PNNL-15007

Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

Chief Joseph Kokanee Enhancement Project

Strobe Light Deterrent Efficacy Test and Fish Behavior Determination at Grand Coulee Dam Third Powerplant Forebay

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Prepared for the Bonneville Power Administration
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Richland, Washington 99352

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Summary

This report documents a four-year study[(a)] to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee (*Oncorhynchus nerka kennerlyi*) and rainbow trout (*O. mykiss*) at the entrance to the forebay of the third powerplant at Grand Coulee Dam. The work was conducted for the Bonneville Power Administration, U.S. Department of Energy, by Pacific Northwest National Laboratory (PNNL) in conjunction with the Confederated Tribes of the Colville Reservation (Colville Confederated Tribes). In this report, emphasis is placed on the methodology and results associated with the fourth project year and compared with findings from the previous years to provide an overall project summary.

Background

Since 1995, the Colville Confederated Tribes have managed the Chief Joseph Kokanee Enhancement Project as part of the Northwest Power and Conservation Council Fish and Wildlife Program. Project objectives have focused on understanding natural production of kokanee (a land-locked sockeye salmon) and other fish stocks in the area above Grand Coulee and Chief Joseph dams on the Columbia River (Figure S.1).

Figure S.1 Location of Grand Coulee Dam in Washington State, USA

(a) The study was extended by one year to capture three years of consistent data because the first year was exploratory.

A 42-month investigation from 1996 to 1999 determined that from 211,685 to 576,676 fish, including kokanee and rainbow trout, were entrained annually at Grand Coulee Dam. Analysis of the data found that 85% of the total entrainment occurred at the dam's third powerplant. Because these entrainment rates represent a significant loss to the tribal fisheries upstream of the dam, they have been judged unacceptable to fishery managers responsible for perpetuating the fishery in Lake Roosevelt.

In an effort to reduce fish entrainment rates, the scope of work for the Chief Joseph Kokanee Enhancement Project was modified in 2001 to include a multiyear study of the efficacy of using strobe lights to deter fish from entering the third powerplant forebay. Pacific Northwest National Laboratory initiated the four-year study in collaboration with Colville Tribal Fisheries.

Study Objective

The objective of the study was to determine the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee and rainbow trout under field conditions.

Study Site

On advice of regional researchers and scientific advisors, efforts were concentrated at the entrance to the third powerplant forebay (Figure S.2). The goal was to eventually deploy a strobe light "fence" across the forebay entrance if the study found that fish avoided the strobe lights.

Figure S.2. Study Site Location (red) at Grand Coulee Dam, 2001 through 2004

The third powerplant contributes more than 60% of the generating capacity at Grand Coulee Dam and, during the study period in 2004, contributed more than 60% of the total powerplant discharge during the day.

Methodology

These studies were designed to capture the response of fish entering the third powerplant forebay to the presence of strobe lights. The response of fish to the strobe lights was evaluated to answer two questions: 1) How were fish distributed in relation to the lights? and 2) What was the swimming response of fish to the lights?

The prototype system consisted of six strobe lights affixed to an aluminum frame suspended 15 m vertically underwater from a barge secured in the center of the entrance to the third powerplant forebay. The lights, controlled by a computer, illuminated a region directly upstream of the barge (Figure S.3).

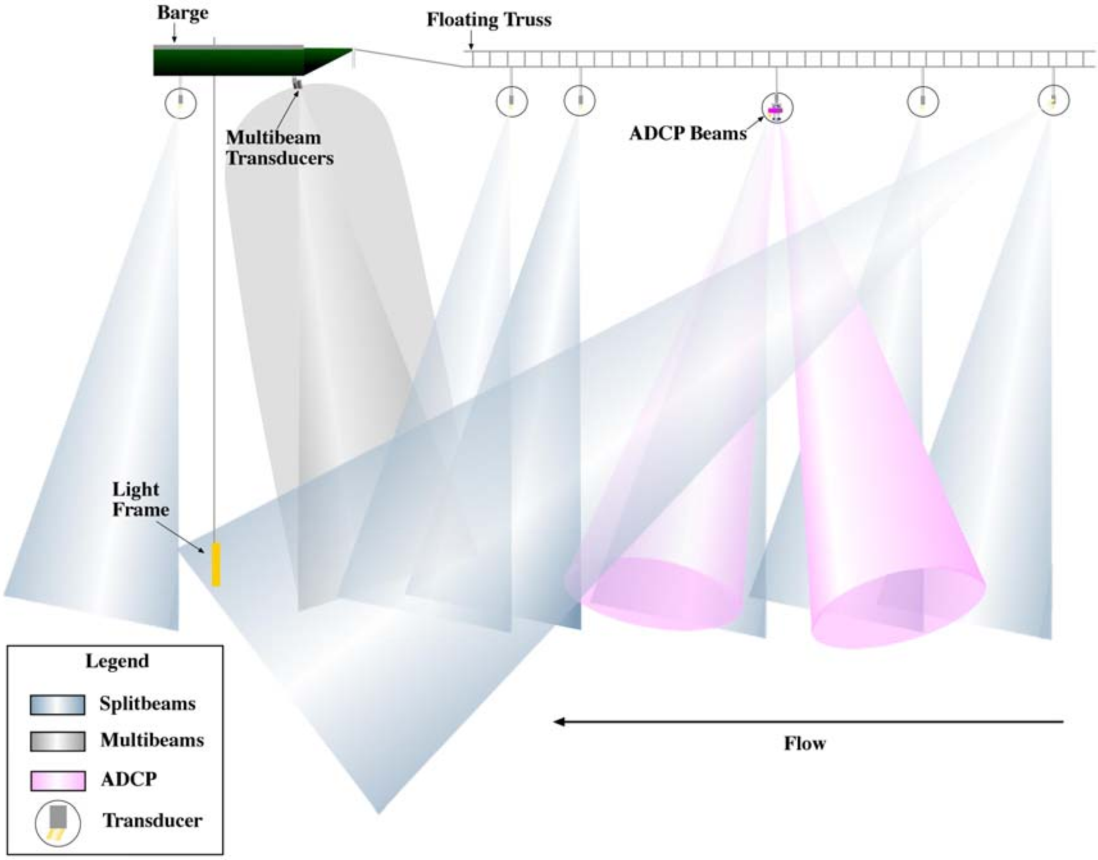


Figure S.3. Strobe Light and Hydroacoustic Transducer Frame Configuration at Grand Coulee Dam

The response of fish to the strobe lights was monitored 24 hours a day by hydroacoustic systems including six splitbeam transducers placed upstream and in line with the strobe lights, two multibeam sonar heads oriented to ensonify regions to the side of the strobe lights, and a single splitbeam transducer located downstream of the lights. In addition, weekly surveys of the third powerplant forebay, upstream and downstream of the lights, were made with a mobile hydroacoustic system using a single splitbeam transducer. The hydroacoustic approach provides an index of fish abundance and not an absolute count.

We were concerned that the fish detected by the splitbeam transducers upstream from the strobe lights may not be representative of the population of fish entering the forebay. To quantitatively evaluate this concern, we conducted weekly, nighttime, mobile splitbeam hydroacoustic surveys to obtain spatial and vertical fish distribution data within the greater third powerplant forebay region and upstream of the strobe lights to the security boom. We also determined the acoustic size of the fish for comparison with our fixed location monitoring activity in the illuminated region immediately upstream of the strobe lights.

Three light treatments were evaluated each year of the study. In all years, two of the treatments consisted of all strobe lights on (six lights) and all strobe lights off for a 24-hour period. The third treatment was either three strobe lights on for 24 hours (2002), or lights alternating on and off on an hourly basis over the 24-hour period (2003 and 2004). In 2003, three lights were used for this third treatment, six lights in 2004. The three treatment conditions were randomly assigned within a 3-day block throughout the study period. Each 24-hour period encompassed a complete daily cycle of power generation and ambient light conditions. Each sequential block of 3 days constituted a pseudo-replicate in which all three treatment conditions had equal time allocation within a block. Start and end dates for each year were based on previous year observations on when fish were present.

Acoustic data files from the stationary splitbeam transducers were processed using software developed by PNNL to identify linear traces. Data collected from the multibeam sonar system were processed using Battelle's tracking software, Gfish (version 1.21). While data from the mobile splitbeam surveys was processed using Echoview software from SonarData Pty Ltd. The software programs filtered out permanent structures and grouped targets together based on their proximity in space, time, and angle units.

In analyzing and interpreting the data, a number of environmental and system factors, aside from the strobe light treatments, were considered. Factors associated with the sampling method (i.e., hydroacoustics) included the shape of the area sampled, the presence of noise in the data, and inability to distinguish species and identify unique targets. Factors included in the analysis were distance from the strobe lights, level of discharge through the third powerplant, time of day, and treatment block. Table S.1 lists and defines the factors or classification variables used in the statistical analysis.

With respect to the distribution of fish, statistical analyses were used to test the null hypothesis that the strobe lights had no effect on the number of fish within distance categories upstream of the strobe lights. For fish detections, we were interested in differences in the distribution of fish detections for similar regions and periods of the day. If the strobe lights had no effect on distribution, we would expect the number of fish detected by each of the splitbeam transducers would be independent of the light

Table S.1. Factor Variable Definitions

Factor Variables	Survey Year		
	2002	2003	2004
Distance of Splitbeam Transducer from Strobe Lights (m)	4	6	8.6
	8	10	10.6
	12	14	16.4
	16	18	20.6
	20	22	24.4
Strobe Light Treatments	Lights Off – 24 hours	Lights Off – 24 hours	Lights Off – 24 hours
	6 Lights On – 24 hours	6 Lights On – 24 hours	6 Lights On – 24 hours
	3 Lights On – 24 hours	3 Lights Alternating On/Off Every Hour	6 Lights Alternating On/Off Every Hour
Time of Day (based on 1 hour before and after sunrise and sunset)	Sunrise, Day, Sunset, Night	Sunrise, Day, Sunset, Night	Sunrise, Day, Sunset, Night
Blocks (number of 3-day treatment blocks)	16	16	17
Discharge Categories (m^3/s)	<1,181	<227	NA
	1,181 – 3,361	227 – 1,586	NA
	>3,362	>1,586	NA
Target Strength (dB)	≤47	NA	NA
	>-47	NA	NA
NA = Not analyzed.			

condition (i.e., on or off). For fish detected by the multibeam transducers, we looked at the distribution of fish in a two-dimensional plane (depth versus distance from the transducer).

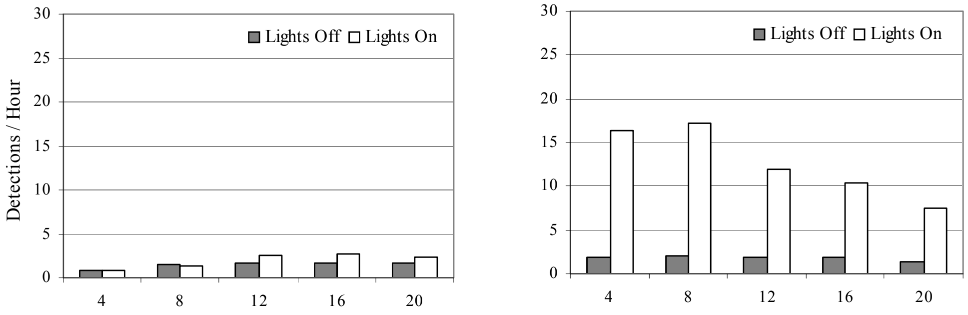
The swimming response of fish to the lights was analyzed by evaluating the swimming speed and direction for each fish detection Direction and speed were referenced to a single coordinate frame for each of three directions as follows: laterally (across the forebay), vertically (by depth), and upstream/downstream.

Three additional studies were conducted to augment the hydroacoustic data. First, kokanee implanted with acoustic tags were released immediately upstream of the strobe lights and subsequently tracked. The tracking data provided information on species-specific fish movement into and out of the illuminated region in the third powerplant forebay. Second, the third powerplant forebay was characterized hydrodynamically using an acoustic Doppler current profiler. Water velocity measurements, taken in front of the strobe lights, were used to determine flow rates in the region where fish encountered the strobe lights. Researchers also collected zooplankton samples in the forebay in an effort to understand how prey species responded to the lighted environment.

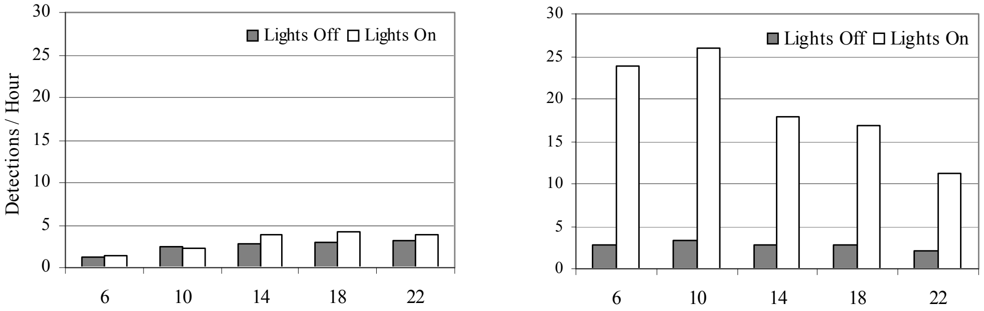
Results

Detections of fish by the splitbeam system in 2004 were similar to those found in 2002 and 2003 (Figure S.4), with detections increasing at night when the lights were on compared to lights off or to detections during the daytime. Generally, few fish were detected at night with the lights off. Fish detections during the day were similar for lights-on and lights-off conditions. The highest detections always were associated with lights on at night, especially in areas closer to the strobe lights. These differences were statistically significant in all three years (Figure S.5). While there were year-to-year differences in the number of fish detected, the pattern of detections remained the same.

Day 2002 Night



2003



2004

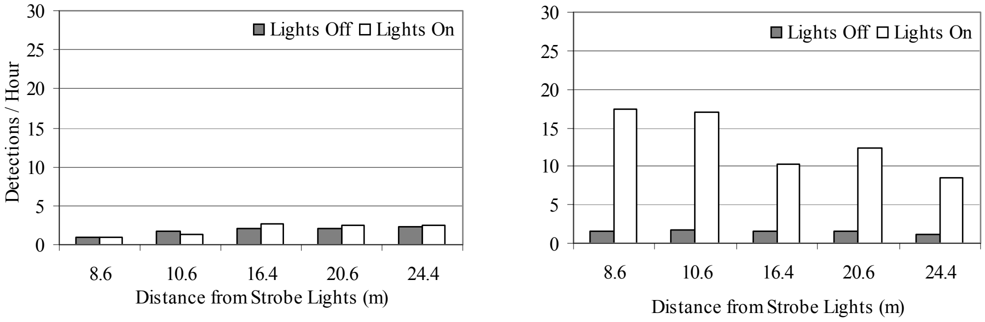


Figure S.4. Number of Fish Detected per Hour by Five Downlooking Splitbeam Transducers in 2002, 2003, and 2004 During the Day and Night When the Strobe Lights Were Off and On for 24 Hours

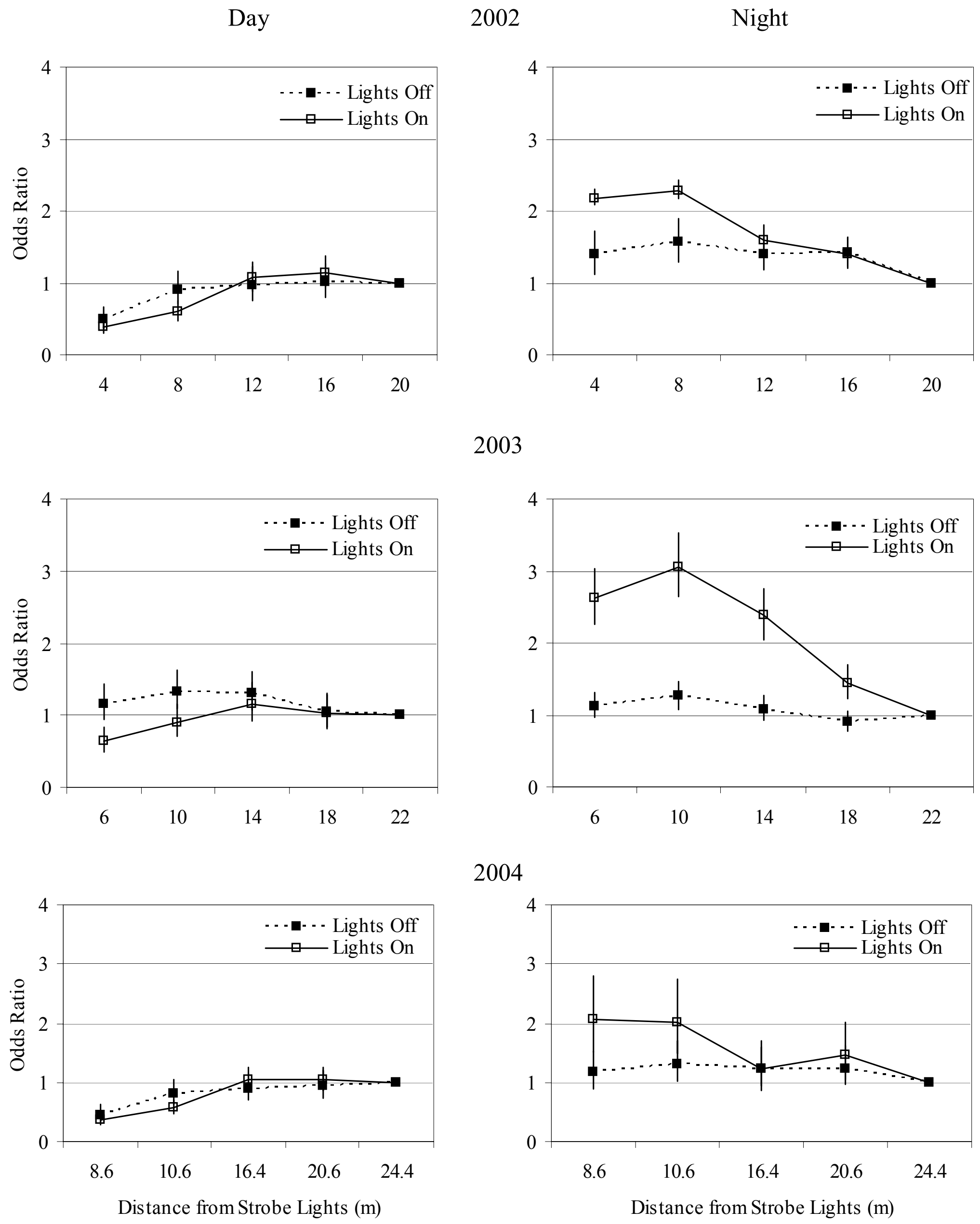


Figure S.5. Odds Ratio Statistic for the Relative Prevalence of Fish at Various Distances Compared to the Reference Location (2002: 20 m; 2003: 22 m; 2004: 24.4 m). Vertical error bars are the 95% confidence intervals.

The number of fish detected by the multibeam system also showed an increase at night with lights on compared to the number of fish present under lights-off conditions at night or during the daytime (Table S.2).

Table S.2 Hourly Fish Detections in 2004 by the Multibeam Sonar Heads During Day and Night When the Strobe Lights Were Off and On. Number in parentheses is the standard error.

Region Ensonified	Day		Night	
	Lights Off	Lights On	Lights Off	Lights On
West (Dam)	3.2 (0.5)	4.0 (0.7)	4.2 (0.6)	14.8 (1.9)
East (Bank)	4.1 (0.6)	4.8 (0.9)	4.6 (0.5)	17.4 (2.1)

Fish swimming activity was analyzed by evaluating the direction of travel in each fish track. Plots of direction reveal that during the daytime when flows were high, fish were generally headed in a downstream direction although not necessarily in the direction of flow. When the lights were on during the daytime, fish closer to the lights swam across the axis of the lights (i.e., they were swimming across the forebay). At night, under low flow conditions, with the lights off, fish showed little preference for direction. However, when lights were on at night, fish again appeared to swim across the axis of the lights. This behavior was observed during each study year and was apparent for fish detected close to the lights and those detected by the most distant transducer. Table S.3 compares the directions of travel for fish detected during the day and nighttime, with lights off and on. The east and downstream probability are the percentage of the fish swimming in that direction. Thus, for all conditions except night with lights on, 60% of the fish were headed toward the east or bank side of the forebay. At night with the lights on, the percentage was 50%, with the other 50% headed toward the west or dam side. The downstream probability was calculated only for those fish headed downstream within 15 degrees on either side of the lights. If there was no preference for swimming direction, we would expect approximately 8.3% of the fish to be headed downstream. This was similar to the percentage seen during the daytime and at night with the lights off. When the lights were on at night, fewer fish (~5%) were headed downstream.

Table S.3. Swimming Direction of Fish Detected by Splitbeam Transducers in 2004 During the Day and Night When the Strobe Lights Were Off and On for 24 Hours. East probability refers to the percentage of fish headed toward the east or bank side of the forebay; downstream probability refers to the percentage of fish downstream within 15 degrees of the position of the strobe lights.

Estimate	Day		Night	
	Lights On	Lights Off	Lights On	Lights Off
East Probability (%)	60.3	60.1	50.0	59.1
Downstream Probability (%)	8.9	8.9	4.9	9.0

Discussion

This study reinforced the notion that the response of fish to strobe lights is complicated by many factors including fish behavioral propensities and their environment. The environmental conditions associated with our sample site were dynamic and, at times, unpredictable. Ambient light and flow were the two primary complicating environmental factors. Ambient light appeared to have rendered the strobe lights largely ineffective during daylight hours, and flows complicated the study design. Flow conditions during the day were usually high when peak demand was highest, and low during nighttime when demand was lowest. Flow dynamics at the entrance to the third powerplant forebay were observed to be quite different between high flow (daytime) and low flow (nighttime) conditions.

The study clearly demonstrated the complex nature of free-ranging fish response to strobe lights at the Grand Coulee Dam third powerplant forebay. Thus, while fish were attracted to the general lighted region at night, fish movements were mostly away from the lights within 10 m of the light frame, and much of the apparent increase in detections in that zone was a by-product of increased activity rather than a large increase in the actual number of fish. An important caveat to these results is that we lack information on species composition and associated feeding data. This was because we were unable to capture fish that were detected near our strobe light array due to site logistics and conflict with the hydroacoustic sampling. It is possible that many of the fish that were accumulating at night in the forebay region near the strobe lights were not kokanee or rainbow trout. However, when we examine the target strength distribution and consider the tagging data, we are reasonably confident that at least a portion of the sampled population would have been either kokanee or rainbow trout.

Conclusions and Recommendations

Based on the results from three years of study (2002 through 2004) at the Grand Coulee Dam third powerplant, we have drawn the following key conclusions:

- Strobe lights had little effect on fish during daylight hours at the third powerplant forebay.
- Strobe lights had a dramatic effect on fish at night, causing them to accumulate in the general region of the lights with increased swimming activity. Increased fish detections and increased activity were observed at night in all three years of our study. In 2004, we observed fish redistributing in proximity to the strobe lights (<10 m) thus avoiding the volume illuminated directly in front of the lights and to the east and west sides.
- Strobe lights at night elicited an apparent avoidance response very close to the lights (<10 m) based on behavior patterns such as distribution, swimming activity, and swimming direction.

Recommendations for future work are as follows:

- **Deploy a trial strobe light array at the entrance to one penstock at the Grand Coulee Dam third powerplant forebay.** Strobe lights should be deployed near the top of the entrance to one penstock on the upstream side of the trash rack in at least four places around the trash rack. If strobe lights can keep fish away from the trash rack to the range that we observed avoidance response (<10 m), then the fish are likely to be able to swim away from the entraining flows. The location of the penstocks is well suited to this deployment. Because of this, a strobe light deployment at this location would have an increased likelihood of effectiveness, even during daytime when the entraining flows are greatest. Adjacent penstocks should also be monitored along with the regions between the penstocks to determine if the fish are being displaced away from the lighted penstock trash rack toward the adjacent unlit trash racks.

- **Monitor the test strobe light deployment using a combination of synchronized video (optical and/or acoustic) and splitbeam hydroacoustics.** Initial deployment of strobe lights on the Grand Coulee Dam third powerplant trash racks should be monitored carefully to ensure that the lights are preventing entrainment of kokanee and rainbow trout. Continued monitoring as the application of lights is expanded to other penstocks will provide quality control and assurance that the fish continue to be protected. Additionally, the flow in the region in front of the trash racks within the influence of the strobe lights should be measured to provide prototype data on entrance velocities and to calibrate a flow model of the entrances.

- **Additional research should be conducted to determine if high-intensity strobe lights attract free ranging fish to a region and to what extent this relates to feeding behavior.** Future applications of strobe lights at Grand Coulee Dam and other locations would benefit from knowing the extent to which feeding behavior is associated with strobe lights. As an initial examination, gillnets should be used to capture fish in the vicinity of the “old” barge location to provide an initial estimation of the species composition and diet associated with strobe light operation. Mobile survey sampling should also be conducted in the vicinity of the gillnet with lights on and lights off to determine if fish are accumulating in or near the lighted zone.

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Abbreviations Used in This Report

ADCP	acoustic Doppler current profiler
°C	degrees Celsius
cm	centimeter
cfs	cubic feet per second (ft^3/s; 0.0283 m^3/s)
dB	decibel
dB counts||μPa	decibel counts relative to microPascal
DGPS	differential global positioning system
E	east
e.g.	(exempli gratia) for example
et al.	(et alii) and others
etc.	(et cetera) and so forth
°F	degrees Fahrenheit
ft	foot
GDOP	geometric dilution of precision
hr	hour
i.e.	(id est) that is
in.	inch
kcfs	1000 cubic feet per second
kHz	kilohertz
lx	lux
m	meter
mi	mile
MS	millisecond
MW	megawatt
N	north
NTU	nephelometric turbidity unit(s)
NWPPC	Northwest Power Planning Council
Pa	Pascal
PAS	Precision Acoustic Systems
pdf	probability density function
PNNL	Pacific Northwest National Laboratory
pps	pings per second (acoustics) or pulses per second (light)
QA	quality assurance
s	second
S	south
SI	International System of Units
V	volt
VDOP	vertical dilution of precision
W	west

Glossary

anadromous	pertaining to fish that ascend rivers from the sea for spawning
decibel	dimensionless unit used to express logarithmic ratios of sound intensity; abbreviated as **dB**
diel	involving a 24-hour period that usually includes a day and the adjoining night (e.g., diel fluctuations in temperature)
forebay	portion of a reservoir or canal that is immediately upstream from a dam or pumping plant from which water is taken to run equipment (e.g., a turbine)
hectare meter	the metric unit of volume used to measure the capacity of reservoirs – In the United States, the *acre-foot* is used more commonly. One acre-foot contains 43,560 cubic feet or about 1233.482 cubic meters (0.123348 hectare meter).
hydroacoustics	the use of transmitted sound to detect objects (e.g., fish) in water
hypolimnion	the cooler, lower level of a thermally stratified water body – This layer extends vertically from the thermocline to the bottom.
littoral	the region along the shore of a nonflowing body of water
lumen	SI unit for measuring the flux of light produced by a light source or received by a surface
lux	SI unit for measuring the illumination of a surface - One lux is defined as an illumination of one lumen per square meter.
nephelometric turbidity unit	see *turbidity*
odds	ratio of the probability of an occurrence of an event to that of non-occurrence
odds ratio	quotient obtained by dividing one set of odds by another – It shows the strength of association between two responses of interest. If the odds ratio is one, there is no association.
penstock	a sluice or gate for regulating flow of water; a conduit or pipe used to carry water
phototaxis	reflex translational or orientational movement by a freely motile organism in relation to stimulation from a light source

ping	a pulse of transmitted sound
polytomous	divided into several parts
pulse	a dose of a substance over a short period of time (e.g., a pulse of light)
target strength	a measure of the proportion of sound (in decibels) reflected back to the transducer from an acoustic target (e.g., fish) – The strength of the return is dependent on the size and orientation of the object. Target strength is measured in decibels (dB) referenced at 1 meter from the object's acoustic center.
thermocline	the temperature gradient in a thermally stratified body of water that separates warmer oxygen-rich surface water from cold oxygen-poor deep water and in which temperature decreases rapidly with depth
track	a trajectory associated with a single target; composed of a series of echo returns
transducer	a pressure-sensitive device that converts electrical energy into sound energy for sound transmission, and sound energy into electrical energy during reception
transect	a sample area of the study site, usually in the form of a long continuous strip
turbidity	the extent to which water is thick or opaque with suspended particles – It is usually measured by nephelometry (the relative measurement of light scattering through a restricted range of angles to the incident light beam).
wind rose	graphic representation commonly used to present frequency distributions of wind direction – The direction frequencies are arranged in "petals" aligned with the wind directions.

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1.0 Introduction

This report documents the fourth year of a four-year study[a] to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee (*Oncorhynchus nerka kennerlyi*) and rainbow trout (*O. mykiss*) at the entrance to the forebay of the third powerplant at Grand Coulee Dam. This work was conducted for the Bonneville Power Administration, U.S. Department of Energy, by Pacific Northwest National Laboratory (PNNL) in conjunction with the Confederated Tribes of the Colville Reservation (Colville Confederated Tribes).

1.1 Background

The construction of Grand Coulee and Chief Joseph dams on the Columbia River in 1933 and 1956, respectively, resulted in the complete extirpation of the anadromous fishery upstream of these structures. Today, the area above the two dams is totally dependent upon resident fish resources to support local fisheries. Target species in the existing fishery include, but are not limited to, kokanee, rainbow trout, white sturgeon (*Acipenser transmontanus*), and walleye *(Sander vitreum*). Kokanee, a land-locked sockeye salmon, is a species of special interest because of its historical significance to native cultures and its role in the functioning ecosystem within the affected area. Factors limiting hatchery and wild kokanee stocks in Lake Roosevelt, the reservoir impounded by Grand Coulee Dam, are related to annual water regimes, shoreline spawning, entrainment, early maturation of age-2 fish, sex ratios skewed toward males, predation by walleye, and forage production (Scholz et al. 1985; Peone et al. 1990; Griffith and Scholz 1990; Baldwin et al. 2003; McLellan et al. 2004).

The Chief Joseph Kokanee Enhancement Project, managed by the Colville Confederated Tribes, was accepted into the Northwest Power Planning Council (NWPPC) Fish and Wildlife Program in 1995. Project objectives have focused on obtaining data needed to fill several critical gaps in information relating to natural production of kokanee in Lake Roosevelt. Specific objectives include

1. assessment of annual adult spawning abundance in tributary habitats
2. micro-satellite analysis of deoxyribonucleic acid (DNA) to determine the specific origin of all kokanee stocks found in Lake Roosevelt, Lake Rufus Woods, and other upriver stocks, including the "free-ranging" upriver kokanee stocks found in the Spokane River/Coeur d'Alene Lake system, the Lake Pend Oreille/Pend Oreille River system, the Arrow Lake system, and the Kootenai Lake/River system of British Columbia
3. use of hydroacoustic technology to determine fish entrainment rates and species composition at Grand Coulee Dam and to quantify fish distributions at the dam relative to hydropower operation and time of day.

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[a] The study was extended by one year to capture three years of consistent data because the first year was exploratory.

A 42-month entrainment investigation (1996-1999) concluded that entrainment at Grand Coulee Dam was substantial, ranging from 211,685 to 576,676 fish annually (LeCaire 1999; Sullivan 2000). These studies found that high entrainment was potentially correlated with annual reservoir water regimes, hydropower operations, and timing of reservoir net pen and hatchery releases. Further data analysis determined that entrainment was highest (85%) at the dam's third powerplant (LeCaire 1999; Sullivan 2000). Peak entrainment rates of 51 to 66 fish per hour were measured in June and July 1999 (LeCaire 1999).

The Independent Scientific Review Panel of the NWPPC suggested that because entrainment was substantial, something needed to be done to reduce or eliminate this loss of resident fish. It was suggested that it would be best to keep the fish entirely out of the third powerplant forebay. The panel noted that studies conducted at Dworshak Dam and other areas in Idaho by Idaho Fish and Game indicated that kokanee avoided areas illuminated by strobe lights (Maiolie et al. 2001). It was further suggested that strobe light technology might also deter kokanee from entering the third powerplant forebay at Grand Coulee Dam.

1.2 Study Scope

The scope of work for the Chief Joseph Kokanee Enhancement Project was modified to include a multiyear pilot test of a strobe light system to determine its effectiveness in reducing fish entrainment. The pilot test consisted of suspending six strobe lights in the center of the third powerplant forebay and using hydroacoustic systems to remotely and unobtrusively monitor fish distribution and behavior. The hydroacoustic systems in 2002 through 2004 comprised seven splitbeam transducers, two multibeam transducers, and a mobile splitbeam hydroacoustic system. The seven fixed splitbeam transducers were used to monitor fish as they approached or passed the lights, while the distribution of fish to the sides was evaluated by the two multibeam transducers. The mobile system looked at the distribution of fish within the entire third powerplant forebay.

To augment the hydroacoustic data, three additional studies were conducted. The water velocity directly in front of the strobe lights was measured; acoustically tagged kokanee were released upstream of the strobe lights and tracked; and zooplankton samples were collected in the forebay. Water velocity measurements were used to determine fish swimming effort in the region illuminated by the strobe lights. Tracking tagged kokanee provided data on fish movement into and out of the third powerplant forebay in relation to the strobe lights. The zooplankton study was designed to help better understand the role of lights in attracting prey species.

This report details these studies conducted from 2002 to 2004 by researchers affiliated with the Chief Joseph Kokanee Enhancement Project and the Pacific Northwest National Laboratory.

1.3 Report Contents

Section 2 of this report describes the study site at Grand Coulee Dam. Section 3 provides the methods of sampling and analysis. Results are presented in Section 4. Section 5 provides a discussion of results from the 2004 study period as well as those from 2002 and 2003. Conclusions and recommendations are listed in Section 6. References are in Section 7.

A series of appendixes provides supporting information: environmental conditions at the study site (A); hydroacoustic system calibration (B); mobile splitbeam hydroacoustics (C); details of the statistical analysis (D); acoustic tagging study (E); hydrodynamic characterization of the forebay (F); and zooplankton sampling (G).

2.0 Study Site Description

The study site was the entrance to the forebay of the third powerplant at Grand Coulee Dam. This restricted entrance was thought to be the most logical place to deploy strobe lights according to project reviewers, if the lights proved effective. The center of the entrance was chosen as the test area to study the deterrence capability of the strobe lights because the dam structure and bank would not interfere with the free-ranging behavior of the fish. Also, lacking data on fish behavior in this area, we felt that the area closer to the penstocks would present flow conditions that would be too severe for fish to overcome. The study site is described in this section.

2.1 Grand Coulee Dam

Grand Coulee Dam, located at river kilometer 960.1 (mile 596.6) on the Columbia River, is the northernmost of the 11 U.S. dams on the river (Figure 2.1). The dam complex contains four powerplants (pumping plant, left powerplant, right powerplant, and third powerplant) and a spillway (Figure 2.2). Construction of the main dam complex (left and right powerplants and spillway) began in December 1933 and was completed in 1942. Construction of the pumping plant was initiated in 1946 and completed in 1951. Four additional pump/generators were added to the pumping plant in 1983.

Figure 2.1. Location of the 11 Columbia River Dams, Including Grand Coulee, in Washington State, USA

Figure 2.2. Study Site Location (red) Near Third Powerplant, Grand Coulee Dam in 2001 through 2004

Construction of the third powerplant and forebay dam began in 1967, with the first unit (G-19) commissioned in 1975 and the last (G-24) in 1980. The original dam was modified for the third powerplant by adding a forebay dam, 357 m (1170 ft) long by 61 m (201 ft) high, along the right abutment approximately parallel to the river and at an angle of 64 degrees to the axis of Grand Coulee Dam. The width of the forebay tapers from the entrance to the downstream end and varies slightly with water surface elevation. At the test site it is approximately 170 m (560 ft) wide. Each of the six generators at the third powerplant is fed by an individual penstock approximately 12 m (40 ft) in diameter and carrying up to 990 cubic meters per second (35,000 cfs) of water.

The 33 generators at Grand Coulee have a total generating capacity of 6809 MW (Table 2.1). The spillway, situated between the left and right powerplants, is 498 m (1635 ft) long with 11 spill gates. The forebay pool level ranges from 368 m (1208 ft) (minimum pool) to 393 m (1290 ft) (full pool) above mean sea level. Lake Roosevelt, the 243-km (151-mi) -long reservoir impounded by the dam, contains approximately 1.2 million hectare-meters (9.5 million acre-feet) of water and serves as a multiple-use body of water for both commercial and recreational purposes. In addition to power generation, water from Lake Roosevelt is pumped into adjacent Banks Lake, supplying more than 0.2 million hectares (0.5 million acres) of irrigated land that extends from Coulee City, Washington, in the north to Pasco, Washington, in the south. Grand Coulee Dam also provides flood control for the remainder of the Columbia River basin.

Table 2.1. Generating Capacity for Grand Coulee Dam (Bureau of Reclamation 2003)

Location	Description	Number of Generators	Capacity, Each (MW)	Total (MW)
Pumping plant	Pump/generator	2	50	
		4	53.5	314
Left powerplant	Station service generator	3	10	30
	Main generator	9	125	1125
Right powerplant	Main generator	9	125	1125
Third powerplant	Main generator	3	600	1800
	Main generator	3	805	2415
Totals		33		6809

2.2 Powerplant Operations

The third powerplant contributes more than 60% of the generating capacity at Grand Coulee Dam (Table 2.1) and, during the study period in 2004, contributed more than 60% of the total powerplant discharge during the day (Figure 2.3). Over the three years of this study, the discharge patterns and amounts were similar for 2003 and 2004, peaking during the daytime and falling to near zero during the night hours (Figure 2.4). Nighttime discharges were higher in 2002. Operations data were supplied by the Bureau of Reclamation (Randy Spotts, personal communication).

Additional data relating to the environmental conditions at Grand Coulee Dam during the three study years are found in Appendix A. These data include forebay elevation, water temperature, turbidity, and ambient light levels.

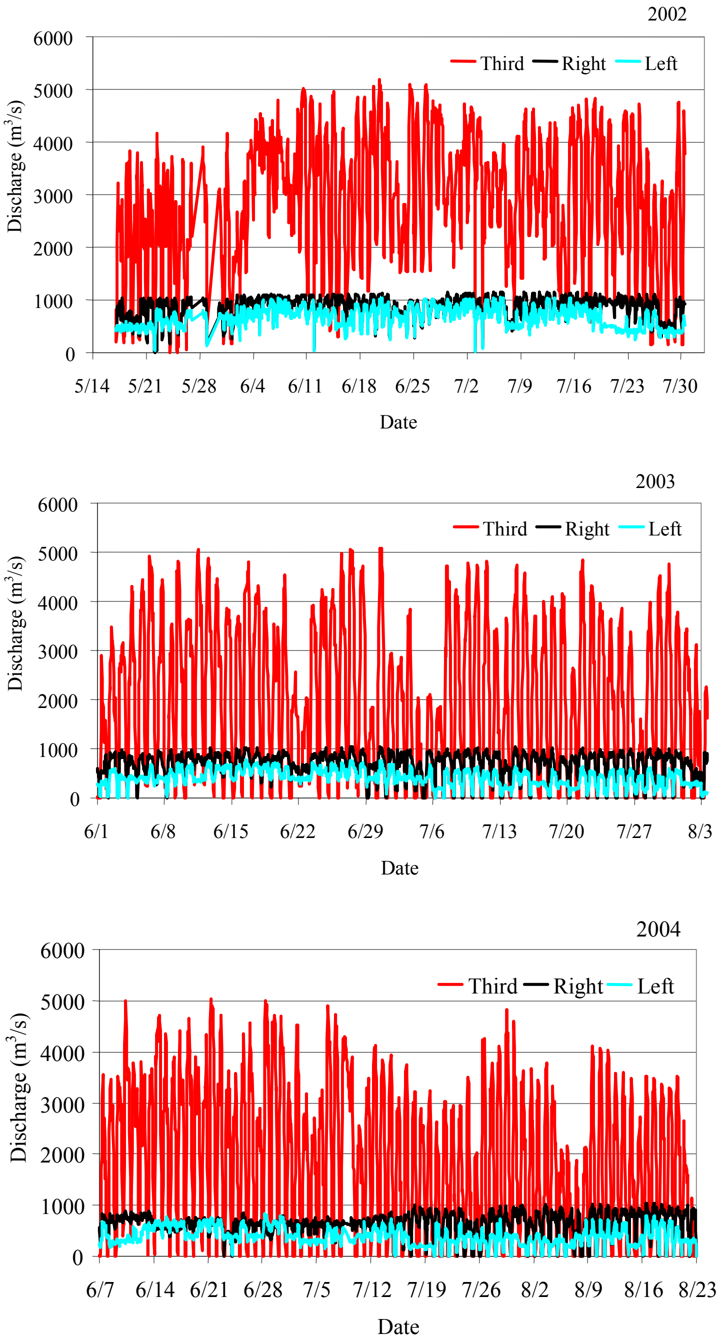

Figure 2.3. Discharge (m^3/s) at Grand Coulee Dam for 2002, 2003, and 2004. Hourly average discharges for each powerplant are plotted separately.

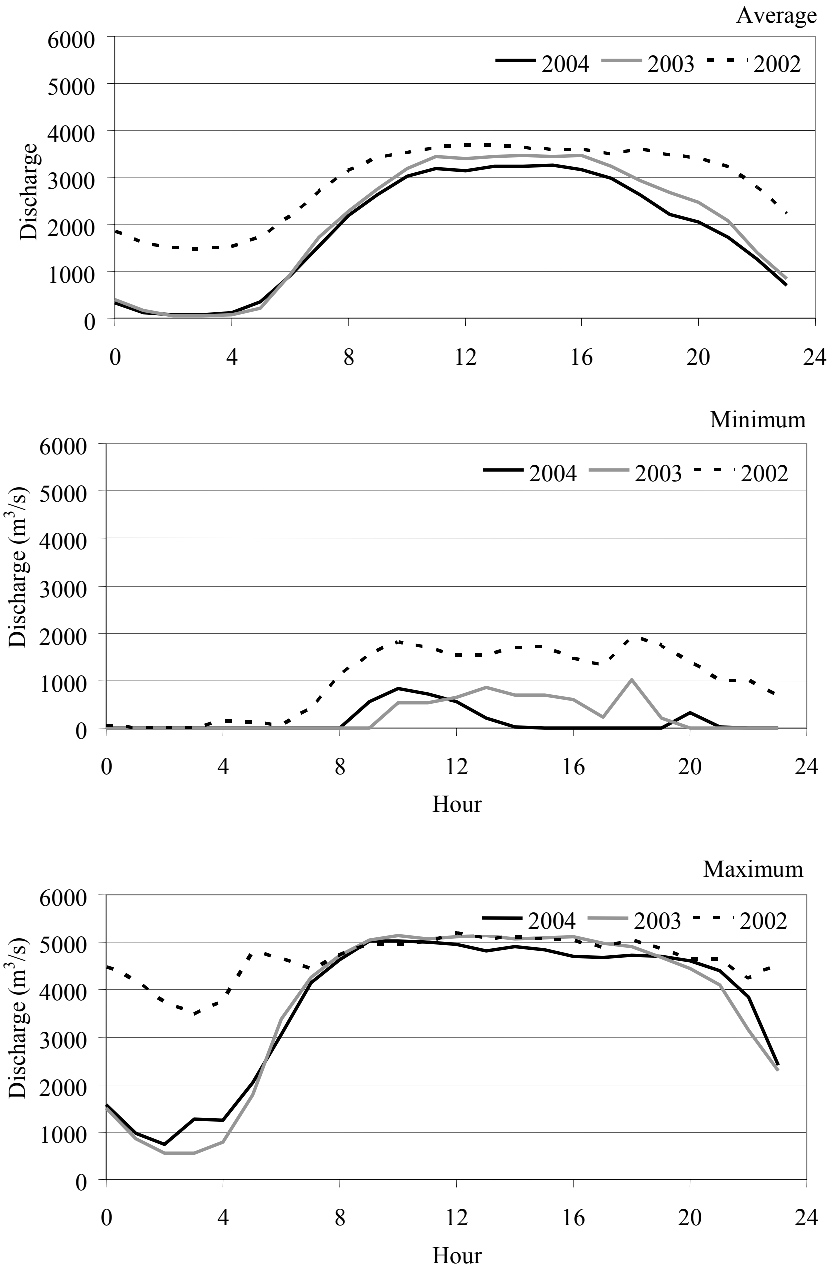

Figure 2.4. Average, Minimum, and Maximum Hourly Discharge at the Third Powerplant over 24 Hours for 2002, 2003, and 2004. Data were averaged over the study period for each year. Zero hour is midnight.

3.0 Methods

This section presents descriptions of the prototype strobe light system and its deployment at the study site. The methods described in this section are for the 2004 field season. Methods used in other years may be found in Simmons et al. (2002 and 2004) and in Johnson et al. (2003). The hardware, software, and protocols used for collecting and processing the data also are detailed. The study design is described, followed by documentation of the statistical analyses applied to the data on fish distribution and behavior. Additional studies conducted to augment the hydroacoustic data are summarized, and the supplementary hydroacoustic and ancillary data collected during the study are noted.

3.1 Strobe Lights

Six strobe lights, each producing a maximum of 20,000 lumens-s/flash (Flash Technology specification), were mounted across the top and bottom of a 1.3-m^2 aluminum frame. The strobe lights, supplied by Flash Technology, Franklin, Tennessee, were adapted specifically for underwater deployment. The frame was deployed from a barge secured in the center of the entrance to the third powerplant forebay (Figure 3.1). The frame was attached to a system of suspension cables that permitted the frame to be nearly vertical in the water column when flow was minimal but also permitted the frame to move downstream during high flows. The orientation of the frame was stabilized in the flow by a dihedral hydrodynamic tow vehicle (V-fin) attached to a bridle at the base of the frame. The strobe lights were controlled by a computer located in the equipment trailer on the deck of the dam via RS485 communication links with the light controller/power supply located on the deck of the barge. In addition, an attitude sensor, attached to the frame, monitored tilt and rolling movement. The attitude sensor also incorporated a flux gate compass for relative directional information.

The strobe lights were aimed to illuminate a restricted region directly upstream of the barge location (Figure 3.2). The depth to the top of the light frame was approximately 15 m, and the flash rate was set at 300 flashes per minute. Flash rate in 2002 and 2003 was 360 flashes per minute (Johnson et al. 2003; Simmons et al. 2004). A lower flash rate was used in 2004 because of strobe light equipment instability. In 2002, we measured the characteristics of the strobe lights used in this study both in the field and in the laboratory using two types of light detectors. The light measurements are described in detail in Johnson et al. (2003, Appendix C).

3.2 Transducer Deployment

The response of fish to the strobe lights was monitored 24 hours a day by hydroacoustic systems including six splitbeam transducers placed upstream and in line with the strobe lights, two mulitbeam sonar heads oriented to ensonify regions to the side of the strobe lights, and a single splitbeam transducer located downstream of the lights. In addition, weekly surveys of the third powerplant forebay, upstream and downstream of the lights, were made with another hydroacoustic system using a single splitbeam transducer (Appendix C). The hydroacoustic approach provides an index of fish abundance and not an absolute count.

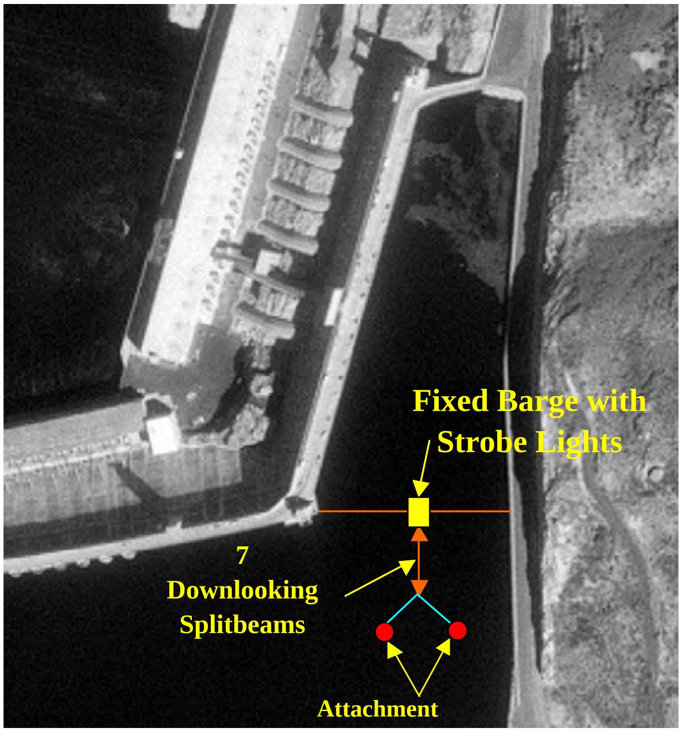

Figure 3.1. Location of Strobe Light Test Site at Third Powerplant Forebay of Grand Coulee Dam

A seven-transducer splitbeam system, arrayed upstream and downstream of the strobe lights, was used to evaluate the effectiveness of the strobe lights in eliciting a negative phototactic response by fish to the lights. The seven transducers were deployed in a manner to track fish entering and within the region illuminated by the strobe lights. Precision Acoustic Systems (PAS), Seattle, Washington, supplied the splitbeam hydroacoustic system. The system comprised a Model PAS-103 Multimode Scientific Splitbeam Echo Sounder operating at 420 kHz; a Model PAS-203 Remote Underwater Quad Multiplexer; a Model PAS-203 Local Quad Multiplexer; seven 6-degree, 420-kHz splitbeam transducers lensed to 10 degrees; and associated power and telemetry cables. The seven transducers were fast-multiplexed at 20 pings per second (pps). The system was powered from a load center stationed on the deck of the dam by the Bureau of Reclamation. A personal computer was used for system control and data logging using the Hydroacoustic Assessment Research Package (HARP, Hydroacoustic Assessments, Seattle, Washington), a software program for splitbeam data acquisition. Calibration information for the splitbeam data acquisition system is in Appendix B.

Six of the splitbeams and the acoustic Doppler current profiler (ADCP) were suspended from an aluminum truss floating 6 m upstream of the barge (Figure 3.2). The aluminum truss was attached to the starboard and port sides of the barge by two aluminum arms and tethered to a floating line that connected the barge to the upstream anchor buoys. The ADCP was positioned in the center of the truss, with one of the splitbeam transducers attached to the mounting bracket and canted 10 degrees downstream from vertical.

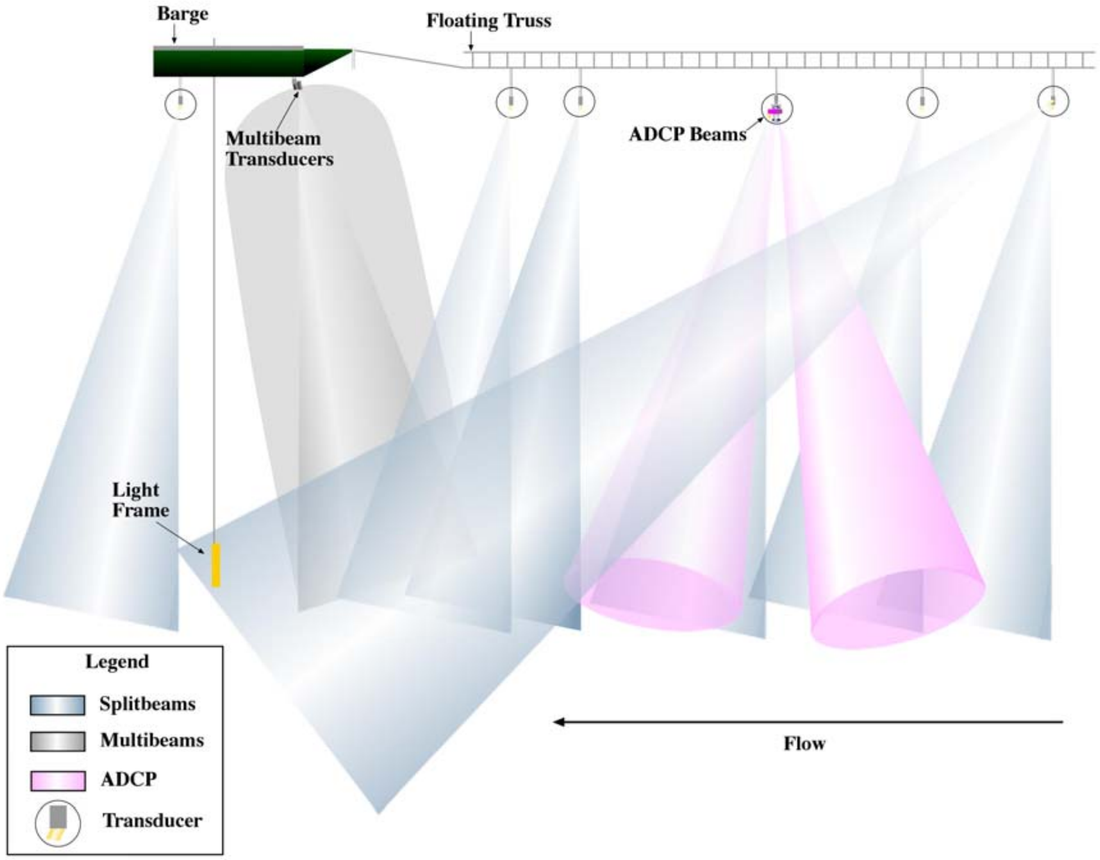

Figure 3.2. Strobe Light and Hydroacoustic Transducer Frame Configuration at Grand Coulee Dam. Side view showing area ensonified (not to scale). Light frame was at 15 m.

Another transducer was mounted at the upstream end of the aluminum truss and aimed 30 degrees downstream toward the light frame. The remaining four splitbeam transducers were spaced approximately 4 m apart on the aluminum truss starting 8 m upstream of the light frame location, with the exception of the first two transducers, which were only 2 m apart because of obstructions on the truss. These transducers looked downward and were canted approximately 10 degrees toward the barge from vertical to minimize bottom echo interference. The seventh splitbeam transducer was positioned behind the barge aimed 7.5 degrees downstream into the third powerplant forebay.

For the multibeam system, two Simrad(a) SM2000™, 200-kHz sonar heads were mounted near the end of a 1.0-m pole that was partially submerged and attached to the middle of the barge approximately 1 m upstream from the light frame placement. The two sonar heads were oriented at approximately a 90-degree angle to each other and operated at a ping rate of 3 per second. The control and data logging system of the dual-head multibeam sonar comprised two Simrad SM2000 surface processor units and a computer running Battelle's Multibeam Data Acquisition Software (MBAQ).

(a) Kongsberg Simrad Mesotech Ltd., Port Coquitlam, British Columbia, Canada.

The mobile hydroacoustic surveys were conducted from a boat using a BioSonics, Inc.[a] DT-X digital scientific echo sounder system. The system consisted of a digital splitbeam transducer, a surface unit with programmable Linux-based Emb processor inside, and, a laptop computer to control the system operation and log data. A differential global positioning system (DGPS) with real-time position correction was used to determine the position of the transducer during the surveys.

For the mobile surveys, seven parallel transects were laid out beginning at the upstream security boom and extending downstream to the back of the third powerplant forebay (Figure 3.3). Each transect was marked at both ends by a flashing amber light to ensure that transects were closely replicated during a survey and from week to week. Four of the transect markers were on floats attached to the inner security boom. As wind conditions changed, the boom moved back and forth, varying the length of each of the upstream transects (i.e., upstream of the barge location).

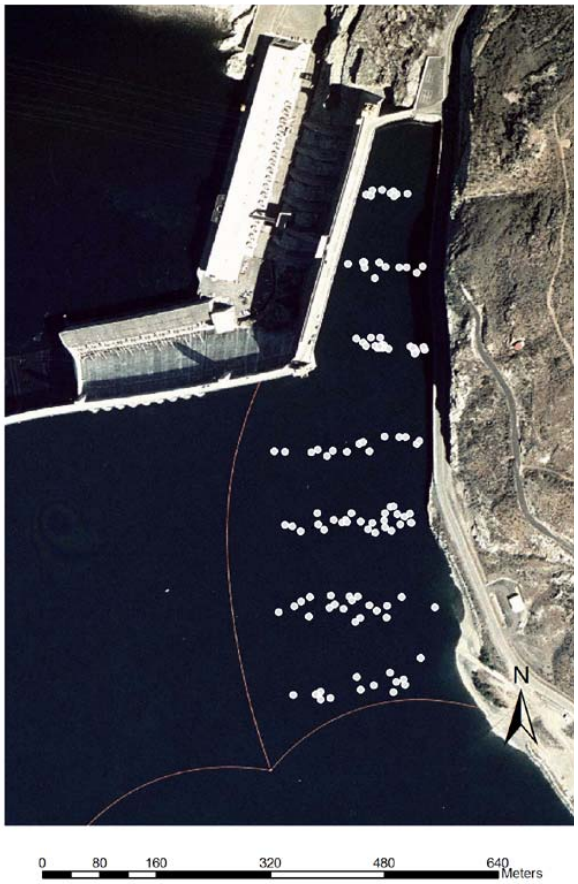

Figure 3.3. Mobile Survey Transect Locations Depicted by Fish Locations for 2004 Field Season

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[a] BioSonics, Inc., Seattle, Washington.

The mobile surveys typically began at the most upstream transect adjacent to the boat launch, sequentially completed to the back of the third powerplant forebay, and then repeated back to the boat launch. The mobile surveys began at approximately 2200 hours on Monday nights when the lights on the dam were extinguished for the nightly laser light show. Each survey was normally completed by the time the lights were turned back on for the night (about 2300 hours) after the laser light show. A detailed description of the mobile surveys can be found in Appendix C.

3.3 Study Design

Three light treatments were evaluated over the three years of this study (Table 3.1). In all three years, two of the treatments consisted of all strobe lights on (six lights) and all strobe lights off for a 24-hour period. In 2002, the third treatment was three strobe lights on for 24 hours, while in 2003 and 2004, the third treatment consisted of lights alternating on and off on an hourly basis over the 24-hour period. In 2003, three lights were used for this third treatment, six lights in 2004. The three treatment conditions were randomly assigned within a 3-day block throughout the study period. Each 24-hour period encompassed a complete daily cycle of power generation and ambient light conditions. Each sequential block of 3 days constituted a pseudo-replicate in which all three treatment conditions had equal time allocation within a block.

Table 3.1. Treatment Designs for 2002, 2003, and 2004 Field Seasons

				Treatment		
Survey Year	Start Date	End Date	Number of Blocks	Light Configuration	Number of Lights	Duration (hr)
2002	5/18/2002	8/1/2002	22	Off	6	24
				On	3	24
				On	6	24
2003	6/14/2003	8/1/2003	14	Off	6	24
				On	6	24
				Alternating on/off	3	1
2004	6/19/2004	8/16/2004	17	Off	6	24
				On	6	24
				Alternating on/off	6	1

The study period in 2002 started in mid May. However, few fish were detected in May, so in subsequent years the starting date was delayed until mid June. The end date was August 1 in 2002 and 2003. In both those years, there was an increase in the number of detections through the end of July, so in 2004 the study was extended into mid August.

3.4 Data Processing

Data collected from the splitbeam and multibeam systems were stored in a centralized location for transfer, storage, and archiving. Computers were linked via the PNNL intranet to the field site server at Grand Coulee Dam. Raw data and supporting files were downloaded via file transfer protocol. Daily backups of data were written to compact disks at the field site and transferred to PNNL's Richland laboratory. All raw and processed data and supporting files were archived to tape for long-term storage.(a) A data management system based on the Hierarchical Data Format Version 5 (HDF5) software platform was used to organize and store all the data.

Acoustic data files from the stationary splitbeam transducers were processed using software developed by PNNL to identify linear traces. The software allowed the user the option of manually choosing tracks (manual tracking) or having the software choose the tracks (autotracking). Manual tracking allowed us to develop the tracking criteria needed for autotracking calibration and to screen the data for possible noise events. All the splitbeam data were processed using the autotracking software. Parameters for the autotracking included setting the acoustic size threshold between −60 and −10 dB.

Data collected from the multibeam sonar system were processed using Battelle's tracking software, Gfish (version 1.21). The software filtered out permanent structures and grouped targets together based on their proximity in space, time, and angle units. Manual processing was used to make the final determination of fish tracks. Only a subset of the data was processed through the final selection. A stratified random sample strategy was used to select files from the time period 15 minutes before and after the hour. This time period was selected to sample the hourly shift between lights off and on during the 1-hour on/off treatment. Additionally, more files were selected from nighttime because previous studies have shown the response to lights occurs predominantly during that period. Enhancements to the processing software allowed us to increase the number of the files processed so that in 2004, approximately 33% of the multibeam data files were tracked manually, compared to 16% in 2003.

Following this initial processing, the tracks were subjected to additional filtering to select targets containing enough information to determine that they exhibited fish-like behavior. A track is a sequence of locations (position vectors)—that is, echo locations—for which the displacement between locations depends on the fish velocity and the sample rate of the equipment (acoustic pings sent out per second, pps). However, each track contains random departures resulting from movement of the equipment, inaccuracy in locating the angular direction, and basic accuracy limitations of the tracking software. Therefore, the tracks must be filtered to remove location errors and smoothed to remove or reduce random departures from the actual path of a fish. The processing of target tracks by filtering and smoothing must be done to obtain the most accurate estimate possible of the overall velocity allowed for by the measurement conditions. Criteria and procedures used to filter and smooth the splitbeam data included excessive position and velocity shifts and tracks containing too few echo locations (<6) given the angle of the splitbeam and the ping rate. Additional details about the data filters are given in Simmons et al. (2004).

The Echoview® software from SonarData Pty Ltd.(b) operating under Microsoft® Windows was used to process the mobile splitbeam data. Echoview is a visual processing and analysis package that allows the user to visually scan echogram data in the context of bottom and surface and verify auto-tracking results. Refer to Appendix C for a detailed description of the data processing for the mobile surveys.

(a) At the completion of the project, a final backup of all data will be made to tape, catalogued, and moved to a permanent storage location.

(b) SonarData Pty Ltd., Hobart, Australia.

3.5 Data Analysis

In analyzing and interpreting the data, a number of environmental and system factors, aside from the strobe light treatments, must be considered. Factors associated with the sampling method (i.e., hydroacoustics) include the shape of the area sampled, the presence of noise in the data, and inability to distinguish species and identify unique targets. Splitbeam transducers sample a conical volume, with the narrower sample volume close to the transducer, expanding to a larger volume further away. Thus, the distribution of fish within the beam is not invariant with distance from the transducer.

Noise in the hydroacoustic data can make it difficult to identify fish targets. In 2002, the vertical orientation of the downlooking transducers produced a false-bottom effect, obscuring target recognition beyond 30 m. In 2003 and 2004, the false-bottom effect was eliminated by tilting the downlooking splitbeam transducers 10 degrees downstream. For the multibeam transducers, in 2003, the transducers were place behind the light frame which caused areas to be obscured by the noise. In 2004, the multibeam transducers were moved upstream of the frame eliminating some of the noise. Additional filtering considerations during processing also helped remove extraneous hydroacoustic echoes or noise.

While it is not possible to identify fish species using hydroacoustics, we do obtain information from the splitbeam data (both mobile and stationary) about the size of the target ensonified, which allows an inference as to the fish species. Another system factor affecting the interpretation of results is that the same fish may be counted more than once, so counts do not represent unique fish occurrences.

Due to all these factors, the count estimates of fish used in the analysis cannot be considered as a measure of abundance but rather as an index of activity based on target detections. Analysis of these detections provides information about fish activity in the form of swimming speed and direction in the vicinity of the strobe lights.

Factors included in the analysis were distance from the strobe lights, level of discharge through the third powerplant, time of day, and treatment block. Table 3.2 lists and defines the factors or classification variables used in the statistical analysis.

These studies were designed to capture the response of fish entering the third powerplant forebay to the presence of strobe lights. The response of fish to strobe lights was evaluated to answer two questions: 1) How were fish distributed in relation to the lights? and 2) What was the swimming response of fish to the lights?

For the question relating to the distribution of fish, statistical analyses were used to test the null hypothesis that the strobe lights had no effect on the number of fish within distance categories upstream of the strobe lights. For fish detections, we were interested in differences in the distribution of fish detections for similar regions and periods of the day. If the strobe lights had no effect on distribution, we would expect the number of fish detected by each of the splitbeam transducers would be independent of the light condition (i.e., on or off). For fish detected by the multibeam transducers, we looked at the distribution of fish in a two-dimensional plane (depth versus distance from the transducer).

Table 3.2. Factor Variable Definitions for Odds Ratio Analysis

Factor Variables	Survey Year		
	2002	2003	2004
Distance of Splitbeam Transducer from Strobe Lights (m)	4	6	8.6
	8	10	10.6
	12	14	16.4
	16	18	20.6
	20	22	24.4
Strobe Light Treatments	Lights Off – 24 hours	Lights Off – 24 hours	Lights Off – 24 hours
	6 Lights On – 24 hours	6 Lights On – 24 hours	6 Lights On – 24 hours
	3 Lights On – 24 hours	3 Lights Alternating On/Off Every Hour	6 Lights Alternating On/Off Every Hour
Time of Day (based on 1 hour before and after sunrise and sunset)	Sunrise, Day, Sunset, Night	Sunrise, Day, Sunset, Night	Sunrise, Day, Sunset, Night
Blocks (number of 3-day treatment blocks)	16	16	17
Discharge Categories (m^3/s)	<1,181	<227	NA
	1,181 – 3,361	227 – 1,586	NA
	>3,362	>1,586	NA
Target Strength (dB)	≤47	NA	NA
	>-47	NA	NA
NA = Not analyzed.			

Statistical analysis of the detection data from the splitbeam transducers was based on multidimensional contingency tables that display fish detections as a function of the factors in Table 3.2. For the position factor, only data from the five splitbeam transducers aligned along the axis of the lights were used. Detections from the transducer at greatest distance from the strobe lights were used as the reference in all three years; light levels measured in 2001 and 2002 indicated that light levels at this distance should be minimal (Simmons et al. 2002; Johnson et al. 2003). Each detection or track was classified into one and only one class level for each factor variable shown in Table 3.2.

Contingency tables were statistically evaluated using a log-linear model (sometimes called a Poisson regression model), which is widely used, particularly in fisheries and wildlife research where data are frequently in the form of survey counts (Jackson et al. 1992; Van Der Meer and Camphuysen 1996). Fitting a log-linear model involves setting one of the class levels for each factor as a reference level, with comparisons made to the reference level. Results from the model are point estimates of the relative prevalence of tracks for a factor level when compared to the reference level. These point estimates are called an odds ratio—that is, the ratio of track counts observed at a given location compared to a common reference location. A simulated example of an odds ratio plot is given in Figure 3.4. In the

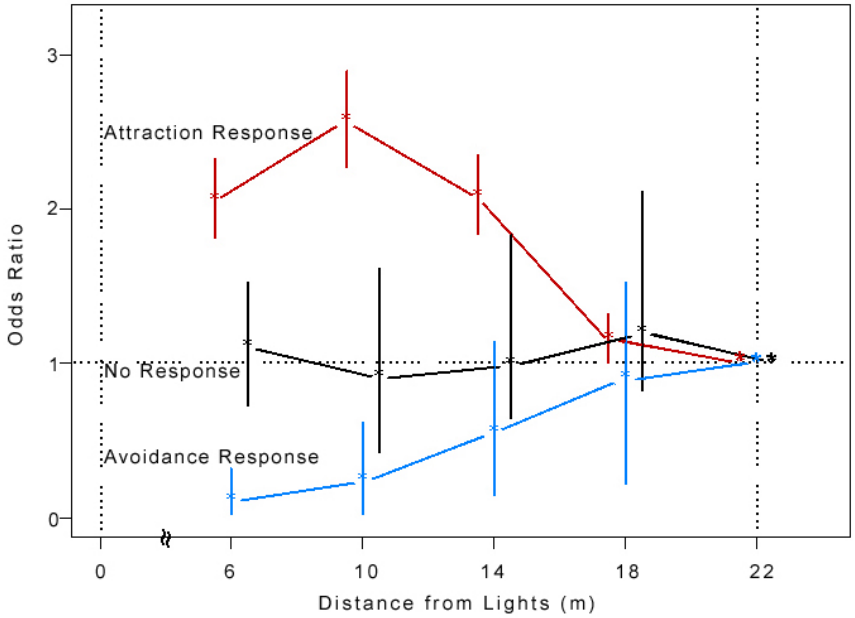


Figure 3.4. Sample Odds Ratio Plot Illustrating Patterns for Attraction, Avoidance, and No Response

plot, the reference point is at 22 m, farthest from the stimulus source (e.g., lights), and has a value of 1. Each colored line in Figure 3.4 illustrates a different behavioral response to the stimulus. The upper line illustrates an attractive response, with an odds ratio greater than 2, indicating that more than twice as many fish tracks were detected at 6, 10, and 14 m than at the reference location. The middle line is indicative of no response, with the odds ratio staying near 1 at all distances from the stimulus. Finally, the lower line is below the no-response level of 1 and is indicative of an avoidance response, with fewer fish tracks close to the stimulus compared to the reference location. The vertical error bars in Figure 3.4 are 95% confidence intervals on the odds-ratio estimates. The statistical significance of these points was inferred when estimates had error bars that did not intersect the horizontal reference line at 1. When discussing a relationship between a stimulus and a response, the word attraction or avoidance is often used to describe the results. This does not imply that the fish "prefer" or "dislike" the stimulus but rather that the stimulus and factors occurring with the stimulus are associated with a measurable significant difference in fish activity with proximity to the stimulus source (i.e., strobe lights).

Statistical significance for the parameter estimates from the fitted log-linear model was evaluated using the Wald χ^2 test of significance with 1 degree of freedom. A more complete description of these statistical methods is found in Appendix D.

Swimming speed and direction were calculated from the difference between the estimated start and end locations of each track divided by the observation time, which is the time during which the detected fish passed through the splitbeam zone. Direction and speed were referenced to a single coordinate frame for each of three directions as follows: laterally (across the forebay), vertically (by depth), and upstream/downstream.

The direction of movement can be converted to polar coordinates and analyzed using the methods of circular statistics (Fisher 1993). One of the circular statistics metrics is the concentration parameter that provides a measure of the dispersion of the data, similar to a variance. Large values of the concentration parameter are indicative of a data distribution defined by a dominant direction of movement, while a small concentration parameter suggests data with no dominant direction. Distributions of the displacement vector can be modeled using the von Mises probability distribution function. These distributions can be overlaid on the actual data to indicate the goodness of fit. Appendix D contains a more complete description of these methods.

One of the constraints on the analysis of target detections is that hydroacoustic systems cannot distinguish unique targets, so the counts for a particular area and time include an unknown number of duplicates. That is, a fish leaving and reentering the ensonified region for a particular transducer beam would be counted as two separate fish. To determine what proportion of the number of fish detections represent fish density and which represent duplicate counting, a method was developed to categorize and count distinct or unique tracks within the ensonified region of a single transducer. Tracks were considered unique if they overlapped in time or if a fish tracked at a particular time and place could not physically reach the beginning time of another track (based on swimming speed). A coincidence number or index was assigned to each target detection to represent the number of other distinct targets present. Thus a coincidence index of 3 would indicate that a particular target was probably counted three times. These indices were averaged to obtain a measure of coincidence for a set of conditions. This number does not account for possible duplicates when a fish entirely leaves the ensonified region and returns later.

Finally, the hydroacoustic systems record activity in the form of swimming speed and direction in the ensonified conical regions. Thus the counts do not represent accumulations of fish in a region but measure passage activity. Using the coincidence index, we can estimate the number of passages per distinct fish target.

3.6 Ancillary Data

Implementation of a hydroacoustic study involves not only the collection of data from the hydroacoustic systems but also ancillary data used to support and evaluate the hydroacoustic data. Ancillary data used to check on the system performance included tilt and direction measurements from sensors on the light frame to determine frame orientation and light readings at the frame to confirm the light treatment. Ancillary data used in data interpretation included discharge levels from the third powerplant, temperature measurements from the water profile, and turbidity measurements. Methods used and results from these last three ancillary data sources are presented in Appendix A.

3.7 Additional Studies

Three additional studies were conducted to augment the hydroacoustic data. Kokanee implanted with acoustic tags were released immediately upstream of the strobe lights and subsequently tracked (Appendix E). The tracking data provided information on species-specific fish movement into and out of the illuminated region in the third powerplant forebay.

The third powerplant forebay was characterized hydrodynamically using an acoustic Doppler current profiler (Appendix F). Water velocity measurements, taken in front of the strobe lights, were used to determine flow rates in the region where fish encountered the strobe lights.

Researchers also collected zooplankton samples in the forebay (Appendix G). The zooplankton study was an effort to understand how prey species responded to the lighted environment.

4.0 Results

Detections of fish by the splitbeam system in 2004 were similar to those found in 2002 and 2003 (Figure 4.1), with detections increasing at night when the lights were on compared to lights off or to detections during the daytime. Generally, few fish were detected at night with the lights off. Fish

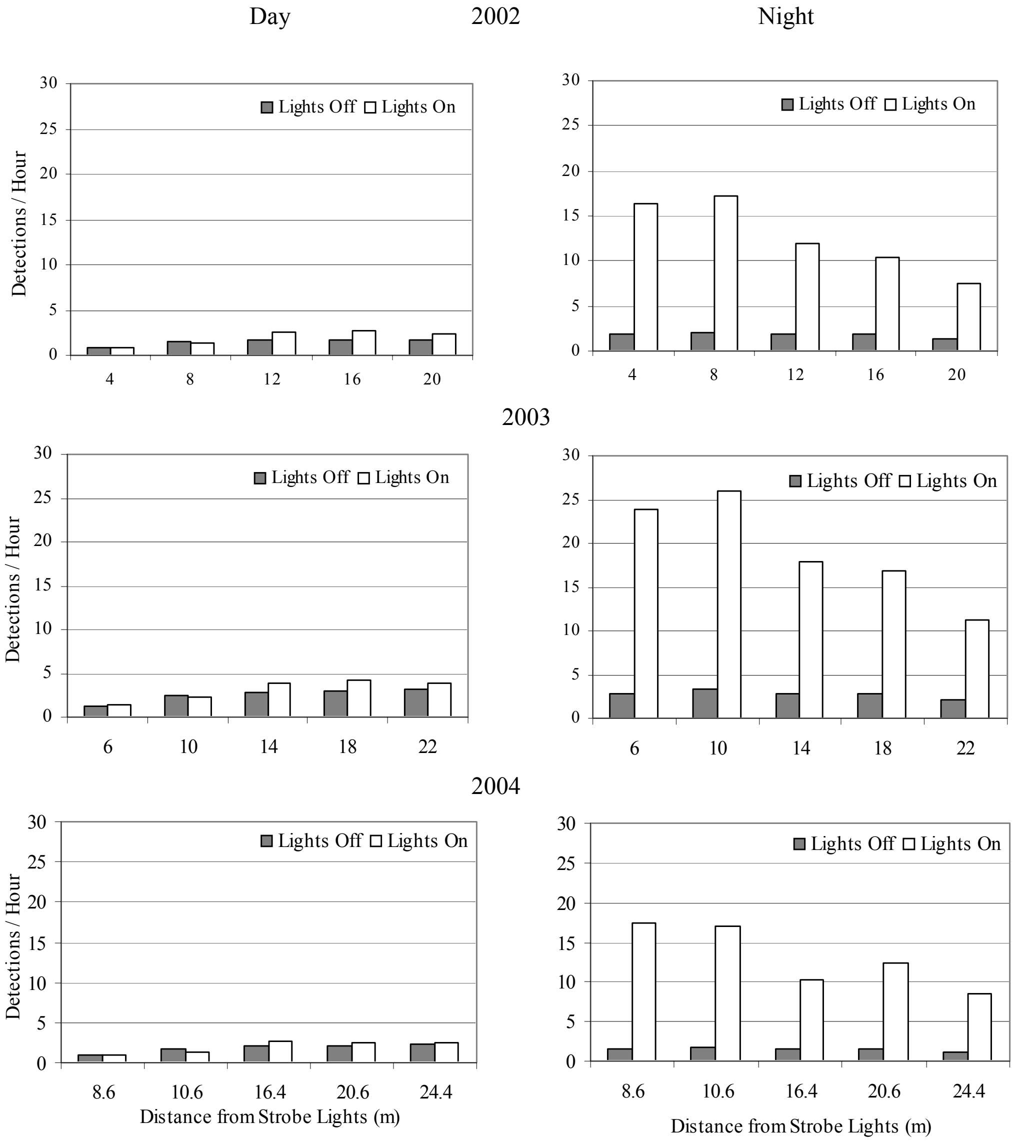


Figure 4.1. Number of Fish Detected per Hour by Five Downlooking Splitbeam Transducers in 2002, 2003, and 2004 During the Day and Night When the Strobe Lights Were Off and On for 24 Hours

detections during the day were similar for lights-on and lights-off conditions. The highest detections always were associated with lights on at night, especially in areas closer to the strobe lights. These differences were statistically significant in all three years (Figure 4.2). While there were year-to-year differences in the number of fish detected, the pattern of detections remained the same.

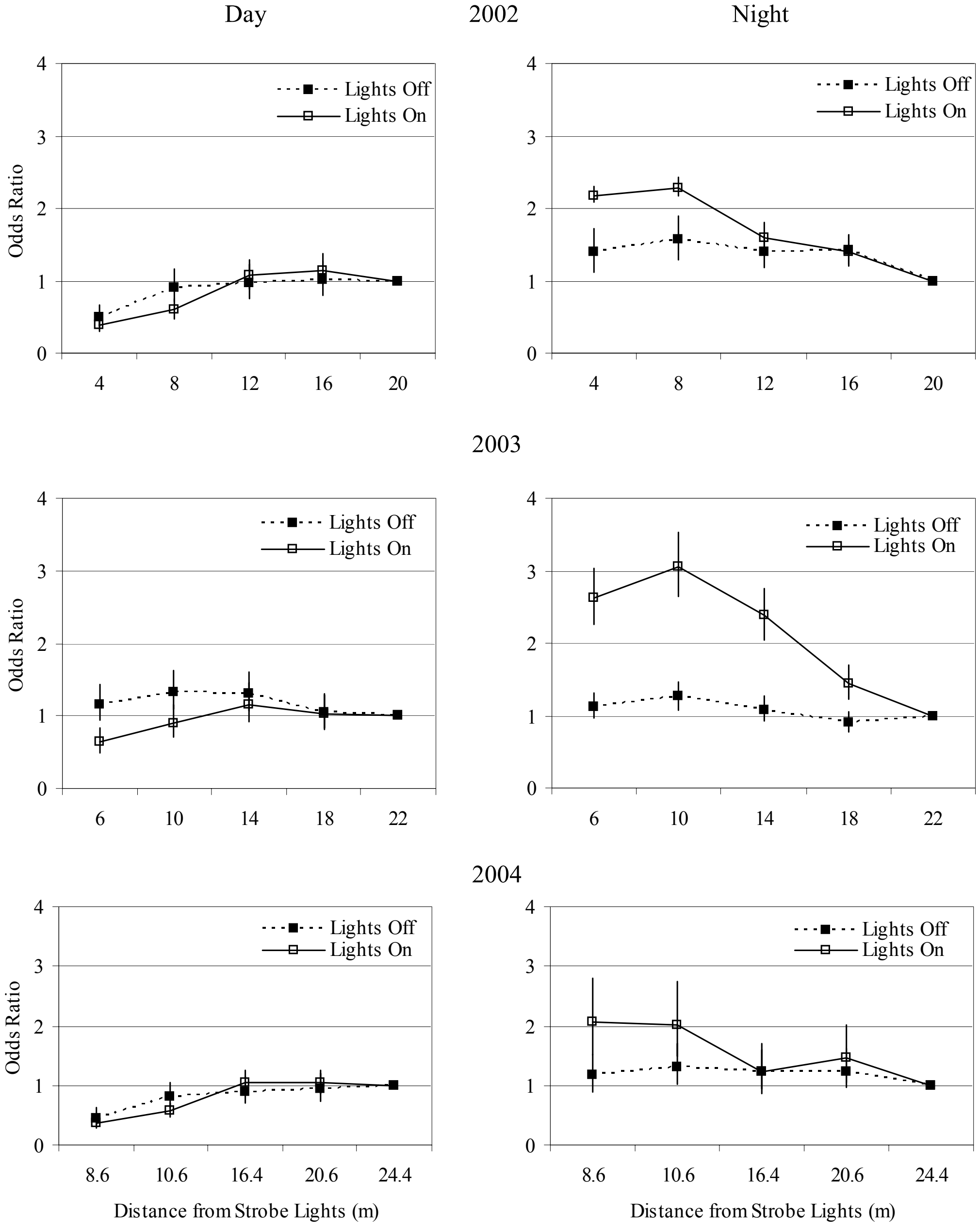


Figure 4.2. Odds Ratio Statistic for the Relative Prevalence of Fish at Various Distances Compared to the Reference Location (2002: 20 m; 2003: 22 m; 2004: 24.4 m). Vertical error bars are the 95% confidence intervals.

The number of fish detected by the multibeam system also showed an increase at night with lights on compared to the number of fish present under lights-off conditions at night or during the daytime (Table 4.1).(a) These results are similar to those found in 2003 when the multibeam system was placed behind the light frame (Simmons et al. 2004). Differences in hourly detections between data collected by the multibeam and splitbeam systems are probably related to differences in the ensonified volumes. Each splitbeam ensonified a volume of approximately 200 m^3, while each multibeam ensonified approximately 10 times that. Results from the multibeam system showed little difference in the number of fish detected between day and night (lights off).

The distribution of fish by depth in the areas ensonified by the splitbeam system is shown in Figure 4.3. During the day, fish approaching the strobe light array from upstream (beyond 16 m) were generally at or below the depth of the light frame (15 m). Closer to the lights (8 to 10 m upstream), more fish were at or above the 15-m depth. At night, with the lights off, fish appear to have been distributed throughout the water column. In contrast, with the lights on at night, fish detected beyond 16 m again were distributed uniformly throughout the water column. However, closer to the strobe lights, fish were generally below the depth of the light frame.

Table 4.1. Hourly Fish Detections in 2004 by the Multibeam Sonar Heads During Day and Night When the Strobe Lights Were Off and On. Number in parentheses is the standard error.

Region Ensonified	Day		Night	
	Lights Off	Lights On	Lights Off	Lights On
West (Dam)	3.2 (0.5)	4.0 (0.7)	4.2 (0.6)	14.8 (1.9)
East (Bank)	4.1 (0.6)	4.8 (0.9)	4.6 (0.5)	17.4 (2.1)

The distribution of fish detected by the multibeam transducers (Figure 4.4) shows more fish below the light frame during the day. At night with lights off, the fish were distributed throughout the ensonified area in relatively low numbers. When the lights were on at night, the highest concentration of fish was detected approximately 10 to 15 m from the lights, at a depth of 5 to 10 m.

Fish detected during the nighttime mobile splitbeam surveys of the third powerplant forebay were distributed fairly evenly across the seven transects (Appendix C). An average of 17 fish were detected over the nine surveys, and most of the fish were detected either between 15- and 25-m depth or around 35 to 40 m (Figure 4.5).

(a) When results from the two multibeam transducers were compared, slightly more fish were detected by the multibeam pointing toward the east (bank) side than detected by the multibeam pointed toward the west (dam) side. The difference was not statistically significant.

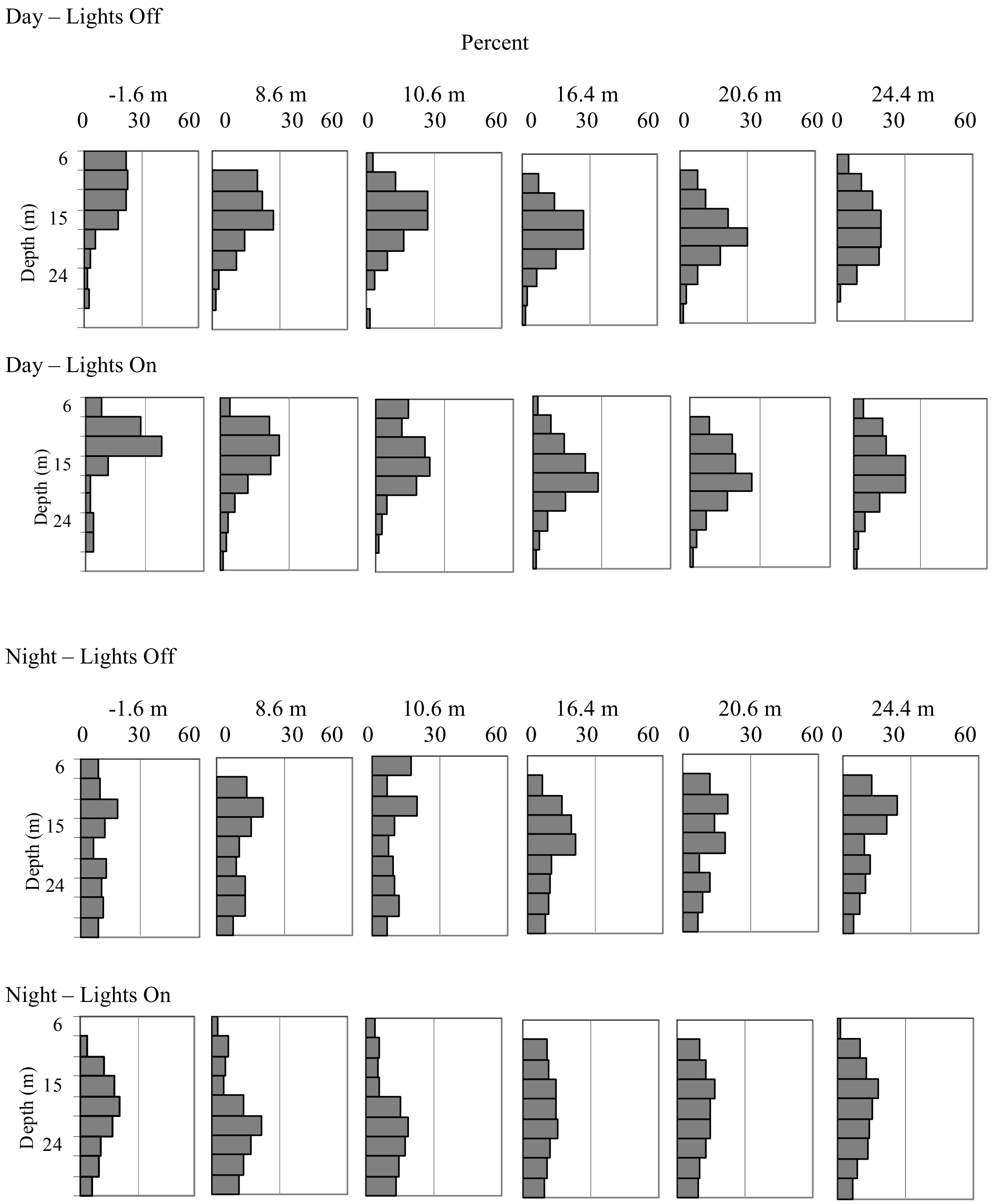


Figure 4.3. Depth Distribution of Fish Detected in 2004 by Six Downlooking Splitbeam Transducers at Various Distances from the Strobe Lights During the Day and Night When the Strobe Lights Were Off and On for 24 Hours. Densities were normalized and converted to percentages. The transducer at −1.6 m was behind the lights pointing downstream.

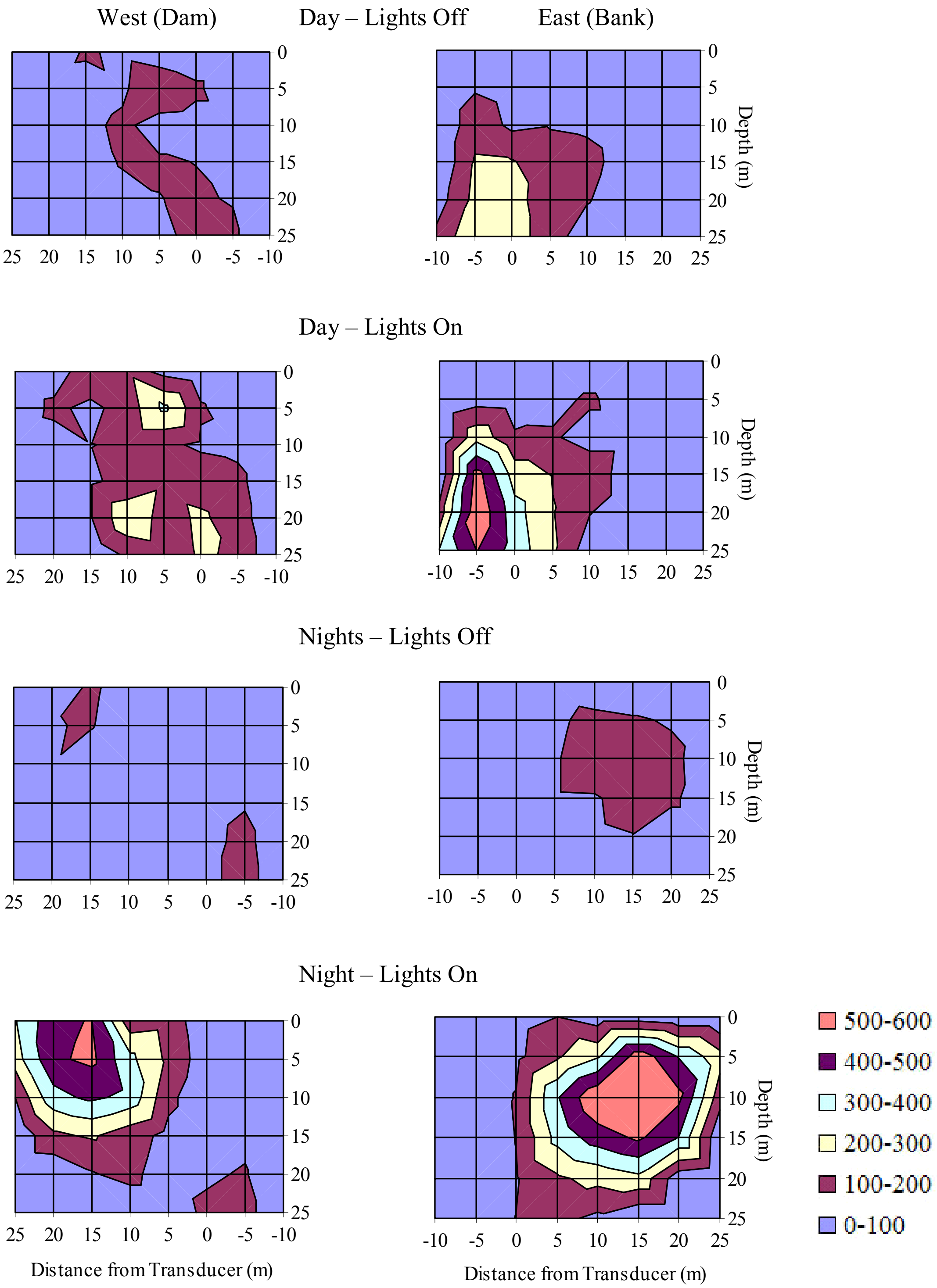


Figure 4.4. Distribution of Fish Detections in 2004 by Two Multibeam Sonar Heads During the Day and Night When the Strobe Lights Were Off and On for 24 Hours. The west sonar head was pointed toward the dam, the east sonar head toward the opposite bank.

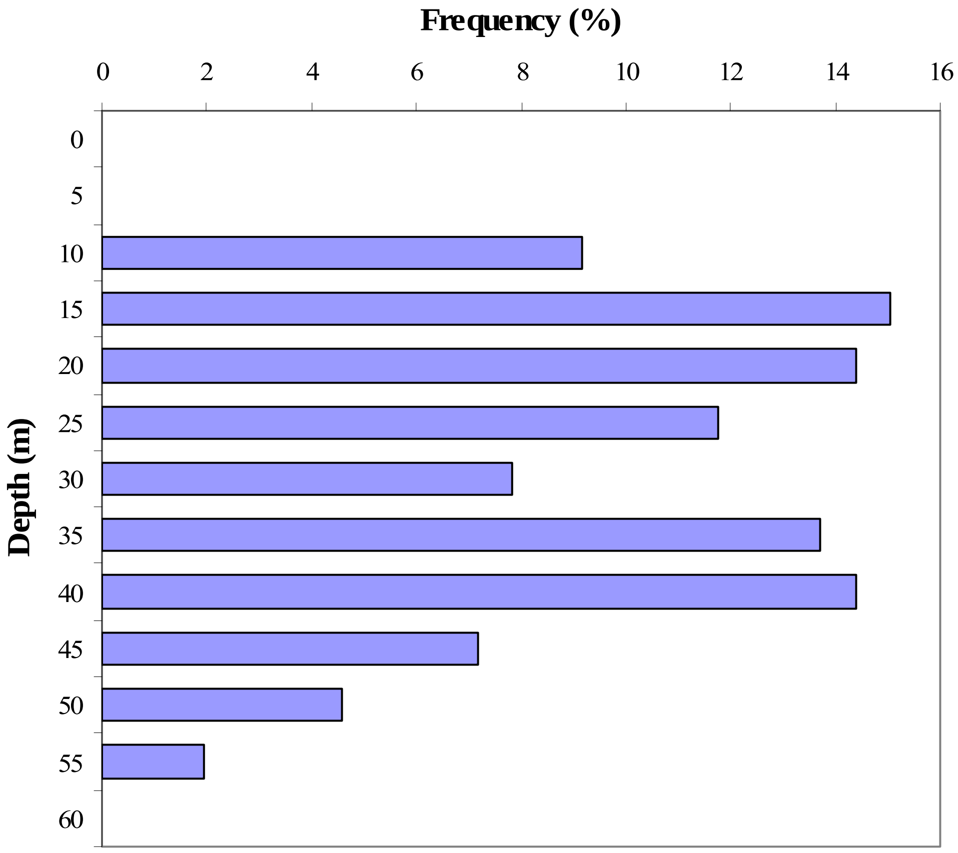
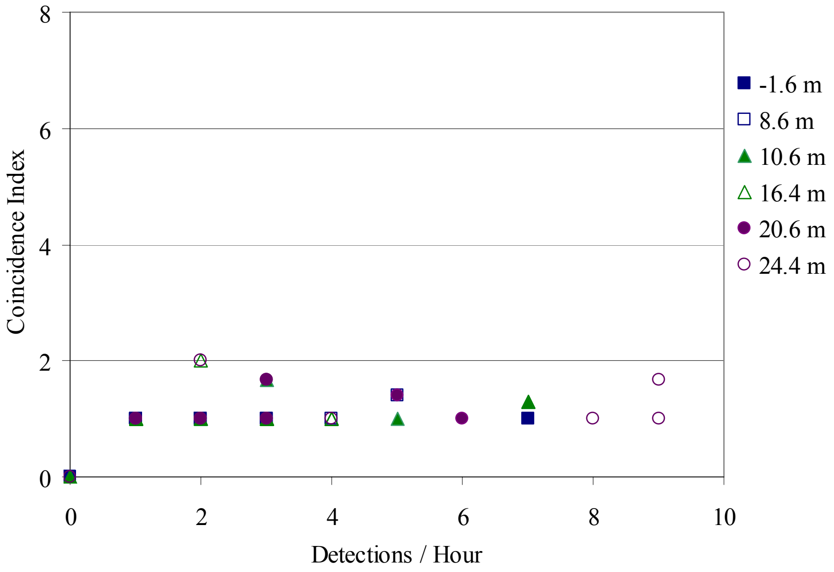


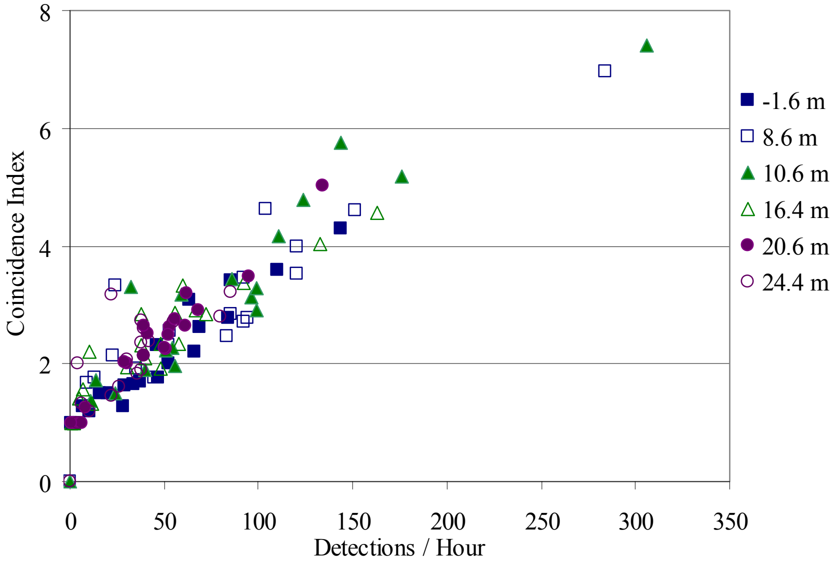
Figure 4.5. Depth Distribution of Fish Detected in 2004 by the Weekly Mobile Splitbeam Surveys

To determine if the increase in detections seen at night when the lights were on was due to an actual increase in the number of fish detected in the sampled region or to an increase in their swimming activity, a coincidence index was calculated. The coincidence index (Section 3) is a measure of whether a detection represent a single fish or multiple counts of the same fish which could occur if the fish swam into and out of the ensonified beam. Analysis reveals that when the strobe lights are off and detections per hour are less than 10, the coincidence index was generally 2 or less (Figure 4.6a), indicating that these targets probably represent unique fish detections. However, when there were more than 10 fish/hour, the coincidence index increased linearly (Figure 4.6b). This level of detections generally occurred at night when lights were on. Under these conditions, part of the increase in detections appears to be due to increase in swimming activity. Thus, for a count of 150 fish/hour, the coincidence index may be as high as 6, indicating that the number of unique fish detected was closer to 25 fish/hour (150/6). The linear relationship between fish detections per hour and the coincidence index was similar across all the splitbeam transducers (Figure 4.6b).

Fish swimming activity was analyzed by evaluating the direction of travel in each fish track. Plots of direction reveal that during the daytime when flows were high, fish were generally headed in a downstream direction although not necessarily in the direction of flow (Figure 4.7). When the lights



a) Strobe Lights Off



b) Strobe Lights On

Figure 4.6. Coincidence Index for Fish Detected at Night in Early August 2004 When the Strobe Lights Were Off (a) and On (b). Data for all splitbeam transducers upstream of the strobe lights.

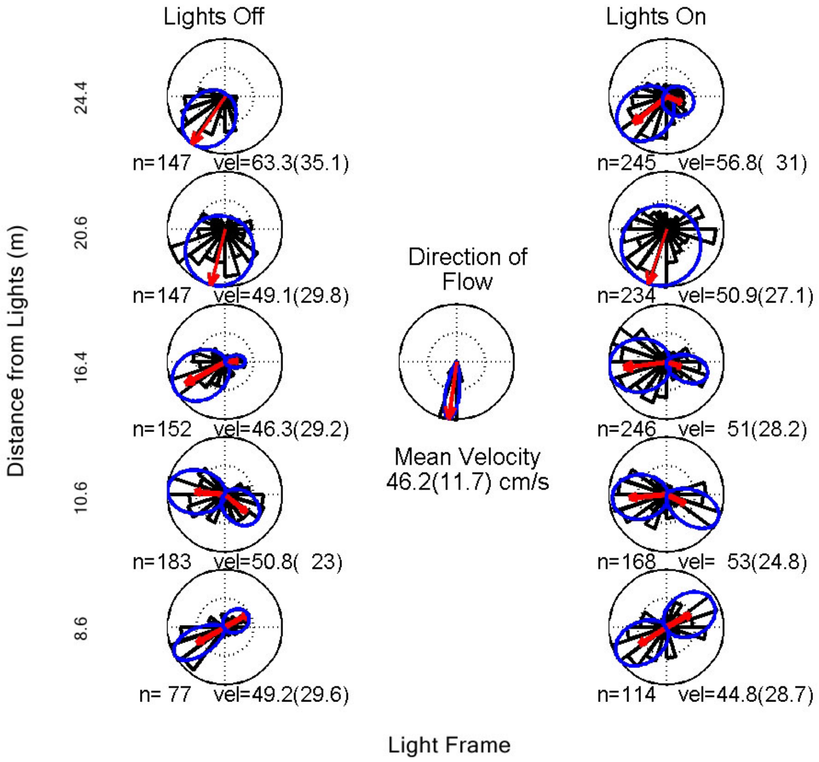


Figure 4.7. Swimming Direction for Fish Detected by the Splitbeam Transducers in 2004 During the Day When the Strobe Lights were Off and On for 24 Hours. Direction of water flow shown in center figure. Blue ovals are the probability densities for the fitted Von Mises (VM) distribution (1 oval – uni-modal VM; 2 ovals – bi-modal VM; none – uniform); red arrows are the mean vectors for the distributions. Average swimming speed, standard deviation, and sample size (n) are given for each distribution.

were on during the daytime, fish closer to the lights appeared to swim across the axis of the lights (i.e., they were swimming across the forebay). At night, under low flow conditions, with the lights off, fish showed little preference for direction (Figure 4.8). However, when lights were on at night, fish again appeared to swim across the axis of the lights. This behavior was observed during each study year (Johnson et al. 2003; Simmons et al. 2004) and was apparent for fish detected close to the lights and those detected by the most distant transducer. Table 4.2 compares the directions of travel for fish detected during the day and nighttime, with lights off and on. The east and downstream probability are the percentage of the fish swimming in that direction. Thus, for all conditions except night with lights on, 60% of the fish were headed toward the east or bank side of the forebay. At night with the lights on, the percentage was 50%, with the other 50% headed toward the west or dam side. The downstream probability was calculated only for those fish headed downstream within 15 degrees on either side of the lights. If there was no preference for swimming direction, we would expect approximately 8.3% of the fish to be headed downstream. This was similar to the percentage seen during the daytime and at night with the lights off. When the lights were on at night, fewer fish (~5%) were headed downstream.

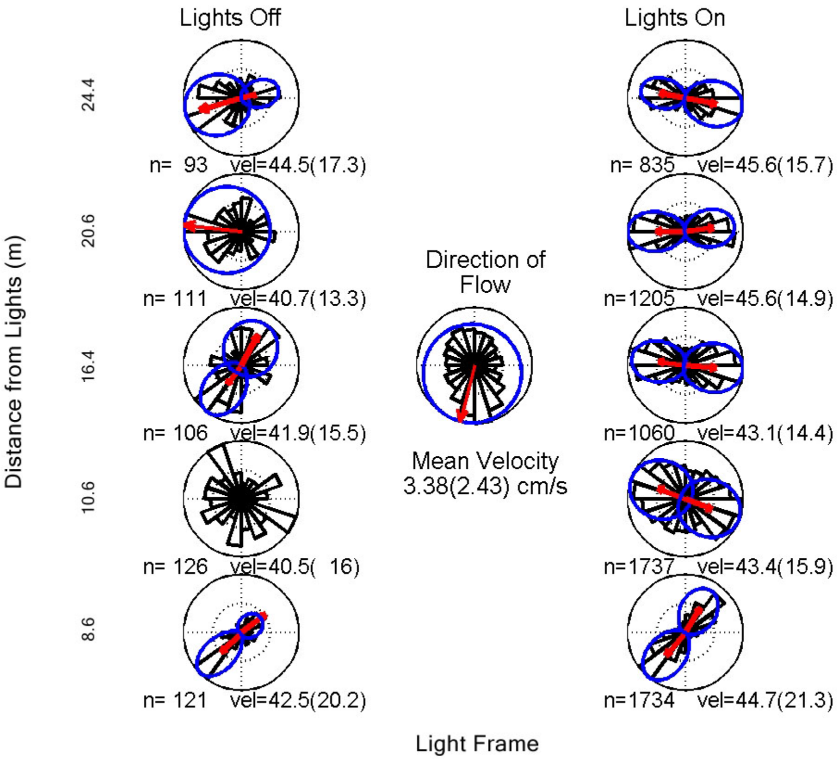


Figure 4.8. Swimming Direction for Fish Detected by the Five Downlooking Splitbeam Transducers in 2004 During the Day When the Strobe Lights were Off and On for 24 Hours. Direction of water flow shown in center figure. Blue ovals are the probability densities for the fitted Von Mises (VM) distribution (1 oval – uni-modal VM; 2 ovals – bi-modal VM; none – uniform); red arrows are the mean vectors for the distributions. Average swimming speed, standard deviation, and sample size (n) are given for each distribution.

Table 4.2. Swimming Direction of Fish Detected by Splitbeam Transducers in 2004 During the Day and Night When the Strobe Lights Were Off and On for 24 Hours. East probability refers to the percentage of fish headed toward the east or bank side of the forebay; downstream probability refers to the percentage of fish downstream within 15 degrees of the position of the strobe lights.

Estimate	Day		Night	
	Lights On	Lights Off	Lights On	Lights Off
East Probability (%)	60.3	60.1	50.0	59.1
Downstream Probability (%)	8.9	8.9	4.9	9.0

The behaviors described above were seen in fish detected throughout the 2004 study period, over all distances from the strobe lights (i.e., from the nearest to the farthest transducer), and at different depths. The number of fish detected, however, was not constant over the study period. Approximately 50% of the fish were detected between August 1 and August 13. An increase in the number of detections was evident in 2003; however, that increase was much less dramatic. Taking into account the coincidence index, detection rates for the period after August 1 were 208 fish/hour compared to 39 fish/hour prior to August 1.

Detection rates were not constant over the nighttime period when lights were on constantly but increased throughout the night, peaking around 3:00 to 4:00 a.m. before decreasing (Figure 4.9). Swimming activity also increased through the night, with the coincidence index also peaking during early morning hours (Figure 4.9). When the lights were switched hourly between off and on, passage rates and the coincidence index still show an increase over the nighttime hours (Figure 4.10). However, when the lights were switched off, the number of detections did not always decrease, indicating that fish may stay in the area even when the lights were off.

Splitbeam hydroacoustics do not provide information on fish species. However, the target strength of the returning signal is related to the size of the fish (Love 1977). The distribution of target strengths for fish detected in 2004 (Figure 4.11) was similar to that seen in 2002 (Johnson et al. 2003) and 2003 (Simmons et al. 2004). Target strengths were calculated for the kokanee released as part of the tagging study (Appendix E) in early June. The average target strength for that size of fish would have been −42 dB (standard deviation 0.7). This is within the range of target strengths detected during the 2004 field season.

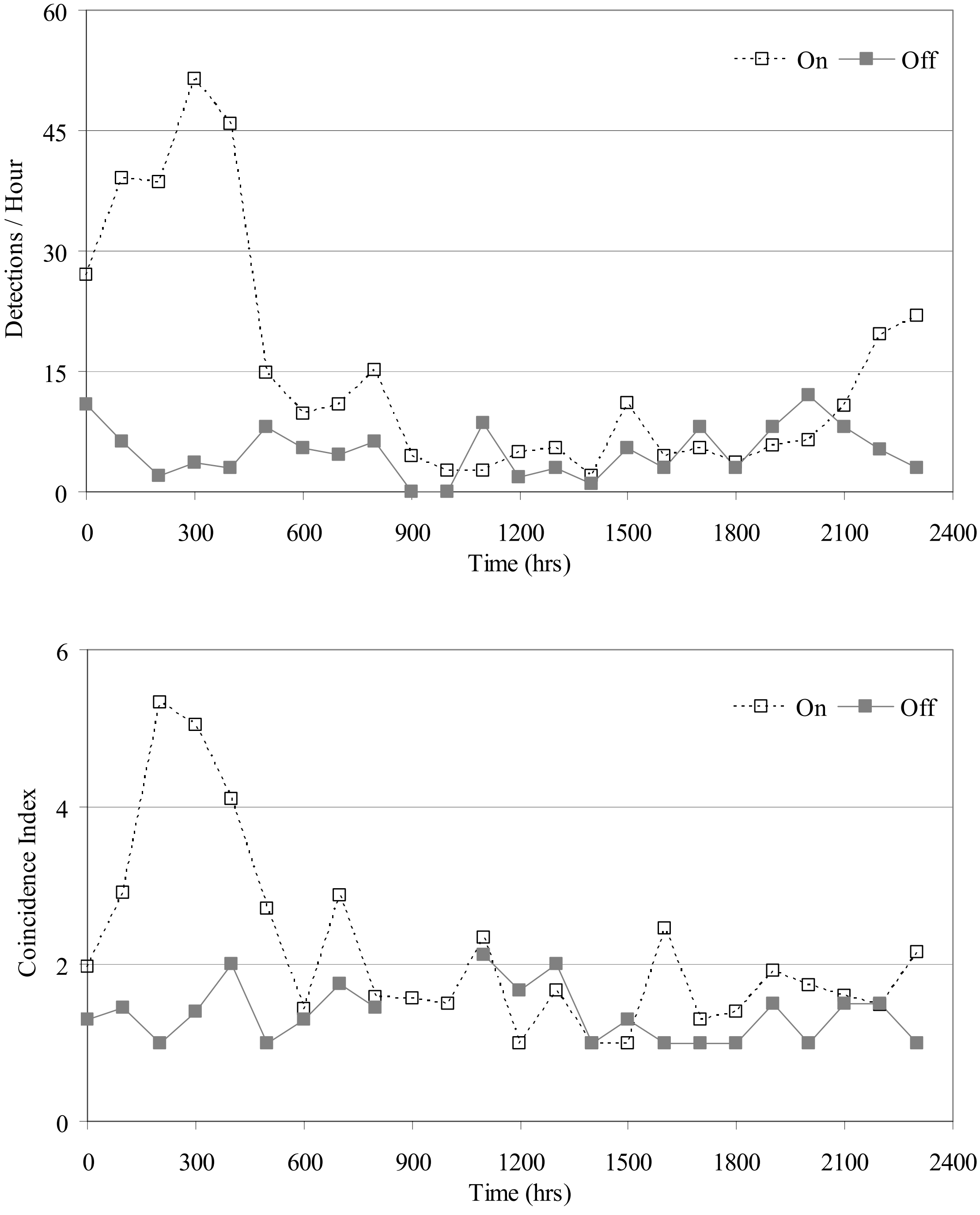


Figure 4.9. Fish Detection Rates and Coincidence Index for Fish Detected in Mid July When the Strobe Lights Were Off and On Continuously for 24 Hours

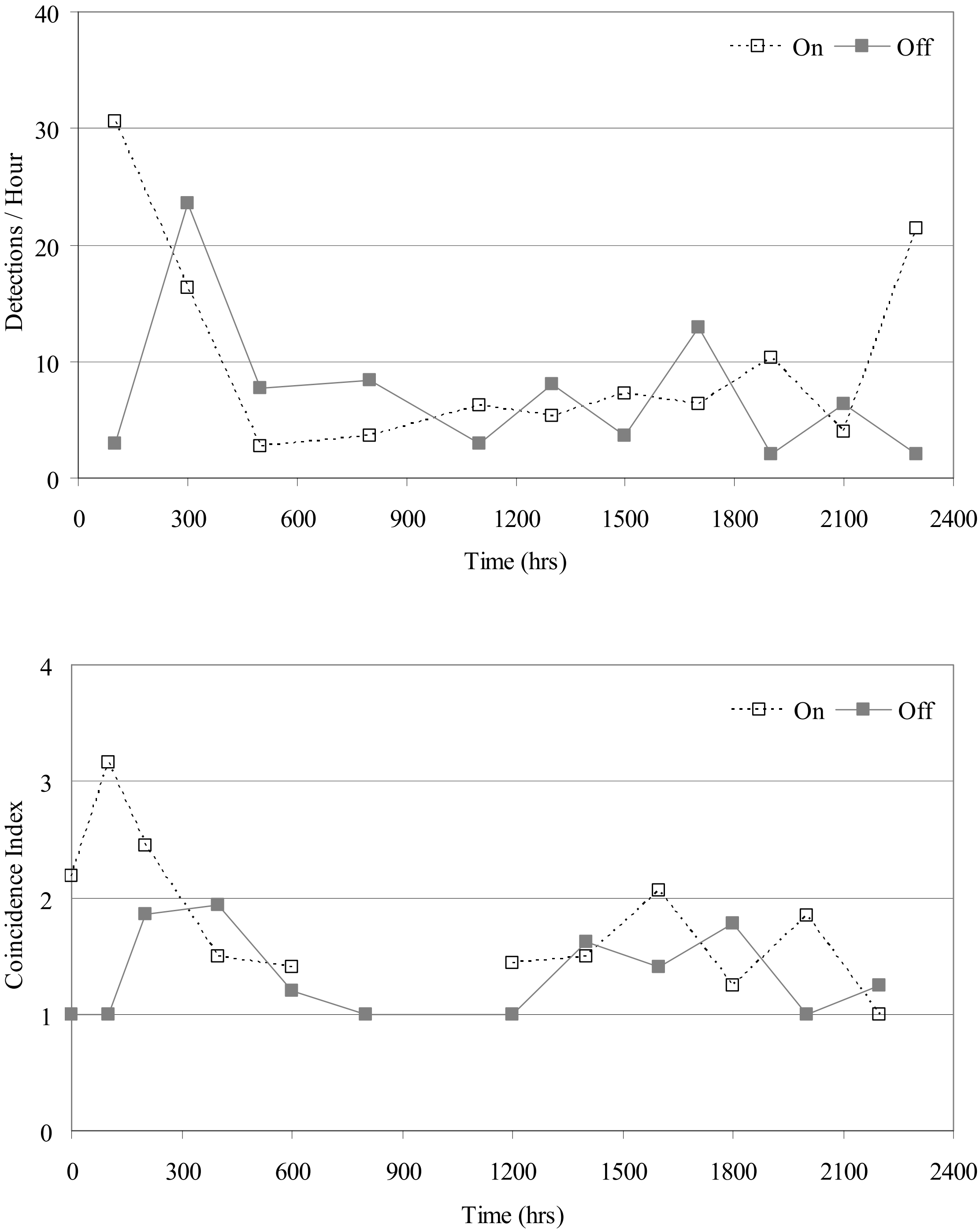


Figure 4.10. Fish Detection Rates and Coincidence Index for Fish Detected in Mid July When the Strobe Lights Alternated Hourly Between Off and On

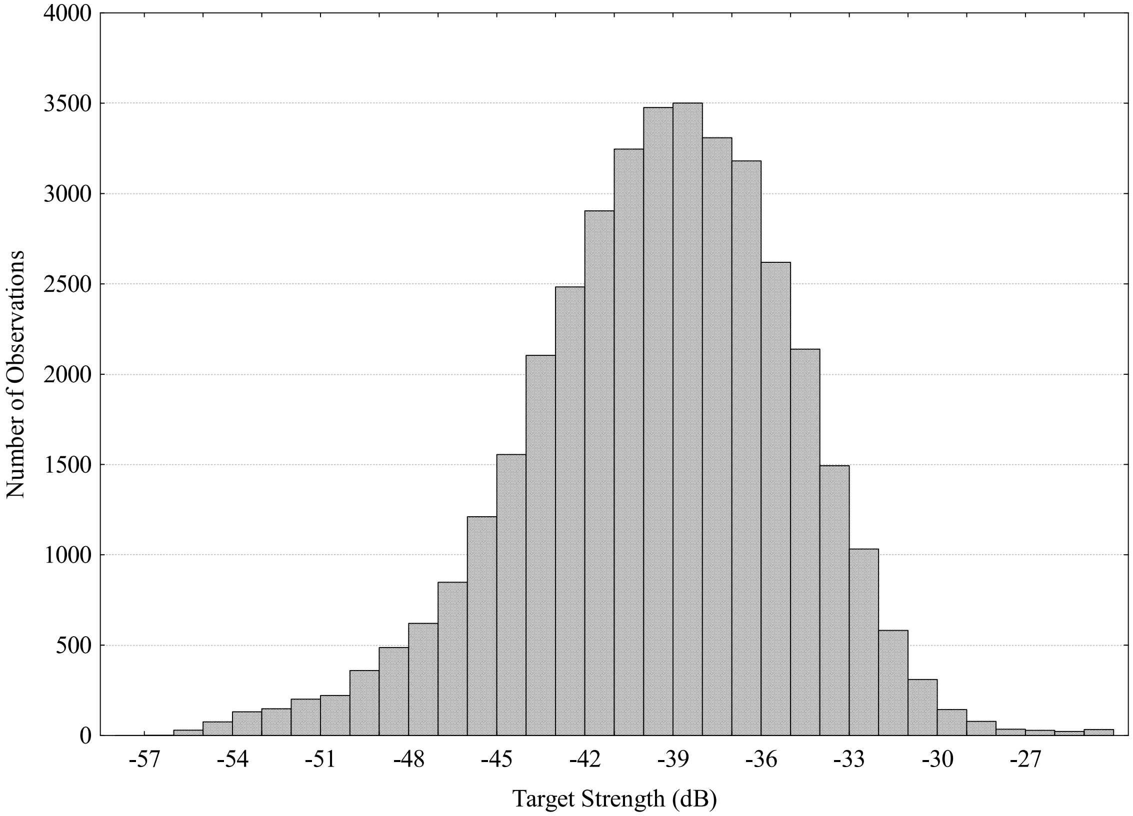


Figure 4.11. Target Strengths for Fish Detected by Splitbeam Hydroacoustics in 2004

5.0 Discussion

Entrainment rates of kokanee and rainbow trout at Grand Coulee Dam have been judged unacceptable to fishery managers responsible for the perpetuation of the fishery in Lake Roosevelt. In 2001, in collaboration with Colville Tribal Fisheries, we initiated a four-year study to evaluate the efficacy of using strobe lights to deter fish from entering the third powerplant forebay at Grand Coulee Dam. The first year of the study was exploratory in nature and provided data to better address the sampling design that was used in subsequent years. On advice of regional researchers and scientific advisors, our efforts were concentrated at the entrance to the third powerplant forebay with the goal of eventually deploying a strobe light "fence" across the entrance to the forebay, should the studies find that fish avoided the strobe lights. During the ensuing three years of studies, we discovered that the strobe lights do not have the desired effectiveness at Grand Coulee Dam to be used at the third powerplant forebay entrance. As a result, we propose an alternative deployment at the third powerplant penstocks. The rationale for this decision and specific findings are discussed in the following paragraphs.

Lights have been investigated for many years as a mechanism to affect the movement of fish. Brett and MacKinnon (1953) examined the use of lights and bubbles to keep migrating juvenile salmon away from turbines. Their results and subsequent studies; found that the response is species-specific. Fields et al. (1958) found that migrant salmon could be repulsed by high intensity constant light in both clear and turbid flowing water with effectiveness decreasing as turbidity increased. They also noted that dim light could be used as an attractant. Others have noted that the response to light can be affected by factors such as turbidity (McIninch and Hocutt 1987) and fish age (Kwain and MacGrimmon 1969; Anderson et al. 1988; Fernald 1988). Strong avoidance response to strobe light has been noted for Chinook salmon smolts during nighttime hours under laboratory controlled conditions (Amaral et al. 2001; Mueller et al. 2001), while in another study fewer juvenile salmon were present when lights were on during daylight (Johnson et al. 2001). Juvenile rainbow trout (10 months old) showed a preference for darkness when given the choice between light (0.01 lx) and darkness. The minimum threshold was between 0.01 and 0.005 lx (Kwain and MacGrimmon 1969). Younger fish generally show a stronger aversion to light than do adults (Hoar et al. 1957). This is probably related to predator-prey relationships, where younger fish are more vulnerable to predation and so avoid light, compared to older fish. Fish not responding to lights include cutthroat trout fry and hatchery-reared trout (Brett and MacKinnon 1953) and eastern brook trout (Mueller et al. 2001). Pioneering studies of free ranging kokanee in an Idaho lake reported an immediate avoidance reaction to strobe lights, with a more pronounced response in winter when turbidity was reduced (Maiolie et al. 2001). Similar behavior was observed during five nighttime tests conducted between December 2001 and January 2002 when fish densities dropped from an average density of 110 fish/ha with strobe lights off to 13 fish/ha with strobe lights on (Maiolie and Stark 2003).

This study has reinforced the notion that the response of fish to strobe lights is complicated by many factors including fish behavioral propensities and their environment as noted by Nemeth and Anderson (1992). We also have determined that the population of fish inhabiting the third powerplant forebay at Grand Coulee Dam does not exhibit the dramatic dispersion noted by Maiolie et al. (2001) on Spirit Lake and Lake Pend Oreille, and at Dworshak Dam (Maiolie and Stark 2003). The environmental conditions associated with our sample site at the entrance to the third powerplant forebay were dynamic and, at times, unpredictable. Ambient light and flow were the two primary complicating environmental factors. Ambient light appeared to have rendered the strobe lights largely ineffective during daylight hours, and flows complicated the study design. Hydropower operations at Grand Coulee Dam are controlled by the U.S. Army Corps of Engineers Reservoir Control Center (RCC), which oversees the entire watershed; as the dam farthest upstream on the mainstem Columbia, Grand Coulee thus is important for flood control and power production. Because of these priorities, it was impossible to obtain operational flow control for our tests. Therefore, all data collection was conducted under flow regimes as dictated by the RCC. This resulted in regular periods of high flow, usually during daytime when peak demand is highest, and low flows, usually during nighttime when demand is lowest.

Flow dynamics at the entrance to the third powerplant forebay were observed to be quite different between high flow (daytime) and low flow (nighttime) conditions (Appendix F). Also, in 2001 during our pilot study (Simmons et al. 2002), mobile surveys of the forebay region found that fish were located at a depth of about 15 m. Due to the low densities of fish within this entire region, we lowered our light platform from 10 m to 15 m to correspond to the depth of the fish. Coincidentally, this depth corresponds to the depth of the thermocline (Appendix A). This added further complexity to the fishes' environment because the hydrodynamics were found to vary substantially around the thermocline. When the discharge was moderate, flows above the thermocline were nearly quiescent, while below the thermoclines, flows were as high as 0.6 m/sec. At night when flows were minimal and the contrast in fish detections between lights on and lights off was highest, water velocity direction became chaotic and the flow magnitude was less than 0.2 m/sec. Under all conditions flows were generally higher below the thermocline.

The other environmental factor affecting the response of fish to the strobe lights was ambient light conditions. Weather conditions at Grand Coulee Dam in the late spring and early to mid summer are typically characterized by cloudless days. In addition, turbidity levels are near drinking water standards (NTU < 1.0) (Johnson et al. 2003; Simmons et al. 2004; Appendix A). As such, the effectiveness of the strobe lights to elicit behavioral response in fish was compromised by the ambient light conditions during daylight periods. Even at 15 m, ambient light overshadowed the output from the six strobe lights (Appendix A). Only at night were the lights clearly visible. Fish detections may have been lower during the day than at night with lights on because fish would have a difficult time detecting the lights at long distances under ambient light conditions. This does not imply that fish would not respond to the lights but rather that the detectability distance would be limited. At night, with the high contrast between light and dark areas, the presence of the lights would have been more detectable by fish at longer distances, affording the opportunity to accumulate and orient to the area influenced by the light. Other studies have also shown that migrant salmon are attracted to low light conditions (Fields et al. 1958). Juvenile Chinook salmon also were found to be attracted to dim mercury lights, but were repelled by high-intensity strobe lights under tests conducted in a confined raceway channel (Nemeth and Anderson 1992).

The detection of fish upstream of the light frame, sampled by the fixed splitbeam transducers, was similar in all three study years, with contrasts noted between day and night, and between strobe lights on and off at night. We caution the reader at this time that the numbers referred to in this discussion are a relative index of abundance and not absolute counts. We found that only moderate numbers of fish were detected during the day, regardless of lights-on or lights-off conditions. This corroborates the findings of others who have found that lights have minimal effect in the upper water column when the ambient illumination (daylight) exceeds the stimulus (strobe lights) as noted in *Fish Passage Technologies* (1995), a Congressionally mandated examination by the Office of Technology Assessment of the role of fish passage and protection technologies in addressing the adverse effects of hydropower development on North American fish populations. The distribution of detections during daytime also was similar in all three years, with the number of detections decreasing within 15 m of the light frame. This suggests that, close to and in direct line with the lights, there could have been a response to the strobe lights during daytime. However, the odds ratio analysis showed that there was no significant difference between lights on and lights off during daytime, and the decreasing trend occurred for both lights on and lights off treatments. Also, during the day, fish were found above the level of the lights within 8 m of the light frame, while they were generally below the level of the lights at 24 m. Fish may have been seeking the shadows cast by the floating equipment (barge and truss) or orienting to the structure itself. We also noted that the transducer placed to sample the area behind the barge in 2004 showed fish distributed toward the surface during daytime with lights on or off, no water column preference with lights off at night, and preference at or below the light frame when lights were on at night.

Lower fish detections during the day, regardless of the light treatment, suggest that other cues such as visual perception of the light frame, barge, and floating truss or shadows cast from them may be causing some fish to avoid the area 12 to 16 m from the lights. It is also possible that the structures or cables were generating audible noise that could have caused some fish to avoid the area closer to the light frame. Although infrasound (<20 Hz) typically has only a short-range effect on fish at high intensities, and mixed responses have been obtained from salmonids (Mueller et al. 2001; Sand et al. 2001), much of the noise associated with the structure would not have been present at night when the flows were minimal and when we observed the greatest difference between lights on and lights off. It is also possible that the daytime detections better represent the true density of fish in the region because under daytime high flow conditions, there would be little opportunity for fish to mill and be detected repeatedly.

At night, the lowest numbers of fish were detected with lights off and the highest numbers of fish were detected with lights on. The difference in fish detections between lights on and off at night suggest a positive phototactic response to the strobe lights. However, when we examine factors such as their depth distribution and swimming activity, it appears that the fish are avoiding the area immediately in front of the lights. Thus, the depth distribution of fish detected by the splitbeam transducers shows an increased number of fish detections below the level of the lights at night within 8 to 10 m of the light frame. Other support for avoidance is found from data collected by the multibeam swath sonar, where fish were concentrated higher in the water column to either side of the light frame and displaced 5 to 10 m away from the lights. These results demonstrate a fish avoidance response to the lights in four directions (upstream, downward, east, and west), suggesting a hemispherical zone of avoidance out to approximately 5 to 10 m at night. Although this is far from the avoidance response documented by Maiolie et al. (2001) and Maiolie and Stark (2003), it does represent a near-field avoidance response at night.

An order of magnitude more fish were detected when the lights were on at night compared to when the lights were off, when few fish were detected. These increased numbers appear to be the result of both an increase in the number of fish combined with an increase in swimming activity as measured by the coincidence index (note: the index was a measure of the number of times a fish was detected within the sample collection period). Thus, while more fish were present when the lights were on, the actual increase was probably closer to a doubling than an order of magnitude. More fish also were detected closer to the light frame (within 10 m) than farther away (>16 m) in 2004. Similar results were obtained in 2002 and 2003 with slightly different spacing between the splitbeam transducers. Again, the increase is a result of a few more fish swimming more actively in the region.

Weekly mobile surveys in 2004 found low fish densities within the entire forebay (from the upstream boom to the back of the third powerplant forebay cul de sac). There were on average 17 fish detections per survey, with a survey taking about 0.5 hour of transect time to complete. This agrees with the fish detection rate of 25 fish/hour after applying the coincidence index for the fixed location splitbeam transducers. Limnological surveys of Lake Roosevelt found kokanee abundance to range from 0.08 to 20 fish/hour between 1989 and 1996 (Cichosz et al. 1997). Given the coincidence index adjustment and the densities in the forebay, we would not expect large numbers of fish to populate the region lit by the strobe lights. However, it was likely that fish could be attracted to the lighted region from a long distance, given the clear water conditions and low light level feeding response of kokanee (highest feeding rates were observed at 15 lx [Koski and Johnson 2002]). Haymes et al. (1984) noted that when alewife (also a planktivore) were attracted to mercury vapor lights and strobe lights, their activity level also increased. If kokanee are attracted to the lighted region, for feeding opportunity, it would follow that their activity level would increase as well.

Our behavioral data indicated that not only did the detections increase when the strobe lights were on but the fish activity level increased in contrast to when the lights were off. Observations made by Dr. Kim Hyatt(a) (personal communication) support our observations. While collecting kokanee for research using high-intensity constant light from automobile headlights, Dr. Hyatt noted the following behavior when kokanee were suddenly exposed to the light: 1) "kokanee were initially attracted or at least not repelled as evidenced by a tendency to slowly drift into and through the lighted area (this response lasted less than one minute);" 2) "responses by fish in the beam were to then rapidly leave its influence;" and finally, 3) "other kokanee also suddenly emerged from the darkened periphery of the immediate lake area and then into and through the lighted area while exhibiting erratic and relatively high speed swimming movements." Further, Dr. Hyatt notes "These fish were not in schools at the time and appeared to be roused from a more quiescent state by the lights. Transit times through the 3-5 m lighted diameter of lake area by these latter fish were on the order of 3-5 seconds." Attraction of fish to the lights might be motivated by increased feeding activity associated with the zooplankton concentrations that were present

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(a) Dr. Kim Hyatt is Head of the Salmon in Regional Ecosystems Program, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC V9T 6N7 and Adjunct Professor at the Institute for Resources, Environment and Sustainability, University of British Columbia, Canada.

at the level of the lights (Appendix G). It is not unreasonable to assume that fish might use the lighted region as an extension of the light levels they prefer during their crepuscular feeding periods, particularly when the food source is large and readily visible when lighted at low levels of light. Koski and Johnson (2002) reported that kokanee selectively feed on larger *Daphnia* typical of those captured in our zooplankton sampling. Cichosz et al. (1997) found a positive relationship between zooplankton densities and temperatures at 12 m depth in Spring Canyon, located approximately 3 km upstream of Grand Coulee Dam. This was also supported by our mobile acoustic surveys with a prominent zooplankton scattering layer visible from 12 to 15 m depth. Our analysis shows that the large number of fish detections near the strobe lights at night were a result of both increased fish detections and increased activity level. This was also reflected in the increased fish detections by the multibeam sonar to the sides of the strobe light array at night but closer to the surface.

Another measure of fish activity was direction of travel. Direction of travel during daytime was largely in the direction of the flow until fish were close to the light frame and barge. Regardless of treatment, they began to swim increasingly across the flow as if to avoid the structure, which they might have been able to visually detect with or without the lights on. At night with the lights off, there was no preferred swimming direction. The structure would have been nearly invisible to them at night, and the low flows would not have created "noise" from strumming cables or water passing structures. However, with the lights on, fish oriented strongly orthogonal to the direction of the lights and swam from east to west and west to east, with only about 5% headed downstream. Most of this activity occurred 10 m or more upstream of the strobe lights, beyond the avoidance zone defined earlier. Close to the lights, the fish sounded under the lights. Preliminary modeling of the light field based on measurements obtained in 2002 (Johnson et al. 2003) suggests that the light field from the six-light array would have totally merged at a range of about 5 m. Also, the high-intensity light field is limited to ±2 m in all directions orthogonal to the direction of the lights. Therefore, given the dispersion of light from reflection, absorption, and attenuation, conditions were probably acceptable, if not optimal, for increased feeding opportunities in proximity to the strobe light source at night. This suggests that deployment of a strobe light net would need to incorporate a high-density light field so that "holes" would not allow fish to pass between lights, particularly if fish are attracted to and using the light field to optimize or extend their feeding.

While hydroacoustic techniques can determine the approximate size of the fish detected, they cannot determine the species of fish. Netting fish was attempted, but the flow dynamics in the area hindered this approach. Another approach was to release radio-tagged kokanee and monitor their movements in the vicinity of the strobe lights. In years prior to 2004, the number of fish in the vicinity of the strobe lights was too sparse to evaluate the behavioral response to the strobe lights. In 2004, radio-tagged kokanee were released 20 and 40 m upstream of the strobe lights. Analysis of this year's data confirmed much of what was found by the splitbeam and multibeam transducers (Appendix E). When the lights were on, the tagged kokanee continued to swim in the direction of the lights although their trajectory took them toward the bank or east side of the forebay. There was no apparent avoidance of the lighted region. If the results reported by Maiolie and Stark (2003) and Maiolie et al. (2001) had applied, we would have expected the kokanee to swim away from the lights under the low flow conditions typical of the nighttime releases (Appendix E).

This study has clearly demonstrated the complex nature of free-ranging fish response to strobe lights at the Grand Coulee Dam third powerplant forebay. Thus, while fish were attracted to the general lighted region at night, fish movements were mostly away from the lights within 10 m of the light frame and much of the apparent increase in detections in that zone was a by-product of increased activity rather than a large increase in the actual number of fish. An important caveat to these results is that we lack information on species composition and associated feeding data. This was because we were unable to capture fish that were detected near our strobe light array due to site logistics and conflict with the hydroacoustic sampling. It is possible that many of the fish that were accumulating at night in the forebay region near the strobe lights were not kokanee or rainbow trout. However, when we examine the target strength distribution and consider the tagging data, we are reasonably confident that at least a portion of the sampled population would have been either kokanee or rainbow trout.

6.0 Conclusions and Recommendations

The conclusions and recommendations presented below are the culmination of three years of study (2002 through 2004) at the Grand Coulee Dam third powerplant.

6.1 Conclusions

- Strobe lights had little effect on fish during daylight hours at the third powerplant (see Figure 4.1).
- Strobe lights had a dramatic effect on fish at night, causing them to accumulate in the general region of the lights with increased swimming activity. Increased fish detections and increased activity were observed at night in all three years of our study. In 2004, we observed fish redistributing in close proximity to the strobe lights (<10 m) thus avoiding the volume illuminated directly in front of the lights and to the east and west sides (see Figure 4.3 and Figure 4.4).
- Strobe lights at night elicited an apparent avoidance response very close to the lights (<10 m) based on behavior patterns such as distribution, swimming activity, and swimming direction (see Figures 4.3, 4.6, and 4.8, respectively).

6.2 Recommendations

- **Deploy a trial strobe light array at the entrance to one penstock at the Grand Coulee Dam third powerplant forebay.** Strobe lights should be deployed near the top of the entrance to one penstock on the upstream side of the trash rack in at least four places around the trash rack. The new generation of commercially available lights would work best for this application because they are omni-directional. Velocities at the face of the trash racks are typically 0.3 m/s (1 ft/s) on Corps of Engineers dams. However, Grand Coulee third powerplant velocities, modeled at a maximum Q of 990 m^3/s (35 kcfs) per unit for the larger units, would be about 2 m/s (6 ft/s) near the trash racks. If strobe lights can keep fish away from the trash rack to the range that we observed avoidance response (<10 m), then the fish are likely to be able to swim away from the entraining flows. The location of the penstocks is well suited to this deployment. They are near the bottom of the forebay on the east side of the third powerplant dam with an overhang at the deck level, which provides a shadowed and darkened environment most of the day. Because of this, a strobe light deployment at this location would have an increased likelihood of effectiveness, even during daytime when the entraining flows are greatest. To be entrained, a fish would need to first swim down to a depth of 36 m (120 ft) below the surface and then must volitionally swim into a darkened area inside the trash racks through a high intensity strobe lit volume. Adjacent penstocks should also be monitored along with the regions between the penstocks to determine if the fish are being displaced away from the lighted penstock trash rack toward the adjacent unlit trash racks.

- **Monitor the test strobe light deployment using a combination of synchronized video (optical and/or acoustic) and splitbeam hydroacoustics.** Initial deployment of strobe lights on the Grand Coulee Dam third powerplant trash racks should be monitored carefully to ensure that the lights are having the desired effect—preventing entrainment of kokanee and rainbow trout. Continued monitoring as the application of lights is expanded to other penstocks will provide quality control and assurance that the fish continue to be protected. After 2 to 3 years of monitoring at the full implementation, monitoring efforts could be discontinued or applied on a periodic basis. Additionally, the flow in the region in front of the trash racks within the influence of the strobe lights should be measured to provide prototype data on entrance velocities and to calibrate a flow model of the entrances.

- **Additional research should be conducted to determine if high-intensity strobe lights attract free ranging fish to a region and to what extent this relates to feeding behavior.** This study generated new questions about the relationship between fish feeding response, and particularly kokanee feeding response, to lighted regions including those produced by strobe lights. The accumulation of fish at night with strobe lights on may have been a function of our sampling location, at or near the thermocline, where zooplankton concentrations were presumed the highest. Future applications of strobe lights at Grand Coulee Dam and other locations would benefit from knowing the extent to which feeding behavior is associated with strobe lights. As an initial examination of this, gillnets should be used to capture fish in the vicinity of the “old” barge location to provide an initial estimation of the species composition and diet associated with strobe light operation. Mobile survey sampling should also be conducted in the vicinity of the gillnet with lights on and lights off to determine if fish are accumulating in or near the lighted zone.

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Appendix A

Environmental Conditions at Grand Coulee Dam

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Mary Ann Simmons and Christopher B. Cook

Environmental factors at the time of the study play a role in data processing and interpretation and are important for year-to-year comparisons. The river conditions (water elevation, temperature, and turbidity) can affect fish distribution (vertical and spatial), immigration, and visual discernment (Levy 1990; Merigoux and Ponton 1999). Light conditions may affect fish distribution and activity levels (Thorpe 1978). Meteorological conditions such as wind and precipitation affect light penetration from the surface and can introduce bubbles into the water column; the bubbles affect data processing and hydroacoustic detectability.

A.1 Forebay Elevation

Forebay elevation data in front of the left powerplant were obtained from the U.S. Department of the Interior Bureau of Reclamation. Over the 2004 field season, the water level in the forebay changed approximately 4 m, starting at 392 m in mid June, reaching maximum high pool elevation of 393 m (1290 ft) in early July (Figure A.1), and then dropping to 390 m by the end of the study in mid August. The forebay elevation in 2004 was similar to that in 2003 in June and early July and to 2002 in late July.

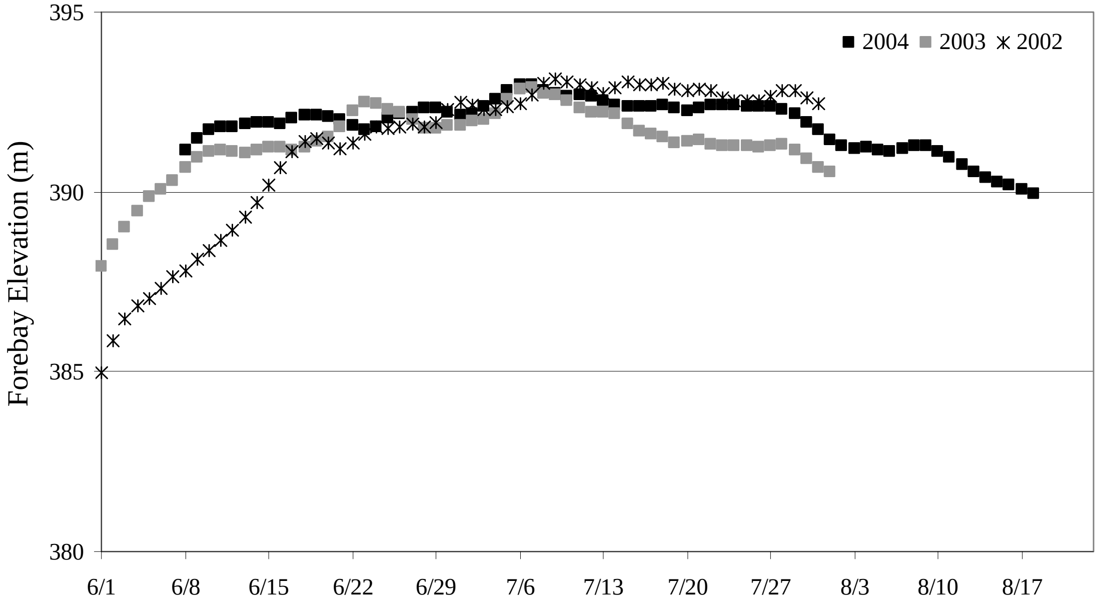

Figure A.1. Forebay Elevation in Front of the Left Powerplant During the Field Seasons for 2002, 2003, and 2004

A.2 Water Temperature Measurements at the Barge Site

While light is a well-known stimulus to diel cycles of fish (Thorpe 1978), temperature also has been found to have an effect on their behavioral rhythms (Valdimarsson et al. 1977; Levy 1991). For this reason, a time-series of water temperatures was collected by placing self-contained temperature loggers (14 in 2002 and 2003, 15 in 2004) along a vertically oriented wire rope. The wire rope was installed immediately upstream of the floating barge and truss system and was attached to the west buoy that secured the truss in place (Figure 3.1). A metal weight was affixed to the bottom of the wire rope to hold the line vertical throughout the water column.

Onset optical StowAway® temperature loggers were used during all years of the study. These self-contained loggers have a manufacturer's reported accuracy of ±0.2ºC, although all loggers also were validated during the study using a thermistor traceable to the National Institute of Standards and Technology and a constant-temperature water bath.

Water temperature data observed during the 2004 field season are displayed in Figure A.2. Similar figures displaying data collected during previous field seasons may be found in Johnson et al. (2003) and Simmons et al. (2004). Color contours in Figure A.2 represent a time-series of water temperatures collected at the 15 depths indicated by the thick black horizontal lines. The loggers were spaced at 3-m intervals except between the uppermost two loggers, where the spacing was decreased to 2.5 m. The uppermost logger was 2.2 m beneath the water surface, and the deepest logger was at 44 m.

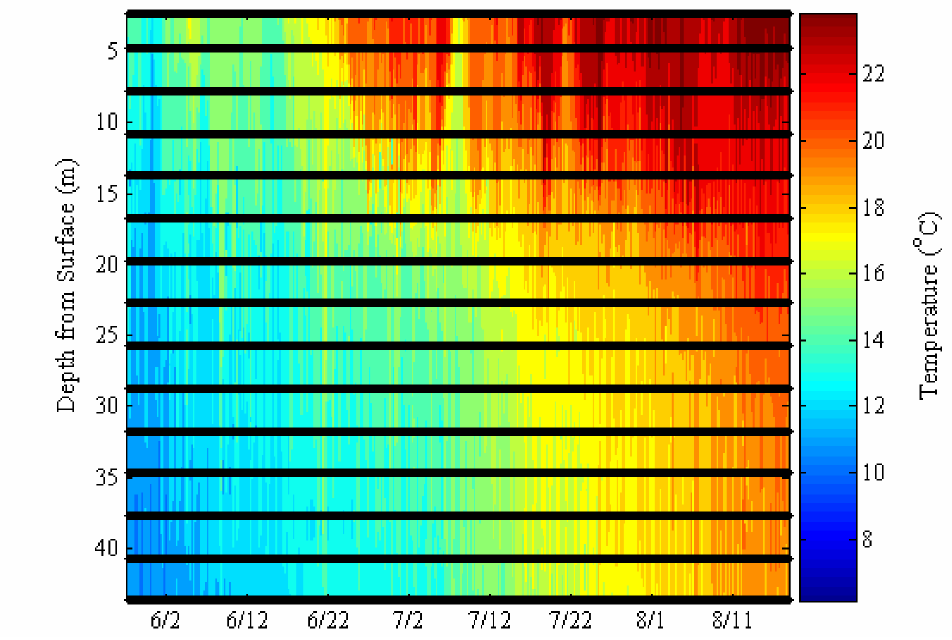

Figure A.2. Water Temperature Contours (°C) as a Function of Depth in the Forebay of the Third Powerplant at Grand Coulee Dam in 2004. Black horizontal lines indicate temperature logger locations.

Differences in water column temperatures during the three study years are shown in Figure A.3. Data displayed in these figures are at two depths (approximately 4 m and 40 m beneath the water surface). A 6-hour moving average was applied to the data to remove high-frequency oscillations.

During all three years, the lower portion of the water column warmed slowly throughout the season, increasing from approximately 10ºC in May to approximately 16ºC in July (and to above 19ºC in August 2004). The rate of warming in the lower portion of the water column was nearly identical during all three years.

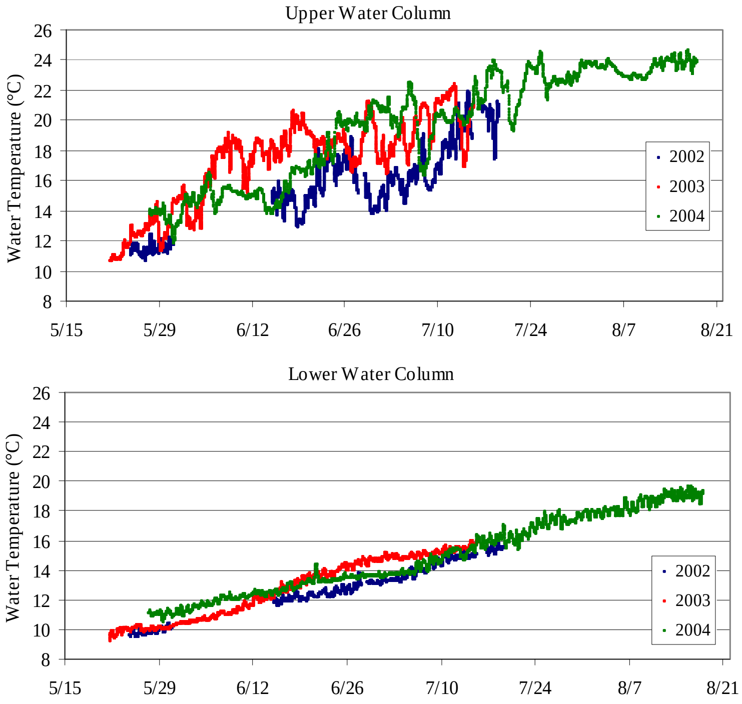

Figure A.3. Water Temperatures at Approximately 4 m (top) and 40 m (bottom) Collected During 2002, 2003, and 2004 in the Forebay of the Third Powerplant

The upper portion of the water column also warmed noticeably throughout each field season; however, there were larger inter-year variations. In 2002, the water was cooler, on average, than during the 2003 season. During the 2004 field season, the water was colder than 2003 in early to mid June. However, a sharp warming occurred in late June; by early July 2004, temperatures were above 20ºC.

Around July 7, 2004, a large mixing event cooled the upper water column water temperatures; the event can be seen in both Figure A.2 and the upper portion of Figure A.3. Although the upper portion of the water column cooled by approximately 6ºC during the event, the water column still was stratified by more than 2ºC. The upper water column warmed quickly after the event, and lower water column temperatures apparently were not affected (i.e., the rate of hypolimnetic warming was approximately constant during the period).

The thermocline is typically defined as the vertical depth layer that separates the upper warmer water from the lower cooler water in a thermally stratified water body. The approximate depth of the thermocline during the 2004 field season is shown in the top portion of Figure A.4. The thermocline depth was estimated by first calculating the maximum temperature gradient in the water column, which is shown in the bottom portion of Figure A.4. The maximum gradient represents the change in water temperature measured in degrees Celsius per 2 m of water column depth. A 48-hour running average was used to smooth out high-frequency oscillations. The corresponding depth of the maximum gradient was defined to be the thermocline depth.

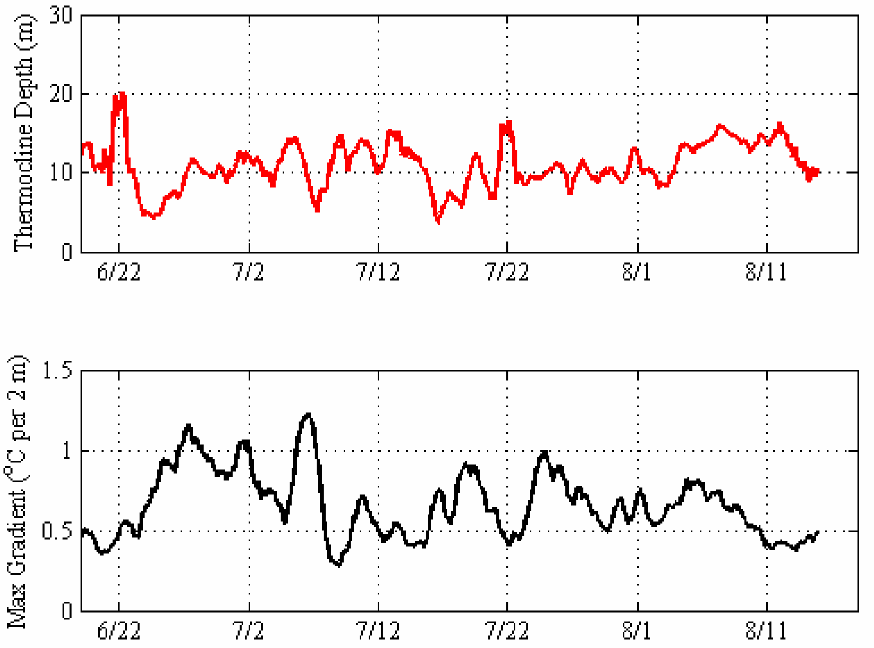

Figure A.4. Thermocline Depth (top) and Maximum Temperature Gradient (bottom) During the 2004 Field Season

During the entire 2004 field season, the water column beneath the barge site was stratified and the thermocline depth hovered near 10 m. The maximum thermal gradient at the thermocline was generally between 0.5° and 1.0°C for much of the season. The same general trends were observed also during the 2002 and 2003 field seasons.

The maximum gradient shown in Figure A.4 is not equivalent to the difference in temperature between the upper and lower portions of the water column. As noted from Figure A.3, the difference between upper and lower portions of the water column was greater than 2°C for the entire 2004 field season, with maximums larger than 8°C during the early and latter part of July.

A.3 Turbidity

Turbidity can affect the distribution of fish both vertically and spatially (Swenson 1978; Matthews 1984). Turbidity measurements were taken weekly during the field seasons in 2001, 2002, and 2003, at several depths at the upstream buoy location closest to the right bank of the reservoir in the forebay of the third powerplant. Turbidity measurements were taken with Van Doren bottle grab samples and analyzed using a Hach Model 2100P Portable Turbidimeter.(a) Three replicates were analyzed at each depth.

Turbidity levels were not measured in 2004. In the previous three years, turbidity was generally below 1 nephelometric turbidity unit (NTU) after mid-June (Figure A.5). In those years, turbidity decreased from June through July. The higher turbidity levels were associated with the filling of the reservoir. In 2001, the reservoir was at its maximum elevation when the study began. No adverse physiological effects have been noted in salmonids at turbidity levels less than 10 NTU (Bash et al. 2001). However, turbidity as low as 3 NTU was found to affect the response of lake trout to prey under low light levels (Vogel and Beauchamp 1999). In addition, increased turbidity would affect the visible range of the strobe lights.

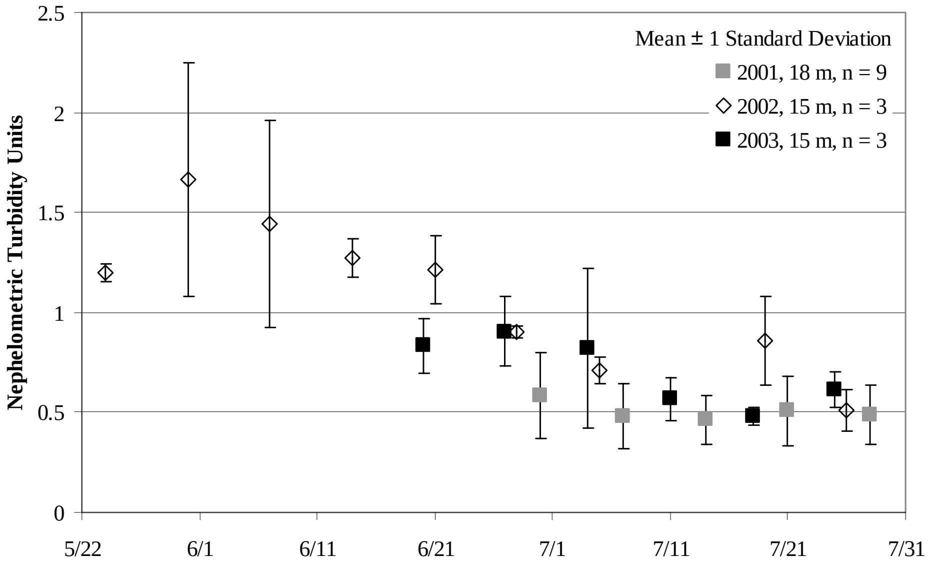

Figure A.5. Turbidity Levels at Grand Coulee Dam for Three Study Years (June 30 through August 1, 2001; May 24 through July 26, 2002; and June 20 through July 25, 2003)

A.4 Light Conditions

Ambient light levels have a direct effect on the effectiveness of the strobe light system by providing competing illumination during daylight hours. In addition, the diel light cycle influences fish distribution within the water column (Thorpe 1978).

(a) Hach Company, Loveland, Colorado.

Ambient light conditions were monitored at the surface and on the strobe light frame using two Model LI-19SA Underwater Quantum light sensors supplied by LI-COR, Lincoln, Nebraska. Light conditions were monitored 24 hours/day and reported every second to a data logger on the sensor mast of the fixed barge.

Maximum daily ambient light levels fluctuated between 2000 and 3000 μmole/m^2/s over the course of the study; 2000 μmole/m^2/s is considered clear sky, midday sunlight, while light levels on a cloudy day would be around 500 μmole/m^2/s. Daily light levels peaked between noon and 1 p.m. Light levels on the strobe light frame at 15 m depth showed a similar fluctuation over 24 hours with levels ranging from near zero at night to around 23 μmole/m^2/s between noon and 1 p.m, irrespective of whether the strobe lights were on or off.

A.5 Wind and Precipitation

Wind and precipitation disturb the surface of a body of water, affecting light penetration (McFarland and Lowe 1983). These two events also can introduce bubbles into the water column, which can acoustically obscure fish tracks. Wind speed, direction and precipitation data were downloaded from the Bureau of Reclamation AgriMet database (Bureau of Reclamation 2004).

For the three study years, average wind speed was 6.8 km/h (4.2 mph) in 2002, 6.0 km/h (3.8 mph) in 2003 and 6.2 km/h (3.8 mph) in 2004. The 90th percentile for the three years was 12.9 km/h (8.0 mph) in 2002, 11.6 km/h (7.2 mph) in 2003, and 12.2 km/h (7.6 mph) in 2004. While wind speeds were generally below 20 km/h (12 mph) in all three years, wind gusts up to 60 km/h (37 mph) were recorded in all three years.

Precipitation in this arid area averages around 27 cm per year (11 in.). Much of this occurs during the winter and spring months; precipitation during the summer usually is associated with sporadic thunderstorms. The cumulative precipitation totals for the three years indicate that precipitation varied from a low of 0.08 cm (0.03 in) in 2003 to 2.5 cm (1 in.) in 2004.

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Appendix B

Hydroacoustic System Calibration

Appendix B

Hydroacoustic System Calibration

Robert L. Johnson

Pacific Northwest National Laboratory (PNNL) has a formal quality assurance (QA) program that provides the structure within the Laboratory for the development and delivery of quality products. The QA program is based upon the basic requirements as defined in U.S. Department of Energy Order 414.1A, *Quality Assurance*, and 10 CFR 830 Subpart A, *Energy/Nuclear Safety Management/Quality Assurance Requirements*.

PNNL has chosen to implement the requirements of 414.1A and 10 CFR 830 Subpart A by integrating them into the Laboratory's management systems and daily operating processes. The Quality Management System administers the QA program with a focus on integrating the four basic quality principles (plan, perform, assess, and improve) into the work of PNNL. The procedures necessary to implement the requirements have not been consolidated into a single, stand-alone QA manual but are documented throughout PNNL’s Standards-Based Management System.

The PNNL formal QA program has been designed to ensure that appropriate technical and administrative controls are applied to work activities commensurate with the risk associated with the Laboratory’s responsibility for health and safety, environmental protection, reliability and continuity of operation, and acquisition of valid research and development data. Work at the Laboratory is managed through a hierarchy of governing documents—policies, standards, management systems, and subject areas with procedures and guidelines.

The hydroacoustic equipment manufacturer, Precision Acoustic Systems, Seattle, Washington, performed all hydroacoustic system calibrations. Precision Acoustic Systems is an authorized calibration facility subject to triennial audit by the PNNL QA program. The next audit will occur in fall 2005.

This appendix lists results for two calibrations. The first calibration was conducted on April 3, 2003, prior to initiation of the study (pre-season calibration) on June 16, 2003. The system operated under the preseason calibration conditions until the end of the data collection period on August 1, 2003. Subsequent to the data collection period, we discovered a problem with one of the transducers during data processing and ordered a post-season calibration. The calibration was performed October 6 through 8, 2003, after an inspection of the complete system to ascertain the cause of the problem. It was ultimately discovered that a component in one of the multiplexers had failed, causing the transducer to lose data on one or more of its quadrants. The data from the faulty channel was adequate for counting but did not permit behavior or within-beam tracking analysis. This problem was rectified and the calibration continued. This last calibration became the preseason calibration for the work undertaken in 2004. The calibrations performed pre- and post-season were found to agree within measurement error levels established under the QA criteria.

Date: **4/3/2003**
Calibration: **Split Beam System for Grand Coulee Dam**

Echo Sounder #: PAS-103 #29	Description: PAS-103 Split Beam 420 kHz Sounder
L MUX Breakout Cable: PAS-01-6DS-60-100	Description: 6-Channel Breakout Cable, 60' Long
L MUX Deck Cable #: PAS-01-6DS-483-103	Description: 6-Channel Local Multiplexer Cable, 483' long
Local Multiplexer #: PAS-203-21	Description: 4-Channel Local Surface MUX W/RM Interfaces
Xducer Cable #: PAS-01-4D-157-95, 96 & 97	Description: 157' 4-Channel Xducer Cable, Wet/MS, Ports 1-3
Transducer #: PAS-420-SPB-06-447, 438 & 449	Description: Split Beam 6 deg With 10 Deg. Lens, Ports 1-3
R MUX Deck Cable #: PAS-02-6D-17-115	Description: 6-Channel Remote MUX Cable, 17' long, Port 0
Remote Multiplexer #: PAS-203-RU-015	Description: 4-Channel Remote UW Multiplexer
Xducer Cable #: PAS-01-4D-157-70, 91, 92 & 93	Description: 157' 4-Channel Xducer Cable, Wet/Wet, Ports 0-3
Transducer #: PAS-420-SPB-06-434 & 431-433	Description: Split Beam 6 deg With 10 Deg. Lens, Ports 0-3

Frequency: 420 kHz. Operating Mode: Standard
Receiver Gain, L: 20 dB. Bandwidth: 10 kHz. Xmit Pulse Width: 0.4 ms.
Sounder TVG Start Range: 1.0 m. Gx Measurement Range, Rx: 10 m.
Absorbtion Coeff: 0 dB/km. (Off)

Standard Type: PAS Standard Transducer #: 236
Receive Sensitivity of Standard, Ss: -204.67 dBV||uPa
Transmit Sensitivity of Standard, Ts: 171.55 dBuPa/Vrms @ 1 meter.
Separation Between Transducers, Rs: 3.416 m 20 Log (Rs) = 10.67 dB.
Water Temperature: 13.89 deg. C

Calibration Data

Source Level, SL = Vs + 20 Log (Rs) - Ss in dB uPa @ 1 meter

Where Vs is the voltage out of the standard in dBV.

Stat Xmit Level	Dyn Xmit Level	Vs	SL
-6	-6	-5.69	-5.69
-5	-6	-4.08	-4.08
-4	-6	-2.63	-2.63

Stat Xmit Level	Dyn Xmit Level	Vs	SL	
-3	-6	-1.32	-1.32	Pattern

Receive Sensitivity, Gx = Vout + 20 Log (Rs) - Ts - Vs in dBV || uPa @ Rx

Where Vs in the voltage drive to the standard transducer in dBV,
and Vout is the voltage out of the receiver in dBV.

Receive Sensitivity, G1 = Gx - Gtvg - L in dBV || uPa Referred to 1 meter @ 0 dB Receiver Gain.

Where Gtvg = 40 or 20 Log (Rx) = 40.00 dB-40 or 20.00 dB-20

Receiver Output	-58 dB Cal Osc	Vs	Vdet Out	Vout-dB	Gx	G1
Receiver #1, Log Sum Beam, 40 Log (R)	4.004	-26	4.068	81.36	107.36	-113.52
Receiver #2, X Phase (AC/BD)	2.484	-26	2.491	N/A	N/A	N/A
Receiver #3, Y Phase (AB/CD)	2.506	-26	2.548	N/A	N/A	N/A

Splitbeam Conversion Coefficients for Phase to Mechanical Angle and Phase to Beam Pattern Factor
All Transducers with Lens #09 (10 deg.)

Transducer	Axis	SAx	SAy	OAx	OAy	SBx	SBy	OBx	OBy
434	X	191.83		2044.05		-174066.69		2028.95	
434	Y		191.80		2081.49		-171122.05		2053.25
431	X	192.73		2003.39		-164249.21		1981.02	
431	Y		186.99		2097.10		-162322.08		2119.90
432	X	193.87		2038.17		-170780.14		2041.04	
432	Y		195.31		2054.42		-170088.25		2049.63
433	X	193.88		2023.63		-165807.92		2016.51	
433	Y		196.97		2061.28		-165524.75		2071.54
447	X	190.95		2059.23		-170142.75		2054.77	
447	Y		190.46		2041.58		-168186.95		2056.49
438	X	194.29		2065.73		-166250.76		2041.86	
438	Y		192.54		2023.78		-165990.48		2049.25
449	X	188.50		2041.05		-167293.41		2035.83	
449	Y		188.56		2024.49		-167156.19		2043.29

Splitbeam Calibration for Grand Coulee Dam- Source Levels

			Xmit			Xmit			Xmit			Xmit (Patterns)		
Date	Xducer	Axis	Level	Vs	SL	Level	Vs	SL	Level	Vs	SL	Level	Vs	SL
4/3/2003	434	X	-6	-5.69	209.65	-5	-4.08	211.26	-4	-2.63	212.71	-3	-1.32	214.02
4/3/2003	434	Y	-6	-5.63	209.71	-5	-4.05	211.29	-4	-2.62	212.72	-3	-1.3	214.04
4/3/2003	431	X	-6	-6.01	209.33	-5	-4.4	210.94	-4	-2.98	212.36	-3	-1.65	213.69
4/3/2003	431	Y	-6	-6.02	209.32	-5	-4.42	210.92	-4	-2.98	212.36	-3	-1.65	213.69
4/3/2003	432	X	-6	-5.16	210.18	-5	-3.57	211.77	-4	-2.16	213.18	-3	-0.87	214.47
4/3/2003	432	Y	-6	-5.15	210.19	-5	-3.58	211.76	-4	-2.17	213.17	-3	-0.89	214.45
4/3/2003	433	X	-6	-6.04	209.30	-5	-4.45	210.89	-4	-3	212.34	-3	-1.66	213.68
4/3/2003	433	Y	-6	-6.07	209.27	-5	-4.46	210.88	-4	-3.03	212.31	-3	-1.68	213.66
4/3/2003	447	X	-6	-5.95	209.39	-5	-4.37	210.97	-4	-2.94	212.40	-3	-1.62	213.72
4/3/2003	447	Y	-6	-5.92	209.42	-5	-4.33	211.01	-4	-2.9	212.44	-3	-1.59	213.75
4/3/2003	438	X	-6	-5	210.34	-5	-3.41	211.93	-4	-2.01	213.33	-3	-0.74	214.60
4/3/2003	438	Y	-6	-5	210.34	-5	-3.43	211.91	-4	-2.02	213.32	-3	-0.75	214.59
4/14/2002	449	X	-6	-5.7	209.64	-5	-4.14	211.20	-4	-2.74	212.60	-3	-1.45	213.89
4/14/2002	449	Y	-6	-5.73	209.61	-5	-4.16	211.18	-4	-2.75	212.59	-3	-1.46	213.88

Splitbeam Calibration for Grand Coulee Dam- Receiving Sensitivities

Date	Xducer	Axis	Vdet Out	G1	X Out	Y Out	-58 dB Cal	X Cal	Y Cal
4/3/2003	434	X	4.068	-113.52	2.491	2.548	4.004	2.484	2.506
4/3/2003	434	Y	4.068	-113.52	2.49	2.549	4.005	2.484	2.506
4/3/2003	431	X	4.055	-113.78	2.45	2.567	4.005	2.485	2.507
4/3/2003	431	Y	4.055	-113.78	2.449	2.567	4.006	2.485	2.507
4/3/2003	432	X	4.089	-113.10	2.492	2.519	4.006	2.485	2.507
4/3/2003	432	Y	4.089	-113.10	2.493	2.518	4.006	2.486	2.507
4/3/2003	433	X	4.072	-113.44	2.469	2.528	4.006	2.486	2.507
4/3/2003	433	Y	4.07	-113.48	2.467	2.529	4.006	2.488	2.506
4/3/2003	447	X	4.096	-112.96	2.517	2.502	4.006	2.488	2.507
4/3/2003	447	Y	4.097	-112.94	2.518	2.501	4.006	2.488	2.506
4/3/2003	438	X	4.11	-112.68	2.532	2.466	4.006	2.488	2.507
4/3/2003	438	Y	4.109	-112.70	2.531	2.466	4.006	2.489	2.507
4/14/2002	449	X	4.111	-112.66	2.498	2.476	4.006	2.489	2.507
4/14/2002	449	Y	4.109	-112.70	2.498	2.476	4.006	2.489	2.506

Date: **10/6/03 & 10/7/03 & 10/8/03**
Calibration: Split Beam System for Grand Coulee Dam

Echo Sounder #: PAS-103 #29	Description: PAS-103 Split Beam 420 kHz Sounder
L MUX Breakout Cable: PAS-01-6DS-60-100	Description: 6-Channel Breakout Cable, 60' Long
L MUX Deck Cable #: PAS-01-6DS-483-103	Description: 6-Channel Local Multiplexer Cable, 483' long
Local Multiplexer #: PAS-203-21	Description: 4-Channel Local Surface MUX W/RM Interfaces
Xducer Cable #: PAS-01-4D-157-95, 96 & 97	Description: 157' 4-Channel Xducer Cable, Wet/MS, Ports 1-3
Transducer #: PAS-420-SPB-06-447, 438 & 449	Description: Split Beam 6 deg With 10 Deg. Lens, Ports 1-3
R MUX Deck Cable #: PAS-02-6D-17-115	Description: 6-Channel Remote MUX Cable, 17' long, Port 0
Remote Multiplexer #: PAS-203-RU-015	Description: 4-Channel Remote UW Multiplexer
Xducer Cable #: PAS-01-4D-157-70, 91, 92 & 93	Description: 157' 4-Channel Xducer Cable, Wet/Wet, Ports 0-3
Transducer #: PAS-420-SPB-06-434 & 431-433	Description: Split Beam 6 deg With 10 Deg. Lens, Ports 0-3

Frequency: 420 kHz.
Receiver Gain, L: 20 dB.
Sounder TVG Start Range: 1.0 m.
Absorbtion Coeff: 0 dB/km. (Off)

Operating Mode: Standard
Bandwidth: 10 kHz. Xmit Pulse Width: 0.4 ms.
Gx Measurement Range, Rx: 10 m.

Standard Type: PAS
Standard Transducer #: 238
Receive Sensitivity of Standard, Ss: -203.86 dBV||uPa
Transmit Sensitivity of Standard, Ts: 170.25 dBuPa/Vrms @ 1 meter.
Separation Between Transducers, Rs: 3.416 m. 20 Log (Rs) = 10.67036 dB.
Water Temperature: 18.33 deg. C

Calibration Data

Source Level, SL = Vs + 20 Log (Rs) - Ss in dB uPa @ 1 meter

Where Vs is the voltage out of the standard in dBV.

Stat Xmit Level	Dyn Xmit Level	Vs	SL		Stat Xmit Level	Dyn Xmit Level	Vs	SL	
-6	-6	-4.27	210.2604		-3	-6	-0.1	214.4304	Pattern
-5	-6	-2.73	211.8004						
-4	-6	-1.35	213.1804						

Receive Sensitivity, Gx = Vout + 20 Log (Rs) - Ts - Vs in dBV || uPa @ Rx

Where Vs in the voltage drive to the standard transducer in dBV,
and Vout is the voltage out of the receiver in dBV.

Receive Sensitivity, G1 = Gx - Gtvg - L in dBV || uPa Refered to 1 meter @ 0 dB Receiver Gain.

Where Gtvg = 40 or 20 Log (Rx) = 40 dB-40 or 20 dB-20

Receiver Output	-58 dB Cal Osc	Vs	Vdet Out	Vout-dB	Gx	G1
Receiver #1, Log Sum Beam, 40 Log (R)	4.005	-26	4.071	81.42	-52.15964	-112.1596
Receiver #2, X Phase (AC/BD)	2.484	-26	2.495	N/A	N/A	N/A
Receiver #3, Y Phase (AB/CD)	2.511	-26	2.556	N/A	N/A	N/A

Splitbeam Conversion Coefficients for Phase to Mechanical Angle and Phase to Beam Pattern Factor
All Transducers with Lens #09 (10 deg.)

Transducer	Axis	SAx	SAy	OAx	OAy	SBx	SBy	OBx	OBy
434	X	191.30		2046.63		-169074.49		2028.31	
434	Y		191.09		2085.99		-166418.38		2059.28
431	X	197.32		2005.72		-165235.58		1979.92	
431	Y		192.62		2101.30		-164365.34		2121.77
432	X	194.51		2026.00		-167384.89		2042.04	
432	Y		195.40		2044.13		-166900.68		2055.60
433	X	197.47		2016.89		-161860.00		2011.56	
433	Y		199.80		2061.92		-160498.09		2075.85
447	X	190.06		2059.97		-164437.48		2052.47	
447	Y		190.18		2052.33		-163328.52		2061.40
438	X	198.26		2061.93		-167702.22		2038.97	
438	Y		196.76		2025.11		-167566.14		2048.61
449	X	189.47		2046.55		-163578.78		2036.96	
449	Y		189.84		2032.75		-162710.19		2049.77

Splitbeam Calibration for Grand Coulee Dam-Source Levels

Date	Xducer	Axis	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit (Patterns)		
												Level	Vs	SL
10/6/2003	434	X	-6	-4.27	210.26	-5	-2.73	211.80	-4	-1.35	213.18	-3	-0.1	214.43
10/6/2003	434	Y	-6	-4.28	210.25	-5	-2.73	211.80	-4	-1.36	213.17	-3	-0.11	214.42
10/6/2003	431	X	-6	-4.95	209.58	-5	-3.4	211.13	-4	-1.99	212.54	-3	-0.7	213.83
10/6/2003	431	Y	-6	-4.96	209.57	-5	-3.4	211.13	-4	-2.01	212.52	-3	-0.7	213.83
10/6/2003	432	X	-6	-4.01	210.52	-5	-2.46	212.07	-4	-1.1	213.43	-3	0.14	214.67
10/6/2003	432	Y	-6	-4.03	210.50	-5	-2.49	212.04	-4	-1.12	213.41	-3	0.12	214.65
10/6/2003	433	X	-6	-4.85	209.68	-5	-3.28	211.25	-4	-1.87	212.66	-3	-0.8	213.73
10/6/2003	433	Y	-6	-4.84	209.69	-5	-3.28	211.25	-4	-1.88	212.65	-3	-0.57	213.96
10/7/2003	447	X	-6	-5.2	209.33	-5	-3.64	210.89	-4	-2.22	212.31	-3	-0.91	213.62
10/7/2003	447	Y	-6	-5.2	209.33	-5	-3.63	210.90	-4	-2.21	212.32	-3	-0.9	213.63
10/8/2003	438	X	-6	-4.15	210.38	-5	-2.6	211.93	-4	-1.21	213.32	-3	0.03	214.56
10/8/2003	438	Y	-6	-4.16	210.37	-5	-2.61	211.92	-4	-1.23	213.30	-3	0.02	214.55
10/7/2003	449	X	-6	-5.09	209.44	-5	-3.53	211.00	-4	-2.13	212.40	-3	-0.83	213.70
10/7/2003	449	Y	-6	-5.01	209.52	-5	-3.45	211.08	-4	-2.06	212.47	-3	-0.76	213.77

Splitbeam Calibration for Grand Coulee Dam-Receiving Sensitivities

Date	Xducer	Axis	Vdet Out	G1	X Out	Y Out	-58 dB Cal	X Cal	Y Cal
10/6/2003	434	X	4.071	-112.16	2.495	2.556	4.005	2.484	2.511
10/6/2003	434	Y	4.071	-112.16	2.495	2.556	4.005	2.485	2.511
10/6/2003	431	X	4.043	-112.72	2.456	2.567	4.005	2.484	2.511
10/6/2003	431	Y	4.043	-112.72	2.455	2.568	4.005	2.484	2.511
10/6/2003	432	X	4.076	-112.06	2.492	2.519	4.005	2.484	2.511
10/6/2003	432	Y	4.077	-112.04	2.492	2.509	4.005	2.485	2.511
10/6/2003	433	X	4.063	-112.32	2.467	2.524	4.004	22.481	2.511
10/6/2003	433	Y	4.062	-112.34	2.467	2.524	4.004	2.483	2.511
10/7/2003	447	X	4.073	-112.12	2.517	2.511	4.002	2.482	2.508
10/7/2003	447	Y	4.075	-112.08	2.518	2.512	4.003	2.483	2.509
10/8/2003	438	X	4.079	-112.00	2.525	2.472	4.003	2.485	2.508
10/8/2003	438	Y	4.079	-112.00	2.526	2.473	4.003	2.486	2.508
10/7/2003	449	X	4.074	-112.10	2.508	2.486	4.005	2.485	2.511
10/7/2003	449	Y	4.077	-112.04	2.504	2.487	4.005	2.486	2.511

Appendix C

Mobile Splitbeam Hydroacoustics

Appendix C

Mobile Splitbeam Hydroacoustics

Robert L. Johnson

The overall purpose of the study was to determine the efficacy of strobe lights to deter kokanee and rainbow trout from entering the third powerplant forebay at Grand Coulee Dam. Our deployment of strobe lights was limited to a restricted region due to logistical considerations and the cost of deploying lights across the full breadth and depth of the forebay. We were concerned that the fish detected by the splitbeam transducers upstream from the strobe lights may not be representative of the population of fish entering the forebay. To quantitatively evaluate this concern, we conducted periodic mobile splitbeam hydroacoustic surveys to obtain spatial and vertical fish distribution data within the greater third powerplant forebay region and upstream of the strobe lights to the security boom. We also determined the acoustic size of the fish for comparison with our fixed location monitoring activity in the illuminated region immediately upstream of the strobe lights. This appendix describes the methods and results of the mobile splitbeam hydroacoustic surveys. The implications of these results are discussed in the main body of the report.

C.1 Methods

C.1.1 Equipment

Mobile hydroacoustic surveys were conducted from a boat using a BioSonics, Inc.[a] DT-X digital scientific echo sounder system. The system comprised three components as pictured in Figure C.1: 1) a digital splitbeam transducer; 2) a ruggedized surface unit with programmable Linux-based Emb processor; and 3) a ruggedized laptop computer to control the system operation and log data.

The calibration data for the system used at Grand Coulee Dam in 2004 are listed in Table C.1. These values are stored internally in the system, carried through the logging and processing stages, and are unique to our specific transducer/transceiver combination.

A differential global positioning system (DGPS) with real-time position correction was used to determine the location of the boat during the weekly surveys. The antenna was mounted above (3 m), behind (0.5 m), and starboard of the transducer (0.5 m). The DGPS provided input to the DT-X echo sounder through a serial connection to the back of the surface unit. Locations in latitude and longitude were generated every 5 seconds throughout the survey. The position data were integrated with the echo data in real time in a Panasonic Toughbook laptop running BioSonics' DT-X Visual Acquisition software version 5.0.3. A single 12-V dc deep cycle gel cell battery powered the entire system (echo sounder, transducer, and DGPS). The laptop computer was powered by its internal battery.

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[a] BioSonics, Inc., Seattle, Washington.

Figure C.1. DT-X Splitbeam Hydroacoustic System Used for Mobile Surveys at Grand Coulee Dam Third Powerplant in 2004

Table C.1. DT-X Digital Splitbeam Echo Sounder Specifications and Calibration Data[(a)] (Grand Coulee Dam 2004)

System Serial Number	DTX03015
Operating Frequency	201 kHz
Source Level	223.0 dB//µPa
Receiving Sensitivity	−57.0 dB counts || µPa
Pulse Width	0.4 milliseconds
Ping Rate	5 pings per second
Sound Velocity	Based on average water column temperature for each survey
Sound Absorption Coefficient	Based on average water column temperature for each survey

(a) The calibration data fall under the auspices of the PNNL QA program described in Appendix B. BioSonics, Inc. is an authorized calibration facility in compliance with PNNL QA standards.

The boat used for the mobile transect surveys had a 6.4-m (21-ft) heavy-gauge aluminum hull and a 2.4-m (7-ft 10-in.) beam and was powered by a 150-hp outboard motor. The Chief Joseph Kokanee Enhancement Project provided the boat and expert operator during the study.

C.1.2 Field Data Collection

Our field data collection was based on established methods of fish stock assessment in lakes and reservoirs (Burczynski and Johnson 1986). Mobile hydroacoustic data collection was based on replication of seven parallel numbered beginning at the upstream security boom and extending downstream to the back of the third powerplant forebay. Each transect was marked at both ends by a flashing amber light to ensure that transects were closely replicated during a survey and from week to week. The lights were photocell-activated and would flash only at night to preserve their batteries. Four of the transect markers were on floats attached to the inner security boom. As wind conditions changed, the boom moved back and forth, varying the length of each of the upstream transects (i.e., upstream of the barge location). For this reason, the locations of these transects were more variable in length than the three with fixed markers located within the forebay.

Transects typically were initiated at the most upstream location adjacent to the boat launch, then sequentially completed to the back of the third powerplant forebay, and finally replicated back to the boat launch on each night. Surveys began at approximately 2200 hours on Monday nights when the lights on the dam were extinguished for the nightly laser light show. We normally completed our surveys by the time the lights were turned back on for the night (about 2300 hours) after the laser light show unless we encountered an unforeseen problem.

C.1.3 Data Processing

Data processing was accomplished using Echoview® software from SonarData Pty Ltd.[(a)] operating under Microsoft® Windows. Echoview is a visual processing and analysis package that allows the user to import a broad range of scientific echo sounder data and process those data under a common processing system. The visual-based system permits the user to visually scan echogram data in context of bottom and surface and verify auto-tracking results. Figure C.2 shows an example of an echogram segment from our August 16, 2004, survey of the third powerplant forebay. A single distinct target is displayed at two depths in relation to the bottom contour. Note that the automatic bottom tracking has been overridden by the operator to better represent the contour of the steep bottom on the left of the echogram (green line) and prevent detection of bottom as a fish target.

Colors displayed on the echogram were set to represent echo levels so that relative intensity of the echo return could be discerned easily during processing. Bottom echoes also were examined to ensure that bottom structure was not included as fish targets. The final data from the survey was then output in comma-separated-variable (*.csv) format for further analysis.

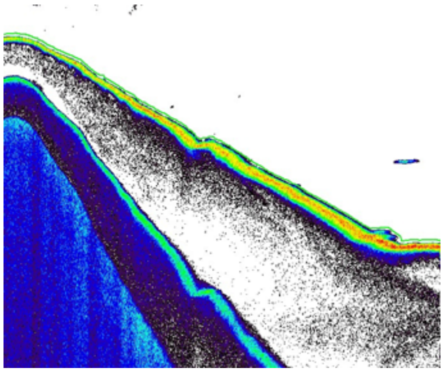

Figure C.2. Echoview Screen Showing Bottom Track and One Fish in the Water Column (Grand Coulee Dam, August 16, 2004)

(a) SonarData Pty Ltd., Hobart, Australia.

The analysis was based on graphical representation of the spatial and vertical distributions of fish targets detected by the hydroacoustic surveys and determining the acoustic size distribution of the sampled population. The spatial and vertical distributions provided us with an indication of where the fish were located at night. The acoustic fish size (target strength, typically expressed in decibels) can be compared to the fish population detected near the strobe lights by the fixed-location system to determine if they might represent the same population.

In addition to the surveys conducted weekly in the area associated with the third powerplant forebay, we conducted weekly surveys of the area associated with the pumping plant on the left bank side of the dam.

C.2 Results

C.2.1 Third Powerplant Forebay

Fish Distributions

There were 153 verifiable fish targets detected during the nine weekly night surveys of the third powerplant forebay area using mobile splitbeam hydroacoustics from June 22 through August 16, 2004. The number of targets collected in a given survey ranged from 6 to 31. Spatially, fish generally were widely and evenly distributed throughout most of the sampled region from the upstream security boom to the back of the third powerplant forebay (Figure C.3). Exceptions were noted for the transect located immediately north (downstream) of the strobe light location and the transect located furthest into the third powerplant forebay. On the transect immediately downstream of the strobe lights, fish were located either toward the right (east) bank or in the center of the transect corresponding to the location of the strobe lights. On the transect near the back of the forebay, fish were located mostly toward the dam or west side of the transect. Historically, this has been a favored area for anglers; the fish may accumulate there due to currents or other physical phenomena.

Fish targets were distributed over a wide range of depths from 10 to 52 m. Figure C.4 shows the extent of the distribution with two distinct peaks in the distribution. One mode appeared to peak at about 15 m, corresponding to the level of the strobe lights and thermocline during temperature-stratified periods. The other mode peaked much deeper at about 40 m. The mean depth for all targets was 26 m with a standard deviation of 12 m. When we examined the target strength/depth relationship (Figure C.5), it was apparent that all sizes of fish could be found anywhere in the water column. There was no clear relationship between either of the modes and a specific fish size as measured by backscatter target strength.

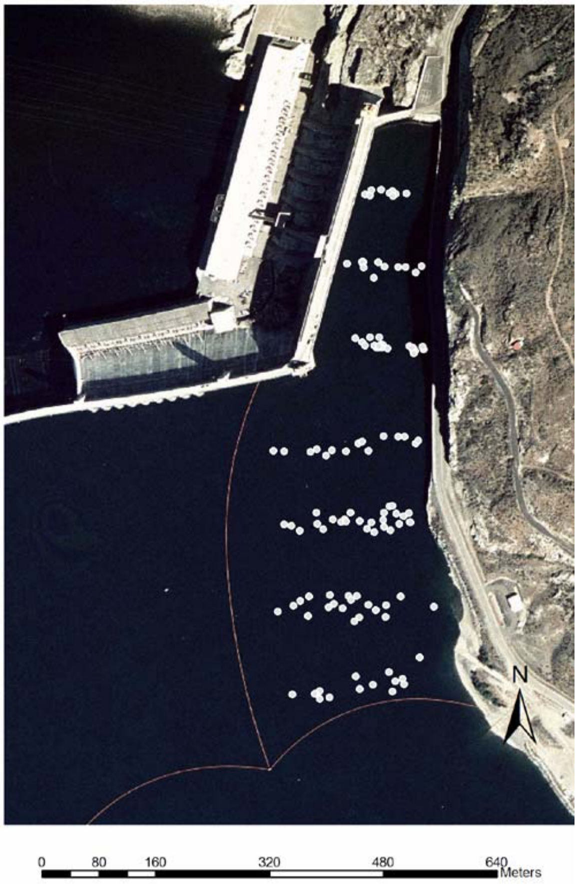

Figure C.3. Location of Fish Detected During Mobile Surveys of the Third Powerplant (right bank of Lake Roosevelt) Forebay at Grand Coulee Dam from June 22 through August 16, 2004

Target Strength Measurements

As noted in our 2003 study, target strength measurements using the splitbeam approach varied widely throughout the third powerplant forebay during the season (Figure C.6) (Simmons et al. 2004). Smaller targets (<−54 dB) may have been debris dropout, which usually was associated with a growing raft of debris at the north end of the third powerplant forebay. These smaller targets are more difficult to identify as fish because their effective sample volume is much smaller than that of larger fish targets and thus do not tend to have long durations in the acoustic beam. The 2004 target strength distribution takes on a bimodal appearance with peaks at about −48 dB and −42 dB compared to −50 dB and −38 dB in 2003. This may suggest the presence of two distinct size classes of fish in the area of interest, with the fish centered on −42 dB most likely representing the kokanee population of interest. The smaller fish targets centered on −48 dB could be age 0+ fish from the wild population or small fish of other species. For instance, smallmouth bass (*Micropterus dolomieu*) and Piute sculpin (*Cottus beldingi*) have been observed in the area but usually are associated with the shoreline or structure.

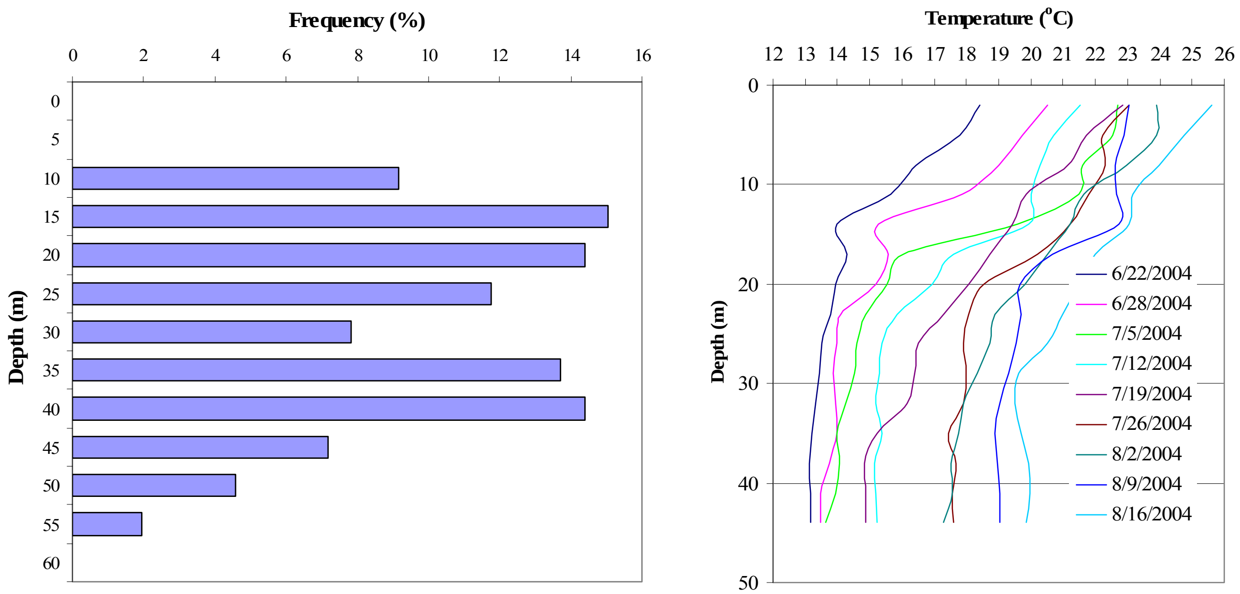

Figure C.4. Fish Depth Distribution (left) and Water Temperature Profiles (right) at Third Powerplant Forebay in 2004 (n = 153). Surveys conducted on Monday nights of each week from approximately 2200 to 2300 hours.

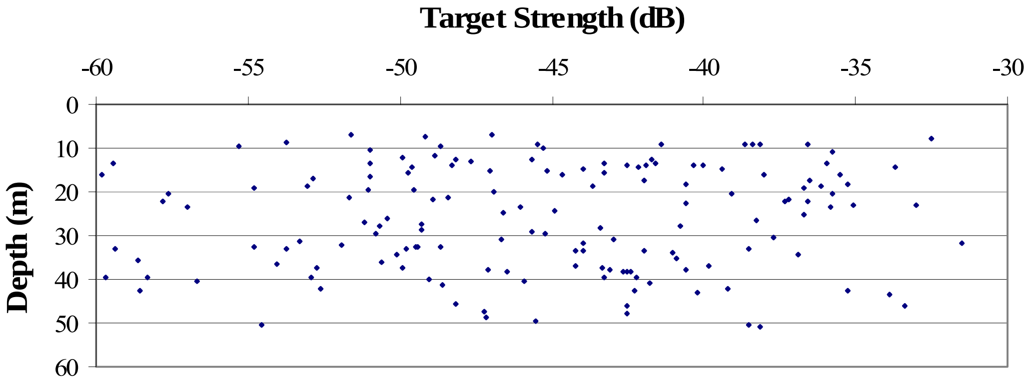

Figure C.5. Fish Target Strength Distribution Relative to Depth at Third Powerplant Forebay in 2004 (n = 153). Surveys conducted on Monday nights of each week from approximately 2200 to 2300 hours.

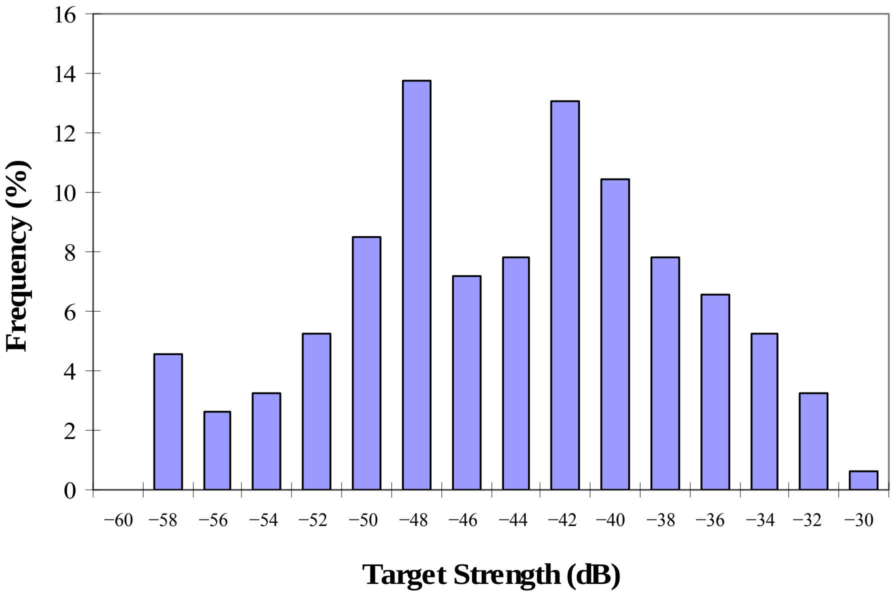

Figure C.6. Acoustic Size Distribution (Target Strength) of Fish in Third Powerplant Forebay in 2004 (n = 153)

C.2.2 Pumping Powerplant Forebay

Fish Distributions

Using a mobile 3D acoustic telemetry system in 2001 and 2002, the U.S. Geological Survey found kokanee and rainbow trout that had been tagged on the opposite east bank of the reservoir (Perry et al. 2003).

In 2003, we conducted a preliminary survey of the pumping plant forebay to determine if fish were present in the immediate vicinity of the pumping plant and upstream toward the security boom. Fish were noted in the vicinity of the pumping plant in 2003. In 2004, we expanded on that initial work to better document the location of fish targets relative to the pumping plant. Earlier plans to conduct fixed location hydroacoustic sampling were replaced with mobile surveys to better understand the extent of the fish distribution from the dam to the security boom for comparison with the right bank side of the dam. During the 2004 surveys, we detected 571 verifiable fish targets during surveys conducted from July 6 through August 17, 2004. This represented about 3.5 times as many fish detections than the third powerplant forebay in a smaller area with two fewer surveys. Fish were distributed widely throughout the sampled region from the upstream security boom to the corner of the dam where the pumping plant is located (Figure C.7). The highest concentrations occurred directly in front of the pumping plant and in the corner where the pumping plant and main dam meet. Fish locations that appear to be outside the security boom at the south end of the survey area were inside the boom when the wind moved the boom southward.

During the survey period from July 6 through August 17, 2004, the pumping plant was idle from 2200 to 2300 hours each day. Pumping operations typically were undertaken during the weekends to

Figure C.7. Location of Fish Detected at the Pumping Plant (left bank) at Grand Coulee Dam (July 6, 2004, through August 17, 2004)

optimize power consumption rates based on demand. However, on July 27, 2004, 4 of the 12 pumps were turned on for an unknown reason. During that period when the pumps were operating, we noted that higher background noise was detected by our 200-kHz echo sounder. We may have lost smaller fish targets to the background noise on that night. This experience suggests that if continuous monitoring is undertaken on the pumping plant, it would be advisable to select an alternative operating frequency for the hydroacoustic component to avoid the background noise (presumably 420 kHz would work, as it is used routinely on other hydropower dams).

The fish depth distribution at the pumping plant was unimodal, with peak detections around 20 m depth (Figure C.8). The mean depth of fish detections was 21 m with a standard deviation of 12.5 m. The depth distribution is likely a result of the concentration of fish in the corner of the pumping plant and the left powerplant, as those fish often were observed relatively high in the water column. Figure C.9 shows the depth/target strength distribution at the pumping plant. Unlike the third powerplant forebay data, there appears to be a concentration of fish with target strengths ranging from −45 to −35 dB at 10 to 20 m depth. The pump intakes are approximately 30 m deep, so these fish would largely be above the intakes and able to avoid entrainment. It might be expected that in low-water years when the forebay is drawn down, these fish might be more susceptible to entrainment during the pumping operations.

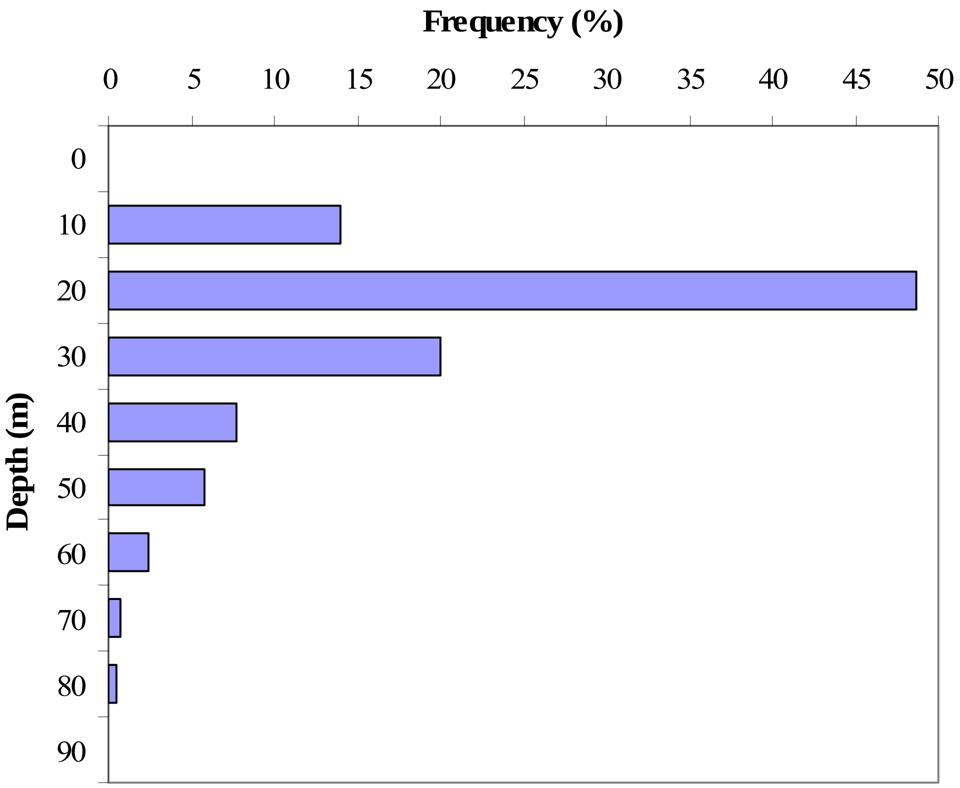

Figure C.8. Fish Depth Distribution at Grand Coulee Dam Pumping Plant Forebay in 2004 (n = 571). Surveys conducted during Tuesday nights of each week.

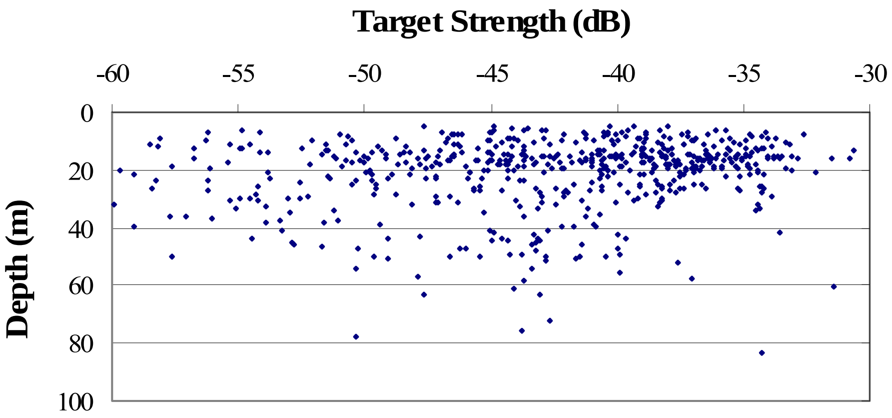

Figure C.9. Fish Target Strength Distribution Relative to Depth at Grand Coulee Dam Pumping Plant Forebay in 2004 (n = 571). Surveys conducted on Tuesday nights of each week from approximately 2200 to 2300 hours.

Target Strength Measurements

Target strength measurements using the splitbeam approach varied widely throughout the pumping plant forebay during the season (Figure C.10). The target strength distribution was unimodal but skewed toward larger fish targets, with the peak at −38 dB. The mean target strength was −42.6 dB with a standard deviation of 6.3 dB. This falls within the range of kokanee-sized fish but also may be inclusive of other species such as bass, which often associate with such structures. During daytime tests to measure pressures and accelerations through the pumping system, bass were noted on the release video at the depth of the intake with the pump in operation.

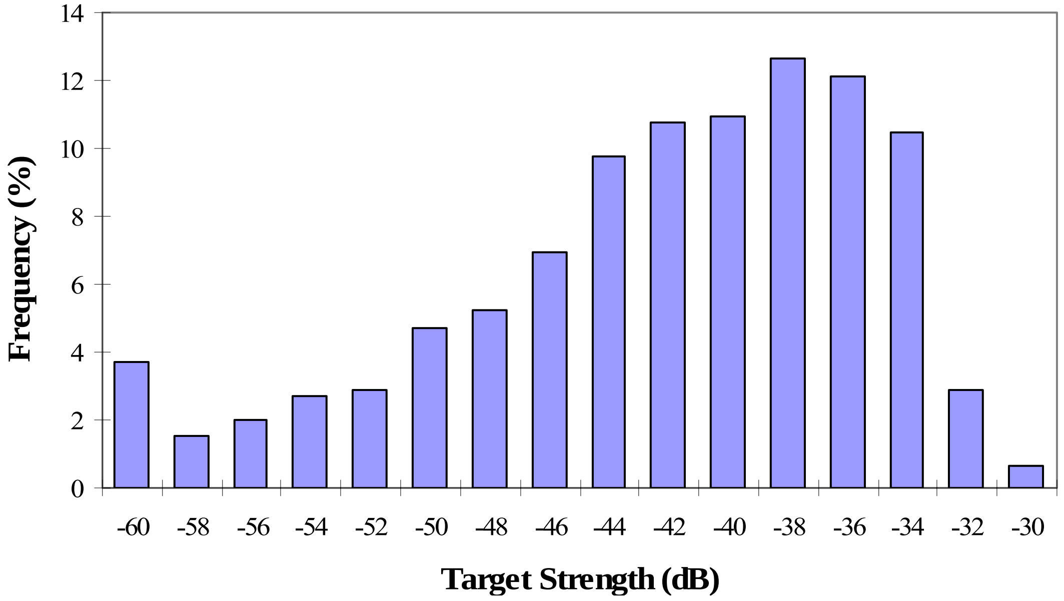

Figure C.10. Acoustic Size Distribution (Target Strength) of Fish at the Pumping Plant Forebay of Grand Coulee Dam in 2004 (n = 571)

C.3 References

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Appendix D

Statistical Synopsis

Appendix D

Statistical Synopsis

Craig A. McKinstry

D.1 Track Count Analysis

Log-linear models were fit to contingency tables on replicate block, transducer position, and light treatment factor variables (Table D.1). A design matrix was constructed for each polytomous factor variable using the reference cell coding method detailed in Hosmer and Lemeshow (1989). Using this method, one level of a polytomous factor variable is coded as the reference level, and coefficients for the other levels are estimated as log odds ratios from the reference level.

Table D.1. Factor Variable Definitions

Factor Variable	Code	Class Level	Description
Treatment			The strobe light treatment variable of interest.
	0	0 lights	Strobe lights off. This is the treatment control or reference condition.
	1	6 lights	3 or 6 strobe lights on.
Position			The position of five down-looking transducers located upstream from the strobe lights.
	1	8.6 m	Fish tracks located by the splitbeam transducer 8.6 m from the strobe lights.
	2	10.6 m	Fish tracks located by the splitbeam transducer 10.6 m from the strobe lights.
	3	16.4 m	Fish tracks located by the splitbeam transducer 16.4 m from the strobe lights.
	4	20.6 m	Fish tracks located by the splitbeam transducer 20.6 m from the strobe lights.
	5	24.4 m	Fish tracks located by the splitbeam transducer 24.4 m from the strobe lights. Note: Because this transducer was located farthest from the lights, any light effects on the fish detected by this transducer would be at a minimum. Therefore, this position is used as the control or reference for the other positions.
Block	1-18	Values 1 to 18	Randomized block composed of 3 days each with the treatments randomly ordered.
Time of Day			The times of the day as defined by sunrise and sunset.
	1	Sunrise	From an hour before to an hour after sunrise.
	2	Day	From an hour after sunrise to an hour before sunset.
	3	Sunset	From an hour before to an hour after sunset.
	4	Night	From an hour after sunset to an hour before sunrise.

The fish track data were partitioned into three distinct sets (one for each level of strobe light treatment), and log-linear models were fit separately to each of these. The model used two factor variables: pseudo-replicate block and transducer position. Comparing treatments in this fashion placed the focus on how tracks redistribute with distance from the lights in response to the light treatments, while the randomized blocking factor incorporated the replication and randomization from the experimental design into the analysis.

The three models, one for each of the three strobe light treatments, were then summarized graphically by plotting their estimated odds ratios and approximate 95% confidence intervals on the same graph. An additional factor for diel period (Table D.1) was subsequently incorporated into the analysis by further partitioning the data and summarized graphically.

The essential model used in each analysis is shown in Equation (D.1). For strobe light treatment *i*,

$$\ln(\mathbf{Y}_i) = \alpha_i + \boldsymbol{\beta}_{i1}\mathbf{X}_{i1} + \boldsymbol{\beta}_{i2}\mathbf{X}_{i2} + \boldsymbol{\varepsilon}_i \tag{D.1}$$

where $\mathbf{Y}_i$ is the vector of track counts

α_i is a constant term or intercept in the model

$\boldsymbol{\beta}_{i1}$ and $\mathbf{X}_{i1}$ are the vector of fitted coefficients and design matrix for the replicate block factor, respectively

$\boldsymbol{\beta}_{i2}$ and $\mathbf{X}_{i2}$ are the vector of fitted coefficients and design matrix for the transducer distance factor, respectively

$\boldsymbol{\varepsilon}_i$ is the vector of residual Poisson errors

The model was fit using maximum-likelihood estimation and coefficients determined with Wald confidence intervals assuming asymptotic normality (these turned out to be virtually indistinguishable from confidence intervals based on profile likelihoods). With sufficient sample size, exponentiation of these estimates and confidence interval limits as shown in Equation (D.2) give the corresponding odds ratios and 100(1 - α)% confidence intervals (Hosmer and Lemeshow 1989; Agresti 1990).

$$\exp[\hat{\beta}_{2i} \pm z_{1-\alpha/2}\sigma_{\hat{\beta}_{2i}}] \tag{D.2}$$

D.2 Direction of Movement

Straight-line trajectories in the horizontal plain from the initial to the final position in each track were converted from Cartesian (X,Y) to polar (r,θ) coordinates and statistically analyzed as circular data on the angles (θ). Analysis of angles describing the overall direction of movement has been extensively covered in the literature (Lockhart and Stephens 1985; Fisher 1995; Jammalamadaka and SenGupta 2001) and has been used to assess the directional movements of animals (Underwood and Chapman 1985; Fisher 1995).

An appropriate and commonly used probability model for circular data is the von Mises, with probability density function (pdf) $f(\theta)$ on periodic support with period 2π:

$$f(\theta) = f(\theta + 2\pi).$$

The von Mises pdf is shown in

$$f(\theta | \mu, \kappa) = [2\pi I_0(\kappa)]^{-1} \exp[\kappa \cos(\theta - \mu)]; 0 \le \theta \le 2\pi; 0 \le \kappa < \infty \qquad \text{(D.3)}$$

where

$$I_p(\kappa) = \sum_{r=0}^{\infty} \frac{\left(\kappa/2\right)^{2r+p}}{r!\Gamma\left(p+r+1\right)} \qquad \text{(D.4)}$$

Equation (D.4) is the modified Bessel function of the first kind of order p (Jammalamadaka and SenGupta 2001, p. 288). The von Mises pdf takes two parameters (μ, κ), which are estimated from the angular data by the method of trigonometric sample moments.

Let $S = \sum_{i=1}^{n} \sin(\theta_i)$, $C = \sum_{i=}^{n} \cos(\theta_i)$, $R^2 = C^2 + S^2$ $(R \ge 0)$, and $\bar{R} = R/n$.

The estimated mean direction angle ($\hat{\mu}$) is computed as

$$\hat{\mu} = \tan^{-1}(S/C) \qquad \text{if S>0, C>0} \qquad \text{(D.5)}$$

$$= \tan^{-1}(S/C) + \pi \qquad \text{if C<0}$$

$$= \tan^{-1}(S/C) + 2\pi \qquad \text{if S<0, C>0}$$

The maximum likelihood estimate for the concentration parameter ($\hat{\kappa}$) is computed by finding the value for $\hat{\kappa}$ that minimizes ε

$$\min_{\kappa} \left| I_1(\kappa)/I_0(\kappa) - \bar{R} \right| = \varepsilon \ge 0 \qquad \text{(D.6)}$$

The expressions $I_1(\kappa)$ and $I_0(\kappa)$ in Equation (D.6) are modified Bessel functions of order 1 and 0, respectively, given in Equation (D.4). The concentration parameter (κ) of the von Mises distribution on a circular probability scale is analogous to the precision (σ^{-1}) on a linear scale in that both give a quantitative measure of the dispersion in the data. Larger estimated values of κ indicate a more orderly or concentrated data distribution with a more defined dominant direction of movement. However, unlike data on a linear scale, circular data can be recentered about the mean parameter (μ) but cannot be rescaled.

Multimodal distributions of angles may be modeled as a mixture of von Mises distributions. In particular, the parameters for a bimodal mixture of two von Mises (VM) distributions (Equation [D.7]), $VM(\mu_1, \kappa_1)$ and $VM(\mu_2, \kappa_2)$, and unknown mixture proportion p may be estimated from angular data by simultaneous solution of six equations in five unknown parameters as follows (Fisher 1995, p. 97).

$$\begin{aligned} f(\theta | \mu_1, \kappa_1, \mu_2, \kappa_2, p) = [2\pi I_0(\kappa_1)]^{-1} p \exp[\kappa_1 \cos(\theta - \mu_1)] + \\ [2\pi I_0(\kappa_2)]^{-1} (1-p) \exp[\kappa_2 \cos(\theta - \mu_2)] \end{aligned} \tag{D.7}$$

First, compute the first three trigonometric sample moments as

$$\overline{C}_r = \sum_{i=1}^{n} \cos(r\theta_i)/n \text{ and } \overline{S}_r = \sum_{i=1}^{n} \sin(r\theta_i)/n, \; r \in \{1,2,3\}.$$

Next, let $A_r(\kappa) = I_r(\kappa)/I_0(\kappa)$;

The six equations are given in

$$\begin{aligned} pA_1(\kappa_1)\cos(\mu_1) + (1-p)A_1(\kappa_2)\cos(\mu_2) = \overline{C}_1 \\ pA_2(\kappa_1)\cos(2\mu_1) + (1-p)A_2(\kappa_2)\cos(2\mu_2) = \overline{C}_2 \\ pA_3(\kappa_1)\cos(3\mu_1) + (1-p)A_3(\kappa_2)\cos(3\mu_2) = \overline{C}_3 \\ pA_1(\kappa_1)\sin(\mu_1) + (1-p)A_1(\kappa_2)\sin(\mu_2) = \overline{S}_1 \\ pA_2(\kappa_1)\sin(2\mu_1) + (1-p)A_2(\kappa_2)\sin(2\mu_2) = \overline{S}_2 \\ pA_3(\kappa_1)\sin(3\mu_1) + (1-p)A_3(\kappa_2)\sin(3\mu_2) = \overline{S}_3 \end{aligned} \tag{D.8}$$

Simultaneous solution to this system of equations in the five unknown parameters gives the method of moments estimates for the four von Mises parameters and the mixture parameter p by iterative minimization of the sum of squares criterion (Equation [D.9]):

$$r^2(\Delta C_1, \Delta C_2, \Delta C_3, \Delta S_1, \Delta S_2, \Delta S_3) = \Delta C_1^{\;2} + \Delta C_2^{\;2} + \Delta C_3^{\;2} + \Delta S_1^{\;2} + \Delta S_2^{\;2} + \Delta S_3^{\;2} \tag{D.9}$$

where each ΔC_i and ΔS_i are expressed, for example, as

$$\Delta C_1 = pA_1(\kappa_1)\cos(\mu_1) + (1-p)A_1(\kappa_2)\cos(\mu_2) - \overline{C}_1$$

This algorithm may be generalized to mixtures involving more than two von Mises distributions. However, only mixtures of at most two von Mises distributions were considered in this analysis.

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Appendix E

Acoustic Tag Tracking

Appendix E

Acoustic Tag Tracking

Richard S. Brown, Ian D. Welch, Abigail E. Capetillo

The kokanee (*Oncorhynchus nerka*) fishery in Lake Roosevelt is important for its cultural and sport fishing value. For years, the native fishery has been enhanced by stocking of juvenile kokanee. However, it appears that many of these fish, stocked and native, are being entrained past Grand Coulee Dam and lost to the fishery (LeCaire 1999; Sullivan 2000). It was proposed that strobe lights placed across the entrance to the third powerplant forebay of the dam might reduce entrainment. In 2001, a study was initiated to determine if kokanee would exhibit a negative rheotaxic response to strobe lights (see Section 1 of this report). Part of this study involved tracking juvenile kokanee that had been implanted with ultrasonic transmitters. These transmitters made it possible to track the fish as they approached the dam, were exposed to the strobe lights, and were entrained. The transmitters also enabled the tracking of fish at the pumping station, which provides an indication of the number of fish entrained into Banks Lake. Unfortunately, in previous studies, very few fish were found near the strobe light array. In 2004, fish were released 20 and 40 m in front of the lights at night.

This task had two objectives. The first was to study the behavior of fish within 20 to 40 m of the strobe lights. Behavioral aspects that were analyzed included the amount of time spent by the fish in front of the lights, fish swimming velocity, and the distribution of fish with respect to the lights. The second objective was to determine the number of fish entrained through the pumping station into Banks Lake. This appendix describes the details of the acoustic tag tracking task of the overall study.

E.1 Methods

E.1.1 Fish Tagging and Releases

Juvenile kokanee were acquired from the Colville Tribal hatchery program sited on Lake Rufus Woods. In late May 2004, a net pen filled with juvenile kokanee was transported from its winter location at the Old Lincoln Sawmill site, approximately 64 km (40 mi) upstream of the dam, downstream to the forebay of the dam.

Between June 8 and 12, 2004, 181 fish were surgically implanted with an ultrasonic transmitter (Model 795m, Hydroacoustic Technology Inc., Seattle, Washington). The transmitters weighed 0.75 g and were 6.8 mm in diameter and 16.5 mm in length. Ultrasonic transmitters emitted a pulse every 0.7 to 1.5 seconds with a frequency-modulated pulse duration of 2 ms. With these parameters, it was expected that a tag's battery life would be 10 to 12 days.

Each fish was anaesthetized with tricaine methanesulfonate (MS-222, 70 mg L^{-1}). Fork lengths (to the nearest millimeter) and weights (in grams) were measured while fish were immobile. After a fish was anaesthetized, it was placed ventral side up in a groove within a piece of wet foam rubber saturated with a solution of PolyAqua® (Kordon Quality Aquarium Products). A small tube inserted in the fish's mouth during surgery provided a continuous solution of 20 mg L^{-1} MS-222. A 5- to 10-mm incision was made 3 mm from the midventral line, anterior to either of the pelvic fins. Incisions were closed with two or three simple, interrupted sutures (Ethicon absorbable 5-0 coated vicryl violet braided). After surgery, fish were held in aerated coolers while they recovered.

For the fish to be released directly in front of the light array at a depth of 15 m, they needed to first be acclimated to that depth. After their implantation and recovery in coolers for a short period, fish were placed in cages and suspended 15 m below the water surface. Up to 10 implanted fish were placed in each cage. They were held in these cages for at least 24 hours before being released into the forebay.

Each release cage was constructed from a rectangular (61 cm by 56 cm by 76 cm) metal wire dog crate. A net (0.635-cm mesh) was sewn into the inside of the cage. The door of the cage also was covered with netting. The cage was suspended from ropes attached to its four upper corners. The door of the cage faced downward. Cotter pins held the kennel door closed, and a thin rope was tied to the pins. The rope extended to the surface and was pulled to allow the door to open. The lower four corners of the cage were attached by rope to a weight suspended approximately 1 m below the cage. The 1-m clearance allowed the door to swing open. The weight held the cage at 15 m when suspended from a buoy or a barge.

As fish are lowered from the surface to 15 m in depth, the air in their air bladders will compress and the fish then would be negatively buoyant. It is not known whether juvenile kokanee, which naturally occur at 15 m depth in the forebay of the dam, are negatively or neutrally buoyant. Because salmonids are physostomes, they cannot increase the amount of air in their swim bladders and, thus, their buoyancy without gulping air (Tait 1959; Harvey et al. 1968; Fried et al. 1976). For this reason, we built a plastic container into the top of each holding cage and filled it with air. This bubble of air enabled the fish to gulp air and attain neutral buoyancy while being held at 15 m depth. Each holding cage had an air hose that led from the surface to the plastic container in the cage. After cages were dropped to 15 m in depth, air was pumped down into the container. After fish were released, bubbles rose to the surface, indicating that this air remained in the container during acclimation.

During a trial run, a camera was attached to the top of one of the cages to see if the fish were able to achieve neutral buoyancy. The camera showed fish slowly swimming throughout the cage. No fish were seen lying on the cage bottom or swimming excessively, all indications of negative buoyancy (Gallepp and Magnuson 1972).

To release fish, the rope from the cage was tied to a boat and the cage was slowly dragged through the water while maintaining its depth. The suspended cage was brought into position at either 20 m or 40 m directly upstream of the light array. The thin rope attached to the cotter pins was pulled up to remove the two pins holding the door in place. The pins could be felt popping free, indicating the door was open and the fish could escape. This was noted as the release time. The cage was slowly pulled to the surface and it was noted if any fish were still in the cage or seen near the surface.

For half of the releases (randomly ordered), the strobe lights were switched on immediately at the time of release and left on until the fish from that release had cleared the area near the lights (usually within 1 to 2 hours).

Problems arose in 9 of the 20 releases. Most of the problems occurred due to entanglement of the lines leading to the cages. During these problem releases, the cages had to be raised until untangled or, in some cases, they were pulled all the way to the surface to fix the problem. After the problem was corrected, the cage was lowered again and fish were released. Data from these releases were excluded from analysis when we examined the influence of strobe lights on fish.

Ninety-eight fish were successfully released at a depth of 15 m and a distance of 20 or 40 m upstream of the strobe light array (Figure E.1). All fish were released at night between 22:36 and 03:24.

E.1.2 Acoustic Telemetry Systems

All equipment associated with the tagging—the tags, hydrophones, receivers, and processing software—were manufactured by Hydroacoustic Technology, Inc. (HTI) (Seattle, Washington). Signals from fish were detected on a three-dimensional acoustic telemetry hydrophone array (Model 290) while they were near and within the third forebay of the dam. This array consisted of nine hydrophones (Figure E.1), four of which were stationed on the bottom of the forebay. Another four were attached to the side of the dam or the rock wall on the east bank of the third powerplant forebay. One hydrophone was attached to a barge in the forebay. Signals were received and logged with the Model 290 acoustic tag receiver. The location of all hydrophones was determined through standard surveying techniques using a robotic total station manufactured by Trimble Corporation (Sunnyvale, California).

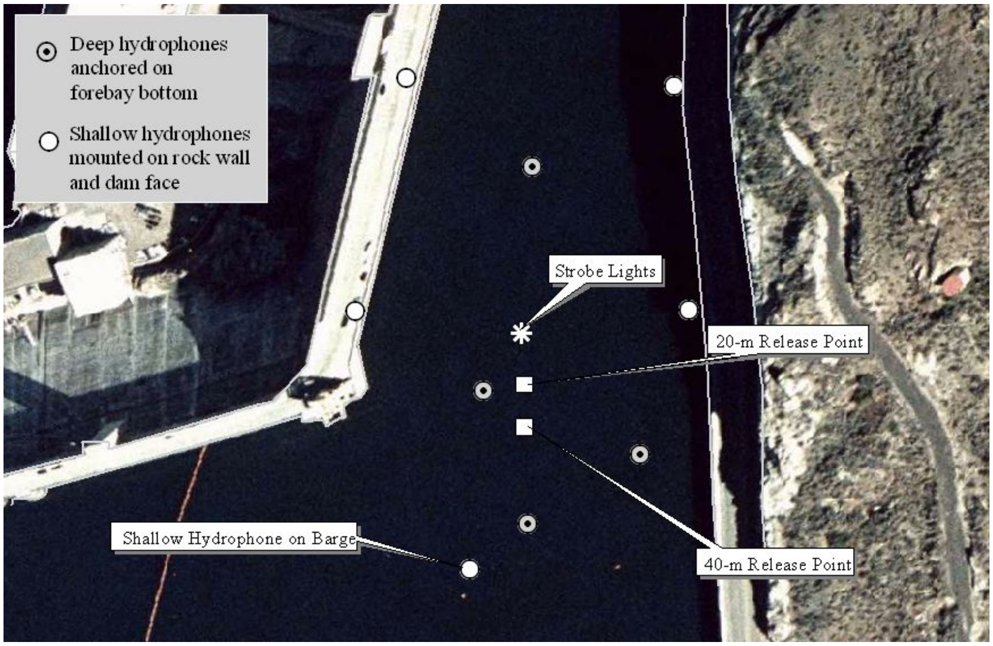

Figure E.1. Locations of the 20- and 40-m Fish Releases, Hydrophone Array, and Strobe Light Array near the Third Powerplant Forebay, June 2004

Signals from fish were received also by two separate receiving arrays not configured for three-dimensional positioning. One was located near the pumping station on Grand Coulee Dam, and the second was located in the canal leading into Banks Lake. The array near the pumping station (Figure 2.2) was deployed approximately 2 m below the surface, off a barge. This array consisted of two hydrophones (Model 594) facing away and toward the pumping station. The array in the canal consisted of one hydrophone (Model 594) placed at the bottom of the canal. Signals were received and logged with a Model 291-4 acoustic tag receiver.

The speed of sound is an important input into the fish-tracking software because the time of arrival is used to solve for a tag's position relative to the position of the hydrophones receiving the tag signals. The speed of sound was estimated using the equations developed by Del Grosso and Mader (1972) for use in fresh water; these equations require data on water temperature. We used the average water column temperature because the water temperature in the Grand Coulee forebay can vary from the surface to the reservoir bottom. Temperature data (Table E.1) were collected every 3 m using individual Onset Optic StowAway® temperature loggers (Onset Computer Corporation, Pocasset, Massachusetts).

Table E.1. Water Temperature (˚C) at Different Depths Within Third Powerplant Forebay, June 2004

Depth (m)	Mean	SD	Range	
			Minimum	Maximum
2.7	15.0	0.2	13.6	15.5
5.2	14.9	0.2	13.5	15.6
8.2	14.7	0.3	12.8	15.3
11.2	14.4	0.5	12.7	15.4
14.2	14.1	0.6	12.6	15.3
17.2	13.7	0.6	12.4	15.2
20.2	13.3	0.6	12.4	15.0
23.3	13.1	0.5	12.3	14.9
26.2	12.9	0.4	12.3	14.3
29.2	12.8	0.4	12.2	14.2
32.2	12.6	0.4	11.9	14.1
35.2	12.5	0.3	11.8	14.0
38.2	12.4	0.2	11.6	14.1
41.2	12.3	0.2	11.8	13.0
44.2	12.1	0.2	11.8	12.7

E.1.3 Data Processing

Acoustic tag receivers collected the incoming signals from the hydrophones and stored the data in hourly files. Data were collected the entire time tagged fish were in the three-dimensional acoustic array in the forebay of the third powerplant. Every hour was tracked automatically using the HTI tagging software, Mark Tags. Upon completion of the auto tracking process, a database was created for each fish tag code. From this database, the software program, Acoustic Tag, estimated the transmitter location for each detected transmission. Sequences of individual location estimates formed a three-dimensional position track for each fish detected within the tracking baseline. This allowed the behavior of fish to be tracked when they were released, as they approached the strobe light array and to examine the location and timing of their exit from the forebay.

Data collected from the pumping station and canal were manually tracked using the Mark Tags tagging software. Fish tag codes and times were recorded in a database.

E.1.4 Data Analysis

Positioning errors were determined prior to and during the study using data collected from ultrasonic tags located at known positions. Both the geometric dilution of precision (GDOP) and the vertical dilution of precision (VDOP) were estimated from the data using the FishTrack3D software (Faber et al. 2002) (Figures E.2 and E.3). GDOP is a combination of the horizontal and vertical error inherent for positioning when using time-of-arrival estimates, and VDOP is the absolute vertical error. These two metrics provide an estimate of the accuracy of fish positions.

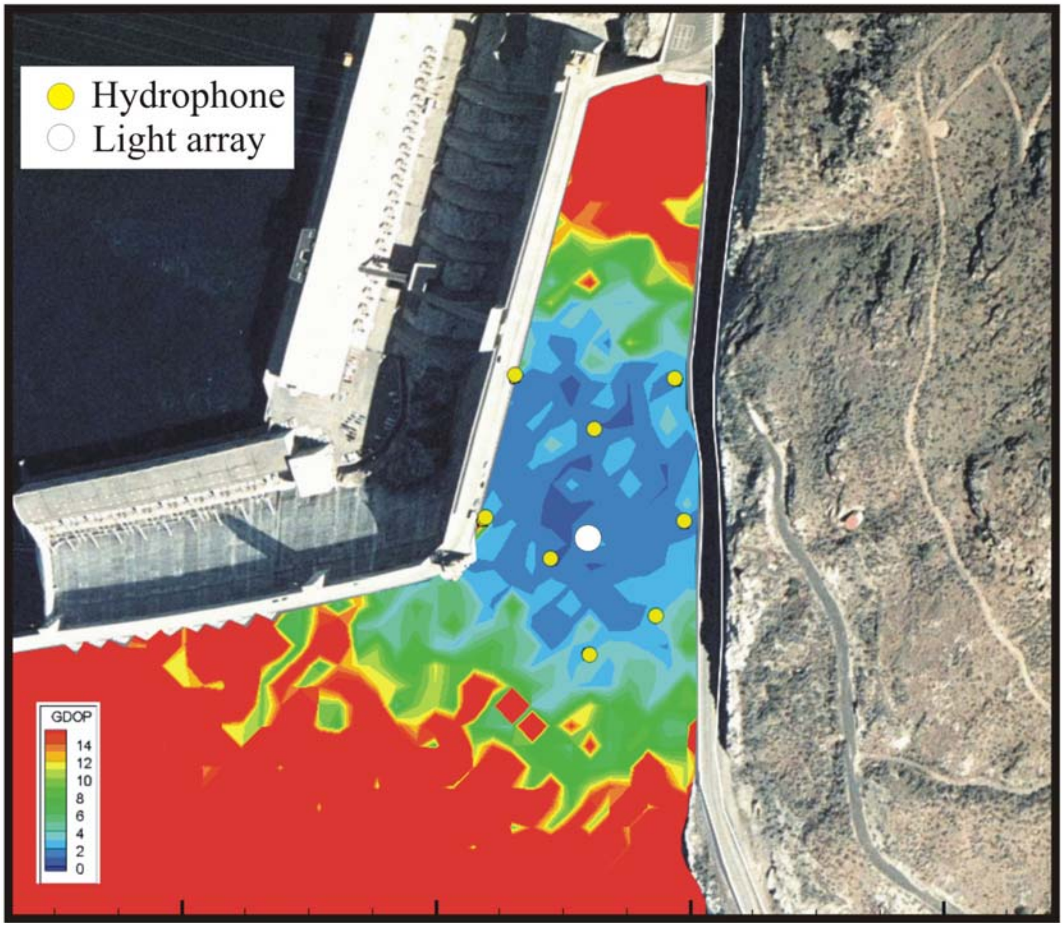

Figure E.2. Geometric Dilution of Precision (GDOP in meters) for the Area Within and Upstream of the Third Powerplant Forebay, 2004. The GDOP contour shown is the absolute error in meters from FishTrack3D at a depth of 15 m.

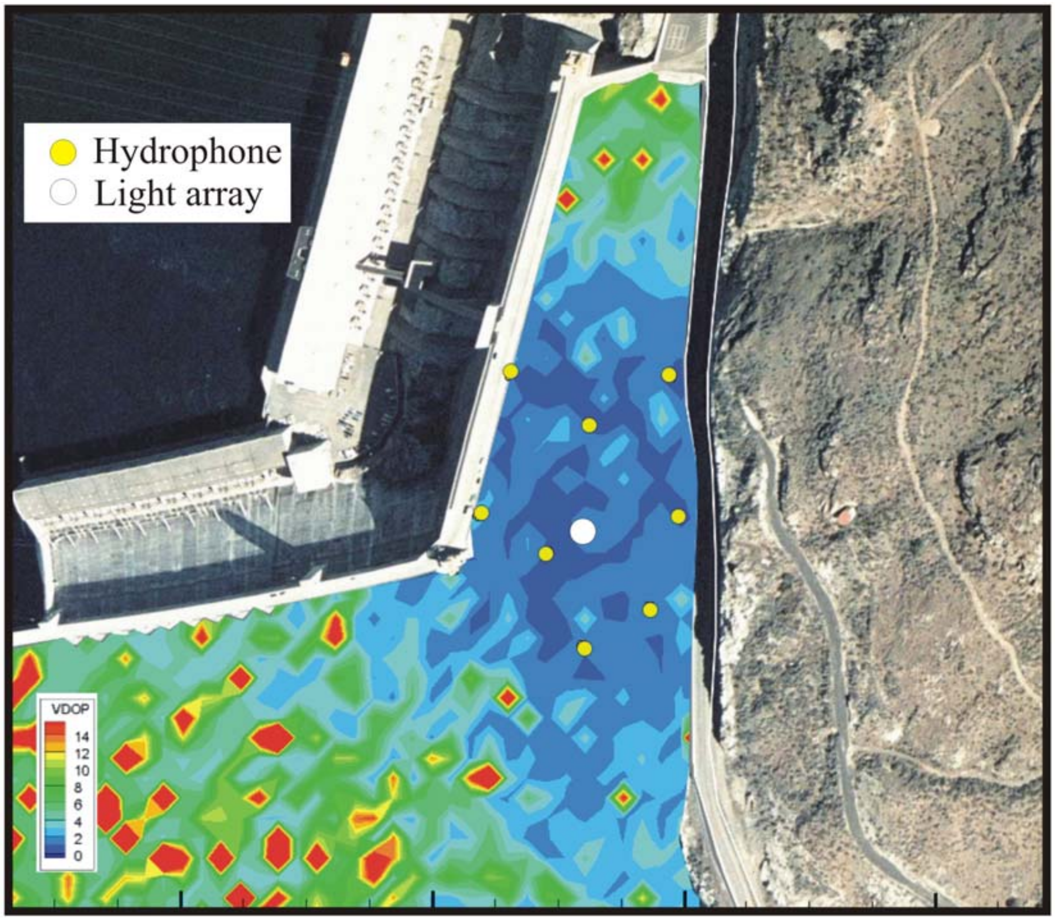

Figure E.3. Vertical Dilution of Precision (VDOP in meters) for the Area Within and Upstream of the Third Powerplant Forebay, 2004. The VDOP contour shown is the absolute error in meters from FishTrack3D at a depth of 15 m.

Two acoustic transmitters were used to test the accuracy of the reception array. One transmitter was positioned in the center of the array, on the barge deploying the strobe lights (Figure E.1), while the other was situated along the east bank of the forebay. The tag attached to the barge had a standard deviation of 0.13 m in the horizontal plane and 0.77 m in depth. The tag placed near the edge of the forebay (and therefore the edge of the array) had a standard deviation of 0.58 m in the horizontal plane and 0.56 m in depth.

To determine if there were differences between release groups in the length of time fish spent in areas or in fish velocities, or between groups present when lights were on and off, data were checked for normality and homogeneity of variances. If data were normal and variances homogeneous, then data were analyzed using a *t*-test; otherwise, data were analyzed using a Mann-Whitney *U* test.

E.2 Results

The behavior of juvenile kokanee (N = 98) was examined to determine if strobe lights influenced their path of travel, trajectory, velocity, and residence time. Approximately half of the fish were released near the light array when the lights were on (47); the others were released when lights were off (51). Fish released when the lights were on had a mean fork length of 139 mm (standard deviation = 14.6, range 118 to 181 mm) and a mean weight of 32 g (standard deviation 12.5, range 18 to 70 g). The 51 fish released when lights were off had a mean fork length of 139.5 mm (standard deviation 11.7, range 125 to 173 mm) and a mean weight of 30.8 g (standard deviation 9.5, range 20 to 63 g). There was no significant difference ($p > 0.05$, *t*-test) between the fork length of fish released with the lights on or off.

As fish approached the strobe light array, there was little difference in their travel path across the forebay whether the lights were on or off (Figures E.4 and E.5). As fish approached the lights, they tended to move to the right of the lights (Figures E.6 and E.7), similar to the water velocities in this area (approximately 3 cm/s). However, when the lights were on, a small subset of fish tended to pass farther to the right of the lights than the main group of fish (Figures E.4 and E.6).

The fact that fish passed to the right side of the strobe light array is confirmed by the angular trajectory of the fish. The trajectory for fish (Figures E.8 and E.9) tended to be toward the right of the lights, at angles primarily between 290 degrees and 340 degrees. In most areas in front of the lights, there did not appear to be any significant differences in the trajectories when the strobe lights were on or when they were off. However, when fish were within 5 m of the strobe lights and the lights were on, the mean vector shifted so that fish were moving perpendicular to the lights (Figure E.8).

Fish were released 15 m below the surface, at the same depth as the strobe light array. Fish generally stayed at or above this depth as they moved toward the lights (Figures E.10 and E.11). However, when fish were within 5 m of the lights, they tended to increase their depth slightly, so the median depth was below the lights. With respect to the light treatment, there was little difference in the median elevation for fish released when the lights were off or on.

As fish approached the strobe lights, their mean velocity was generally between 0.3 and 0.6 m/s (Figure E.12). Velocity data from the fish released at 20 m and 40 m did not differ significantly ($p > 0.05$), so the data were grouped. Only at the distance farthest from the lights (i.e., 35 to 40 m) were fish velocities significantly different ($p < 0.05$) between lights-on and lights-off conditions. In this region, fish velocities were higher when the lights were off compared to when the lights were on. However, as fish approached closer to the light array, there were no significant differences ($p > 0.05$) in the velocities with respect to the light treatment.

The amount of time that fish spent in the vicinity of the lights also was analyzed (Figure E.13). The data from the groups released 20 m and 40 m from the lights could not be grouped because fish released 20 m from the lights spent significantly more time ($p < 0.05$) between 5 and 20 m from the lights, when the were lights off, than when they were released 40 m from the lights. Thus, data for the 20-m and 40-m releases were analyzed separately.

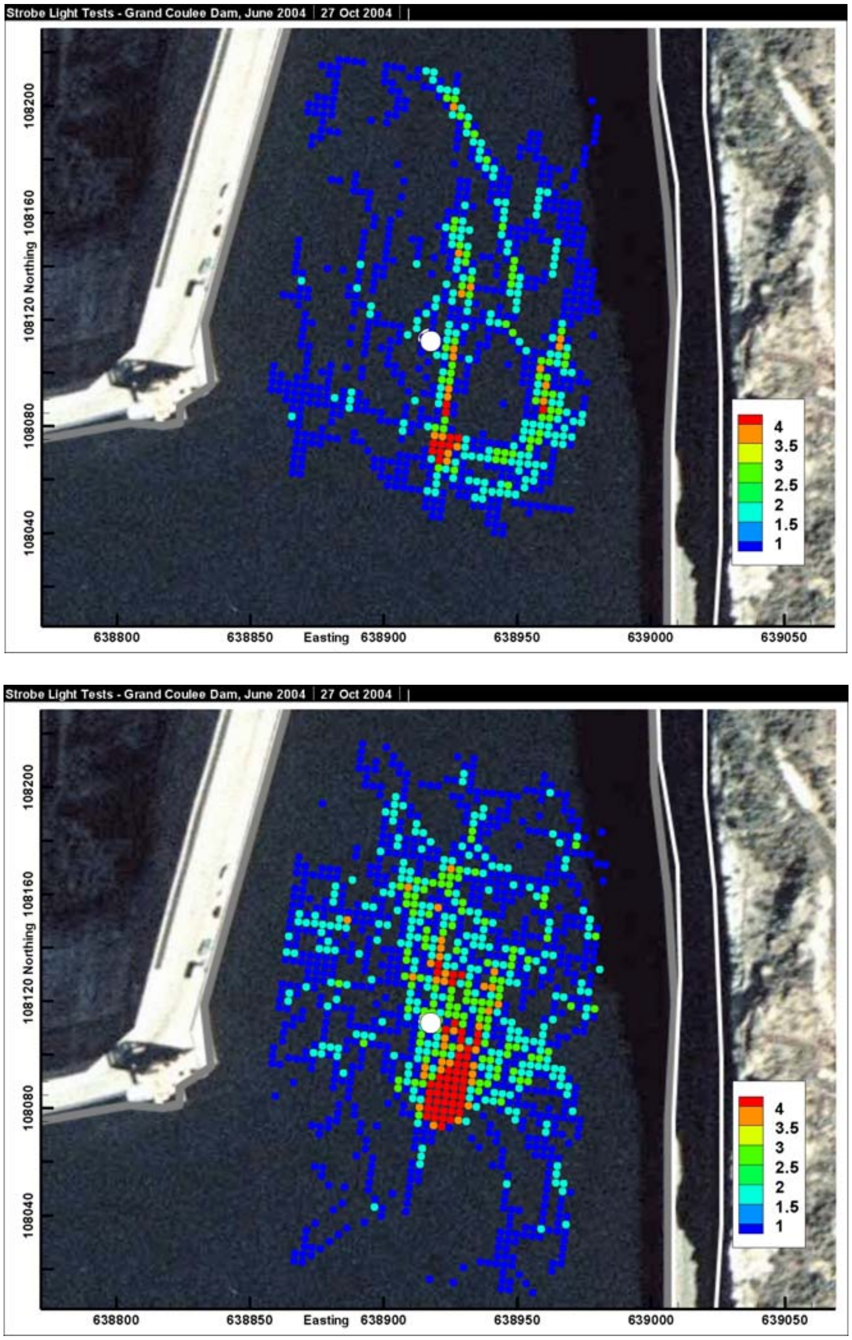

Figure E.4. Density of Juvenile Kokanee Within 3-m^2 Grids Released 40 m Upstream of Strobe Lights (white circle). Distribution shown for fish released when lights were on (top) and when lights were off (bottom).

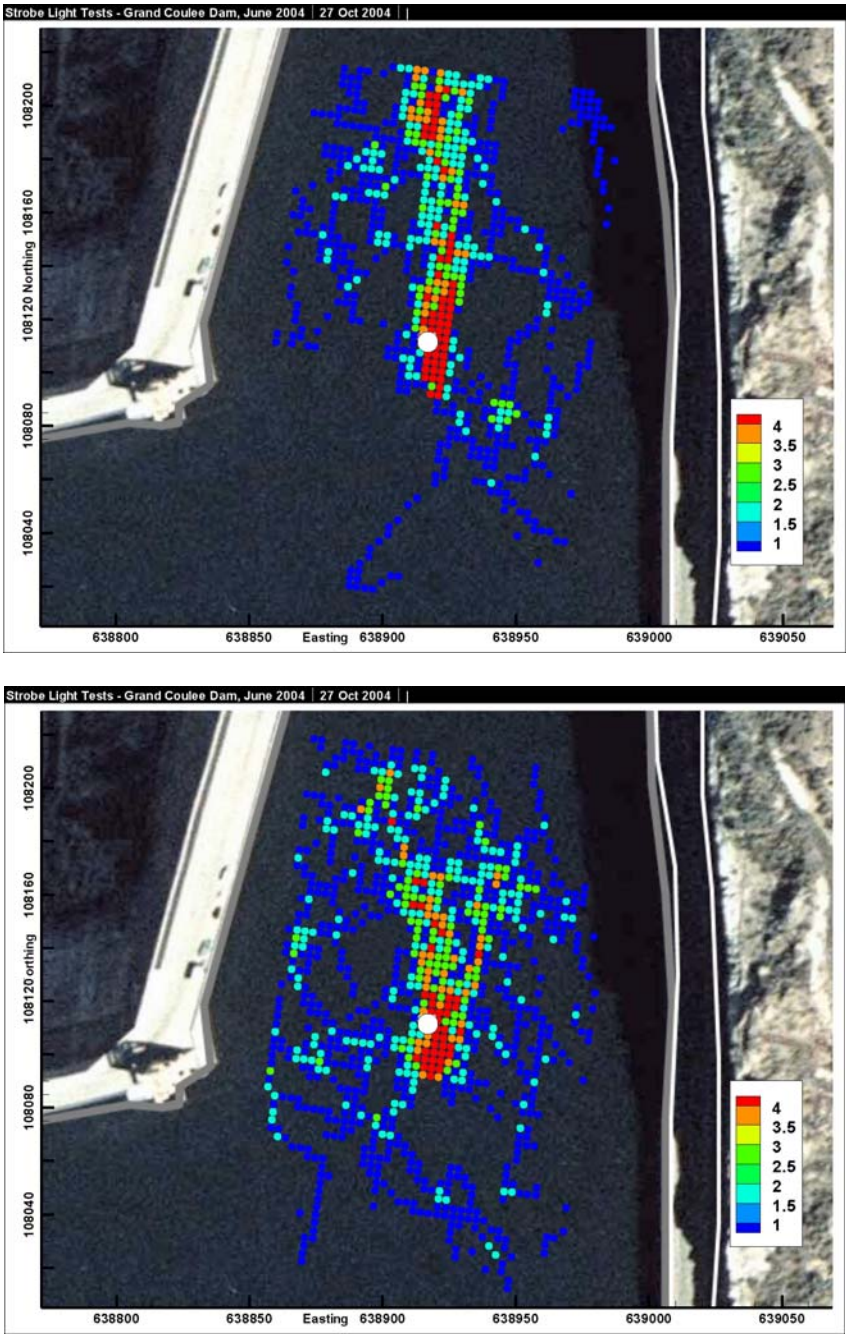

Figure E.5. Density of Juvenile Kokanee Within 3-m^2 Grids Released 20 m Upstream of Strobe Lights (white circle). Distribution shown for fish released when lights were on (top) and when lights were off (bottom).

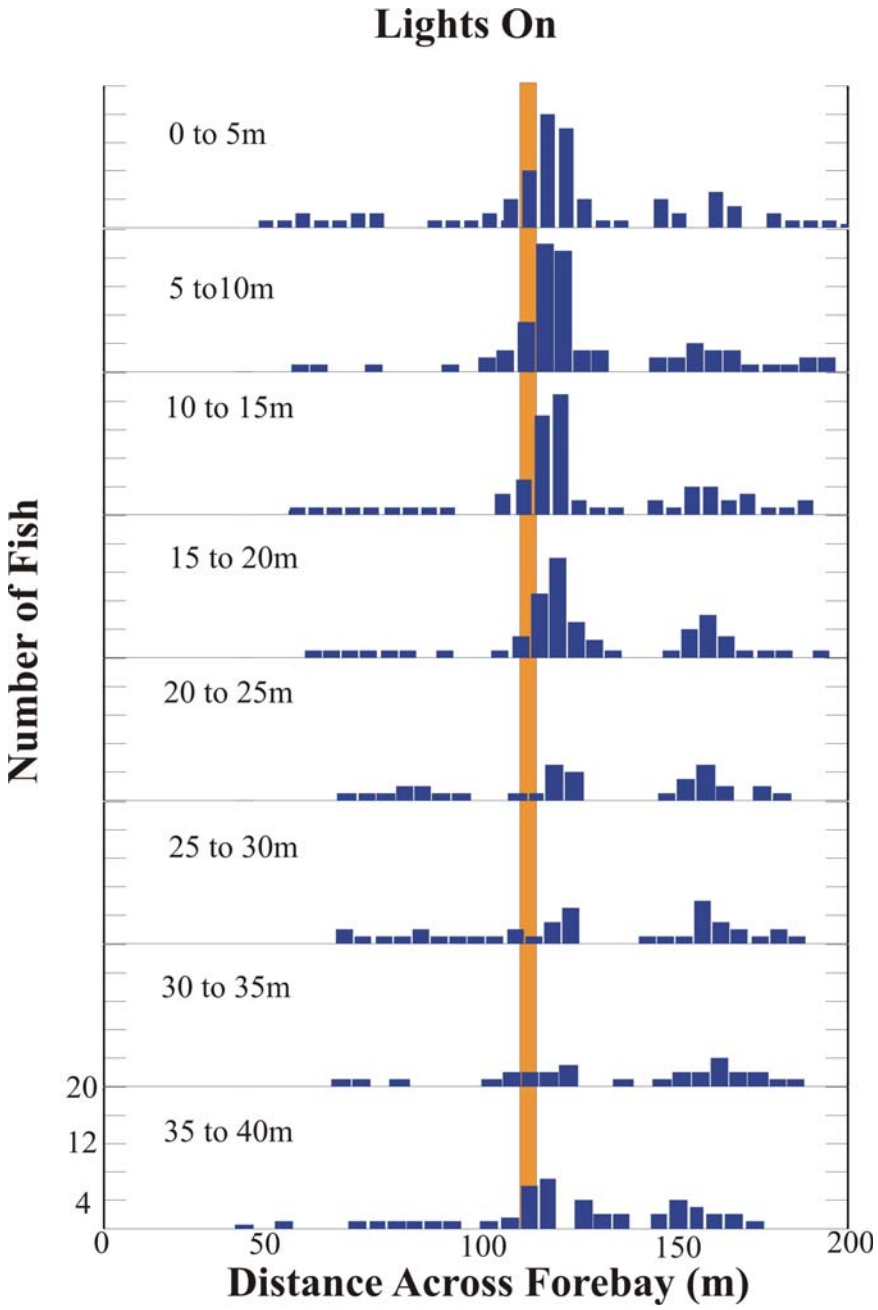

Figure E.6. Distribution of Juvenile Kokanee Across Third Powerplant Forebay and with Distance from Strobe Lights When Lights Were On. Data for both 20- and 40-m releases are grouped. Orange line represents strobe light location.

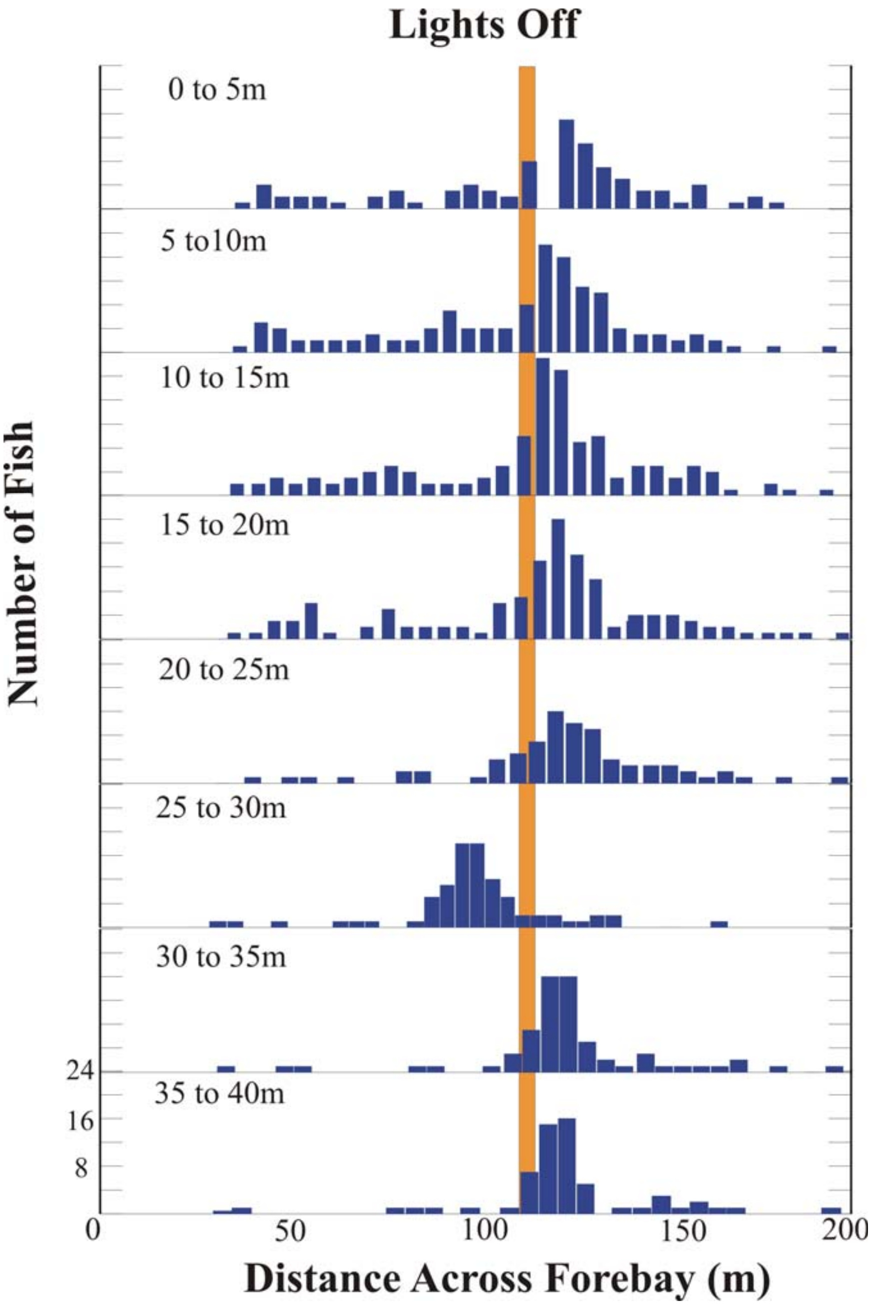

Figure E.7. Distribution of Juvenile Kokanee Across Third Powerplant Forebay and with Distance from Strobe Lights When Lights Were Off. Data for both 20- and 40-m releases are grouped. Orange line represents strobe light location.

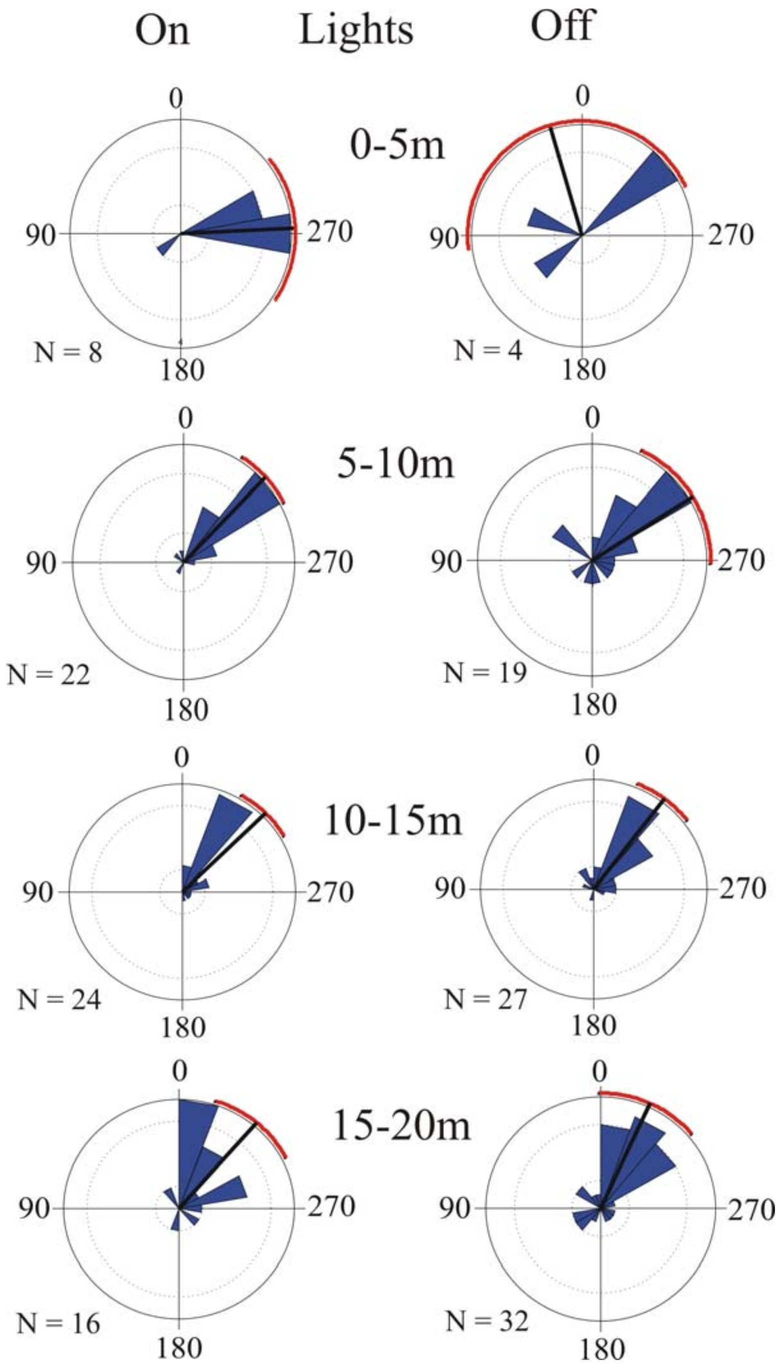

Figure E.8. Trajectory of Juvenile Kokanee Released 20 m Upstream of Strobe Lights with Distance from Strobe Lights. The mean trajectory is indicated by the heavy black line, while 95% confidence intervals are indicated by the red semicircle. Direction to strobe lights is at zero degrees, third powerplant is at 90 degrees, and east bank is at 270 degrees.

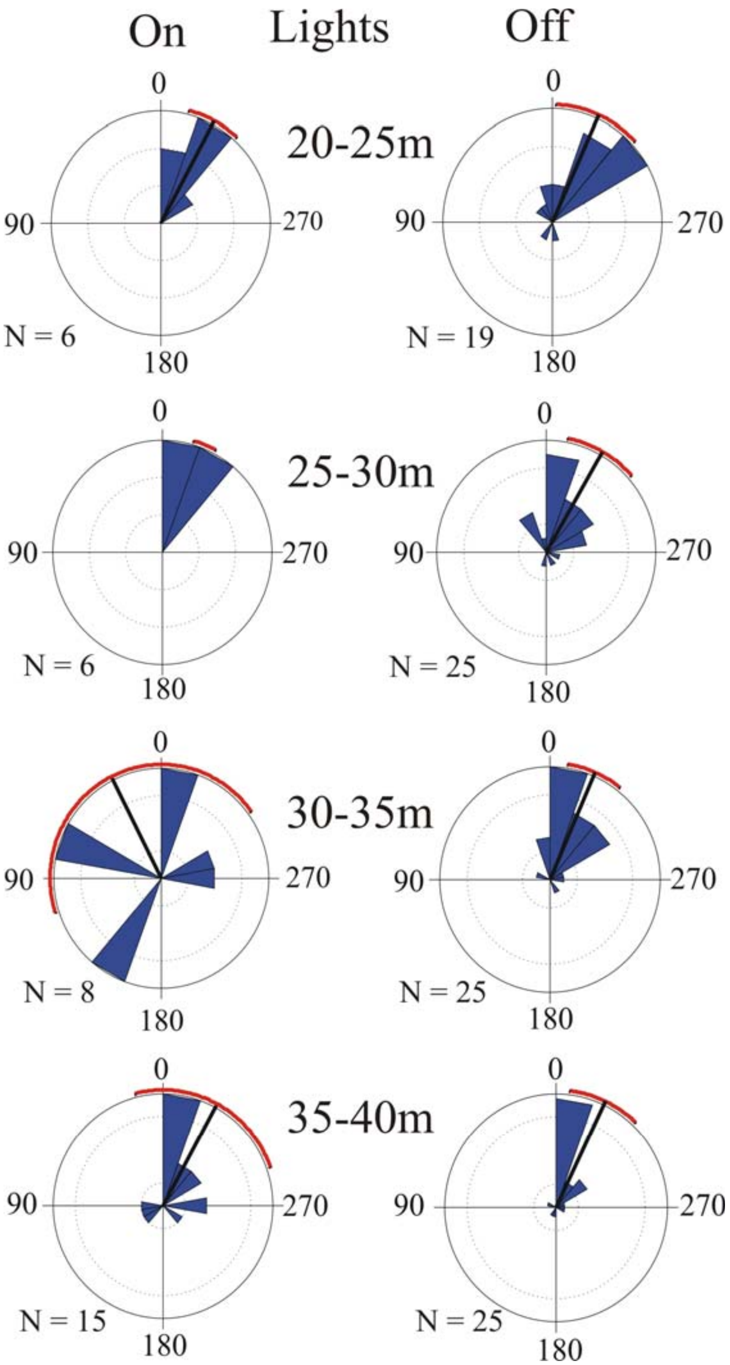

Figure E.9. Trajectory of Juvenile Kokanee Released 40 m Upstream of the Strobe Lights with Distance from Strobe Lights. The mean trajectory is indicated by the heavy black line, while 95% confidence intervals are indicated by the red semicircle. Direction to strobe lights is at zero degrees, third powerplant is at 90 degrees, and east bank is at 270 degrees.

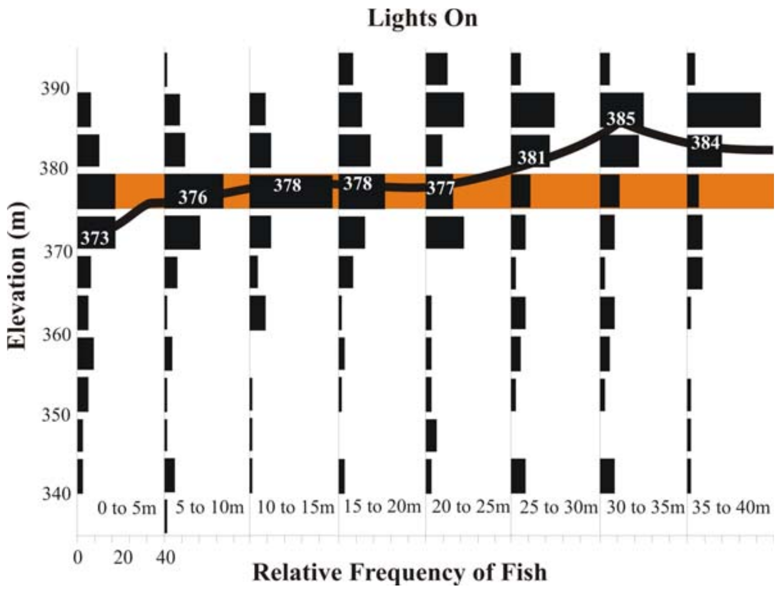

Figure E.10. Depth Distribution of Juvenile Kokanee with Distance from Strobe Lights When Lights Were On. Data for 20- and 40-m releases are grouped. Depth of the strobe lights is represented by the orange line. The median depth for fish approaching the lights is indicated by the black line .

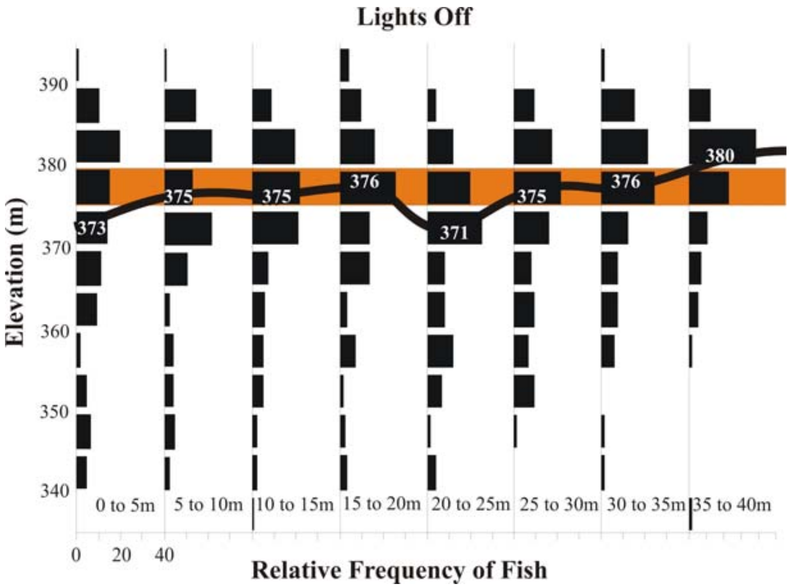

Figure E.11. Depth Distribution of Juvenile Kokanee with Distance from Strobe Lights When Lights Were Off. Data for 20- and 40-m releases are grouped. Depth of the strobe lights is represented by the orange line. The median depth for fish approaching the lights is indicated by the black line.

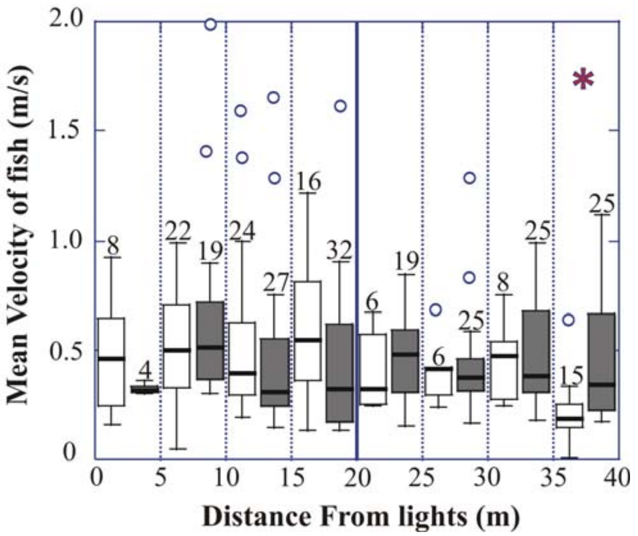

Figure E.12. Velocity (m/s) of Juvenile Kokanee with Distance from Strobe Lights When Lights Were Off (grey) and On (white). Asterisk indicates a significant difference ($p < 0.05$) in velocity between light treatments. Fish were released 20 or 40 m (data grouped within 20 m) upstream of the strobe lights at night. Boxes represent the 25th and 75th percentile of data; line is the median; whiskers are 1.5 *interquartile range beyond the box.

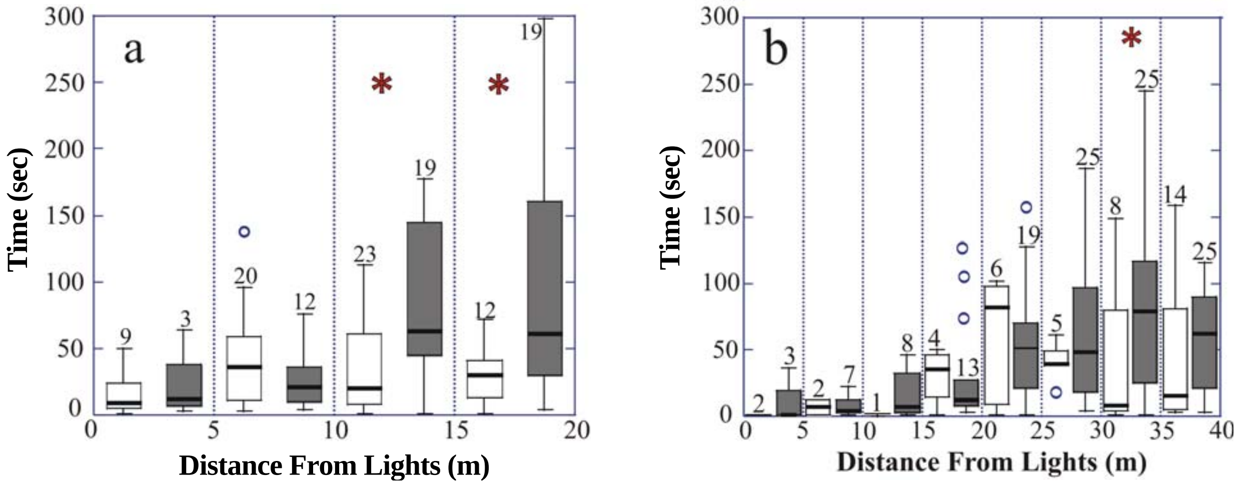

Figure E.13. Amount of Time (sec) Juvenile Kokanee Released 20 m (a) 40 m (b) from Strobe Lights Spent in 5-m Zones with Distance from Strobe Lights When Lights Were Off (grey) and On (white). Zones represent 5-m half-spheres upstream of the strobe lights. Asterisk indicates a significant difference ($p < 0.05$) between light treatments. Boxes represent the 25th and 75th percentile of data; line is the median; whiskers are 1.5 * interquartile range beyond the box. Outlying data points were not included; all occurred when lights were off (a) 15 to 20 m – 435 sec; (b) 25 to 30 m – 516 and 376 sec; 30 to 35 m - 440, 366, and 977 sec; 35 to 40 m - 448 and 402 sec.

Fish released 20 m from the lights spent significantly less time ($p < 0.05$) between 10 and 20 m from the lights when the lights were on than when they were off. However, when these fish were within 10 m of the lights, there was no significant difference ($p > 0.05$) in their residence times between when the lights were on or off. For fish released 40 m from the lights, the only area in which residence time differed significantly when lights were on compared to off was 30 to 35 m from the lights. In this area, fish spent significantly more time ($p < 0.05$) when the lights were off than when they were on.

Three fish released in the third powerplant forebay were found later at the pumping station. It took a median of 5.8 hours for them to reach the pumping station from their release point. None of the released fish was detected in the canal leading to Banks Lake.

E.3 Discussion

This is the fourth year in which acoustic telemetry has been used to examine the behavior of juvenile fish in relation to a strobe light array at Grand Coulee Dam. In the previous three years, very few implanted fish came near the strobe light array (Perry et al. 2003a, 2003b; Simmons et al. 2004), so no solid conclusions could be made about the influence of the lights on juvenile kokanee. In addition, species other than kokanee were studied during several of those years; at times, the size of kokanee implanted was not within the size range of the kokanee expected to be common at the dam following release from cage-rearing programs.

During the 2004 field season, fish were released 20 and 40 m directly upstream of the strobe lights, and large numbers of fish were observed near the strobe lights. However, there was no strong indication the strobe lights influenced the behavior of fish implanted with transmitters. Following release, the majority of the tagged kokanee moved with the flow toward the light array and passed within 10 to 20 m of the light array whether strobe lights were on or off. The fish tended to veer slightly to the right of the light array whether lights were on or off. Only a small number of fish passed farther to the right of the strobe lights while they were on (Figure E.5), and this was observed only for fish released 40 m from the lights. Furthermore, fish did not appear to alter their depth as they approached the strobe lights. They were released at the same depth as the lights (15 m), and the majority of the fish remained within 10 m above or below their release depth (and the depth of the lights) as they passed the light array. In addition, there were few differences in velocity or in the amount of time fish spent near the lights.

These results are contradictory to the results of several researchers who have found that strobe light arrays repel fish. One of the most relevant studies was conducted by Maiolie et al. (2001) on kokanee in Spirit Lake and Lake Pend Oreille, Idaho. They reported that at night, fish avoided strobe lights suspended from a boat. They found that kokanee densities within 30 m of the lights decreased from between 72% and 100% compared to control tests. They suggested due to test netting that most of these fish were kokanee, but sizes were not reported.

In a laboratory study, Mueller et al. (2001) found that during darkness, juvenile Chinook salmon (40 to 50 mm) and rainbow (25 to 44 mm) were startled by and avoided strobe lights. However, they also found that juvenile brook trout (30 to 40 mm) were not influenced by the operation of the strobe lights in the dark. These tests were conducted in a tank 7.3 m long and 3 m wide, precluding conclusions on the influence of lights on fish at longer distances. In addition, in previous years of this study, Simmons et al.

(2004) reported that using hydroacoustics in the third powerplant forebay at Grand Coulee Dam, fish (species unknown but assumed to be kokanee) actually congregated in proximity to the strobe lights. This response was observed during darkness and periods of low flow, whereas during daylight and higher flow rates, there was little evidence of a response by the fish to the strobe lights.

Several other studies have been conducted on other salmonid species. All of these studies found salmonids repelled by strobe lights. Johnson et al. (2001) found that during the day, strobe lights repelled fish (mostly sockeye salmon approximately 14 cm long) from the entrance of a culvert in Hiram M. Chittenden Locks, Seattle, Washington. Nemeth and Anderson (1992) examined coho and Chinook salmon (74.1 to 115 mm long, fork length) in a cement raceway 8.8 m long by 1.6 m wide. They determined that both species avoided the strobe lights, although Chinook salmon showed an attraction to dim mercury light.

Few conclusions could be made about the influence of strobe lights on juvenile kokanee from tagging studies in prior years at Grand Coulee Dam. In 2003, only 9 of the 198 released juvenile kokanee (mean length 147 mm, mean weight 31 g) were detected within 30 m of the strobe lights (Simmons et al. 2004). This was similar to the number of tagged kokanee (i.e., 11 out of 106; mean fork length 182 mm, mean weight 72 g) observed by Perry et al. (2003b) within 25 m of the strobe lights in 2002.

Some marginal examples of fish behavior during this study could be considered avoidance of the strobe lights. A small subset of fish released 40 m upstream of the lights did appear at release to move off to the right of the lights. They then turned left into the forebay and passed approximately 50 m to the right of the strobe light array (Figures E.5 and E.6). However, this pattern was not noticed in fish released 20 m from the lights. The second example is that within 5 m of the lights, fish that were released 20 m upstream of the lights veered away to the right of the strobe lights. The vector of their travel was different from that of control fish. However, this pattern was not observed among fish that were released 40 m upstream of the lights. In the third example, when the lights were on, fish released 20 m upstream of the lights spent less time in the zone between 10 and 20 m from the lights than did control fish. However, once again, this pattern was not observed among fish released 40 m from the lights. Presumably, if this were a light-induced behavior, then it would be expected to continue as the fish moved closer to the lights. However, as seen in Figures E.12 and E.13, this was not the case.

It is possible that fish did not react to the strobe lights because they were not released far enough away from them. In the area close to the lights (<20 m, for example), fish may have been confused and relied on other environmental cues such as flow to navigate. Possible reasons for this are that they may have been unable to isolate the direction of the light source or sources of refuge from the light. At distances >40 m, juvenile kokanee may be able to better isolate the direction from which the lights are coming in order to find refuge from the lights. However, several other studies (Nemeth and Anderson 1992; Mueller et al. 2001) found that fish responded to strobe lights when they were in proximity to them. Another experiment would be needed to determine the distance at which juvenile kokanee might respond to the lights with releases at greater distances from the lights.

E.4 Conclusion

This research has focused on the behavior of individuals of a known species and size class. The data from tracking juvenile kokanee implanted with acoustic transmitters do not show any clear influence from operating strobe lights on path of travel, vector of travel, velocity, or time in the area near the strobe lights. It is possible that if larger strobe light arrays were present, the behavior of fish may have been altered by their presence. However, in the current deployment, this was not apparent.

E.5 References

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Appendix F

Hydrodynamic Characterization of the Third Powerplant Forebay

Appendix F

Hydrodynamic Characterization of the Third Powerplant Forebay

Christopher B. Cook

During the 2002, 2003, and 2004 field seasons, an acoustic Doppler current profiler (ADCP) was deployed near the light frame. Specific details of the 2002 and 2003 deployments can be found in Johnson et al. (2003) and Simmons et al. (2004), respectively. Processing methods for the 2004 survey season were similar to those used in previous years. Brief details and data analysis relating to the 2004 field deployment are included in this appendix, as well as summary remarks for all three years of ADCP measurements.

During the 2004 field season, a 20-degree RD Instruments Workhorse ADCP operating at 600 kHz was deployed 16.4 m upstream of the light frame and barge from the aluminum truss in a downward-looking orientation. The deployment location is shown in Figure F.1 and corresponds to the vertex of the two arrows. During the 2002 and 2003 field seasons, the ADCP was attached directly to the barge; however, at the scale of Figure F.1, these locations are approximately the same.

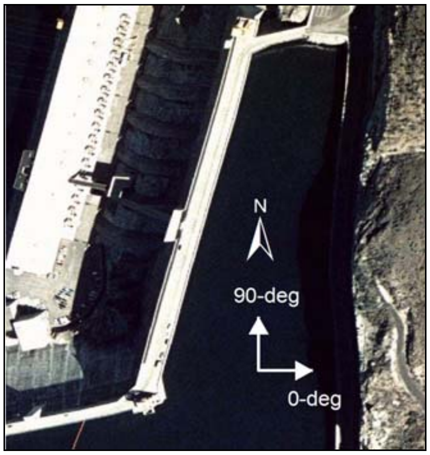


Figure F.1. Overhead View of the Third Powerplant Forebay Showing the Location of the ADCP Deployment (vertex of arrows). The arrows indicate the angular definition applied to ADCP measurements reported in this appendix.

ADCP data from the 2003 field season contained significant acoustic “cross-talk” with the splitbeam hydroacoustic transducers. To remove cross-talk during the 2004 field season, the ADCP was set up to collect data only when it received an electronic “tap” pulse. This pulse was generated by the multiplexer controlling the splitbeam hydroacoustic transducers and effectively made the ADCP part of the splitbeam multiplexer cycle. The splitbeam hydroacoustic system collected data at a rate higher (greater than 20 pings per second) than the ADCP could effectively sample, process, and return to a ready state in order to accept the next tap pulse. Therefore, a separate controller box was constructed to tap-pulse the ADCP at an integer multiple of the split-beam data collections. During the field season, the ADCP primarily collected data at a sampling frequency of once every 2 seconds, although several days of data were collected at a sampling rate of once every second (fastest rate possible using tap-pulse configuration).

F.1 The 2004 Field Season

ADCP data were collected continuously between June 28 and August 18, 2004, at a sampling rate of (at least) once every 2 seconds. These data were collected in beam coordinates and converted to Earth coordinates using PNNL-developed MATLAB® programs. The ADCP was programmed to collect data from 3 m beneath the water surface to the bottom of the water column (distance of approximately 49 m), and water velocities were gated with a vertical resolution of 1 m. Because the splitbeam hydroacoustic system data were depth-limited to only the top 30 m of the water column, all ADCP data displayed in this appendix were limited to the same range. It should be noted that when the water column was strongly stratified and the third powerplant was operating at mid-range discharges, water velocities at depths below 30 m may, in fact, be larger than those higher up in the water column. This phenomenon was noted in previous years (see Simmons et al. 2004, Figure D.4) and is attributed to the relatively deep placement of the penstock entrances.

Because water flow at the forebay entrance is turbulent, ADCP data were time-averaged to extract the principal flow component characteristics. The time scale used to average these data was 1 minute and is based upon the averaging interval used to process fish trajectories with the splitbeam system. These 1-minute averages were composed of (at least) 30 independent measurements of the three-dimensional flow field. A graphical summary of these averages spanning the entire 2004 field season is shown in Figure F.2.

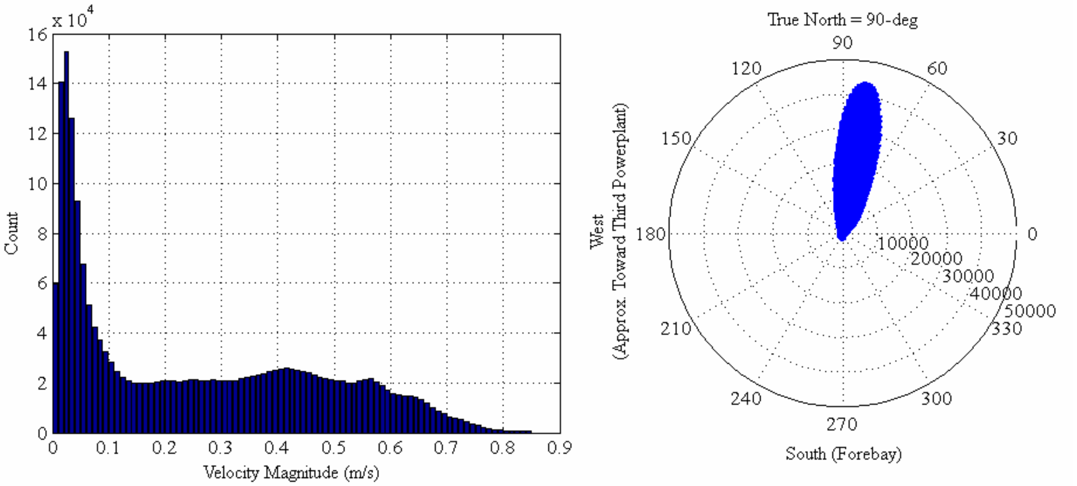


Figure F.2. ADCP-Measured Velocity Magnitude and Direction for the 2004 Field Season. Principal flow direction is approximately parallel to the third powerplant face.

Water velocity magnitudes ranged from near zero to 1.6 m/s during the 2004 field season, but very few values were larger than 0.8 m/s. Because the third powerplant is used for peaking power needs, only a small amount of flow is released during nighttime hours when power demands are low. Consequently, a large number of the ADCP velocity magnitudes were less than 0.1 m/s.

The principal flow direction throughout the 2004 field season is approximately 10 degrees east of true north. The third powerplant face is approximately 17 degrees east of true north; hence, the principal flow direction is roughly (within 10 degrees) parallel to the face of the third powerplant at the entrance to the forebay. Obviously the flow must turn 90 degrees to enter the penstocks; however, this occurs farther into the forebay as observed during the 2003 mobile ADCP collection (Simmons et al. 2004).

Depth-averaging of the ADCP data over the upper 30 m of the water column provides a smooth index of flow conditions experienced by fish detected within the splitbeam hydroacoustic system. Figure F.3 displays depth-averaged data for the entire 2004 field season and can be compared to Figure F.2. Depth averaging shifts the histogram distribution toward lower magnitude values, with the peak occurring at 0 m/s. The directional histogram range also narrowed, but the principal direction remained at approximately 10 degrees east of north and roughly parallel to the face of the third powerplant.

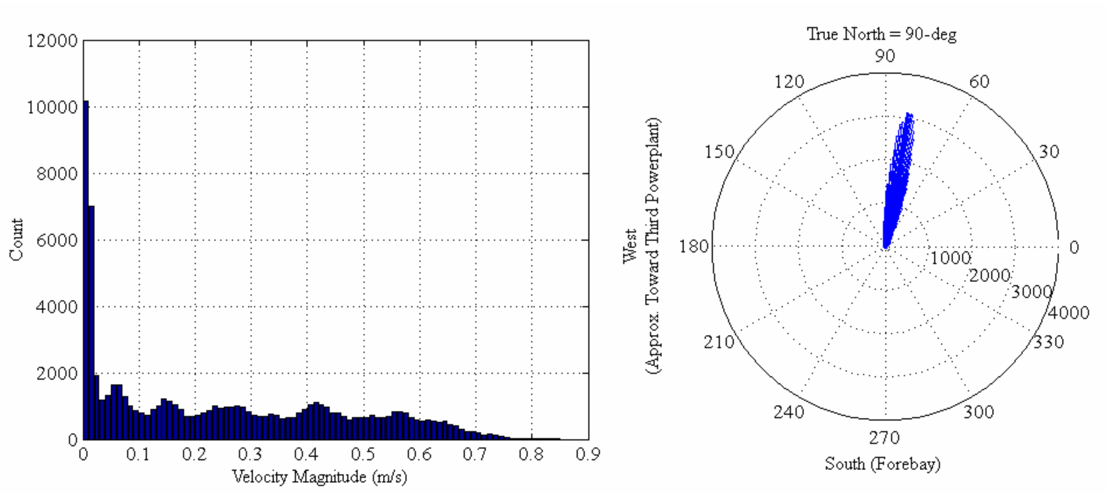


Figure F.3. Depth-Averaged (3- to 30-m) ADCP Measured Velocity Magnitude and Direction for the 2004 Field Season. Principal flow direction is approximately parallel to the face of the third powerplant.

F.2 Thermocline Effects

Appendix D of Simmons et al. (2004) discusses three water circulation modes at the barge site. The water circulation mode was found to be dependent upon two conditions: 1) discharge through the third powerplant and 2) temperature difference between the upper and lower portions of the water column (i.e., strength of thermal stratification). These same modes were observed also during the 2004 field season, and each mode can be summarized as follows:

- **Mode 1: high discharge with vertically uniform water column velocity**. This occurs when the third powerplant discharge is above approximately 2,265 m^3/s (80 kcfs) and momentum forces overwhelm any influence of thermal stratification on circulation patterns at the barge site. Under these conditions, water velocities and direction throughout the water column at the barge site are approximately uniform. The third powerplant discharge necessary to achieve Mode 1 may be less when the reservoir is weakly stratified.

- **Mode 2: medium discharge with vertically nonuniform velocity**. This mode occurs when discharge through the third powerplant is moderate (approximately 1,130 to 1,700 m^3/s [40-60 kcfs]) and when there is strong thermal stratification. In Mode 2, water velocities and direction throughout the water column are highly nonuniform, and in the extreme can be up to 180 degrees different. A distinct shear layer at the thermocline is noticeable, and water velocity magnitudes in the lower portion of the water column are generally higher than in the upper portion because the third powerplant intakes are near the bottom of the water column.

- **Mode 3: low (less than 570 m^3/s [20 kcfs]) to zero discharge**. Because of the lower discharge through the third powerplant, weaker driving forces appear to be influencing water currents near the barge. A force such as the wind at the water's surface can affect water velocities in the upper portion of the water column. Further, under strong stratification conditions, seiching of the thermocline can occur, causing internal waves to propagate through the reservoir and influencing flows near the barge site.

Appendix A of this report discusses water temperature data measured at the barge site. From these data, the water column during the 2004 season was continuously stratified, although the strength of stratification varied from 2°C to 8°C over the field season. The depth of the thermocline was relatively consistent and generally 10 m below the water surface. To examine differences in velocity magnitude and direction between the upper and lower portions of the sampled water column, equal-sized depth ranges from both portions were selected and averaged. For the upper portion, the range extended from 3 to 10 m, starting with the first good bin beneath the ADCP head (the ADCP head was deployed 1.5 m beneath the water surface, and the next 1 m was blanked out) and extended downward to the start of the thermocline. The bottom water portion range extended from 23 to 30 m, which corresponds to the bottom range sampled by the splitbeam hydroacoustic system.

Histograms of water velocity magnitude and direction during the 2004 field season are displayed in Figure F.4. Although the trends are similar, two items are of note: 1) velocity magnitudes in the lower portion of the water column are higher than in the upper portion and 2) the direction in the lower portion is slightly west (i.e., closer to 90 degrees) and contains more angular spread than the upper portion of the water column. Both items may be explained by considering the location of the intakes relative to the thermocline. Because the intakes are deep in the lower water column, that portion of the water column is highly energized (Mode 2). Only when the third powerplant discharge overcomes buoyancy effects does

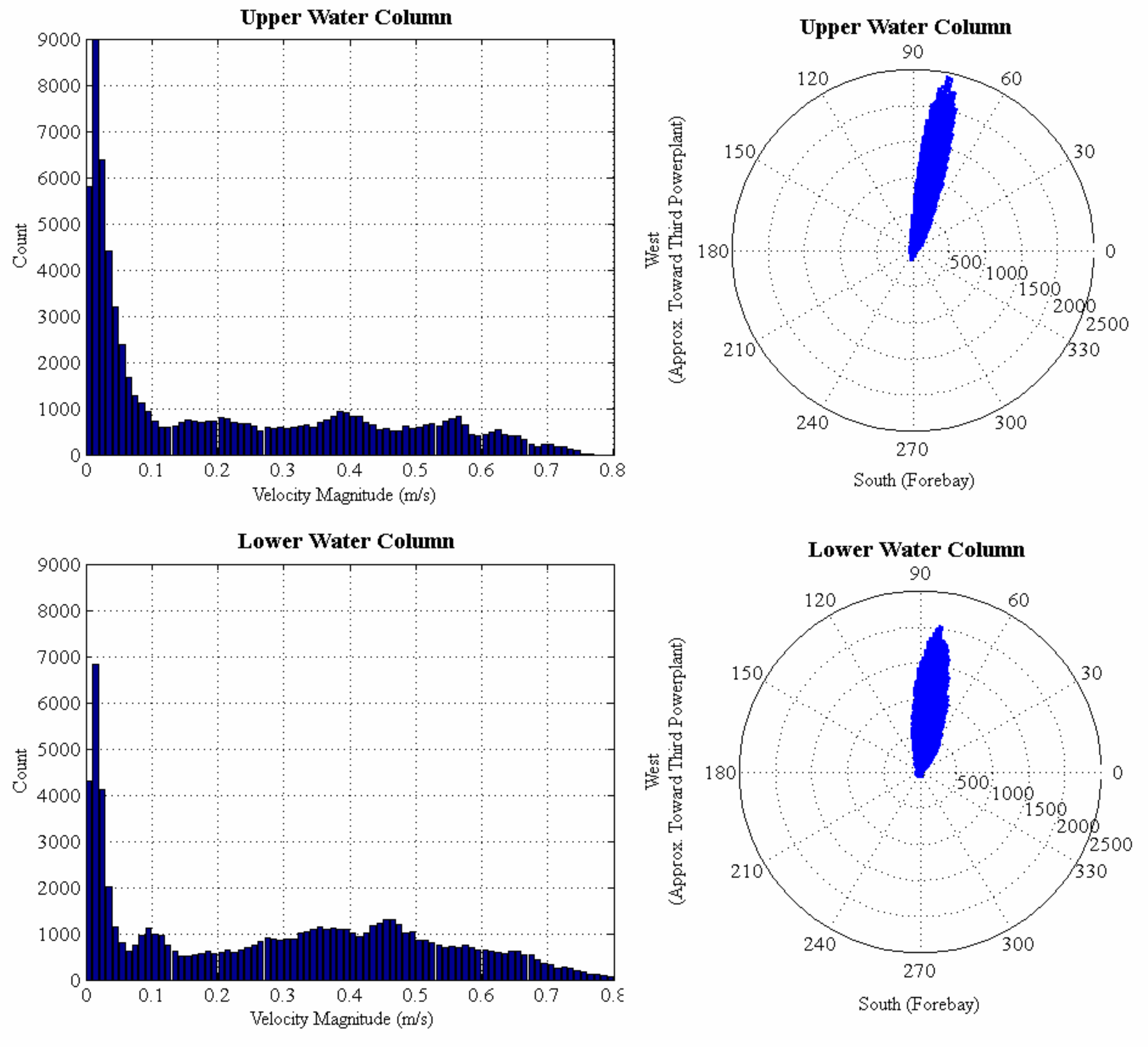


Figure F.4. Upper (3- to 10-m) and Lower (23- to 30-m) Depth-Averaged ADCP Measured Velocity Magnitude and Direction for the 2004 Field Season

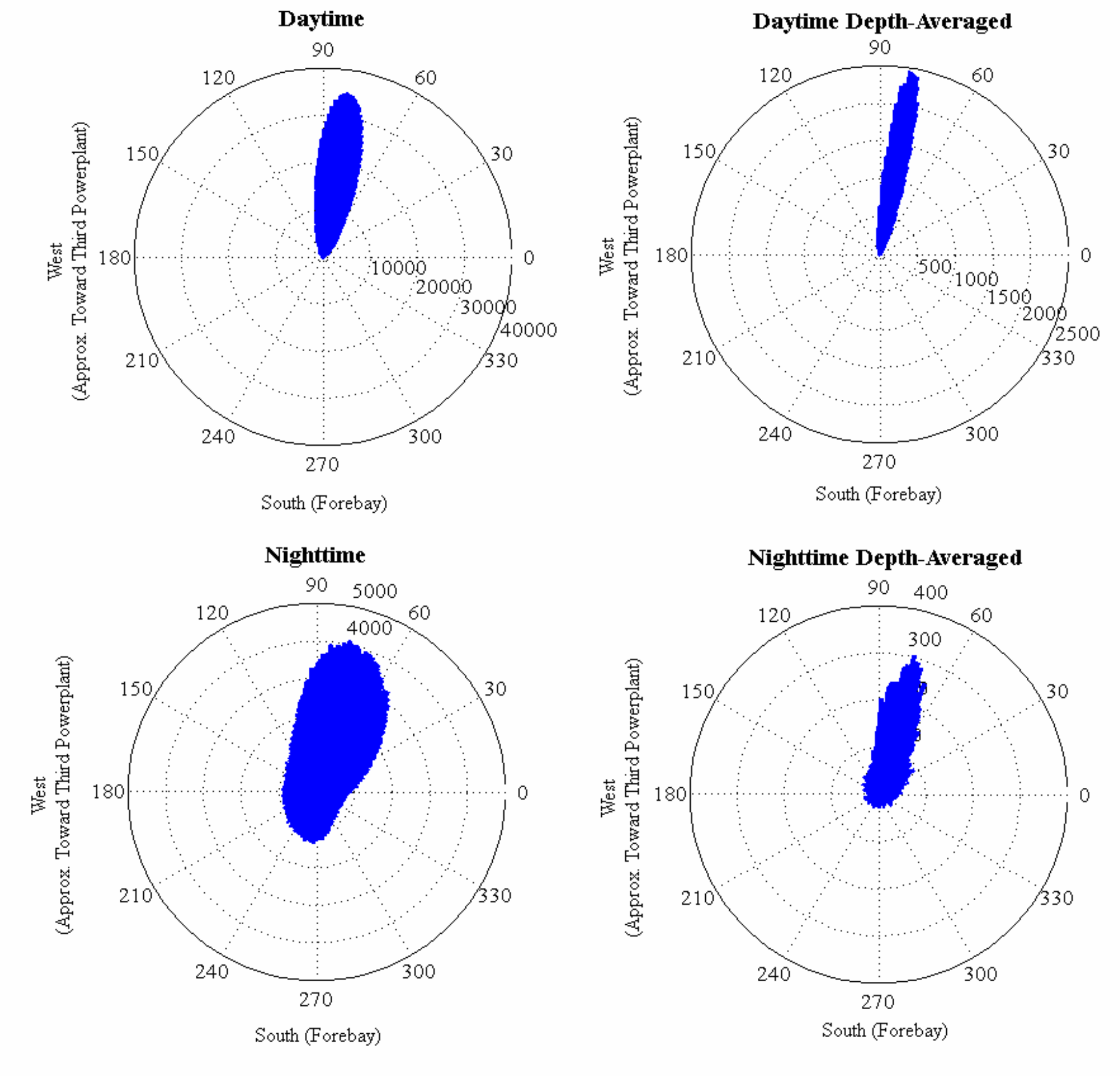
the upper portion of the water column become strongly energized at the barge site (Mode 1). For both the upper and lower water column, however, the principal direction of flow is approximately parallel to the face of the third powerplant.

F.3 Daytime Compared to Nighttime Angular Flow Distributions

The times of sunrise and sunset were determined at the site based upon location and U.S. Naval Observatory data (http://aa.unso.navy.mil/data/docs/RS_OneYear.html). At the end of June, sunrise occurs at approximately 05:00, and sunset occurs at 21:00 (Pacific Daylight Time). Daytime and nighttime hours referred to in this section were defined to occur 1 hour after/before sunrise and sunset; that is, daytime occurred between 06:00 and 20:00, and nighttime occurred between 22:00 and 04:00.

Angular histograms of velocity direction for the 2004 field season, grouped by daytime and nighttime hours, are shown in the left-hand column of Figure F.5. As discussed in the following section, nighttime velocity magnitudes are generally small and less directionally structured. Also, nighttime flows can be directed upstream from the forebay and may be highly influenced by internal waves and operations of the right powerplant. Daytime velocity directions are more coherent and are generally directed parallel to the third powerplant face.

Daytime and nighttime vector components were depth-averaged over the 3- to 30-m sampling range (right-hand column of Figure F.5). Depth averaging removed many of the upstream nighttime velocity measurements and significantly reduced angular spread of the daytime velocity measurements.



Daytime

Daytime Depth-Averaged

Nighttime

Nighttime Depth-Averaged

Figure F.5. Daytime and Nighttime Water Velocity Directions During the 2004 Field Season. Depth-averaged histograms were created using identical data sets; however, velocity components were averaged over a 3- to 30-m depth range.

F.4 Large Velocity Magnitude Flows

Data collected during the 2004 field season were depth-averaged from 3 to 30 m and filtered by velocity magnitude. Magnitude values larger than 0.2 m/s are shown in Figure F.6. This velocity magnitude threshold corresponds to a powerplant discharge of approximately 1,700 m^3/s (60 kcfs).

A total of 73,703 minutes of ADCP water velocity data were recorded during the 2004 field season. Of those minutes, 36,656 (49%) were collected when large velocity magnitudes occurred at the barge site.

All large velocity magnitudes at the barge site occurred between 05:00 and midnight during the field season. The vast majority of these flows occurred during daytime hours between 06:00 and 20:00 (Figure F.6). Large velocity flows were relatively consistent and oriented primarily 10 degrees east of north (roughly parallel to the third powerplant face).

Of the large velocity flows, 1,924 minutes (5.2%) occurred in nondaytime hours and only 724 (2.0%) occurred in nighttime hours. Of the nondaytime large velocity minutes, 1,278 (66.4%) had velocity magnitudes just above the large velocity threshold (range 0.2 to 0.3 m/s).

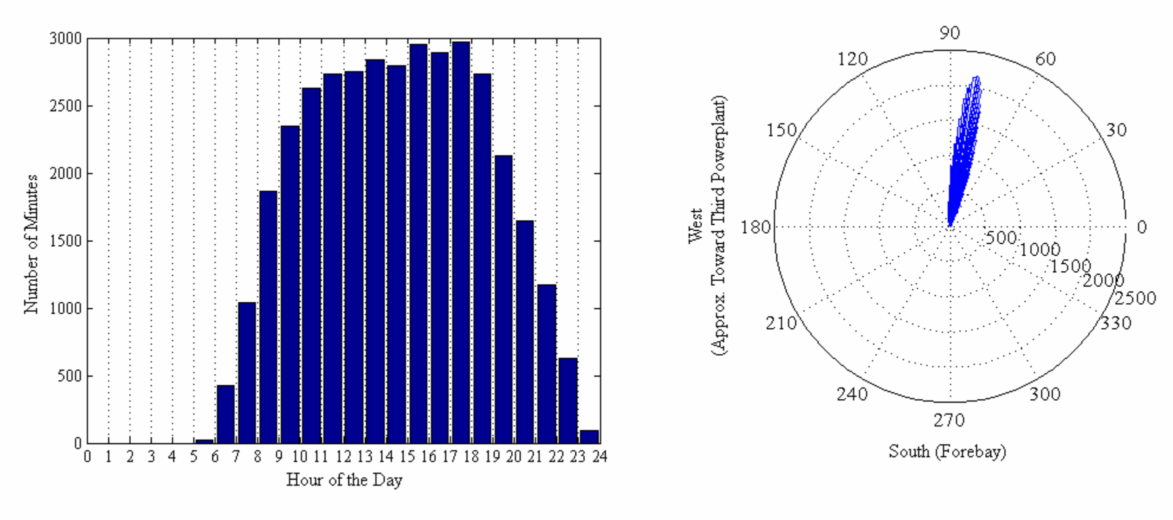


Figure F.6. Hour and Direction of 3- to 30-m Depth-Averaged Water Velocity Magnitudes Greater Than or Equal to 0.20 m/s

F.5 Small Velocity Magnitude Flows

Data collected during the 2004 field season were depth-averaged from 3 to 30 m and filtered by velocity magnitude. Magnitude values smaller than 0.05 m/s are shown in Figure F.7. This velocity magnitude threshold corresponds to a powerplant discharge of approximately 140 m^3/s (15 kcfs).

A total of 73,703 minutes of ADCP water velocity data were recorded during the 2004 field season. Of those minutes, 21,550 (29%) were collected when small velocity magnitudes occurred at the barge site.

The hourly distribution of small velocity flows is shown in Figure F.7. These flows occur primarily during the nighttime hours between 22:00 and 06:00. Small velocity flow directions were not as directionally consistent as the large velocity flows, although the principal flow direction is in the first quadrant of the unit circle.

Of the small velocity flows, 5,130 minutes (23.8%) occurred in nonnighttime hours and 2,560 (11.9%) occurred in daytime hours. Daytime hour small velocity flows occurred primarily in the early to mid morning and late afternoon.

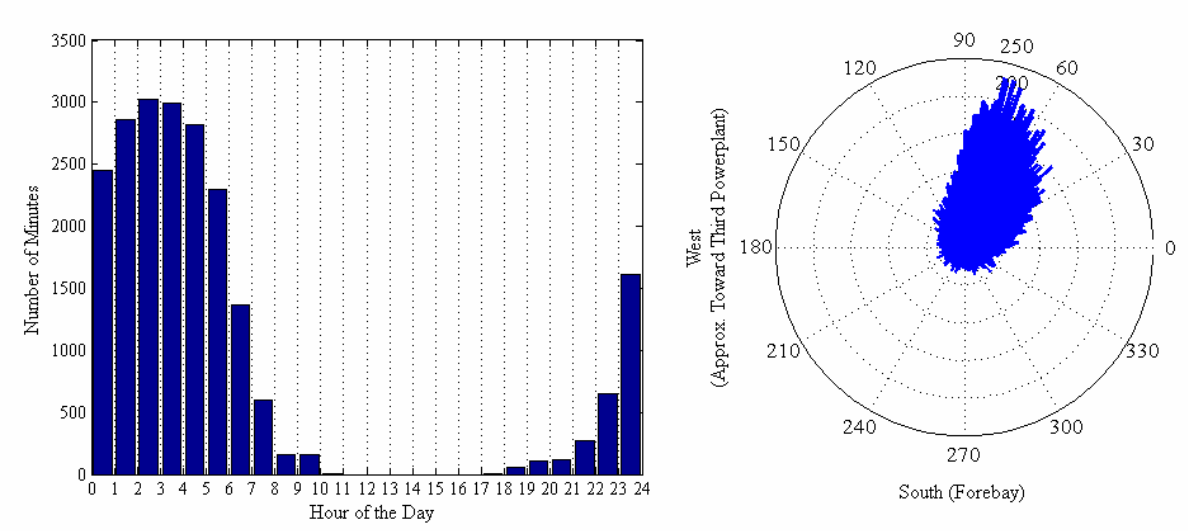


Figure F.7. Hour and Direction of 3- to 30-m Depth-Averaged Water Velocity Magnitudes Less Than or Equal to 0.05 m/s.

F.6 Summary of Results

Results obtained from the three field seasons of moored (stationary) ADCP measurements in the forebay of the third powerplant at Grand Coulee Dam are summarized in the following paragraphs.

F.6.1 2002 Field Season (Johnson et al. 2003)

- **The forebay in front of the third powerplant remained thermally stratified during the entire field season after onset of thermal stratification.**

- **Discharges through the third powerplant varied widely during the field season**. However, no evidence was found that the third powerplant discharge broke down the thermal stratification at the barge site.

F.6.2 2003 Field Season (Simmons et al. 2004)

- **The reservoir became strongly thermally stratified during the field season, with a corresponding deepening of the thermocline.** At the start of the field season, the vertical temperature differences were less than 2°C, and a weak thermocline (if present) was high in the water column. At the end of the field season, vertical differences were in excess of 6°C, and the thermocline was approximately 24 m beneath the water surface. This change in vertical temperature structure adds complexity to the hydrodynamic analysis, especially as water column velocity magnitudes oscillate frequently from vertically uniform (Mode 1) to heterogeneous (Modes 2 and 3).

- **Water velocities at the barge can be classified into one of three modes, roughly dependent upon powerplant discharge.** For each mode, there is also a submode based upon the strength of stratification. These modes were researched by examining discrete periods before and after the field season when the stratification was the weakest and strongest, respectively. These modes, and the corresponding third powerplant discharge range for each, apply only for this 2003 field season. That is because these values, developed under one set of conditions, may be expected to vary in other years based upon operations of the Grand Coulee spillway, right and left powerplants, and Banks Lake. In addition, it is not possible to further refine these modes based upon data collected in 2002 because water velocities were not obtained beneath 15 m (light frame).

- **Velocities along the truss were approximately uniform. Mobile profiles of water velocities were collected when the water column was in Mode 2 (larger hypolimnetic water velocities).** Epilimnetic magnitudes and directions were approximately equal at all locations measured along the truss. In addition, slight hypolimnetic magnitude variations appear to be attributable to slight powerplant discharge operations during the discrete period necessary to collect these data (approximately 1 hour). Based upon these measurements, application of ADCP measurements to all hydroacoustic fish detection units on the truss is a reasonable assumption.

F.6.3 2004 Field Season

- **The water column beneath the barge site remained continuously stratified during the entire 2004 field season**. Although third powerplant discharges were large for long periods of time, dam operations did not cause the water column to destratify.

- **Presence and strength of stratification influenced water column velocities.** All three circulation modes described in Simmons et al. (2004) were observed during the 2004 field season. Flow patterns were consistent with previously developed theories. Flow mode under the barge is predictable and is a function of third powerplant operations and stratification strength.

- **Daytime and nighttime water velocity directions were consistently oriented parallel to the third powerplant face.** Daytime velocity vectors were directionally coherent, and most values fell within a narrow 20-degree swath just east of true north. The swath narrowed considerably to 10 degrees when the vectors were depth-averaged over a 3- to 30-m range. Nighttime velocity vectors were less coherent, and sometimes-large directional shifts occurred within the water column at a specific time. This is not unexpected because the water velocities were generally small and not as highly influenced by powerplant operations. Depth-averaging over a 3- to 30-m zone resulted in a more consistent directional pattern. As with the daytime values, nighttime values were oriented principally parallel to the face of the third powerplant.

- **Large velocity magnitudes were measured 49% of the time and were most likely to occur during midday and afternoon.** Large velocity magnitudes correspond to third powerplant discharge greater than 1,700 m^3/s (60 kcfs), and the vast majority occurred between 06:00 and 20:00. Large velocity flow directions were coherently structured and were oriented primarily 10 degrees east of true north.

- **Small velocity magnitudes were measured 29% of the time and were most likely to occur during the early morning hours between midnight and sunrise.** Small velocity magnitudes correspond to third powerplant discharge of 425 m^3/s (15 kcfs) or less, and the vast majority occurred during nighttime hours between 22:00 and 06:00. Small velocity flow directions were not as coherently structured as the high velocity flows. However, the principal flow direction remained in the first quadrant of the unit circle (i.e., west of true north).

F.7 References

Johnson RL, MA Simmons, CA McKinstry, CB Cook, CS Simmons, SL Thorsten, R LeCaire, and S Francis. 2003. *Strobe Light Deterrent Efficacy Test and Fish Behavior Determination at Grand Coulee Dam Third Powerplant Forebay*. PNNL-14177, Pacific Northwest National Laboratory, Richland, Washington.

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Appendix G

Zooplankton Sampling and Analysis

Appendix G

Zooplankton Sampling and Analysis

Daniel K. Tano and Brett Nine

Maiolie and Stark (2003) found that kokanee avoided strobe lights in the reservoir of Dworshak Dam, while results from studies at Grand Coulee Dam in 2002 and 2003 showed an apparent accumulation of fish near the lights when the strobe lights were on at night (Johnson et al. 2003; Simmons et al. 2004). A possible explanation for the presence of fish near the lights at night was that zooplankton may be attracted to the illuminated region and provide visual predators a distinct feeding opportunity (Johnson et al. 2003; Simmons et al. 2004).

Research has found that the introduction of an artificial light source may affect the amplitude of diel vertical migration (DVM), depending on the depth of the zooplankton and the depth of the light source (Moore et al. 2000). Many zooplankton have evolved DVM as a mechanism to avoid predation by fish, much of which is a visual process requiring light (Ringelberg 1964; Zaret and Suffern 1976). Most species migrate upward from deeper strata to surface regions as darkness approaches to feed, and return to the deeper areas at dawn to hide from visual predators (Stich and Lampert 1981; Pearre 1973).

The purpose of this study was to determine whether strobe lights were attracting zooplankton toward the light array or repelling them. To make this determination, we compared zooplankton densities and biomass in front of the light array to determine whether there was a significant difference in these factors when the strobe lights were on compared to when the strobe lights were off.

G.1 Materials and Methods

Zooplankton samples were collected on seven Friday nights from 2230 to 0030 starting on June 25, 2004, and ending on August 13, 2004. All samples were taken from the upstream end of the barge, within 2 m of the strobe lights. A 30-L Schindler-Patalas trap was used to collect zooplankton at a depth of 15 m (depth of light array). Duplicate or triplicate samples were taken with the strobe lights on and off, for a total of four to six samples per night. All samples were fixed in 95% ethanol and stored in 70% ethanol as suggested by Black and Dodson (2003) for preserving *Daphnia*. Samples were transferred from Grand Coulee to PNNL in Richland for laboratory-based counting and identification.

In the laboratory, samples were sorted, enumerated, and identified to genus using the taxonomic key of Thorp and Covich (2001). When samples contained a large number of zooplankton, up to four sub-samples were taken using a rotary drum plankton splitter. Densities of individual species in the sample were calculated by averaging the triplicate tows. Densities were determined using

$$\mathrm{D} = \frac{n * s}{v} \tag{G.1}$$

where D = density (number/L)
n = number of individuals counted (by species)
s = number of subsamples
v = volume of water sampled (30 L).

For each sample, a maximum of five organisms for each predominant Cladoceran and Copepod genus were measured using an Olympus SX-PP dissecting scope with an optical micrometer. Measurements were taken from the top of the head to the base of carapace, excluding the spine. Biomass was determined using length/weight regression equations summarized by Downing and Rigler (1984). Mean length was calculated for each Cladoceran and Copepod species and then used to estimate biomass. Average Cladoceran and Copepod biomass was calculated as follows:

$$B = (\ln w)(D) \tag{G.2}$$

where B = biomass (µg/m^3)
$\ln w$ = log of the dry weight estimate by species (µg)
D = density (number of organisms/m^3).

Statistically, p values from a two-sample, two-tailed t-test were used to determine if density and biomass means were equal for samples collected under lights-on and lights-off conditions.

G.2 Results

The predominant species collected during the sampling period were the Cladoceran, *Daphnia*, and Calanoid and Cyclopoid copepods. Other species included the Cladocerans: *Leptodora*, *Chydorus*, and *Sida*, and a chironomid.

A weekly summary of densities for calanoid copepods, cyclopoid copepods and *Daphnia* reveals a unique pattern of densities for each group (Figure G.1). At times, densities appear higher when the strobe lights are on. This generally was due to one of the three replicates having a high density. In general, densities were similar between lights-on and lights-off configurations.

Over the study period, the mean density of *Daphnia* was 2.56/L (±0.78) for samples collected when the strobe lights were on, compared to 2.65/L (±0.77) for samples collected when the lights were off (Figure G.2). This difference was not statistically significant ($p = 0.72$).

For Calanoid copepod, mean densities were 2.46/L (±1.16) for samples collected when the strobe lights were on, compared to 2.09/L (±0.51) for samples collected when the strobe lights were off (Figure G.2). This difference was not statistically significant ($p = 0.58$).

Cyclopoid copepod densities were 2.63/L (±0.88) for samples collected when the strobe lights were on, compared to 2.22/L (±0.45) for samples collected when the lights were off (Figure G.2). This difference was not statistically significant ($p = 0.49$).

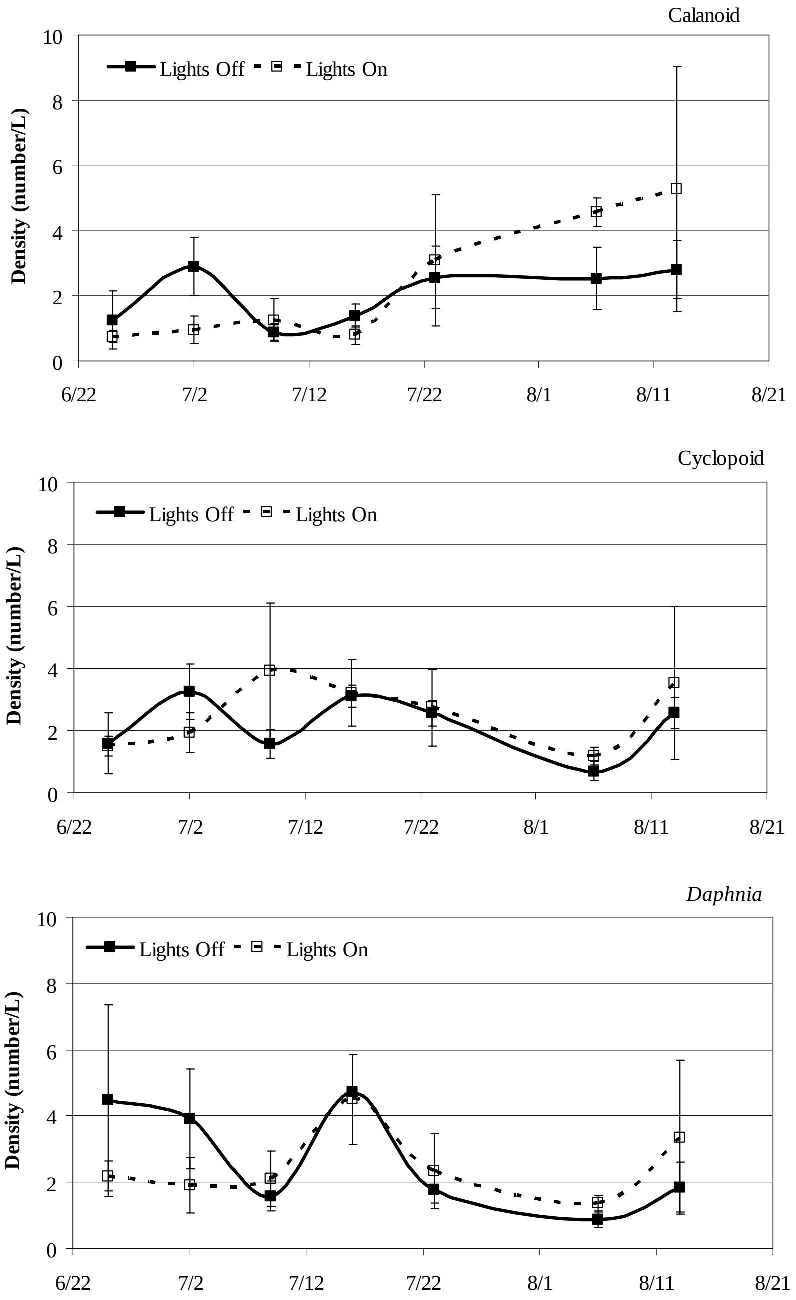

Figure G.1. Densities (number/liter) for *Daphnia*, Calanoid Copepods, and Cyclopoid Copepods Collected When Strobe Lights Were On and Off Between June 25, 2004, and August 13, 2004, in the Forebay of the Third Powerplant, Grand Coulee Dam

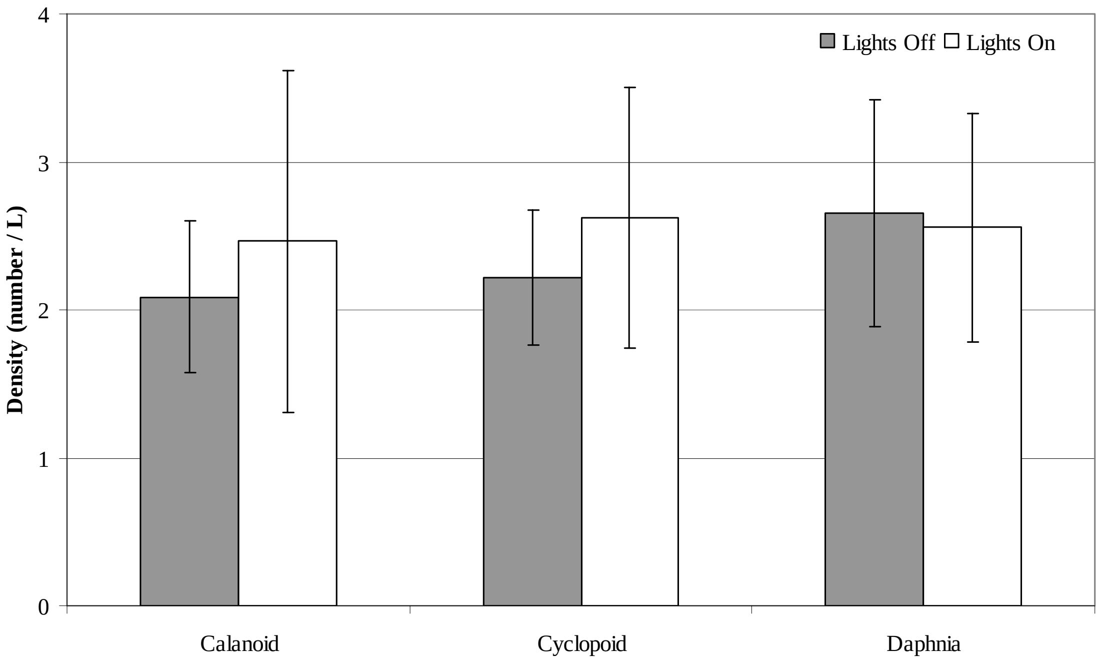

Figure G.2. *Daphnia*, Calanoid Copepod, and Cyclopoid Copepod Densities When Strobe Lights Were On and Off in 2004. Bars are standard errors.

Three other species of zooplankton identified in the study were *Leptodora*, *Chydorus*, and one species of Ctenopoda. Densities for *Leptodora* were 0.12/L for samples collected when the strobe lights were off and 0.10/L for samples collected when the strobe lights were on. Statistically there was no significant difference in densities collected during the two light configurations (p = 0.47). *Chydorus* and the Ctenopoda densities were not calculated due to their low abundance.

G.3 Discussion

Results indicate that the strobe lights had no effect on zooplankton densities within the illuminated area. Zooplankton are known to migrate in response to light intensity (Ringelberg 1987; Haney 1993; Moore et al. 2000) as an avoidance mechanism against predators (Hardy and Gunther 1935; Zaret and Suffern 1976; Stich and Lampert 1981; Bollens and Frost 1989, 1991; Pearre 1973). These migrations generally occur at dusk. Moore et al. (2000) found that DVM could be reduced in both amplitude and magnitude due to urban light pollution at the surface. However, at Grand Coulee there appears to be no such effect due to the strobe lights or the lights on the dam.

Densities of *Daphnia* and copepods for this study are similar to those reported for Spring Canyon upstream of Grand Coulee Dam in 1996 (Cichosz et al. 1997). That study found a positive relationship with densities and temperatures at 12 m. These temperatures generally peak in July and August along with the zooplankton densities.

Zooplankton in Lake Roosevelt are very large, averaging 1.51 mm (Cichosz 1999), which makes them visible to the naked eye. Koski and Johnson (2002) measured the feeding rates of kokanee under different light rates and found that at light intensities of 15 and 30 lx (0.2 and 0.4 µmoles/m^2/s), fish actively pursued *Daphnia* of similar lengths. Light levels measured on the light frame when the strobe lights were on averaged 0.37 µmoles/m^2/s at 2300 hours. At these light levels, Koski and Johnson reported that kokanee selectively fed on larger *Daphnia*. This suggests that the apparent positive attraction of fish to the light array during the three years of the strobe light study may be due to enhanced feeding opportunity provided by the increased illumination as the zooplankton passed through the lighted region upstream of the array.

G.4 Recommendations

A follow up study is recommended in order to determine whether zooplankton are migrating away from the light array or are being drawn into the forebay due to illumination from the lights. The following are recommendations for a follow-up survey:

- Examine zooplankton biomass and densities at three depths (near the surface, at 15-m depth, and below the light array).
- Systematically sample zooplankton throughout the diurnal cycle (dusk, dawn, midnight, and midday).

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