelhead were most strongly concentrated in the top (73% and 74%).

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Marquette W, F Ossiander, R Duncan, C Lond, and RF Krema (1970)	Measure the effect of illumination of the gatewells and orifices on the passage of salmonids into the sluiceway at McNary Dam	Chinook,, coho, and sockeye salmon; steelhead trout	Smolt	Test conditions were covered (i.e., dark) or uncovered gatewells and dark or lighted orifices. Light for orifice was either ambient or a 150-W floodlight placed 1 ft above the orifice exit.	Not given	Retention in the gatewell was less for all species when the gatewell was darkened. Coho salmon and steelhead trout showed no preference for orifice lighting, while Chinook salmon preferred the lighted orifice.
Nemeth RS and JJ Anderson (1992)	Investigate fish behavior with exposure to mercury vapor and strobe lights under a variety of ambient lighting conditions. Determine if differences in ambient lighting altered initial and subsequent behavior in response to strobe and mercury lights.	Coho and Chinook	Juvenile (pre-smolt to smolt)	Day and night tests (April–June); fish were adapted to one of four conditions (daytime, nighttime, dark-adapted; light-adapted); fish were exposed to strobe or mercury lights and behavior monitored for 1 hr.	Units: microeinsteins/m^2/s). Adaptation levels: daytime (1 to >1000); nighttime (dusk to complete darkness); light-adapted (5). Test levels: mercury lights (100 at 1 m to 0 at 6 m); strobes (~5 at 1 m to 0 at 4 m)	Coho hid when in ambient daylight. At night, they were still until exposed to mercury or strobe lights; they hid when exposed to strobe lights and actively swam with mercury lights. No clear response was noted under reversed adaption. Chinook were active (cruising or actively milling) for all treatments and adaptations. Chinook salmon (adapted to darkness) initially moved toward the mercury light when it was first turned on but slowly retreated as the intensity increased. Reversals of ambient lighting (darkening the raceway during the day or illuminating it at night) had little effect on fish behavior.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Novales-Flamarique I (2000)	To determine the ontogeny of UV sensitivity	Sockeye salmon	Alevin through adult	Wild sockeye alevins were raised in tanks for 4 years and were tested for UV sensitivity. Fish were adapted to a given back-ground light for 1 hr, after which sensitivity was assessed at wavelengths from 350 to 720 nm. For a given wavelength, light intensity was increased in a step-wise fashion and the response measured. Response consisted of ON component (onset of light) and OFF component (offset of light).		UV sensitivity greatly diminished in the smolt stage but reappears in the adult. UV cones disappear from the dorsal and temporal retina at the smolt stage.
Novales-Flamarique I (2005)	Microspectrophotometry and histological techniques were used to characterize the visual pigments and photoreceptor types in three species of Pacific salmon as a function of time of year, developmental stage, and retinal location	Coho salmon, Chinook salmon, chum salmon	All life stages	Hatchery-reared stock raised either outdoors or indoors. Indoor rearing facilities had same photoperiod regime as outdoor but different intensity and spectral content.		All three species had cone visual pigments with maximum absorbance in the UV, blue, green, and red parts of the spectrum. The yoke-sac alevin stage did not have the blue visual pigment. Smolts had predominantly single cones with blue visual pigment. Coho and Chinook smolts switched from vitamin A1- to vitamin A2-dominated retina in the spring. Adult spawners had vitamin A2-dominated retina. The central retina of all three species had three types of double cones (large, medium, and small). Temperature increases in the spring correlated with rises in porphyropsin.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Novales-Flamarique I and HI Browman (2001)	Test whether polarized light improves prey location	Rainbow trout	Mean length = 1.55 cm	Three treatments: diffuse white light; polarized white light; and short-wavelength light (52% to 97% polarized). Prey location distances were measured.	White light: 5.62 x 10^{16} photons/m^2/s; short-wavelength light: 4.2 3 x 10^{16} photons/m^2/s	Prey location distances were significantly longer under white polarized light compared to nonpolarized light. Under short-wavelength polarization, distances were longer under 85% and 97% polarization than under 52% polarization. That is, fish detected prey at greater distances under polarized light.
Novales-Flamarique I, A Hendry, and CW Hawryshyn (1992)	Characterize the spectra of available light in Lake Cowichan, a nursery lake for various salmonid species	None		Seven sampling stations were established around the lake; light was measured using a LiCor spectro-radiometer; measurements were taken from a depth of 18 m to 0.3 m of the surface at 3-m intervals.	UV light most attenuated with depth; near surface, short-wavelengths constitute a major part of the light; with increasing depths, the maximum is at 560 nm (green); during crepuscular periods, there was an increase toward shorter wavelengths.	See light intensity.
Novales-Flamarique I, S Hiebert, and J Sechrist (2006)	Assess whether strobo-scopic illumination has any effect on the visual system of fish	Kokanee and sockeye	Kokanee spawner; sockeye smolt	Fish were exposed to one of three experimental conditions: 1-min, 5-min, or 1-hr exposure to strobe lights.		Overall, retinal morphology and lens appearance were similar between controls and fish exposed for 1 to 5 min. Fish exposed for 3 hr died. Fish exposed to strobe lights showed delayed escape response to a shadow stimulus. The delay ranged from 5 min for the 1-min exposure to 25 min for the 5-min exposure.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Parkyn DC and CW Hawryshyn (2000)	Characterize and compare daylight spectral and polarization sensitivity in salmonids	Rainbow trout, steelhead, cutthroat trout, kokanee, brook char	Juvenile (parr)	Recordings were made of the optic nerve of fish exposed to white-light background conditions and UV-isolating background conditions.	Two quartz/halogen light channels fitted with both a 700-nm short-pass filter and 2.0 neutral-density filter were used for white-light condit-ions; for UV back-ground, tungsten background with 450-nm filter in one channel and a 550-nm filter in second.	Spectral response of steelhead, rainbow, cut-throat trout, and brook char was dominated by the red and green cone mechanisms. The green cone mechanism domi-nated in kokanee (ON-response). The sensitivity of OFF-responses was dominated by green cone mechanisms in all species. All species were sensitive to UV radiation.
Parkyn DC, JD Austin, and CW Hawryshyn (2003)	To test whether hatchery-reared rainbow trout would orient to a plane-polarized light; to compare orientation responses of potamodromous vs. anadromous salmonids; and to examine the orienta-tion response of laboratory-trained rainbow trout relative to natural polarized light	Rainbow trout, steelhead, brook char	Juvenile	Fish were trained using operant conditioning methodology	100-W tungsten-halogen light with UV-transmitting optics	Fish could be trained to orient to polarized light; however, untrained fish did not orient to polarized light.
Pauley GB, BM Bortz, and MF Shepard (1986)	The review is designed to provide a brief, comprehen-sive sketch of the biological characteristics and environ-mental requirements	Steelhead trout	All			
Pauley GB, Risher, and GL Thomas (1989)	The review is designed to provide a brief, comprehen-sive sketch of the biological characteristics and environ-mental requirements	Sockeye	All			

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Puckett KJ and JJ Anderson (1988)	Test the response of fish to different ratios of stimulus light to adaptation light.	Chinook salmon	Juvenile (2 months; average length = 53 mm)	15 salmon were placed in experimental tank at a specific adaptation light intensity. After 20 min, the adaptation light was turned off and the stimulus light turned on. Fish behavior was videotaped for 2 min. There were 6 replicates of each combination of adaptation/stimulus light.	Light intensity (microeinsteins/m^2/s): 0.005 to 10 for stimulus light; 0.1 to 1 for adaptation light. Adaptation light provided by two 100-W incandescent bulbs; stimulus light consisted of a 200-, 40-, or 15-W bulb.	Fish were attracted to light, and the strength of the attraction was proportional to the logarithm of the ratio of stimulus light to adaptation light. The relationship was pyramidal, with the strongest attraction at a ratio of 0. When the stimulus light was stronger than the adaptation light, fish were attracted to the dim zone that bounded the light spot. At the highest ratio (100, where the stimulus was 100 times more intense than the adaptation light), fish swam to the farthest corner of the tank and appeared to actively avoid the light.
Rainey WS (1985)	Overview of the design of juvenile bypass systems					Juvenile salmonids normally face upstream during outmigration; avoidance by juvenile fish is based on visual response, touch, or perception of a changed hydraulic condition. Visual response is dependent on time of day, water turbidity, and turbulence. Juveniles tend to resist being drawn through dark slots or conduits.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Schilt CP (2007)	Review of the progress to develop bypass and protect fish at hydropower dams on the Snake and Columbia rivers					Juvenile salmonids pass the large Columbia and Snake River dams deep (via turbine or spill bays) at night and surface passage is generally higher during the daytime. Response to light is limited by turbidity, which is often high at mainstem dams. Many factors act in concert to determine the response to a stimulus, including season, time of day, light levels, presence of predators, distance to cover, temperature, group size, noise regime, current, species, and even subspecies.
Simenstad CA, BJ Nightingale, RM Thom, and DK Shreffler (1999)	Review the literature with respect to the response of juvenile salmon to light. The review was looking at probable impacts of ferry terminals on migrating salmonids.					Extensive review of the literature; used to access articles not readily available.

Reference	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Results
Tabor RA, GS Brown, and VT Luiting (2004)	Determine the effect of light intensity on the migratory behavior of sockeye salmon fry and on the predation of fry by cottids	Sockeye salmon	Fry	Predation rates were evaluated under six light intensities in a circular tank with minimum flow and under four light intensities in a flowing system.	Circular tank: 0.0, 0.03, 0.06, 0.11, 1.08, and 10.8 lux. Flowing system: 0.00, 0.22, 1.08, and 5.4 lux	In the flowing system, the fry quickly passed through the system under complete darkness; as light intensity increased, fewer fish migrated and at a slower speed. When predators were present and light intensity was high, even fewer fry migrated, but those that did swam at a higher speed. In the field, the shoreline abundance of fry and predation by cottids increased with increasing light intensity. When lights were turned off, the abundance of fry declined dramatically.
Wert M (1988)	Evaluate the effectiveness of a passive pressure screen bypass system under varied conditions, including lighting	Rainbow trout, coho salmon, Chinook salmon, and steelhead trout	Smolt	Fish were tested in the bypass system using two screen types, three angles of inclination, and a variety of inflow to bypass flow ratios. Light was incidental in that one side of the bypass model was constructed of clear Plexiglas for viewing.	Not applicable	During tests, it was determined that 70% to 90% of the fish passed the model close to the clear front wall. When the Plexiglas was covered with opaque black plastic, only 48% favored that side of the model.

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