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Pacific Northwest National Laboratory
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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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January 2003

Prepared for the Bonneville Power Administration,
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under Contract DE-AC06-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

(a) Confederated Tribes of the Colville Reservation, Nespelem, Washington.

Summary

Since 1995, the Confederated Tribes of the Colville Reservation (Colville Confederated Tribes) have managed the Chief Joseph Kokanee Enhancement Project as part of the Northwest Power Planning Council (NWPPC) 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.

A 42-month investigation concluded that entrainment at Grand Coulee Dam ranged from 211,685 to 576,676 fish annually. Further analysis revealed that 85% of the total entrainment occurred at the dam's third powerplant. These numbers represent a significant loss to the tribal fisheries upstream of the dam.

In response to a suggestion by the NWPPC Independent Scientific Review Panel, the scope of work for the Chief Joseph Kokanee Enhancement Project was expanded to include a multiyear pilot test of a strobe light system to help mitigate fish entrainment. This report details the work conducted during the second year of the study by researchers of the Colville Confederated Tribes in collaboration with the Pacific Northwest National Laboratory. The 2002 study period extended from May 18 through July 30.

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. The prototype system consisted of six strobe lights affixed to an aluminum frame suspended vertically underwater from a barge secured in the center of the entrance to the third powerplant forebay. The lights, controlled by a computer, were aimed to illuminate a specific region directly upstream of the barge.

Three light level treatments were used: 6 of 6 lights on, 3 of 6 lights on, and all lights off. These three treatment conditions were applied for an entire 24-hr day and were randomly assigned within a 3-day block throughout the study period.

A seven-transducer splitbeam hydroacoustic system was used to evaluate the effectiveness of the strobe lights in eliciting a negative phototactic response in fish. The transducers were deployed so they tracked fish entering and within the region illuminated by the strobe lights. Two of the seven transducers were mounted to the frame containing the strobe lights and were oriented horizontally. The remaining five transducers were spaced approximately 4 m apart on individual floating frames upstream of the barge, with the transducers looking vertically downward.

Analysis of the effect of strobe lights on kokanee and rainbow trout focused on fish detected by the five downlooking transducers. Metrics for the analysis were the number of fish detected in each of the areas covered by one of the downlooking transducers (i.e., 4, 8, 12, 16, and 20 m from the strobe lights), fish swimming effort (detected velocity minus flow velocity), and fish swimming direction. Study findings include the following:

- Under all three treatment conditions, the number of fish increased as the distance from the lights decreased (Section 4.1, p. 4.3).

- More fish were found when 6 strobe lights were on (n = 3745) compared to the number found with 3 strobe lights on (n = 2819) and strobe lights off (n = 2507) (Section 4.1, p. 4.3).

- The difference in numbers of fish between the three treatments was greatest for fish detected by the downlooking transducer closest to the lights (i.e., 4 m) at night. This difference was statistically significant ($p < 0.05$) (Section 4.1, p. 4.5).

- There were no statistically significant differences in counts or behavior metrics for fish detected during the day (Section 4.1, p. 4.5, and Section 4.2, p. 4.11).

- In general, fish swimming effort was mostly upstream and slightly toward the bank side of the forebay for both the 6-lights-on and all-lights-off treatments. Fish swimming effort at night was directed more upstream and at higher speeds when light were on compared to when lights were off (Section 4.2, p. 4.11).

- At night, when the strobe lights were on, fish in the area closest to the lights (4 m) were swimming in all directions. Under the same conditions, farther from the lights, fish were swimming across the forebay, while during the day, the predominant direction of movement was downstream, regardless of treatment (Section 4.2, pp. 4.12 and 4.13).

- The count and behavioral results present contrasting views on the response of fish to the strobe lights. Higher numbers of fish were detected near the strobe lights, but those fish appear to exhibit an avoidance behavior. The precise reason for this is unknown, but it may be speculated that the strobe lights have a secondary effect such as attracting prey species to the lighted region, creating a foraging opportunity for the fish. Given the behavioral results, we speculate that the higher counts may reflect more activity close to the lights rather than a higher density of fish (Section 4.2, p. 4.14).

These results are for the second year of a three-year study, and, as such, any conclusions are preliminary.

Based on the experience and data acquired during 2001 and 2002, along with a general review of strobe lights, the researchers recommend several modifications and enhancements to the follow-on study in 2003. These include the following:

- All splitbeam transducers should be deployed at the surface looking down immediately upstream of the strobe lights to sample the region close to the lights.

- The experimental design should be simplified to include only two strobe light treatments of 24 hr on and 24 hr off. The 24-hr-on treatment should use 6 strobe lights (the 6-lights-on condition elicited a higher response than the 3-lights-on).

- Approximately 500 fish or more from the nearest hatchery/net pen operation should be tagged with radio telemetry tags or acoustic tags to determine the arrival timing of fish to the test site in the third powerplant forebay. This will provide valuable information on the presence of the target species in the strobe light region.

- A controlled experiment should be conducted to determine the effect (attraction or repulsion) of strobe lights on prey species of zooplankton and the relative level of opportunistic feeding that occurs when the prey species are illuminated by strobe lights.

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Abbreviations Used in This Report

ac	alternating current
ADCP	acoustic Doppler current profiler
af	acre-foot
°C	degrees Celsius
cm	centimeter
cfs	cubic feet per second (ft^3/s; 0.0283 m^3/s)
dB	decibel
dc	direct current
df	degrees of freedom
DGPS	digital global positioning system
DNA	deoxyribonucleic acid
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
HDF5	Hierarchical Data Format, version 5
hr	hour
i.e.	(id est) that is
kcfs	1000 cubic feet per second
kHz	kilohertz
lx	lux
m	meter
mi	mile
MW	megawatt
N	north
NTU	nephelometric turbidity unit(s)
NWPPC	Northwest Power Planning Council

Pa	Pascal
pdf	probability density function
PNNL	Pacific Northwest National Laboratory
pps	pings per second (acoustics) or pulses per second (light)
s	second
S	south
SI	International System of Units
TS	target strength
UPS	universal power supply
V	volt
W	west

Glossary

anadromous	ascending rivers from the sea for breeding
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	a reservoir or canal 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 (0.123 348 hectare meter).
hydroacoustics	the use of transmitted sound to detect objects (e.g., fish) in 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
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 region 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
tortuosity	the extent to which a fish's behavior is marked by repeated turns
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.

Contents

Figures

Tables

1.0 Introduction

This report documents the second year of a three-year study to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee salmon (*Oncorhynchus nerka*) and rainbow trout (*O. mykiss*) in the forebay to 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 above 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 salmon, rainbow trout, white sturgeon (*Acipenser transmontanus*), and walleye *(Stizostedion 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 kokanee stocks in Lake Roosevelt, the reservoir behind Grand Coulee Dam, are related to annual water regimes, shoreline spawning, fish entrainment, and forage production (Scholz et al. 1985; Peone et al. 1990; Griffith and Scholz 1990).

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 stock or stocks. 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 up-river stocks, including the “free-ranging” up-river 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.

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 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/hr 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 mitigate this loss of resident fish. The panel further suggested 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).

There is a long history of using lights 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 were similar to those found in subsequent studies; that is, the response is species-specific. 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 has been noted for chinook salmon smolts during nighttime hours (Amaral et al. 2001; Mueller et al. 2001), while in another study the density of juvenile salmon was lower 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, while older predator fish are less likely to shun light. 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). Studies of kokanee exposed to strobe lights showed an immediate avoidance reaction to lights, with a more pronounced response in winter when turbidity was reduced (Maiolie et al. 2001).

The scope of work for the Chief Joseph Kokanee Project was modified to include a multiyear pilot test of a strobe light system to help reduce fish entrainment. This report details the work conducted during the second year of the study by researchers affiliated with the Chief Joseph Kokanee Project and the Pacific Northwest National Laboratory.

1.2 Report Contents

Section 2 of this report describes the study site at Grand Coulee Dam. Section 3 provides the methods for hydroacoustic assessment techniques and statistical analysis. Results are presented and discussed in Section 4. Section 5 lists the conclusions and recommendations based on the study results. References are in Section 6. Appendixes A through F provide supporting information: ancillary data collected during the study, details of the statistical analysis, results from the characterization of the strobe lights and hydroacoustic system, characterization of the water flow within the forebay of the third powerplant, and additional figures showing the direction of movement for fish detected near the strobe lights.

2.0 Study Site Description

The study site was the entrance to the third powerplant forebay on Lake Roosevelt, the reservoir impounded by Grand Coulee Dam. The study site description is presented 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.

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 power-plant 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° to the axis of Grand Coulee Dam. 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 (Figure 2.3).

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

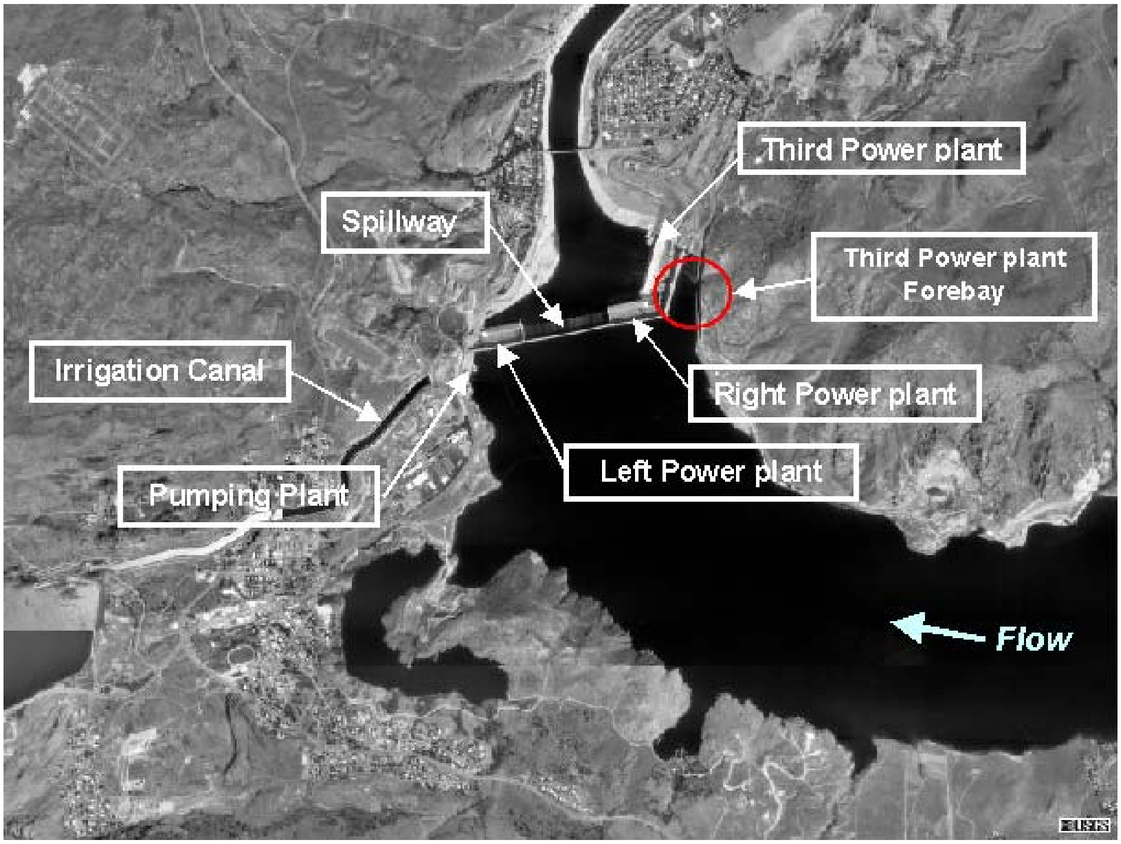

Figure 2.2. Study Site Location (red circle) Near Third Powerplant, Grand Coulee Dam in 2002

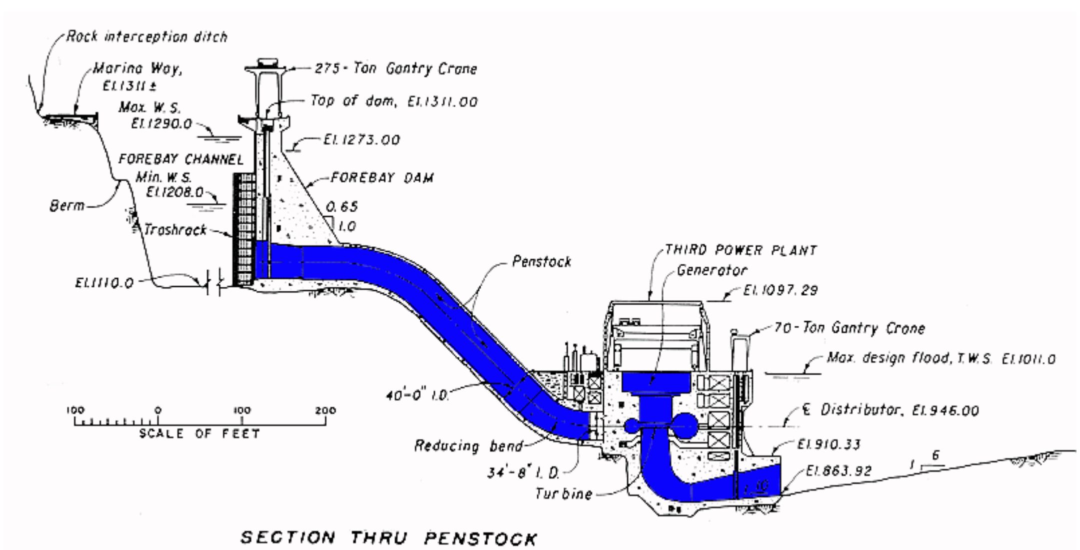

Figure 2.3. Cross Section of Third Powerplant and Forebay Dam at Grand Coulee Dam, Washington (Hubbard 2002)

The 33 generators at Grand Coulee have a total generating capacity of 6809 MW. Table 2.1 shows the distribution of power generation at various locations within the dam. 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. The 243-km (151-m) -long reservoir created by the dam, Lake Roosevelt, 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 (Hubbard 2002)

Location	Description	Number of Generators	Capacity, Each (MW)	Total (MW)
Pumping plant	Pump/generator	2	50	314
		4	53.5	
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 and, during much of the study period in 2002, represented 60% to 75% of the total powerplant discharge (Figure 2.4). As in 2001, much of the third powerplant discharge during 2002 occurred during the daylight hours (Figure 2.5). Current-year operations data were supplied by the U.S. Bureau of Reclamation (Randy Spotts, personal communication).

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

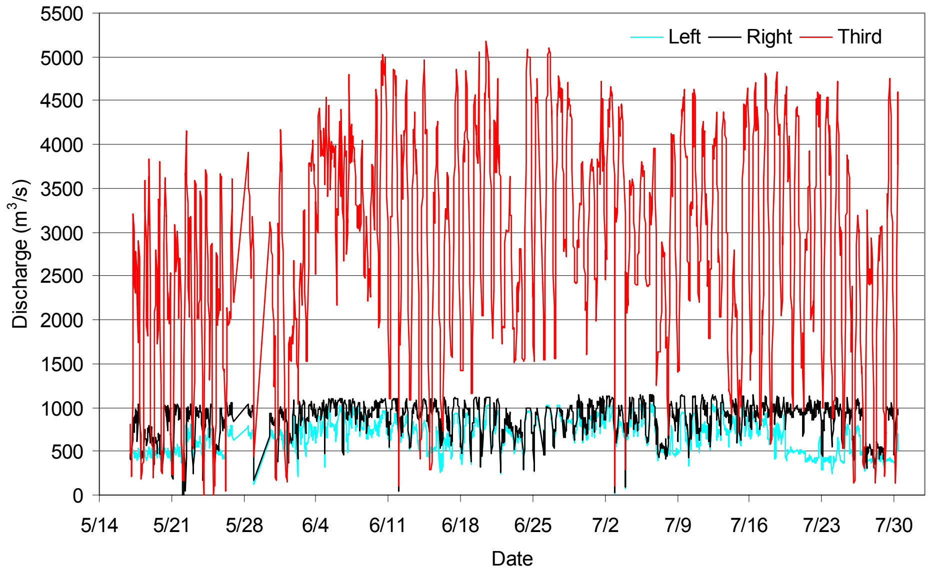

Figure 2.4. Discharge (m^3/s) at Grand Coulee Dam from May 18 through July 30, 2002. Data for the average discharge for each powerplant are plotted separately.

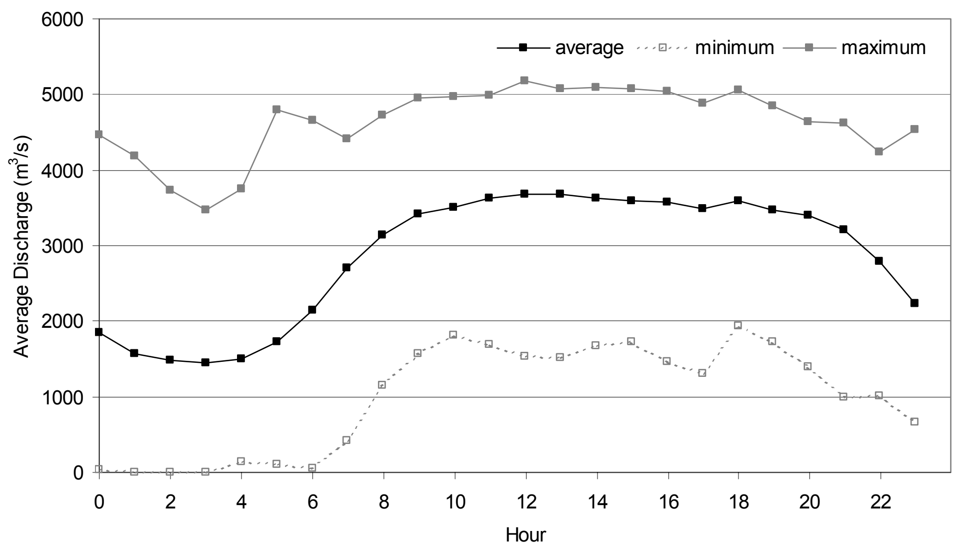

Figure 2.5. Discharge over 24 Hours at Third Powerplant at Grand Coulee Dam. Data were averaged over the period May 18 through July 30, 2002. Zero hour is midnight.

3.0 Methods

The objective of this study was to determine the efficacy of a prototype strobe light system to elicit negative phototactic response in kokanee and rainbow trout at the entrance to the forebay of the third powerplant at Grand Coulee Dam. The methods used to support that determination are documented in this section.

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 (Figure 3.1). The strobe lights, supplied by Flash Technology, Franklin, Tennessee, were sealed specifically for underwater deployment. The frame was deployed from a barge secured in the center of the entrance to the third powerplant forebay (Figure 3.2). 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 directional information.

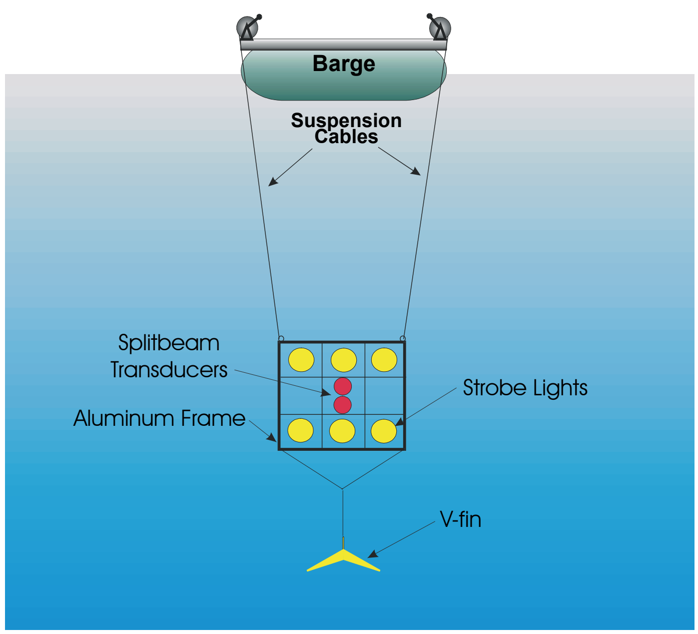

Figure 3.1. Strobe Light and Splitbeam Hydroacoustics Deployment from Fixed Barge. View from upstream (not to scale).

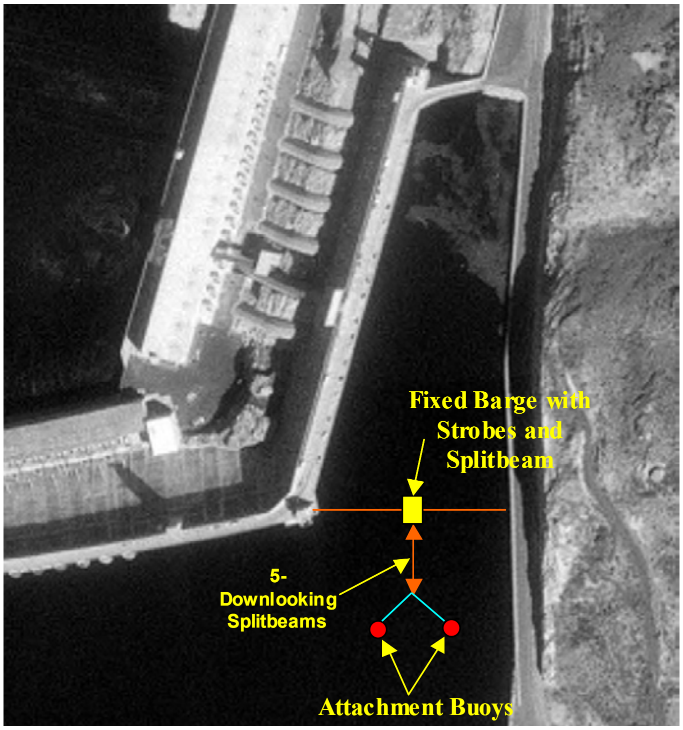

Figure 3.2. Location of Strobe Light Test Site at Third Powerplant Forebay of Grand Coulee Dam

The strobe lights were aimed to illuminate a restricted region directly upstream of the barge location (Figure 3.3). The depth to the top of the light frame was approximately 15 m, and the flash rate was set at 360 flashes per minute as in 2001 (Simmons et al. 2002). Little has been published about the characteristics of the strobe lights used in this study. Therefore, we measured their characteristics both in the field and in the laboratory using two types of light detectors. The light measurements are described in detail in Appendix C, Strobe Light Characterization.

3.2 Hydroacoustic Deployment

A seven-transducer splitbeam system 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°, 420-kHz splitbeam transducers lensed to 10°; and associated power and telemetry cables (Figure 3.4). The seven transducers were fast-multiplexed at 20 pings per second (pps). The system was powered by a 110-V alternating current (ac) load center stationed on the deck of the dam by the U.S. Bureau of

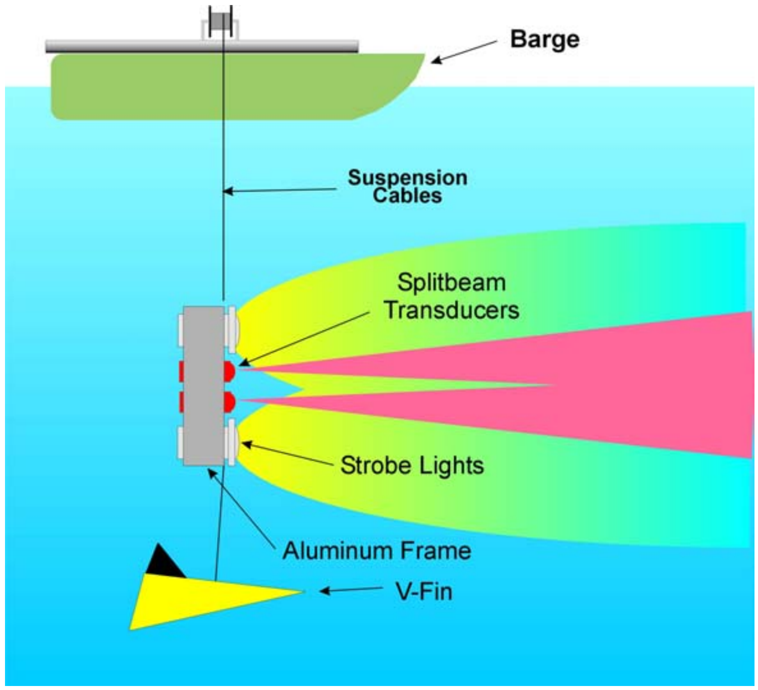

Figure 3.3. Strobe Light and Hydroacoustic Transducer Frame Configuration at Grand Coulee Dam, Spring 2002. Side view showing area illuminated and ensonified (not to scale).

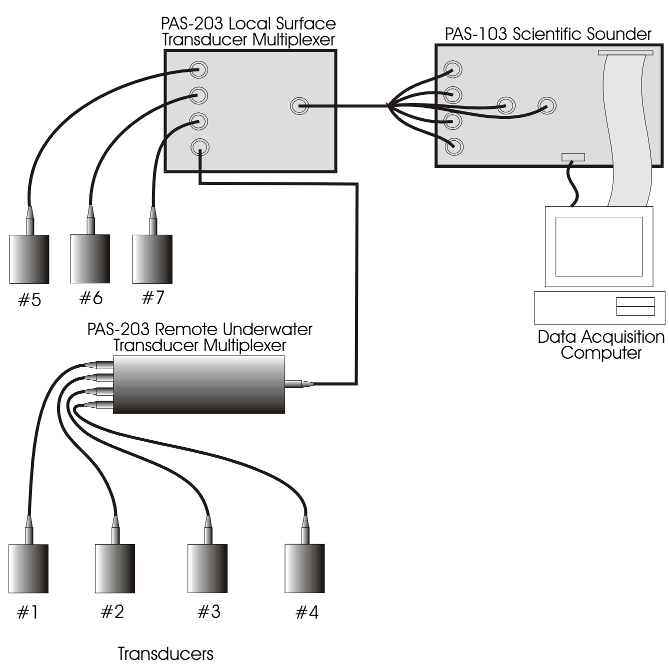

Figure 3.4. Seven-Transducer Multiplexed Splitbeam Hydroacoustic System (Precision Acoustic Systems, Seattle, Washington)

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 D.

Two of the seven splitbeam transducers were mounted to the frame containing the strobe lights (Figure 3.1). The two transducers faced horizontally and were canted upward and downward, respectively, approximately 5° from horizontal at the center of the frame. The frame-mounted transducers were used to provide data for comparison to results from the 2001 study. The remaining five transducers were spaced approximately 4 m apart on individual floating frames upstream of the barge with the transducers looking vertically downward. The floating frames were tethered to a floating line that connected the barge to the upstream anchor buoys (Figure 3.5).

3.3 Current Profiler Deployment

Water velocities beneath the barge site were sampled at frequent intervals during the summer study period (May 2 through July 30). Water velocities were gathered using a 600-kHz acoustic Doppler current profiler (ADCP) mounted onto the bow of the barge (downward orientation) as shown in Figures 3.5 and 3.6. The RD Instruments Workhorse ADCP emits four acoustic beams that are placed 90° apart around the head of the unit (Figure 3.7). Each beam of this custom workhorse is also tilted 6° off axis from the centerline of the unit. The resulting swath from the four beams is pyramidal in shape, with the smallest part of the pyramid at the head of the unit.

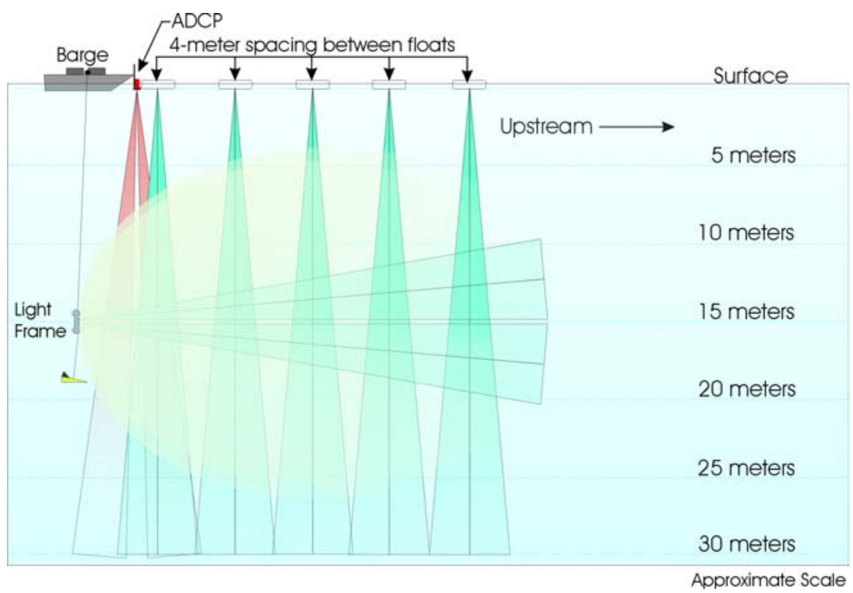

Figure 3.5. Deployment of Splitbeam Transducers, Acoustic Doppler Current Profiler, and Strobe Lights at Grand Coulee Dam, Spring 2002. Side view showing area illuminated and ensonified is approximately to scale.

Figure 3.6. Downlooking Acoustic Doppler Current Profiler Mounted on Chief Joseph Kokanee Project Boat

Figure 3.7. Acoustic Doppler Current Profiler (RD Instruments, Inc.)

The ADCP was programmed to collect data in 5-min intervals. During the interval, the ADCP collected 420 individual readings. These readings were averaged together internally by the instrument to reduce the theoretical error standard deviation for each ensemble measurement to 3 cm/s. The ADCP was also programmed to gate (i.e., average) the results over 0.5-m vertical bins. Over the sampling period (May through July 2002), approximately 61 days of data were collected.

Mobile ADCP measurements were performed in Lake Roosevelt on May 2 and 3, 2002. A 300-kHz 20° workhorse ADCP capable of profiling throughout the entire water column depth was used for this study. The ADCP was programmed to collect ensemble velocity measurements at 30-s intervals, with 40 pings per ensemble reading. The theoretical error standard deviation for each ensemble measurement was approximately 3 cm/s. Results from these surveys are presented in Appendix E.

Velocity measurements were collected at 19 locations around the reservoir. At each location, the horizontal position was recorded using a real-time differential global positioning system (GPS) with horizontal accuracy of 1 to 2 m. In addition, because the flows measured by the ADCP are turbulent and fluctuate over time, more than 20 velocity measurements (i.e., at least 10 min of data) were recorded at each location.

3.4 Data Processing

The data collected at Grand Coulee in 2002 were stored in a centralized location to allow for data transfer, storage, and archiving. The centralized location also facilitated access to data during the processing and analysis phases. A Microsoft® Windows® 2000 server with 300 GB of storage and a digital linear tape autoloader were dedicated to this project to serve as the main storage and processing system (Figure 3.8). Several other Windows-based machines provided additional support with processing and analysis. Computers were linked via the Pacific Northwest National Laboratory intranet with an external wireless Internet link 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, then transferred via wireless internet to PNNL's Richland office. All raw and processed data and supporting files were archived to tape for long-term storage.[a]

A data management system was utilized to organize and store all the data. This management system is based on the Hierarchical Data Format (HDF5) software platform developed by the National Center for Supercomputing Applications in collaboration with Lawrence Livermore National Laboratory, Sandia National Laboratories, and Los Alamos National Laboratory. The HDF5 system was developed to manage large, complex data sets and consists of an input/output library and utilities, which are used to store data in a self-describing format. Data entry into the HDF5 is facilitated through a series of "windows" developed at PNNL (Figure 3.9). These access points ensure that all the data and metadata (information about the data) are collected and stored. A web-based browser is used to access the data.

Acoustic data files were processed using software developed in-house 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). Approximately 1% of the data was tracked manually; these data were selected randomly from periods of maximum darkness (around midnight) and light (around noon).

(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.

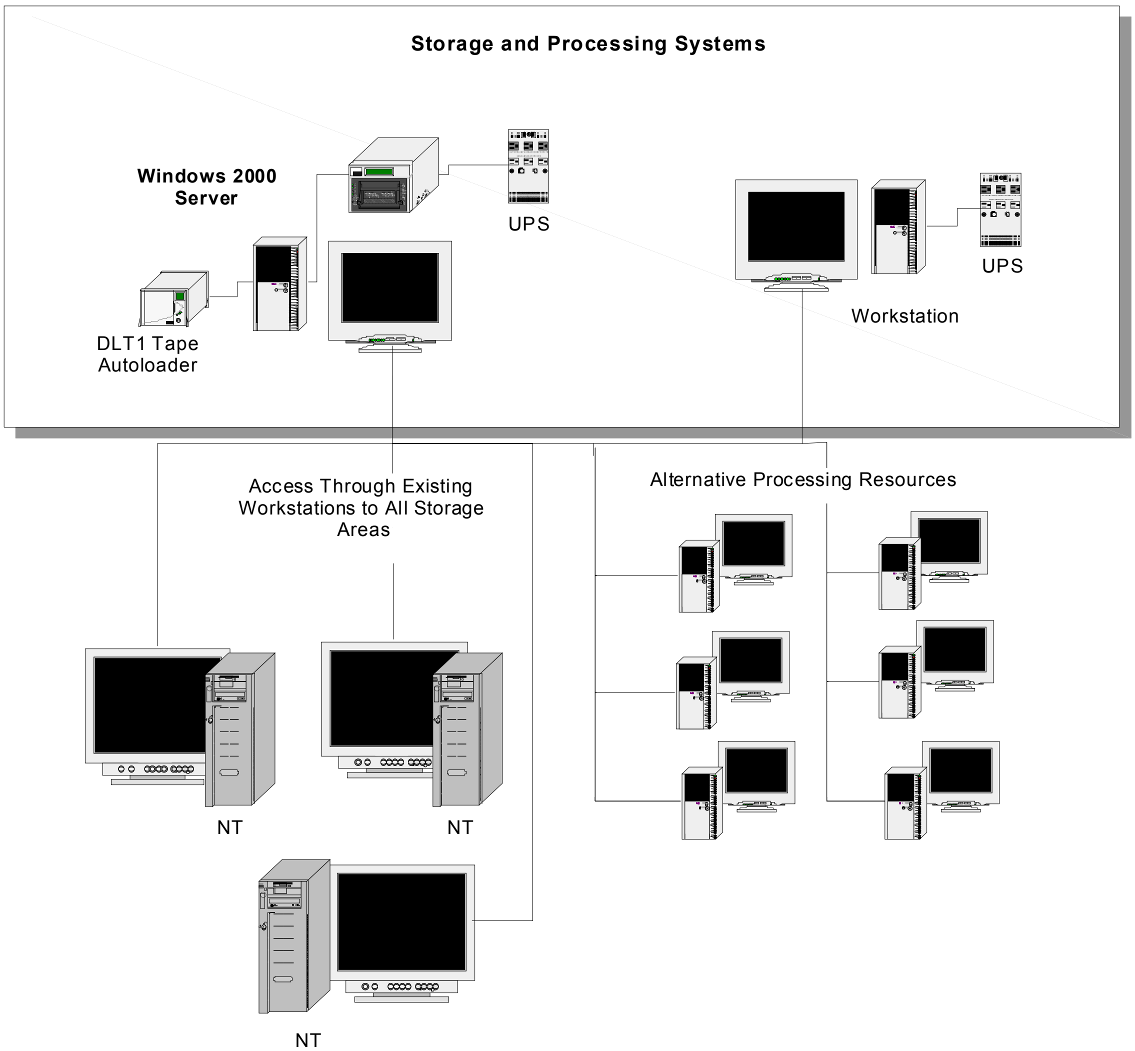

Figure 3.8. Computer Resources in Support of Data Processing Tasks

Manual tracking allowed us to develop the tracking criteria needed for autotracking calibration and to screen the data for possible noise events. The autotracking software subsequently processed all data collected from the splitbeam transducers.

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. The movement of a fish is described by a sequence of locations (position vectors), which are 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 (Figure 3.10). Before analysis, 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

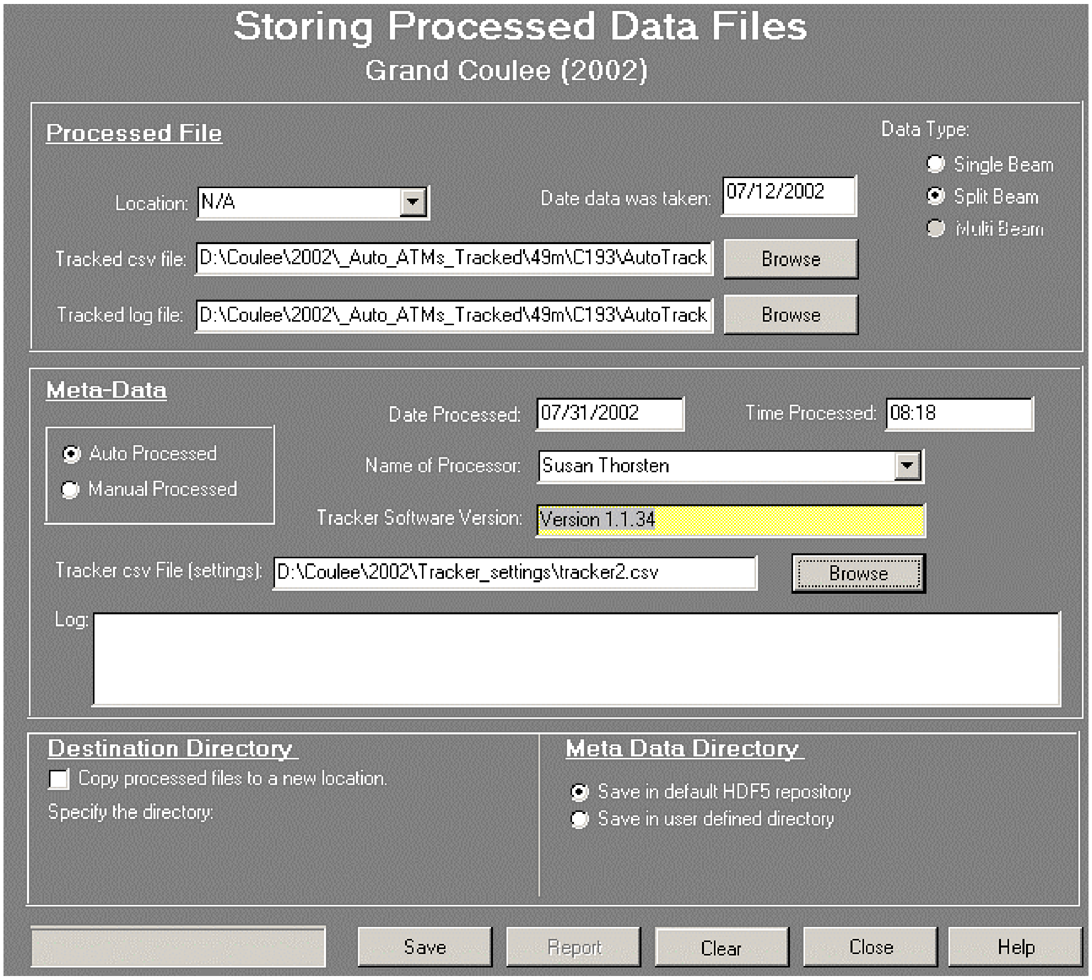

Figure 3.9. Example of Data Entry Tool for the HDF5 Data Storage System

tracks by filtering and smoothing must be done to obtain the most accurate estimate possible of the overall displacement velocity that is allowed for by the measurement conditions.

In filtering the tracks, a restriction is placed on the amount of angular deviation expected between sequential track segments. For this study, we allowed no more than a 2° deviation in the x/y plane between sequential position vectors. Deviations greater than a 2° mechanical angle are viewed as physically impossible based on the likely swimming velocity of the particular fish species being tracked. (Note that the choice of allowed angular deviation is a judgment based on prior knowledge of how quickly a fish could actually move between locations. Using smaller or larger allowed angular deviation controls the aesthetic smoothness of a target path.) Displacement vectors with mechanical angle change exceeding this limit were eliminated from the track. A second filter eliminated tracks with less than six echo locations remaining after the first filter. The selection of six echo locations was based on an analysis of the minimum number of echoes expected for the angle of the splitbeam (6°) and ping rate (10 pps). A

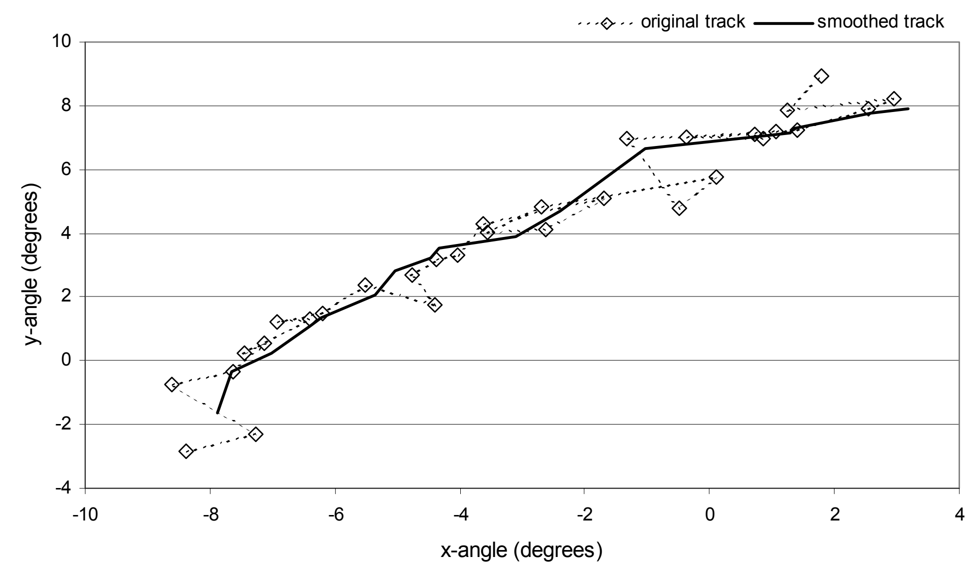

Figure 3.10. Example Fish Track as Developed by Hydroacoustic Hardware and Software and After Filtering and Smoothing. This view shows the track's projection (image) in the x/y plane, perpendicular to the beam's range axis.

minimum number of echoes ensured that tracks included enough information to calculate the behavior metrics. Allowing a sufficient number of echoes in a track ensures that the path is adequately defined to identify a fish's passage through the acoustic beam. A track that contains too few echoes may be only a segment of another track or the detection of a temporary air bubble.

After filtering, the tracks were smoothed by fitting a second-degree polynomial in time to the echo locations (for each of the x, y, z coordinates) for each track. Thus, the shape of a fish track was interpreted as parabolic in its most general form. Usually, fish tracks passing through a narrow splitbeam zone (about a 10° cone) have only slightly curved apparent trajectories. Of course, the track of a fish would be more complicated if it were observed over greater distance and time, but a polynomial description is considered adequate to represent the shorter track segments detected in the conical hydroacoustic beam. The parabolic description is also adequate to estimate the displacement velocity over the track segments as measured within the splitbeam zone. The accuracy of each parabolic fit or track rendition is monitored by a joint correlation coefficient calculated for each target. A correlation value can be used to select a target population that does not have ambiguous movement behavior.

3.5 Study Design

Three light level treatments were used in this study: 6 of 6 lights on, 3 of 6 lights on, and all lights off. These three treatment conditions were applied for an entire 24-hr day and were randomly assigned within a 3-day block throughout the study period (Table 3.1). To equalize the usage of the strobe lights, there were two configurations of the 3-lights-on treatment: 1) 2 outside lights on the top and the middle

Table 3.1. Treatment Design of the 2002 Grand Coulee Dam Study

Date	Treatment	Block	Date	Treatment	Block
5/18/2002	off[(a)]	1	6/25/2002	off	12
5/19/2002	6-on[(b)]	1	6/26/2002	6-on	12
5/20/2002	3-on[(c)]	1	6/27/2002	3-on	12
5/21/2002	off	2	6/28/2002	calibration	
5/22/2002	6-on	2	6/29/2002	off	13
5/23/2002	3-on	2	6/30/2002	6-on	13
5/24/2002	calibration[(d)]		7/1/2002	3-on	13
5/25/2002	off	3	7/2/2002	6-on	14
5/26/2002	3-on	3	7/3/2002	off	14
5/27/2002	6-on	3	7/4/2002	3-on	14
5/28/2002	off	4	7/5/2002	calibration	
5/29/2002	6-on	4	7/6/2002	6-on	15
5/30/2002	3-on	4	7/7/2002	off	15
5/31/2002	calibration		7/8/2002	3-on*	15
6/1/2002	off	5	7/9/2002	off	16
6/2/2002	6-on	5	7/10/2002	6-on	16
6/3/2002	3-on	5	7/11/2002	3-on	16
6/4/2002	6-on	6	7/12/2002	calibration	
6/5/2002	3-on	6	7/13/2002	off	17
6/6/2002	off	6	7/14/2002	6-on	17
6/7/2002	calibration		7/15/2002	3-on	17
6/8/2002	3-on	7	7/16/2002	6-on	18
6/9/2002	off	7	7/17/2002	off	18
6/10/2002	6-on	7	7/18/2002	3-on	18
6/11/2002	6-on	8	7/19/2002	calibration	
6/12/2002	off	8	7/20/2002	off	19
6/13/2002	3-on	8	7/21/2002	6-on	19
6/14/2002	calibration		7/22/2002	3-on	19
6/15/2002	off	9	7/23/2002	3-on	20
6/16/2002	3-on	9	7/24/2002	6-on	20
6/17/2002	6-on	9	7/25/2002	off	20
6/18/2002	3-on	10	7/26/2002	calibration	
6/19/2002	6-on	10	7/27/2002	6-on	21
6/20/2002	off	10	7/28/2002	3-on	21
6/21/2002	calibration		7/29/2002	off	21
6/22/2002	off	11	7/30/2002	3-on*	22
6/23/2002	6-on	11	7/31/2002	6-on	22
6/24/2002	3-on	11	8/1/2002	off	22

(a) Off: all six strobe lights off.
(b) 6-on: all six strobe lights on.
(c) 3-on: three strobe lights on.
(d) calibration: ancillary and calibration data collected.
* Grayed-out areas indicate periods during which strobe lights were not functioning.

light on the bottom and 2) the middle light on the top with the 2 outside lights on the bottom. The first configuration was assigned to odd-numbered blocks, the second configuration to even-numbered blocks. Each 24-hr 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.

3.6 Data Analysis

Statistical analyses were used to test the null hypothesis that the strobe lights had no effect on the number or behavior of fish within the illuminated region. For fish counts, we were interested in differences in the distribution of fish counts for similar regions and periods of the day. For fish behavior, we examined the data for direction, speed of fish tracks, and swimming effort. If the strobe lights had no effect on swimming behavior, we expected the direction and speed of movement would be independent of the light condition (i.e., on or off).

3.6.1 Fish Track Distribution

The fundamental premise of this analysis is that the response of kokanee and rainbow trout to strobe lights can be characterized by the relative number of fish present under the all-lights-off, 3-lights-on, and 6-lights-on treatment conditions. In addition, the number of fish may be affected by environmental and experimental factors occurring in concert with the strobe light treatments. For example, the volume sampled by the hydroacoustic transducers is conical, with the narrower sample volume close to the transducer, expanding to a larger volume farther away. Thus, the distribution of fish within the beam is not invariant.

Another factor that could potentially bias counting of fish is the presence of noise in the hydroacoustic data, which makes it more difficult for the software to identify real fish targets. For the downlooking transducers, this noise was most prevalent beyond 30 m. The noise in this region was due in part to a false-bottom effect. Also, the sidelooking transducer detected a preponderance of small targets with little structure in the trace (i.e., no progression in the x/y plane) beyond the last downlooker (>20 m from the light frame). For this reason, we restricted our analysis to targets detected within 30 m of the surface for data from the downlooking transducers and 30 m from the light frame for data from the sidelooking transducers.

Also, identification of fish is affected by the aspect of ensonification, which can influence the resulting counts. For the 2002 study, fish approaching the strobe lights presented a primarily dorsal aspect to the downlooking transducers, while the aspect for the sidelooking transducers could be head or tail or lateral. Thus, fish tracks detected by the sidelooking transducers are more variable and require more filtering to distinguish them from noise. Because the data from the downlooking transducers were more comparable – that is, they ensonified similar regions – and because fish have similar orientations within the acoustic beam, only these data were used for the analysis of count data. Data from both sets of transducers were used in the fish behavior analysis (Section 3.6.2).

Two further considerations can affect interpretation of the results. First, it is not possible to identify fish species using hydroacoustics. We do obtain information, indirectly, about the size of the target ensonified, which allows an inference as to the fish species. The second consideration is that the same fish may be counted more than once, so counts do not represent unique fish occurrences.

Due to the factors discussed above, the estimates of fish abundance used in the analysis should not be considered as absolute but rather as indices of abundance.

Table 3.2 shows the factor or classification variables used in the statistical analysis and their definitions. In addition to the strobe light treatments, factors included in the analysis were position with respect to the strobe lights (each downlooking transducer corresponds to a distance from the lights), discharge through the third powerplant, time of day, treatment block (3-day period encompassing all three treatments), and target size (TS ≤-47 dB, >-47 dB). Each track is classified into one and only one class level for each factor variable shown in Table 3.2.

Statistical analysis of the count data were based on multidimensional contingency tables that display fish counts as a function of the factors in Table 3.2. The tables were evaluated statistically using a log-linear model (sometimes called a Poisson regression model). This model is widely used, particularly in fisheries and wildlife research where data are frequently in the form of survey counts (Van Der Meer and Camphuysen 1996; Jackson et al. 1992).

Fitting a log-linear model to data involves setting one of the class levels for each factor as a reference level, with comparisons made to the referenced 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 also called an odds ratio. Statistical significance for the parameter estimates from the fitted log-linear model were 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 B.

3.6.2 Fish Behavior

Analyzed behavior quantities included regressed initial and final track locations to determine target distributions, and displacement velocity vectors. Displacement vectors are the difference between the estimated end locations of each track. Displacement velocity is the displacement vector divided by the observation time, which is the time during which the detected fish passed through the splitbeam zone. Vectors 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 velocity vectors were used to determine fish swimming speed for each of the three directions. Velocity vectors were used also in conjunction with flow data to estimate swimming effort. The observed fish swimming speed is a function of the fish's swimming effort plus the flow field velocity in which it was detected. Swimming effort is calculated by subtracting the effect of the flow field velocity from the observed swimming activity (displacement velocity) using vector arithmetic. Plots of swimming effort reveal a fish's actual behavior because these vectors indicate whether a fish was actively swimming with the flow, against the flow, or crossing flow lines. Flow data used in this analysis were collected by the

Table 3.2. Definition of Factor Variables

Factor Variable	Code	Class Level	Description
Treatment			The strobe light treatment variable of interest.
	1	0 lights	Lights off. This is the treatment control or reference condition.
	2	3 lights	3 of 6 strobe lights on.
	3	6 lights	6 of 6 strobe lights on.
Position			The position of down-looking transducers located at 4-m intervals upstream from the strobe lights.
	1	4 m	Fish tracks located 4 m from the strobe lights.
	2	8 m	Fish tracks located 8 m from the strobe lights.
	3	12 m	Fish tracks located 12 m from the strobe lights.
	4	16 m	Fish tracks located 16 m from the strobe lights.
	5	20 m	Fish tracks located 20 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.
Discharge category			Total discharge in thousands of cubic feet per second (kcfs) through the third powerplant, recorded on 5-min time intervals. Each fish track was matched to the nearest-in-time recorded value.
	1	Low	Low - 1st quartile: 0 – 41.69 kcfs
	2	Medium	Medium - 2nd to 3rd quartile: 41.70 - 118.66 kcfs
	3	High	High - 4th quartile: 118.67 - 182.84 kcfs
Target strength/size			Mean target strength computed on all echoes used to define a fish track.
	1	TS $\leq$-47	Fish tracks with mean target strength less than or equal to -47 dB.
	2	TS >-47	Fish tracks with mean target strength greater than -47 dB.
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.
Block	1-22	Values 1-15 and 19-21	Randomized block composed of 3 days each with the three levels of treatment randomly ordered. Note: blocks 15-18 and 22 were incomplete and not used in this analysis.

ADCP at the barge. Because the flow field data were not collected exactly where the fish were located, the results are only suggestive of swimming effort. However, given the small study area and the apparent uniformity in flow (Appendix E), we used the flow measurements as an approximate estimate of what the fish experienced.

Fish behavior is described primarily by the displacement vector, which indicates both direction and speed of movement. The direction of movement can be converted to polar coordinates that may then be analyzed using the methods of circular statistics (Fisher 1993). One of the metrics in circular statistics is the concentration parameter that gives 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. The statistical test for comparing the concentration parameter is the null hypothesis that all concentration parameters are equal (i.e., $H_o : \kappa_1 = \kappa_2 = \ldots = \kappa_r$ vs H_a: at least one κ not equal). The test statistic was evaluated using a randomization analysis on 500 random permutations of the data (Manly 1998). A more complete description of these methods is in Appendix B.

Behavioral metrics are also evaluated using *probability distributions*. A probability distribution is the normalized frequency of occurrence. Cumulative probabilities indicate the percentage of the population having values less than a given percentile for a particular metric, and the derivative of the cumulative probability is the *probability density function* (pdf) for the metric. If samples of fish behavior metrics from different treatment conditions (6-lights-on or lights off) have nearly the same pdf for a specific metric, then fish behavior with respect to that metric probably was not influenced by the treatment. One way to compare the distributions is to use the median of the pdf, which is the 50th percentile of the distribution, where one-half of the observations have a value less than the median, and one-half of the observations have a value greater than the median.

Probability is nearly essential to use in behavior interpretation because the tracks of a sampled fish population are essentially random events. Probability density allows for identifying certain aspects of movement when there is going to be a multitude of not exactly identical responses to influences such as water flow velocity, lights, or other treatment variables. Thus, a probability frequency interpretation of fish behavior quantities (random variables) was used as a basic tool in this study.

4.0 Results and Discussion

Analysis of the effect of strobe lights on the abundance and behavior of kokanee and rainbow trout was based on fish detected between May 18, 2002, and July 30, 2002 in the forebay of Grand Coulee Dam. The results of our quantitative and statistical analyses are presented and discussed in this section.

4.1 Fish Distribution

Fish tracks used in the analysis represent a subset of a larger dataset; selection criteria described in Section 3 were used to ensure that the selected tracks exhibited fish-like behavior. Initially, the tracking program identified approximately 145,000 potential fish tracks. This number was reduced to 44,403 through the use of selection criteria. Of the remaining 44,403 fish tracks, subsets based on distance from the strobe lights (range), treatment block, target size, and transducer orientation were used in various analyses.

As discussed in Section 3, an increase in noise beyond 30 m depth for the downlooking transducers and beyond 30 m in range for the sidelooking transducers hindered track detection. For this reason, we restricted our analysis to fish tracks identified within 30 m depth (downlookers) and 30 m from the lights (sidelookers). A further restriction used for the statistical analysis of count data was that each treatment be represented by a 24-h period in each block (i.e., complete block). On the morning of July 8, 2002, a storm event inundated the equipment stored on the barge and caused all equipment to fail. This resulted in a number of non-sampled blocks and some that did not include all the treatments. Of the 22 planned blocks, 17 were complete.

Hydroacoustic techniques provide little information on the fish species detected. However, data are available in the form of fish lengths that can be used to estimate the acoustic size (target strength, TS) of the fish detected (Love 1977). Based on data supplied by the Lake Roosevelt Net Pen Program on the sizes of rainbow trout released upstream of Grand Coulee Dam in Lake Roosevelt in 2002, we calculated that these fish would have target strengths around -40 dB. Release data were not available for kokanee at the time of this report; however, we did have data from a kokanee derby, where fish lengths ranged from 21.5 to 49.2 cm which yields target strengths of -38 to -32 dB. These target strengths are similar to those reported last year for released kokanee (Simmons et al. 2002). Figure 4.1 shows the distribution of target strength for fish detected during this study period using splitbeam hydroacoustics. The distribution is bimodal, suggesting the presence of two or more size classes of targets. We used the midpoint between the two peaks to divide the target strength into two size categories: TS ≤-47 dB and TS >-47 dB. It is assumed that the larger target strengths (TS >-47 dB) represent kokanee and rainbow trout. Smaller target strengths (i.e., TS ≤-47 dB) may represent sculpins (*Cottus* sp.) (size range 15 to 40 mm), which have been reported at fairly high densities (66 fish/ha) in the lower end of Lake Roosevelt (Voeller 1996). Other species collected in the lower end of Lake Roosevelt near Grand Coulee Dam include carp (*Cyprinus carpio*), largescale sucker (*Catostomus macrocheilus*), walleye (*Stizostedion vitreum*),

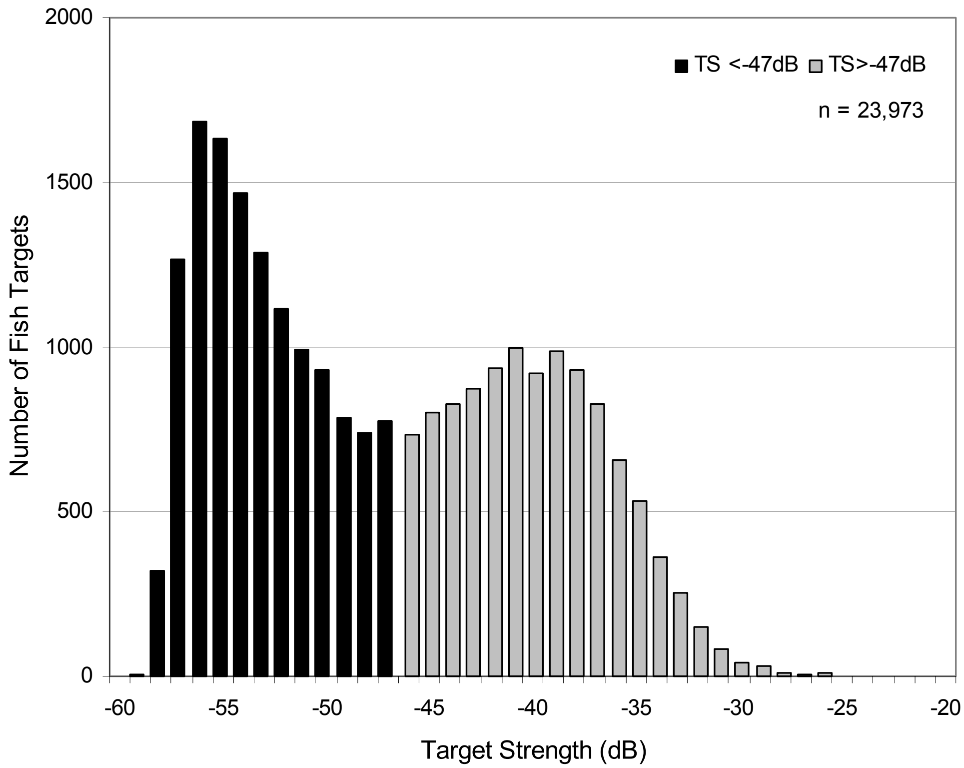

Figure 4.1. Average Target Strength (dB) for Fish Detected Within 30 m of the Transducers in Third Powerplant Forebay of Grand Coulee Dam in 2002

smallmouth bass (*Microptenus dolomieui*), and burbot (*Lota lota*) (Cichosz et al. 1997). We had planned to use nets to collect information on species composition; however, the effectiveness of nets was hindered by high flow in the study area.

Of the seven transducers used in this study, two were oriented horizontally (sidelooking) and five were vertical (downlooking). Because the two sets of transducers ensonified different areas and had different target detection properties, results for each set were analyzed separately. Table 4.1 lists the resulting fish counts for each of these groups. It is evident that most of the small fish (TS ≤-47 dB) were detected by the sidelooking transducers at ranges greater than 30 m. Figure 4.2 shows the distribution of fish within the five downlooking and two sidelooking transducers.

Table 4.1. Fish Counts for Study Period (May 18, 2002–July 30, 2002). Counts are grouped by transducer orientation, acoustic target size (dB), and depth (downlookers) or distance from the lights (sidelookers).

Depth/Distance	Downlookers (5)			Sidelookers (2)			Total
	TS ≤-47 dB	TS >-47 dB	Total	TS ≤-47 dB	TS >-47 dB	Total	
≤30 m	4,459	6,808	11,267	8,548	4,158	12,706	23,973
>30 m	3,065	3,195	6,260	11,421	2,749	14,170	20,430
Total	7,524	10,003	17,527	19,969	6,907	26,876	44,403

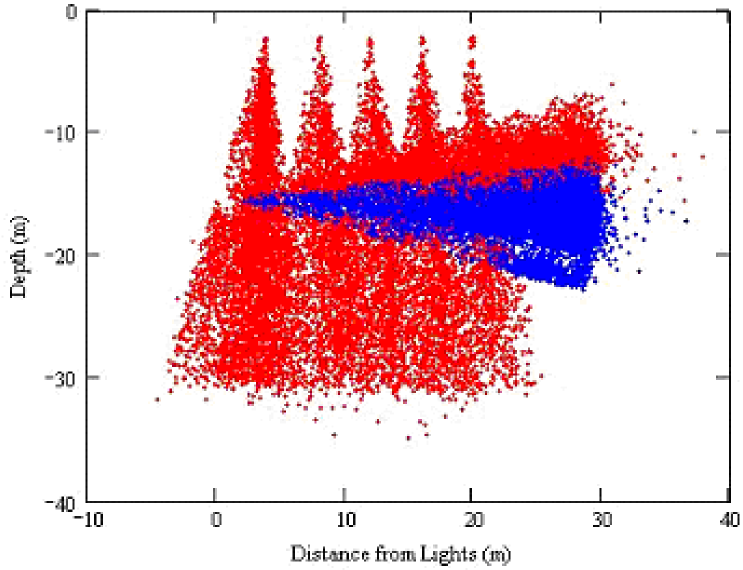

Figure 4.2. Distribution of Fish Targets Detected by Five Downlooking and Two Sidelooking Transducers in Third Powerplant Forebay of Grand Coulee Dam in 2002. Figure shows all echos for each fish where initial position was within 30 m of the transducers. Strobe lights were at 15 m depth.

Of the 11,267 fish detected by the downlooking transducers within 30 m depth, there were 9,071 fish in the 17 complete treatment blocks. These 9,071 fish were analyzed with respect to distance from the light source, time of day, flow conditions at the third powerplant, and target size. Figure 4.3 shows that substantially more fish were detected closer to the light frame at 4 m for all three treatment conditions (i.e., lights off, 3 lights on, and 6 lights on). For the two lights-on conditions, the number of fish targets increased as the distance to the light source decreased. In addition, more fish were detected when 6 lights were on (n = 3,745) compared to 3 lights on (n = 2,819).

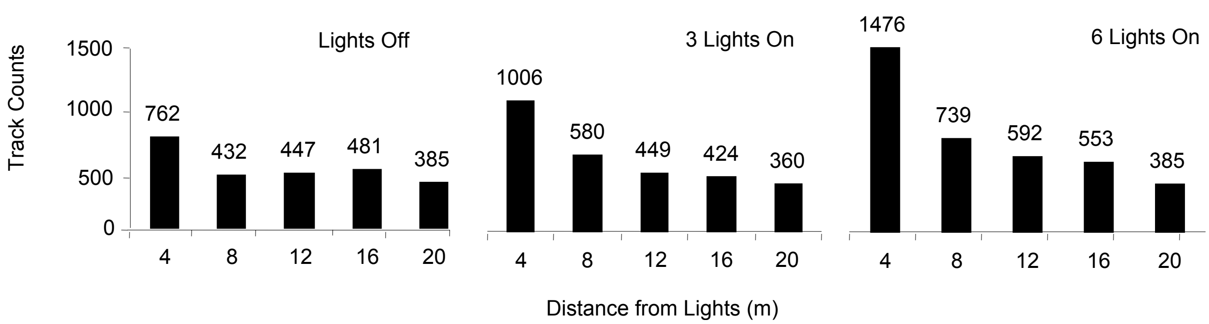

Figure 4.3. Fish Counts for Three Light Treatments as a Function of Distance from Strobe Lights (n = 9,071) for Five Downlooking Transducers (all target sizes, complete blocks only)

A plot of the odds ratio statistic by treatment group and distance from the strobe lights (Figure 4.4) illustrates the statistical analysis of the data in Figure 4.3. The odds ratios (Figure 4.4) are parameter estimates from a fitted log-linear model and provide a statistic to compare the count data from each treatment. Each of the lines in Figure 4.4 shows the relative prevalence of counts for each treatment. For example, the value of 3.83 for the 6-lights-on treatment at the 4-m transducer location indicates that there were approximately 3.83 times as many fish observed under these conditions compared to 6-lights-on treatment at 20 m (i.e., 1476/385). All comparisons in Figure 4.4 are made to the reference condition at 20 m. Statistical significance of the difference between any two odds-ratio point estimates is easily seen in Figure 4.4. If the point estimate of one odds ratio does not overlap the error bar of another, then the difference in the two point estimates is statistically significant at $p < 0.05$, or with 95% confidence.

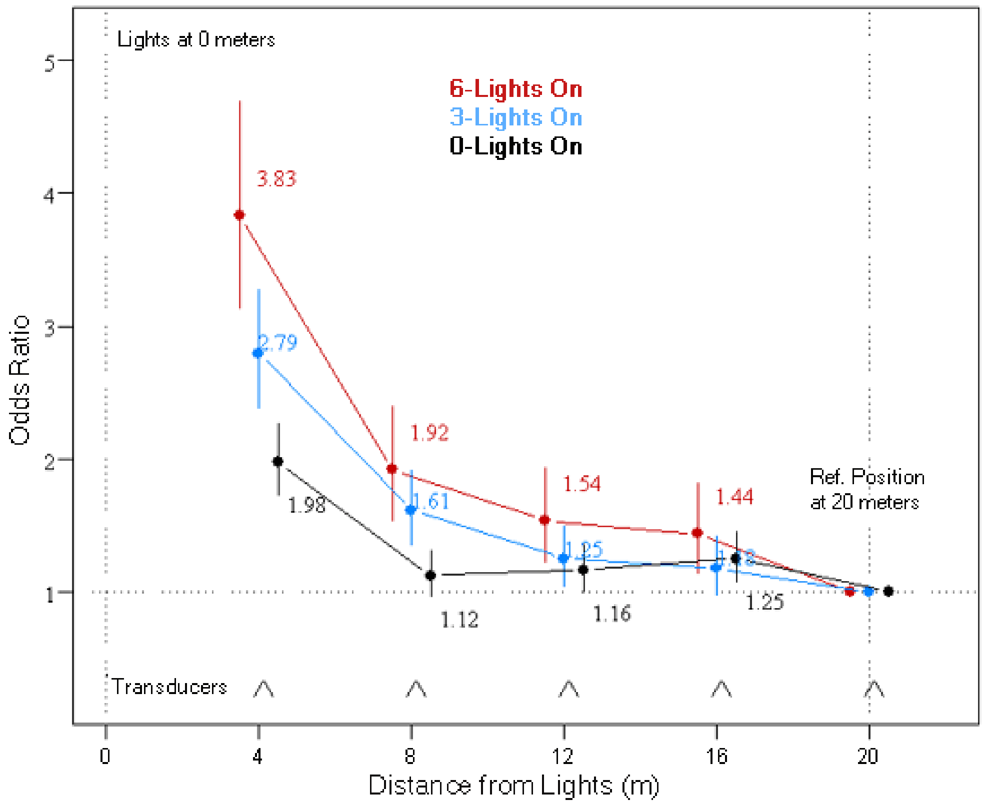

Figure 4.4. Odds Ratio Plot Showing Relative Prevalence of Fish Tracks Under Each Treatment Compared to Common Reference Location at 20 m. Error bars represent 95% confidence intervals based on the χ^2 distribution with 1 degree of freedom. Data represents both size categories detected by downlooking transducers for a 24-hr period.

Based on Figure 4.4, there were no statistically significant differences between treatments at 16 m from the lights; at 12 m, the odds ratio for the 6-lights-on treatment is significantly different from 3-lights-on and lights-off treatments. At 8 m from the lights, a clear difference between the treatments was evident. And, at 4 m, the odds ratios for all three treatments are statistically different from one another ($p < 0.05$). Thus, at 4 m and 8 m, there were significantly more fish present when lights were on (3-lights-on and 6-lights-on) compared to lights off.

Figure 4.3 shows that each treatment has nearly equal counts at 20 m from the lights; that is, 385, 360, and 385 for lights-off, 3-lights-on, and 6-lights-on treatments, respectively. This suggests the effect of the lights, with respect to numbers of fish, is negligible at 20 m, and that the use of 20 m as a common reference was valid.

The data presented in Figure 4.3 and analyzed in Figure 4.4 include all the data collected within a 24-hr period for all 17 complete treatment blocks. The effect of time of day on fish counts with respect to light treatment is shown in Figure 4.5. To obtain the greatest contrast between effects of strobe lights in daytime and at night, fish observed during the hours designated sunrise and sunset (i.e., the hour before and after the event) were not included in the analysis. In Figure 4.5, it is evident that treatment effects

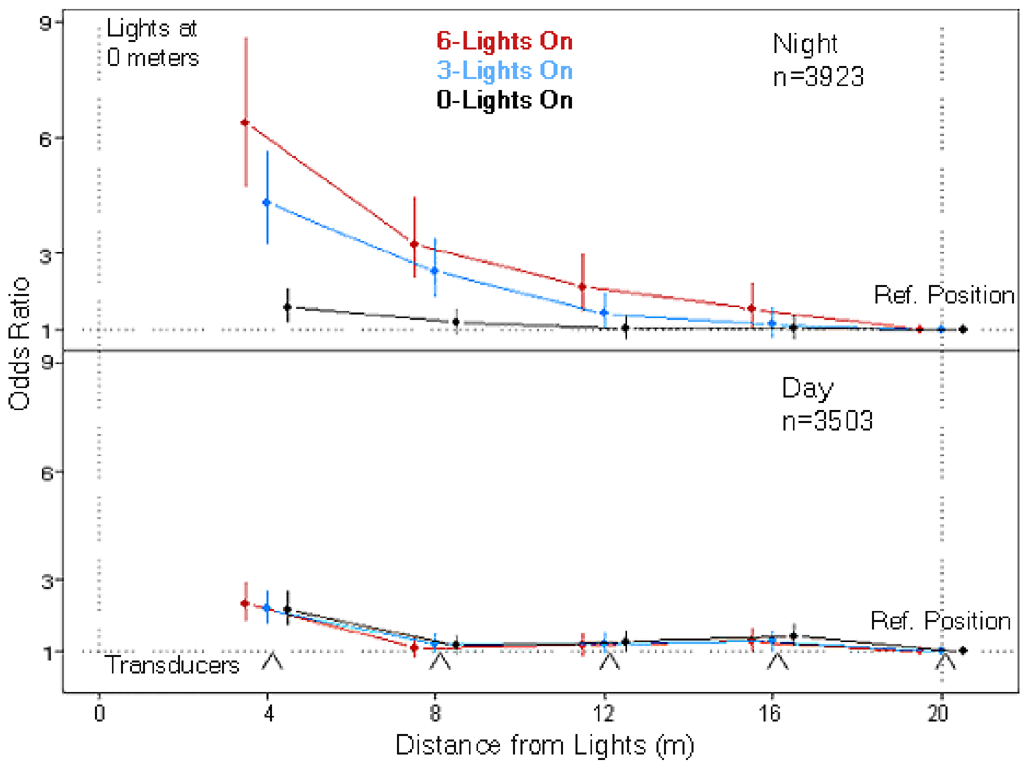

Figure 4.5. Odds Ratio Plot Showing Relative Prevalence of Fish Tracks for Each Treatment Compared to Common Reference Location at 20 m for Fish Detected During Night and Day. Error bars represent 95% confidence intervals based on the χ^2 distribution with 1 degree of freedom. Data represent both size categories detected by downlooking transducers.

were only observed at night. Again, at 4, 8, and 12 m there are significantly more fish present when the lights were on compared to lights off. There were no treatment effects during the day, with the odds ratio being the same for all treatments at all distances from the light. However, during the day, more fish are present closer to the light frame compared to the reference at 20 m. Fish appear to be attracted to the frame regardless of light treatment.

After last year's study, it was determined that discharge levels through the third powerplant were confounding the results; low discharge levels occurred at night, while higher discharge levels occurred during daylight hours. We had hoped to resolve this issue by having periods of controlled discharge so that there would be periods of higher discharge at night and periods of lower discharge during the daytime. However, project operational constraints precluded this option. Once again, daytime discharge levels were generally higher than those at night (see Figure 2.5), confounding the response to ambient light conditions.

To analyze the effect of water flow through the third powerplant, fish counts were matched to average 5-min discharge values. Because some of the flow data were missing, only 8307 fish were used in this analysis. Additionally, ancillary analysis of discharge data indicated that discharge during day and sunset periods and those during night and sunrise periods were similar. Therefore, fish counts were combined into two groups: day-sunset and night-sunrise.

Figure 4.6 shows there are significant differences between treatments at night when discharge through the third powerplant was low (i.e., below 42 kcfs). Again, more fish were present when the lights were on

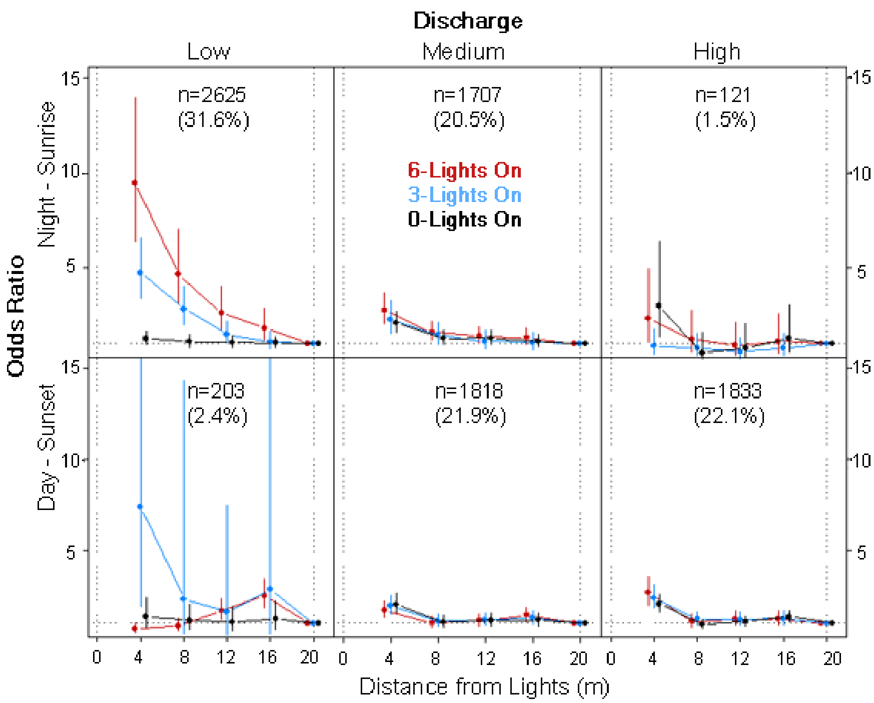

Figure 4.6. Odds Ratio Plot Showing Relative Prevalence of Fish for Three Discharge Levels at the Third Powerplant in Day-Sunset and Night-Sunrise. Discharge levels are defined as low = <42 kcfs; medium = 42 to 119 kcfs; and high = 119 to 183 kcfs.

(both 3 and 6 lights) compared to lights off. There appears to be some treatment effect during the day at low discharge levels; however, the sample size was not sufficient to declare the difference statistically significant. At medium (42 to 119 kcfs) and high (119 to 183 kcfs) discharge levels, there was no difference in the number of fish present under the three treatment conditions, even during the night-sunrise period.

Counts from the medium and high discharge periods all display a similar general pattern with no discernable difference from the reference position at 20 m, except at 4 m, where the odds ratios for all the treatments are statistically different from the reference (Figure 4.6). This indicates that more fish were observed at 4 m from the lights than were observed at 20 m, and the numbers were proportionally the same for all treatments. Again, it appears that fish congregate, to some extent, near the frame, regardless of treatment conditions.

Finally, the effect of target size on the response of fish to strobe lights was analyzed (Figure 4.7). Again there are more fish, of both sizes, present within 4 m of the light frame. The response to lights is statistically significant for both size classes of fish at 4 m, at night. For larger fish (TS >-47 dB), significant treatment effects are evident also at 8 and 12 m. It appears that the increase in the number of fish close to the lights (4 m) for the two lights-on treatments (Figure 4.3) are primarily larger fish (TS >-47 dB) at night when discharge levels are low.

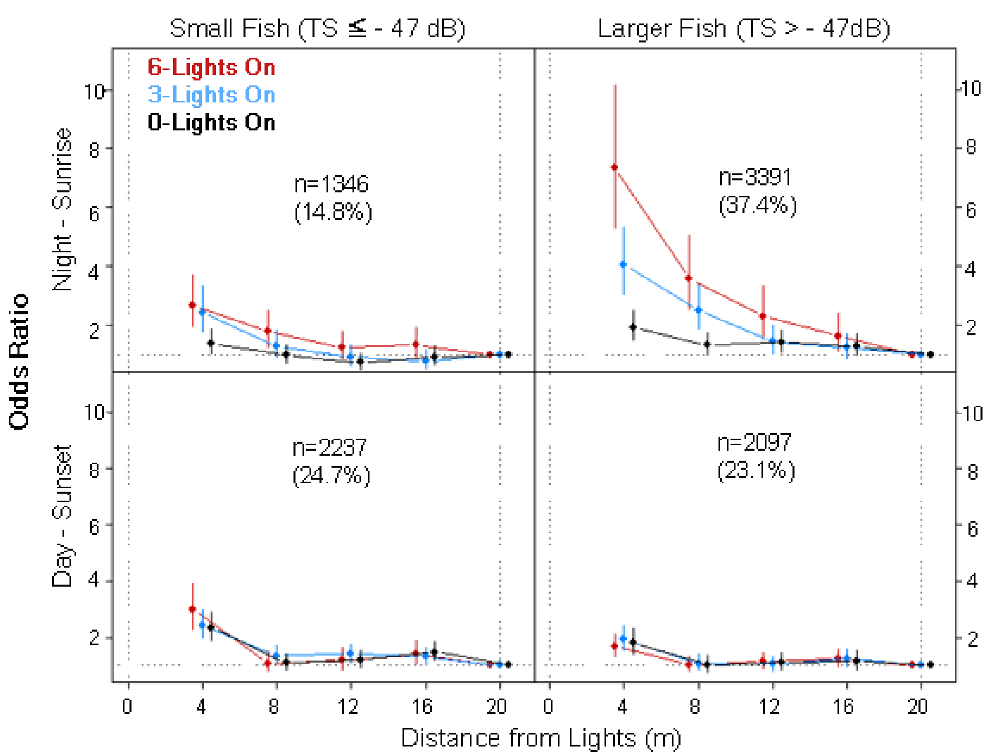

Figure 4.7. Odds Ratio Plot Showing Relative Prevalence of Fish Tracks for Two Size Groups in Daylight and at Night

4.2 Fish Behavior

The behavioral response of fish to the three light treatments will be examined with respect to their distribution in the water column and swimming behavior. Results are presented for the lights-off compared to the 6-lights-on treatments. Results from the 3-lights-on treatment were generally similar to the 6-lights-on configuration and provided no additional insight into fish behavior except as noted below.

When the strobe lights were on at night, larger fish were distributed deeper than when lights were off (Figure 4.8). Using the median of the distribution, 50% of the larger fish were distributed above and below 17 m when the lights were off, while when lights were on, the median was at approximately 19 m. During the day, the difference between lights on and off was about 1 m, with the median being 18 m when lights were off and 17 m when lights were on.

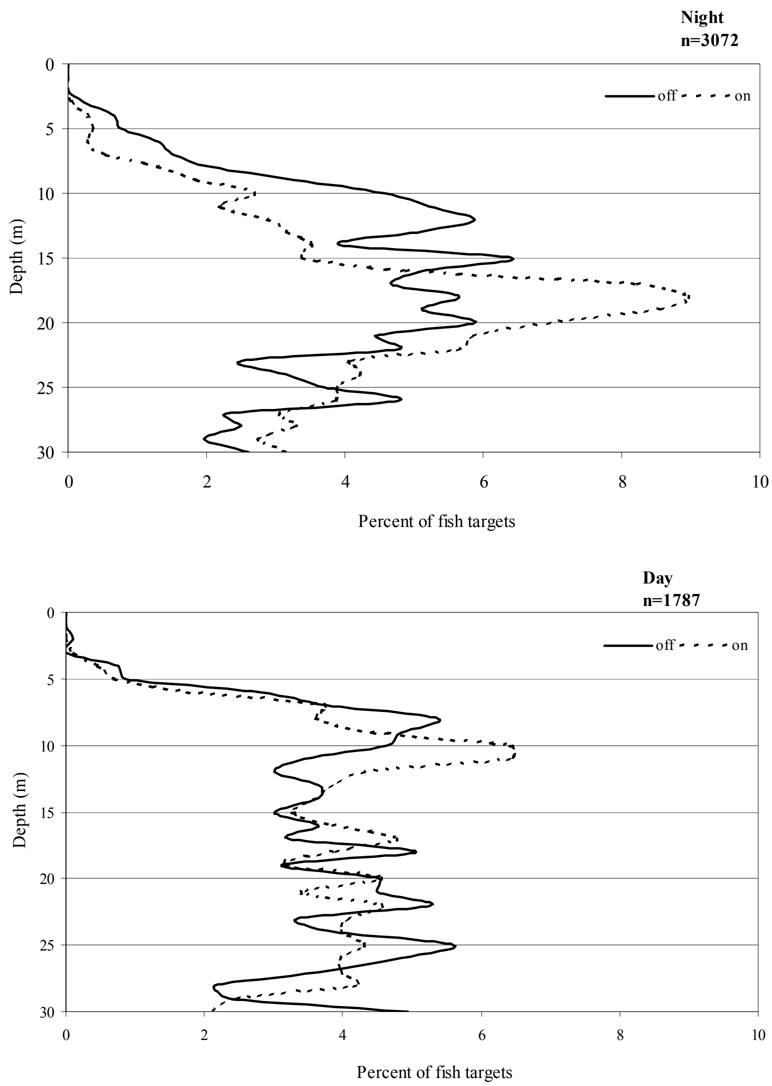

Figure 4.8. Depth Distribution of Large Fish (TS >-47 dB) at Night and During Daylight for Lights-Off and 6-Lights-On Treatments. Data are for downlooking transducers.

In 2001, only sidelooking transducers were used to detect fish. That data appeared to indicate that there were fewer fish near the lights (Simmons et al. 2002), although results for one of the four transducers indicated significantly more fish were present when the lights were on. In the present study, there were two sidelooking transducers attached to the light frame. In Figure 4.9, we note that during the day there was a peak in fish abundance, for larger fish, within 5 m of the lights. This corresponds to the count data from the downlooking transducers indicating a higher fish count close to the light frame independent of the light treatment.

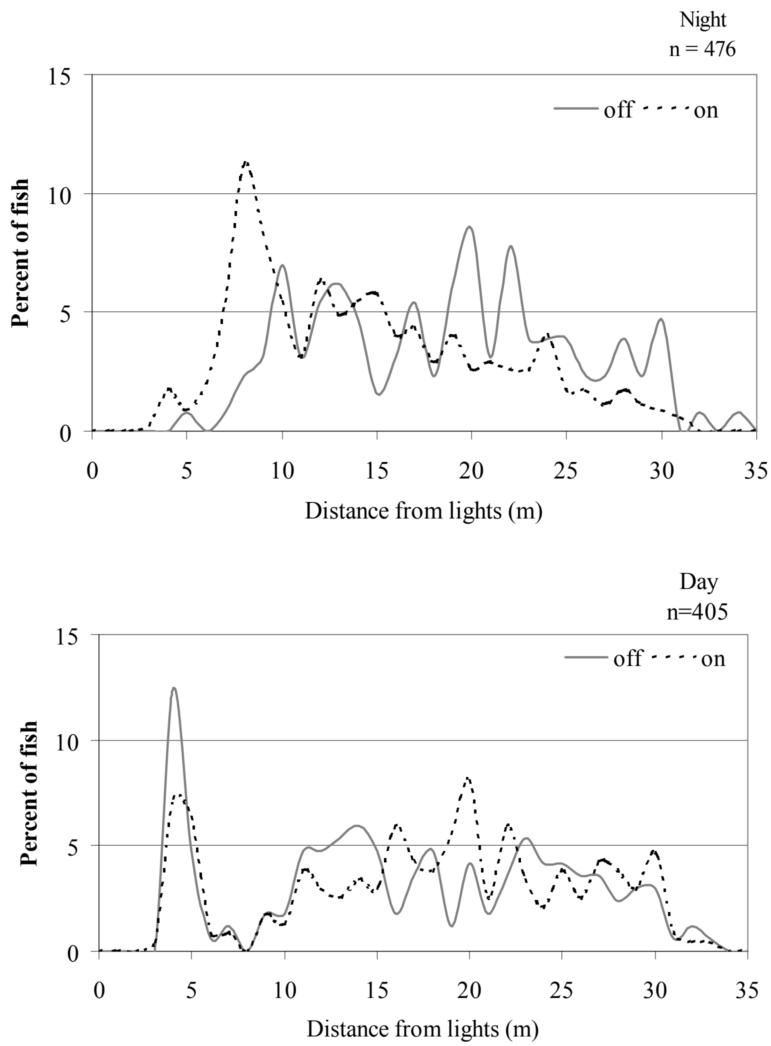

Figure 4.9. Distribution of Large Fish (TS >-47 dB) Detected with Sidelooking Transducers as a Function of Distance from the Strobe Lights (lights-off versus 6-lights-on treatments) and Time of Day

An additional example of the response of fish to the presence of the lights is indicated by the difference in the depth distribution between the two 3-lights-on configurations. When the 3-lights-on configuration consists of two lights on the bottom and one on the top (i.e., 3b-on), the median for the distribution is around 24 m compared to 18 m for the configuration of two lights on top and one on the bottom (i.e., 3a-on) (Figure 4.10). The distribution figures suggest that while there are more fish closer to the lights, they are distributed deeper in the water column.

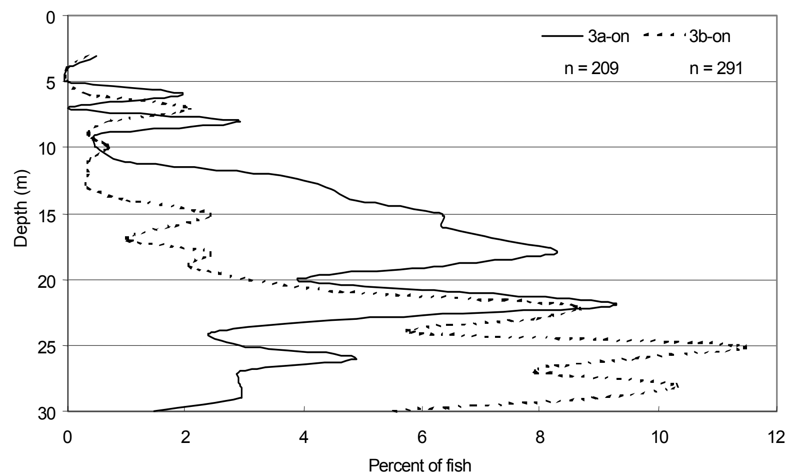

Figure 4.10. Distribution of Large Fish (TS >-47 dB) with Depth at Night in Ensonified Region Closest to Strobe Lights (i.e., 4 m) for Two 3-Light Configurations (a = 2 top lights/ 1 bottom light; b = 1 top light/2 bottom lights)

Another aspect of behavior is swimming effort. Swimming effort is indicative of the direction and speed of the fish within the flow field. Fish swimming speed determined by the hydroacoustic system includes both water flow and the fish's swimming effort. By subtracting water flow from the overall swimming speed, the effort the fish is expending within the flow field can be estimated. A fish swimming with effort velocity equal in magnitude and opposite in direction to flow would appear motionless. Exerting no effort velocity, a fish would be carried along by the flow. For this study, water flow was measured at only one location at the barge, so flow measurements at each fish location were not available. However, given the small study area and the apparent uniformity in flow (Appendix E), we used the barge flow measurements as an approximate estimate of what the fish experienced.

When swimming effort is examined, we found that instead of swimming downstream toward the dam, fish were actually oriented upstream and away from the third powerplant turbines. Figure 4.11 illustrates these findings. Figure 4.11 is similar to a wind rose, showing the direction of the water flow and swimming fish. The length of the arrows gives the magnitude of the velocity. In Figure 4.11, the blue lines represent the flow velocities. As expected, flow is directed toward the forebay and turbine intakes (lower right). The red and black lines represent the swimming effort of fish under the lights-off and 6-lights-on

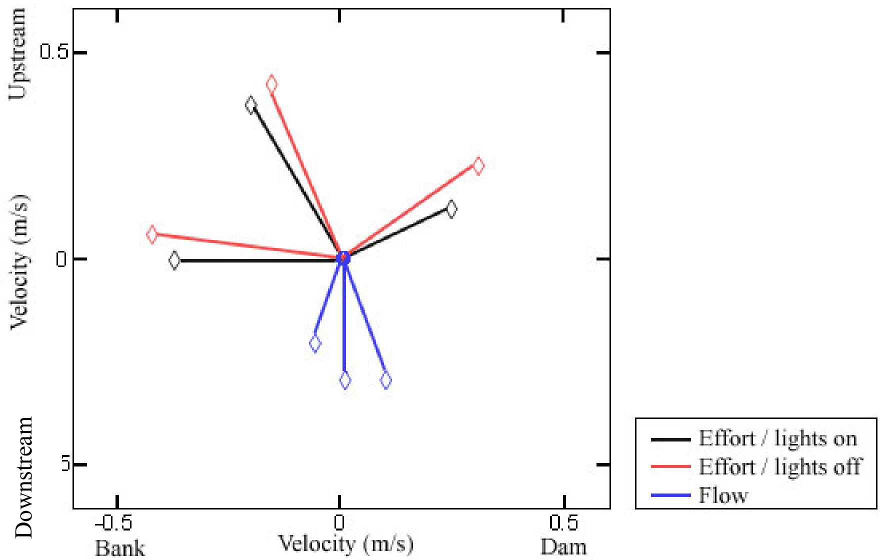

Figure 4.11. Flow and Fish Swimming Effort Vectors. Data for larger fish targets (TS >-47 dB); lights on refers to 6-lights-on treatment. The three lines of each color represent the mean and the upper and lower quartiles of the distribution.

treatments, respectively. It is evident that under both conditions the fish are swimming upstream and away from the turbines. There appears to be a slight direction change between the two light treatments, with the swimming effort for lights on being more toward the opposite bank, while under lights off, the direction is more toward the forebay.

Results so far have indicated that more fish were detected close to the lights, when the lights were on at night. Most of these fish were located just below the light frame and were oriented upstream away from the lights. Additional insight into fish behavior is gained from an analysis of the displacement velocities. Displacement velocities are indicative of the direction and speed of the fish upstream of the strobe lights. The analysis was confined to fish with target strengths greater than -47 dB, data from the downlooking transducers, and day and night periods excluding the hour before and after sunrise and sunset. Figures 4.12 and 4.13 show the displacement vectors for fish detected during the day and night under the three treatment conditions (i.e., lights off, 3-lights-on, and 6-lights-on). These distributions were analyzed using the concentration parameter (κ), which is indicative of the amount of dispersion in a circular distribution. Results are summarized in Table 4.2.

Comparing the two series of concentration parameter estimates between the lights-off and 6-lights-on treatments using the Wilcoxon sign-rank test for paired estimates yields a significant difference for the night results ($p = 0.031$), while there was no significant difference for the day results ($p = 0.313$). These statistical results indicate that the displacement vectors for fish detected at night were more dispersed when the lights were on compared to when the lights were off. The increased dispersion of displacement vectors, especially for fish detected within 8 m of the lights, indicates that there was no dominant swimming direction in this region. This could be indicative of milling or of fish repeatedly swimming into and out of the lighted region.

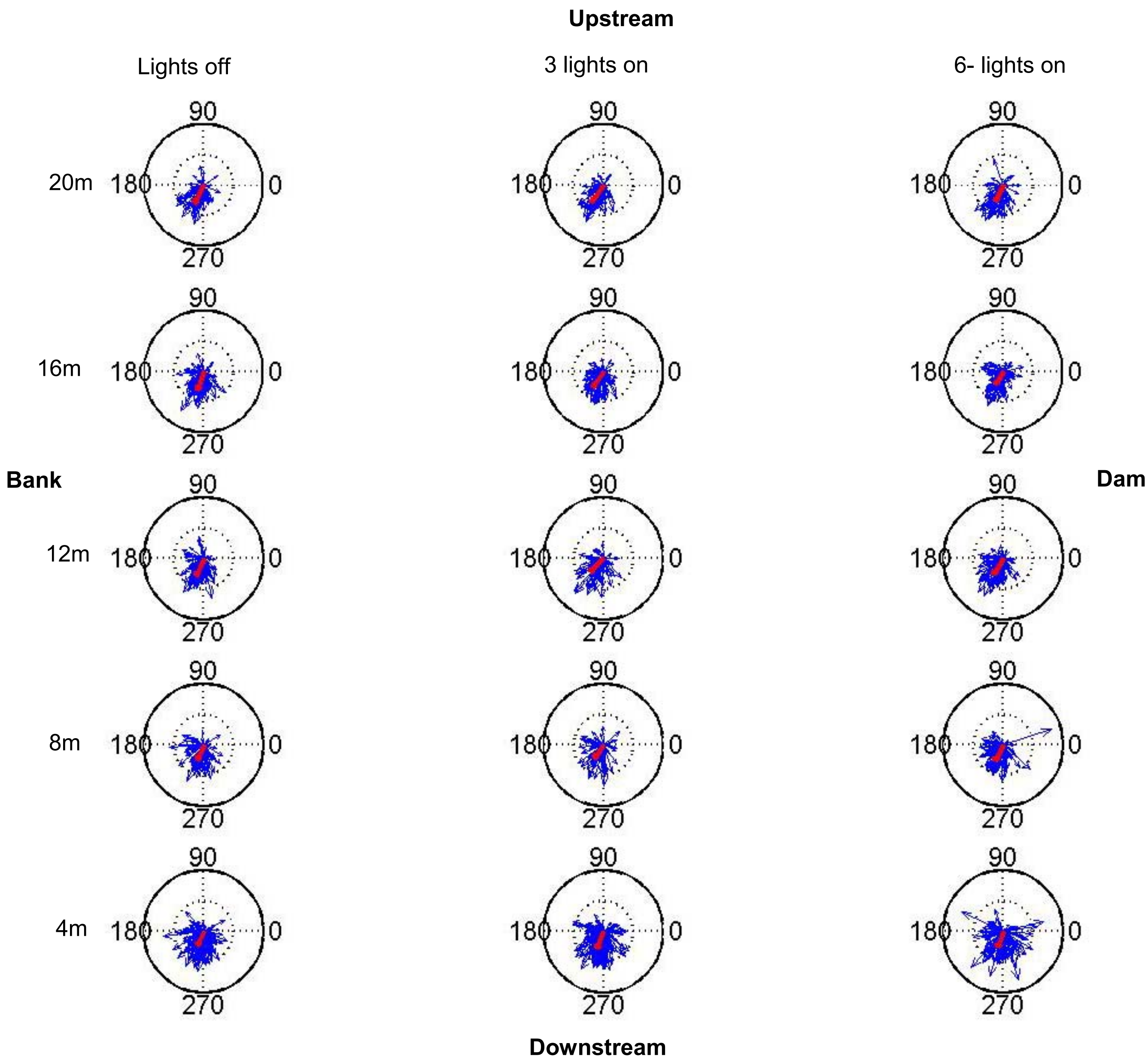

Figure 4.12. Displacement Vectors for Large Fish (TS >-47 dB) During the Day for the Three Treatment Configurations and Five Distances from the Strobe Lights. Red arrow is the mean vector.

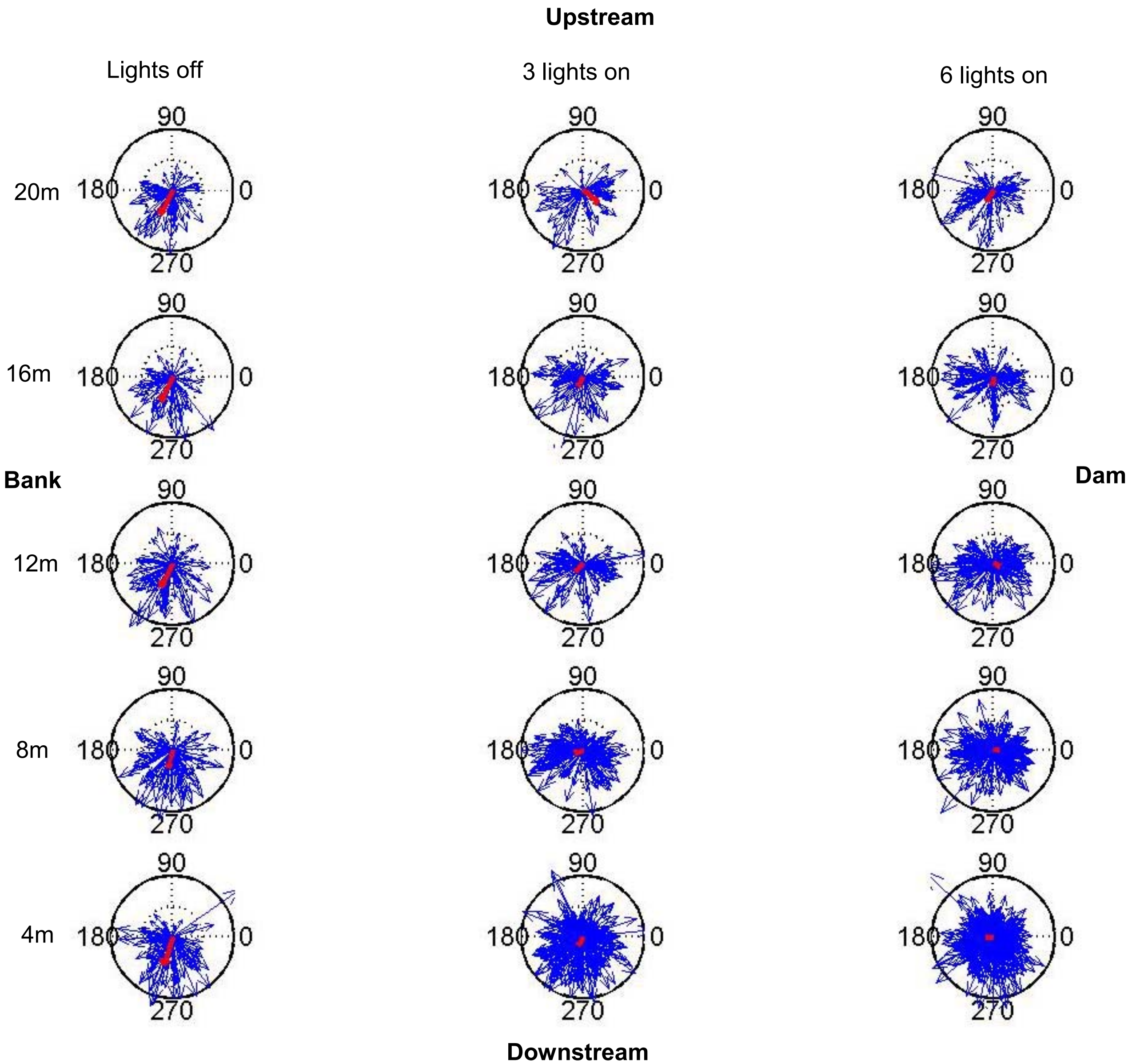

Figure 4.13. Displacement Vectors for Large Fish (TS >-47 dB) During the Night for the Three Treatment Configurations and Five Distances from the Strobe Lights. Red arrow is the mean vector.

Table 4.2. Estimated Concentration Parameters (κ) Values and Parameter Differences for Larger Fish Detected by the Downlooking Transducers During Day and Night Time Periods

Day				
Distance from Lights (m)	Treatment			Diff. (δ)[a]
	Lights Off	3 Lights On	6 Lights On	
4	1.12	1.46	1.28	-0.16
8	1.26	1.21	1.42	-0.16
12	1.54	1.59	1.48	0.06
16	1.66	1.59	1.10	0.56
20	1.81	1.95	1.47	0.34
Night				
Distance from Lights (m)	Treatment			Diff. (δ)[a]
	Lights Off	3 Lights On	6 Lights On	
4	1.07	0.29	0.22	0.85
8	0.59	0.26	0.17	0.42
12	0.91	0.33	0.22	0.69
16	0.97	0.34	0.27	0.70
20	0.97	0.68	0.42	0.55

(a) Difference in concentration parameters: lights off – 6 lights on.

The distributions of effort velocities (Figure 4.14) indicate that fish are swimming faster at night in the direction perpendicular to flow, and while there is no dominant direction of movement directly in front of the lights (i.e., within 4 m), in areas farther from the lights, the fish are swimming across the flow toward either the dam or the opposite bank (Appendix F). Another point of interest in the analysis of the response of fish to the presence of strobe lights includes the shift in the size of fish detected when 6 lights on are compared to lights off (Figure 4.15). Larger-sized fish are predominant when lights are on over all distances compared to lights off.

The results of the count data and behavior data appear contradictory in that the analysis of counts indicates significantly more fish present when the lights were on at night, while behavior results indicate these same fish were swimming away from the lights in all directions. There are a number of possible explanations for this apparent contradiction:

1. Fish may be keying on illuminated prey in the vicinity of the strobe lights and thus accumulating near the lights as a result of increased prey visibility.
2. Associated with this hypothesis (1), increased numbers of fish may be a result of increased feeding activity (fish detected many times as they move in and out of the illuminated region) as they forage on highly visible prey.

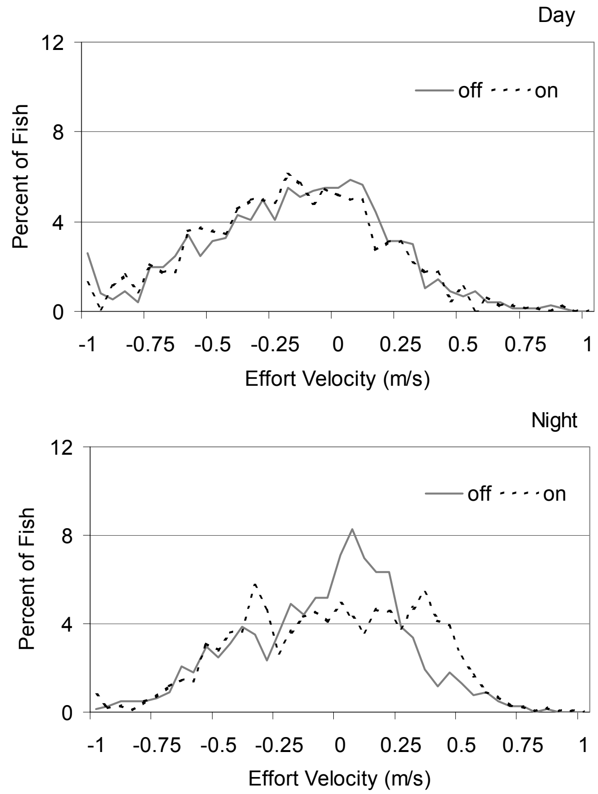

Figure 4.14. Effort Velocity in Bank (-)/Dam (+) Direction for Large Fish (TS >-47 dB) Exposed to Lights-Off and 6-Lights-On Treatments at Night and During the Day

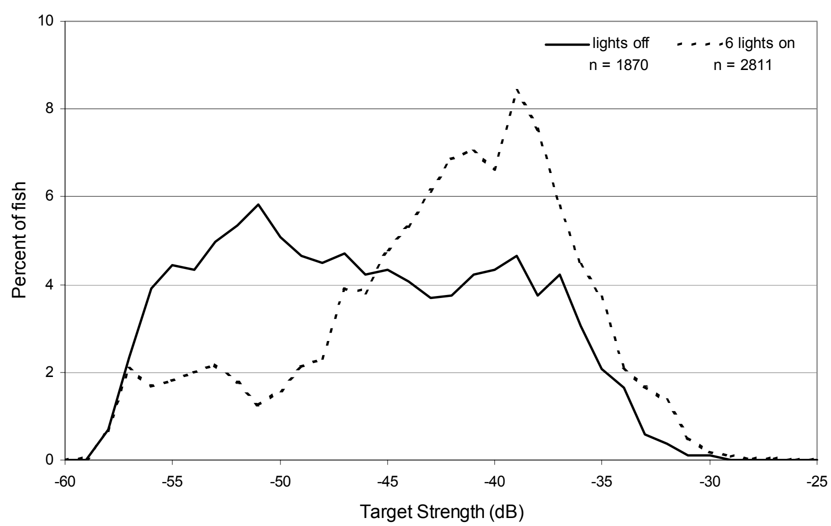

Figure 4.15. Target Strength Distribution for Targets Detected at Night with Lights-Off or 6-Lights-On Treatments. Data for downlooking transducers only.

3. Fish may be using the illuminated structure and/or position of the lights as an orientation key similar to how they might use the surface or bottom during daytime. This may result in an apparent buildup of fish in the vicinity of the lights or structures as long as they can maintain position and the flow velocities did not exceed their critical swimming speed.
4. In a similar manner to (3) above, fish may be keying on one another under lighted conditions, in essence "schooling" or accumulating as they attempt to maintain positional control in the flowing environment. We did not observe schools of fish in the classic sense, but the attraction of several fish combined with repeated entering and exiting of the ensonified region may give the appearance of schooling.
5. Species composition of the population may play a role in the apparent numbers detected. Other species may be attracted to the lighted region directly or be more prone to predation on the highly visible prey in the lighted region. Smaller fish also may attract predators to the lighted region.
6. Finally, the increased numbers may be a direct result of the flow regime. Fish attempting to avoid the strobe lights in the flowing environment might "pile up" in front of the strobe lights resulting in increased detections in that zone over time.

It is apparent from the results in 2001 and 2002 that the response of fish to strobe lights at the Grand Coulee Dam third powerplant forebay is not as transparent as that reported in Maiolie (2001). The analysis is further complicated by the difference in densities in the two studies. Maiolie (2001) reported densities in excess of 1,000 fish/ha in two Idaho lakes while a 1997 survey of fish in Lake Roosevelt yielded less than 2 fish/ha (LeCaire 1999). Higher densities of a target species permit a snapshot to be captured in a relatively short period of time, while at much lower densities many fish need to be sampled over a longer period of time. The extended sample period may result in more complex behavior, due in part to varying conditions over time and contamination by other species.

5.0 Summary and Recommendations

The response of fish to strobe lights in the forebay of the third powerplant at Grand Coulee Dam in 2002 was based on analysis of the distribution of fish targets and on fish swimming effort and direction. More than 145,000 potential fish targets were detected by splitbeam hydroacoustics upstream of the strobe lights. Of these, a subset of 9,071 were identified as fish and were analyzed with respect to 1) distance from the strobe lights; 2) time of day; 3) flow conditions at the third powerplant; and 4) target size.

5.1 Summary

In summary, the following results were obtained from the study:

- Substantially more fish were detected closer to the light frame (at 4 m) for all three treatment conditions (lights off, 3-lights-on, and 6-lights-on) in both day and night.

- The target strength (TS) distribution of trackable fish was strongly bimodal, suggesting two (or perhaps more) distinct populations [small fish and other targets (TS ≤-47 dB) and larger fish (TS >-47 dB)].

- For the two lights-on conditions (3-lights-on and 6-lights-on), the number of fish detections increased as distance to the strobe light decreased.

- More fish were detected when 6 strobe lights were on (n = 3,745) compared to 3 strobe lights on (n = 2,819) and strobe lights off (n = 2,507).

- At 4 m from the lights, there was a statistically significant difference ($p < 0.05$) in numbers of fish among the three treatments (for all data above 30 m depth).

- At 4, 8, and 12 m from the lights, there was a statistically significant difference ($p < 0.05$) among the three treatments at night. No differences were noted during day.

- Treatment effect was statistically significant ($p < 0.05$) at night when the turbine discharge was low.

- Treatment effect at 4 m was statistically significant ($p < 0.05$) at night for fish TS ≤-47 dB and fish TS >-47 dB. Additionally, statistically significant treatment effects were noted for fish with TS >-47 dB at 8 and 12 m.

- Fish were distributed deeper in the water column (median = 19 m) when the strobe lights were on at night compared to when the strobe lights were off (median = 17 m). During daytime, there was no notable difference in depth distribution between the lights-on or lights-off treatments.

- On average, fish swimming effort (detected velocity vector minus flow velocity vector) was mostly upstream and slightly toward the bank side of the forebay for both lights-on and lights-off treatments (only the 6-lights-on treatment was included in this analysis).

- Fish swimming effort velocities, at night, were directed upstream and at higher speeds than when lights were off.

- Analysis of displacement velocities indicates that fish detected close to the lights (i.e., within 4 m) at night are swimming in all directions compared to fish detected farther from the lights. This result, based on concentration parameters, is significant.

- Beyond 4 m from the lights, at night, fish are swimming in either direction across the forebay. During the day, and at night when the lights are off, fish are swimming downstream.

- When lights are on at night, more larger fish (TS >-47 dB) are detected.

These results are for the second year of a three-year study to determine the efficacy of using strobe lights to elicit a negative phototactic response in kokanee and rainbow trout in the forebay to the third powerplant at Grand Coulee dam. As such any conclusions are preliminary. For the past two years, count and behavioral results have presented contrasting views on the response of fish to strobe lights. Higher counts of fish detected near the lights indicate attraction, while behavioral results indicate the fish are swimming away from the lighted region. The precise reason for this dichotomy is still unclear. The strobe lights may be attracting prey species that, in turn, attract predators such as kokanee and rainbow trout, or the lights may provide visual orientation cues. The higher counts appear to reflect more activity rather than a higher density of fish. The results from both years indicate that strobe lights have an effect only at night when flows are lower.

5.2 Recommendations

In 2001 and 2002, we deployed strobe lights and a hydroacoustic monitoring technology at the third powerplant forebay. Based on these studies and general review of strobe lights and their effects on living organisms, we recommend a similar effort during the follow-on study in 2003 to further substantiate our findings and clarify ambiguities. The implementation of these recommendations will enhance the study design, provide additional data where data were lacking in 2002, and set the stage for future strobe light installation, should it be deemed efficacious as a fish deterrent.

Our continued study recommendations are as follows:

1. The study should begin at about the same time (mid-May to early June, depending on water levels) to capture the kokanee and rainbow trout populations as the fish move down the reservoir toward the dam. In 2001 (a low water year), the peak was thought to have occurred in late June while in 2002 (a high water year), the population apparently peaked in mid-July.

2. All splitbeam transducers should be deployed at the surface looking down immediately upstream of the strobe lights to sample the region close to the lights. The transducers should be angled slightly upstream or downstream to prevent the occurrence of a strong second bottom reflection in the region of interest. It may be efficacious to deploy two transducers with a lateral orientation as well to detect fish skirting the lighted region.

3. The experimental design should be modified to include only two strobe light treatments of 24 hr on and 24 hr off. The 24-hr-on treatment should use 6 strobe lights (during 2002, the 6-lights-on condition elicited a statistically increased response compared to 3-lights-on).

4. An acoustic Doppler current profiler should be deployed to provide flow information that could be used to better interpret behavioral results and permit estimation of fish swimming effort.

5. Continued effort should be devoted to determining species composition. Colville tribal members should conduct a multiple-mesh gill net test fishery in the vicinity of the strobe lighted region.

6. Additional plankton net sampling should be conducted in proximity to the strobe-lighted region to estimate the relative numbers of zooplankton present with strobe lights on and off during daylight and dark hours.

7. Approximately 500 fish or more from the nearest hatchery/net pen operation should be tagged with radio telemetry or acoustic tags to determine the arrival timing of fish to the test site in the third powerplant forebay. This will provide valuable information on the presence of the target species in the strobe-light region.

8. The pumping plant irrigation canal should be sampled using an acoustic camera during a "typical" irrigation-pumping period to determine the extent of fish entrainment during those events. Tribal biologists are concerned that fish may be entrained during irrigation supply pumping activities. Strobe lights may be a deterrent alternative to fish entrainment to the pumping station if entrainment is substantiated and the use of the lights is found to be effective.

9. A controlled experiment should be conducted to determine the effect (attraction or repulsion) of strobe lights on prey species of zooplankton and the relative level of opportunistic feeding that occurs when the prey species are illuminated by strobe lights.

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Appendix A

Environmental Conditions at Grand Coulee Dam

Appendix A

Environmental Conditions at Grand Coulee Dam

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 were obtained from the Fish Passage Center DART database (University of Washington 2002) and the U.S. Bureau of Reclamation. Over the 2002 study period, the water level in the forebay increased over 15 m and reached normal high pool elevation of 393 m (1290 ft) in early July (Figure A.1). The forebay elevation during July was approximately 2 m (6.6 ft) above the level for 2001.

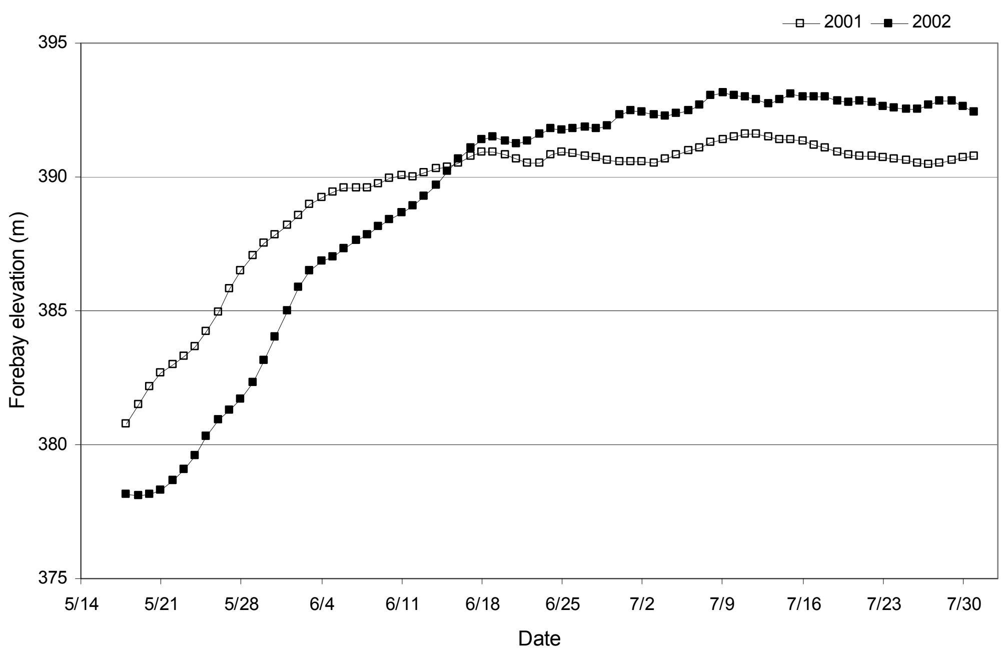

Figure A.1. Forebay Elevation in Front of the Left Powerplant During the Period May 18–July 30 for 2001 and 2002

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. 1997). For this reason, we examined the seasonal changes in water temperature across depth next to the barge. Water temperatures were measured by placing 14 self-contained temperature loggers along a steel cable extending from the barge to 40 m beneath the water surface. A metal weight was affixed to the bottom of the cable to keep the line vertical throughout the water column. The temperature logger line was raised and lowered using a standard Cannon downrigger. The Onset Optical StowAway® temperature loggers used during this study have a reported accuracy of ±0.2ºC (Figure A.2). All loggers were validated before deployment by exposing them to a constant-temperature environment. All loggers were found to measure temperatures at or better than the manufacturer's reported accuracy.

The temperature loggers were programmed to record data at 5-min intervals. The loggers were spaced 2 or 4 m apart to cover the water column from the surface to a maximum depth of 40 m. The loggers were placed at surface (0 m), 2 m, 4 m, 6 m, 10 m, 12 m, 16 m, 18 m, 22 m, 24 m, 28 m, 32 m, 36 m, and 40 m. The loggers were deployed on May 2, and data were collected through July 19. Unfortunately, data are available for only 41 days during the period due to various operational mishaps.

Figure A.2. Self-Contained Temperature Loggers. Loggers are approximately 12 cm in length.

Time history data from the 14 temperature loggers are plotted in Figure A.3. The onset of stratification can be seen to occur during May, and stratification continued to strengthen into the summer months.

A metric to gauge the strength of stratification can be calculated by subtracting the time series of water temperatures gathered at 4 m from the measurements at 32 m. Using this method, the mean difference in temperatures between June 15 and July 19 was 3.3ºC (Figure A.4).

® Product of the Onset Computer Company, Pocasset, Massachusetts.

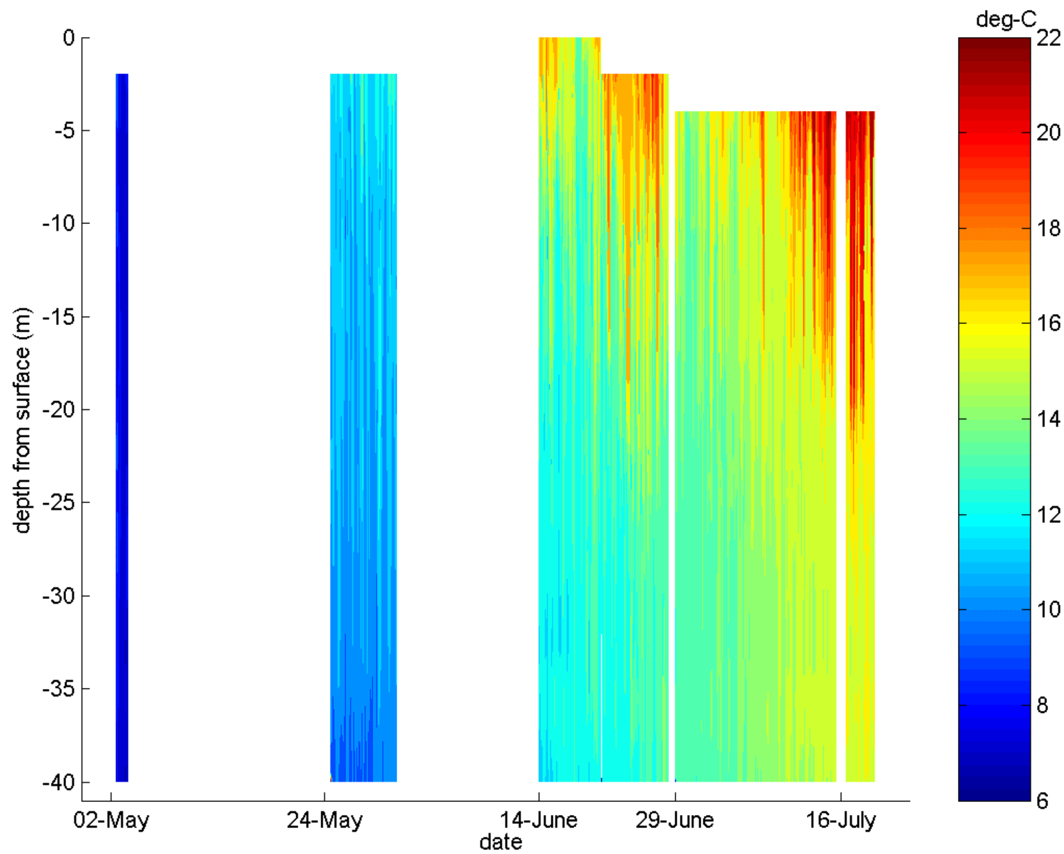

Figure A.3. Summary of Water Temperatures with Depth at the Barge Location in Forebay of the Third Powerplant at Grand Coulee Dam in 2002

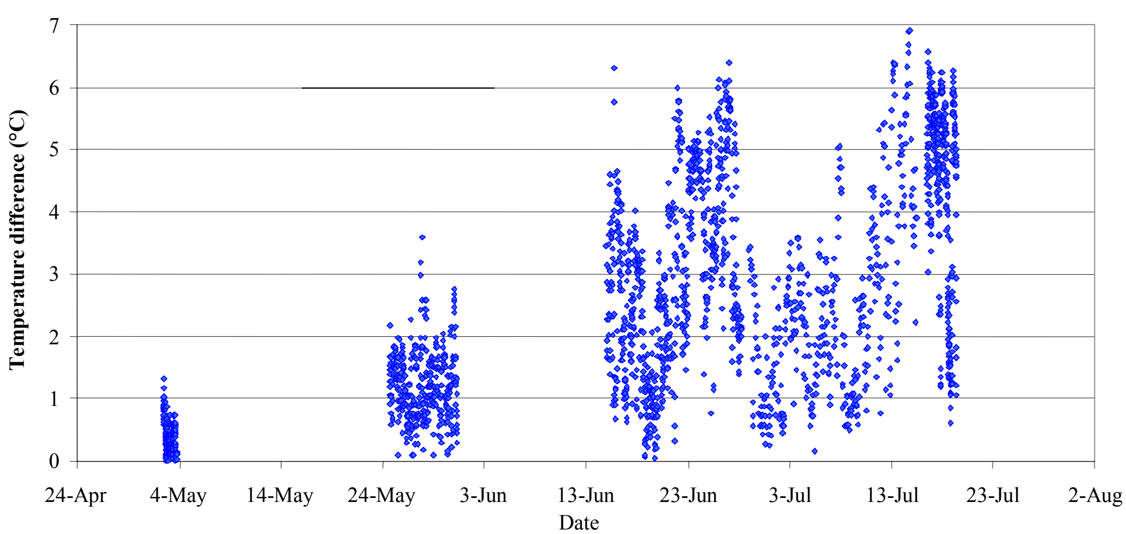

Figure A.4. Temperature Differences Between 4 and 32 m During Study Period in 2002

The composite illustration (Figure A.5) displays color contours of water temperature collected over the study season. The black horizontal lines indicate the depths of the temperature loggers. Contour plot data between the observations were generated using a triangle-based (Delaunay) cubic interpolation method (The MathWorks, Inc. 2002).

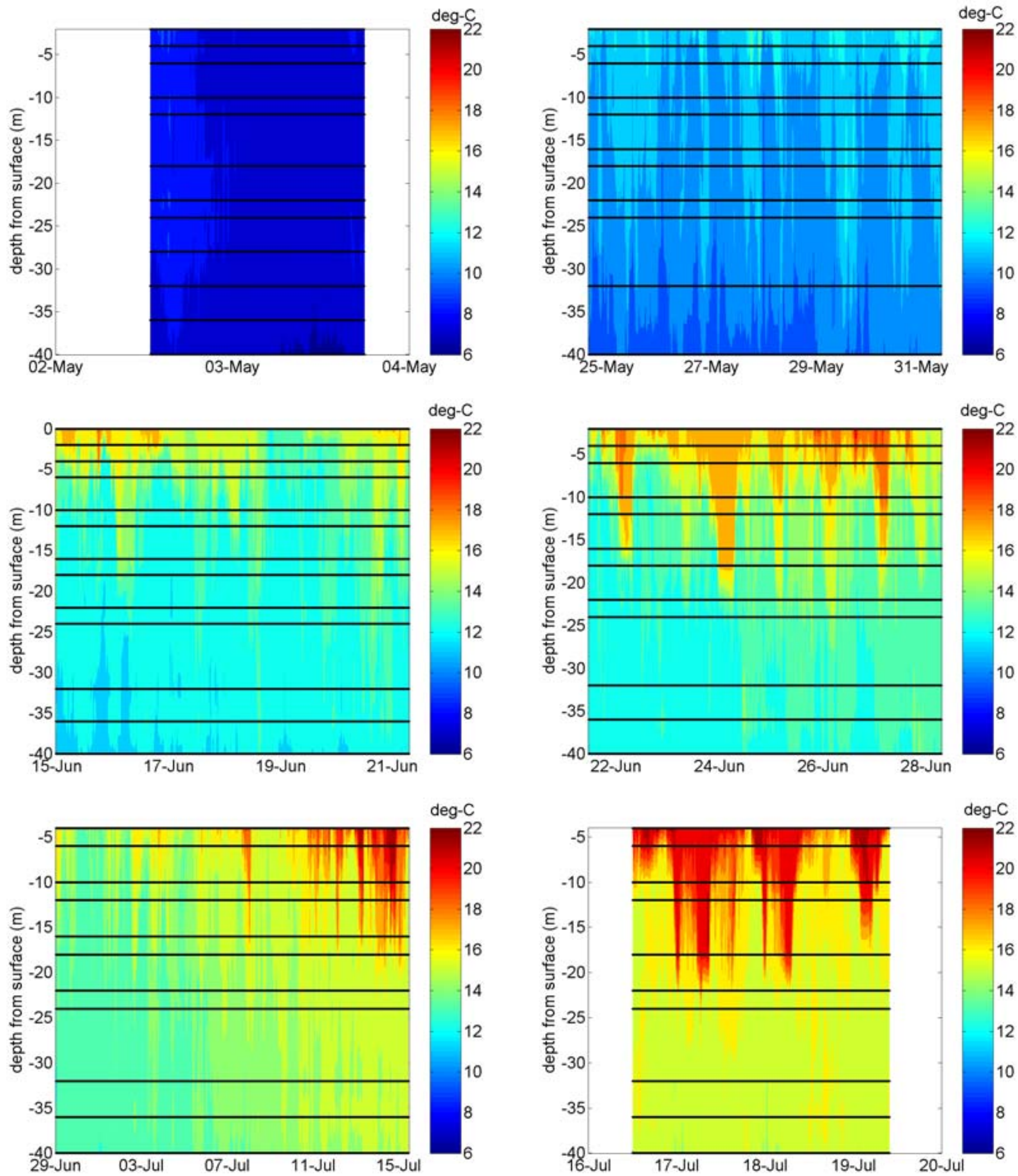

Figure A.5. Contours of Water Temperature with Depth over the Period of May 2 through July 19, 2002, in Forebay of the Third Powerplant at Grand Coulee Dam

A.3 Turbidity

Turbidity can affect the distribution of fish both vertically and spatially (Swenson 1978; Matthews 1984). Turbidity measurements were taken weekly at two depths (15 m and 23 m) at the barge location in the forebay of the third powerplant (Figure 3.1). The turbidity measurements were taken with Van Doren bottle grab samples and analyzed using a Hach Model 2100P Portable Turbidimeter.[a] Three samples were taken from each depth.

Turbidity levels were highest at the beginning of the survey period and decreased through the season, reaching levels similar to those in 2001 (Figure A.6). 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 nephelometric turbidity units (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 (Appendix C).

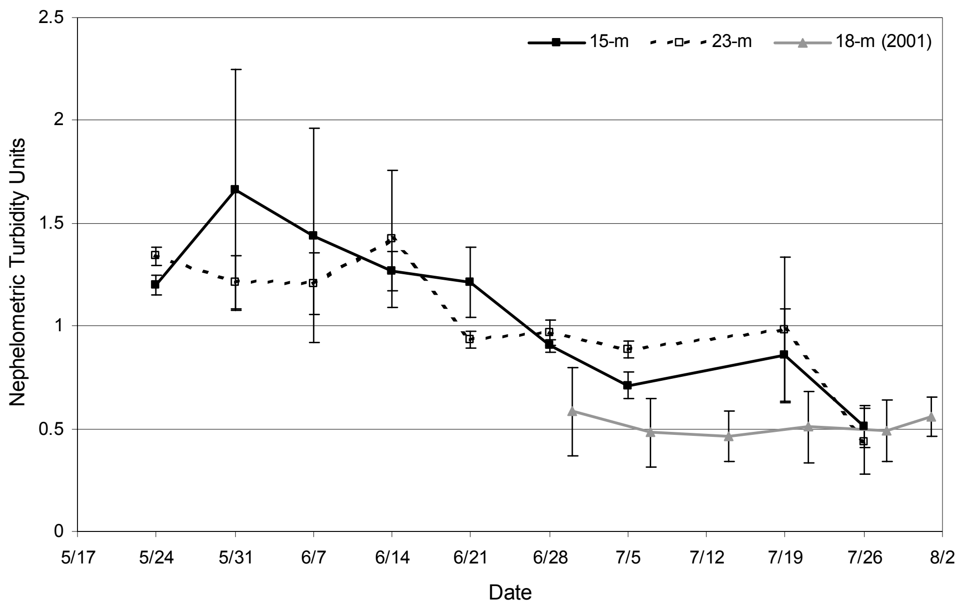

Figure A.6. Turbidity Levels at Grand Coulee Dam for 2001 (June 30 to August 1) and 2002 (May 24 to July 26). Bars are ±1 standard deviation (n = 9 for 2001; n = 3 for 2002).

(a) Hach Company, Loveland, Colorado.

A.4 Ambient 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).

Light conditions were monitored at the surface using a Model LI-19SA Underwater Quantum light sensor supplied by LI-COR, Lincoln, Nebraska. Light conditions were monitored 24 hr/day and reported hourly to a data logger on the sensor mast of the fixed barge.

Maximum daily light levels fluctuated between 2000 and 3000 μmole/m^2/s over the course of the study (Figure A.7); 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 around 1 p.m. (Figure A.8).

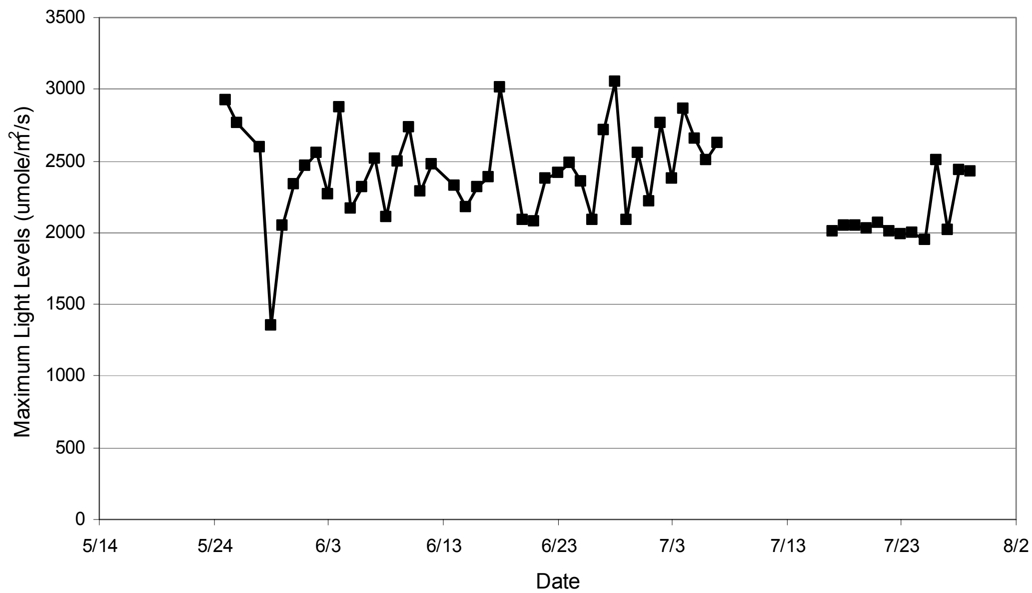

Figure A.7. Maximum Light Levels in Forebay of Third Powerplant at Grand Coulee Dam in 2002

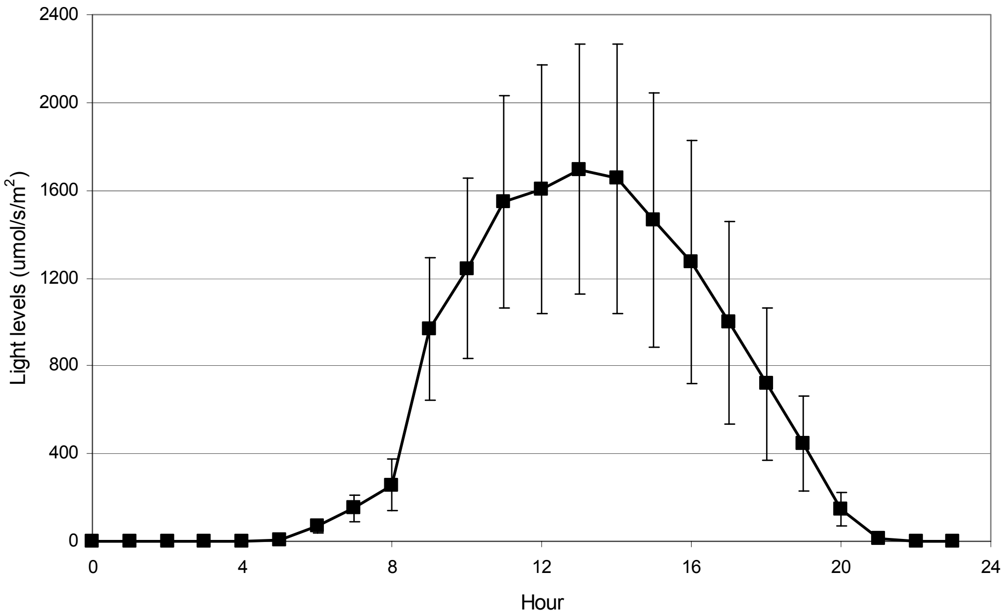

Figure A.8. Hourly Ambient Light Levels Measured at Water Surface. Bars are ±1 standard deviation (n = 57). Zero hour is midnight.

A.5 Wind and Precipitation

Wind and precipitation disturb the surface of a body of water, affecting light penetration. These two events also can introduce bubbles into the water column, which can acoustically obscure fish tracks. Wind speed (hourly average and maximums) and direction were measured during the study period on the fixed barge. A Model 03002V Wind Sentry (R. M. Young Company; Traverse City, Michigan) was secured to the sensor mast on the fixed barge. Wind speed and direction data were input to the LI1400 data logger continuously 24 hr/day and stored as the hourly minimum, maximum, and average speed and direction. Technical difficulties with the sensor resulted in only wind direction being useable. Wind speed and precipitation data were downloaded from the U.S. Bureau of Reclamation's AgriMet database (http://mac1.pn.usbr.gov/agrimet/agrimetmap/gcdwda.html) for Grand Coulee Dam. The AgriMet wind speed data are averaged over an hour. Peak wind gust data are also available and are the maximum wind speed within a 15-min period. Precipitation records are cumulative.

Wind direction, as in 2001, was primarily downstream from the south-southwest (Figure A.9). Wind speed was generally below 20 km/h (12 mph) (Figure A.10). However, on several occasions during the study, gusts were recorded in excess of 50 km/h (30 mph). Average hourly wind speed was 7 km/h (4 mph).

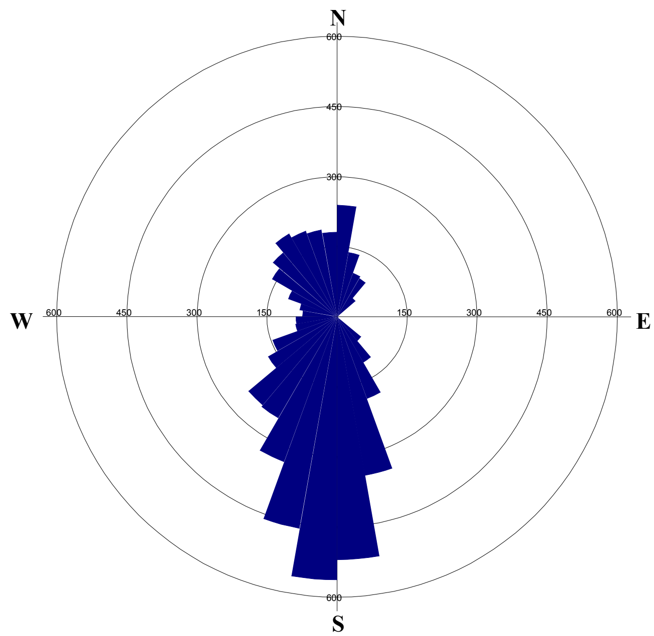

Figure A.9. Wind Rose Showing Predominant Direction from Which Wind Comes in Forebay of Third Powerplant at Grand Coulee Dam in 2002

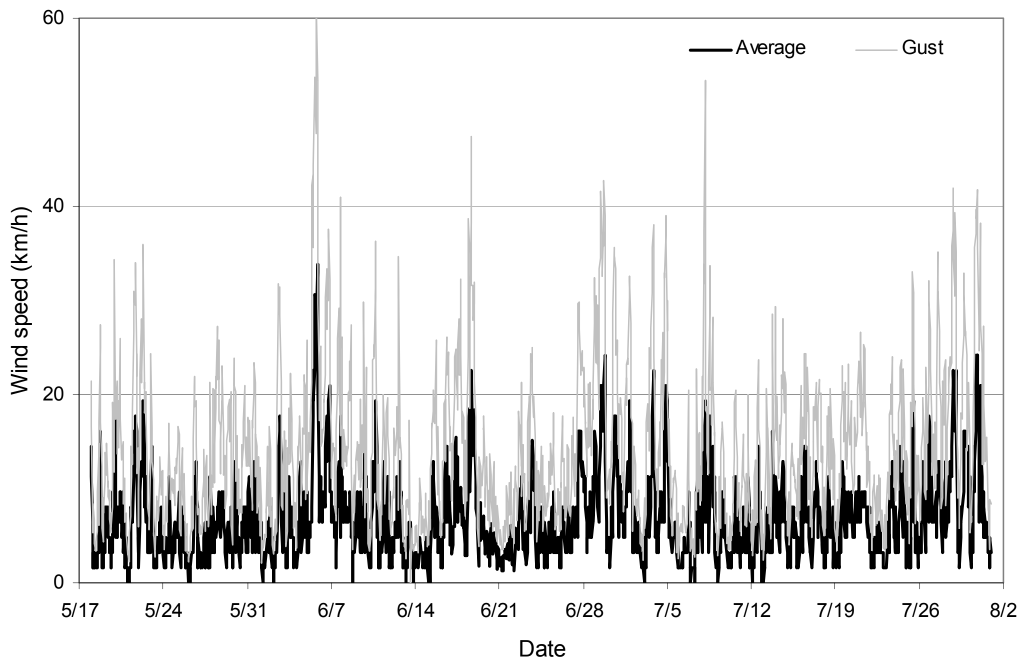

Figure A.10. Wind Speed at Grand Coulee Dam in 2002 as Measured by the U.S. Bureau of Reclamation, AgriMet Station. Wind speed data represent hourly averages, while gusts are the maximum speed within a 15-min period.

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 2002 indicate that approximately 2 cm (<1 in) of rain fell during May, June, and July (Figure A.11), with most of this occurring in May.

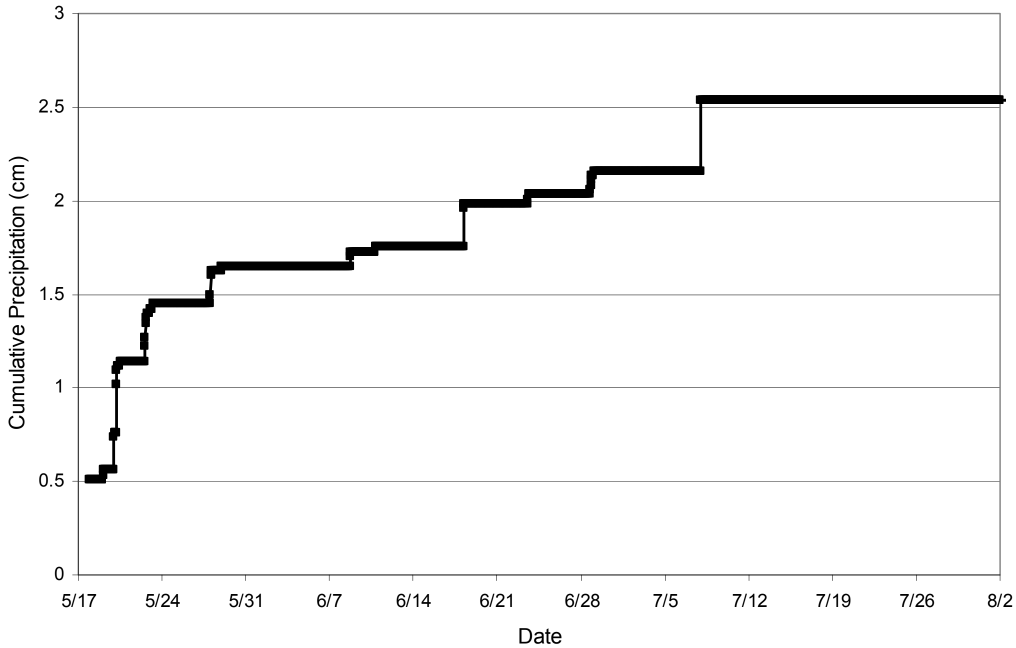

Figure A.11. Cumulative Precipitation (cm) at Grand Coulee Dam in 2002. Data from AgriMet database, U.S. Bureau of Reclamation (http://mac1.pn.usbr.gov/agrimet/agrimetmap/gcdwda.html).

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Appendix B

Statistical Synopsis

Appendix B

Statistical Synopsis

B.1 Experimental Design

Three treatment levels were used: 6 of 6 lights on, 3 of 6 lights on, and lights off (0 of 6 lights on) as a control. Each of these three treatment conditions was applied for a full 24-hr day and randomly ordered into 3-day blocks through the study period. Each 24-hr period encompassed a complete daily cycle of power generation and ambient lighting conditions. Each sequential block of 3 days constitutes a pseudo-replicate in which all three treatment conditions have equal time allocation within the block. Only complete treatment blocks were used in the statistical analysis.

B.2 Track Count Analysis

The fundamental premise of this analysis is that the relative abundance of fish under the three treatment conditions is an indication of the phototactic response, either positive or negative, of fish to strobe lights.

Of further interest are the effects of environmental and experimental factors on the phototactic influence of the strobe light treatments. Table B.1 shows the factor or classification variables used in this analysis and their definitions. Each fish track may be classified into one and only one class level for each factor variable shown in Table B.1. By taking a cross-tabulation on these variables, a contingency table is created. Each cell in the contingency table represents the count of fish observed under the levels defined by the factors. For example, using the factors defined in Table B.1, if *Treatment, Position*, and *Block* were cross-classified into a three-way contingency table, the table would contain 255 cells representing all possible combination of these three factors (3 treatments x 5 positions x 17 complete blocks). Thus, one cell in that table would contain the count of all those fish observed with the no-lights-on treatment, at the position 4 m from the light frame, in block 6. All the counts in these cells are integer values and may be equal to 0 but never less than 0.

Such a multidimensional structure may be difficult to visualize, especially for multiway contingency tables of four or more factor variables. An alternative representation (and the way these data are used by statistical software) is to recode each variable using the values shown in Table B.1. This coding also can impose an ordering on the factor levels where appropriate (e.g., low, medium, and high discharge through the third powerplant). These coded values are then put into a two-dimensional table with columns corresponding to each factor variable. Each column in this table represents a dimension in the contingency table, while each row represents a unique combination of the class levels for the factors used to create the contingency table. A column would then be added to the two-dimensional table with the cell counts associated with each combination of factor levels.

Table B.1. Definition of Factor Variables

Factor Variable	Code	Class Level	Description
Treatment			The strobe light treatment variable of interest.
	1	0 lights	Lights off. This is the treatment control or reference condition.
	2	3 lights	3 of 6 strobe lights on.
	3	6 lights	6 of 6 strobe lights on.
Position			The position of down-looking transducers located at 4-m intervals upstream from the strobe lights.
	1	4 m	Fish tracks located 4 m from the strobe lights.
	2	8 m	Fish tracks located 8 m from the strobe lights.
	3	12 m	Fish tracks located 12 m from the strobe lights.
	4	16 m	Fish tracks located 16 m from the strobe lights.
	5	20 m	Fish tracks located 20 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.
Discharge category			Total discharge in thousands of cubic feet per second (kcfs) through the third powerplant, recorded on 5-min time intervals. Each fish track was matched to the nearest-in-time recorded value.
	1	Low	Low - 1st quartile: 0 – 41.69 kcfs
	2	Medium	Medium - 2nd to 3rd quartile: 41.70 - 118.66 kcfs
	3	High	High - 4th quartile: 118.67 - 182.84 kcfs
Target strength/size			Mean target strength computed on all echoes used to define a fish track.
	1	TS ≤-47	Fish tracks with mean target strength less than or equal to -47 dB.
	2	TS >-47	Fish tracks with mean target strength greater than -47 dB.
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.
Block	1-22	Values 1-15 and 19-21	Randomized block composed of 3 days each with the three levels of treatment randomly ordered. Note: blocks 15-18 and 22 were incomplete and not used in this analysis.

The cell counts in a contingency table constitute random variables. The error or probability structure of such random variables is best represented by the Poisson probability distribution. To relate these values to the class levels in the contingency table, we used a statistical regression model called a log-linear model (sometimes called a Poisson regression model). This type of model is part of a class of Generalized Linear Models that are defined by specifying an error structure on the response variable and a *linking function* for relating the mean estimated response from the model to a linear combination of the predictor variables. For this analysis, the error structure was specified as Poisson, and the log-function specified as the linking-function. This is a widely used and well-represented method across many research disciplines, particularly in fisheries and wildlife research where data are frequently in the form of survey counts. The mathematical form of this model is shown in Equation (B.1) (McCullagh and Nelder 1989).

$$Y_i = \beta_0 \exp(\sum_{j=1}^{p} \beta_j X_{ij}) + \varepsilon_i \qquad \text{(B.1)}$$

where Y_i = the count in the i^{th} contingency table cell
β_0 = a constant term
β_j = the fitted coefficients for the j^{th} covariate X_{ij} (j = 1 to p, predictive factors)
ε_i = the residual Poisson error for the i^{th} observation.

Fitting the statistical model shown in Equation (B.1) to the data involves estimating the β_j parameters that maximize the Poisson likelihood function. When predictor variables are defined as factors, one of the class levels for each factor is defined as the *reference* level, and parameters are estimated for each of the other class levels in that factor in comparison to the reference level. Because the log-linear model uses the log-link function, exponentiation of the parameter estimate gives a point estimate of the relative prevalence or odds ratio of tracks for a factor level when compared to the reference level. Similarly, exponentiation of the upper and lower bounds on a confidence interval for a parameter estimate gives a confidence bound on the point estimate of the odds ratio. Statistical significance for the parameter estimates from the fitted log-linear model was assessed using the Wald χ^2 test of significance with 1 degree of freedom.

Goodness-of-fit of the log-linear model to the data is based frequently on the estimated scale parameter. If the Poisson model is a perfect fit to the data, the value of the scale parameter will be equal to one (1). When this value varies from 1, it indicates that other sources of variation, not accounted for by the model factors and replicate blocks, affected the response. This is nearly always the case when modeling environmental data. When the estimated scale parameter is greater than 1, the data are said to be *over-dispersed*. This was the case for all models used in this analysis. To account for or adjust for this model *lack-of-fit*, the estimated scale parameter from each fitted model was used to appropriately adjust all test statistics.

Odds ratios are best displayed graphically along with their confidence intervals to aid in comparison. Such graphics are used extensively for assessing the results from the log-linear models.

The combined effects of factors defined in Table B.1 on the behavioral response of the fish are of interest as well. The combined effects of factors are interpreted from their interaction term in the log-linear model. Different types of interactions are characterized mathematically by different mathematical forms. The most commonly used is the multiplicative form, which is the element-wise product of the factors whose interaction is of interest. This is the form of interaction terms used for evaluation in this analysis. When odds-ratios are formed from the interaction of factor terms in the model, their combined effects are assessed relative to their combined reference level. To assess the combined effects of an interaction on the response count variable over and above the individual effects of those factors, analysis of interaction terms was undertaken only when the individual effects of the factors involved also were included in the model. In addition, the inherent temporal, climatic, and seasonal variation through the study period was accounted for (at least in part) by the pseudo-replicate treatment blocks (*Block* in Table B.1). This factor variable was never included in any interaction effect, but its individual effect (sometimes called a *main effect*) was included in all models.

B.3 Displacement Vector Analysis

The movement on a 2-dimensional cartesian coordinate plane may be mathematically characterized by a two-component vector as $\vec{v}_1 = x_1 i + y_1 j$ with orthogonal basis vectors *i* and *j*. These may then be converted to 2-dimensional polar coordinates represented by an angle (θ) and radial distance (*r*). The statistical analysis of circular data, as represented by angles (θ), has been extensively covered in the literature (Lockhart et al. 1985; Fisher 1993; Lund et al. 2000) and has been used to assess the directional movements of animals in response to stimuli.

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

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

The von Mises pdf is given in Equation (B.2) below

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

where

$$I_\upsilon(\kappa) = \left(\frac{\kappa}{2}\right)^{\upsilon} \sum_{j=1}^{\infty} \frac{\left(\frac{\kappa^2}{2}\right)^j}{j!\Gamma(\upsilon + j + 1)} \qquad \text{(B.3)}$$

Equation (B.3) is the modified Bessel function.

The von Mises pdf takes two parameters (μ, κ), which are estimated from the data as follows:

First, 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

$$\begin{aligned} \hat{\mu} &= \tan^{-1}(S/C) && \text{if S>0, C>0} \\ &= \tan^{-1}(S/C)+\pi && \text{if C<0} \\ &= \tan^{-1}(S/C)+2\pi && \text{if S<0, C>0} \end{aligned} \tag{B.4}$$

The maximum likelihood estimate for the concentration parameter ($\hat{\kappa}$) is computed by finding the value for $\hat{\kappa}$ that minimizes ε in Equation (B.5)

$$\min_{\kappa} \left| {I_1(\kappa)}\big/{I_0(\kappa)} - \bar{R} \right| = \varepsilon \geq 0 \tag{B.5}$$

The expression $I_{\upsilon}(\kappa)$ in Equation (B.5) is again the modified Bessel function given in Equation (B.3). The concentration parameter (κ) of the von Mises distribution on a circular or periodic probability scale is analogous to the variance on a linear scale in that they both give a quantitative measure of the dispersion in the data. However, larger estimated values of κ indicate a more orderly or 'concentrated' data distribution with a more defined dominant direction of movement in the direction of the mean angular direction (given in Equation [B.2]). By contrast, larger values of the standard deviation parameter (σ) on a linear scale suggests less orderly or concentrated data with more spread about the mean parameter (μ) in a gaussian distribution for example.

The concentration parameter is the metric used in the analysis of displacement vectors to characterize and compare the behavior of fish detected by the split-beam transducers. Comparatively larger values of $\hat{\kappa}$ suggest a more clearly defined dominant direction of movement in the estimated mean angular direction ($\hat{\mu}$), while comparatively smaller values suggest a less defined dominant direction of movement in any angular direction. The latter would suggest the swirling movements of a group of milling fish.

An appropriate statistical test for comparing concentration parameters between two or more von Mises distributions takes the null hypothesis that all concentration parameters are equal

$$H_0 : \kappa_1 = \kappa_2 = \ldots = \kappa_r$$

vs.

H_a: at least one κ_i not equal

The test statistic is computed as follows:

First, let $d_{ij} = |\sin(\theta_{ij} - \hat{\mu}_j)|$ for observations $i = 1 \ldots n_j$ in population *j; j=1 to r.*

Then let $\bar{d}_j = \sum_{i=1}^{n_j} d_{ij} / n_j$ and $\bar{d} = \frac{1}{N}\sum_{j=1}^{r} d_j n_j$, $N = \sum_{j=1}^{r} n_j$

$$f_r = \frac{(N-r)\sum_{j=1}^{r} n_j(\bar{d}_j - \bar{d})^2}{(r-1)\sum_{j=1}^{r}\sum_{i=1}^{n_j}(d_{ij} - \bar{d}_j)^2} \tag{B.6}$$

The statistic computed in Equation (B.6) is compared to an F distribution with *r-1* and *N-r* degrees of freedom. Fisher (1993, page 132) recommends using this statistical test when sample sizes n ≥ 10 and the median of the estimated κ values is $\geq$ 1. Otherwise, the von Mises assumption is not supported in the data and randomized permutation methods as described in Fisher (1993, Section 8.5) or Manly (1998, Chapter 1) are recommended as more robust. A randomization analysis was performed by generating a distribution of values from equation B.6 on 500 random permutations of the data. Then a one-tailed Wilcoxon sign-rank test was used to compare paired estimated concentration parameter values. Differences were computed as follows:

$$\delta_p = \hat{\kappa}_{p0} - \hat{\kappa}_{p6}; p \in \{4,8,12,16,20\} \tag{B.7}$$

where $\hat{\kappa}_{p0}$ is the estimate at position *p* with lights off and $\hat{\kappa}_{p6}$ is the estimate at position *p* with 6-lights-on (positions refer to the location of each downlooking transducers, i.e., 4, 8, 12, 16 and 20 m from the lights). Under the null hypothesis that the two series are random variables of $\hat{\kappa}$ were sampled from the same distribution, the difference between estimates in the series should not be significantly different from zero, or equivalently, the probability that the sign of the difference is positive or negative should be equal at 0.5.

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Appendix C

Strobe Light Characterization

Appendix C

Strobe Light Characterization

The purpose of our research is to evaluate the efficacy of strobe lights to elicit a negative phototactic response in kokanee and rainbow trout. This empirical study at the Grand Coulee Dam third powerplant uses strobe lights provided by Flash Technology, Franklin, Tennessee. Little is known about the characteristics of the strobe lights other than the broad characterization noted in the Flash Technology specifications (1,200 candela-seconds at 360 flashes per minute). We assumed that the light source was a xenon helical arc lamp (personal communication with Mr. Ron Brown, Flash Technology).

Because understanding the extent of the illuminated region produced by the strobe lights is important to evaluate how they affect fish, we characterized the strobe lights for the purpose of our study. We accomplished this with two approaches. First, field measurements of the array of strobe lights were made at the conclusion of our test season at the third powerplant forebay. Second, laboratory measurements of an individual strobe light were made at the Pacific Northwest National Laboratory in Richland, Washington.

C.1 Methods

C.1.1 Field Measurements

Field measurements were made at the strobe light test location in the third powerplant forebay of Grand Coulee Dam on nights of August 7 and 8, 2002. The light frame used during the data collection season was raised to the surface and oriented horizontal with the lights aimed vertically into the water column from the stern of the sample platform (Figures C.1 and C.2). The frame was suspended from cables that could be adjusted to level the frame. We had planned to use a SED033/Y/L30 detector as a part of an IL1711 Flash Photometer System supplied by International Light, Newburyport, Massachusetts, but it was not functional due to flooding in the detector. Instead, an underwater high-gain illuminance detector model SHD033, also supplied by International Light, was used to collect field light measurements. This detector has a much slower response time than the SED033. Therefore, the measurement taken with this detector can be considered only a relative measure of light intensity assuming that the error associated with missed peak energy is random. The advantage of this detector was that the spatial responsivity was much broader than the SED033, resulting in less potential alignment error. Measurements were taken and displayed using an IL1700 Research Radiometer/Photometer also supplied by International Light. The detector was suspended on black polypropylene line weighted by a 5-lb lead weight. The polypropylene line was pre-measured and marked at the desired measurement distances to yield attenuation measures as a function of range. Additionally, measurements were taken at two radial distances from the centerline of the frame: 1) inner (1.02 m from the centerline) and 2) outer (2.02 m

Figure C.1. Six Strobe Lights Aimed Vertically Downward for Light Measurements at Grand Coulee Dam, Washington

from the centerline) to characterize the light drop-off as a function of distance away from the centerline. Turbidity was measured during the light measurements at 0.45 nephelometric turbidity units (NTU) at 2316 hr on August 7, 2002.

The measurements made with the SHD033 detector were average integrated values over a 30-second sample period after the strobe lights had stabilized (usually after about 5 minutes). After the 30-second sample period, the integrated value was recorded manually to a datasheet. Three replicates were taken at each location for each of the three treatment conditions tested during the season (6 lights on, 3 lights-a on, and 3 lights-b on).

C.1.2 Laboratory Measurements

Laboratory measurements of the strobe lights were made at the Pacific Northwest National Laboratory laser research facility and the fish facility. Initial measurements were made at the laser research facility to test the detectors for appropriate response and to obtain “ballpark” estimates of intensity. One strobe light was placed in a Plexiglas tank filled with water for cooling. The lens of the strobe light was placed at the Plexiglas window to minimize the amount of water that the light had to penetrate. These measurements were, therefore, considered air measurements. Two detectors were used. First, a high-speed photodetector (Newport, Irvine, California) was used to characterize individual light pulses in air.

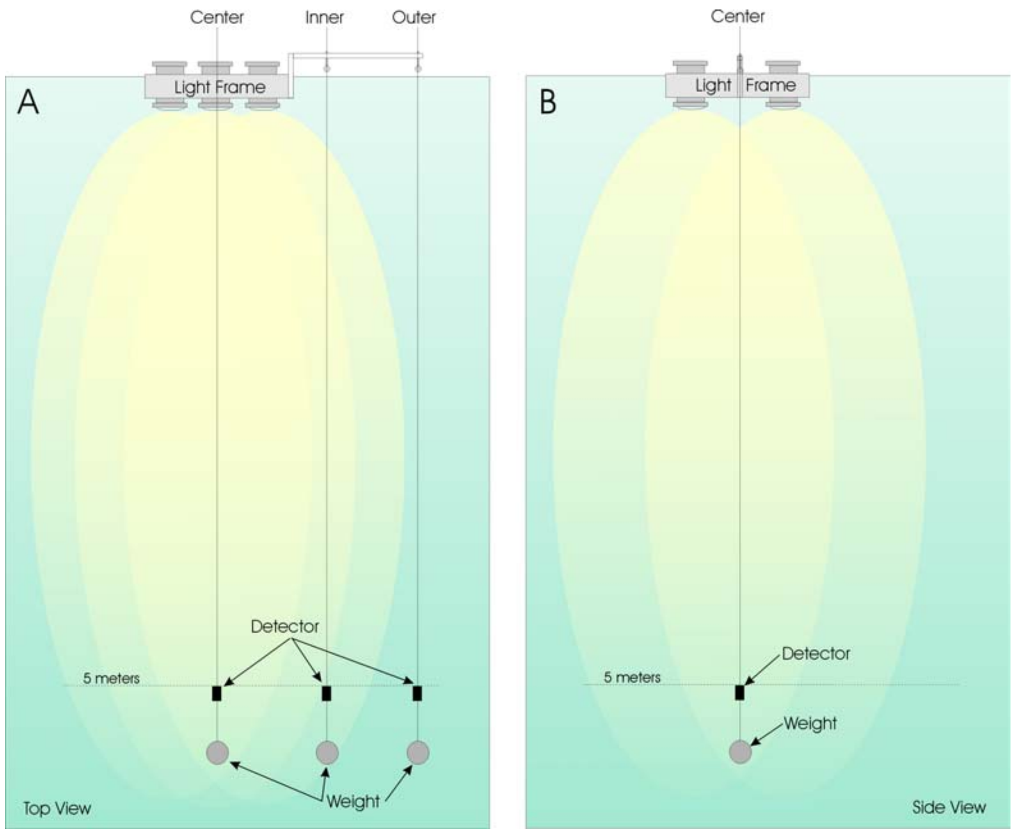

Figure C.2. Placement of Light Detector Beneath the Horizontal Frame. Example depth in this illustration was for measurements at 5 m from the lights. (A) Top view relative to field deployment configuration; (B) side view relative to field deployment configuration.

Next, a Molectron J4-05 Pyroelectric detector (Molectron Detector, Inc., Portland, Oregon) with a fast transistor amplifier was used to make intensity measurements in air. The Molectron J4-05 has a flat spectral response (>0.9 relative spectral response for wavelengths ranging from 0.2 µm to 100 µm). Thus, we measured the irradiation on the detector without any detector sensitivity bias. The detector was optimized for linear integration of short optical pulses from subpicosecond to submillisecond at repetition rates up to 400 pulses per second (pps). A plano-convex lens was used in front of the detector with a 48-mm diameter and 75-mm focal length.

All underwater measurements made at the fish facility were also made with the Molectron J4-05 detector described above. A stabilizing jig and turntable were used to maintain alignment and orientation with the detector, which was placed at the window of a Plexiglas tank (Figure C.3). The entire setup was placed in a fiberglass trough type tank that was 61 cm deep, 79 cm wide, and 5 m long and lined with a non-reflective black paper (Figures C.4 and C.5). Pinholes were placed at 10-degree increments on the turntable to fix the angles for measurement. The light was first aligned on axis at a range of 1 m and then rotated through a number of angles to describe the drop-off of the light with angle relative to the axis.

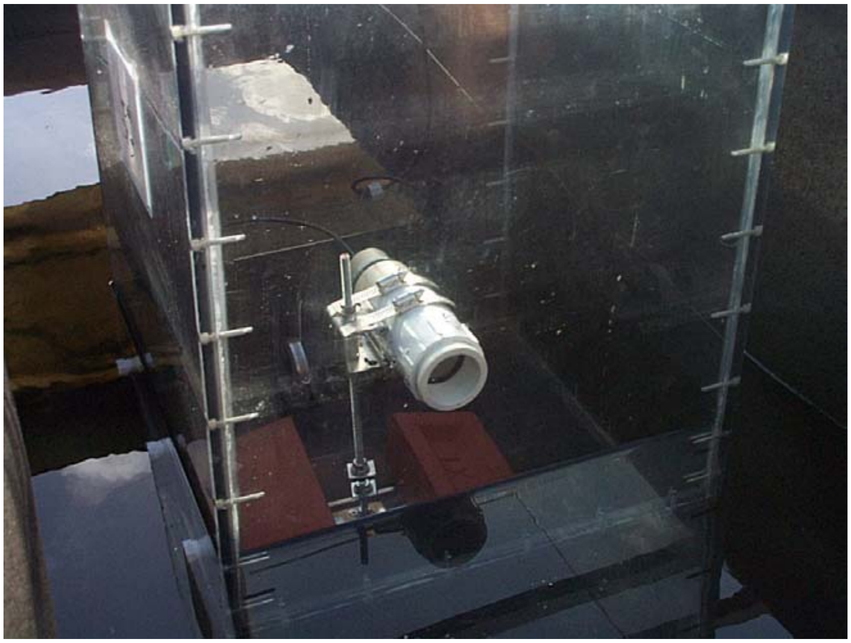

Figure C.3. Molectron Pyroelectric Detector in Plexiglas Tank and Aligned with Strobe Light Axis

Figure C.4. Strobe Light Placed at One End of Trough Tank

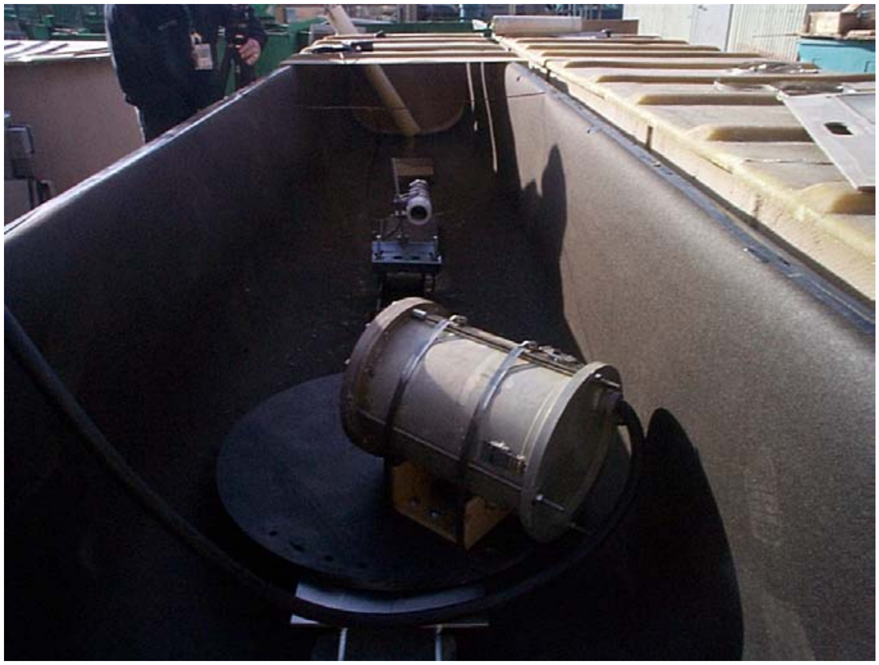

Figure C.5. Initial Setup of Light Jig/Turntable for Orienting Strobe Light at Fixed Angles Relative to Molectron Detector

Next, a series of measurements was performed at varying ranges to the extent of the tank and normal incidence to the strobe light. During each measurement, the detector was re-aimed to provide a peak measurement.

We used two water clarity conditions to match the conditions at Grand Coulee Dam as close as practicable. Turbidity was increased by adding high clay content soil to the water and waiting for the heavy material to fall out. The turbidity levels were chosen to approximate the conditions found at Grand Coulee Dam during the spring/summer sampling period (see Appendix A). First, the measurements were taken at the water clarity of the supply source (0.16 NTU). This closely matched the water clarity at the dam under the most favorable conditions (0.5 NTU). Next, we added silt to the water to create a more turbid condition for the light measurements (1.24 NTU). The higher turbidity closely matched the worst-case turbidity (1.5 NTU) measured in spring 2002 at Grand Coulee Dam. It should be noted that the source of turbidity in this test is likely different from the field source, which may affect the attenuation and scattering properties of the light differently.

C.2 Results

C.2.1 Field Measurements

The average illumination measured during field experiments is illustrated in Figure C.6 for three locations (center, inner, and outer); three depths (5 m, 10 m, and 15 m); and three light conditions (6 lights on, 3 lights-a on, and 3 lights-b on). Note that the center measurement was made only at the

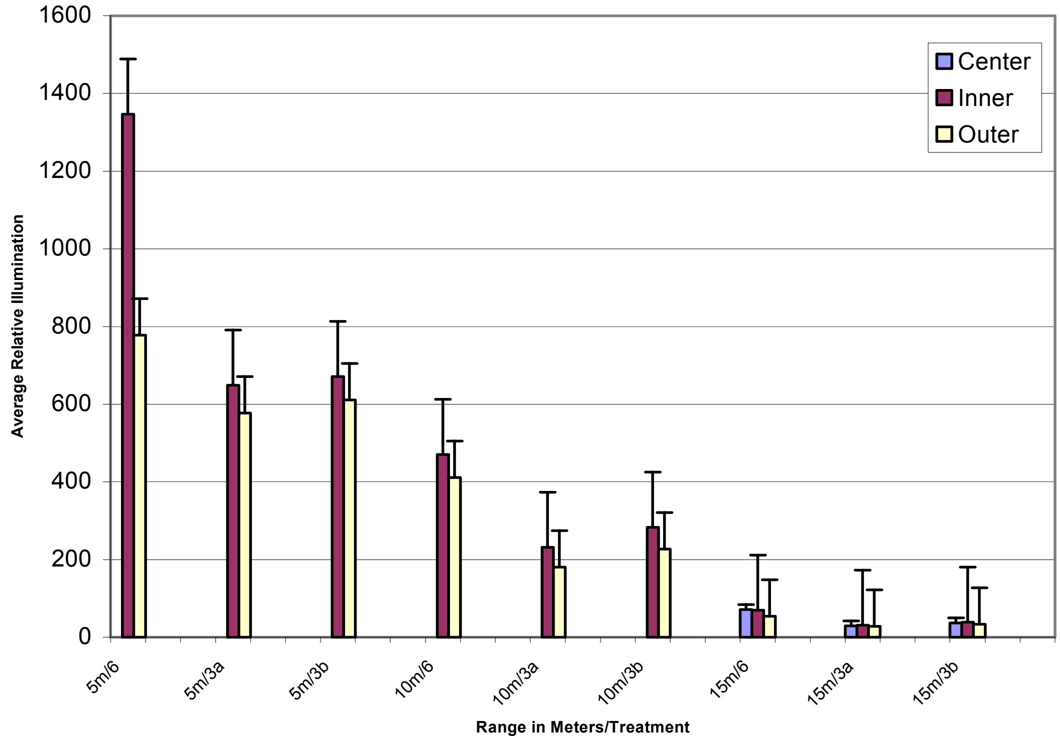

Figure C.6. Average Relative Illumination Measured at Third Powerplant Forebay at Three Locations on the Light Frame (center, inner, and outer); for Three Depths (5 m, 10 m, and 15 m); and, for Three Light Conditions (6 lights on, 3 lights-a on, and 3 lights-b on)

15 m depth for this exercise due to time constraints. Additional center depth measurements were made in a subsequent test to follow (results are in Figure C.7). Because the field measurements were made with a detector not well suited to the high-speed flash of the strobe lights, they should be considered index readings only and are reported as average relative illumination.

The greatest difference between the inner and outer readings occurred with 6 lights on at 5 m. This probably was due to the offset relative to the axis of the light beam. The 3-lights-on levels were consistently approximately half of the 6-lights-on illumination intensity as would be expected.

The next test we performed was to obtain relative illumination measurements at varying ranges to further characterize the light attenuation as a function of range. Figure C.7 shows the relative light levels as a function of range from the light source.

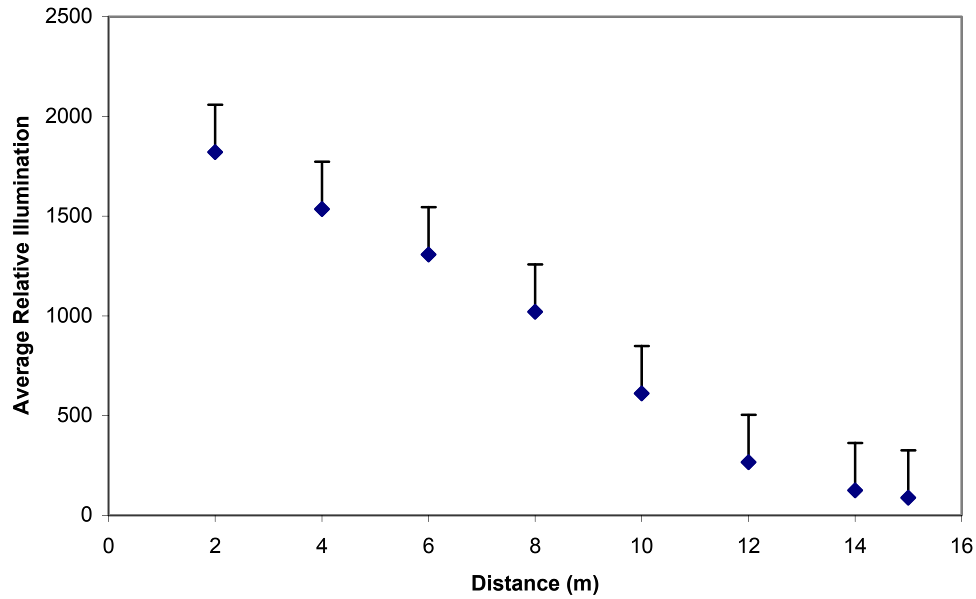

Figure C.7. Average Relative Illumination for 6 Lights on Condition at Various Ranges from Lights (error bars represent positive standard error)

Low measurements are probably a result of the offset of centerline sampling on the frame relative to the axis of the lights. Beyond 4 m, light levels approximated the inverse square law, as would be expected from the assumed theoretical spreading loss. This suggests that the light source was probably seen as one light rather than a distributed source. At 4 m and closer, however, we probably measured off-axis intensities, which were likely lower than would have been expected for the combined axis measurements of each light at those ranges. These types of discrepancies coupled with difficulty measuring in the field led us to make repeat measurements in the laboratory using a single strobe light.

C.2.2 Laboratory Measurements

An important consideration when making light measurements is to ensure that the measurement device has an adequate response time to account for the rise in the signal once the xenon tube is energized. We measured a strobe light pulse to characterize its shape. Figure C.8 is a plot of a strobe light pulse as detected by a Newport Model 815 photodetector. The pulse shape indicates that the pulse rises very fast and then dissipates at a somewhat slower rate. During data collection in the field, we pulsed the strobe light at a rate of 360 pulses per minute (6 pulses per second). Each pulse lasted for approximately 0.0006 second (measured at the 10% level on the curve) or about 3.6 ms for each second sampled. This represents a mere 0.36% of a second, suggesting that measurements made with time-based integration techniques may yield results that are considerably lower than peak pulse-averaged measurements.

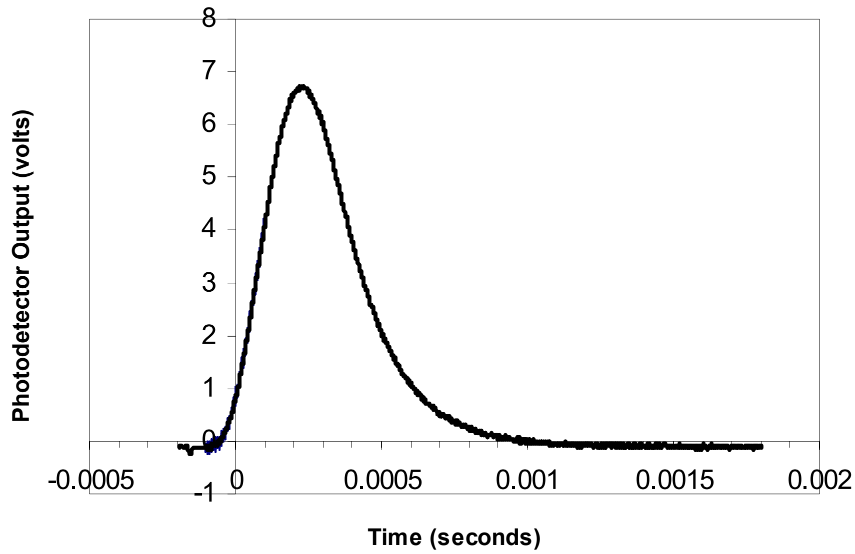

Figure C.8. Photodetector Output for One Pulse of Light from Flash Technology Strobe Light

The next step in our characterization was to measure a typical strobe light, first in air, then in water. Figure C.9 is a plot of the measurement taken as a function of angle relative to the axis of a typical strobe light in air. The on-axis measurement was calculated to be ~66 million lux. This compares favorably to the manufacturer-specified luminous energy of at least 1200 candela-seconds or 66 million lux at our flash rate of 360 flashes per minute (personal communication with Flash Technology).

The measured illumination as a function of distance from the strobe light followed the theoretical (inverse square of the range) values very closely (Figure C.10). Measurements were made to only 7 m range because of the limited size of the darkened room that was used to make the measurements.

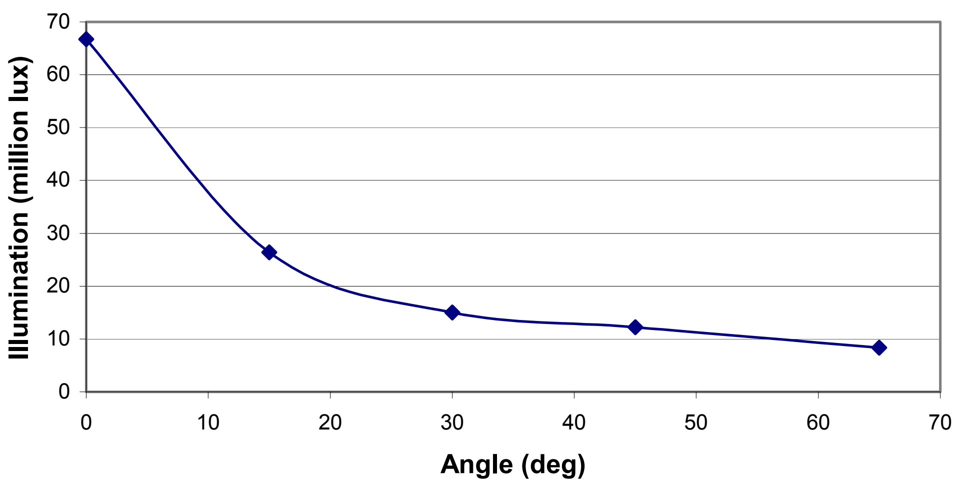

Figure C.9. Illumination as a Function of Angle Measured in Air for One Strobe Light

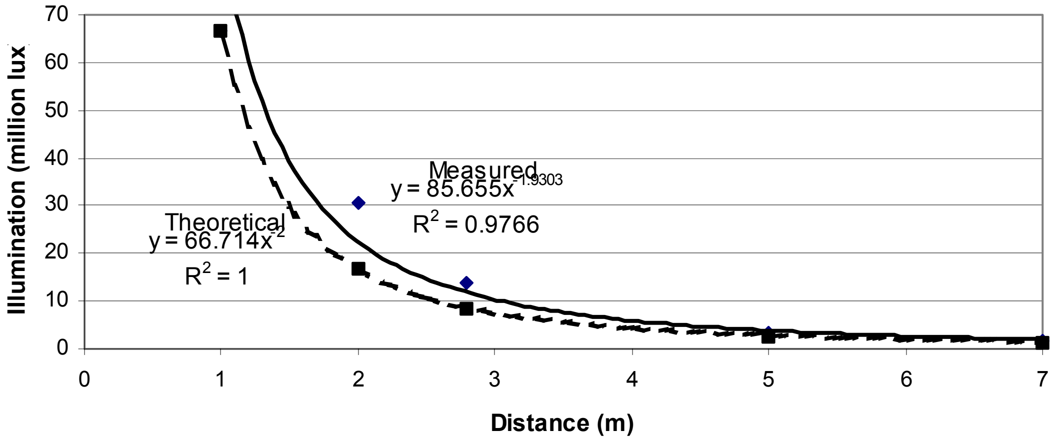

Figure C.10. Illumination as a Function of Distance From One Strobe Light Measured in Air

Measurements made in water were conducted outdoors at our fish facility under extreme temperature conditions. As a result, the data collected in 2002 are minimal. We hope to repeat this process in spring 2003 under more favorable conditions. The results of the illumination measurements as a function of angle off-axis in water are shown in Figure C.11. In the clear water, the illumination level dropped approximately 0.5 million lux in the first 20 degrees off axis. After that, regions of leveling occurred between 20 to 40 degrees off axis on both sides of the beam. This may be an anomaly associated with either the lens or the reflector, or both. Beyond 40 degrees, the illumination dropped rapidly and was not measurable at 60 degrees on either side of the axis.

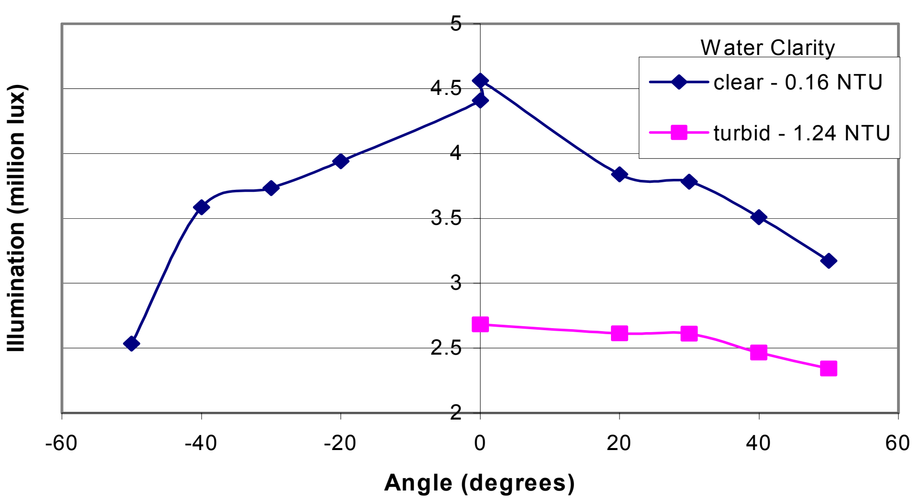

Figure C.11. Illumination as a Function of Angle in Water for Two Water Clarity Levels (clear – 0.16 NTU; turbid – 1.24 NTU)

Measurements with turbid water were made on only one side of the axis. The light level dropped dramatically (~40%) with the addition of a small amount of particulate to the water. Also, the light appeared to be more dispersed with less drop-off relative to the axis. The characteristic leveling between 20 and 40 degrees was still noticeable, and again the light was not measurable at 60 degrees. These radical changes in the light pattern suggest that effective illumination of the water column may be radically affected also by relatively small changes in the nature of the medium with increased light dispersion and attenuation under turbid conditions. We define "effective illumination" in this instance as the light necessary to effect a response in the target species (kokanee and rainbow trout).

When we measured the strobe light illumination as a function of distance, we noted the same 40% drop in relative illumination with the higher turbidity while the relative decrease in intensity with range was less than the theoretical (inverse square of the range) (Figure C.12). We also noted that we lost our signal at a much closer range (~2.5 m).

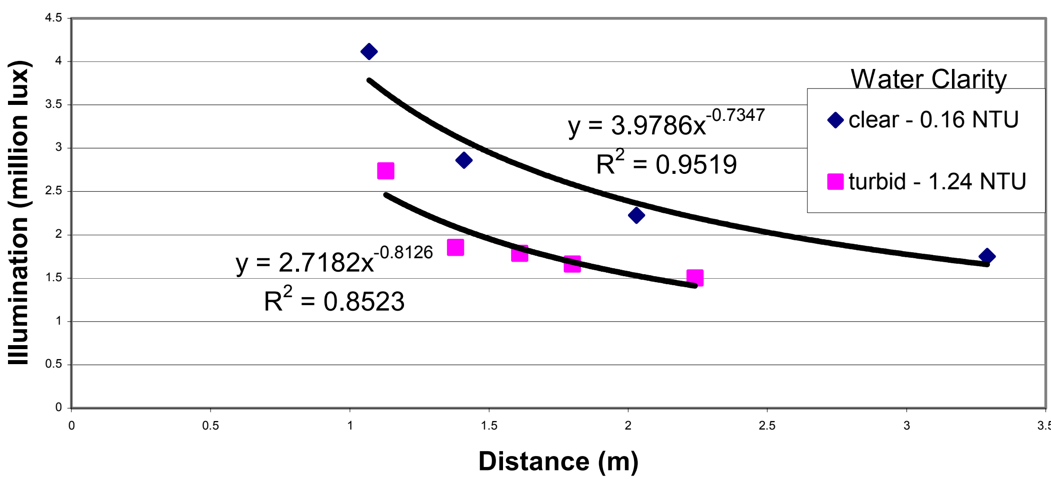

Figure C.12. Illumination as a Function of Distance from One Strobe Light for Two Water Clarity Conditions (clear – 0.16 NTU; turbid – 1.24 NTU)

We conclude from these initial laboratory measurements that a considerable change in the light transmission characteristics was associated with a slight increase in turbidity. This has ramifications with regard to the range of effective illumination, as well as how the water column is illuminated under varying conditions. Although the focused beam of light may penetrate farther when the water is clear, it will have a more scattered effect with increased turbidity. In the first instance, the lights might be expected to have an effect on fish at a greater range but in a relatively confined direction. In the second instance, the range is compromised, but a larger peripheral region might be effectively illuminated.

We also noted, in our test strobe light, that quality of both the lens and the reflector surface potentially could be improved to provide better lighting conditions for fishery applications. Recommendations to that effect will be forthcoming, subsequent to more detailed measurements and modeling of the lighted region.

Appendix D

Hydroacoustic System Calibration

Appendix D

Hydroacoustic System Calibration

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 2002.

This appendix lists results for two calibrations. The first calibration was conducted on April 12 and 14, 2002, prior to initiation of the study. The system operated under those calibration conditions until July 8, 2002. On July 8, 2002, we experienced a catastrophic failure of the system caused by the swamping of electronic components during a violent storm event. The system components affected by the swamping were immediately shipped to Seattle for repair and recalibration. The calibration results are listed under the July 11, 2002, calibration heading; these results were used until the conclusion of the study. To ensure the quality of the data after the system failure, the manufacturer was brought to the field site to thoroughly evaluate the system, including those components that had not been harmed by the swamping event. All systems continued to operate in peak condition through the end of the study period.

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Date: 4/12/02 & 4/14/02
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.
Absorption Coeff: 0 dB/km. (Off)

Standard Type: PAS Standard Transducer #: 236
Receive Sensitivity of Standard, Ss: -204.56 dBV||uPa
Transmit Sensitivity of Standard, Ts: 170.35 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	Max Level?	Stat Xmit Level	Dyn Xmit Level	Vs	SL	Max Level?
-5	-6	-4.11	211.12		-2	-6	-0.21	215.02	
-4	-6	-2.66	212.57		-1	-6	0.78	216.01	**
-3	-6	-1.32	213.91		0	-6			

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 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)	3.997	-26	3.991	79.82	-53.86	-113.86
Receiver #2, X Phase (AC/BD)	2.475	-26	2.475	N/A	N/A	N/A
Receiver #3, Y Phase (AB/CD)	2.494	-26	2.535	N/A	N/A	N/A

Splitbeam Conversion Coefficients for Phase to Mechanical Angle and Phase to Beam Pattern Factor

Axis	Transducer	Lens – 10°	SAx	OAx	SBx	OBx
X	PAS-420-SPB-06-431	#09	192.6867	2003.872	-153822.71	1984.14274
Y	PAS-420-SPB-06-431	#09	189.1676	2080.713	-154096.69	2127.93975
X	PAS-420-SPB-06-432	#09	200.2751	2032.49	-158532.93	2039.05189
Y	PAS-420-SPB-06-432	#09	205.5048	2012.174	-152157.50	2025.29709
X	PAS-420-SPB-06-433	#09	191.887	2013.157	-155872.42	2010.16376
Y	PAS-420-SPB-06-433	#09	196.9529	2050.075	-160140.10	2074.3686
X	PAS-420-SPB-06-434	#09	192.5077	2034.019	-165549.68	2021.8424
Y	PAS-420-SPB-06-434	#09	192.2576	2068.207	-163222.32	2067.5657
X	PAS-420-SPB-06-447	#09	181.935	2053.734	-157024.48	2041.1771
Y	PAS-420-SPB-06-447	#09	180.9287	2030.633	-154230.81	2057.62504
X	PAS-420-SPB-06-438	#09	195.61.29	2050.021	-164080.15	2032.84871
Y	PAS-420-SPB-06-438	#09	195.0537	2019.219	-164764.31	2061.73193
X	PAS-420-SPB-06-449	#09	190.223	2029.213	-160434.47	2032.98838
Y	PAS-420-SPB-06-449	#09	187.273	2010.535	-157512.56	2036.89221

Splitbeam Calibration for Grand Coulee Dam – Source Levels

Date	Xducer	Axis	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit Level	Vs	SL
4/12/2002	434	X	-5	-4.11	211.12	-4	-2.66	212.57	-3	-1.32	213.91	-2	-0.21	215.02
4/12/2002	434	Y	-5	-4.1	211.13	-4	-2.65	212.58	-3	-1.31	213.92	-2	-0.22	215.01
4/12/2002	431	X	-5	-4.66	210.57	-4	-3.2	212.03	-3	-1.86	213.37	-2	-0.72	214.51
4/12/2002	431	Y	-5	-4.73	210.50	-4	-3.28	211.95	-3	-1.93	213.30	-2	-0.78	214.45
4/12/2002	432	X	-5	-4.28	210.95	-4	-2.85	212.38	-3	-1.53	213.70	-2	-0.43	214.80
4/12/2002	432	Y	-5	-4.34	210.89	-4	-2.84	212.39	-3	-1.56	213.67	-2	-0.43	214.80
4/12/2002	433	X	-5	-4.68	210.55	-4	-3.23	212.00	-3	-1.88	213.35	-2	-0.7	214.53
4/12/2002	433	Y	-5	-4.68	210.55	-4	-3.23	212.00	-3	-1.87	213.36	-2	-0.72	214.51
4/14/2002	447	X	-5	-4.37	210.86	-4	-2.91	212.32	-3	-1.61	213.62	-2	-0.48	214.75
4/14/2002	447	Y	-5	-4.33	210.90	-4	-2.91	212.32	-3	-1.58	213.65	-2	-0.46	214.77
4/14/2002	438	X	-5	-3.82	211.41	-4	-2.39	212.84	-3	-1.08	214.15	-2	0.05	215.28
4/14/2002	438	Y	-5	-3.84	211.39	-4	-2.4	212.83	-3	-1.09	214.14	-2	0.04	215.27
4/14/2002	449	X	-5	-4.26	210.97	-4	-2.84	212.39	-3	-1.53	213.70	-2	-0.42	214.81
4/14/2002	449	Y	-5	-4.26	210.97	-4	-2.84	212.39	-3	-1.53	213.70	-2	-0.43	214.80

Splitbeam Calibration for Grand Coulee Dam – Receiving Sensitivities

Date	Xducer	Axis	Vdet Out	G1	X Out	Y Out	-45 dB Cal	X Cal	Y Cal	Date	Xducer	Axis	Vdet Out	G1	X Out	Y Out	-45 dB Cal	X Cal	Y Cal
4/12/2002	434	X	3.991	-113.86	2.475	2.535	3.997	2.475	2.494	4/14/2002	438	X	4.025	-113.18	2.506	2.482	3.998	2.476	2.496
4/12/2002	434	Y	3.992	-113.84	2.475	2.535	3.998	2.476	2.495	4/14/2002	438	Y	4.024	-113.20	2.506	2.484	3.998	2.477	2.495
4/12/2002	431	X	3.967	-114.34	2.452	2.545	3.998	2.476	2.497	4/14/2002	449	X	4.004	-113.60	2.51	2.462	3.999	2.478	2.497
4/12/2002	431	Y	3.962	-114.44	2.451	2.542	3.998	2.475	2.497	4/14/2002	449	Y	4.006	-113.56	2.513	2.461	3.999	2.478	2.497
4/12/2002	432	X	3.974	-114.20	2.488	2.475	3.999	2.476	2.499	4/14/2002	447	X	4.029	-113.10	2.483	2.461	3.999	2.479	2.497
4/12/2002	432	Y	3.97	-114.28	2.483	2.477	3.999	2.477	2.5	4/14/2002	447	Y	4.026	-113.16	2.484	2.461	3.998	2.479	2.498
4/12/2002	433	X	3.979	-114.10	2.457	2.515	3.999	2.477	2.5										
4/12/2002	433	Y	3.978	-114.12	2.457	2.515	3.999	2.477	2.5										

Date: 7/11/02
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-483-101 — 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

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.
Absorption Coeff: 0 dB/km. (Off)

Standard Type: PAS Standard Transducer #: 236
Receive Sensitivity of Standard, Ss: -204.56 dBV||uPa
Transmit Sensitivity of Standard, Ts: 170.35 dBuPa/Vrms @ 1 meter.
Separation Between Transducers, Rs: 3.416 m. 20 Log (Rs) = 10.67 dB.
Water Temperature: 15.55 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	Max Level?	Stat Xmit Level	Dyn Xmit Level	Vs	SL	Max Level?
-5	-6	-4.12	211.11		-2	-6	-0.27	214.96	**
-4	-6	-2.68	212.55		-1	-6			
-3	-6	-1.38	213.85		0	-6			

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 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)	4.004	-26	4.038	80.76	-52.92	-112.92
Receiver #2, X Phase (AC/BD)	2.487	-26	2.521	N/A	N/A	N/A
Receiver #3, Y Phase (AB/CD)	2.505	-26	2.457	N/A	N/A	N/A

Splitbeam Conversion Coefficients for Phase to Mechanical Angle and Phase to Beam Pattern Factor

Axis	Transducer	Lens – 10°	SAx	OAx	SBx	OBx
X	PAS-420-SPB-06-447	#09	188.3695	2072.576	-162744.05	2065.47729
Y	PAS-420-SPB-06-447	#09	188.9483	1995.025	-161391.33	2070.82219
X	PAS-420-SPB-06-438	#09	200.5193	2060.015	-166949.67	2050.43397
Y	PAS-420-SPB-06-438	#09	200.0268	2051.004	-167256.23	2072.05719
X	PAS-420-SPB-06-449	#09	190.0971	2048.546	-162261.49	2049.36789
Y	PAS-420-SPB-06-449	#09	189.9093	2022.878	-161446.39	2055.71027

Splitbeam Calibration for Grand Coulee Dam – Source Levels

Date	Xducer	Axis	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit Level	Vs	SL	Xmit Level	Vs	SL
7/11/2002	447	X	-5	-4.12	211.11	-4	-2.68	212.55	-3	-1.38	213.85	-2	-0.27	214.96
7/11/2002	447	Y	-5	-4.09	211.14	-4	-2.67	212.56	-3	-1.35	213.88	-2	-0.25	214.98
7/11/2002	438	X	-5	-3.59	211.64	-4	-2.17	213.06	-3	-0.87	214.36	-2	0.22	215.45
7/11/2002	438	Y	-5	-3.58	211.65	-4	-2.17	213.06	-3	-0.87	214.36	-2	0.22	215.45
7/11/2002	449	X	-5	-4.16	211.07	-4	-2.75	212.48	-3	-1.44	213.79	-2	-0.34	214.89
7/11/2002	449	Y	-5	-4.17	211.06	-4	-2.76	212.47	-3	-1.45	213.78	-2	-0.34	214.89

Splitbeam Calibration for Grand Coulee Dam – Receiving Sensitivities

Date	Xducer	Axis	Vdet Out	G1	X Out	Y Out	-45 dB Cal	X Cal	Y Cal
7/11/2002	447	X	4.038	-112.92	2.521	2.457	4.004	2.487	2.505
7/11/2002	447	Y	4.038	-112.92	2.521	2.458	4.003	2.489	2.503
7/11/2002	438	X	4.03	-113.08	2.524	2.484	4.004	2.488	2.507
7/11/2002	438	Y	4.03	-113.08	2.523	2.485	4.004	2.489	2.508
7/11/2002	449	X	4.047	-112.74	2.509	2.474	4.005	2.49	2.506
7/11/2002	449	Y	4.047	-112.74	2.507	2.475	4.005	2.489	2.508

Appendix E

Hydrodynamic Characterization

Appendix E

Hydrodynamic Characterization

E.1 Hydrodynamic Conditions at the Barge Site

Approximately 61 days of data were collected using the downlooking acoustic Doppler current profiler (ADCP) mounted on the barge. The ADCP was programmed to collect data at 5-min intervals with a vertical resolution of 0.5 m, resulting in a substantial dataset of three-dimensional water velocities.

A typical subset of these data is presented in Figure E.1. In the upper part of Figure E.1, the combined discharge (i.e., sum of all discharges from the six turbine units) through the third powerplant has been plotted. In the bottom portion of Figure E.1, horizontal velocity magnitudes have been color-contoured from 0 to 100 cm/s.

Velocity magnitudes in the top 15 m of the water column were noted to vary in a regular sinusoidal pattern that closely matches the sinusoidal operations of the powerplant. Between 15 and 20 m, and at 40 m, unusual low velocity (dark blue) zones are noted in the ADCP data when the discharge through the powerplant was low. These result from one or more of the ADCP beams hitting the light frame (15 to 16 m), the V-fin flow stabilizer (18 to 19 m), and the weight used to stabilize the thermistor string (40 m). Echograms show energy spikes in all four beams, not just the beam that hit the obstacle, which is typical when a beam hits a solid object. Although the ADCP can resolve a solution using only three good beams, the reflected noise was received by the other three beams and confounded the measurement, resulting in an unpredictable distortion of the velocity field. When discharges through the third powerplant were high (generally above 120 kcfs), drag caused by the swiftly moving water displaced the light frame, V-fin, and thermistor weight downstream and out of the ADCP beam swath. During periods of high powerplant discharge, velocities recorded throughout the entire water column should be within expected error bounds (accurate to within a standard deviation of 3 cm/s).

Figure E.2 was created using the dataset displayed in Figure E.1. By counting the number of horizontal velocity directions that fell within 15° bins (e.g., count between 0° and 15°, 15° and 30°), a histogram of flow direction was created. A flow direction of 90° (north) is one heading downstream and along centerline of the cul-de-sac of the third powerplant. A slight turning toward the west is expected and indicates a slight turning of the flow toward the intakes along the west side of the cul-de-sac. The histogram of flow directions shown in Figure E.2 is typical for most other dates during the measurement period, with a peak flow direction count occurring in the 90° to 115° bin.

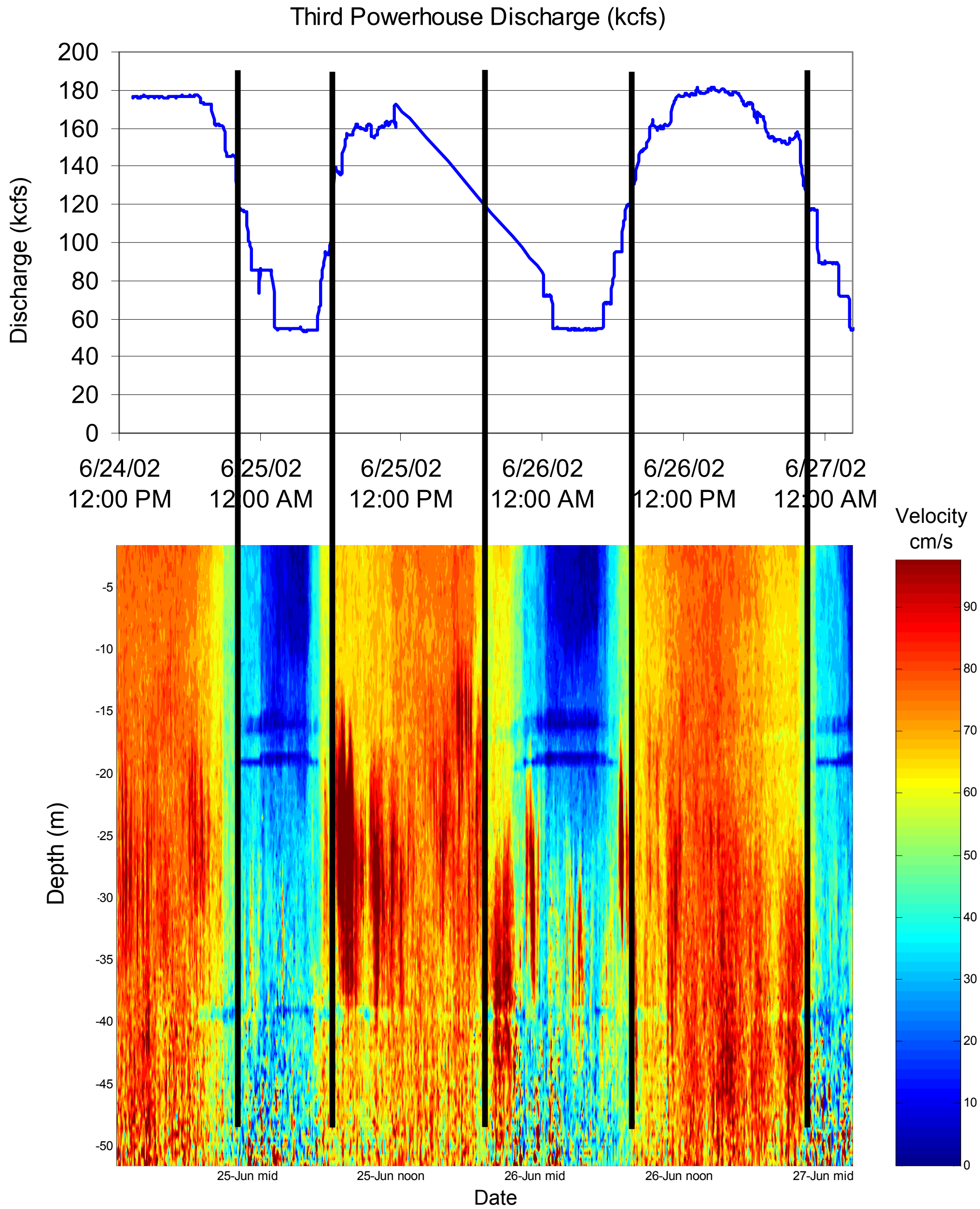

Figure E.1. Third Powerplant Discharge (top) and Horizontal Water Velocity (bottom)

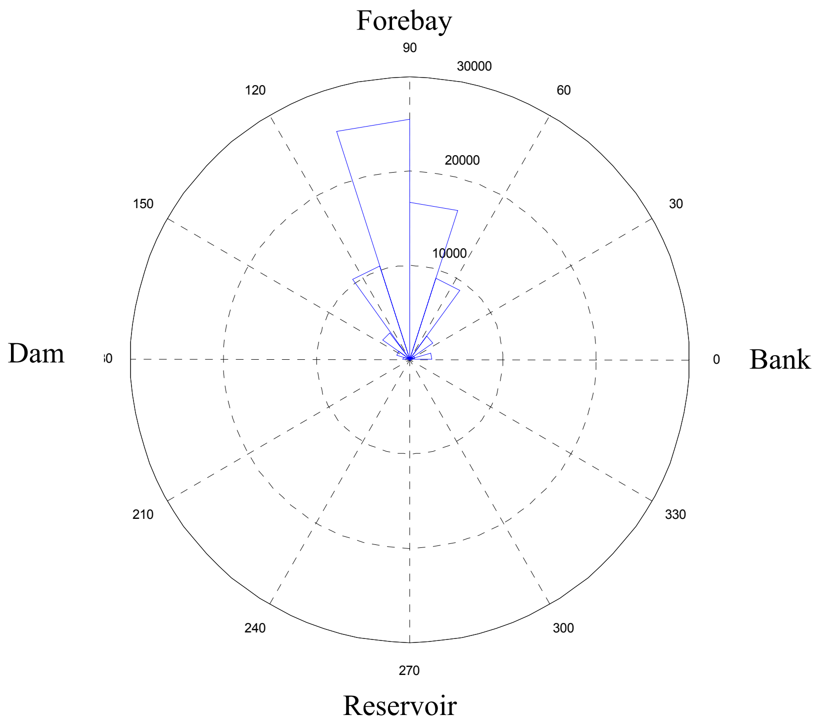

Figure E.2. Count of Water Velocity Directions Between June 24 (noon) and June 27 (2 a.m.)

With respect to the flow field, the following general conclusions can be drawn:

- When the third powerplant was discharging more than 120 kcfs, the entire water column was energized and moving with a more-or-less vertically uniform speed and direction (i.e., a distinct withdrawal zone was not identified).

- At discharges below 120 kcfs, the portion of the water column between the near-surface and 15 m moved slowly (generally less than 40 cm/s), and directions were highly variable.

- Measurements at discharges below 120 kcfs and depths greater than 15 m are suspect because the light frame and V-fin interfered with the ADCP acoustic beams.

- Velocities at depths below 40 m are questionable at all but the highest discharges (approximately >160 kcfs) due to interference from the thermistor weight.

- Peak velocities observed at the site regularly exceeded 70 cm/s.

E.2 Hydrodynamic and Thermal Conditions at the Barge Site

Water temperature data were collected at 14 depths beneath the barge site and are discussed more fully in Appendix A. A small subset of these data is presented in Figure E.3 along with the corresponding discharge through the third powerplant.

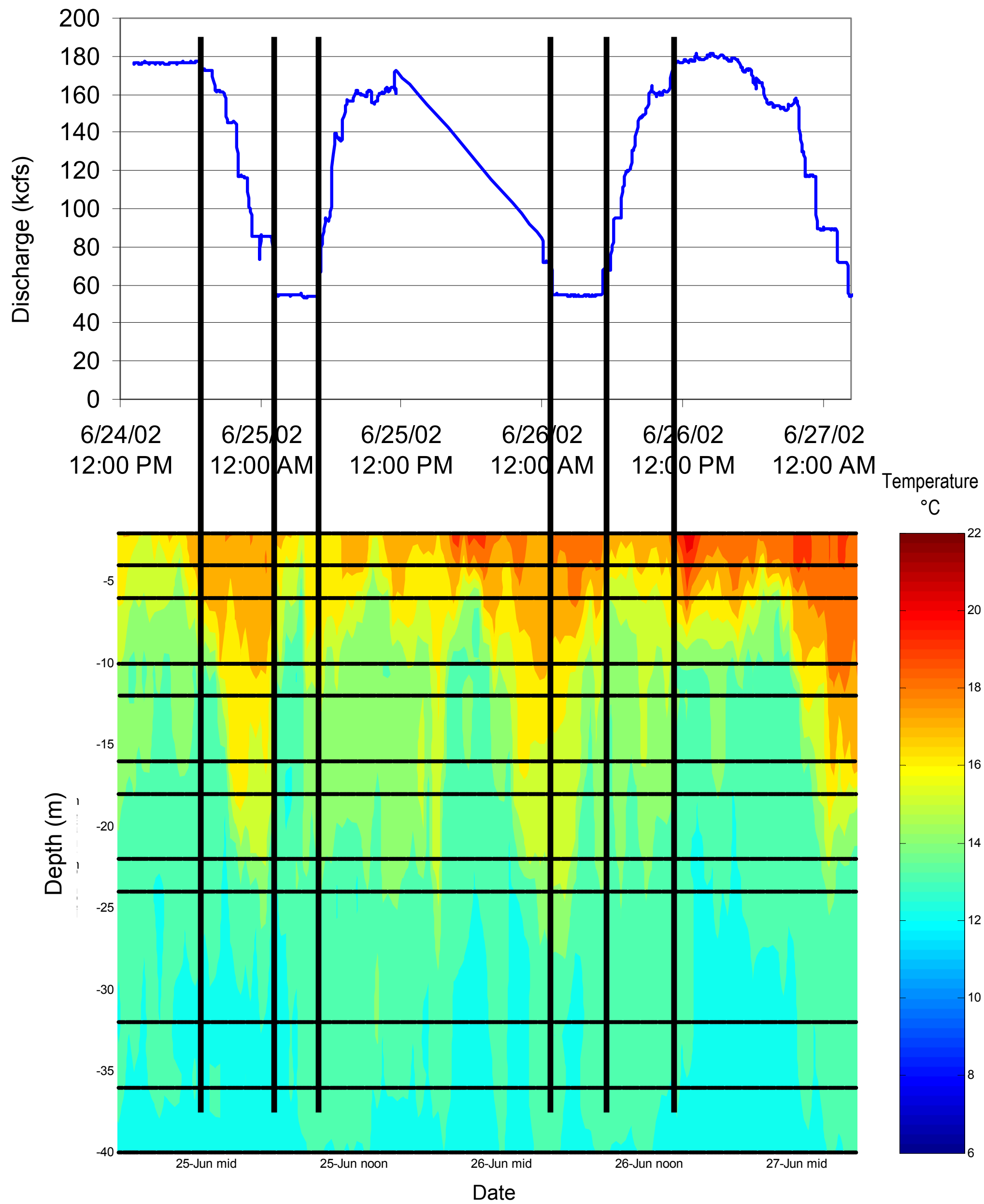

Figure E.3. Third Powerplant Discharge (top) and Water Temperatures (bottom) at the Barge Site, June 24 (noon) to June 27 (2 a.m.)

Several vertical lines have been placed on Figure E.3 for emphasis. These lines set apart zones of low and high discharge through the third powerplant. We note that the water column remains stratified during most of the 3-day period, except for short periods at the start of the subset and after midnight on June 25. During periods of high discharge around noon on June 25 and the afternoon of June 26, the water column remains strongly stratified.

A metric to gauge stratification strength was generated by subtracting time-series of temperatures measured at 4 m and 32 m beneath the water surface. This difference in water temperatures has been plotted in Figure E.4. Also plotted in Figure E.4 are depth-averaged water velocities. The depth averaging extends from 0 to 15 m so as to exclude any questionable data generated by the ADCP beams hitting the light frame.

Figure E.4 shows that water velocities at the barge site (a surrogate for discharge through the third powerplant) and stratification strength are not correlated. Numerous examples exist with both high water-column velocities and high stratification. In fact, for the entire period, the mean temperature difference was 3.3ºC, with maximums reaching above 6ºC.

Two general conclusions can be drawn from these data:

- The forebay in front of the third powerplant remained continuously stratified for a significant portion of time between mid-June and mid-July 2002.
- Discharges through the powerplant varied widely during the same period. However, no evidence was found that the powerplant discharge broke down thermal stratification observed at the barge site.

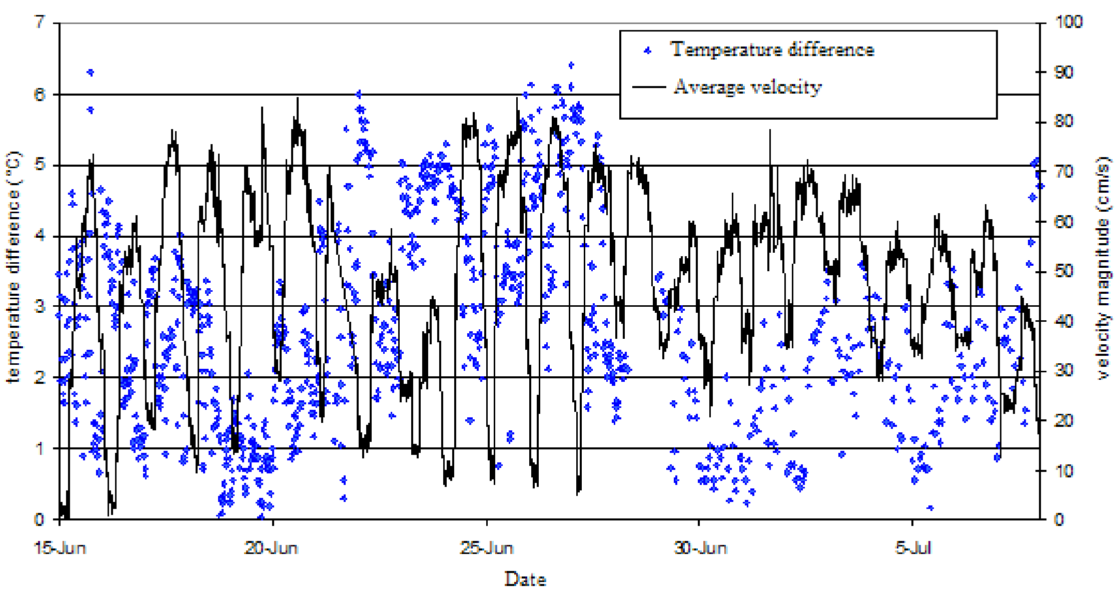

Figure E.4. Difference Between Surface (4 m) and Bottom (32 m) Water Temperatures Compared to Depth-Averaged (0 to 15 m) Water Velocities at Barge Site

E.3 Mobile Hydrodynamic Survey

Water velocities measured by the mobile ADCP were processed and separated into three depth ranges: 0 to 20 m, 20 to 50 m, and greater than 50 m. Water column depths varied from site to site, as illustrated in Figures E.5 through E.7. If the water column depth at a site was less than the depth range stated on each illustration, that site was not included (i.e., there are fewer arrows on Figure E.7 than on Figure E.5).

Interpretation of mobile ADCP data in a reservoir is complicated by non-constant operations through the dam. During the data collection period (5 to 6 p.m. on May 2 and 9 a.m. to 5 p.m. on May 3), forebay elevations varied approximately 0.5 ft (mean elevation ~1244.5 ft), and the discharge through the first and second powerplants varied by approximately 16,000 cfs (mean discharge ~49,000 cfs) – both relatively minor variations. The largest fluctuations appeared at the third powerplant, which is operated for peaking power demands. During the measurement period, discharges from the third powerplant varied between 50,000 cfs and 150,000 cfs, a fluctuation of 75,000 cfs. The impacts of these fluctuations are unknown. However, given the size of Lake Roosevelt, the impacts on forebay velocities away from the dam are assumed minor. Values within the cul-de-sac could be quite variable and should be used as relative indications only of the large-scale flow field.

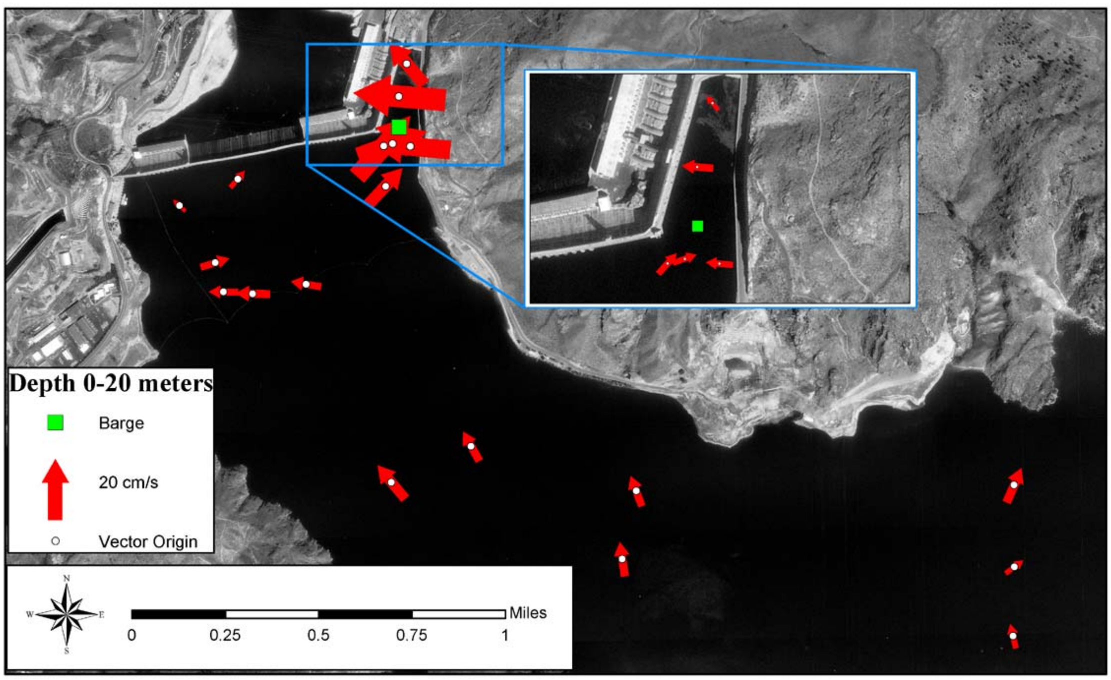

Figure E.5. Depth-Averaged Mobile ADCP Velocities Between Near-Surface and 20 m. Velocity scale of inset figure is different from the remainder of the figure.

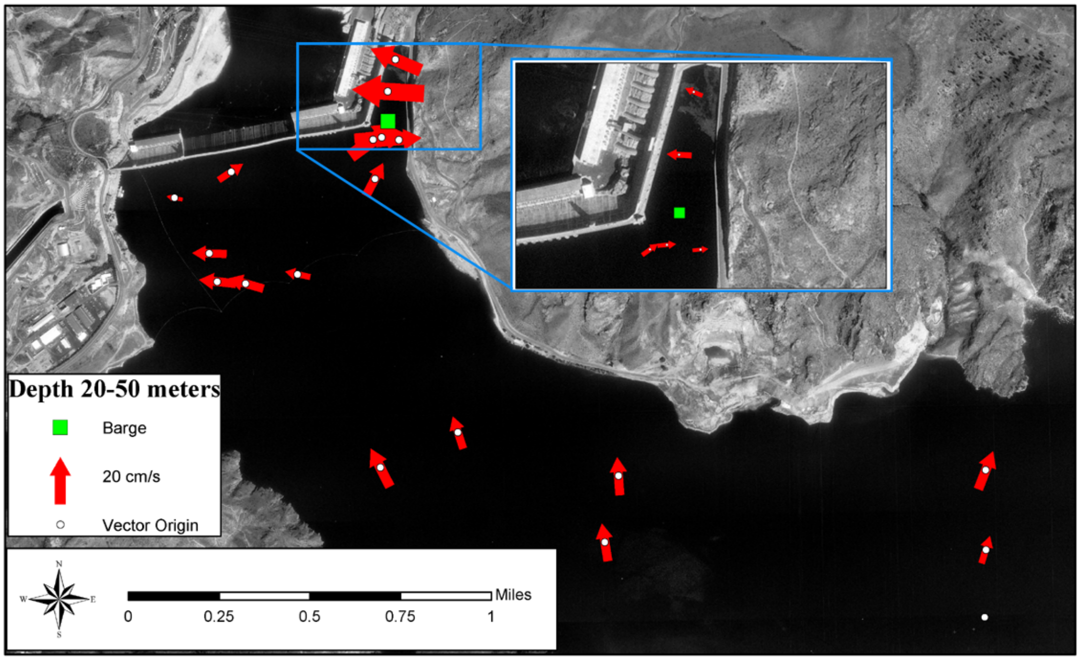

Figure E.6. Depth-Averaged Mobile ADCP Velocities Between 20 and 50 m. Velocity scale of inset figure is different from the remainder of the figure.

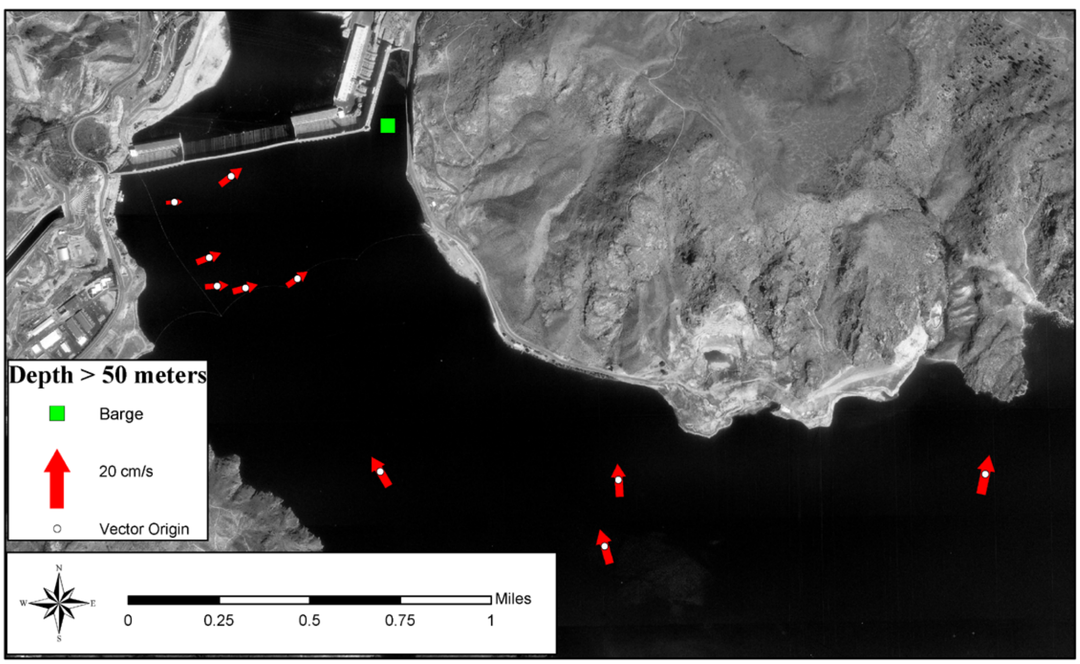

Figure E.7. Depth-Averaged Mobile ADCP Velocities Below 50 m

Appendix F

Angular Direction of Movement Histograms

Appendix F

Angular Direction of Movement Histograms

Figures F.1 and F.2 show the angular direction of movement for all fish targets at each downlooking transducer location. The angular direction is the angle between the displacement velocity vector and the downstream direction into the forebay. A wind rose histogram is used to show the distribution of targets with respect to their direction of movement. In these figures, downstream is at zero degrees, the dam is at 90º upstream, into the forebay, is 180°. The angular direction for a fish track headed directly downstream would be zero. The inner concentric rings indicate the percent probability distribution.

Figures F.1 and F.2 show the angular direction for lights-off (off) and 6-lights-on (on) treatments for day and night and larger (TS >-47 dB) and smaller (TS ≤-47 dB) fish targets. The locations of the downlooking transducers are as follows: beam 30 = 4 m; beam 0 = 8 m; beam 1 = 12 m; beam 2 = 16 m; beam 3 = 20 m.

For larger targets (TS >-47 dB) (Figure F.1) when the lights were on at night, the fish were generally headed across the forebay, toward either the dam or the opposite bank (i.e., angular directions of 90º and 270º, respectively) for all locations beyond 8 m from the strobe lights. At 4 m from the strobe lights, the distribution of angular directions was in all directions indicating the fish were moving equally in all directions. For all other conditions – that is, lights off, daytime and smaller targets – the primary direction of movement was downstream.

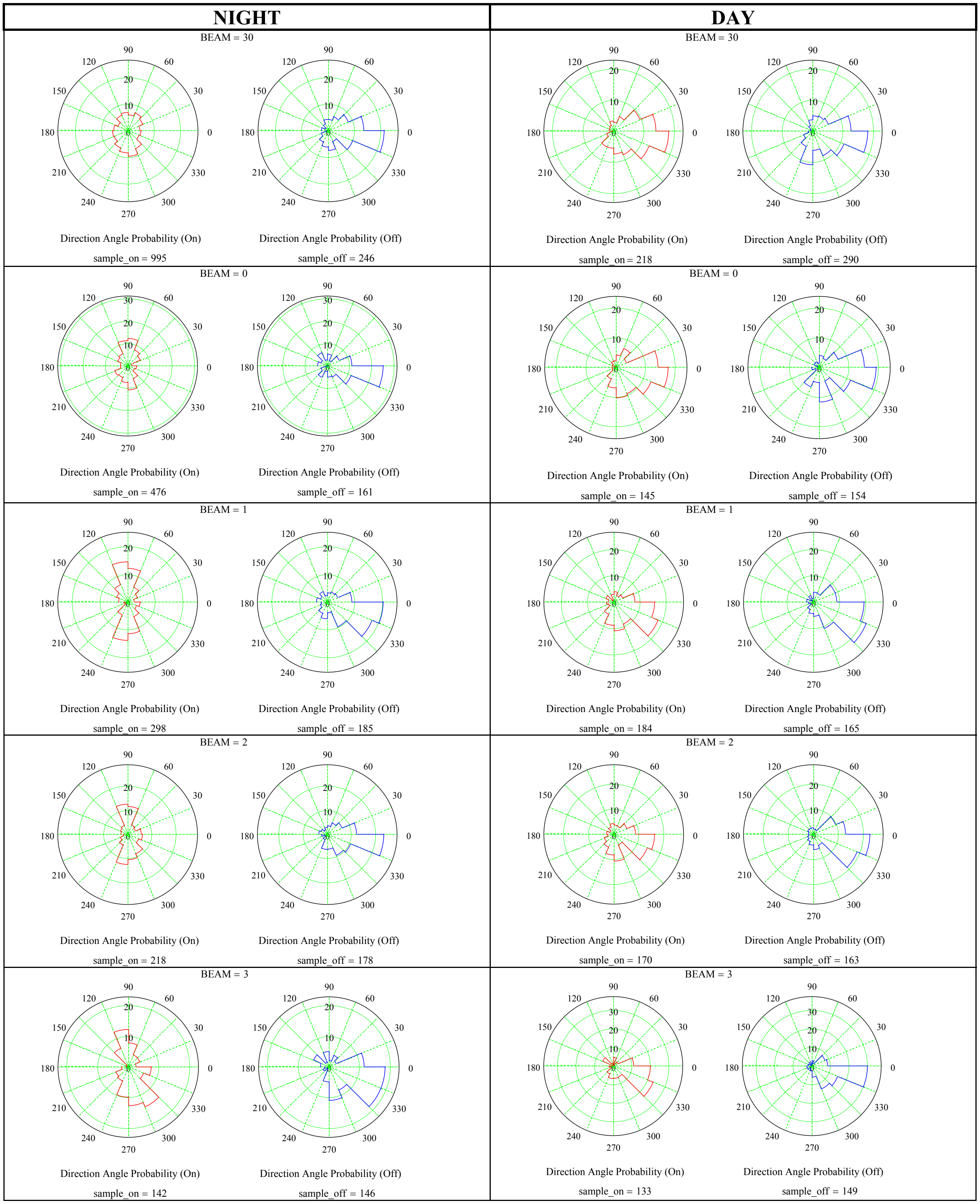

Figure F.1. Direction Angle of Large Targets (TS >-47 dB) at Night (left) and Day (right) for Each Transducer Beam (Beam 30 = 4 m; Beam 0 = 8 m; Beam 1 = 12 m; Beam 2 = 16 m; Beam 3 = 20 m)

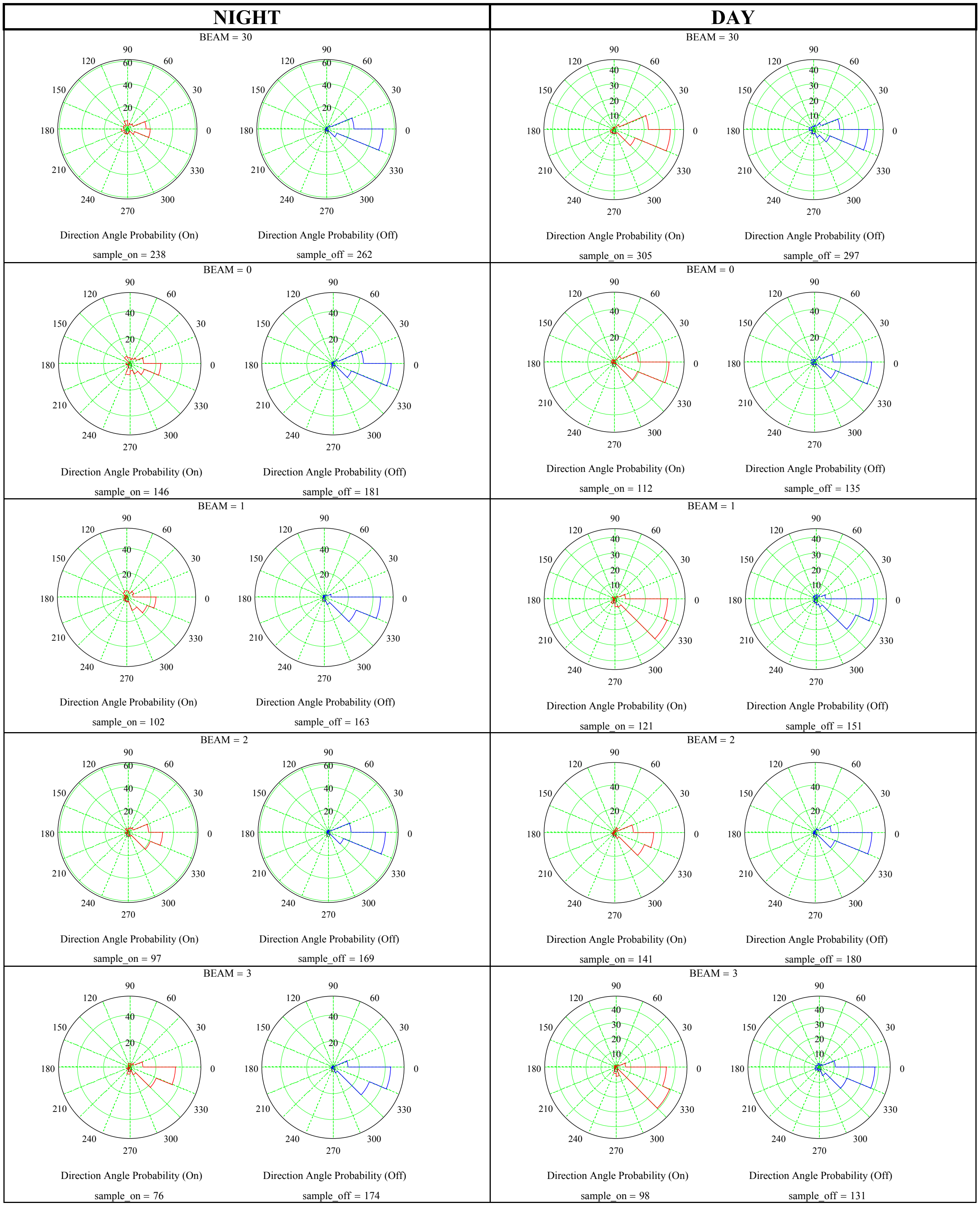

Figure F.2. Direction Angle of Small Targets (TS ≤ -47 dB) at Night (left) and Day (right) for Each Transducer Beam (Beam 30 = 4 m; Beam 0 = 8 m; Beam 1 = 12 m; Beam 2 = 16 m; Beam 3 = 20 m)

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