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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 2004

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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 from 1996 to 1999 determined that from 211,685 to 576,676 fish were entrained annually at Grand Coulee Dam. Analysis of the entrainment data found 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 third year of the strobe light study by researchers of the Colville Confederated Tribes in collaboration with the Pacific Northwest National Laboratory.

The objective of the study is to determine the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee and rainbow trout under field conditions. The prototype system consists of six strobe lights affixed to an aluminum frame suspended 15 m vertically underwater from a barge secured in the center of the entrance to the third powerplant forebay. The lights, controlled by a computer, illuminate a region directly upstream of the barge.

The 2003 study period extended from June 16 through August 1. Three light treatments were used: all six lights on for 24 hours, all lights off for 24 hours, and three of six lights cycled on and off every hour for 24 hours. These three treatment conditions were assigned randomly within a 3-day block throughout the study period.

Hydroacoustic technology was used to evaluate the effectiveness of the strobe lights in eliciting a negative phototactic response in fish. The hydroacoustic system in 2003 comprised seven splitbeam transducers arrayed in front of the strobe lights, two multibeam transducers behind the lights, and a mobile splitbeam system. The seven splitbeam transducers were deployed so they tracked fish entering and within the region illuminated by the strobe lights. These transducers were spaced approximately 4 m apart on an aluminum frame floating upstream of the barge and looked vertically downward. The multibeam transducers monitored the distribution of fish directly behind and to both sides of the lights, while the mobile splitbeam system looked at the distribution of fish within the third powerplant forebay.

To augment the hydroacoustic data, additional studies were conducted. The hydrodynamic characteristics of the third powerplant forebay were measured, and acoustically tagged juvenile kokanee were released upstream of the strobe lights and tracked within the forebay and downstream of the dam.

Analysis of the effect of strobe lights on kokanee and rainbow trout focused on the number of fish detected in each of the areas covered by one of the downlooking transducers, the timing of fish arrivals after the status of the strobe lights changed, fish swimming effort (detected velocity minus flow velocity), and fish swimming direction. Water velocity measurements were used to determine fish swimming effort. The tracking of tagged kokanee provided data on fish movements into and out of the third powerplant forebay, including entrainment.

Findings from the study in 2003 include the following:

- At night, more fish were present when the strobe lights were on (12,283) compared to when the lights were off (2,163) (Section 4.1, p. 4.5).

- There were no statistically significant differences in counts or behavior metrics for fish detected during the daytime (Section 4.1, p. 4.4, and Section 4.2, p. 4.11).

- Fish swimming effort at night when the strobe lights were on was directed primarily across the forebay (i.e., toward the right bank side of the forebay or toward the dam). This effort was evident for fish detected at all distances from the lights. During the day, swimming effort was upstream, while at night when the lights were off, effort was more variable, with no dominant direction (Section 4.2, p. 4.13).

- The increase in the number of fish detected when the lights were on at night does not appear to be the result of increased activity on the part of the fish but was an actual increase in the number of fish present (Section 4.2, p. 4.12).

- Accumulation of fish near the lights showed a cyclic pattern, with the highest accumulations occurring between 1 and 3 a.m. when the strobe lights were on and water flows were nearly zero (Section 4.2, p. 4.10).

- Water flow appears to be a factor in how fish respond to the strobe lights, particularly at night when flows are low compared to the daytime (Section 4.2, p. 4.14).

- The count and behavioral results present conflicting views on the response of fish to the strobe lights. Higher numbers of fish were detected near the strobe lights at night; however, those fish were not staying in front of the lights but swimming across the lighted area. We speculate that fish may be accumulating near the strobe lights because the lights are an orientation point in an environment that is otherwise devoid of reference features, or the lights may be attracting prey species that create a foraging opportunity for the fish. (Section 4.2, p. 4.14).

- Thirty-seven percent of the acoustically tagged juvenile kokanee were detected below Grand Coulee Dam. However, only half of the fish that were entrained at the third powerplant were detected, indicating a potentially higher rate of entrainment (Appendix E.3.4, p. E.17).

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

Based on the experience and data acquired between 2001 and 2003, along with a general review of strobe lights, the researchers recommend several modifications and enhancements to the follow-on study in 2004. These include the following:

- The 2003 experimental design should be repeated with all six lights used for all treatments. The study should begin and end later in the summer to better capture the kokanee and rainbow trout populations as they move down the reservoir.

- The multibeam acoustic system should be deployed again to examine fish distribution to the side of the lights. The deployment should be further upstream to avoid interference with the light frame.

- A dual-frequency identification sonar (DIDSON) acoustic camera should be deployed for a limited time to provide qualitative evaluation of fish movement near the lights.

- At least 250 or more juvenile kokanee should be tagged with radio telemetry tags or acoustic tags to determine the behavior of kokanee in the third powerplant forebay. This will provide valuable information on the presence of the target species in the strobe light region and an index of entrainment.

- A comprehensive zooplankton survey should be conducted during the study season to determine species composition and abundance in relation to strobe light status.

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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)
epilimnion	the upper, relatively warm, surface layer above the thermocline in a thermally stratified water body
forebay	portion of a reservoir or canal that is immediately upstream from a dam or pumping plant from which water is taken to run equipment (e.g., a turbine)
hectare meter	the metric unit of volume used to measure the capacity of reservoirs – In the United States, the *acre-foot* is used more commonly. One acre-foot contains 43,560 cubic feet or about 1233.482 cubic meters (0.123 348 hectare meter).
hydroacoustics	the use of transmitted sound to detect objects (e.g., fish) in water
hypolimnion	the cooler, lower level of a thermally stratified water body – This layer extends vertically from the thermocline to the bottom.
littoral	the region along the shore of a nonflowing body of water
lumen	SI unit for measuring the flux of light produced by a light source or received by a surface
lux	SI unit for measuring the illumination of a surface - One lux is defined as an illumination of one lumen per square meter.
nephelometric turbidity unit	see *turbidity*
odds	ratio of the probability of an occurrence of an event to that of non-occurrence
odds ratio	quotient obtained by dividing one set of odds by another – It shows the strength of association between two responses of interest. If the odds ratio is one, there is no association.
pelagic	of, relating to, or living or occurring in the open water away from the shore (littoral)
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)

rheotaxis   movement of an organism in response to a current of water or air

seiche   A wave that oscillates in lakes, bays, or gulfs from a few minutes to a few hours as a result of seismic or atmospheric disturbances

target strength   a measure of the proportion of sound (in decibels) reflected back to the transducer from an acoustic target (e.g., fish) – The strength of the return is dependent on the size and orientation of the object. Target strength is measured in decibels (dB) referenced at 1 meter from the object's acoustic center.

thermocline   the temperature gradient in a thermally stratified body of water that separates warmer oxygen-rich surface water from cold oxygen-poor deep water and in which temperature decreases rapidly with depth

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.

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
dB counts‖μPa	decibel counts relative to microPascal
dc	direct current
df	degrees of freedom
DGPS	differential global positioning system
DHMS	dual-head multibeam sonar
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
HARP	Hydroacoustic Assessment Research Package
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
PAS   Precision Acoustic Systems
pdf   probability density function
PNNL   Pacific Northwest National Laboratory
pps   pings per second (acoustics) or pulses per second (light)

QA   quality assurance

s   second
S   south
SI   International System of Units

TS   target strength

UPS   universal power supply

V   volt

W   west

Contents

Figures

Tables

1.0   Introduction

This report documents the third year of a four-year study[a] to assess the efficacy of a prototype strobe light system to elicit a negative phototactic response in kokanee 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

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

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 fewer juvenile salmon were present when lights were on during daylight (Johnson et al. 2001). Juvenile rainbow trout (10 months old) showed a preference for darkness when given the choice between light (0.01 lx) and darkness. The minimum threshold was between 0.01 and 0.005 lx (Kwain and MacGrimmon 1969). Younger fish generally show a stronger aversion to light than do adults (Hoar et al. 1957). This is probably related to predator-prey relationships, where younger fish are more vulnerable to predation and so avoid light, compared to older predator fish. Fish not responding to lights include cutthroat trout fry and hatchery-reared trout (Brett and MacKinnon 1953) and eastern brook trout (Mueller et al. 2001). Studies of kokanee inhabiting a lake found an immediate avoidance reaction to strobe lights, with a more pronounced response in winter when turbidity was reduced (Maiolie et al. 2001).

1.2   Study Scope

The scope of work for the Chief Joseph Kokanee Enhancement Project was modified to include a multiyear pilot test of a strobe light system to determine its effectiveness in reducing fish entrainment. The pilot test consisted of suspending six strobe lights in the center of the third powerplant forebay and using hydroacoustic systems to monitor fish distribution and behavior. The hydroacoustic systems in 2003 comprised seven splitbeam transducers arrayed in front of the strobe lights, two multibeam transducers behind the lights, and a mobile splitbeam system. The seven splitbeam transducers were used to monitor fish as they approached the lights, while the distribution of fish behind the lights and to the side was evaluated by the two multibeam transducers. The mobile system looked at the distribution of fish within the entire third powerplant forebay.

To augment the hydroacoustic data, three additional studies were conducted. The water velocity directly in front of the strobe lights was measured; acoustically tagged kokanee were released upstream of the strobe lights and tracked; and zooplankton samples were collected in the forebay. Water velocity measurements were used to determine fish swimming effort in the region illuminated by the strobe lights.

The tracking of tagged kokanee provided data on fish movement into and out of the third powerplant forebay. The zooplankton study was an initial effort at understanding the role of lights in attracting prey species.

This report details these studies conducted during the third year of the study by researchers affiliated with the Chief Joseph Kokanee Enhancement Project and the Pacific Northwest National Laboratory.

1.3   Report Contents

Section 2 of this report describes the study site at Grand Coulee Dam. Section 3 provides the methods for the seven-splitbeam hydroacoustic assessment techniques and statistical analysis. Results are presented and discussed in Section 4. Section 5 lists the conclusions and recommendations prior to the last year of the study. References are in Section 6. Appendixes A through I provide supporting information: environmental conditions at the study site (A), hydroacoustic system calibration (B), details of the statistical analysis (C), hydrodynamic characterization of the forebay (D), acoustic tagging study (E), mobile splitbeam hydroacoustics (F), multibeam acoustics (G), additional figures showing the direction of movement for fish detected near the strobe lights (H), and zooplankton sampling (I).

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
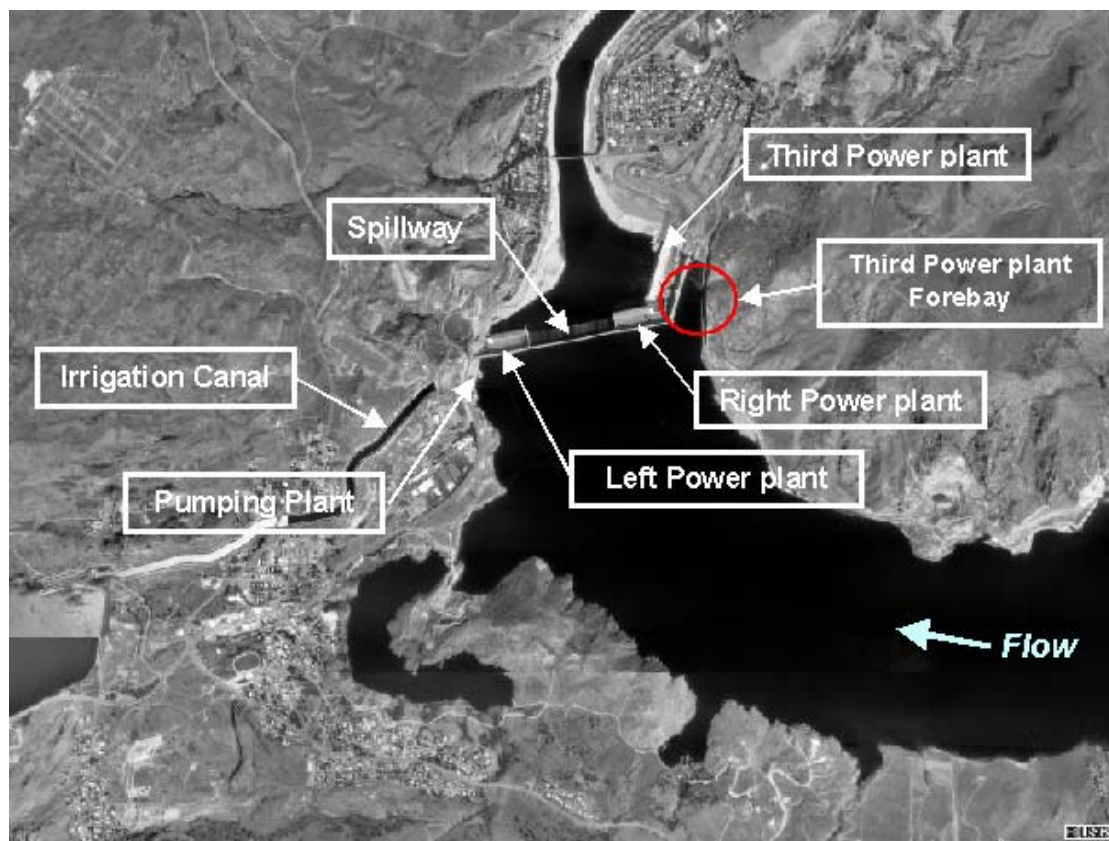
Figure 2.2.   **Study Site Location (red circle) Near Third Powerplant, Grand Coulee Dam in 2003**
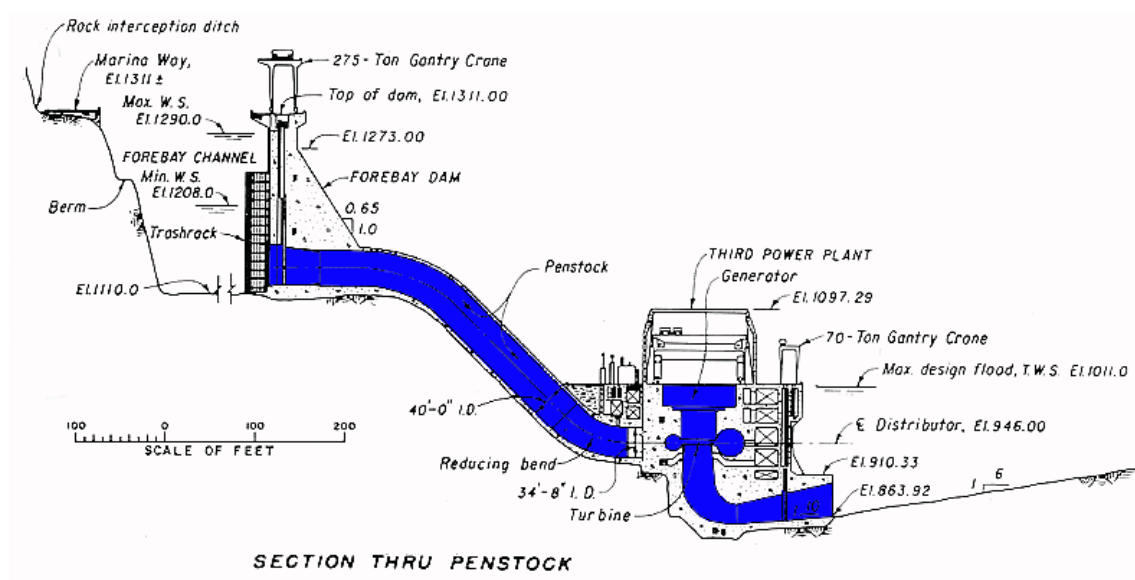
Figure 2.3.   **Cross Section of Third Powerplant and Forebay Dam at Grand Coulee Dam, Washington (Hubbard 1995)**

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-mi) -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.

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 2003, represented 60% to 75% of the total powerplant discharge (Figure 2.4). As in the first two study years (2001 and 2002), much of the third powerplant discharge during 2003 occurred during the daylight hours (Figure 2.5). Current-year operations data were supplied by the Bureau of Reclamation (Randy Spotts, personal communication).

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

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

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

2.3
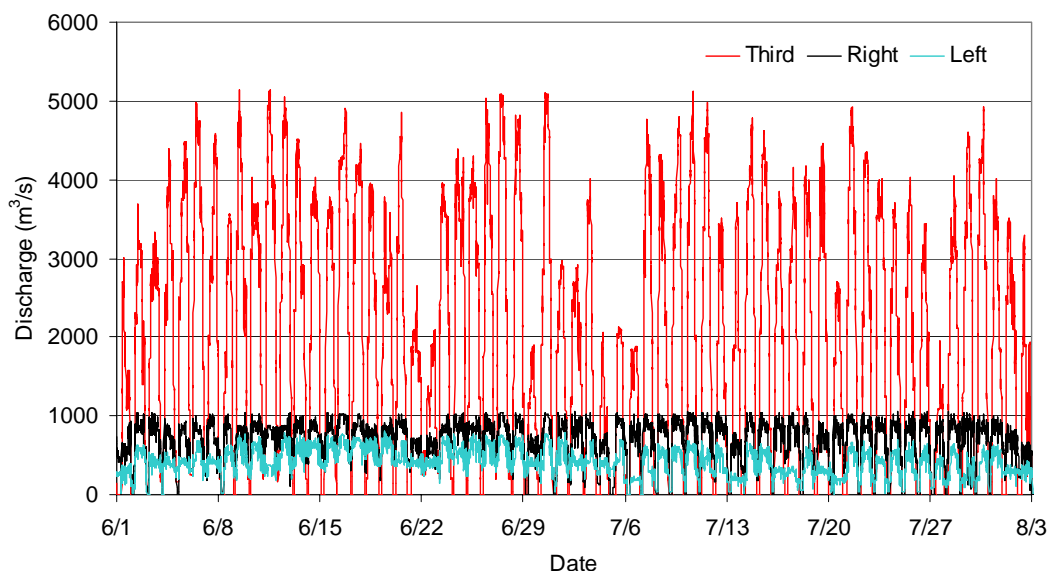
Figure 2.4.   **Discharge (m³/s) at Grand Coulee Dam from June 1 Through August 3, 2003. Data for the average discharge for each powerplant are plotted separately.**
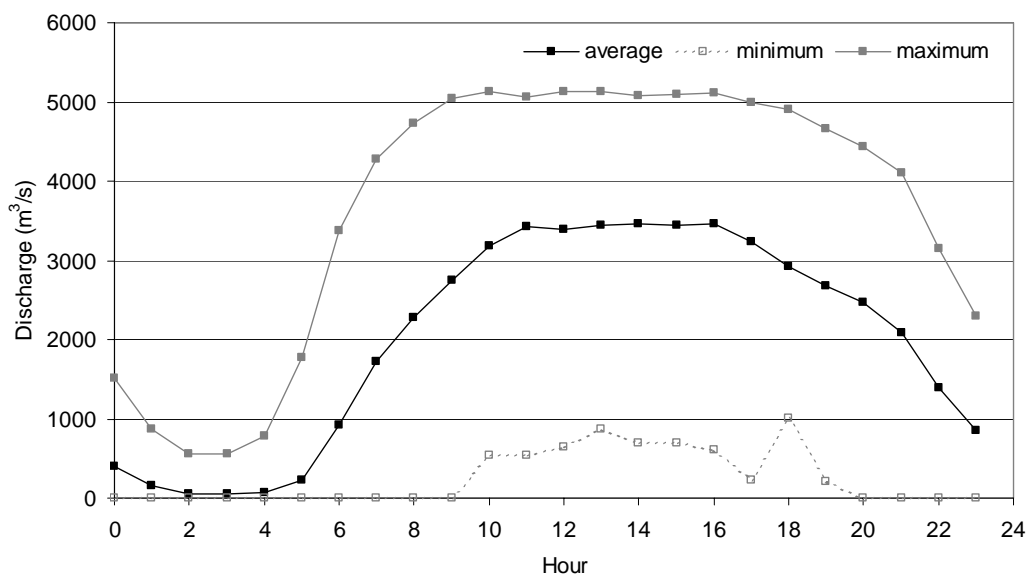
Figure 2.5.   **Discharge over 24 Hours at Third Powerplant at Grand Coulee Dam. Data were averaged over the period June 1 through August 1, 2003. Zero hour is midnight.**

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. This section presents descriptions of the prototype strobe light system and its deployment at the study site. The hardware, software, and protocols used for processing the data also are detailed. The study design is described, followed by documentation of the statistical analyses applied to the data on fish distribution and behavior. The three additional studies conducted to augment the hydroacoustic data are summarized, and the supplementary hydroacoustic and ancillary data collected during the study are noted.

3.1   Strobe Lights

Six strobe lights, each producing a maximum of 20,000 lumens-s/flash (Flash Technology specification), were mounted across the top and bottom of a 1.3-m^2 aluminum frame (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
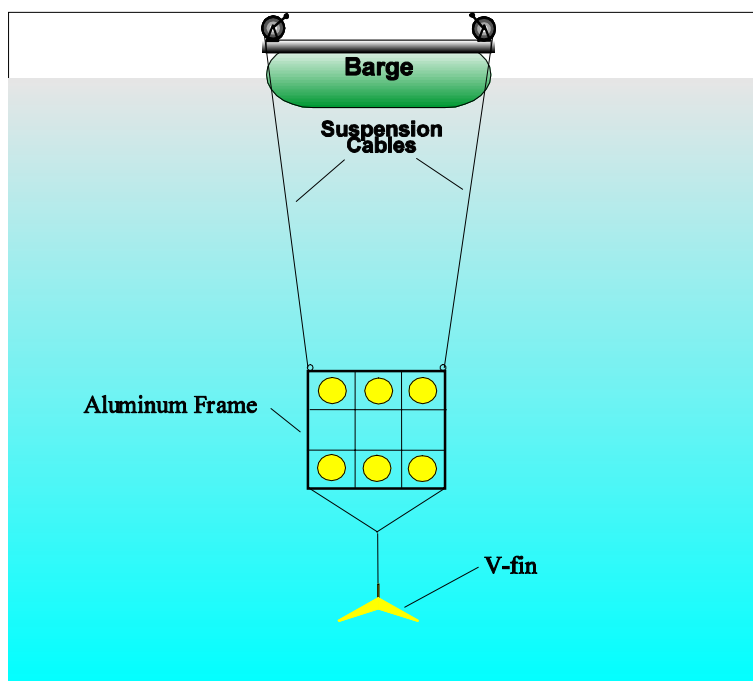
Figure 3.1.   Strobe Light Frame Configuration at Grand Coulee Dam, 2003. Front view showing the placement of the strobe lights (yellow circles) and dihedral V-fin depressor.
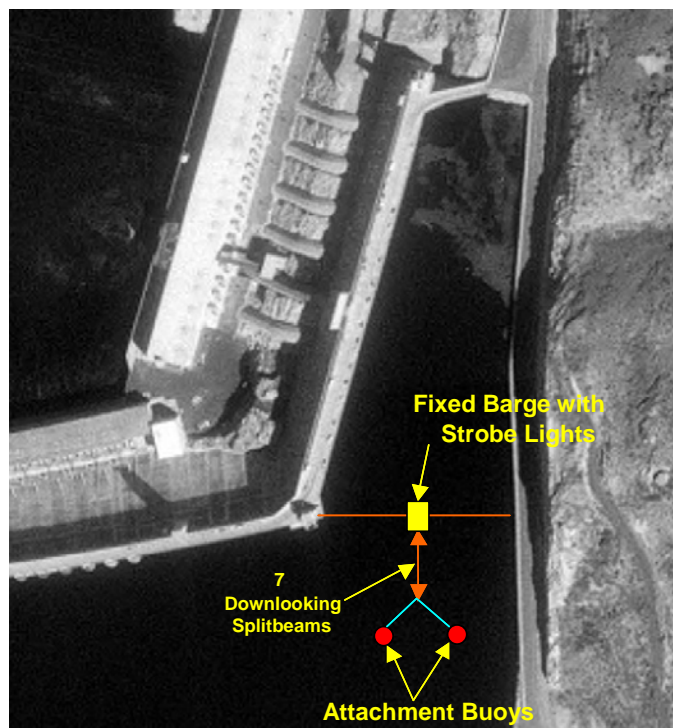
Figure 3.2.   Location of Strobe Light Test Site at Third Powerplant Forebay of Grand Coulee Dam

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.

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). In 2002, we measured the characteristics of the strobe lights used in this study both in the field and in the laboratory using two types of light detectors. The light measurements are described in detail in Johnson et al. (2003, Appendix C).

3.2   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
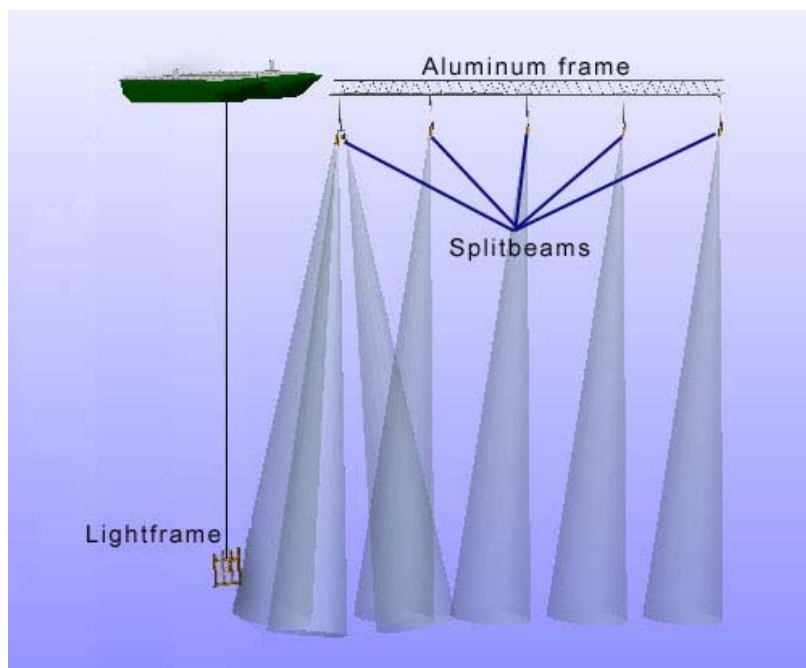
Figure 3.3.　Strobe Light and Hydroacoustic Transducer Frame Configuration at Grand Coulee Dam. Side view showing area ensonified (not to scale).
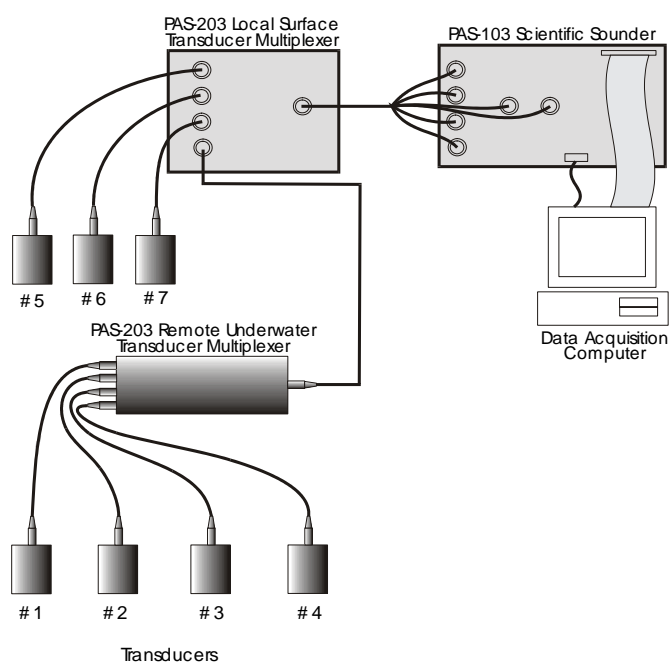
Figure 3.4.　Seven-Transducer Multiplexed Splitbeam Hydroacoustic System (Precision Acoustic Systems, Seattle, Washington)

by a 110-V alternating current (ac) load center stationed on the deck of the dam by the Bureau of Reclamation. A personal computer was used for system control and data logging using the Hydroacoustic Assessment Research Package (HARP, Hydroacoustic Assessments, Seattle, Washington), a software program for splitbeam data acquisition. Calibration information for the splitbeam data acquisition system is in Appendix B.

The seven splitbeams and the ADCP were suspended from an aluminum frame floating 6 m upstream of the barge. Three of the seven splitbeam transducers were attached to the ADCP mounting bracket and were spaced equally (i.e., at points 120° apart) around the circumference of the ADCP and canted 10° from vertical. This was done to provide intense coverage of the area directly in front of the light frame. The remaining four splitbeam transducers were spaced approximately 4 m apart starting 4 m upstream of the ADCP mounting bracket. These transducers looked downward and were canted approximately 10° toward the barge from vertical. The aluminum truss was attached to the starboard and port sides of the barge by two aluminum arms and tethered to a floating line that connected the barge to the upstream anchor buoys.

3.3   Data Processing

The data collected at Grand Coulee in 2003 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 gigabytes of storage and a digital linear tape autoloader were dedicated to this project to serve as the main storage and processing system (Figure 3.5). Several other Windows-based machines provided additional support for data processing and analysis. Computers were linked via the PNNL 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] Archival versions of the raw data were maintained at Grand Coulee Dam through the end of the study season.

A data management system was used 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 3.6). 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.

(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.
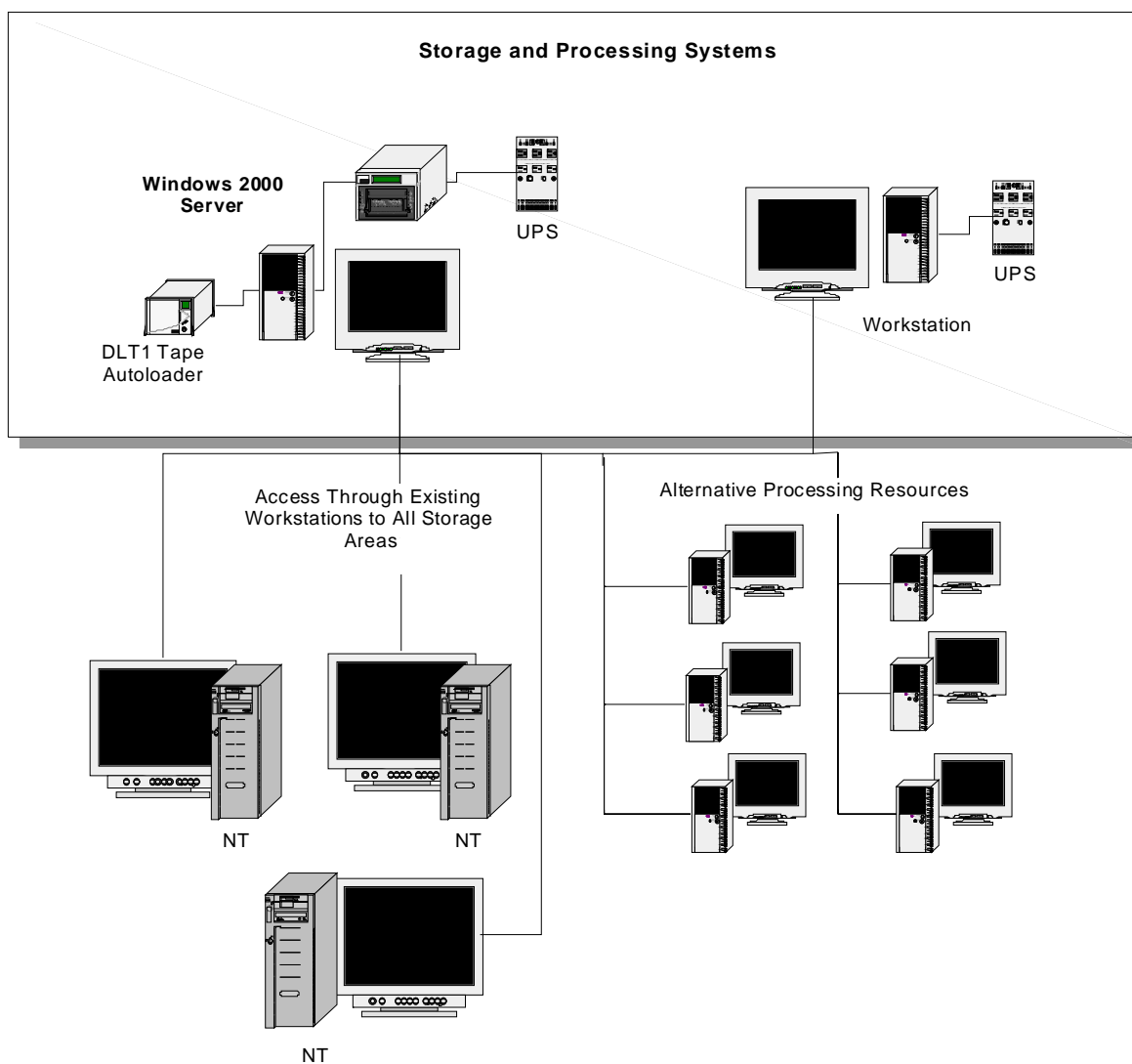
Figure 3.5.   Computer Resources Used to Support the Data Processing Tasks at Grand Coulee Dam in 2003

Acoustic data files from the splitbeam transducers were processed using software developed by PNNL to identify linear traces. The software allowed the user the option of manually choosing tracks (manual tracking) or having the software choose the tracks (autotracking). Approximately 7% of the data was tracked manually. The manually tracked files were randomly selected, with the restriction that 95% of the files come from the night period and the rest from the daylight period.

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. Parameters for the autotracking included setting the acoustic size threshold between –60 and –10 dB.

3.5

Figure 3.6.   Example of Data Entry Tool for the HDF5 Data Storage System

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 move-ment of the equipment, inaccuracy in locating the angular direction, and basic accuracy limitations of the tracking software. 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 tracks by filtering and smoothing must be done to obtain the most accurate estimate possible of the overall displacement velocity allowed for by the measurement conditions (Figure 3.7).

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 1.5° deviation in the x/y plane between sequential position vectors. Deviations greater than a 1.5° 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
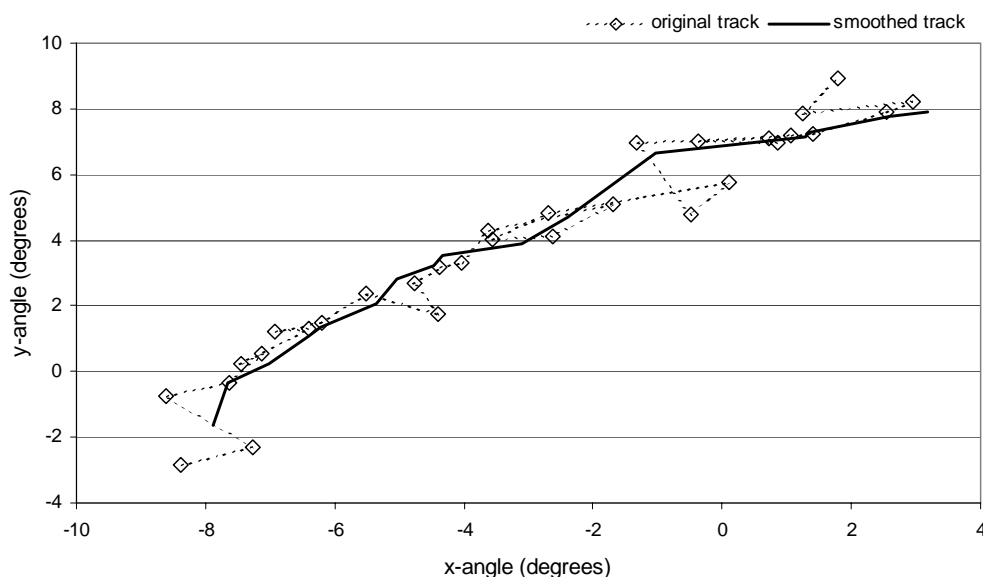
Figure 3.7.   Example of Fish Track As Developed by Hydroacoustic Hardware and Software and After Filtering and Smoothing. This view shows the track's projection (image) in the x/y plane, perpendicular to the beam's range axis.

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 (lensed to 10°) and ping rate (20 pps). A 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 polynomial as a function of 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, at a minimum, 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, and a higher order polynomial description was used when needed. This smoothed description was used to estimate the displacement velocity over the track segments as measured within the splitbeam zone. The accuracy of the polynomial fit was 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.

3.4   Study Design

Three light level treatments were used in this study: all strobe lights on (six lights), all strobe lights off, and strobe lights alternating on and off every hour (three lights). These three treatment conditions were applied for an entire 24-hr period and were randomly assigned within a 3-day block throughout the

study period (Table 3.1). The setup of the strobe lights did not allow all six of them to be synchronized for the hour on/off treatment, so only three lights were used for that treatment. 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.

The study period was scheduled to start June 14, 2003, but equipment problems delayed the start until June 16, resulting in the first treatment block being incomplete (Table 3.1). The study period ended on August 1, 2003. While equipment was being tested, some hydroacoustic data were collected between June 9 and June 16, 2003.

Table 3.1.   Treatment Design of the 2003 Grand Coulee Dam Study

Date	Treatment	Block	Date	Treatment	Block
6/14/2003	on/off[(a)]	1*	7/9/2003	on/off	8
6/15/2003	off[(b)]	1*	7/10/2003	on	8
6/16/2003	on[(c)]	1*	7/11/2003	calibration	
6/17/2003	on	2	7/12/2003	on	9
6/18/2003	off	2	7/13/2003	off	9
6/19/2003	on/off	2	7/14/2003	on/off	9
6/20/2003	calibration[(d)]		7/15/2003	on/off	10
6/21/2003	on	3	7/16/2003	on	10
6/22/2003	on/off	3	7/17/2003	off	10
6/23/2003	off	3	7/18/2003	calibration	
6/24/2003	off	4	7/19/2003	off	11
6/25/2003	on	4	7/20/2003	on	11
6/26/2003	on/off	4	7/21/2003	on/off	11
6/27/2003	calibration		7/22/2003	off	12
6/28/2003	on	5	7/23/2003	on	12
6/29/2003	off	5	7/24/2003	on/off	12
6/30/2003	on/off	5	7/25/2003	calibration	
7/1/2003	on/off	6	7/26/2003	off	13
7/2/2003	off	6	7/27/2003	on	13
7/3/2003	on	6	7/28/2003	on/off	13
7/4/2003	calibration		7/29/2003	off	14
7/5/2003	on	7	7/30/2003	on	14
7/6/2003	on/off	7	7/31/2003	on/off	14
7/7/2003	off	7	8/1/2003	calibration	
7/8/2003	off	8			
(a) on/off: strobe lights alternating three lights on, three lights off every hour					
(b) off: all six strobe lights off.					
(c) on: all six strobe lights on.					
(d) calibration: ancillary and calibration data collected.					
* Equipment problems delayed start of study to 6/16/2003.					

3.5   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 quantitatively examined the data for arrival rates, direction of travel, fish velocity, 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).

3.5.1   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 lights-off versus 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 hydro-acoustic data, which makes it more difficult for the software to identify real fish targets. In 2002, the vertical orientation of the downlooking transducers produced a false-bottom effect, obscuring target recognition beyond 30 m. In 2003, the false-bottom effect was eliminated by tilting the downlooking splitbeam transducers 10° downstream.

Two further considerations can affect interpretation of the results. First, it is not usually 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, level of discharge through the third powerplant, time of day, and treatment block (3-day period encompassing all three treatments). For the position factor, data from five of the seven splitbeam transducers were used. Two of the transducers closest to the strobe lights were canted to the side and therefore did not follow the pattern of increasing distance from the strobe lights. The transducer at 22 m from the strobe lights was used as the control point; light levels measured in 2001 and 2002 indicated that light levels at this distance should be minimal (Simmons et al., 2002; Johnson et al., 2003). Each fish track was classified into one and only one class level for each factor variable shown in Table 3.2.

Statistical analysis of the count data was 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

Table 3.2.   Definition of Factor Variables

Factor Variable	Code	Class Level	Description
Treatment			The strobe light treatment variable of interest.
	0	0 lights	Strobe lights off. This is the treatment control or reference condition.
	1	6 lights	3 or 6 strobe lights on.
Position			The position of five down-looking transducers located at 4-m intervals upstream from the strobe lights.
	1	6 m	Fish tracks located 6 m from the strobe lights.
	2	10 m	Fish tracks located 10 m from the strobe lights.
	3	14 m	Fish tracks located 14 m from the strobe lights.
	4	18 m	Fish tracks located 18 m from the strobe lights.
	5	22 m	Fish tracks located 22 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 thousand 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 - 8 kcfs / 0 – 3 cm/s[a]
	2	Medium	Medium - 2nd to 3rd quartile: 8 – 56 kcfs / 3 – 51 cm/s
	3	High	High - 4th quartile: >56 kcfs / 51 – 91 cm/s
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	2-14	Values 2 to 14	Randomized block composed of 3 days each with the three levels of treatment randomly ordered. Note: Block 1 was incomplete and not used in this analysis.
(a) Velocity measured by acoustic Doppler current profiler (ADCP) 6 m from light frame.			

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 (Jackson et al. 1992; Van Der Meer and Camphuysen 1996).

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 reference level. Results from the model are point estimates of the relative prevalence of tracks for a factor level when compared to the reference level. These point estimates are called an odds ratio—that is, the ratio of track counts observed at a given location compared to a common reference location. A simulated example of an odds ratio plot is given in Figure 3.8. In the plot, the reference point is at 22 m, farthest from the stimulus source (e.g., lights) and has a value of 1. Each colored line in Figure 3.8 illustrates a different behavioral response to the stimulus. The upper line illustrates an attractive response, with an odds ratio greater than 2, indicating that more than twice as many fish tracks were found at 6, 10, and 14 m than at the reference location. The middle line is
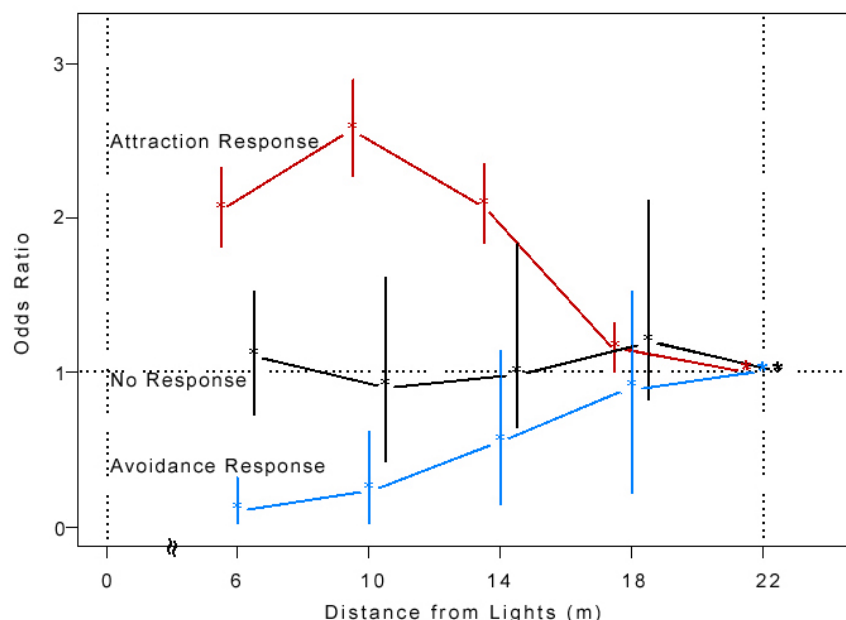
Figure 3.8.   Sample Odds Ratio Plot Illustrating the Patterns for Attraction, Avoidance, and No Response

indicative of no response, with the odds ratio staying near 1 at all distances from the stimulus. Finally, the lower line is below the no-response level of 1 and is indicative of an avoidance response, with fewer fish tracks close to the stimulus compared to the reference location. The vertical error bars in Figure 3.8 are the 95% confidence intervals on odds-ratio estimates. The statistical significance of these points may be inferred on those estimates whose error bars do not intersect the horizontal reference line at 1. When discussing a relationship between a stimulus and a response, the word attraction or avoidance is often used to describe the results. This does not imply that the fish "prefers" or "dislikes" the stimulus but that the stimulus and factors occurring with the stimulus are conducive to fish aggregating near it.

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

3.5.2   Fish Behavior

An objective of the study during 2003 was to look at what happened to the number of fish when the strobe lights were turned on or off, i.e., arrival rates. A difficulty or shortcoming of comparing aggregated numbers of fish during extensive periods with lights either off or on is that the random influence of population size during any particular treatment is unknown. By switching the strobe lights at hourly intervals during day or night, it is expected that the influence of the population present that day should be about equivalent for each on-off state of the lights. Thus, the cumulative arrival curves for each hour were obtained and viewed as if independently acquired.

The rates of fish arrival on a number-per-hour basis were calculated as influenced by lights-on and lights-off treatments for both lights turned on and off for both the 1-hr and 24-hr treatments for both nighttime and daylight hours. The evaluation constitutes an assessment of the dynamic interaction of fish with the lighted zone ensonified by seven hydroacoustic splitbeam transducers detecting the passage locations of fish and their associated passage velocity.

The primary measure of fish behavior was the displacement vector, which indicates both direction and speed of movement. Displacement vectors are the difference between the estimated start and 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 displacement vectors were used 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 ADCP located 6 m from the strobe light and surrounded by three splitbeam transducers (Figure D.2). The resulting swimming effort is an approximate estimate because flow measurements were averaged over a longer time period than fish detection, and the ADCP beams sample a very small proportion of the ensonified area. However, given the small study area and the apparent uniformity in flow (Appendix D), the calculated swimming effort is a useful tool in understanding fish behavior.

Behavioral metrics were 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 (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 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 non-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.

The direction of movement also can be converted to polar coordinates and analyzed using the methods of circular statistics (Fisher 1993). One of the circular statistics metrics is the concentration parameter that provides a measure of the dispersion of the data, similar to a variance. Large values of the concentration parameter are indicative of a data distribution defined by a dominant direction of

movement, while a small concentration parameter suggests data with no dominant direction. Distributions of the displacement vector can be modeled using the von Mises pdf. These distributions can be overlaid on the actual data to indicate the goodness-of-fit. A more complete description of these methods is in Appendix C.

3.6 Additional Studies

Three additional studies were conducted to augment the hydroacoustic data. The third powerplant forebay was characterized hydrodynamically using an acoustic Doppler current profiler (Appendix D). Water velocity measurements taken directly in front of the strobe lights were used to determine fish swimming effort in the region illuminated by the strobe lights.

Kokanee implanted with acoustic tags were released upstream of the strobe lights and tracked (Appendix E). The tracking data provided information on fish movement into and out of the third powerplant forebay.

Researchers also collected zooplankton samples in the forebay (Appendix I). The zooplankton study was an initial effort at understanding the role of lights in attracting prey species.

Supplementary hydroacoustic data collected during the study period were used to look at the distribution of fish away from the strobe lights. Mobile splitbeam surveys were collected weekly to monitor fish usage of the forebay at night (Appendix F), while two multibeam transducers were used to monitor the distribution of fish behind and to the side of the lights (Appendix G).

3.7 Ancillary Data

Ancillary data collection comprised two basic types: 1) data collected automatically during the study and stored directly to file and 2) data collected periodically by manually sampling during the study. Data collected automatically included ambient daylight measurements, light measurements at the submerged light frame, tilt and direction measurements, wind speed/direction measurements, water temperature measurements, Grand Coulee Dam operations, and underwater video monitoring. Data collected using manual sampling included turbidity levels and global positioning system-determined positions (barge and structure). Methods and results are presented in Appendix A for forebay elevation, water temperature, turbidity, ambient light levels, and weather.

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 June 16 and August 1, 2003, 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 the dataset from the autotracking software; selection criteria described in Section 3.3 were used to ensure that the selected tracks exhibited fish-like behavior. Initially, the tracking program identified 64,532 potential fish tracks. This number was reduced to 48,701 through the use of selection criteria. In 2002, only 30% of the tracks identified by the autotracking software were used in the final analysis compared to 75% this year.

Two changes in the deployment of the splitbeam transducers probably accounted for this difference. The first was reorienting the two sidelooking transducers to downlooking positions. Downlooking trans-ducers generally ensonify the dorsal aspect of a fish, while the aspect of ensonification for the sidelooking transducers deployed in 2001 and 2002, was primarily the head or tail. Love (1977) has shown that the acoustic cross section (which is used to calculate target strength) is significantly lower near the head and tail aspects. It was noted last year that much of the data collected by the sidelooking transducers had smaller target strengths (i.e., < -47 dB) compared to the target sizes collected from the downlooking trans-ducers (Johnson et al. 2003). In addition to increasing the number of smaller targets, there was more noise associated with the sidelooking transducers since as a fish swims the head or tail aspect are more difficult to distinguish. The second change was tilting the downlooking transducers 10º from vertical to reduce the false-bottom effect. This change substantially reduced the amount of noise in the data files. The result was longer and better-formed fish tracks that were not obscured by noise. These tracks provide better information about numbers of fish as well as their swimming behavior.

Splitbeam hydroacoustic techniques provide little information on fish species. However, data were available in the form of fish lengths that were 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 2003, we calculated a mean fish target strength of about -38 dB. Kokanee used in this year's acoustic tag study (Appendix E) had lengths between 120 to 170 mm, which would correspond to target strengths between -44 and -40 dB. Figure 4.1 shows the distribution of target strengths for fish detected using splitbeam hydro-acoustics during the study period. The distributions peak between -38 and -40 dB and are unimodal for fish detected both during the day and at night. However, at night when the lights were off, there was an increase in the proportion of smaller targets (i.e., < -38 dB) and a decrease in the proportion of fish with target strengths greater than -38 dB. This difference is significant (chi-square test; $p < 0.01$). During the daytime, there was no difference in the distribution of target strengths between fish detected when the lights were off versus lights on ($p = 0.30$).
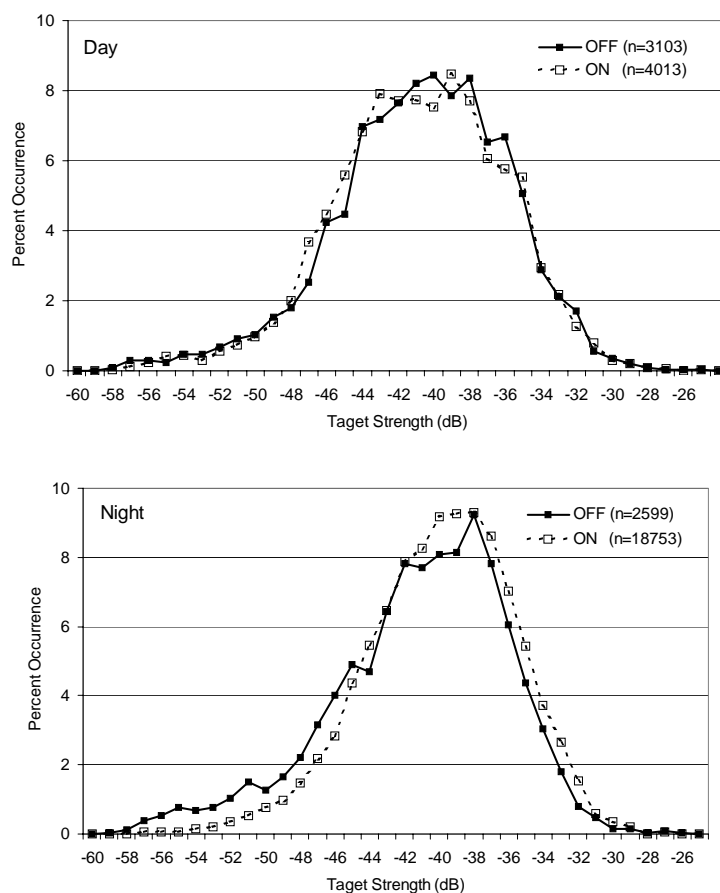
Figure 4.1.   Target Strength (dB) for Fish Detected During the Day and at Night for Lights Off and On Treatments in 2003

The unimodal distribution of target strength differs from the distribution seen in the previous two study years (Simmons et al. 2002; Johnson et al. 2003) where the distribution of target strength was bimodal with peaks in the distribution around -55 dB and -40 dB. The reduction in the number of smaller targets (i.e., < -55 dB) in 2003 may be related to the change in transducer orientation from side-looking to downlooking, and suggests that many of the small targets seen in previous years represented noise or incomplete tracks. However, the presence of smaller fish in previous years should not be ignored until stronger evidence is available from our planned 2004 study. This finding does not affect the conclusions from previous work because analysis results were based primarily on data from fish tracks with a target strength > -47 dB.

Weekly mobile surveys conducted throughout the season indicated the presence of smaller targets (< -55 dB) in other areas of the forebay and in the approach to the forebay (Appendix F). Mobile surveys also substantiated the presence of fish of similar acoustic size to those detected with the fixed-aspect transducers immediately upstream of the barge (-36 to -39 dB), both in the third powerplant forebay and in front of the pumping plant.

Overall, the number of fish detected during the study period increased dramatically in late July (Figure 4.2). Numbers started to increase in mid July (Block 10). A similar phenomenon was noted in 2002, when counts for the final treatment block were approximately four times the average count. There also was an increase in the number of detections through the season in 2002, although there was more variability. The reason for this increase currently is unknown but may be related to the time it takes for fish to travel down the reservoir.

Of the 48,701 fish detected by the seven downlooking transducers, a subset of 22,550 fish was used in the statistical analysis of fish distribution. Two selection criteria were used to obtain the subset. First, only data collected from complete treatment blocks were used. Second, within those complete treatment blocks, only fish detected by one of the five splitbeam transducers arrayed at increasing distance from the strobe lights were included. The resulting 22,550 fish were analyzed with respect to light treatment, distance from the light source, power plant discharge, and time of day. Data from the 1-hr on/off light treatment were analyzed separately from the 24-hr light treatments.

Figure 4.3 shows the depth distribution and counts for fish detected during the daytime when the strobe lights were on or off for 24 hr. The median depth for fish detected close to the lights was slightly higher in the water column (i.e., 12 m depth for fish at 6 m from the lights) compared to fish detected farther from the strobe lights (15 m depth for fish at 22 m from the lights). With respect to counts, more fish were detected at 14 m from the lights than at 6 m when the lights were on. When the strobe lights were off, the fish were somewhat closer—6 to 14 m—to the light frame. These data suggest a possible weak deterrence with respect to the lights. However, slightly more fish were detected when the lights were on for 24 hr compared to when the lights were off (2,689 versus 2,142).
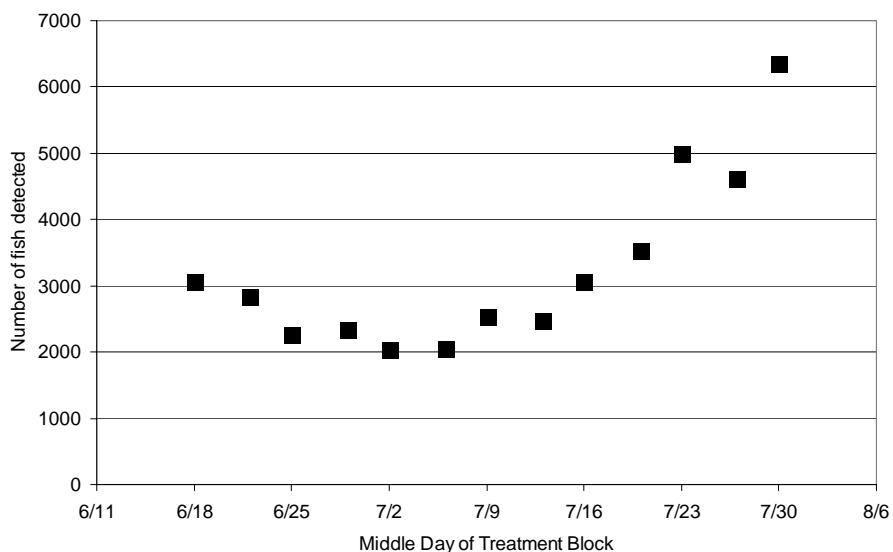
Figure 4.2. **Total Number of Fish Detected for Treatment Blocks (2–14) at Grand Coulee in 2003. Block 1 (June 14–16) was incomplete and not included in this comparison. Data from all seven splitbeams.**

4.3

Figure 4.3.   Depth Distribution and Number of Fish Detected During the Daytime for the Two 24-hr Light Treatments as a Function of Distance from Strobe Lights for Five Down-looking Transducers (Blocks 2–14). In the upper half of the figure, the box represents the middle 50 percent of the data (25th to 75th percentile); the notch near the center of each box represents the median. Lines bracketing the box are the approximate widths of the 1st to the 99th percentiles. The dotted line at zero represents the water surface, while the lines bracketing 15 m represent the depth of the strobe lights.

At night, fish were distributed deeper compared to daytime (Figure 4.4), around 19 m when the lights were off for 24 hr, and from 19 to 22 m when the lights were on for 24 hr. Similar depths were noted during mobile surveys throughout the forebay (Appendix F). Fish counts were similar to those found in previous years—numbers increased as distance to the lights decreased when the lights were on, and equal numbers of fish were counted at all distances when the lights were off. In addition, 85% of all fish were detected at night when the strobe lights were continuously on for 24 hr.

A plot of the odds ratio statistic by treatment group and distance from the strobe lights (Figure 4.5) illustrates the statistical analysis of the data in Figures 4.3 and 4.4. Comparisons of the odds ratios (see Figure 3.11 for a discussion of the interpretation of an odds ratio plot) are made to the reference location (22-m range from the strobe lights). Point estimates are statistically significant ($p < 0.05$) if the point estimate of one odds ratio does not overlap the error bar of another.

Based on the analysis displayed in Figure 4.5, the response of fish at night when the lights are on would be categorized as a statistically significant attraction response. Possible interpretations of whether this result is indicative of actual attraction or some other factor such as accumulation are discussed at the end of this section. When the strobe lights were off, either during the daytime or at night, the odds ratio is nearly 1, indicating no response to the lights. During the day, when the strobe lights were on, there was a very weak avoidance response at 6 m (i.e., odds ratio < 1).
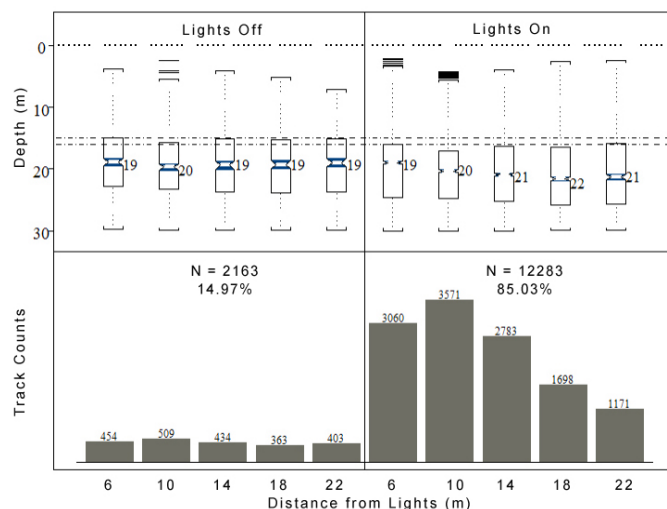
Figure 4.4. **Depth Distribution and Number of Fish Detected at Night for the Two 24-hr Light Treatments as a Function of Distance from Strobe Lights for Five Downlooking Transducers (Blocks 2–14). In the upper half of the figure, the box represents the middle 50 percent of the data (25th to 75th percentile); the notch near the center of each box represents the median. Lines bracketing the box are the approximate widths of the 1st to the 99th percentiles. The dotted line at zero represents the water surface, while the lines bracketing 15 m represent the depth of the strobe lights.**
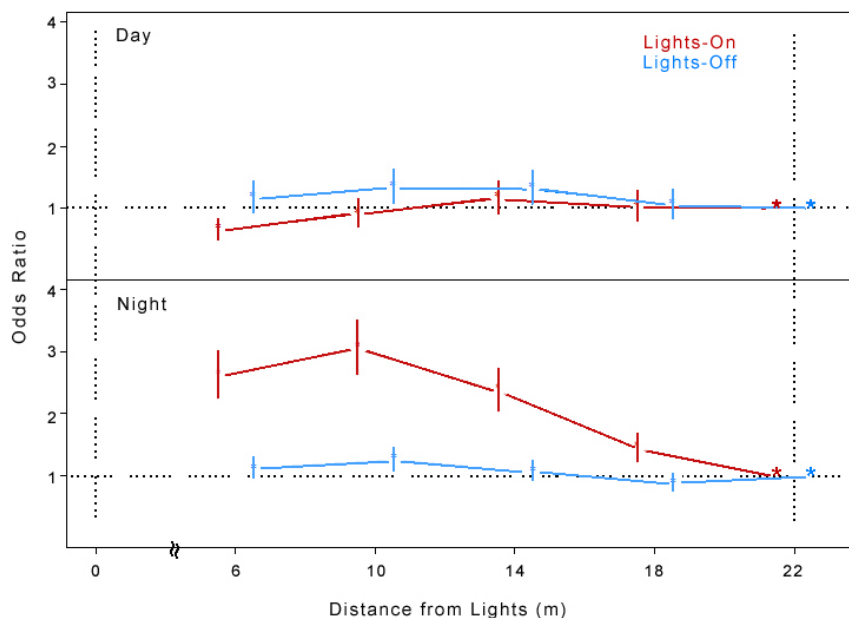
Figure 4.5. **Relative Prevalence of Fish Tracks Under Each 24-hr Light Treatment Compared to Common Reference Location at 22 m. Error bars represent 95% confidence intervals based on the χ^2 distribution with 1 degree of freedom. Data represent fish detected by five of the seven downlooking transducers.**

The counts and depth distribution of fish detected during the 1-hr on/off treatment are shown in Figure 4.6 (daytime) and Figure 4.7 (nighttime). The depth distribution was similar to that for the 24-hr treatments, with the fish being at or above the level of the lights during the daytime and below the lights at night. The primary difference between the results for the 1-hr and 24-hr treatments was at night when the difference in the number of fish detected when the lights were on compared to off was 8% for the 1-hr treatments compared to 70% for the 24-hr treatments. The odds ratio for the 1-hr treatments (Figure 4.8) is similar to that for the 24-hr treatments (Figure 4.5).

Results from the multibeam hydroacoustic survey behind the lights (Appendix G) confirm the increase in fish at night when the lights are on. More than twice as many fish were detected per hour when the lights were on compared to when the lights were off at night (Figure G.1). During the day, there was no apparent difference in fish detections between lights on and off. Other results from the multibeam survey indicate that when the strobe lights were on at night, fish were distributed between 6 and 9 m, compared to 19 to 20 m in front of the lights.

Third powerplant discharge also affects fish counts and distribution in the third powerplant forebay. To analyze the effect of water flow through the third powerplant, fish counts were matched to average 5-min discharge values. Additionally, ancillary analysis of discharge data indicated that discharges 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.
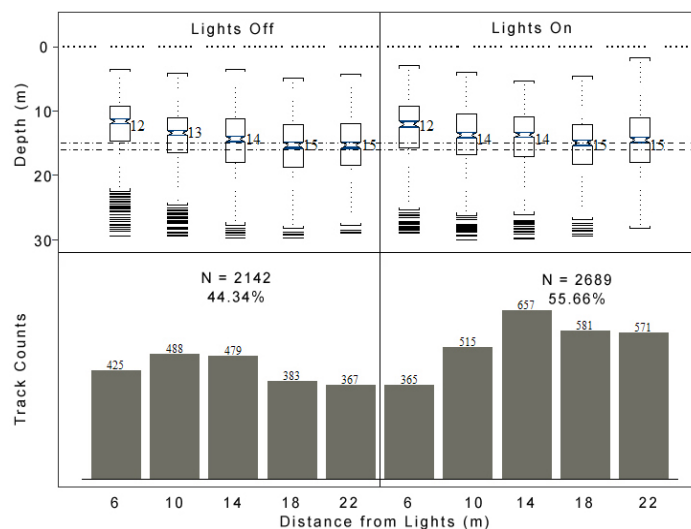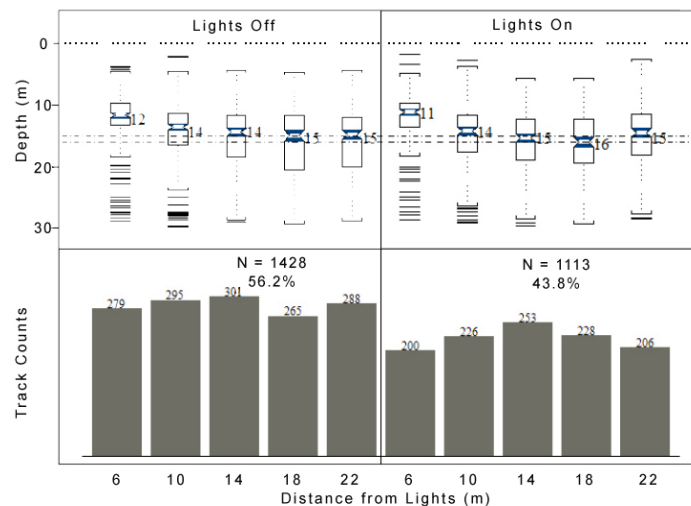

Figure 4.6. **Depth Distribution and Number of Fish Detected During the Daytime for the 1-hr Light Treatment as a Function of Distance from Strobe Lights for Five Downlooking Transducers (Blocks 2–14). In the upper half of the figure, the box represents the middle 50 percent of the data (25th to 75th percentile); the notch near the center of each box represents the median. Lines bracketing the box are the approximate widths of the 1st to the 99th percentiles. The dotted line at zero represents the water surface, while the lines bracketing 15 m represent the depth of the strobe lights.**
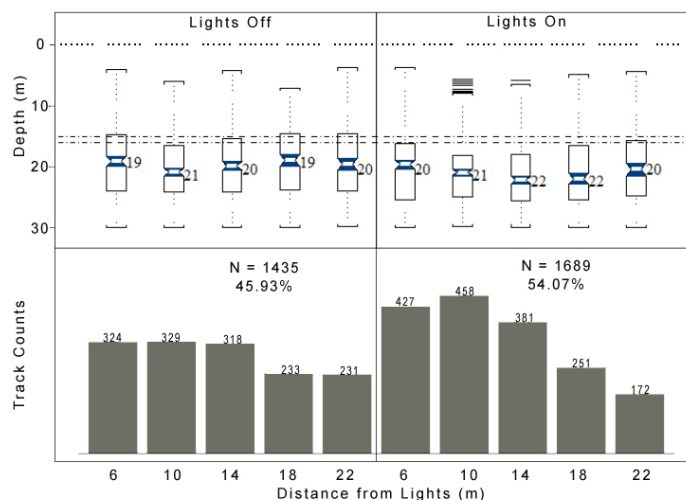
Figure 4.7. **Depth Distribution and Number of Fish Detected at Night for the 1-hr Light Treatment as a Function of Distance from Strobe Lights for Five Downlooking Transducers (Blocks 2–14). In the upper half of the figure, the box represents the middle 50 percent of the data (25th to 75th); the notch near the center of each box represents the median. Lines bracketing the box are the approximate widths of the 1st to the 99th percentiles. The dotted line at zero represents the water surface, while the lines bracketing 15 m represent the depth of the strobe lights.**
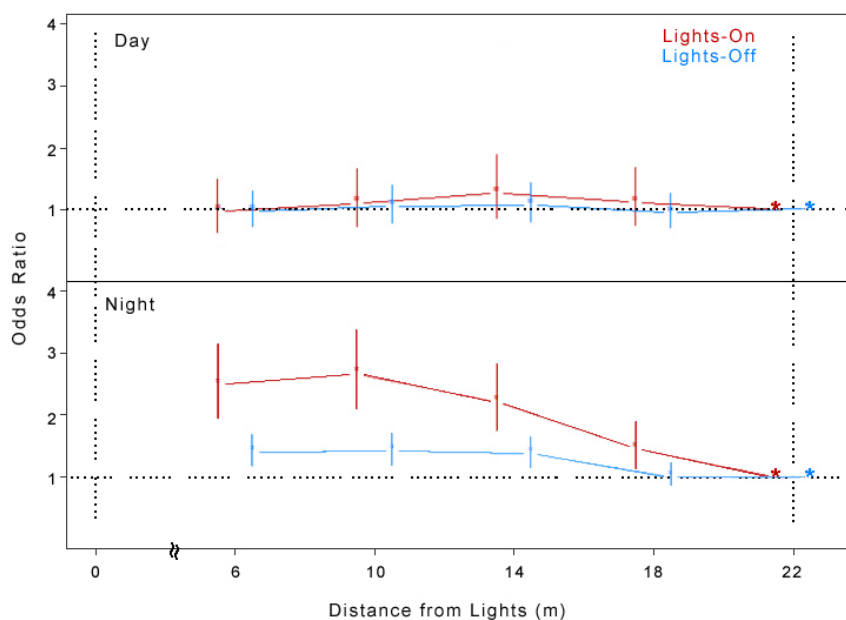
Figure 4.8. **Relative Prevalence of Fish Tracks Under the 1-hr Light Treatment Compared to Common Reference Location at 22 m. Error bars represent 95% confidence intervals based on the χ^2 distribution with 1 degree of freedom.**

As in 2001 and 2002, daytime discharge levels were higher than those at night (see Figure 2.5), confounding the response to ambient light conditions. Thus, high discharge levels (i.e., > 56 kcfs) occurred during 83% of the daytime sampling period, and 84% of the fish were detected at these levels. Low discharge levels (i.e., < 8 kcfs) occurred only between 6 and 9 a.m. and represented less than 4% of the daytime sample period. At night, low discharge levels occurred primarily between midnight and 6 a.m. and represented 46% of the nighttime sample period. However, 72% of the fish were detected at these discharge levels. Thus, it is unclear whether the predominance of fish at night is reflective of flow conditions or a natural circadian activity pattern.

Results from the analysis of third powerplant discharge on the number of fish present under different light conditions and time of day are presented in Figure 4.9. The odds ratios for fish detected during the day under the three discharge regimes all show a similar mild avoidance response when the lights are on. At the lowest discharge level (< 8 kcfs), the small number of fish targets caused the inconclusive results (i.e., large confidence intervals). Night samples, at all discharge levels, show an attraction response when the lights are on.
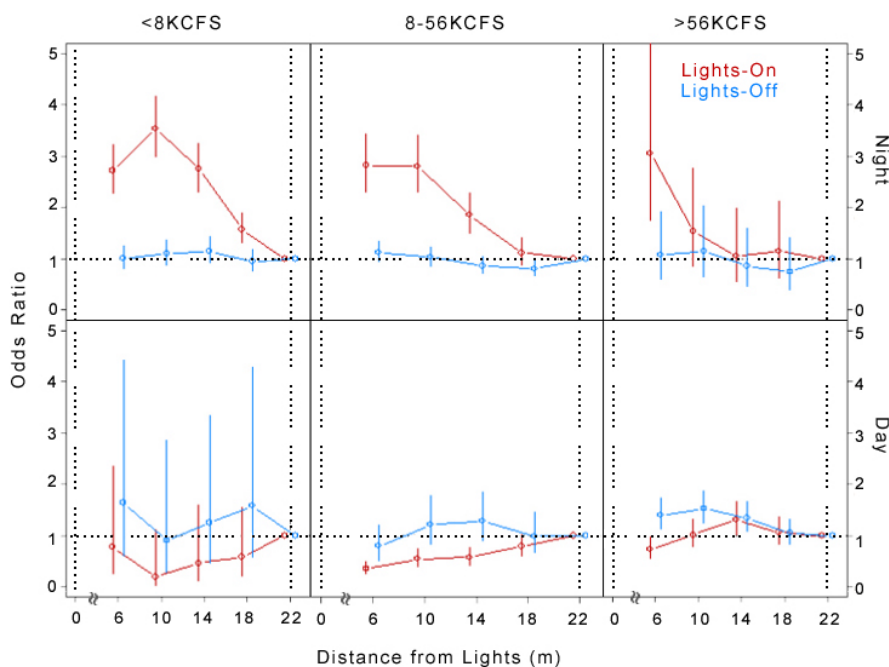
Figure 4.9. **Relative Prevalence of Fish Tracks Under Three Discharge Levels, Light Conditions, and Time of Day. Comparisons are made to the reference location at 22 m. Error bars represent 95% confidence intervals based on the χ^2 distribution with 1 degree of freedom. Data represent fish detected by five of the seven downlooking transducers for a 24-hr period.**

4.2   Fish Behavior

The behavioral response of fish to the light treatments was examined with respect to arrival rates and swimming behavior. Results are presented for the strobe lights-off compared to the strobe lights-on treatments, for both the 1-hr and 24-hr treatments. Additionally, data from all seven transducers were included in the analysis. The arrangement of the splitbeam transducers constituted an effective system for detecting the arrival of fish targets as they moved downstream or across the forebay.

4.2.1   Arrival Rates

Figure 4.10 shows the cumulative arrival rates for fish detected during the day and at night for the 1-hr treatments. The rate is the slope of the curve at any particular part of the hour. Arrival rates were definitely variable over the study period, and more fish did not always arrive when the lights were on compared to lights off at night. However, Figure 4.10 shows that at the end of an hour, there were substantially more fish present at night when the lights were on compared to lights off at night. During the day (Figure 4.10), the arrival rates for lights on and off were not substantially different. Figure 4.11 shows the same phenomenon based on the number of fish detected within the lighted zone in 15-min increments.

Figure 4.12 is an example of the arrival count rate calculated for the 24-hr treatments (Block 12 - July 22 through 24). Two sequential days are involved because the lights could not be both on or off within the same 24-hr period. The counting in Figure 4.12 begins in the morning and continues to the same time the next day. Plots are provided in Appendix H for all blocks. The important result is that the pattern of all curves was similar, although the total number of fish counted was variable and different for each day. For every treatment block, the rate of arrival began to increase at night when lights were on, reached a steady maximum level at approximately 3 a.m., and then declined into the morning hours before sunrise. The rates remained level with some fluctuations throughout the daylight hours. When the strobe lights
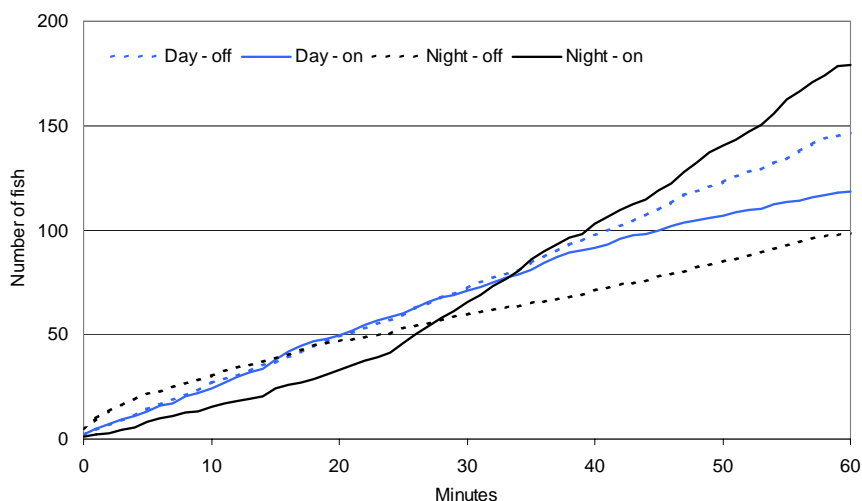
Figure 4.10.   Average Cumulative Arrival Rates for Fish Detected During the 1-hr Treatments. Data for all blocks (n = 13).
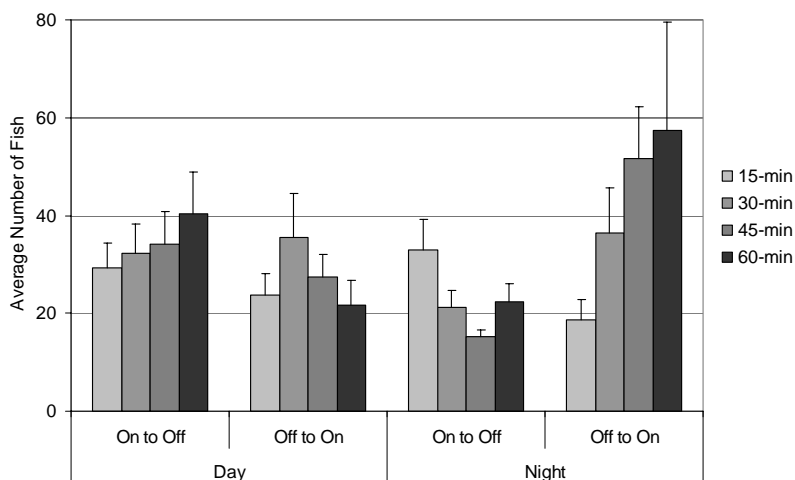
Figure 4.11.   Fish Counts at 15-min Intervals After Light Configuration Changed. Results from the 1-hr treatment scenario. Bars are standard errors.
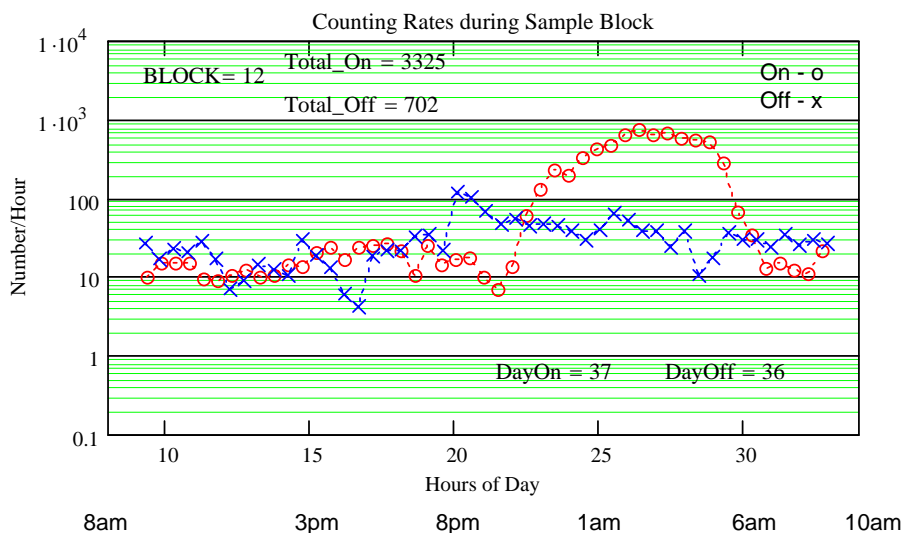
Figure 4.12.   Arrival Rate for Fish Detected During 24-hr Light Treatments for Block 12 (July 22 through 24, 2003)

were off, this pattern did not occur. There was often a period after 8 p.m. when the lights-off count rate exceeded that for lights on, but the lights-on rate eventually exceeded the lights-off rate during the night-time for every block. This demonstrates that fish are accumulating at an increasing rate at night when lights are on. Because the rate appears to attain a plateau, it suggests that a certain maximum number of fish produce the track counts at night based on the proximity population. It is noteworthy that counting rates during the day were similar for lights either on or off.

4.2.2   Fish Swimming Direction and Effort Velocity

Another attribute of fish behavior is swimming direction and effort. The direction in which a fish is swimming as measured by the splitbeam hydroacoustic system is the true direction of movement with respect to a fixed reference frame. By subtracting water velocity from the overall swimming velocity, the effort the fish expends 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 velocity was measured at the same location as the three splitbeam transducers closest to the strobe lights using an ADCP (see Appendix D). Given the small study area and the apparent uniformity in flow (Appendix D), flow measurements were used as approximate estimates of what the fish experienced for the other transducers. The transducer at 18 m from the strobe lights experienced a malfunction in its multiplexer during the study period, preventing estimation of swimming direction. Data from that transducer were not included in this analysis. Results are presented only for the transducer closest to the lights at 6 m and furthest from the lights at 22 m. Swimming direction, effort velocities, and water velocities for all transducers are in Appendix H.

The swimming direction of fish during the day under both light treatments (i.e., on and off) and at night with the lights on was similar (Figures 4.13 and 4.14). In these three cases, the fish were swimming across the axis of the lights toward either the dam or the right bank. This directional movement is more pronounced for fish detected by the farthest transducer (i.e., 22 m) but is still evident at 6 m. Results for fish detected at splitbeam transducers 10 and 14 m from the strobe lights mirrored those obtained for fish at 6 m. There was no preferred swimming direction at night when the lights were off.

Figure 4.13. Swimming Direction for Fish Detected 6 m (beam = 10) and 22 m (beam = 0) from the Light Frame During the Day When the Lights Are On (red) and Off (black). Zero direction is downstream, 90º is toward the dam.

Night Movement Continuous

BEAM = 10

Direction Angle Probability (On)
sample_on= 3666

Direction Angle Probability (Off)
sample_off= 423

Night Movement Continuous

BEAM = 0

Direction Angle Probability (On)
sample_on= 1347

Direction Angle Probability (Off)
sample_off= 409

Figure 4.14.   Swimming Direction for Fish Detected 6 m (beam = 10) and 22 m (beam = 0) from the Light Frame at Night When the Lights Are On (red) and Off (black). Zero direction is downstream, 90º is toward the dam.

When water velocity is removed from swimming direction, the crossing movement evident during the day is now seen to be the result of fish swimming upstream against the flow field (i.e., effort) (Figure 4.15). During the day, discharge through the third powerplant was generally high (exceeding 56 kcfs 84% of the time) and constant, with water flowing across the forebay toward the right bank. Swimming effort during this time was upstream for both lights on and off.

At night, discharge was generally low, below 8 kcfs; consequently, water flows in the forebay were subject to substantial directional variability (Appendix D). Because of the low nighttime flows, the fishes' swimming effort still exhibited the same pattern as the actual swimming direction (Figure 4.16). Thus, when the strobe lights were on, the fish were headed toward either the dam or the right bank. When the lights were off, the fish showed no preferred travel direction.

The distribution and behavioral results indicate that at night when the strobe lights were on, fish arrived and accumulated continuously in front of and slightly below the strobe lights. As they arrived, they tended to cross back and forth, perpendicular to the line of splitbeam transducers. When lights were off at night, fish tended to move in all directions, traveling downstream when flows were higher than the typical values prevailing at night when water release from the dam is reduced compared with daytime. In our analysis last year (Johnson et al. 2003), it was not entirely clear if the number of fish increased at night with lights on, or if the increased counts reflected more crossing activity. From the evaluation of arrival rates and the frequency distribution of swimming speeds in 2003, it is becoming clear that the latter possibility is incorrect. There was an increase in the number of fish near the strobe lights, without their swimming behavior or velocity changing noticeably, except direction of travel. Of course, this does

Day Swimming Effort Continuous

BEAM = 10

Direction Angle Probability (On)   Direction Angle Probability (Off)

Day Swimming Effort Continuous

BEAM = 0

Direction Angle Probability (On)   Direction Angle Probability (Off)
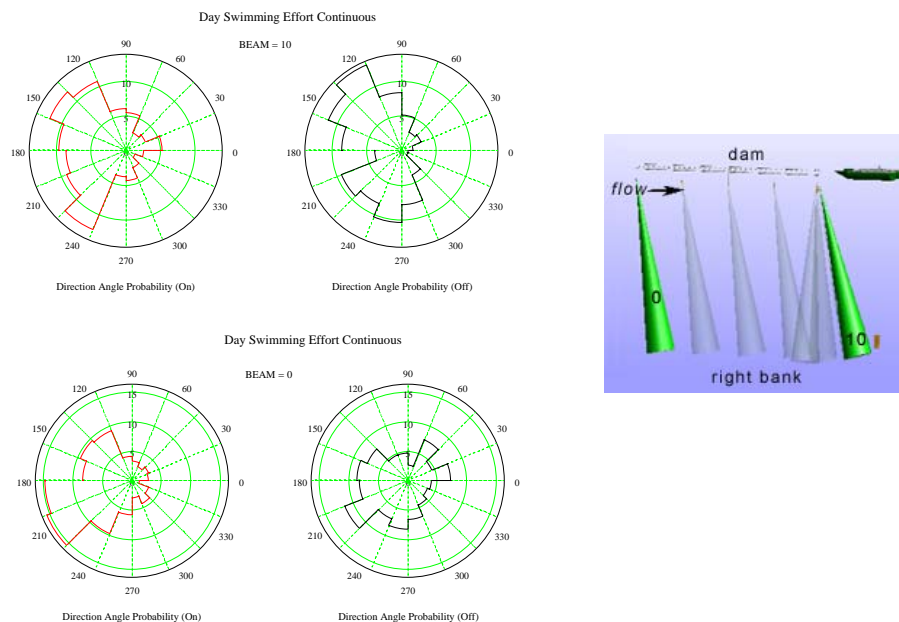
Figure 4.15.   Swimming Effort for Fish Detected 6 m (beam = 10) and 22 m (beam = 0) from the Light Frame During the Day When the Lights Are On (red) and Off (black). Zero direction is downstream, 90º is toward the dam.

Night Swimming Effort Continuous

BEAM = 10

Direction Angle Probability (On)   Direction Angle Probability (Off)

Night Swimming Effort Continuous

BEAM = 0

Direction Angle Probability (On)   Direction Angle Probability (Off)

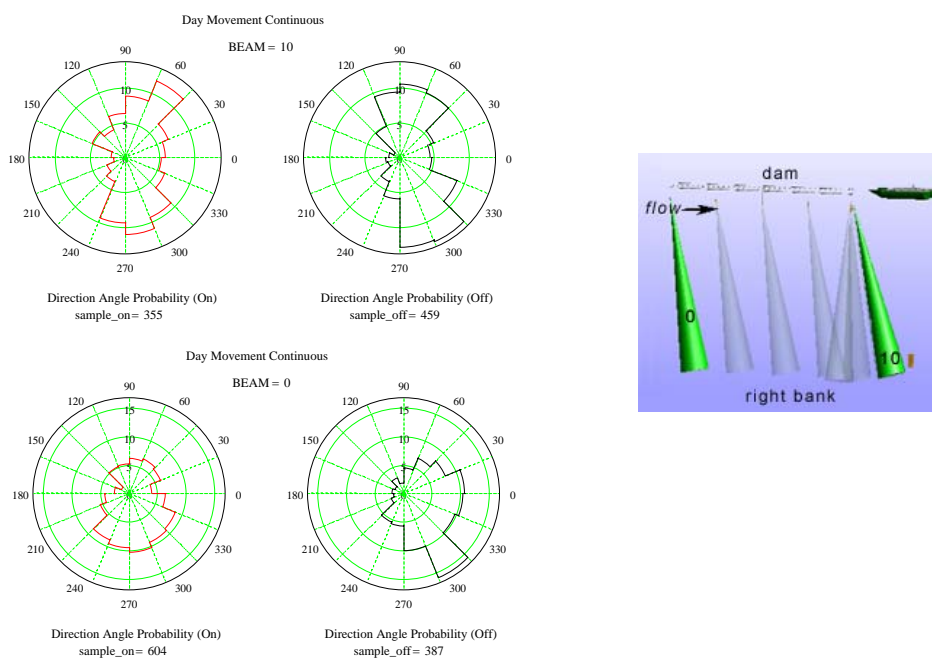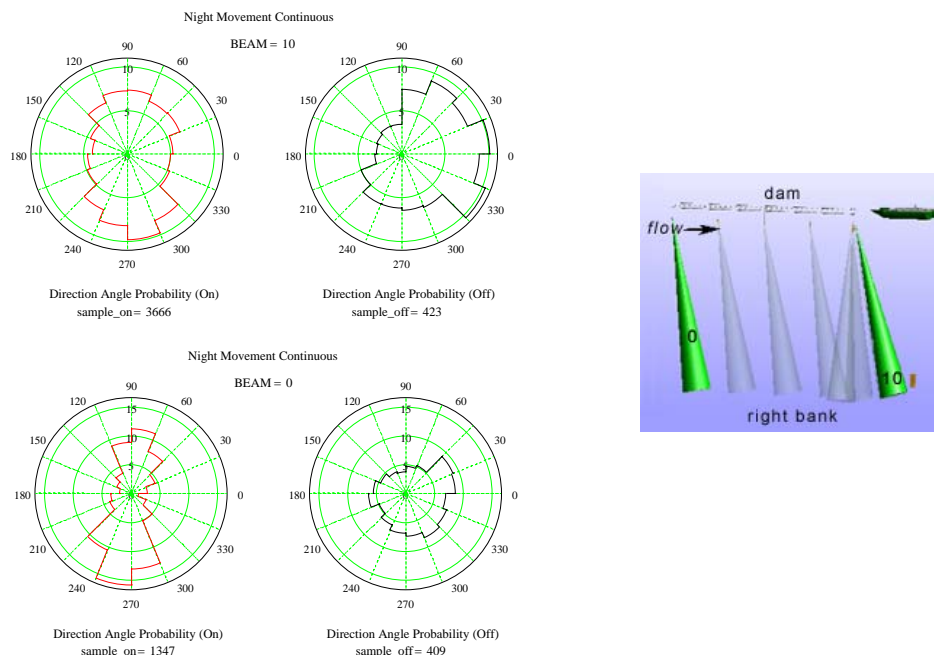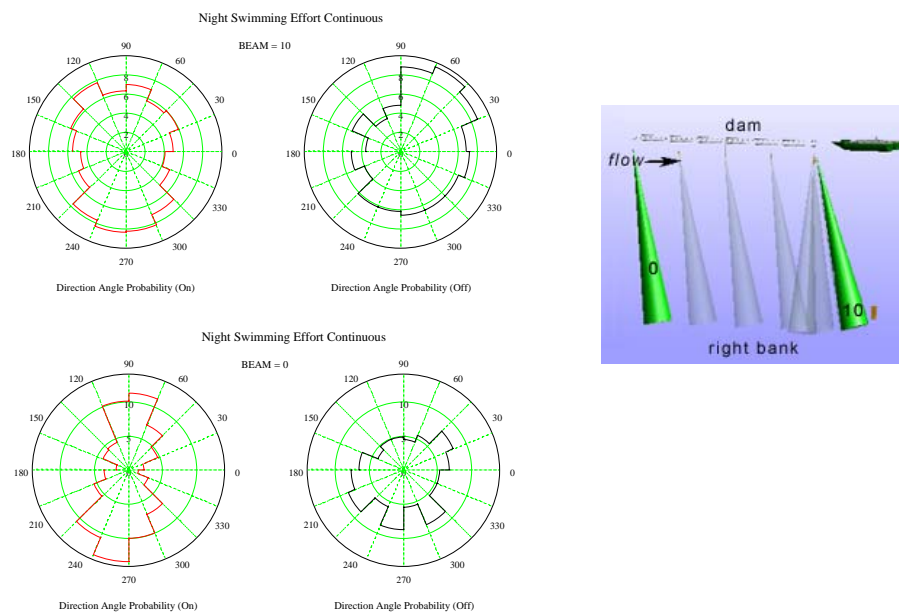**Figure 4.16.   Swimming Effort for Fish Detected 6 m (beam = 10) and 22 m (beam = 0) from the Light Frame at Night When the Lights Are On (red) and Off (black). Zero direction is downstream, 90º is toward the dam.**

not discount the possibility that the same fish remain present in the light vicinity and repeatedly cross the lights. However, given that the crossing frequency remains about the same for individuals, fish must be increasing in numbers when the lights are on at night.

These results and those from the multibeam analysis (Appendix G) support the idea that fish are accumulating in the vicinity of the strobe lights when they are on at night. It has been suggested by several reviewers that this does not constitute attraction and we are not implying that the fish prefer the lights. The fish may be accumulating because they are orienting to the lights in an environment that is otherwise devoid of reference features. In addition, zooplankton such as Daphnia are known to be attracted to a light source, which in turn may attract predatory fish such as salmonids. Daphnia were found in the vicinity of the strobe lights (Appendix I), but sampling was insufficient to determine if densities were affected by operation of the strobe lights. Hoar et al. (1957), in controlled laboratory experiments, found that juvenile salmon did not "hide in the darkened areas or remain constantly in the illuminated area, but were constantly passing to and from both areas." This behavior appears very similar to that seen in this study with fish swimming across the lighted area.

It has also been suggested that fish are piling up near the lights in an avoidance response as they are being carried downstream by the flow. The acoustic tag study in 2003 (Appendix E) found that fish moved easily into and out of the forebay area, even during the day when flows were high (Appendixes D and E). Also, flow velocities at night, near the light frame, were extremely low, between 0 and 0.25 m/s (Appendix D). In addition, the response to lights was not immediate; arrival rates showed a gradual increase in the number of fish, which, when the lights were on for 24 hr, reached a plateau between 1 a.m. and 3 a.m. when flows generally were zero.

Nevertheless, there does exist some evidence that fish may be avoiding the strobe lights at night, when flows are high. Flows were typically low at night (see Figure 2.5) compared with the median displacement velocity of the fish. However, when higher downstream flows occurred at night with the lights on, fish appeared to direct their swimming activity upstream to avoid the lights. Conversely, when the lights were off at night during high flows, fish appeared to allow downstream movement. At this time, we can only speculate about this phenomenon because the occasion of high flows at night has been sporadic at best. However, the speculation is not without precedence. Studies conducted by Johnson et al. (2001) suggest that juvenile sockeye were effectively deterred from intakes at Hiram M. Chittenden Locks in Seattle, Washington, during filling operations when there were substantial flows. Fish were moved upward away from the lock-filling culverts. In that study, strobe lights were determined to be highly effective in reducing fish entrainment into the large lock-filling culverts during periods when both sockeye and coho salmon were present.

Even with the limited evidence at this time, we believe the strobe light and flow interaction warrants further investigation in 2004. Because we cannot control dam operations, perhaps a simple laboratory study could be designed to evaluate the efficacy of the combination of flow and strobe lights to deter fish. The implication, if substantiated, is that by placing lights near the penstock openings where flows are accelerating, it may be possible to cause fish destined for entrainment to move up in the water column before becoming entrained in the high penstock velocities.

5.0   Summary and Recommendations

    The response of fish to strobe lights in the forebay of the third powerplant at Grand Coulee Dam in 2003 was based on analysis of the distribution of fish targets and on fish swimming effort and direction. More than 64,000 potential fish targets were identified by the splitbeam autotracking software in 2003. After filtering, 48,701 targets were determined to exhibit fish-like characteristics and were used in the final analysis. This is a substantial improvement over previous years and may be attributed to a number of factors including no side-looking transducers, down-looking transducers tilted off vertical to eliminate false bottom effect, and improved selection parameters in the autotracking software. Not only were there more fish targets this year, but the tracks were more complete and contained less noise.

    The summarized results that follow are for the third year of a four-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. Thus, these conclusions are preliminary.

5.1   Summary

    For the past three years, count and behavioral results have yielded contrasting views on the response of fish to strobe lights. Higher counts of fish detected near the strobe lights continue to suggest attraction, while behavioral results indicate the fish are swimming laterally or upstream away from the lighted region. This year, we provide growing evidence that water flow plays a significant role in the effectiveness of strobe lights at the third powerplant, Grand Coulee Dam. We still are concerned that there are secondary effects such as lights attracting prey species that, in turn, attract predators such as kokanee and rainbow trout, or the lights are possibly providing visual orientation cues. This year, all reflective structures were painted flat black to minimize the visual effect of structures at night, but turbulence, vibration noise, and bubbles may still alert fish to the presence of structures. Last year, we speculated that the higher counts may have been a result of increased activity. This year, we have shown that this is probably not the case because the crossing rates remain the same with increasing numbers.

    The most promising finding this year was that fish appear to avoid being carried by the flow toward strobe lights at night. Capitalizing on this phenomenon, we speculate that placing the lights near the penstock openings might result in a negative response to the lights when fish sense the increasing flow and thus avoid entering into a region of critical velocity where entrainment is certain. The continuation study in 2004 will be critical to validating this relationship and the potential utility of strobe lights at Grand Coulee Dam.

    Our intent in this report is to avoid drawing conclusions until we have completed data collection and analysis for 2004. At that time, we will have three years of comparable data from which to draw conclusions. Because we have no control of operational aspects of the study site, we expect that the next year will provide yet another hydraulic scenario for inclusion in our analysis. This, combined with our advanced analysis, should provide the basis for final conclusions on the efficacy of strobe lights as a fish deterrent at Grand Coulee Dam.

The results of the 2003 study are summarized in Table 5.1 using a number of the response criteria that we evaluated in our analysis and comparing them qualitatively between strobe lights on and off for both day and night sample conditions. Key words in the table are highlighted to help the reader focus on the key results. Some results presented in Table 5.1 are clearly obvious, while others may not be so obvious. For instance, when we count the number of fish present in response to strobe lights regardless of other stimuli, we discovered the following:

- More fish were present close to the strobe lights when they were on at night, suggesting they were attracted to the lights.

- Fish were below the strobe lights at night and at or above the lights during the day.

- More fish were present near the strobe lights at night than during the day.

- The proportion of small fish to large fish was higher at night when the lights were off.

These responses would lead us to believe that strobe lights may be an attractant to kokanee and rainbow trout. However, when the effect of flow is removed from individual fish velocity, and their swimming effort was examined, we find that

- Fish are actively swimming away from the lights at night (upstream, toward the dam or toward the bank of the reservoir).

- When the lights were off at night, there was no preferred swimming direction.

- Flow appears to be a factor in whether fish avoid the lights, particularly at night.

These less obvious responses may hold the best promise to providing a solution to the entrainment problem at the Grand Coulee Dam third powerplant. The 2003 data set has provided the best information source that we have collected thus far, and we continue to find additional subtle response indicators in the data as we do further analysis. An additional study year will provide three contiguous years of data and will allow a detailed examination of the region close to the strobe lights. The following section contains recommendations for the study in 2004.

5.2   Recommendations

During the study periods in 2001 through 2003, we deployed strobe lights and advanced hydro-acoustic monitoring technology at the entrance to 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 2004 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 2003, and set the stage for future strobe light installation, should it be deemed efficacious as a fish deterrent.

Table 5.1.   Summary of Strobe Light Effects Found in 2003 at the Grand Coulee Dam Third Powerplant

Response Criteria	Lights ON		Lights OFF	
	DAY	NIGHT	DAY	NIGHT
Fish Target Strength Distribution	**Unimodal** (same as lights off) (p. 4.2, Fig. 4.1)	Slight increase in proportion of **medium and large fish** (p. 4.2, Fig. 4.1)	**Unimodal** (same as lights on) (p. 4.2, Fig. 4.1)	Slight increase in proportion of **small fish**. (p. 4.2, Fig. 4.1)
Average Depth of Fish	**At or above lights** (p. 4.4, Fig. 4.3)	**Below lights** (p. 4.5, Fig. 4.4)	**At or above lights** (p. 4.4, Fig. 4.3)	**Below lights** (p. 4.5, Fig. 4.4)
Depth of Fish as Function of Range	Slightly **shallower** near the lights (p. 4.4, Fig. 4.3)	Slightly **shallower** near the lights (p. 4.5, Fig. 4.4)	Slightly **shallower** near the lights (p. 4.4, Fig. 4.3)	Slightly **shallower** near the lights (p. 4.5, Fig. 4.4)
Number of Fish as a Function of Range from Strobe Lights	**Slight increase** to 14 m then decreasing with decreasing distance to lights (p. 4.4, Fig. 4.3)	**Increasing** with decreasing distance to lights (p. 4.5, Fig. 4.4)	**Slight increase** with decreasing distance to lights (p. 4.4, Fig. 4.3)	**Equal numbers** at all distances from the lights (p. 4.5, Fig. 4.4)
Overall Response to Lights	Weak **repulsion** response (p. 4.5, Fig. 4.5)	Highly significant **attraction** response (p. 4.5, Fig. 4.5)	Weak **attraction** response (p. 4.5, Fig. 4.5)	**No response** (p. 4.5, Fig. 4.5)
Swimming Response with Flow (swimming effort)	High discharge - **Swimming effort upstream** (p. 4.13, Fig. 4.15, Appendix H)	Low discharge - **Swimming effort away from lights laterally** (p. 4.13, Fig. 4.16, Appendix H)	High discharge - **Swimming effort upstream** (p. 4.13, Fig. 4.15, Appendix H)	Low to mid discharge – **No preferred swimming direction** (p. 4.13, Fig. 4.16, Appendix H)
Arrival Rates (1-hr on/off)	**Recruitment fairly constant** over time **with slight decrease** in last half hour (p. 4.9, Fig. 4.10)	**Arrival rates increased rapidly** (p. 4.9, Fig. 4.10)	**Recruitment fairly constant** over time (p. 4.9, Fig. 4.10)	**Arrival rates decline** (p. 4.9, Fig. 4.10)
Arrival Rates (24-hr on/off)	**Constant** with some fluctuations (p. 4.10, Fig. 4.12, Appendix H)	**Increased at night** then **declines into morning** hours (p. 4.10, Fig. 4.12, Appendix H)	**Constant** with some fluctuations (p.4.10, Fig. 4.12, Appendix H)	**Little or no accumulation** (p. 4.10, Fig. 4.12, Appendix H)
Swimming Direction	**Swimming across the axis of the lights** toward dam or bank (p. 4.11, Fig. 4.13, Appendix H)	**Swimming across the axis of the lights** toward dam or bank (p. 4.12, Fig. 4.14, Appendix H)	**Swimming across the axis of the lights** toward dam or bank (p. 4.11, Fig. 4.13, Appendix H)	**No directional preference** (p. 4.12, Fig. 4.14, Appendix H)
Distribution behind and to side of lights (multibeam)	**Low numbers**[a] similar to lights off (p. 4.14, Appendix G)	**Detections more than double** than when lights were off (p. 4.14, Appendix G)	**Low numbers**[a] similar to lights off (p. 4.14, Appendix G)	**Half as many detections as** when lights were on (p. 4.14, Appendix G)
(a) Only 5% of files processed.				

Our continuation study recommendations are as follows:

1. The study should begin and end later (mid to late June through mid August) to capture the kokanee and rainbow trout populations as the fish move down the reservoir toward the dam. In both 2002 and 2003, the peak fish count occurred at the end of July.

2. All splitbeam transducers should again be deployed at the surface looking down immediately upstream of the strobe lights to sample the region close to the lights as in 2003. The transducers should be angled slightly downstream to prevent the occurrence of a strong second-bottom reflection in the region of interest. A multibeam system should be redeployed to examine the regions lateral to the light frame as in 2003, except moved upstream of the light frame to avoid interference from the light frame and the counterweights that hold the barge in place.

3. The experimental design from 2003 should be repeated to include three strobe light treatments of 24 hr on, 24 hr off, and 1 hr on/1 hr off for 24 hr. All treatments should use 6 strobe lights (during 2002 and 2003, the 6-lights-on condition elicited a statistically increased response compared to the 3-lights-on treatment in 2002). A final design will be reviewed in the spring of 2004 in consultation with our statistical staff.

4. An acoustic Doppler current profiler should be deployed as in 2003 to provide flow information that can be used to better interpret behavioral results and permit estimation of fish swimming effort. Fish swimming effort is one of the response metrics that enhances our understanding of fish behavior in relation to strobe lights.

5. Approximately 250 or more fish should be tagged with ultrasonic transmitters and released from a strategically located net pen to determine the behavior of known species around the test site in the third powerplant forebay. Monitoring should include the third powerplant forebay, the pumping plant, and the tailrace. This will provide valuable information on the presence of the target species in the strobe-light region and an index of entrainment as a result of dam operations. A strategy for fish releases will be discussed in preseason meetings in spring 2004.

6. Potential entrainment losses to Banks Lake through operation of the pumping plant are of concern to the Colville Confederated Tribes. The pumping plant operations should be investigated with regard to fish accumulations at the pumping plant forebay and the physiological impact to fish pumped up into Banks Lake. Monitoring can be accomplished using mobile hydroacoustics, an acoustic tag detection hydrophone, and a sensor fish developed by PNNL.

7. A dual-frequency identification sonar (DIDSON) acoustic camera should be deployed for a limited time to provide a qualitative evaluation of fish movement around the strobe lights during periods of darkness with lights on and lights off. (Note: the acoustic camera images fish movement without the need for lighting.)

8. The data from 2002 should be reprocessed with newly evolved techniques and algorithms from 2003 so that it is consistent with the analysis in 2003 and 2004. This will result in three years of data for comparison in developing the final analysis for this project to examine fish, flow, and light interactions.

9. The combined effect of strobe lights and flow should be examined using previously collected data, data collected in 2004, and controlled experiments. Controlled experiments should be undertaken to determine the relationship of flow and strobe lights to elicit a combined negative phototactic and positive rheotactic response in kokanee.

10. A more comprehensive zooplankton survey should be conducted during the study season to determine the species composition and abundance of zooplankton in the area illuminated by the 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 U.S. Department of the Interior Bureau of Reclamation. Over the 2003 study period, the water level in the forebay increased approximately 5 m and reached normal high pool elevation of 393 m (1290 ft) in early July (Figure A.1). The forebay elevation in 2003 was similar to 2002 in June and early July, and to 2001 in late July.
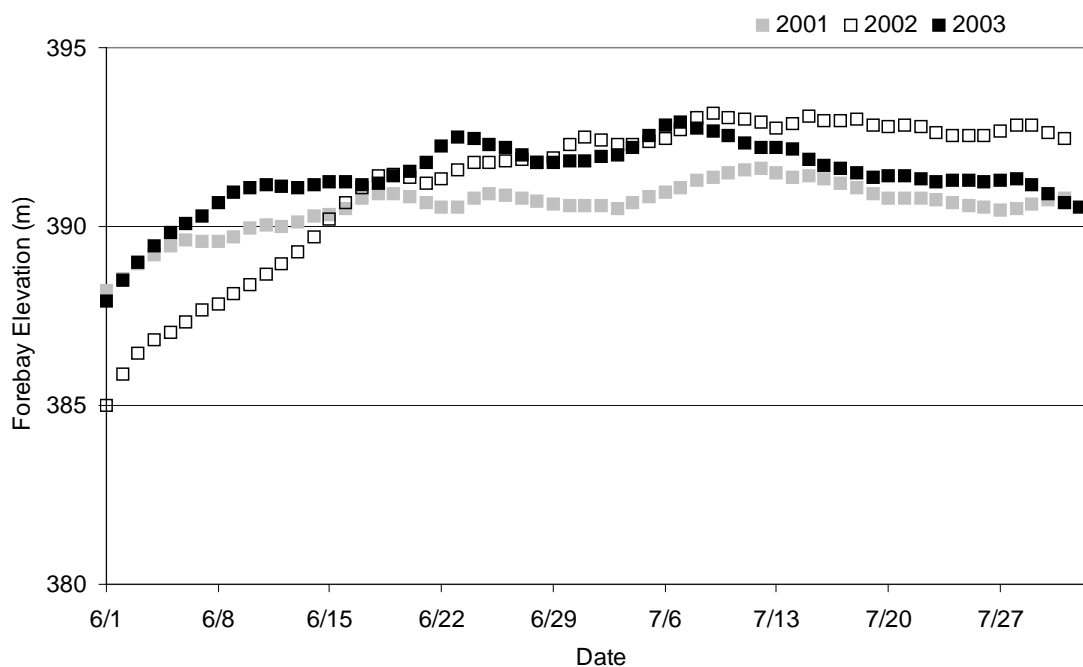
**Figure A.1.   Forebay Elevation in Front of the Left Powerplant During
the Period June 1–August 1 for 2001, 2002, and 2003**

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, vertical water temperatures were measured by placing 14 self-contained temperature loggers along a steel cable extending 40 m beneath the water surface. The cable was attached to a buoy anchored upstream of the barge (Figure 3.2) in the forebay. A metal weight was affixed to the bottom of the cable to keep the line vertical throughout the water column. The Onset Optical StowAway® temperature loggers (Figure A.2) used during this study have a reported accuracy of ±0.2ºC. All loggers were validated before and after deployment by exposing them to a constant-temperature environment and a high-accuracy thermistor. 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 10-min intervals. The loggers were spaced 3 m apart to cover the water column from 4 to 42 m. The depth of the forebay was 52 m on August 6, 2003, at a forebay elevation of 391 m (1282 ft). The loggers were deployed on May 21, and data were collected through July 15.

Temperatures from the 14 temperature loggers are plotted as a function of time in Figure A.3. Initial stratification occurred during early June and intensified during the summer months. As stratification intensified, the depth of the thermocline reached 20 m or more at the end of the study period. As expected, water temperatures beneath the thermocline were vertically constant, although a gradual warming from 8º to 16º C was noted during the two-month period.

A metric to gauge the strength of stratification was calculated by subtracting the time series of water temperatures gathered at 4 m from the bottom measurement at 42 m. Based on this method, the mean temperature difference between May 21 and July 15 was 4.6ºC (Figure A.4). In Figure A.4, the diurnal cycle in temperature is evident, especially at 4 m. The frequent ocscillations in temperature differences (Figure A.4) are caused primarily by the sharp decreases in temperature at 4 m. Warming occurs at both depths, although the rate is slower and less variable at 42 m.

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

®   Product of the Onset Computer Company, Pocasset, Massachusetts.
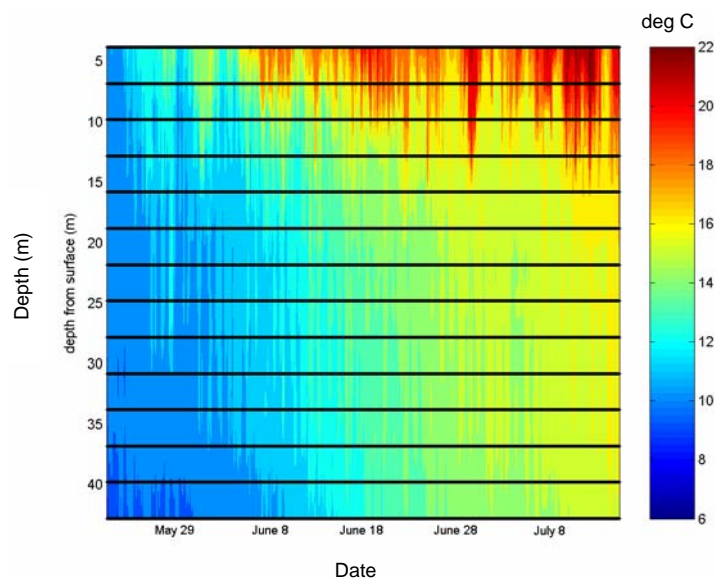
Figure A.3.   **Water Temperature Contours as a Function of Depth in the Forebay of the Third Powerplant at Grand Coulee Dam in 2003. Black horizontal lines indicate location of temperature loggers.**
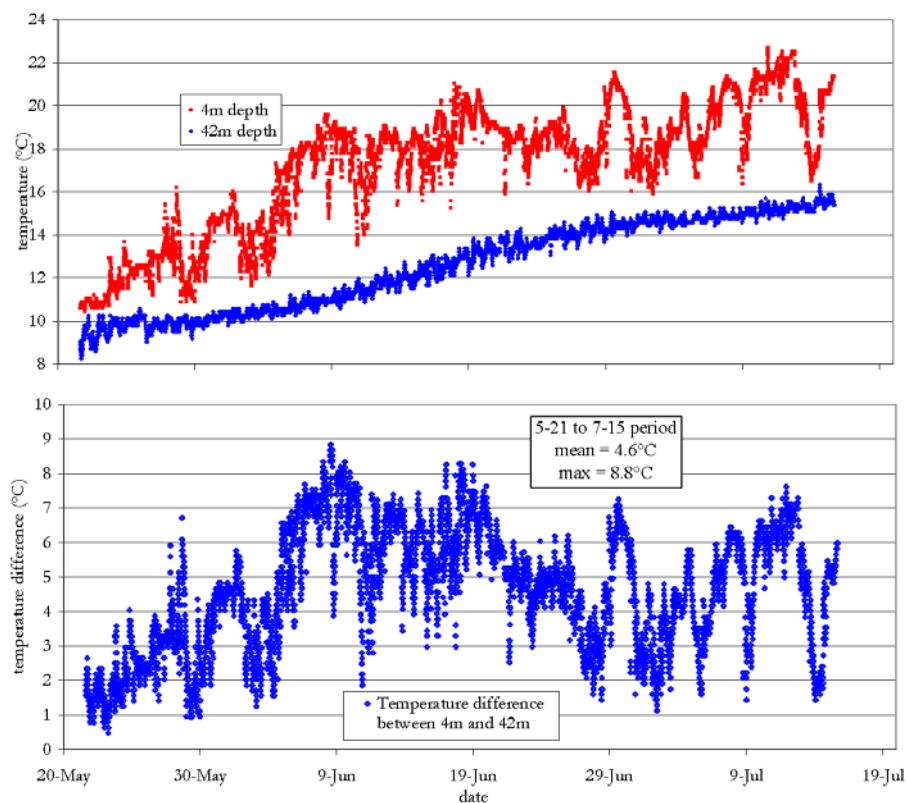
Figure A.4.   **Temperatures at 4 and 42 m (upper) and Temperature Differences Between 4 and 42 m (lower) During Study Period in 2003 in the Forebay of the Third Powerplant at Grand Coulee Dam**

Although water temperatures in both the hypolimnetic and epilimnetic waters in the forebay rose during the period, the difference between the two layers remained approximately constant during June and July (approximately 4° to 5°C), with maximums in excess of 8°C during the daylight hours. At no time during the June-July period was stratification observed to break down entirely, although the strength of the stratification varied. Discrete events when temperature differences between the hypolimnetic and epilimnetic waters were only 1° to 2°C were noted in both June and July. Weakening of the stratification occurs regularly, primarily by sharp cooling of the epilimnetic waters (except for slight fluctuations, the hypolimnetic waters were observed to only warm during the study period). Although the exact mechanisms causing these surface cooling events are unknown at this time, it is suspected these surface layer cooling events may be caused by atmospheric processes (e.g., wind events increasing evaporative cooling, conductive cooling from the air above).

A.3 Turbidity

Turbidity can affect the distribution of fish both vertically and spatially (Swenson 1978; Matthews 1984). Turbidity measurements were taken weekly at three depths (surface, 15 m, and 30 m) at the upstream buoy location closest to the right bank of the reservoir in the forebay of the third powerplant (Figure 3.1). Turbidity measurements were taken with Van Doren bottle grab samples and analyzed using a Hach Model 2100P Portable Turbidimeter.[a] Three replicates were analyzed at each depth.

Turbidity levels were generally below 1 nephelometric turbidity unit (NTU) in 2003, with surface samples having the lowest turbidity (Figure A.5a). Compared to previous years (Figure A.5b), average turbidity levels were similar to those in 2001 and 2002. In all years, turbidity decreased from June through July. The higher turbidity levels were associated with the filling of the reservoir. In 2001, the reservoir was at its maximum elevation when the study began. No adverse physiological effects have been noted in salmonids at turbidity levels less than 10 NTU (Bash et al. 2001). However, turbidity as low as 3 NTU was found to affect the response of lake trout to prey under low light levels (Vogel and Beauchamp 1999). In addition, increased turbidity would affect the visible range of the strobe lights.

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 every second to a data logger on the sensor mast of the fixed barge.

(a) Hach Company, Loveland, Colorado.
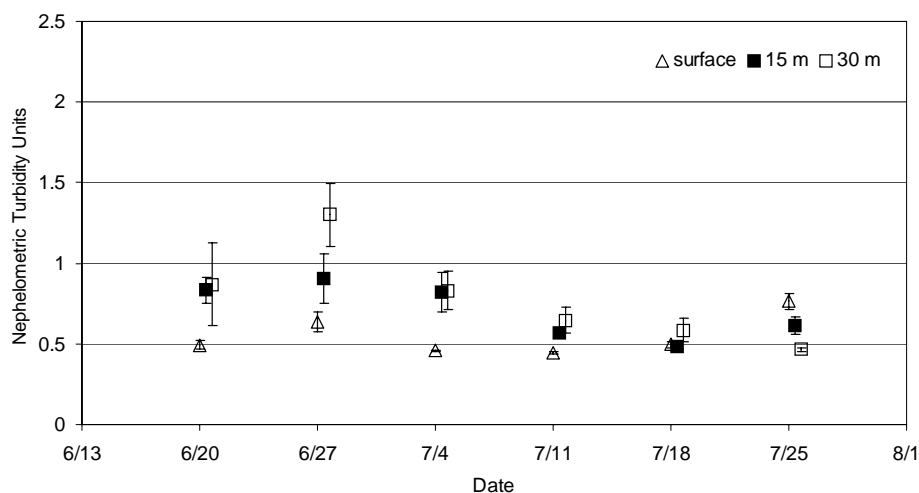
a) Turbidity Levels During 2003 Study Period
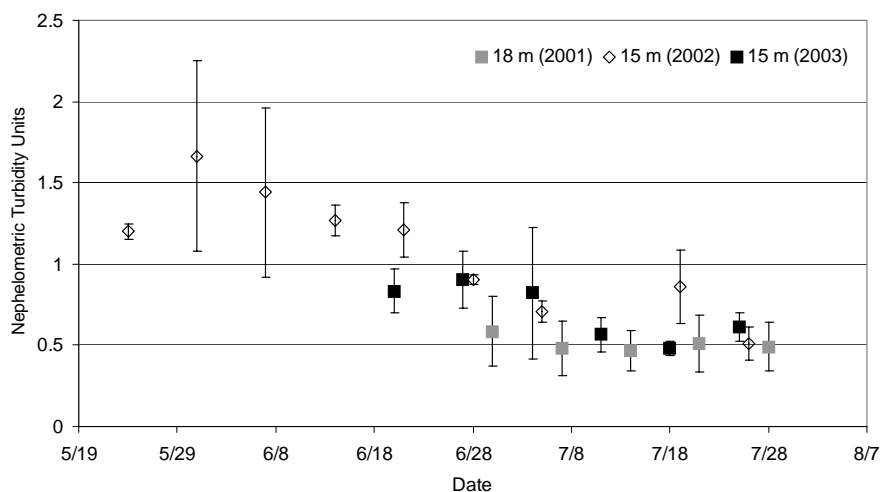
b) Turbidity Levels During Three Study Years

Figure A.5.   Turbidity Levels at Grand Coulee Dam in 2003 for Three Depths (surface, 15, and 20 m) and for Three Study Years (June 30 to August 1, 2001; May 24 to July 26, 2002; and June 20 to July 25, 2003). Bars are ±1 standard deviation (n = 9 for 2001; n = 3 for 2002; n = 3 for 2003).

    Maximum daily light levels fluctuated between 2000 and 3000 μmole/m^2/s over the course of the study (Figure A.6); 2000 μmole/m^2/s is considered clear sky, midday sunlight, while light levels on a cloudy day would be around 500 μmole/m^2/s. Daily light levels peaked between noon and 1 p.m. (Figure A.7).

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.
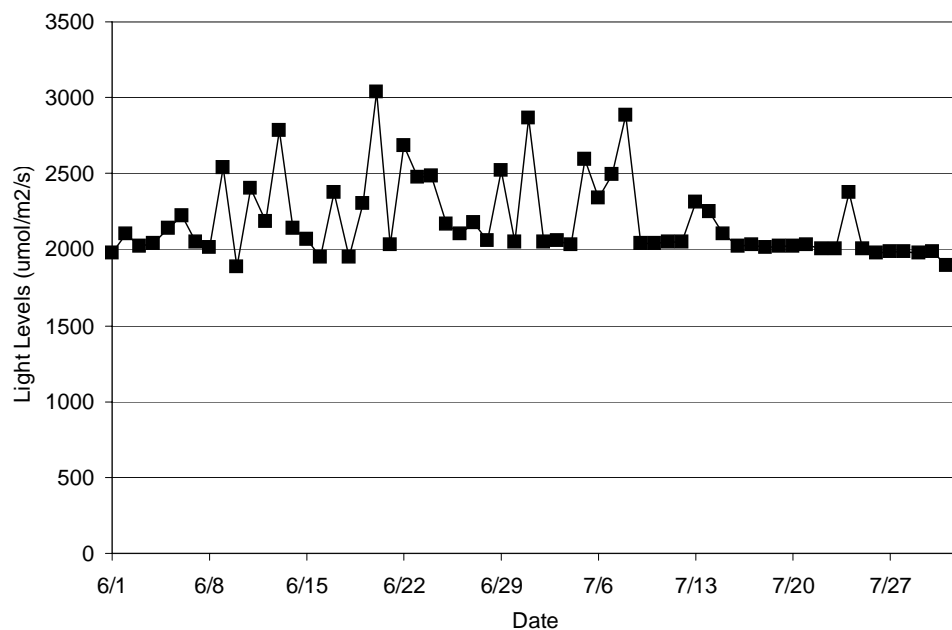
Figure A.6.   Maximum Light Levels in Forebay of Third Powerplant at Grand Coulee Dam in 2003
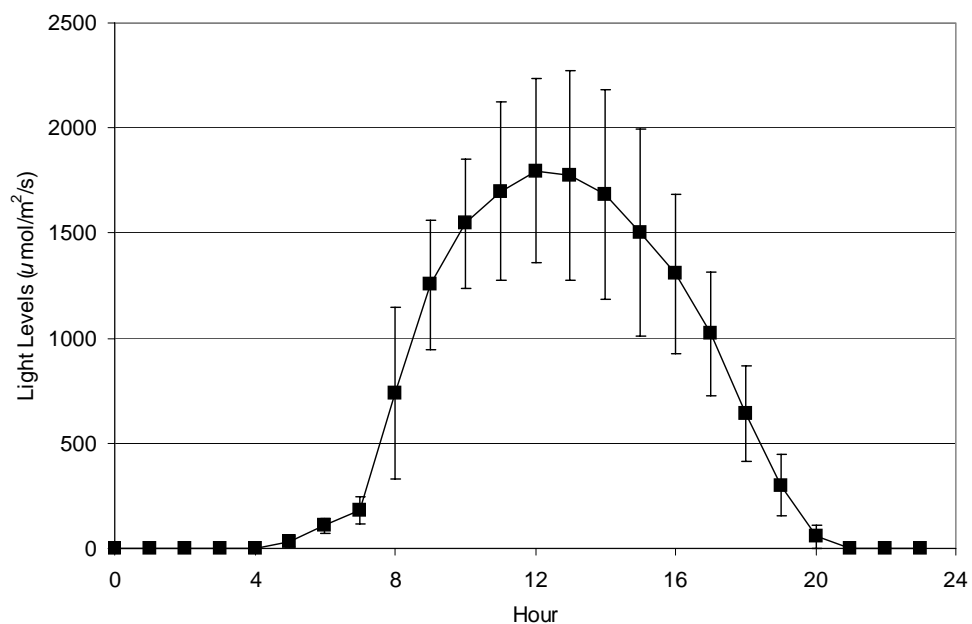
Figure A.7.   Hourly Ambient Light Levels Measured at Water Surface Between June 1 and August 1, 2003. Bars are ±1 standard deviation (n = 830) based on 5-min averages. Zero hour is midnight.

Wind speed and direction were measured during the study period using a Model 03002V Wind Sentry (R. M. Young Company, Traverse City, Michigan) secured to a pole on the equipment trailer on the dam. Wind speed and direction data were input to the LI1400 data logger continuously 24 hr/day and stored as the minimum, maximum, and average speed and direction. Precipitation data was downloaded from the Bureau of Reclamation AgriMet database (Bureau of Reclamation 2003).

Wind direction was primarily downstream from the south-southeast (Figure A.8). Wind speed was generally below 20 km/h (12 mph) (Figure A.9). However, on several occasions during the study, gusts were recorded in excess of 25 km/h (15 mph).
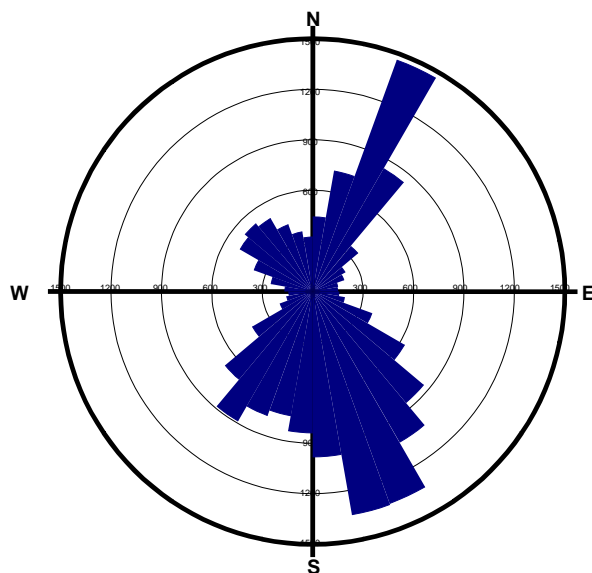
Figure A.8.   Wind Rose Showing Predominant Direction from Which Wind Comes in Forebay of Third Powerplant at Grand Coulee Dam in 2003
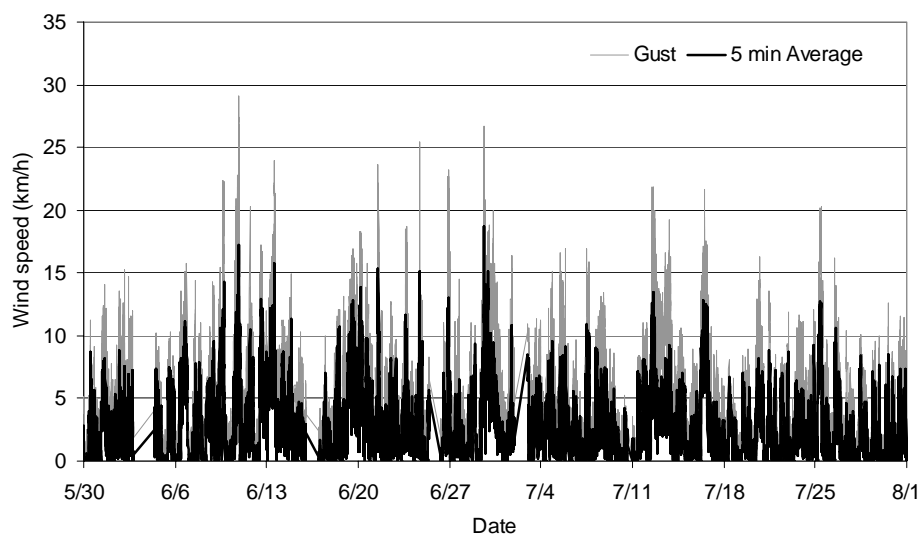
Figure A.9.   Wind Speed at Grand Coulee Dam in 2003. Wind speed data represent 5-min averages.

A.7

    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 2003 indicate that a single rain event occurred during the study period on June 13, and the precipitation total was less than 0.3 cm (0.1 in.).

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Appendix B

Hydroacoustic System Calibration

Appendix B

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 2005.

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

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

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

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

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

Calibration Data

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

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

Stat Xmit	Dyn Xmit				Stat Xmit	Dyn Xmit			
Level	Level	Vs	SL		Level	Level	Vs	SL	
-6	-6	-5.69	-5.69		-3	-6	-1.32	-1.32	Pattern
-5	-6	-4.08	-4.08						
-4	-6	-2.63	-2.63						

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

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

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

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

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

B.2

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

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

Splitbeam Calibration for Grand Coulee Dam- Source Levels

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

Splitbeam Calibration for Grand Coulee Dam- Receiving Sensitivities

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

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

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

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

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

Calibration Data

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

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

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

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

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

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

Where Gtvg = 40 or 20 Log (Rx) =				40 dB-40 or		20 dB-20	
Receiver Output	-58 dB Cal Osc	Vs	Vdet Out	Vout-dB	Gx	G1
Receiver #1, Log Sum Beam, 40 Log (R)	4.005	-26	4.071	81.42	-52.15964	-112.1596
Receiver #2, X Phase (AC/BD)	2.484	-26	2.495	N/A	N/A	N/A
Receiver #3, Y Phase (AB/CD)	2.511	-26	2.556	N/A	N/A	N/A

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

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

Splitbeam Calibration for Grand Coulee Dam-Source Levels

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

Splitbeam Calibration for Grand Coulee Dam-Receiving Sensitivities

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

Appendix C

Statistical Synopsis

Appendix C

Statistical Synopsis

C.1 Experimental Design

Three treatment levels were used in 2003: all lights off (0 of 6 lights) as a control, 6 lights on, and lights alternating on/off every hour (3 of 6 lights). Each of these three treatment conditions was applied for a full 24-hr period 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. In addition, data from the 1-hr on/off treatment were analyzed separately from the treatments where the lights were on or off for the entire 24 hr.

Seven splitbeam transducers were deployed upstream of the strobe lights (Figure 3.4). Five of the transducers were placed perpendicular to the lights and equally spaced from 6 to 22 m. The remaining two transducers ensonified areas to the right and left of the main transducer axis and were at 6 m from the light frame. The main statistical analysis of number of fish tracks is based on data from the five in-line transducers.

C.2 Track Count Analysis

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

We also evaluated the effects of environmental and experimental factors on the phototactic influence of the strobe light treatments. Table C.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 C.1. We cross-tabulated these variables and created a contingency table. 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 C.1, if *Treatment, Position*, and *Block* were cross-classified into a three-way contingency table, the table would contain 130 cells representing all possible combination of these three factors (2 treatments x 5 positions x 13 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 6 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.

Multidimensional structures are 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 C.1. This coding also can impose an

Table C.1. Definition of Factor Variables

Factor Variable	Code	Class Level	Description
Treatment			The strobe light treatment variable of interest.
	0	0 lights	Strobe lights off. This is the treatment control or reference condition.
	1	6 lights	3 or 6 strobe lights on.
Position			The position of five down-looking transducers located at 4-m intervals upstream from the strobe lights.
	1	6 m	Fish tracks located 6 m from the strobe lights.
	2	10 m	Fish tracks located 10 m from the strobe lights.
	3	14 m	Fish tracks located 14 m from the strobe lights.
	4	18 m	Fish tracks located 18 m from the strobe lights.
	5	22 m	Fish tracks located 22 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 thousand 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 - 8 kcfs / 0 – 3 cm/s[a]
	2	Medium	Medium - 2nd to 3rd quartile: 8 – 56 kcfs / 3 – 51 cm/s
	3	High	High - 4th quartile: >56 kcfs / 51 – 91 cm/s
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	2-14	Values 2 to 14	Randomized block composed of 3 days each with the three levels of treatment randomly ordered. Note: Block 1 was incomplete and not used in this analysis.
(a) Velocity measured by acoustic Doppler current profiler (ADCP) 6 m from light frame.			

ordering on the factor levels where appropriate (e.g., low, medium, and high discharge through the third powerplant). These coded values are then placed in 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.

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 frequently are in the form of survey counts. The mathematical form of this model is shown in Equation (C.1) (McCullagh and Nelder 1989):

$$Y_i = \beta_0 \exp\left(\sum_{j=1}^{p} \beta_j X_{ij}\right) + \varepsilon_i \tag{C.1}$$

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

Fitting the statistical model shown in Equation (C.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 compared 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 (Agresti 1990; Hosmer and Lemeshow 1989). 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 often the case when modeling environmental data. When the estimated scale parameter is greater than 1, the data are said to be *overdispersed*. This was the result for all models used in this analysis. We adjusted for this model *lack-of-fit* by using the estimated scale parameter from each fitted model to adjust all test statistics.

Odds ratios are most usefully displayed graphically along with their confidence intervals to aid in comparison. Such graphics are used extensively for assessing the results based on fitting log-linear models.

The combined effects of factors defined in Table C.1 on the behavioral response of the fish were also studied. The combined effects of factors are assessed 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 we evaluated 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 the factors in the interaction, 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 C.1). The block variable was not included in any interaction effect, but its individual effect (sometimes called a *main effect*) was included in all models.

C.3 Displacement Vector Analysis

Displacement velocity vectors from fish tracks were defined as the straight line between the initial and final location for each track. Movement on a two-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 two-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 (Fisher 1995, Jammalamadaka and SenGupta 2001) and has been used to assess the directional movements of animals in response to stimuli.

An appropriate probability model for studying 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 (C.2) as

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

where

$$I_p(\kappa) = \sum_{r=0}^{\infty} \frac{\left(\kappa/2\right)^{2r+p}}{r!\,\Gamma\left(p+r+1\right)}, p = 1, 2, \ldots \tag{C.3}$$

Equation (C.3) is the modified Bessel function of the first kind of order p (Jammalamadaka and SenGupta 2001, p. 288). The von Mises pdf takes two parameters (μ, κ), which are estimated from the data as follows:

First compute the first trigonometric sample moments on a sample of n-angle values as

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

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

$$\hat{\mu} = \tan^{-1}(S/C) \qquad \text{if S>0, C>0} \tag{C.4}$$

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

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

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

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

The expressions $I_1(\kappa)$ and $I_0(\kappa)$ in Equation (C.5) are the modified Bessel functions of order 1 and 0, respectively, given in Equation (C.3). The concentration parameter (κ) of the von Mises distribution on a circular probability scale is analogous to the precision ($\frac{1}{\sigma}$) on a linear scale in that both give a quantitative measure of the dispersion in the data. Larger estimated values of κ indicate a more orderly or concentrated data distribution with a more defined dominant direction of movement. However, circular data can be recentered about the mean parameter (μ), but cannot be rescaled.

Multimodal distributions of angles may be modeled as a mixture of von Mises distributions. In particular, the parameters for a bimodal mixture of two von Mises distributions [Equation (C.6)], $VM(\mu_1, \kappa_1)$ and $VM(\mu_2, \kappa_2)$, and unknown mixture proportion p may be estimated by simultaneous solution of six equations in five unknown parameters as follows (taken from Fisher 1995, p. 97):

$$\begin{aligned} f(\theta | \mu_1, \kappa_1, \mu_2, \kappa_2, p) = & [2\pi I_0(\kappa_1)]^{-1} p \exp[\kappa_1 \cos(\theta - \mu_1)] + \\ & [2\pi I_0(\kappa_2)]^{-1} (1-p) \exp[\kappa_2 \cos(\theta - \mu_2)] \end{aligned} \tag{C.6}$$

First, compute the first three trigonometric sample moments as

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

Next, let $A_v(\kappa) = I_v(\kappa)/I_0(\kappa)$.

The six equations are given in (C.7):

$$pA_1(\kappa_1)\cos(\mu_1)+(1-p)A_1(\kappa_2)\cos(\mu_2)=\overline{C}_1$$
$$pA_2(\kappa_1)\cos(2\mu_1)+(1-p)A_2(\kappa_2)\cos(2\mu_2)=\overline{C}_2$$
$$pA_3(\kappa_1)\cos(3\mu_1)+(1-p)A_3(\kappa_2)\cos(3\mu_2)=\overline{C}_3$$
$$pA_1(\kappa_1)\sin(\mu_1)+(1-p)A_1(\kappa_2)\sin(\mu_2)=\overline{S}_1 \tag{C.7}$$
$$pA_2(\kappa_1)\sin(2\mu_1)+(1-p)A_2(\kappa_2)\sin(2\mu_2)=\overline{S}_2$$
$$pA_3(\kappa_1)\sin(3\mu_1)+(1-p)A_3(\kappa_2)\sin(3\mu_2)=\overline{S}_3$$

Simultaneous solution to this system of equations in the five unknown parameters gives the method of moments estimates for the four von Mises parameters and the mixture parameter *p* by iterative minimization of the sum of squares criterion (C.8):

$$r^2(\Delta C_1,\Delta C_2,\Delta C_3,\Delta S_1,\Delta S_2,\Delta S_3)=\Delta C_1{}^2+\Delta C_2{}^2+\Delta C_3{}^2+\Delta S_1{}^2+\Delta S_2{}^2+\Delta S_3{}^2 \tag{C.8}$$

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

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

This algorithm may be generalized to mixtures involving more than two von Mises distributions.

C.4 References

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Appendix D

**Hydrodynamic Characterization
of the Third Powerplant Forebay at Grand Coulee Dam**

Appendix D

Hydrodynamic Characterization
of the Third Powerplant Forebay at Grand Coulee Dam

Hydrodynamic characterization of the third powerplant forebay just upstream of Grand Coulee Dam was performed using multiple instruments and sampling strategies. During the main in-season period, an acoustic Doppler current profiler (ADCP) and 14 self-contained temperature loggers (see Appendix A) were deployed to continuously monitor the system. The resulting data were used to understand the long-term evolution of stratification and velocities near the strobe light frame. In addition, a mobile survey was performed just after the main study season to more broadly characterize the larger-scale motions over a much smaller temporal period. This appendix presents results from both characterization strategies and attempts to draw some preliminary conclusions regarding circulation patterns during the early to mid summer of 2003.

D.1 Current Profiler Deployment

Two types of current measurements were undertaken in 2003: 1) fixed-location measurements immediately upstream of the strobe light array (i.e., moored configuration) and 2) mobile measurements taken throughout the third powerplant forebay (i.e., mobile configuration). Both types of measurements were taken with the same 600-kHz broadband Workhorse series ADCP manufactured by RD Instruments, San Diego, California. This profiler contains four transducers, arranged in two orthogonal pairs, with each beam tilted 20° off the longitudinal centerline of the unit (i.e., Janus configuration). Broadband acoustic pulses (pings) were emitted from each transducer, which then functioned as a receiver to collect reflected acoustic signals. The ADCP was tuned to collect acoustic signals reflected off small particulate matter that moves passively with the water current; however, care was taken to ensure that the ADCP beams did not hit any part of the light-frame structure. The general deployment of the ADCP by the barge is shown in Figures D.1 and D.2.

The ADCP beams are directional cone shapes that spread out from the 8-cm-diameter transducer head. The width of each beam increases with distance from the head, and the general convention is to cite the radial degree −3 dB down from the peak response at the centerline of the beam. For this specific unit, the −3-dB level was approximately 1.3° to 1.6° (note: in Figure D.1, which was created for planning purposes, the ADCP beam swath plotted represents the location of the fourth side lobe (−65 dB), which lies at an angle of 9° from the centerline). The ADCP also is equipped with internal sensors to determine the orientation of these beams using pitch, roll, and heading, and to measure the water temperature for adjusting the speed of sound. The uncertainty of these sensors, as stated by RD Instruments, is 1) pitch and roll, ±2°; 2) heading, ±5°; and 3) temperature, ±0.4°C.

ADCP velocities were collected in beam coordinates. These coordinates were projected to a true north coordinate system using the pitch, roll, and heading sensors. The magnetic declination for the
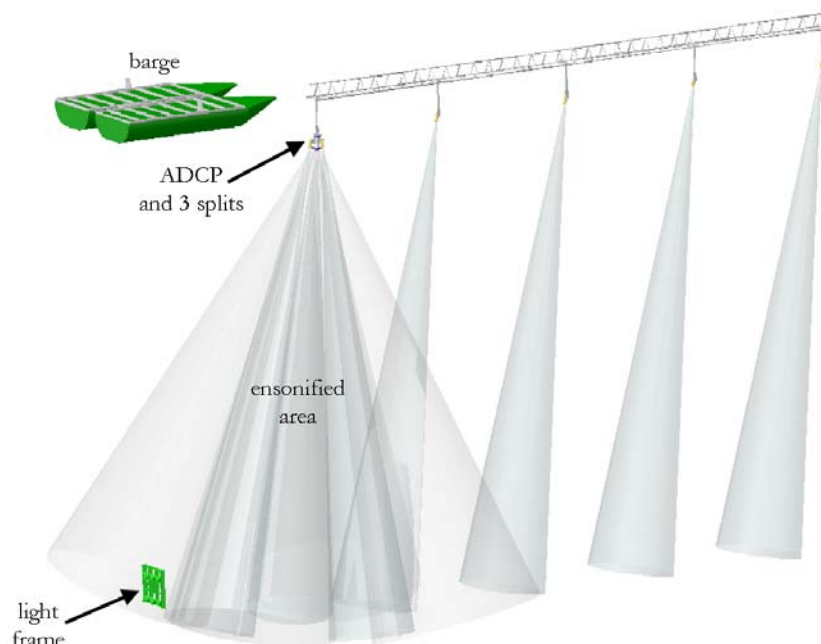
Figure D.1.   **General Deployment of the Barge, Light Frame, and Acoustic Doppler Current Profiler in the Forebay of the Third Powerplant at Grand Coulee Dam in 2003. The beam swath for the ADCP is approximate (see text for details). The other beams represent the areas ensonified by seven splitbeam transducers.**
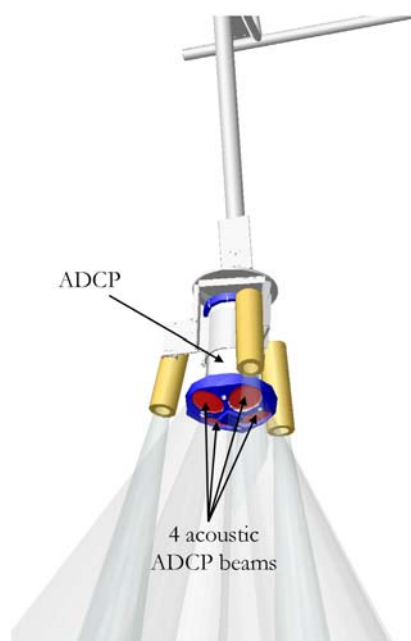

Figure D.2.   **Close-Up Detail of the Acoustic Doppler Current Profiler Surrounded by the Three Splitbeam Hydroacoustic Transducers. The four ADCP transducer/receivers are shaded red.**

region was calculated using a U.S. Geological Survey web utility (USGS 2003) and was calculated to be 17.7° based upon date, latitude, and longitude.

The moored ADCP was deployed as close to vertical as possible on the truss shown in Figures D.1 and D.2. Because the water surface of the reservoir varied over the season, the tensioning lines holding the barge/truss in place changed continually, thus changing the pitch and roll of the ADCP. On average, these changes in pitch and roll were less than ±5°, and at no time did the pitch or roll exceed the ±20° sensor limit.

The ADCP is programmed to average over a set vertical distance (or bins) and a discrete number of pings. Based upon last year's moored ADCP analysis, it was recommended that the averaging time be decreased and the frequency of sampling be increased. The 2003 moored ADCP in-season data were collected using 1.0-m bins, starting at the centroid of the first bin, which was 3.4 m beneath the water surface (the head was placed approximately 1.5 m below the water surface), and extending to the bottom of the reservoir. Each moored ADCP measurement was composed of three pings, which took less than 1 s to collect. This resulted in a theoretical ensemble Doppler error of 2.76 cm/s. The ADCP was programmed to collect ensemble readings every minute during the field season so that the unit's 16-Mb memory would be filled after approximately 10 days. The ADCP generally was downloaded every week.

The mobile ADCP measurements were collected over a two-day period, August 6 and 7, 2003. The unit was programmed to collect data in 1.0-m bins, starting at the centroid of the first bin, which was 2.6 m beneath the water surface (the head was placed 0.3 m beneath the water surface). Data were collected either at fixed points or along transects. During fixed-point measurements, each ensemble ADCP measurement was composed of eight pings (plus four bottom track pings), which took approximately 5 s to collect. This resulted in a theoretical ensemble Doppler error of 3.57 cm/s. At each point location, the ADCP remained on station for more than 10 min, and the boat was held as steady as possible. If the boat did drift during the period, any measurements taken farther than 10 m away from the starting location were culled from the data set. Transecting measurements were collected somewhat differently. Because the boat was moving through rapidly changing flow structures, the number of pings per ensemble was decreased (i.e., the ensemble sampling rate was increased). These data were collected using two pings (plus one bottom track ping), which took just over 1 s to collect. This resulted in a theoretical ensemble Doppler error of 3.38 cm/s.

D.2   Moored (Stationary) ADCP Characterization

Moored ADCP data provided long time-series records of water velocities just upstream of the strobe lights between May 29 and August 5, 2003. These data were used to characterize the general flow patterns near the lights and to determine fish swimming effort.

A subset of time-series records was selected from this large data set; these records were typical of the velocities observed during the study. This subset generally was collected just before and just after the primary hydroacoustic season. This was done because 1) the records bracket the levels of thermal stratification in the reservoir and 2) the August data set was exceptionally free of acoustic noise (i.e., crosstalk) because the other acoustic devices were off. These data are representative of three generic

circulation modes at the barge, which appeared to be a function of the discharge at the third powerplant. Within each generic circulation mode, two additional sub-modes were detected based on the strength of the thermal stratification.

D.2.1   Mode 1: High Discharge with Vertically Uniform Velocity

Mode 1 occurred when discharge through the third powerplant was high (> 80 kcfs) and over-whelmed any influence of thermal stratification on circulation at the barge. Epilimnetic and hypolimnetic waters both moved in approximately the same direction and with the same magnitude. The powerplant discharge necessary to achieve Mode 1 may be less when the reservoir is more weakly stratified. However, the exact value was extremely dynamic and difficult to estimate from the data alone.

D.2.1.1   Weak Thermal Stratification Mode 1

Figure D.3 displays water velocity magnitudes and directions between 11:07 and 12:20 on June 4, 2003. At that time, the vertical difference in water temperatures from top to bottom was 2°C. Discharge through the powerplant during the period was greater than 80 kcfs, with peaks above 100 kcfs.

Water velocities were approximately uniform between 0.4 and 0.6 m/s throughout the measured depth. Velocity directions varied somewhat through the water column and over time. However, directions generally were oriented downstream and slightly east (toward the right bank).

D.2.1.2   Strong Thermal Stratification Mode 1

Figure D.4 displays water velocity magnitudes and directions between 10:21 and 12:01 on August 5, 2003. At that time, the vertical difference in water temperatures was estimated to be > 6°C. Discharge through the powerplant was approximately 120 kcfs during the period.

Although water velocity magnitudes and directions were generally similar from top to bottom, there were noticeable differences compared to the weak stratification mode. Most notable were pulses of faster-moving hypolimnetic water that occurred during the period. These increases in hypolimnetic velocities were noted throughout the entire season.

The mid-depth band of more northward-moving water coincided with the location of the thermocline during the period. The thermocline acted as a buffer between the epilimnetic and hypolimnetic waters, and slight differences in direction along the thermocline were common.

D.2.2   Mode 2: Medium Discharge with Vertically Nonuniform Velocity

This mode occurred when discharge through the third powerplant was moderate (approximately 60 kcfs). In this mode, momentum generated by discharge through the powerplant was not sufficient to overcome the buoyant stratification force. Hence, the area monitored under the barge behaved as a two-layer system, with large differences in both magnitude and direction between the epilimnetic and hypolimnetic waters.
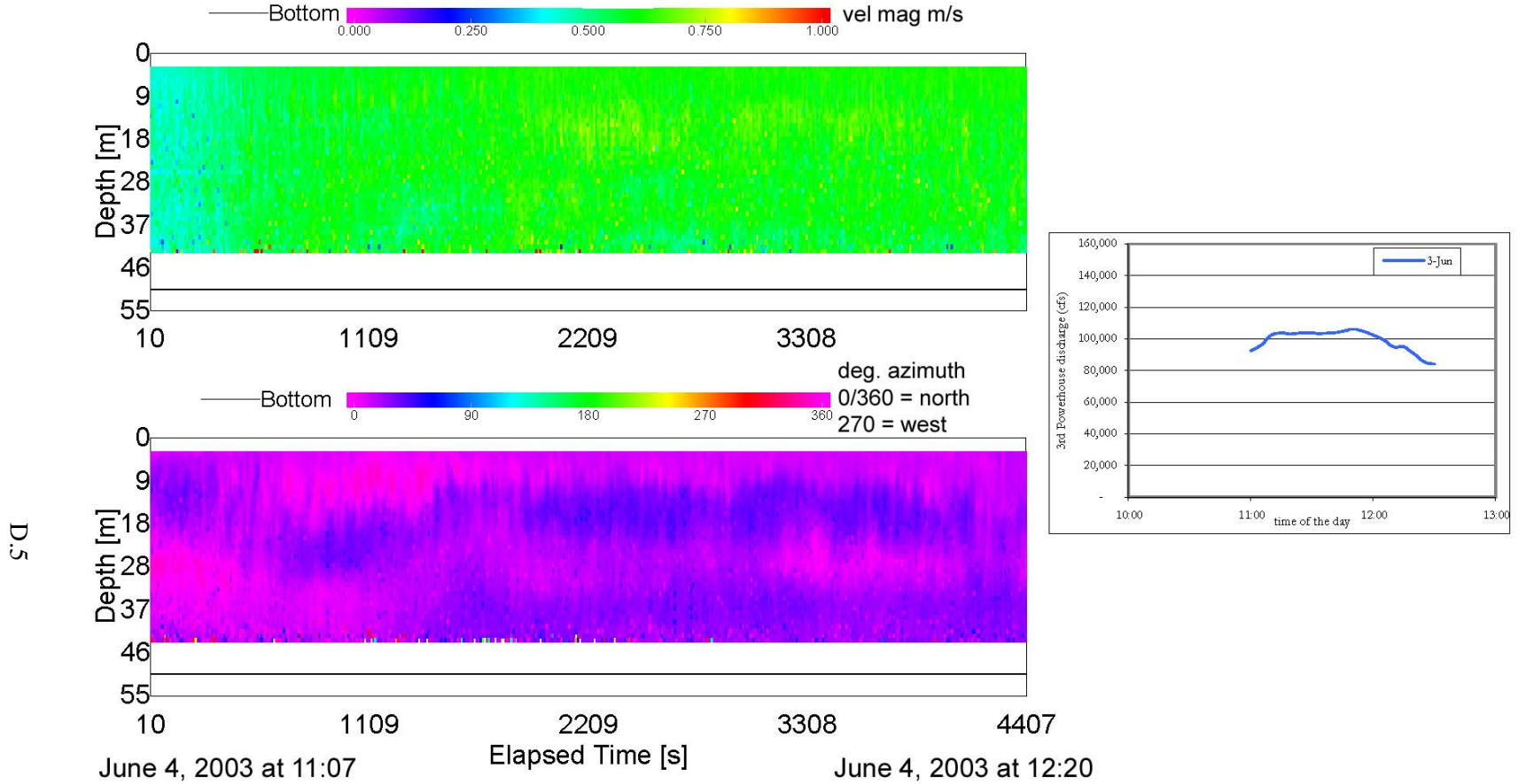
Figure D.3. Circulation Pattern Near the Barge at the Entrance to the Third Powerplant Forebay at Grand Coulee Dam Occurring When Discharge Was High (>80 kcfs) (Mode 1)) and Thermal Stratification Was Weak (2°C). Top left figure shows the velocity magnitude with depth and time; bottom left, the direction of flow with depth and time; and the figure to the right, the discharge levels through the third powerplant.
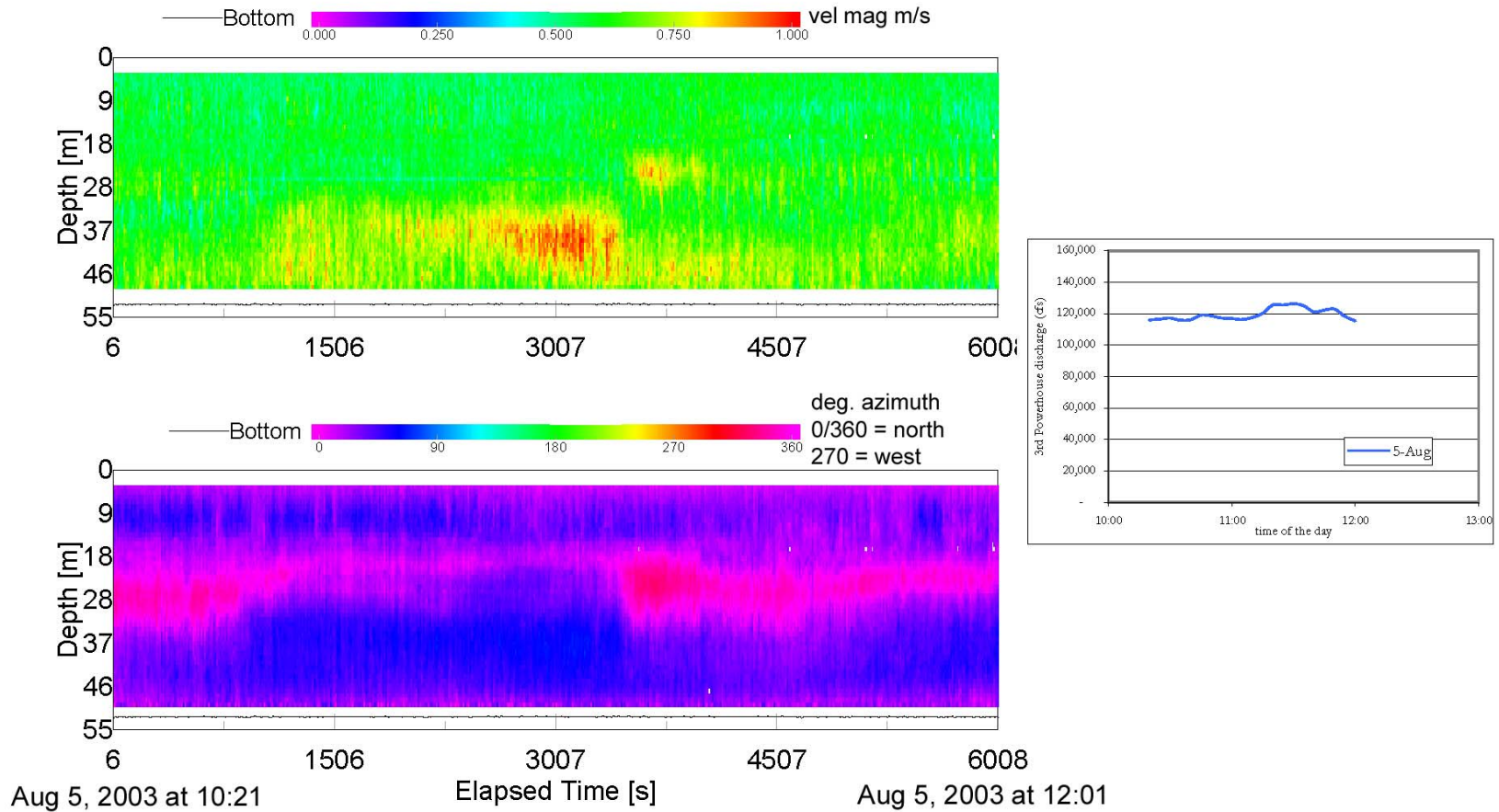
Figure D.4. **Circulation Pattern Near the Barge at the Entrance to the Third Powerplant Forebay at Grand Coulee Dam Occurring When Discharge Was High (>80 kcfs) (Mode 1) and Thermal Stratification Was Strong (>6°C). Top left figure shows the velocity magnitude with depth and time; bottom left, the direction of flow with depth and time; and the figure to the right, the discharge levels through the third powerplant.**

D.2.2.1   Weak Thermal Stratification Mode 2

This mode was not observed during the study period. The reason may be related to the way the third powerplant was operated during the early part of June, when thermal stratification was weak. During this period, discharge was either high or low (Figure D.5). If this mode does exist under weak stratification conditions, the discharge would be expected to be less than when the reservoir is strongly stratified— roughly 40 to 80 kcfs.

D.2.2.2   Strong Thermal Stratification Mode 2

Figure D.6 displays water velocity magnitudes and directions between 15:26 and 18:29 on August 3. At that time, the vertical difference in water temperatures was 6°C and discharge through the powerplant was between 40 and 60 kcfs.

Under this set of conditions, water flow in the epilimnetic and hypolimnetic layers had very different magnitudes, although directionally they were quite similar. Velocities in the upper epilimnetic layers were nearly quiescent, although not zero, and flowed predominantly north and slightly east. While the hypolimnetic water flowed in approximately the same direction, velocities were much greater, reaching peaks above 0.6 m/s. The thermocline that separated the two layers is clearly visible in both the magnitude and direction subplots (Figure D.6).

D.2.3   Mode 3: Low to Zero Discharge

Mode 3 circulation patterns occurred when discharge through the third powerplant was low (i.e., <40 kcfs) to zero. Because of the low discharge, weaker driving forces appear to be influencing water currents near the barge. A force such as wind at the water's surface can affect water velocities in the epilimnion. Further, under strongly stratified conditions, seiching of the thermocline can occur, causing internal waves to propagate through the reservoir, influencing flows near the barge. In general, this mode is the hardest to characterize because flow directions are chaotic. However, the discharge levels associated with this mode are easily specified (generally 20 kcfs when the water column is weakly stratified and 40 kcfs when it is strongly stratified).

D.2.3.1   Weak Thermal Stratification Mode 3

To illustrate this mode under weak stratification, water velocities for the night of June 3 to 4 are displayed (Figure D.7). The graphic begins at 22:31 on June 3 when the water column was not yet in Mode 3. The differences in epilimnetic and hypolimnetic water velocity magnitudes at this time were indicative of Mode 2 circulation patterns. However, the data are inconclusive. At 00:25 on June 4, the discharge levels fell to 20 kcfs. Almost immediately, the epilimnetic waters changed direction by almost 180 degrees to southerly. This reversal in epilimnetic waters continued for the next 6 hr, with a second surface layer forming around 02:00; it was traveling northward when the discharge fell to zero.

Hypolimnetic water continued in a structured northward direction until the discharge fell completely to zero. The direction of the water mass then became more chaotic, with rapid changes in velocity happening over short periods. Velocity magnitudes were quite small during the entire chaotic period.
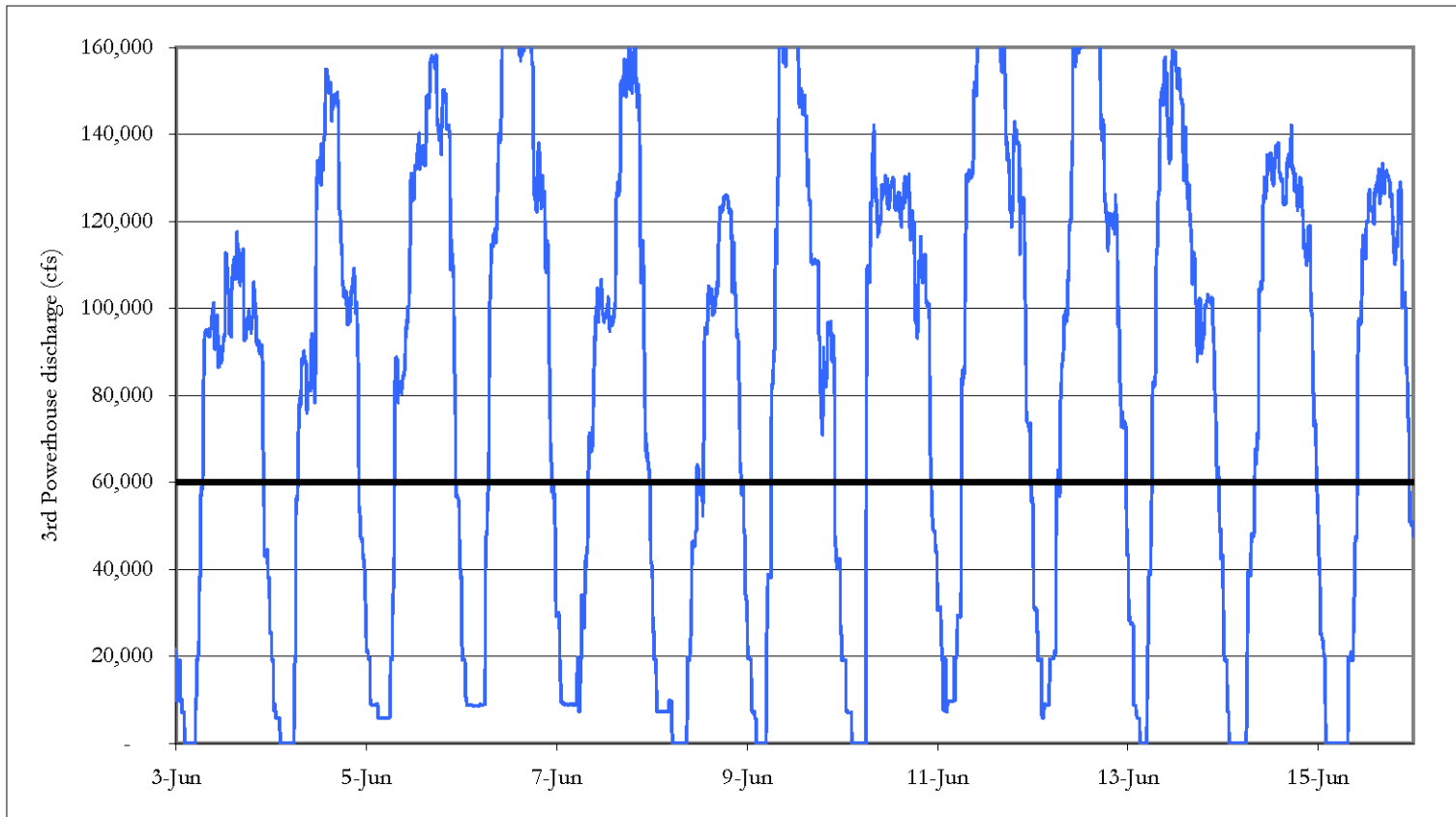
Figure D.5. Discharge Through the Third Powerplant of Grand Coulee Dam Between June 3 and 15, 2003. The line at 60 kcfs is an estimate of the discharge necessary to generate a Mode 2 circulation pattern when thermal stratification is weak. During 2003, discharges were either above or below this threshold.
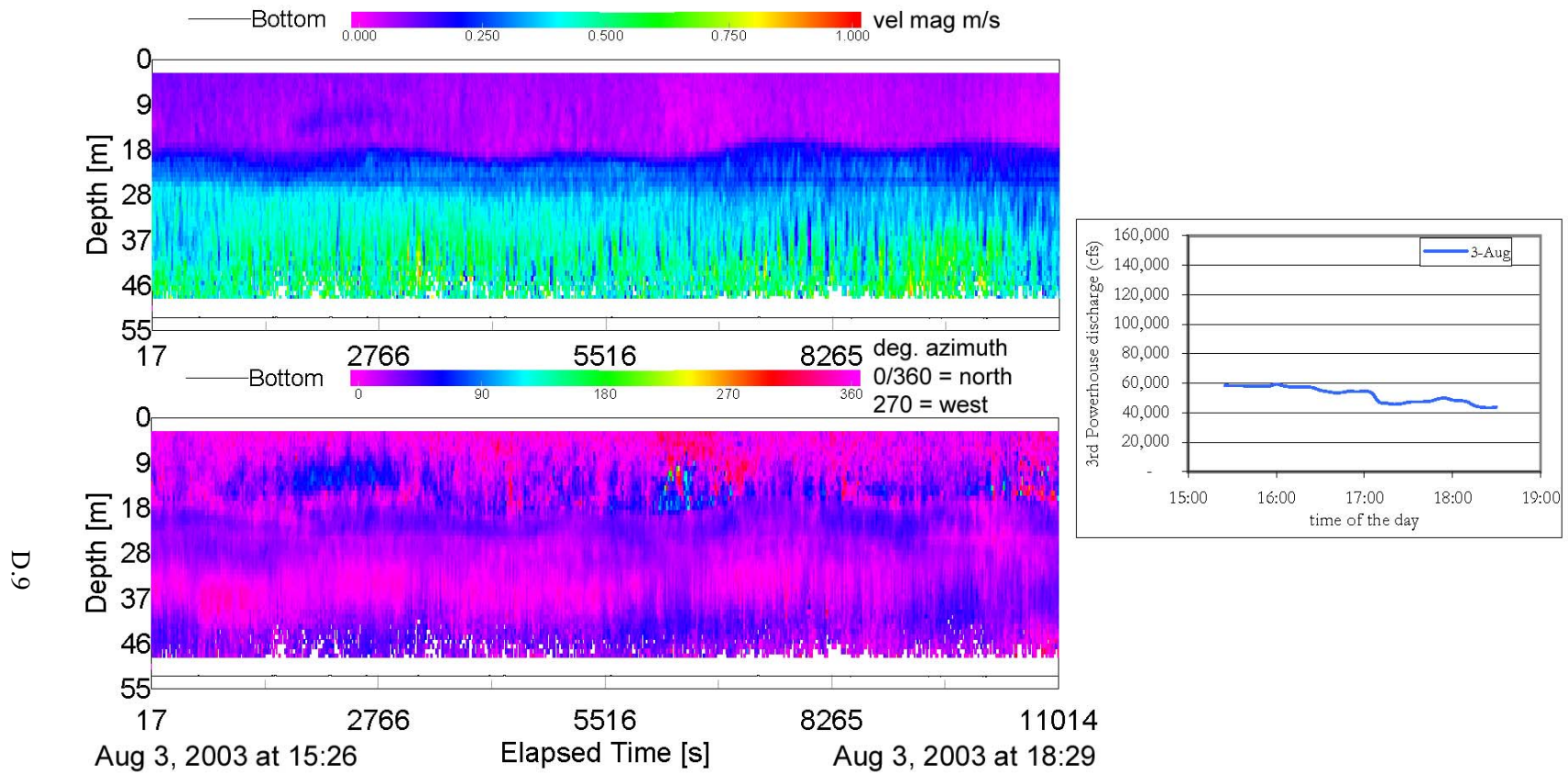
Figure D.6. **Circulation Pattern Near the Barge at the Entrance to the Third Powerplant Forebay at Grand Coulee Dam Occurring When Discharge Was Moderate (40 to 80 kcfs) (Mode 2) and Thermal Stratification Was Strong (>6°C). Top left figure shows the velocity magnitude with depth and time; bottom left, the direction of flow with depth and time; and the figure to the right, the discharge levels through the third powerplant.**
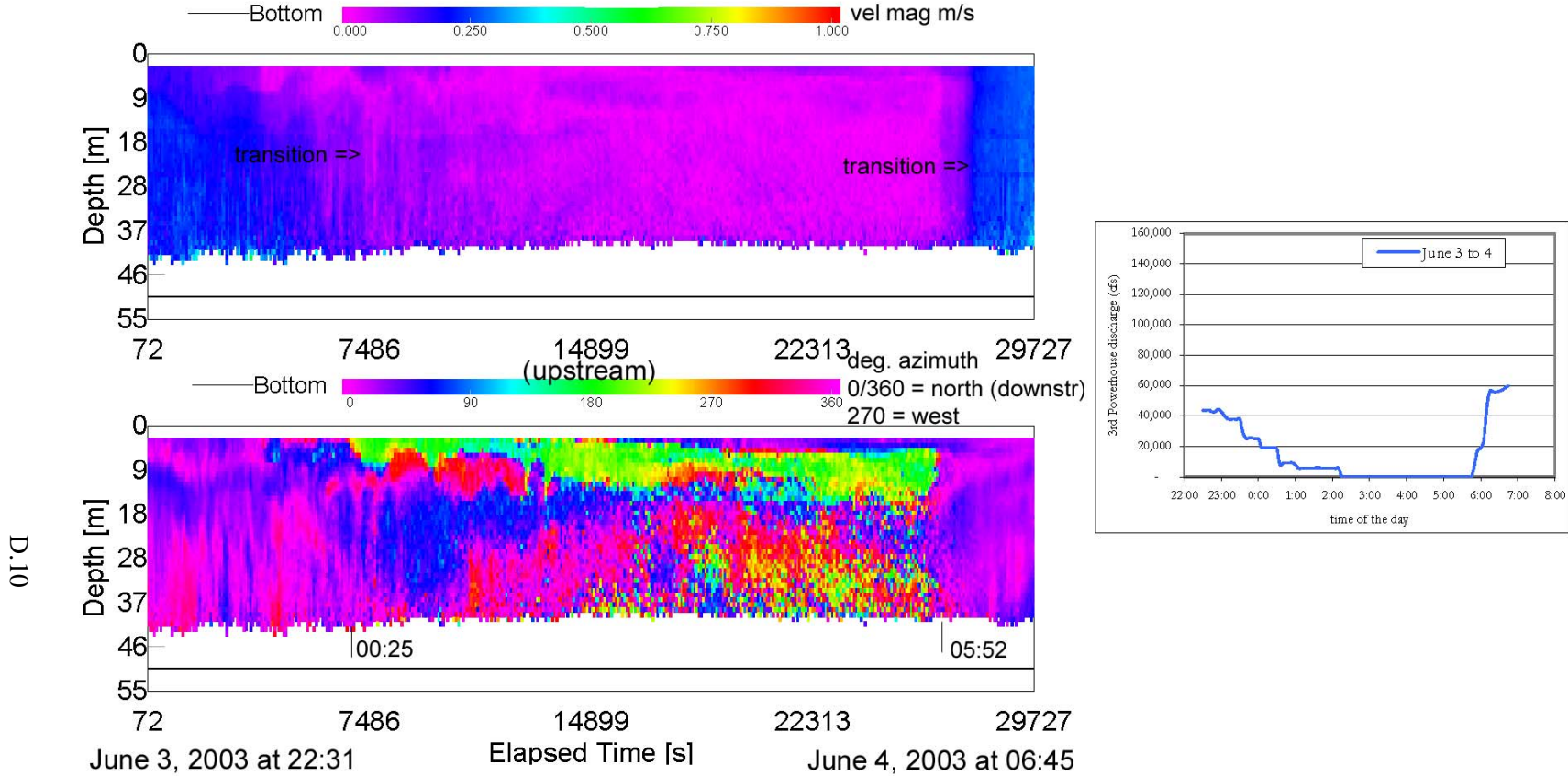
Figure D.7. Circulation Pattern Near the Barge at the Entrance to the Third Powerplant Forebay at Grand Coulee Dam Occurring When Discharge Was Low (<40 kcfs) (Mode 3) and Thermal Stratification Was Weak (2°C). Top left figure shows the velocity magnitude with depth and time; bottom left, the direction of flow with depth and time; and the figure to the right, the discharge levels through the third powerplant.

The mode 3 circulation pattern ended abruptly when the powerplant discharge rose after 06:00. The water column responded almost immediately and appeared to transition quickly to Mode 1.

D.2.3.2   Strong Thermal Stratification Mode 3

Figure D.8 displays another long time series of data collected during the night of August 5. Thermocline depth was between 18 and 24 m and is clearly visible in the velocity direction plot.

At the beginning of the time series, the water column was in Mode 2, with sharp magnitude differences between the epilimnetic and hypolimnetic waters. At 21:55, the flow direction of the surface water changed from northerly to south, corresponding to a decrease in powerplant discharge to below 40 kcfs. Water velocity directions were chaotic throughout the rest of the time series as discharge levels declined to below 20 kcfs.

Velocities in the hypolimnetic declined over time, following the powerplant discharge levels. When discharge fell below 20 kcfs, hypolimnetic directions became more random, and the variability increased dramatically. As noted earlier, these changes probably are due to weak forcing functions, such as wind-forced seiche and other internal waves.

D.3   Mobile ADCP Surveys

Mobile surveys to characterize the hydrodynamics of the forebay occurred on August 6 and 7, 2003. In addition to the ADCP, a Hydrolab-Hach Company (Loveland, Colorado) MiniSonde® 4a multiprobe was used to take vertical profiles of water temperature at each measurement location.

D.3.1   Thermal Stratification During Mobile Collection

Vertical profiles of water temperature were acquired at the locations shown in Figure D.9. At each location, the MiniSonde was lowered and raised slowly through the water column. Lowering and raising the instrument created two, somewhat distinct, temperature profiles at each location (Figure D.9). The difference between the lowering and raising profile can be attributed to one of two factors: 1) actual dynamic fluctuation in the water temperature during the sampling period (about 10 min) or 2) latency in the response time of the thermistor. The sample locations have been numbered in the order collected; for brevity, not all profiles are shown in Figure D.9 (excluded points were virtually identical to Points 1, 2, and 6 through 18).

Water temperatures were measured at various times of the day (between 15:00 and 19:00 on August 6 and between 10:00 and 19:00 on August 7) and, consequently, under various flow conditions throughout the two-day period. Although flows through the powerplant changed dramatically, the general thermal structure of the forebay remained constant between all sample locations. The general thermal structure of the forebay can be characterized as stratified, with a thermocline present at approximately 24 m. Above the thermocline, water temperatures ranged from 18°C to 25°C. Beneath the thermocline, hypolimnetic waters were relatively uniform between 17°C and 20°C.
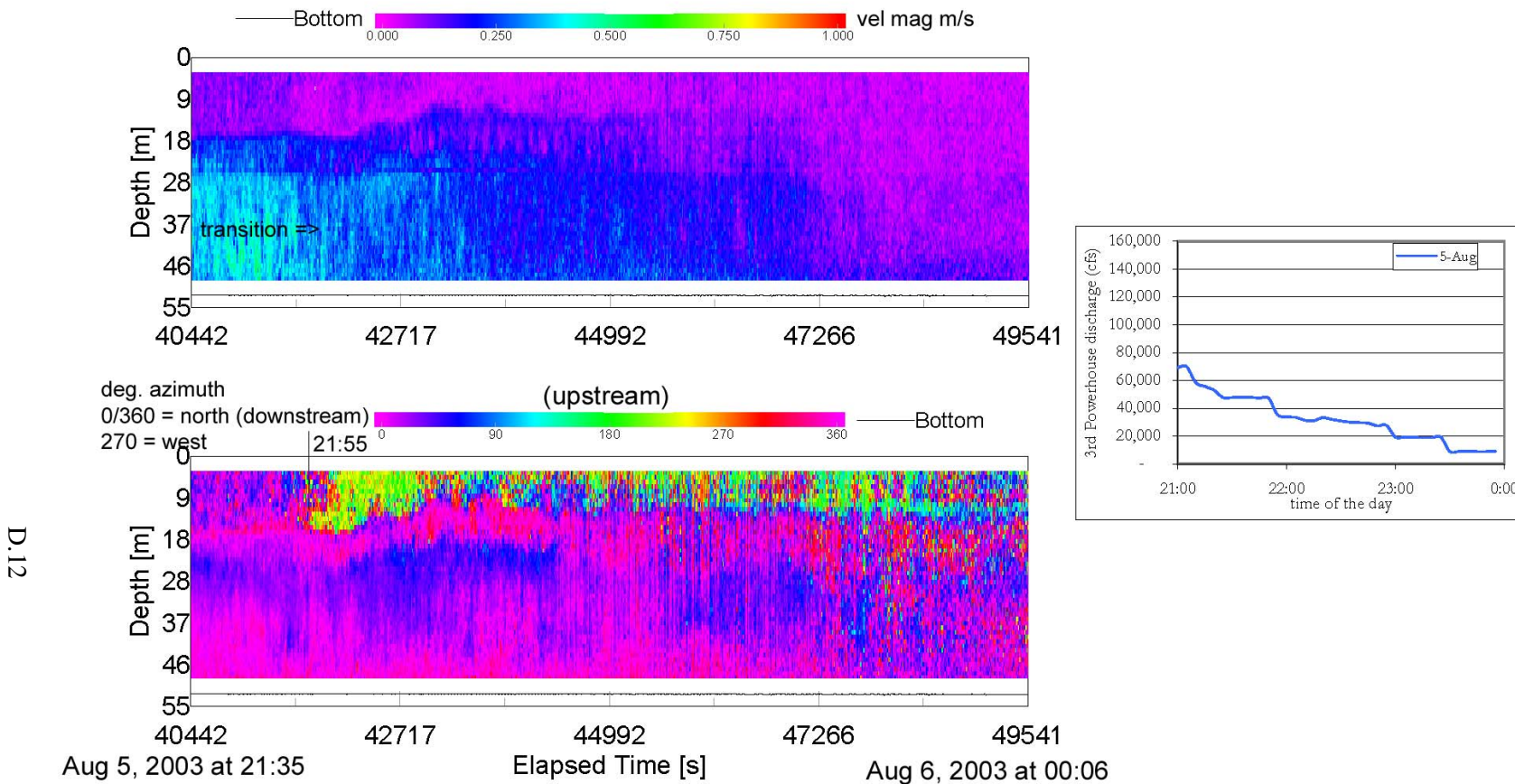
Figure D.8. **Circulation Pattern Near the Barge at the Entrance to the Third Powerplant Forebay at Grand Coulee Dam Occurring When Discharge Was Low (<40 kcfs) (Mode 3) and Thermal Stratification Was Strong (>6°C). Top left figure shows the velocity magnitude with depth and time; bottom left, the direction of flow with depth and time; and the figure to the right, the discharge levels through the third powerplant.`**
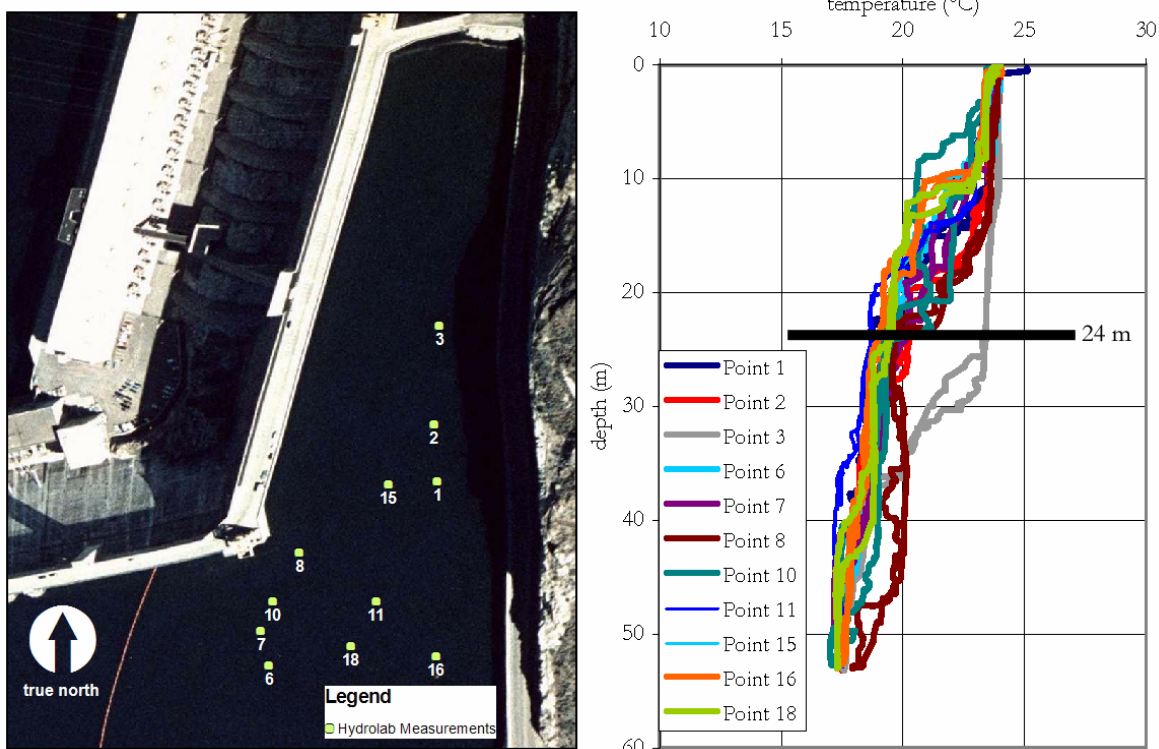
Figure D.9.   Water Temperature Measurements Taken Between August 6 and 7, 2003, in the Forebay of the Third Powerplant at Grand Coulee Dam. Locations of water temperature profile measurements are displayed in the left-hand side of the figure. The corresponding data are displayed in the right-hand side. The approximate location of the thermocline for all sites except location 3 was at 24 m.

Water temperatures at location 3 (acquired between 16:16 and 16:28 on August 6) (Figure D.9) were somewhat anomalous, with more uniform and warmer epilimnetic temperatures occurring with depth and a thermocline deeper than the other locations. As described in Section D.3.2, these changes in the vertical thermal structure have a water velocity analog, with a shear layer generally deeper than at other locations (see velocities in front of Unit 20, Figure D.12).

D.3.2   Powerplant Operations During Mobile Water Velocity Survey

Because the mobile water velocity survey was performed immediately following the hydroacoustic study, powerplant operations for that time period are included in this section. Figure D.10 shows discharges for just the third powerplant. Powerplant operations followed a similar pattern both days, with high discharges during daylight hours, dropping to nearly zero for several hours during the night.

D.3.3   Mobile ADCP Transects

To gather relatively large-scale snapshots of flow conditions within the third powerplant forebay, ADCP measurement were taken on transects along the centerline and entrance to the forebay. The spatial
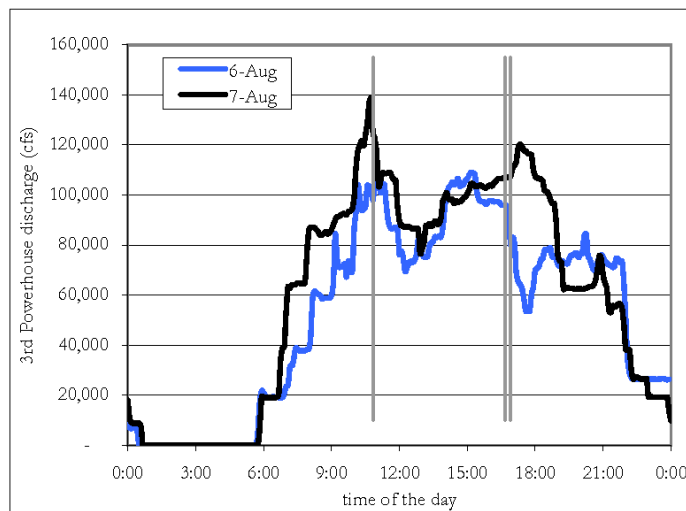
Figure D.10. Discharge Through the Third Powerplant at Grand Coulee Dam During the Mobile Hydrodynamic Characterization Survey on August 6 and 7, 2003. The gray vertical lines indicate the approximate times of the ADCP transects shown in Figure D.11. All mobile ADCP and water temperature surveys were between 10:00 and 19:00 when the powerplant discharge was above 80 kcfs.

length and time to collect data for each transect varied, although collection times generally were less than 20 min. A total of seven transects were completed (Figure D.11). To understand the complex hydrodynamic of the forebay, data from three transects are presented in detail.

Data along the first transect were collected at 16:48 on August 6. Discharge through the third powerplant was 95.7 kcfs (see Figure D.10). The discharge by unit is shown in Figure D.12. Gray vertical lines indicate the location of each penstock opening (i.e., units 19 to 24). This transect was along the centerline of the forebay and was away from the localized effects at each penstock opening. The right side of the contour plot corresponds to the most downstream end of the forebay (the end of the cul-de-sac). A shear line between the upper and lower portions of the water column was evident in the data and was highlighted by a horizontal black line in Figure D.12. Upstream of the barge (left side of Figure D.12), the shear line was less pronounced and harder to distinguish and is represented by a dashed line.

Water temperature measurements (Figure D.9) confirm that the location of the shear line corresponded to the approximate location of the thermocline, possibly indicating that the reservoir was operating in a two-vertical-layer mode (see Section D.2.2).

At the barge site, velocity magnitudes increased with depth. Directions also changed with depth, going from predominantly north in the epilimnion to predominantly northeast in the hypolimnion. Downstream of the barge site, differences in velocity magnitude and direction became more pronounced. At the most downstream end of the cul-de-sac, velocities in the epilimnion were almost zero, and the directional structure was reasonable.
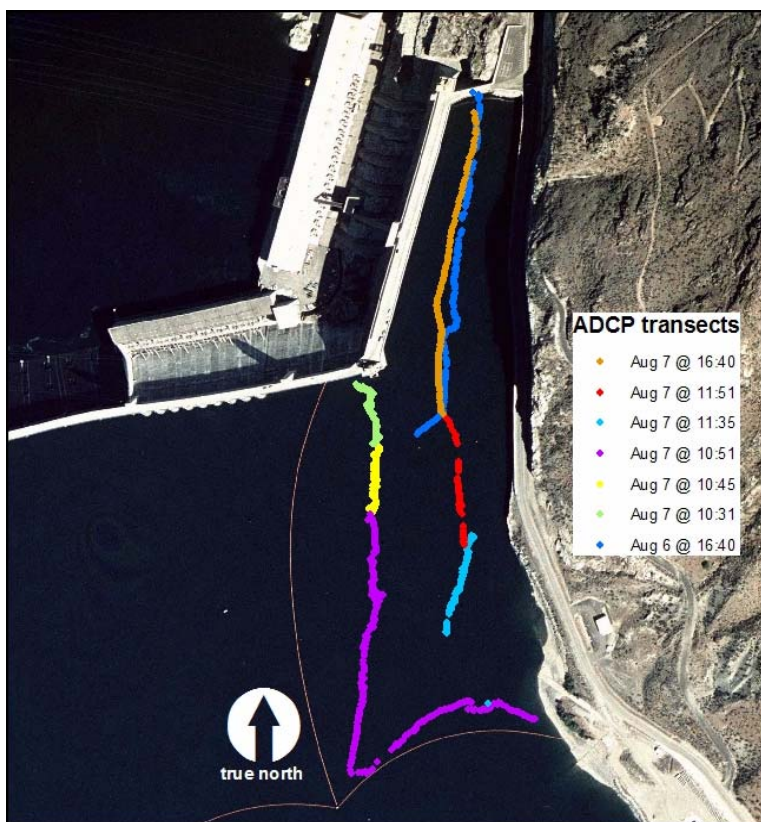
Figure D.11. Location of Mobile ADCP Transects

Velocity data along the second transect were collected approximately 24 hr after the first, at 16:40 on August 7. Discharge through the third powerplant was 11% higher than for the first transect (107.1 kcfs, Figure D.10). The same units were operating as before, except at a higher output (see Figure D.13). Water temperature profiles for both days indicate the thermal structure of the reservoir was approximately constant.

Although the shear layer was again present in the second transect, it was much less pronounced upstream of Unit 19 (Figure D.13). At the barge, there were only small differences in hypolimnetic and epilimnetic water velocities and directions (see Section D.2.1). This indicates that epilimnetic velocity vectors at the barge location may be highly sensitive to small changes in powerplant withdrawals (Sections D.2.1 and D.2.2).

ADCP measurements along the third transect were collected at 10:50 on August 7. This long transect measured water velocity inside the log boom (the boom was in a location slightly different from that shown in Figure D.11). The boat turned toward shore after traveling 340 m, again following the log boom.

Magnitudes along the entire transect were relatively small and uniform, even though the discharge through the third powerplant was the highest for the entire two-day period (125 kcfs, see Figure D.10). A
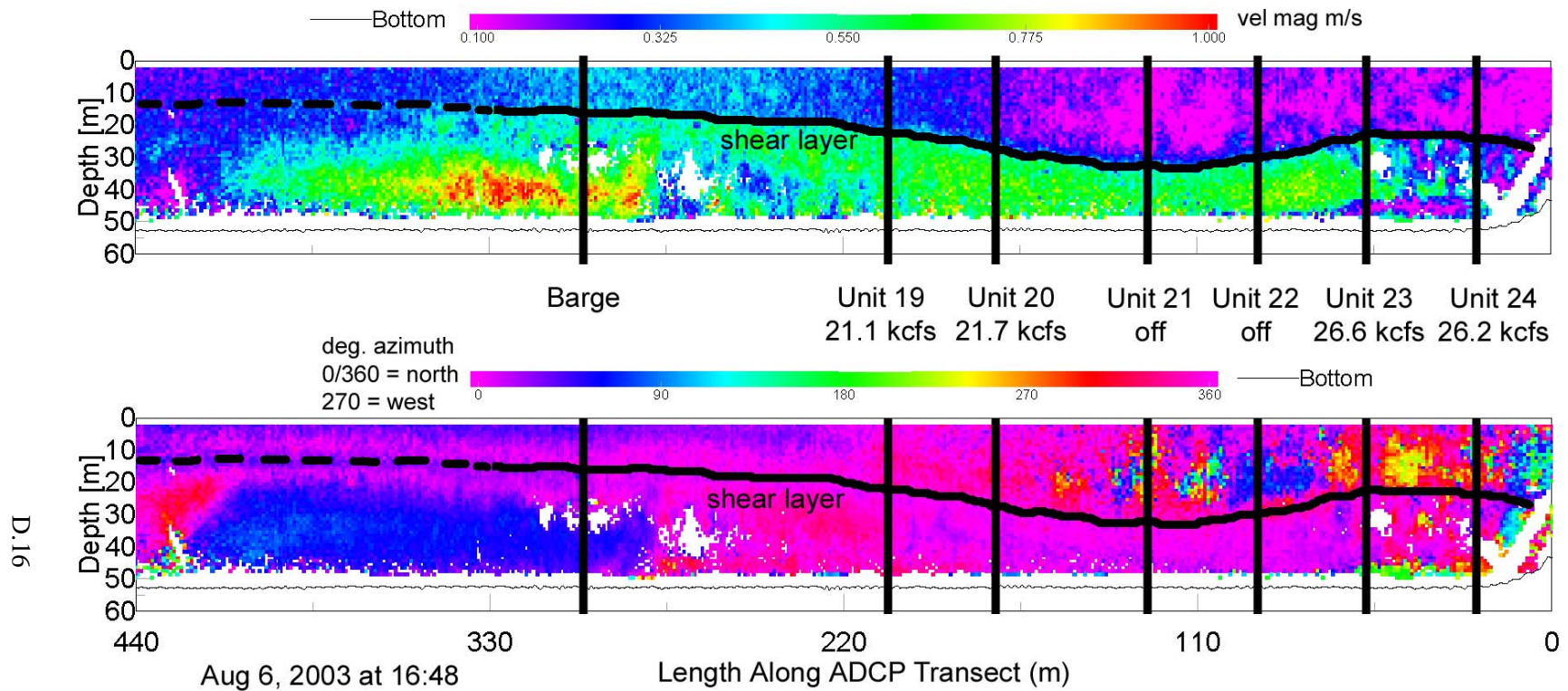
Figure D.12. Water Velocity Magnitude (top), Direction (lower) Collected on August 6, 2002, at 16:48 in the Forebay of the Third Powerplant at Grand Coulee Dam. In the plots, upstream is to the left, downstream to the right. The transect was along the centerline of the forebay (left). The directions in the lower graph are in an earth-referenced coordinate system (middle). Locations of turbine units 19 through 24 are indicated by vertical lines.
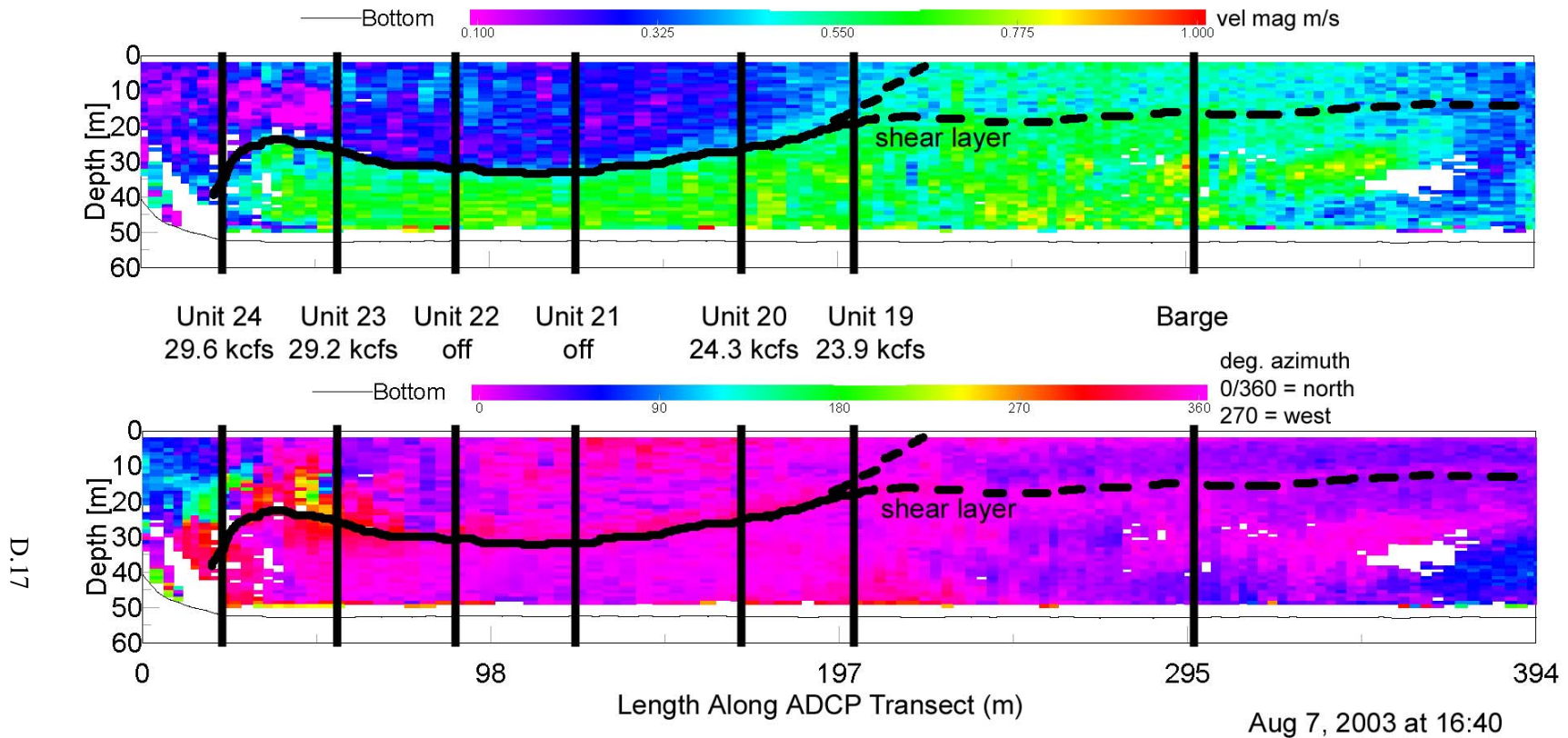
Figure D.13. Water Velocity Magnitude (top), Direction (lower) Collected on August 7, 2002, at 16:40 in the Forebay of the Third Powerplant at Grand Coulee Dam. In the plots, upstream is to the right, downstream to the left. The transect was along the centerline of the forebay (left). The directions in the lower graph are in an earth-referenced coordinate system (middle). Locations of turbine units 19 through 24 are indicated by vertical lines.

shear line separating hypolimnetic and epilimnetic waters was evident in the velocity direction subplot around 20 m; however, it was relatively weak and existed along only the first half of the transect (i.e., before the boat turned toward shore) (Figure D.14). Velocities along the transects outside the cul-de-sac were similar and generally characterized by low water velocities. This is evident also in the first two transects (Figures D.12 and D.13).

D.3.4 Mobile Point ADCP Measurements

ADCP point measurements also were obtained within the forebay. For these measurements, the boat was held in place for over 10 min. By taking measurements over a longer period, both the mean and standard deviations of the velocity vector were calculated. Data were collected at more than 20 points, shown in Figure D.15, during the two-day period August 6 through 7. Each point has been labeled by an arrow scaled by velocity magnitude and oriented in the direction of water flow. Velocity measurements at 5 m and 20 m (both levels above the thermocline) depth are shown on Figure D.15, although at many locations both arrows are coincident.

Because discharge changed dramatically throughout the two-day sampling period, care must be taken not to directly compare the magnitudes of velocity vectors shown in Figure D.15. The discharges corresponding to the labeled arrows in Figure D.15 are displayed in Figure D.16 (inset table).

Mean velocity magnitude and direction data sets associated with several of the labeled points are presented in Figure D.16. Data from Points 10 through 13 were collected as a set in rapid succession along the barge. Point 10 was located at the most upstream point of the aluminum frame (Figure 3.3), and Point 13 was near where the ADCP was deployed. Mean magnitude and velocity variations between the sites were quite small, except for small deviations below 35 m. It is interesting to note that the increase/ decrease in magnitude between these four points exactly follow the rise and fall in discharge from the third powerplant. This may indicate the close linkage and rapid response time of the cul-de-sac to operational changes. Also, at Point 0, water velocities had similar magnitudes and directions in the upper portion of the water column; however, directional differences existed below 30 m. Finally, Points 17 and 18 were collected 2 to 3 hr later than Point 13, when discharge through the powerplant was greater. Although discharges were greater, water velocities at depths below 35 m declined while epilimnetic velocities increased, resulting in an almost homogeneous vertical velocity distribution. These changes are indicative of the complex three-dimensional nature of the hydrodynamics of the cul-de-sac and the expected response of this two-layered stratified system to powerplant withdrawals.

D.4 Hydrodynamic Characterization Summary

The purpose of this appendix is to document the characterization of the hydrodynamic motions of the forebay of the third powerplant at Grand Coulee Dam between June and August 2003. Several instruments were employed for this characterization, including self-contained temperature loggers, a portable temperature probe, and a 600-kHz broadband ADCP.

Data collected by these instruments hint at the complexity of this system. Although the primary force behind water motions at the barge was due to operations of the third powerplant, other factors such as stratification appear to play a role in determining water velocities in front of the strobe lights.
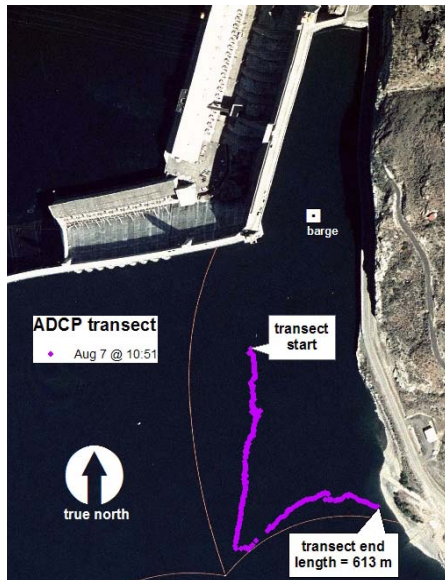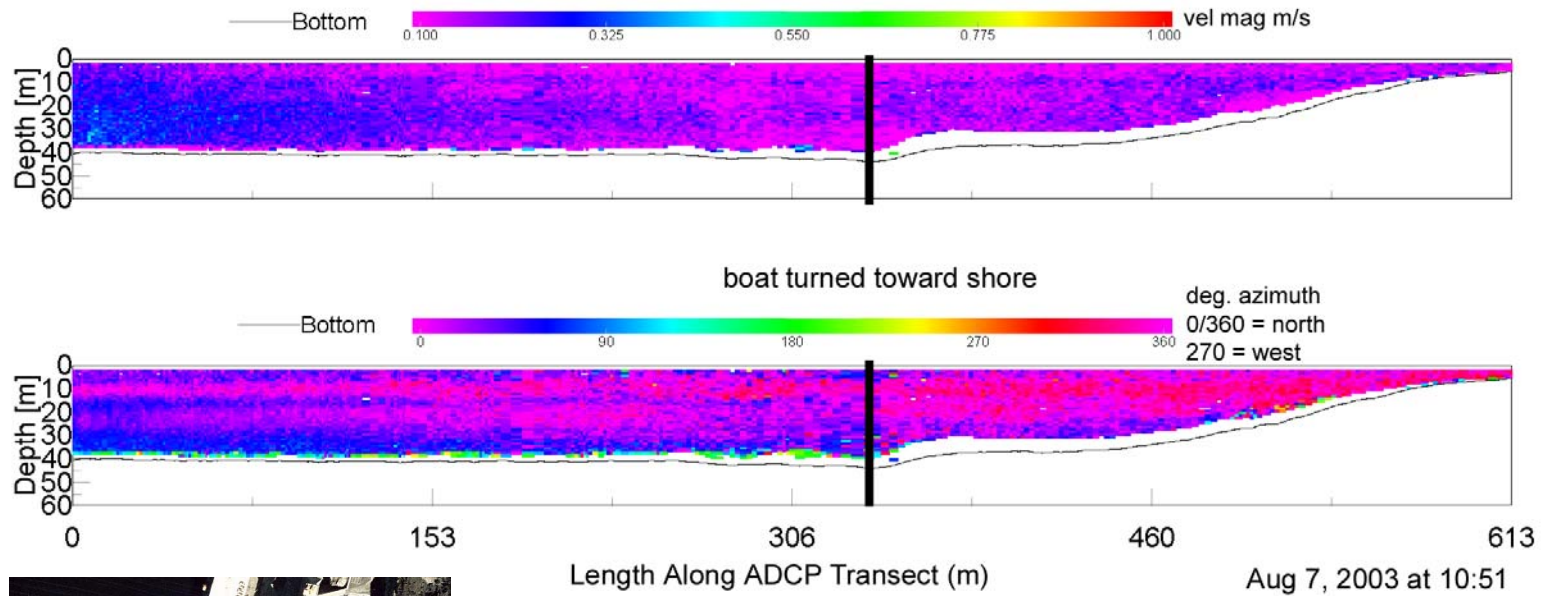
Figure D.14. Water Velocity Magnitude (top), Direction (lower) Collected on August 7, 2002, at 10:51 Along the Log Boom Around the Entrance to the Forebay of the Third Powerplant at Grand Coulee Dam. In the plots, downstream is to the left, upstream to the right. The transect followed the log boom (left). The directions in the lower graph are in an earth-referenced coordinate system (middle). The vertical line indicates where the transect turned toward the right bank.
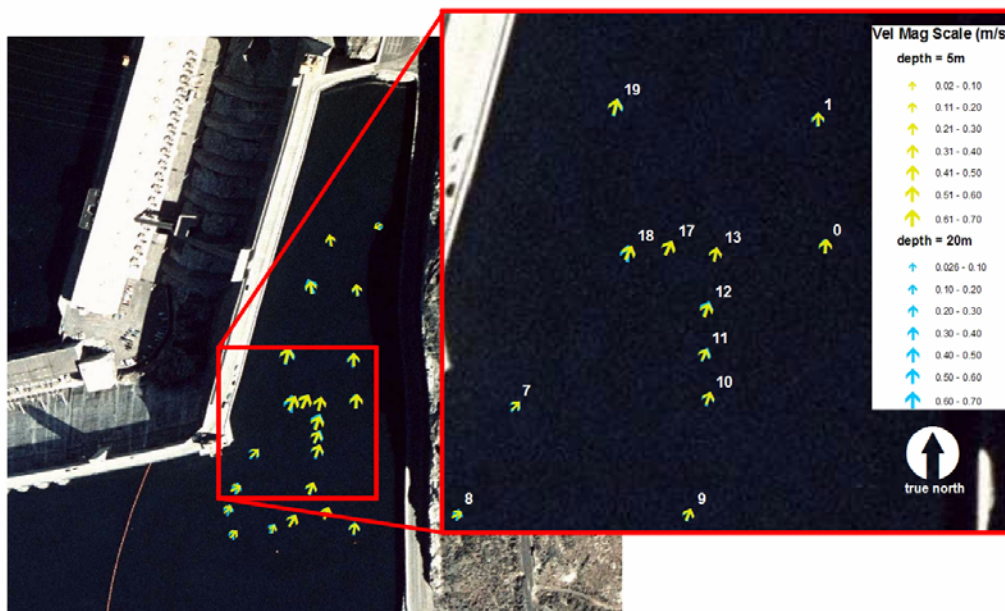
Figure D.15. Mobile Point Water Velocity Measurement Locations in the Forebay to the Third Powerplant at Grand Coulee Dam on August 6 and 7, 2003. The inset displays a zoomed-in view of velocity vectors near the barge. Points have been labeled in the order in which they were collected. Velocities at 5 and 20 m are plotted; however, velocities were generally the same at the two depths.

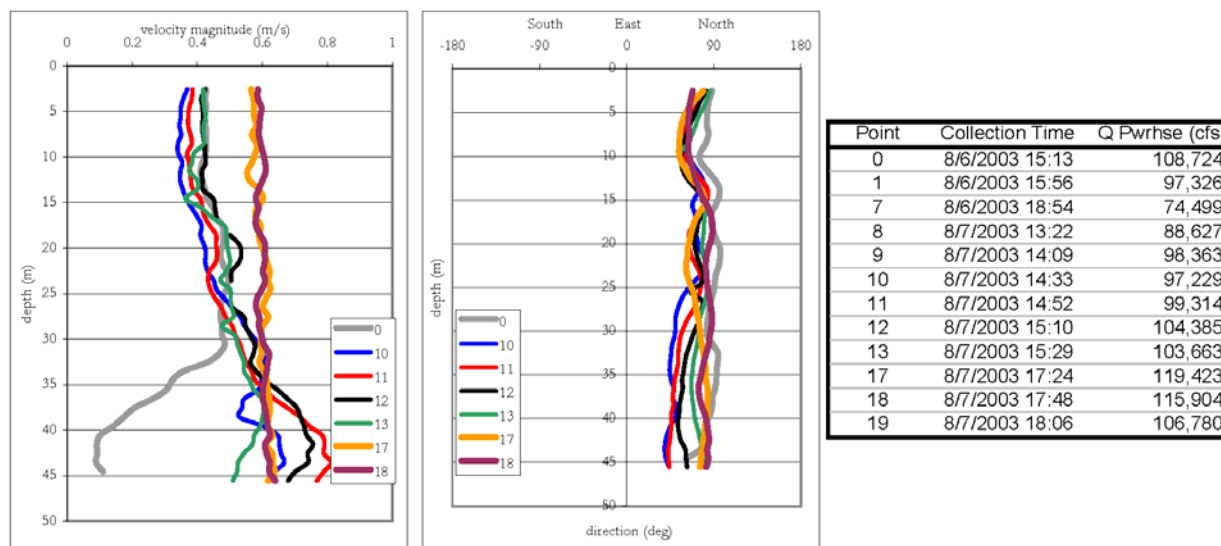| Point	Collection Time	Q Pwrhse (cfs)
0	8/6/2003 15:13	108,724
1	8/6/2003 15:56	97,326
7	8/6/2003 18:54	74,499
8	8/7/2003 13:22	88,627
9	8/7/2003 14:09	98,363
10	8/7/2003 14:33	97,229
11	8/7/2003 14:52	99,314
12	8/7/2003 15:10	104,385
13	8/7/2003 15:29	103,663
17	8/7/2003 17:24	119,423
18	8/7/2003 17:48	115,904
19	8/7/2003 18:06	106,780

Figure D.16. Water Velocity Magnitudes and Direction With Depth for Some of the Point ADCP Measurements. Discharge and collection times are tabulated for all labeled points in Figure D.15.

Several observations can be made regarding circulation during this period:

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

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

- **Velocities along the aluminum frame were approximately uniform.** Profiles of water velocities were developed for points along the aluminum frame from which the splitbeam transducers were deployed. The underlying data were collected when the water column was in Mode 2 (larger hypolimnetic water velocities). Epilimnetic magnitudes and directions were approximately equal at all sites. In addition, slight hypolimnetic magnitude variations appear to be attributable to slight powerplant discharge operations during the discrete period necessary to collect these data (approximately 1 hr). Based upon these measurements, application of ADCP velocity measurements to all hydroacoustic fish detection units on the truss is a reasonable assumption.

D.5   Reference

U.S. Geological Survey. 2003. "On-line Calculations." Available at http://intermagnetusa.org/geomag/geomagAWT.html (25 November 2003).

Appendix E

Acoustic Tag Tracking

Appendix E

Acoustic Tag Tracking

The kokanee salmon fishery in Lake Roosevelt is important for many reasons including its cultural and sport fishing value. For years the native fishery has been enhanced by stocking of juvenile kokanee. However, many of these fish, stocked or native, are being entrained past Grand Coulee Dam and lost to the fishery (LeCaire 1999; Sullivan 2000). In 2001, a study was initiated to determine if entrainment could be reduced by placing strobe lights in the forebay of the dam (see Section 1 of this report for further details about this project). Part of this study involved tracking juvenile kokanee salmon that had been implanted with ultrasonic transmitters. These transmitters allow fish to be tracked as they approach the dam, are exposed to the strobe lights, and are entrained. The transmitters also allow the fish to be tracked below the dam, which provides an indication of the number of fish entrained past the dam and where the entrainment occurred.

This task had three objectives. The first was to determine the elapsed time between when fish were released near the dam and their entrance to and exit from the third powerplant forebay. The second was to study the behavior of fish within 30 m of the strobe lights. The final objective was to determine the number of fish entrained through the third powerplant and through the dam in general. This appendix describes the details of the acoustic tag tracking task of the overall study.

E.1   Methods

E.1.1   Fish Tagging and Releases

Juvenile kokanee salmon (*Oncorhynchus nerka*) were acquired from the Colville Tribal hatchery program sited on Lake Rufus Woods. In late May 2003, net pens filled with juvenile salmon were transported from their winter location at the Old Lincoln Sawmill site, approximately 64 km (40 m) upstream of the dam, downstream to the forebay of the dam. One day before juvenile kokanee were surgically implanted with tags, they were moved from the large net pen to separate, smaller floating net pens.

Between June 3 and 6, 2003, each fish was surgically implanted with an ultrasonic transmitter (Model 795a, Hydroacoustic Technology Inc., Seattle, Washington). Transmitters had a weight of 1.0 g in air. The transmitters were 6.8 mm in diameter and 15 mm in length. Ultrasonic transmitters emitted a pulse every 2 to 3 seconds with a frequency-modulated pulse width of 2 ms. With these parameters, it was expected that a tag's battery life would be 10 to 12 days.

Each fish was anaesthetized with tricaine methanesulfonate (MS-222, 70 mg L^{-1}). Fork lengths (to the nearest millimeter) and weights (in grams) were measured while fish were immobile. After a fish was anaesthetized, it was placed ventral side up in a groove within a piece of wet foam rubber saturated with a solution of PolyAqua® (Kordon Quality Aquarium Products). A small tube inserted in the fish's mouth during surgery provided a continuous solution of 20 mg L^{-1} MS-222. A 5- to 10-mm incision was made

3 mm from the midventral line, anterior to either of the pelvic fins. Incisions were closed with two or three simple, interrupted sutures (Ethicon absorbable 5-0 coated vicryl violet braided). After surgery, fish were held in aerated coolers while they recovered. After recovering for several hours, fish were transported back to net pens in the reservoir and held for approximately 24 hours prior to release. Immediately prior to releasing the tagged fish, researchers checked for an observable avoidance response by casting a shadow on the shallow net pens. This ensured that only responsive fish were released for the study. If a fish was unresponsive—lethargic, sitting on the pen bottom, isolated, or floating ventral-side up—it was removed from the sample and its tag code was recorded.

A total of 198 fish were released upstream of Grand Coulee dam (Figure E.1) in six groups (Table E.1). Half of the groups were released approximately 1 hour after sunset, and the other half were released 1 hour after sunrise.

Figure E.1.   Release Site for Acoustic Tagged Juvenile Kokanee, Grand Coulee Dam, June 2003

Table E.1.   Date, Time, and Sample Data for Acoustic-Tagged Kokanee Released into the Forebay of Grand Coulee Dam in June 2003. Mean and standard deviation are given for fork length and weight.

Date	Time	Number of Fish	Mean Fork Length (mm)	Mean Weight (g)
3-Jun	21:40	26	149 ± 14.6	31 ± 9.8
4-Jun	6:10	36	147 ± 11.2	31 ± 8.0
4-Jun	21:35	40	145 ± 11.0	30 ± 6.5
5-Jun	6:05	36	147 ± 11.6	31 ± 9.7
5-Jun	21:36	26	147 ± 11.1	30 ± 6.8
6-Jun	6:15	34	145 ± 10.0	32 ± 10.0
Overall Total		198	147 ± 10.0	31 ± 8.5

E.1.2   Acoustic Telemetry Systems

All equipment for tagging, receiving tag signals, and processing data were manufactured by Hydroacoustic Technology Inc. (HTI), Seattle, Washington. Signals from fish were received on a three-dimensional acoustic telemetry hydrophone array (Model 290) while they were near and within the third forebay of the dam. This array consisted of eight hydrophones (Figure E.2), three of which were stationed on the bottom of the forebay. Another five were attached to the side of the dam or the rock wall on the right bank of the third powerplant forebay. Signals were received and logged with the Model 290 acoustic tag receiver. The location of all hydrophones was determined through standard surveying techniques using a laser total station manufactured by Topcon Corporation, Tokyo, Japan.

Signals from fish were received also from a separate receiving array (not configured for three-dimensional positioning) downstream of Grand Coulee Dam that was designed to detect fish that passed through the turbines. The array was deployed at a bridge between 0.8 and 1.0 km downstream of the dam (Figure E.1). This array consisted of one hydrophone (Model 594) located approximately 10 m off the left bank of the river and two hydrophones (also Model 594) located approximately 10 m off the right bank of the river. All hydrophones were 20 to 200 m downstream of the bridge (Figure E.1). Signals were received and logged with a Model 291-4 acoustic tag receiver. Two HTI software packages, Mark Tags and Acoustic Tag, were used to analyze fish tracks.

The speed of sound is an important input into the fish-tracking software because the time of arrival is used to solve for a tag's position relative to the position of the hydrophones receiving the tag signals. The speed of sound was estimated using the equations developed by Del Grosso and Mader (1972) for use in fresh water; these equations require data on water temperature. We used the average water-column temperature because the water temperature in the Grand Coulee forebay can vary from the surface of the water to the reservoir bottom. The temperature data were collected every 3 m (10 ft) using individual Onset Optic StowAway® temperature loggers (Onset Computer Corporation, Pocasset, Massachusetts) (Appendix A).
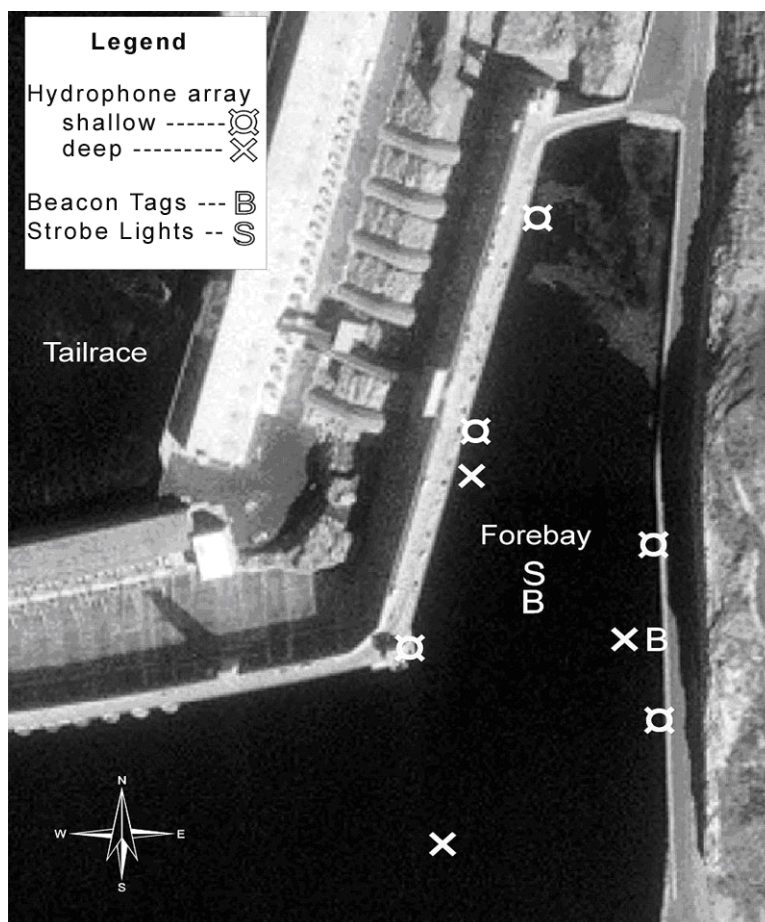
Figure E.2.   **Locations of the Hydrophone Array, Beacon Tags, and the Strobe Light Array near the Third Powerplant Forebay of Grand Coulee Dam, June 2003**

E.1.3 Data Processing

The acoustic tag receivers collected the incoming signals from the hydrophones and stored the data in hourly files. The data from the array near the bridge were examined manually using the HTI tagging software. This allowed us to determine the time at which fish first entered this array.

Data were collected the entire time that tagged fish were in the three-dimensional acoustic array in the forebay of the third powerplant. The first and the last hour of data were analyzed for these fish. These times were chosen for analysis because they were suspected to contain the most relevant information, including the behavior of fish as they approached the strobe light array and the location and timing of the exit from the forebay.

E.1.4 Data Analysis

Positioning errors were determined prior to and during the study using data collected from ultrasonic tags located at known positions. Both the geometric dilution of precision (GDOP) and the vertical

dilution of precision (VDOP) were estimated from the data using the FishTrack3D software (Faber et al. 2002) (Figures E.3 and E.4). GDOP is a combination of the horizontal and vertical error inherent for positioning when using time-of-arrival estimates, and VDOP is the absolute vertical error. These two metrics provide an estimate of the accuracy of fish positions.

Two acoustic transmitters were used to test the accuracy of the reception array. One transmitter was positioned in the center of the array, on the barge deploying the strobe lights (Figure E.2), while the other was situated along the right bank of the forebay. The tag attached to the barge had a standard deviation of 2.6 m in the horizontal plane and 5.5 m in depth. The tag placed near the edge of the forebay (and therefore the edge of the array) had a standard deviation of 6.7 m in the horizontal plane and 11 m in depth.

To determine if the depths at which fish entered the forebay varied by day or night, data were checked for normality and to see if the variances were homogeneous. If data were normal and variances were homogeneous, then data were analyzed using a *t*-test; otherwise, data were analyzed using a Mann-Whitney *U* test.
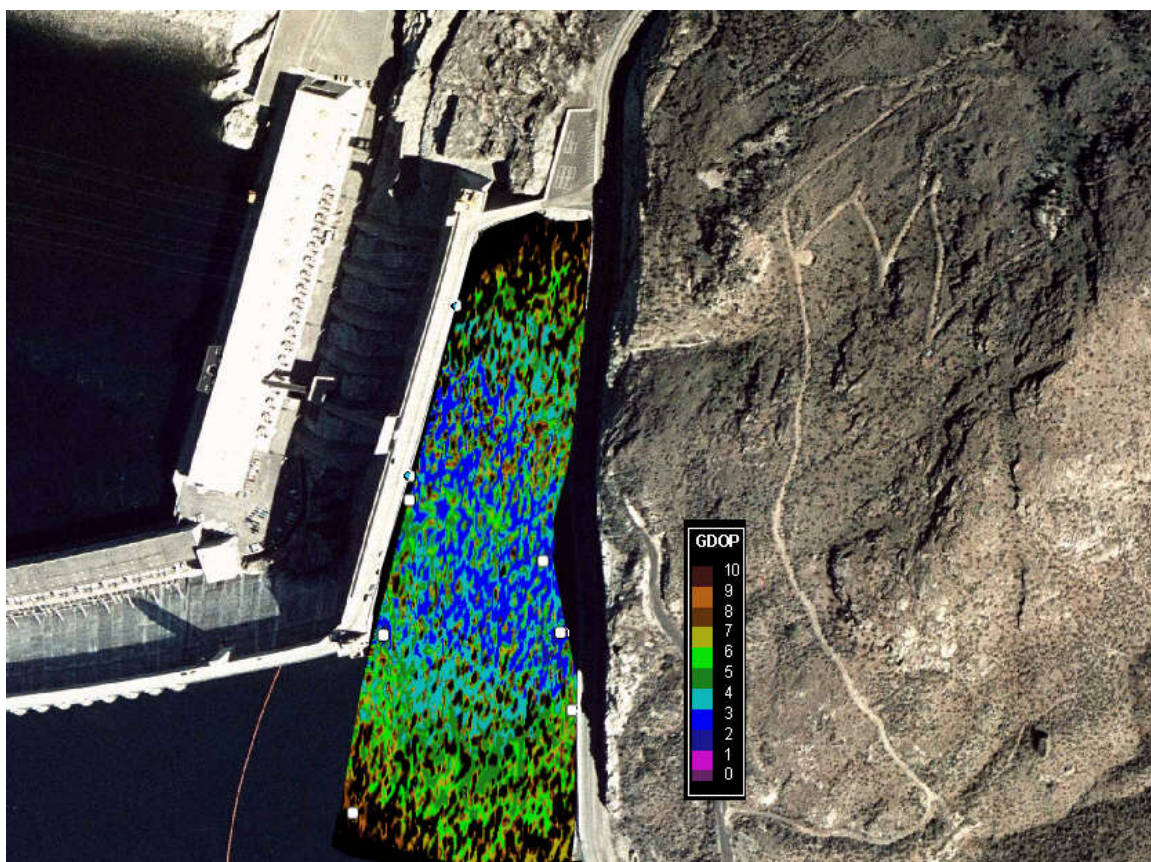

Figure E.3.   **Geometric Dilution of Precision (GDOP in meters) for the Area Within and Upstream of the Third Powerplant Forebay at Grand Coulee Dam, 2003. The GDOP contour shown is the absolute error in meters from FishTrack3D at a depth of 8 m.**
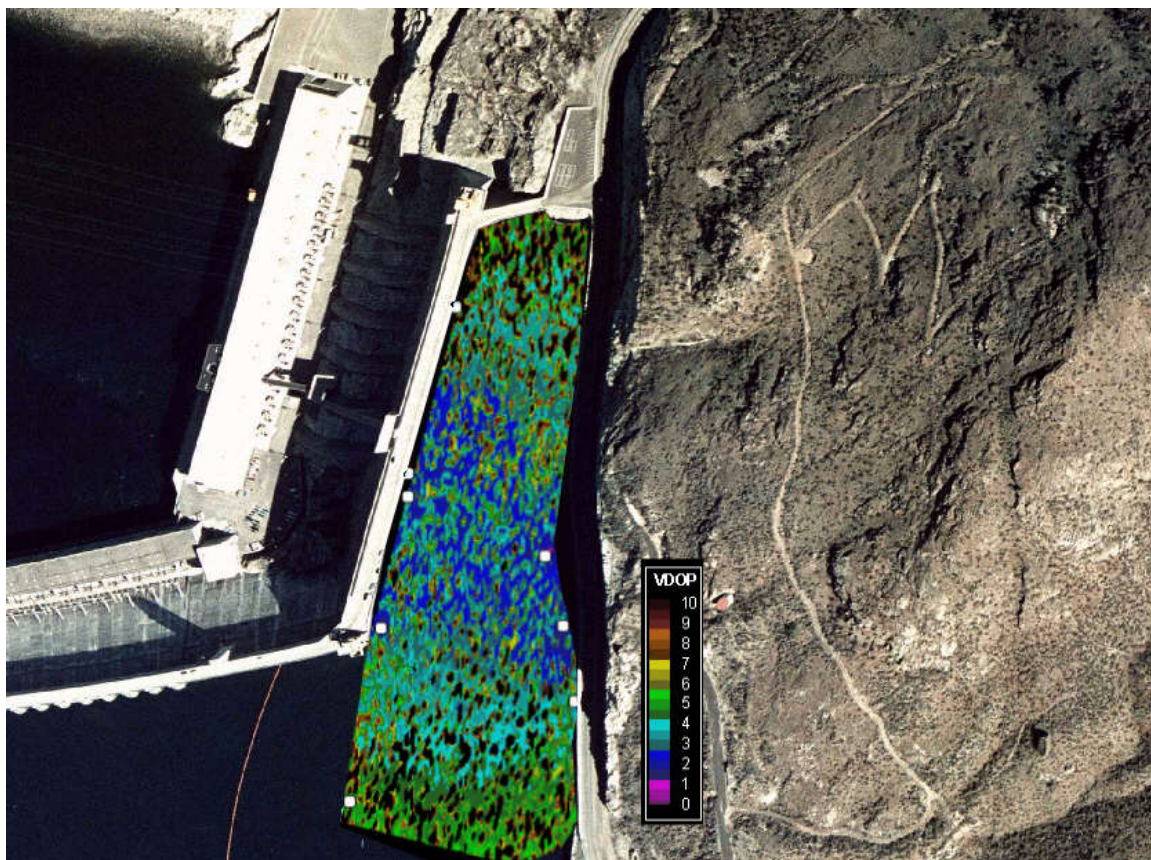
Figure E.4.   Vertical Dilution of Precision (VDOP in meters) for the Area Within and Upstream of the Third Powerplant Forebay at Grand Coulee Dam, 2003. The VDOP contour shown is the absolute error in meters from FishTrack3D at a depth of 8 m.

E.2   Results

E.2.1   Fish Movement

The descriptions of the movement of acoustically-tagged juvenile kokanee are based on analysis of the first and last hour of a fish's transit through the acoustic array (Figure E.2). The acoustic array defines the area in which fish can be located in three dimensions. It was possible to detect, but not locate, a fish in one dimension up to 250 m from the most southerly hydrophone. Thus, we have fairly precise locations for tagged fish only within the array; other possible paths were interpolated.

The dispersion of the acoustically tagged fish is summarized in Figure E.5. Most of the tagged kokanee (82% or 162 of 198 fish released) were detected by the three-dimensional acoustic array. Of those detected, 31 were detected within the third powerplant forebay. The remaining 137 fish apparently left the acoustic array and either went upstream or moved along the upstream face of the dam (left and right powerplant and spillway). It took a median of 0.9 hr (mean 5.4 hr, standard deviation 15.86 hr) for tagged fish to travel approximately 0.8 km from the upstream release site into the acoustic array. The
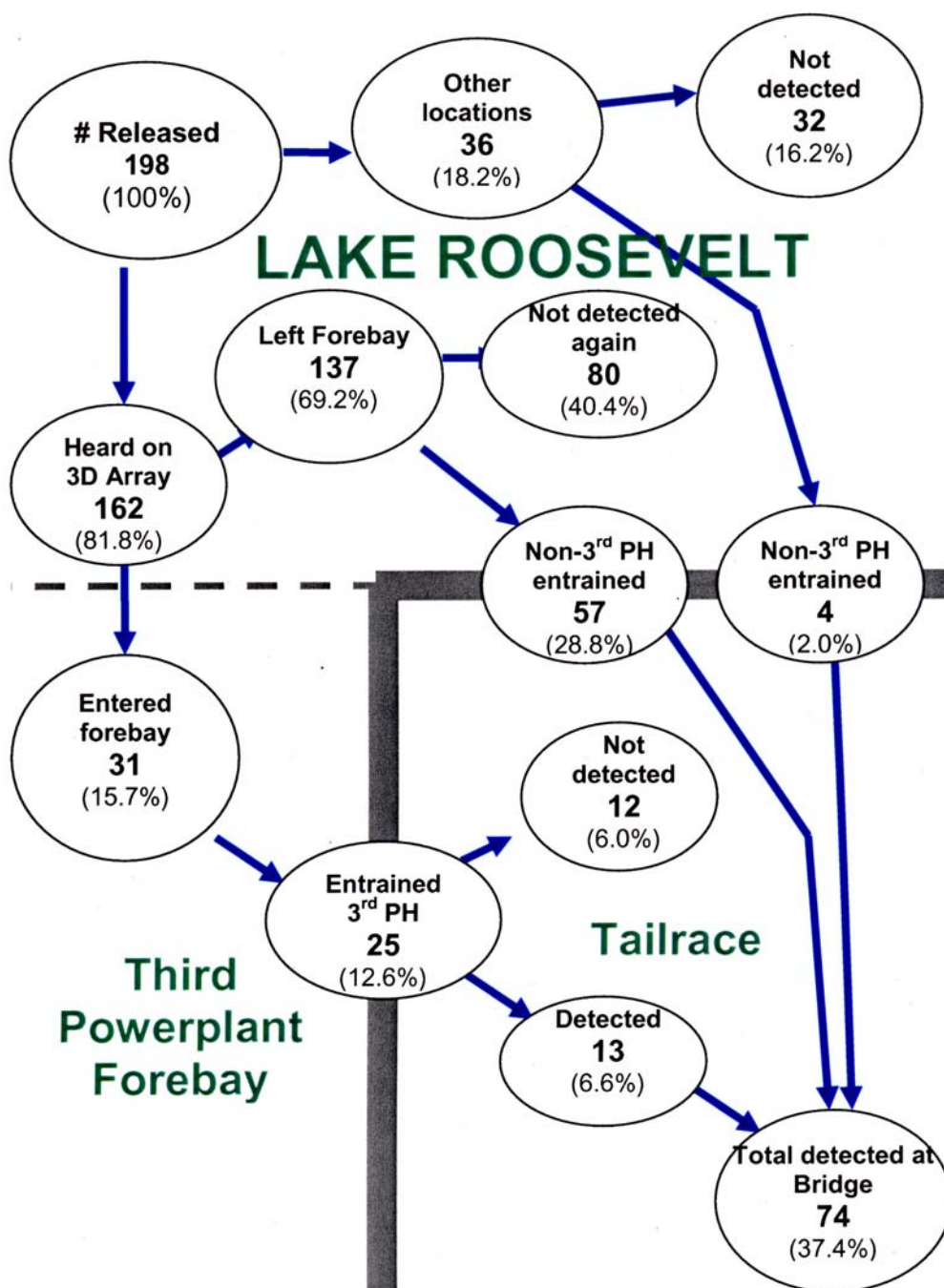
Figure E.5.   **Acoustic Tag Tracking Budget for Juvenile Kokanee Released at Grand Coulee Dam in June 2003. Numbers are based on analysis of first and last hour of detections within the three-dimensional acoustic array and in the array downstream of the bridge, and may underestimate the numbers of fish in the forebay. <u>The heavy solid line represents the dam</u>. (PH – powerplant)**

distribution of times for fish to enter the array was skewed, with most fish arriving in less than an hour, while some took more than 100 hr (Figure E.6). First entry of tagged juvenile kokanee into the array was distributed across the entire forebay entrance (Figure E.7). However, more than one-third (36%) of the tagged fish approached the forebay along the southwest corner.
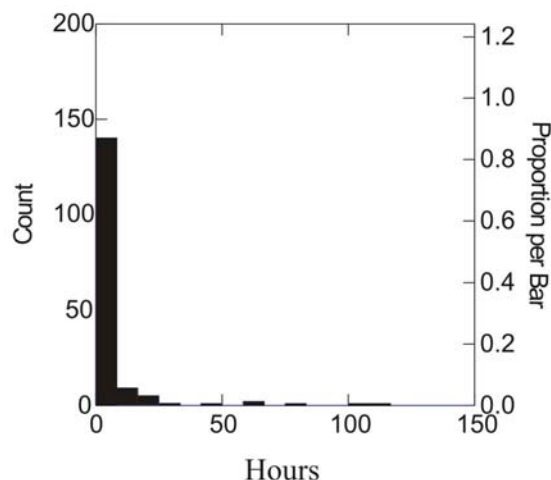

Figure E.6. **Number of Hours for Acoustic Tagged Juvenile Kokanee (n = 162) to Travel 0.8 km from the Release Site into the Three-Dimensional Acoustic Array in the Forebay of the Third Powerplant of Grand Coulee Dam, June 2003**

The depth at which tagged juvenile kokanee first entered the forebay array varied widely between 0 and 50 m (Figure E.8). The mean depth at which tagged fish entered the forebay array was 33 m (median 34 m, standard deviation 13 m). There was no significant (p > 0.05) difference between day (mean 34 m, median 39 m, standard deviation 13 m) and night (mean 32 m, median 33 m, standard deviation 13 m) with respect to the depth at which fish entered the forebay. There was, however, an obvious peak in the number of fish that entered the forebay during the day at between 35 and 40 m depth.

The tracking budget for the 198 tagged fish shows that most of the fish (162) headed toward the third powerplant forebay and were detected in the acoustic array (Figure E.5). However, 137 of these fish may not have entered further into the forebay. They did eventually appear to have swum into the forebay in front of the other two powerplants and the spillway. In all, the fate of 112 (56%) tagged fish was unknown (Figure E.5).

E.2.2   Entrainment

Thirty-seven percent (74) of the tagged fish were entrained and detected in the hydrophone array downstream of the dam. Of these fish, 70 were detected initially in the acoustic array (Figure E.5). Another 25 fish appear to have been entrained through the third powerplant. Of these 25 fish, only 13 were detected by the acoustic array at the downstream bridge.
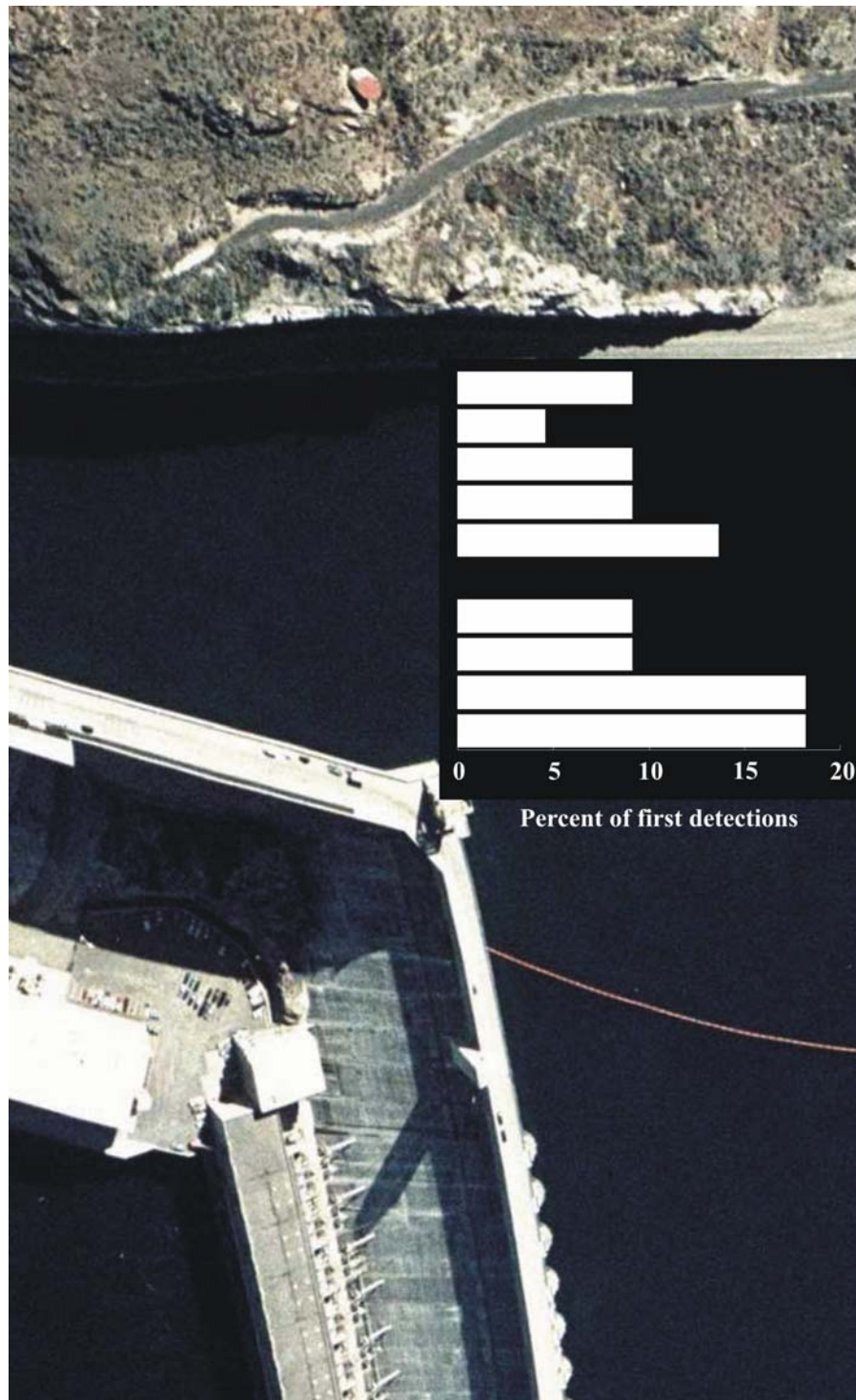
Figure E.7.   **Distribution of First Detections of Acoustic Tagged Juvenile Kokanee (n = 22) Across the Entrance to the Third Powerplant Forebay at Grand Coulee Dam, June 2003. The dam can be seen in the lower left half of the picture, while the third powerplant forebay is in the upper left half of the picture.**
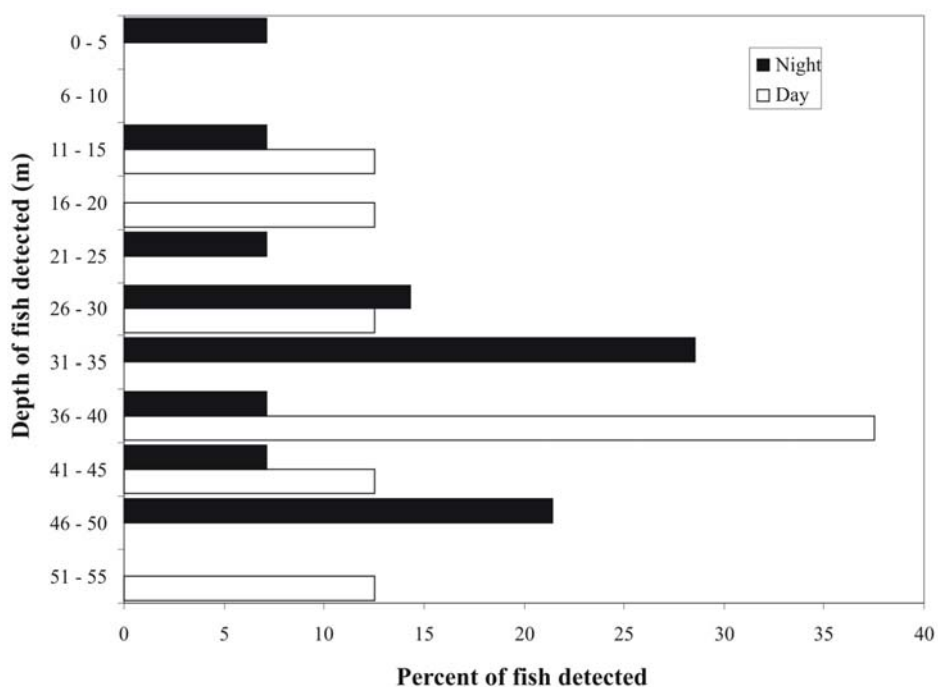
Figure E.8.   **Vertical Distribution of Acoustic Tagged Juvenile Kokanee Detected During the Day and Night (n = 22) Across the Entrance to the Third Powerplant Forebay, Grand Coulee Dam, June 2003**

     Most of the fish entrained through the third powerplant took a relatively short time to reach the bridge (median 0.22 hr, mean 7.3 hr, standard deviation 11.22 hr, n = 11). However, two of the entrained fish took more than 24 hr to reach the bridge (Figure E.9).
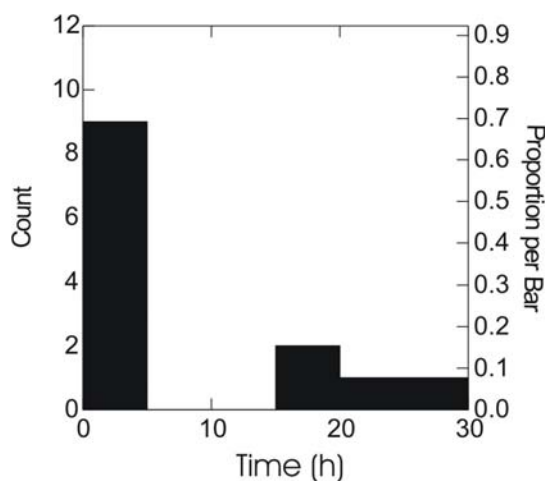

Figure E.9.   **Number of Hours for Acoustic Tagged Juvenile Kokanee to Reach the Bridge Below Grand Coulee Dam After Being Entrained Through the Third Powerplant, June 2003 (n = 13). The bridge is approximately 0.9 km downstream.**

Fish entrained through other areas of the dam and detected at the bridge took a median of 11.7 hr (mean 31.9 hr, standard deviation 42.1 hr, n = 61) to travel from the release point to the bridge. This is longer than the time it took fish entrained through the third powerplant to travel from the release point to the bridge (median 17.8 hr, mean 20.8 hr, standard deviation 16.7 hr, n = 13).

E.2.3   Behavior in Relation to Strobe Lights

A total of nine fish (4.5% of fish released) were located within 30 m of the strobe light arrays. However, the status of the strobe lights was known for only four of these fish. Of these four fish, one was within 30 m of the strobe lights while the lights were off (Figure E.10); the other three fish were near the lights when the lights were on (Figures E.11 through E.13). Of these three fish, one fish was present during daytime (Figure E.11) and the other two were present at night (Figures E.12 and E.13). None of the fish spent more than 3 min within 30 m of the lights (Table E.2).

Unfortunately, due to the low number of fish approaching the strobe lights, no conclusions can be made about behavior in relation to the strobe lights. Only the first and last hours of fish tracks were processed, which was done to provide entrainment information and approach paths of juvenile kokanee. A more detailed analysis of the entire path of each fish might show that more kokanee had encountered the strobe array.

None of the fish detected within 30 m of the strobe lights was at a depth similar to the lights (15 m). The fish that approached the strobe lights while the lights were off during the night increased its depth as it approached the lights (Figure E.10). When it was almost even with the lights, yet about 15 m to the side, the fish turned around and exited the area.

The fish that approached the strobe lights during the day while the lights were on was logged for only a short period as it approached from the downstream direction (Figure E.11). The fish was much deeper (56 m) than the strobe light arrays (15 m).

One of the two fish that approached the strobe lights during the night while the lights were on (Figure E.12) approached from the upstream direction and moved to the side as it came closer to the lights. As the fish passed the lights, it moved upward in the water column (from 46 m to 29 m). The other fish (Figure E.13) approached from approximately 25 m off to the side. The fish remained to the side as it moved downstream past the lights. Like the previously described fish, it also moved up in the water column as it passed the lights. This fish returned later from the downstream direction. However, it turned around and moved back downstream when it came within about 20 m of the lights.

E.2.4   Residence Time

The tagged fish spent a median of 0.4 hr (mean 5.7 hr) inside the third powerplant forebay. Most fish spent only a few hours in the third powerplant forebay. However, some fish spent more than 30 hours in the forebay (Figure E.14).
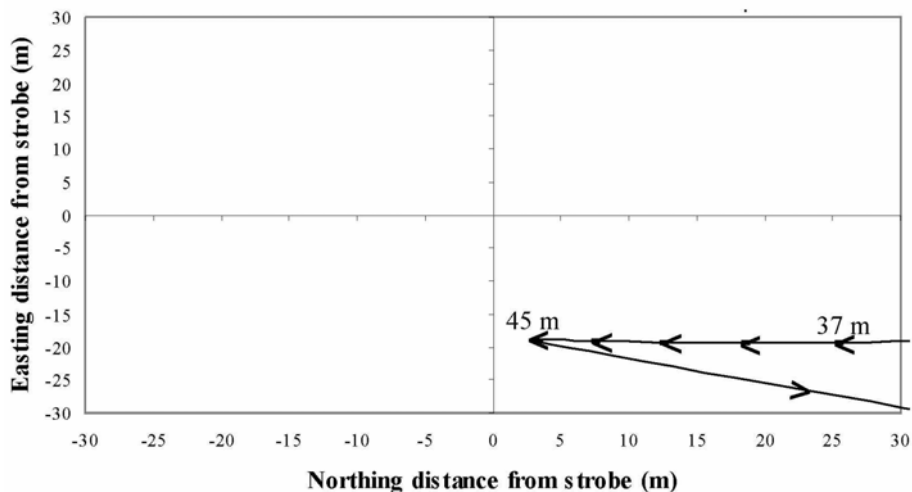
Figure E.10.   Plan View of the Direction and Depth of a Tagged Juvenile Kokanee as It Approached the Strobe Lights in the Third Powerplant Forebay of Grand Coulee Dam, June 2003. Strobe lights were off. Arrows indicate the direction of fish movement. The strobe lights are at the origin in the center of the figure. Depths of the fish are indicated along the trajectory.
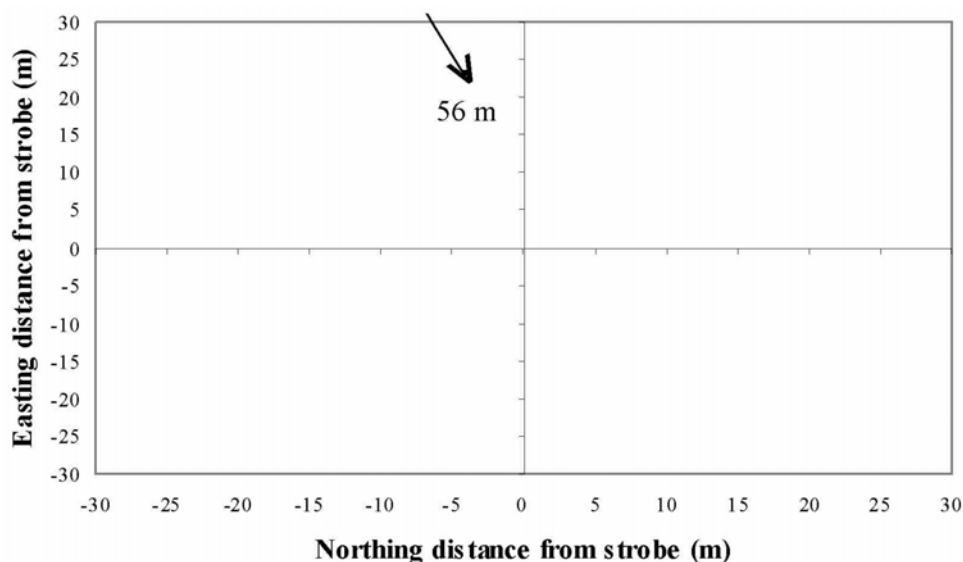

Figure E.11.   Plan View of the Direction and Depth of a Tagged Juvenile Kokanee During the Day as It Approached the Strobe Lights in the Third Powerplant Forebay of Grand Coulee Dam, June 2003. Three strobe lights were on. Arrows indicate the direction of fish movement. The strobe lights are at the origin in the center of the figure. Depths of the fish are indicated along the trajectory.
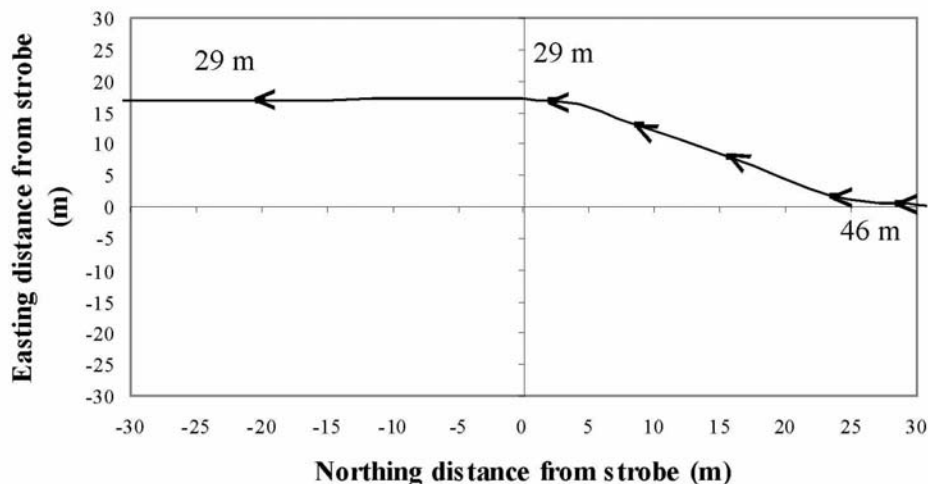
Figure E.12. Plan View of the Direction and Depth of a Tagged Juvenile Kokanee at Night as It Approached the Strobe Lights in the Third Powerplant Forebay of Grand Coulee Dam, June 2003. Three strobe lights were on. Arrows indicate the direction of fish movement. The strobe lights are at the origin in the center of the figure. Depths of the fish are indicated along the trajectory.
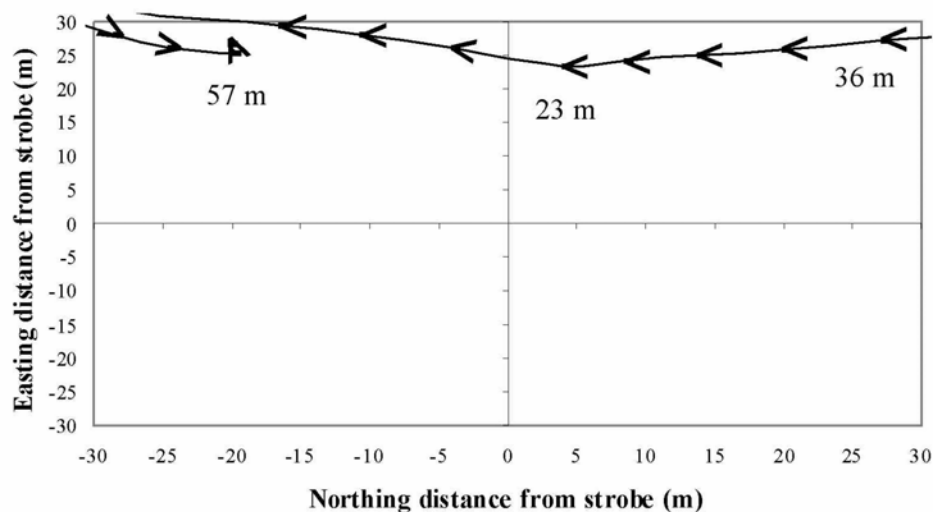

Figure E.13. Plan View of the Direction and Depth of a Tagged Juvenile Kokanee at Night as It Approached the Strobe Lights in the Third Powerplant Forebay of Grand Coulee Dam, June 2003. Three strobe lights were on. Arrows indicate the direction of fish movement. The strobe lights are at the origin in the center of the figure. Depths of the fish are indicated along the trajectory.

Table E.2.   Residence Time (minutes) for Acoustic Tagged Kokanne Detected Within 30 m of an Array of Six Strobe Lights During the Day and Night at Grand Coulee Dam, June 2003

Time of Day	Strobe Light Treatment	Number of Fish	Time in Minutes			
			Mean	Median	Range	Standard Deviation
Day	Off	---	---	---	---	---
	3-On	1	1	1	---	---
	6-On	---	---	---	---	---
Night	Off	1	2	2	---	---
	3-On	2	2.5	2.5	2 to 3	0.7
	6-On	---	---	---	---	---
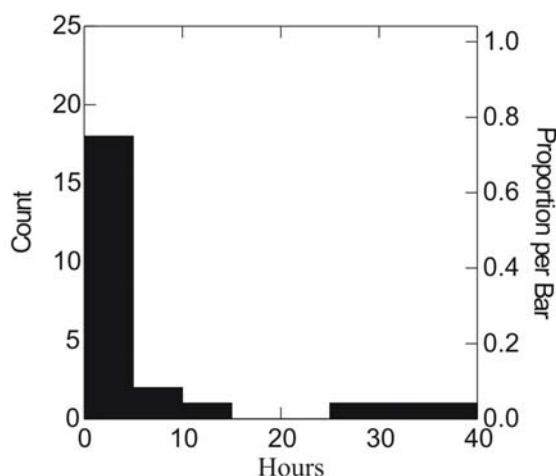
Figure E.14. Residence Time for Acoustic Tagged Juvenile Kokanee in the Third Powerplant Forebay of Grand Coulee Dam, June 2003 (n = 31)

E.3   Discussion

E.3.1   Fish Movement

The percentage of tagged kokanee detected within the three-dimensional array in 2003 was much higher than in previous studies in the same location. We detected 82% (162) of the 198 kokanee released in the acoustic array within and in front of the third powerplant forebay. In 2001 and 2002, Perry et al. (2003a, 2003b) detected only 52% and 47% of the ultrasonic tagged kokanee, respectively. Factors that may have contributed to the difference in detections include size of the released kokanee and release site. The kokanee tagged in 2001 (Perry et al 2003a) had a mean weight of 166 g and mean fork length of 231 mm. In 2002, the tagged kokanee had a mean weight of 72.4 g and mean fork length of 182.4 mm (Perry et al. 2003b). These fish weighed more than double those in the 2003 study (mean weight of 31 g and mean fork length of 147 mm). In addition, in 2001 the fish were released either at the Bureau of

Reclamation boat ramp (16 releases) or at Pine Tree Point (two releases) (Perry et al. 2003a), and at three different locations in 2002—a boat ramp near the boat restricted zone (BRZ) buoy line (two releases); at Spring Creek Canyon (one release) and at the Bureau of Reclamation boat ramp (12 releases) (Perry et al. 2003b). All these locations were along the east (right) side of the reservoir, while the release site for the 2003 study was approximately 300 m from the shore.

The release site of juvenile kokanee for the 2003 study may have been a major factor contributing to where the fish first entered the third powerplant forebay. While first entrances occurred across the entire span of the forebay, their distribution was not uniform. More than a third (36%) of the implanted fish entered through the southwest 20% section of the forebay. In 2002, Perry et al. found that first entrances by the juvenile kokanee (Perry et al. 2003b) were more prevalent along the right bank (i.e., eastern shore) of the forebay (Perry et al. 2003b). They found that 40% of their tagged kokanee entered the third powerplant forebay within 35 m of the right bank. This was likely because most of the fish tagged during that study were released also along the eastern shore approximately 400 m upstream. The release location for this study was about the same distance from the dam but was several hundred meters out in the reservoir (Figure E.1).

Tagged kokanee entered the third powerplant forebay relatively deeply (mean 33 m, median 34 m). This depth differed considerably from the depths observed in 2002 by Perry et al. (2003b). They found kokanee at a median depth of only 14 m during the day and 9.8 m during the night. Perry et al. (2003b) suggest that while in the third powerhouse forebay, tagged kokanee used deeper water during the day than during the night (although no indication of statistical analysis was provided). In contrast, data from the 2001 field season (Perry et al. 2003a) indicated that kokanee were distributed deeper at night (below 25 m) than during the day (however, no statistical analysis was performed). In our 2003 study of tagged juvenile kokanee, no significant differences were found between day and night depths as fish entered the forebay. The depth use by tagged kokanee observed from the previous studies may be a function of the relative location as they entered the forebay. In 2001 and 2002, the distributions of kokanee were skewed toward areas shallower than those in 2003. The 2003 study, however, did not determine the depths of fish locations throughout their entire stay in the third powerplant forebay because only the first and last hour of data were analyzed for each fish.

E.3.2   Behavior in Relation to Strobe Lights

Due to the small number of fish that approached the strobe lights while they were on, no conclusions can be made as to the influence of the lights on fish behavior. Only nine of the 198 released fish were detected within 30 m of the strobe lights. This is similar to the number of tagged kokanee (i.e., 11) observed by Perry et al. (2003b) within 25 m of the strobe lights in 2002. The lower number observed may be due to the fact that this study analyzed the data for each fish for only the first and the last hour during which the fish was heard in the acoustic array. If all data were analyzed, more detections near the lights may be discovered.

E.3.3   Residence Time

The median residence time of tagged kokanee in the third powerplant forebay during this study was 0.4 hr, while the juvenile kokanee tagged by Perry et al. (2003b) in 2002 spent only a median of 0.2 hr in the third powerplant forebay. During 2001, the larger kokanee tagged by Perry et al. (2003a) spent a median of 0.9 hr in the forebay.

The differences in the residence time of kokanee in the forebay of the third powerplant could be due to changes in dam operations from year to year. In the three years of this study, dam discharge rates have varied greatly, as have the median residence times of fish (Table E.3). There appears to be a trend of decreasing residence time in the forebay with increasing water discharge (Figure E.15). However, more data are needed to make any concrete inferences.

Table E.3.   Mean Discharge Through the Third Powerplant of Grand Coulee Dam and Residence Time of Juvenile Kokanee in the Third Powerplant Forebay for Three Study Years (2001–2003). Also shown is the mean weight of kokanee salmon implanted with acoustic transmitters during each study year.

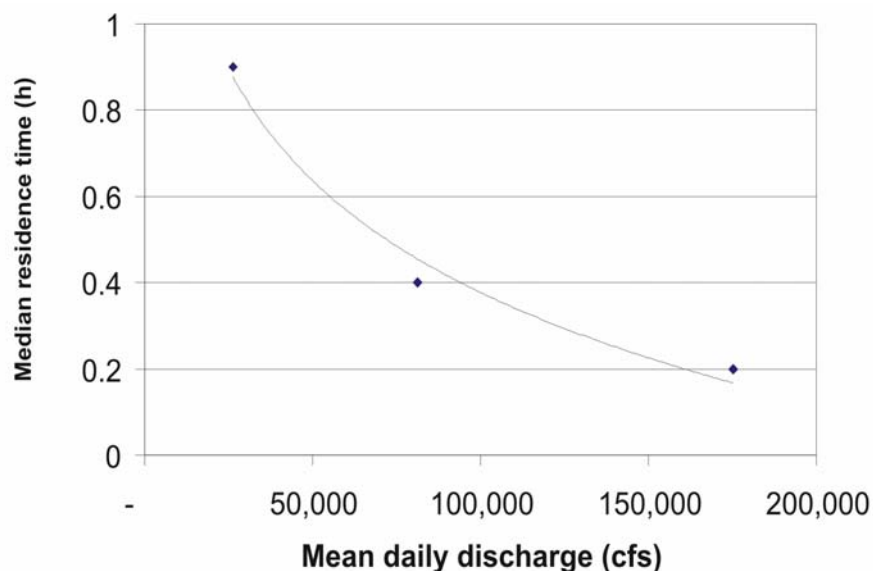| Year	Study Period	Mean Daily Discharge (cfs)	Mean Hourly Discharge (cfs)	Median Residence Time (hr)	Residence Time Range (hr)	Mean Fish Weight (g)
2001	July 1 to Aug. 2	26,209	7,140 to 55,187	0.9	(0.02 to 7.3)	166
2002	June 7 to July 5	175,305	75,197 to 139,063	0.2	(0.01 to 3.57)	72
2003	June 1 to 16	81,237	3,143 to 130,469	0.4	(0.02 to 36.88)	31

Figure E.15.   Relationship Between Mean Daily Discharge Through the Third Powerplant Averaged over the Entire Study Period and the Median Residence Time for Acoustic Tagged Kokanee in the Third Powerplant Forebay, Grand Coulee Dam

E.3.4   Entrainment

Of the 198 tagged fish released, a total of 74 (or 37%) ended up at the bridge array below the dam. However, this is likely an underestimate of entrainment. Only about half (52% or 13 of 25 fish) of the tagged kokanee that were entrained through the third powerplant were logged on the array downstream of the dam. Many of these fish may have died and settled out in the tailrace of the dam before reaching the bridge. If we extrapolate the proportion of fish that may have died in the tailrace after entrainment through the third powerplant to the number of fish exiting through other areas of the dam, then potentially 142 fish (72% of the total released) may have been entrained. If 142 fish were actually entrained past the dam, then entrainment through the third powerplant would appear to account for less than one-fifth the total entrainment (25 fish or 17.6% of fish entrained). This assumes that mortality is equal through all sections of the dam.

E.4   References

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LeCaire R. 1999. *Chief Joseph Kokanee Enhancement Project*, *1999 Annual Report and Final Report on Entrainment at Grand Coulee Dam 96-99*. Colville Confederated Tribes Fish and Wildlife Department. Prepared for the U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Perry RW, MJ Farley, TJ Darland, DH Fiel, GS Hansen, and DW Rondorf. 2003a. *Feasibility of Using 3D Acoustic Telemetry To Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington*. Annual Report 2001 to U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Perry RW, MJ Farley, GS Hansen, DJ Shurtleff, and DW Rondorf. 2003b. *Feasibility of Using 3D Acoustic Telemetry To Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington*. Annual Report 2002 to U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

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Appendix F

Mobile Splitbeam Hydroacoustics

Appendix F

Mobile Splitbeam Hydroacoustics

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

F.1   Methods

F.1.1   Equipment

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

The calibration data for the system used at Grand Coulee Dam in 2003 are listed in Table F.1. These values are stored internally in the system and carried through the logging and processing stages, and are unique to the specific transducer/transceiver combination.

Figure F.1.   DT-X Splitbeam Hydroacoustic System Used for Mobile Surveys at Grand Coulee Dam Third Powerplant in 2003

(a) BioSonics, Inc., Seattle, Washington

Table F.1.   **DT-X Digital Splitbeam Echosounder Specifications and Calibration Data[a] (Grand Coulee Dam 2003)**

System Serial Number	DTX03015
Operating Frequency	201 kHz
Source Level	223.0 dB//µPa
Receiving Sensitivity	−57.0 dB Counts ‖ µPa
Pulse Width	0.4 milliseconds
Ping Rate	5 pings per second
Sound Velocity	Based on average water column temperature for each survey
Sound Absorption Coefficient	Based on average water column temperature for each survey
(a) The calibration data fall under the auspices of the PNNL QA program described in Appendix B.	

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

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

F.1.2   Field Data Collection

Mobile hydroacoustic data collection was based on replication of seven parallel transects consecutively numbered beginning at the upstream security boom and extending downstream to the back of the third powerplant forebay (Figure F.2). Each transect was marked at both ends by a flashing amber light to ensure that transects were closely replicated during a survey and from week to week. The lights were photocell-activated and would flash only at night to preserve their batteries. Four of the transect markers were on floats attached to the inner security boom. As wind conditions changed, the boom moved back and forth, varying the length of each of the upstream transects (i.e., upstream of the barge location). For this reason, the location of these transects (transects 1 to 4) were more variable than those with fixed markers (transects 5 to 7). Also, remnants of exploratory surveys are shown in Figure F.2, but these transect segments were not included in the processing and analysis.

Transects typically were initiated at the most upstream location adjacent to the boat launch (transect 1), then sequentially completed to the back of the third powerplant forebay (transect 7), and finally replicated back to the boat launch on each night. Transecting began at approximately 10 p.m. when the lights on the dam were extinguished for the nightly laser light show. We usually completed our transecting by the time the lights were turned back on for the night after the laser light show.
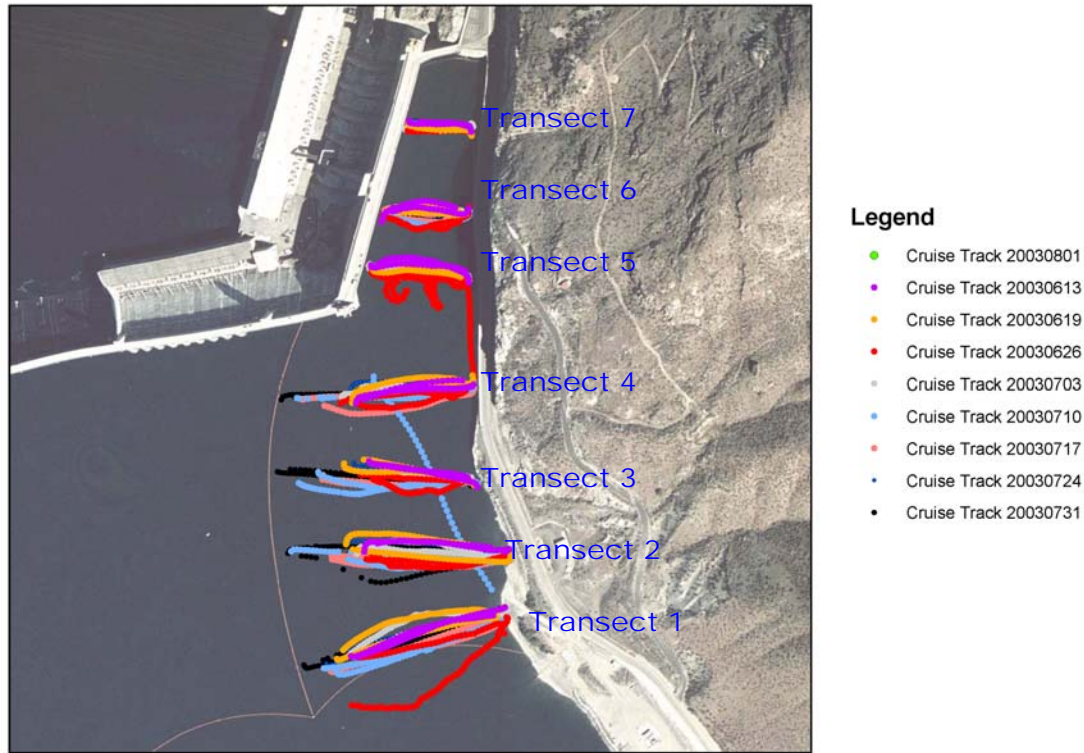
Figure F.2.   Mobile Transects Conducted from June 13, 2003, to August 1, 2003, at Grand Coulee Dam Third Powerplant (shown with replication)

During the daytime following the last nighttime survey, we conducted an exploratory survey of the forebay region adjacent to and upstream of the pumping plant on the left bank side of the reservoir. We used a simple continuous zigzag pattern to cover the area, then a long upstream leg to complete the survey (Figure F.3). We also completed two bottom-tracking surveys in the third powerplant forebay for use in describing the hydrology of the third powerplant region (not illustrated).

F.1.3   Data Processing

Data processing was completed with Echoview® software from SonarData Pty Ltd.[a] running under Microsoft Windows. Echoview® is a visual processing and analysis package that allows the user to import a broad range of scientific echosounder data and process those data under a common processing system. The visual-based system permits the user to scan echogram data manually in context between bottom and surface and verify auto-tracking results. Figure F.4 shows an example of an echogram segment from our July 24, 2003, survey of the third powerplant forebay. Two distinct targets are displayed at two depths in relation to the bottom contour. Note that the automatic bottom tracking has been over-ridden by the operator to better represent the contour of the steep bottom on the right of the echogram (green line) and prevent detection of bottom as a fish target.

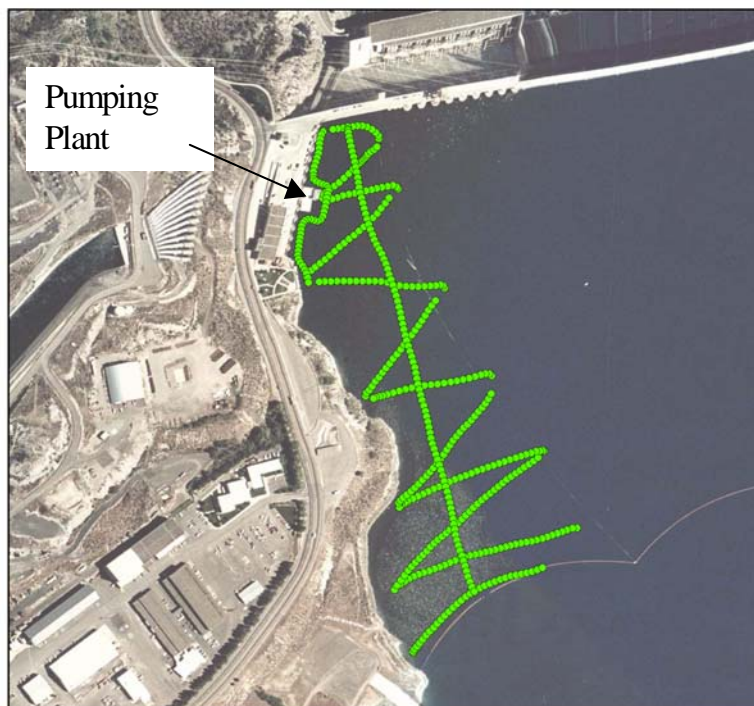(a) SonarData Pty Ltd., Hobart, Australia.

Figure F.3.   Exploratory Mobile Survey Conducted Near the Pumping Plant (Grand Coulee Dam, August 1, 2003)
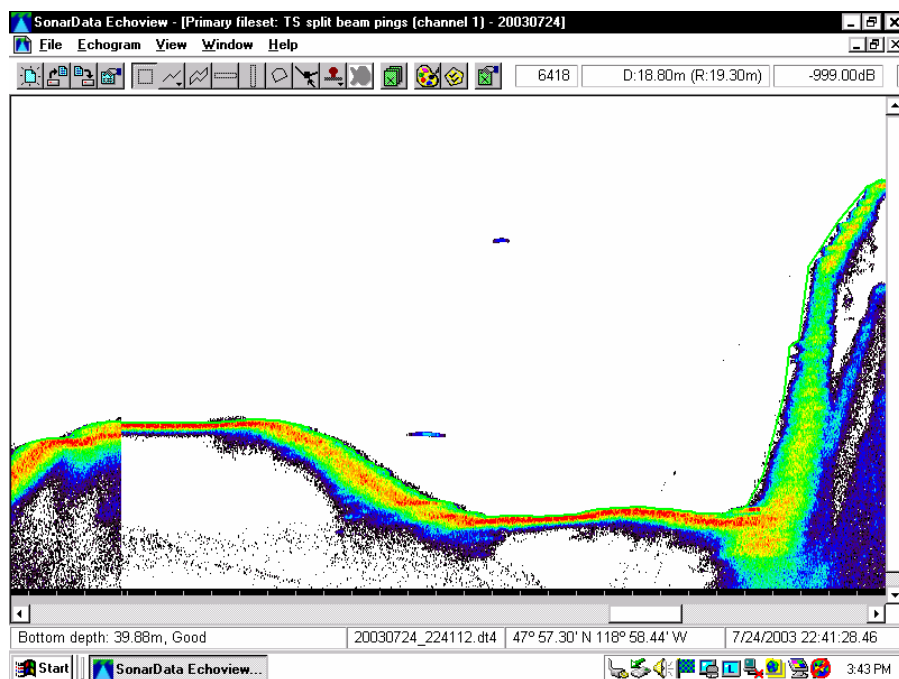

Figure F.4.   Echoview Screen Showing Bottom Track and Two Fish in the Water Column (Grand Coulee Dam, July 24, 2003)

Figure F.5 represents the same echogram segment above but zoomed in to better display the characteristics and continuity of the individual targets detected within each track by the echosounder. The software also allows the user to designate each target as a sample region for analysis. The user then simply points at the target region to obtain instant target results for quality control. If the target appears bogus, it may be deleted from the data using the contextual graphical interface. Each fish target detected by the software was scrutinized in this fashion so that a high degree of certainty was associated with the validity of the final fish target data set.

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

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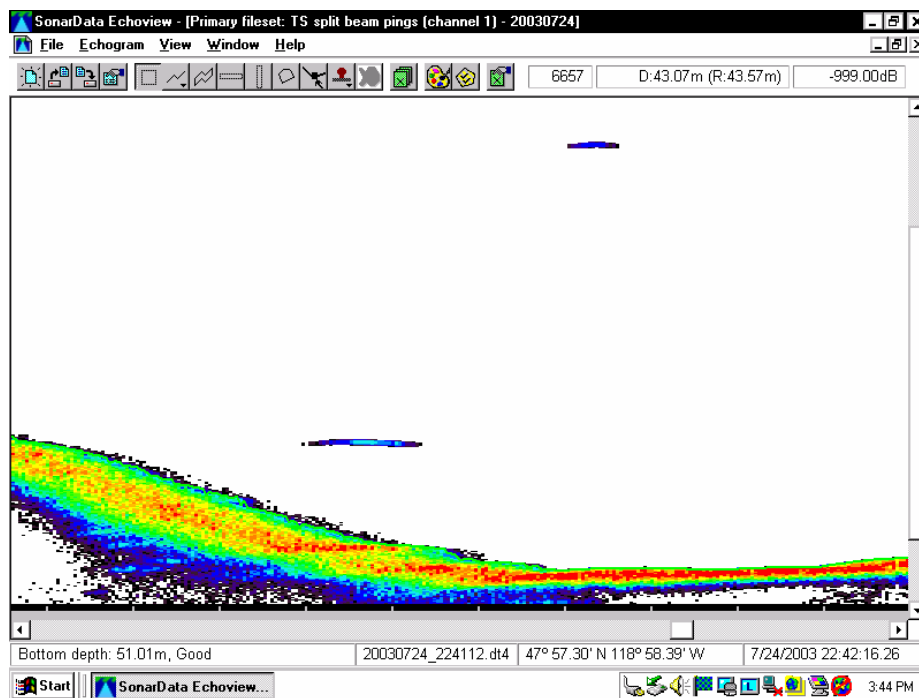

Figure F.5.   Echoview Screen Showing Bottom Track and Two Fish in the Water Column Zoomed in To Better Show the Target Continuity (Grand Coulee Dam, July 24, 2003)

F.2 Results

F.2.1 Fish Distributions

Fish were widely distributed throughout the sampled region from the upstream security boom to the back of the third powerplant forebay (Figure F.6). The displayed data (dots on the image) represent the fish locations detected over the mobile survey activity from June 13 through July 31, 2003. No fish were found in the littoral area adjacent to the upstream boat launch during this time frame. We visually observed other fish species in this region, but they usually were associated with rock outcroppings or bottom structures. This lends credence to our assumption that the majority of the fish detected in the pelagic regions are most likely either kokanee or rainbow trout. At the back of the third powerplant forebay (in the vicinity of transect 7), the fish we detected were associated mostly with the boundaries while remaining pelagic. This was noted also on transect 6 with the exception of fish detected on July 31, 2003 (yellow dots).

On the last day of our regular scheduled sampling in the third powerplant forebay, we also conducted an exploratory survey of the region in front of the pumping plant on the left bank side of the reservoir. This was motivated by having detected acoustic tags in this region during a previous year's sampling (Perry et al. 2003). Although the survey was beyond the scope of this project, we felt it was important to document the distribution of fish in this area because equipment was available and a limited effort
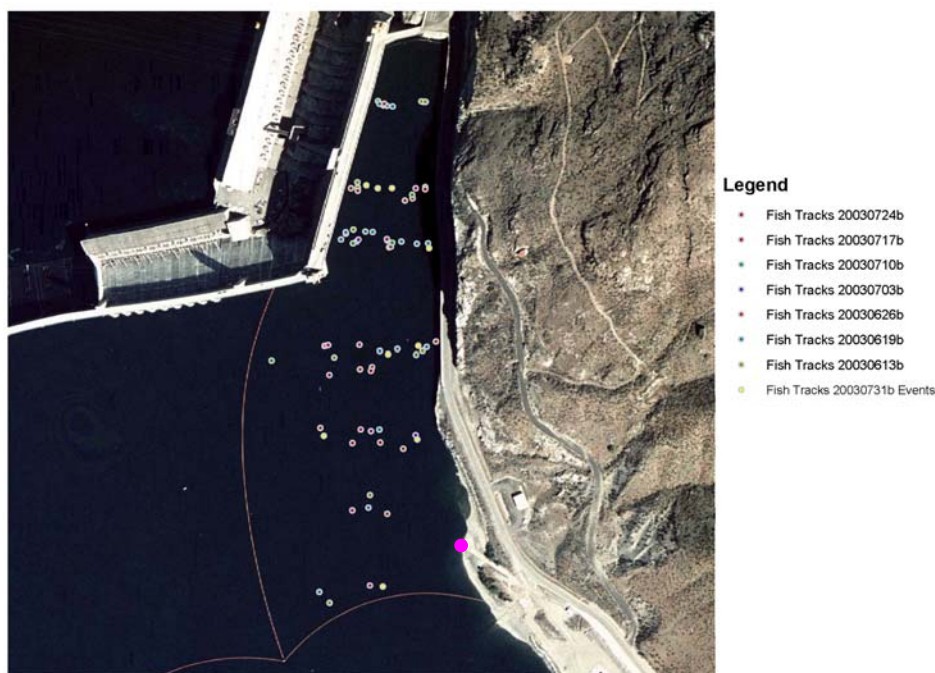

Figure F.6. **Location of Fish Detected During Mobile Surveys of the Third Powerplant (right bank of Lake Roosevelt) Forebay at Grand Coulee Dam from June 13 through July 31, 2003. Pink dot indicates approximate location of boat launch.**

was needed. The survey revealed the presence of several pelagic fish upstream of the pumping plant and another group associated with structures near the pumping plant (Figure F.7).

   Vertical distribution of fish detected in the third powerplant forebay appeared to be bimodal in 2003 (Figure F.8). The majority of the fish were located between 10 and 30 m, with the peak between 15 and

Figure F.7.   Location of Fish Detected (blue dots) at the Pumping Plant (left bank) at Grand Coulee Dam (August 1, 2003)
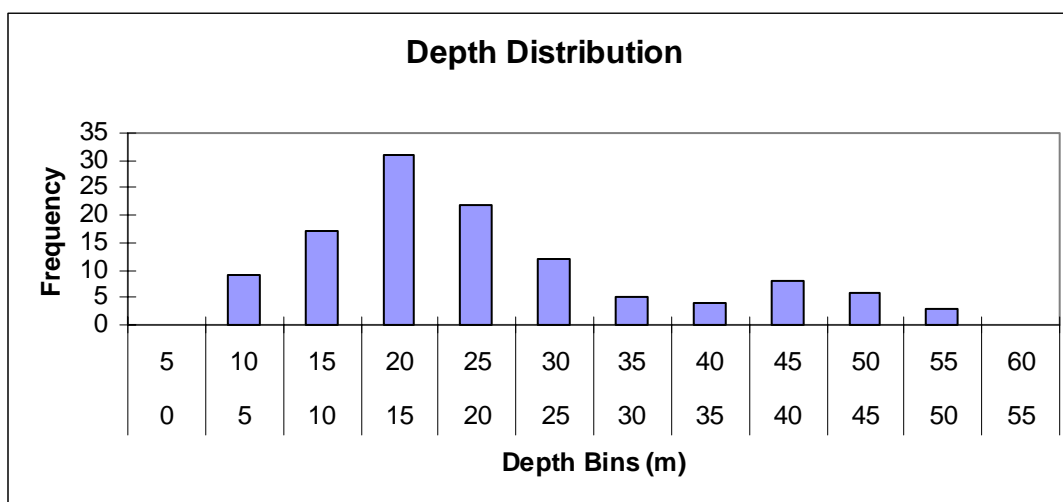

Figure F.8.   Fish Depth Distribution at Grand Coulee Dam Third Powerplant Forebay in 2003 (n = 93). Fish were detected at night.
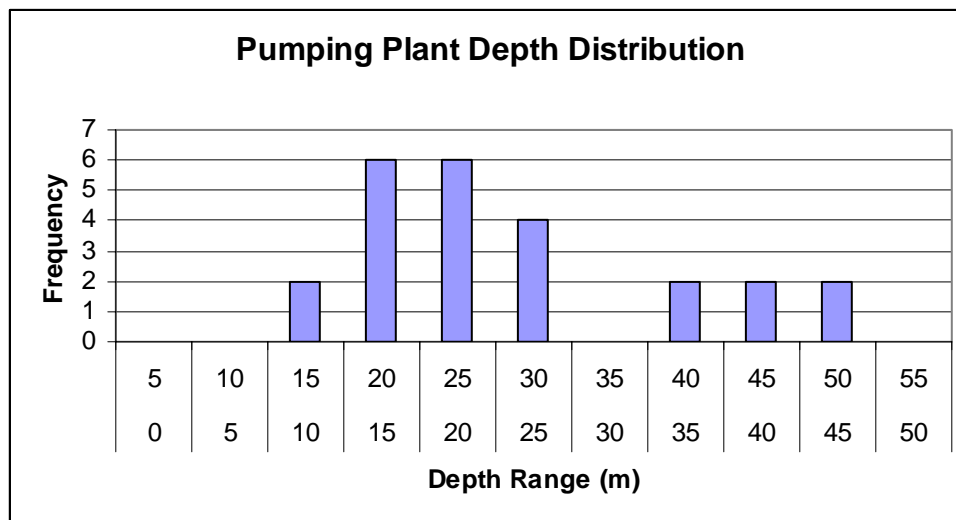
Pumping Plant Depth Distribution

Figure F.9.   Fish Depth Distribution at Grand Coulee Dam Pumping Plant Forebay in 2003 (n = 24). Survey conducted during daytime.

20 m. This was about 5 m below the strobe light frame in 2003, which was consistent with data collected in the illuminated region immediately upstream of the strobe lights at night. A second, much smaller peak in the distribution occurred between 40 and 45 m depth, with the deeper fish distribution ranging from 35 to 55 m.

We also examined the depth distribution of the fish detected in the vicinity of the pumping plant. The distribution was similar to that for fish detected in the third powerplant forebay. This might be construed as an indication, although not quantifiable, that the same or similar pelagic species were represented in both areas of Lake Roosevelt.

F.2.2   Target Strength Measurements

Target strength measurements using the splitbeam approach varied widely throughout the third powerplant forebay during the season (Figure F.10). Smaller targets ($<-$ 54 dB) may have been debris dropout, which usually was associated with a growing raft of debris at the north end of the third power-plant forebay. These smaller targets are more difficult to identify as fish because their effective sample volume is much smaller than that of larger fish targets. Thus, the number of ensonifications is less, usually at or near the minimum established to accept a target. With the small targets removed, the distribution takes on a bimodal appearance with peaks at about -50 dB and -38 dB. This suggests the presence of two distinct size classes of fish in the area of interest.

We also examined the target strength distribution at the pumping plant (Figure F.11). The distribution of target sizes was quite different with the predominant size class being larger at the pumping plant than at the third powerplant forebay. This may be attributed to a couple of factors. First, the survey at the pumping plant was conducted during the day, while all surveys at the third powerplant were conducted at night. Smaller fish may have been seeking refuge during daylight hours to avoid predation. Second,
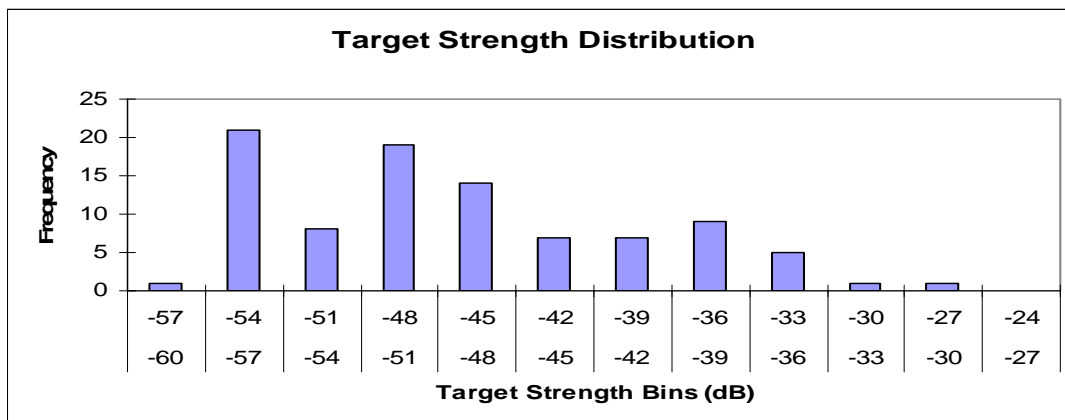
Target Strength Distribution

Figure F.10. **Acoustic Size Distribution (Target Strength) of Fish in the Third Powerplant Forebay of Grand Coulee Dam in 2003 (n = 93)**
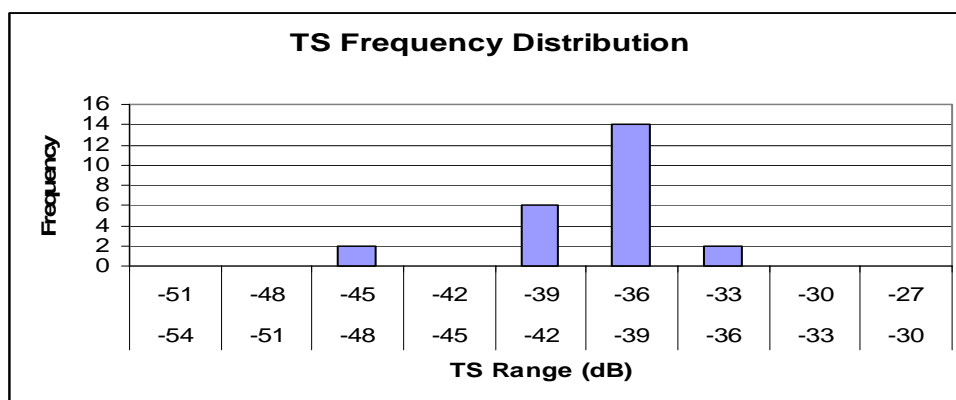
TS Frequency Distribution

Figure F.11. **Acoustic Size Distribution (Target Strength) of Fish at the Pumping Plant Forebay of Grand Coulee Dam in 2003 (n = 24)**

smaller fish may be more susceptible to entrainment at the pumping plant. The pumping plant forebay is a much smaller area with a large number of intakes. Small fish inhabiting this region would be expected to have a higher incidence of entrainment because of the constricted region and the large number of pumping units, particularly at night. However, this reasoning is purely speculative at this point. Additional study should be conducted to verify the true reason for the different size class structure in the two areas.

In future studies, should the pumping plant area be deemed important for study, the diurnal survey periods should be similar, and additional effort should be devoted to acoustically capturing fish so that the sample size in both areas is adequate for comparison.

F.3   Reference

Perry RW, MJ Farley, TJ Darland, DH Fiel, GS Hansen, and DW Rondorf. 2003. *Feasibility of Using 3D Acoustic Telemetry to Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington*. Annual Report 2001 to U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Appendix G

Multibeam Sonar

Appendix G

Multibeam Sonar

Data from previous tagging studies have suggested that fish may be swimming along the shoreline as they enter the forebay and are thus not within the region illuminated by the strobe lights (Perry et al. 2003). The position of the strobe lights in the forebay of the third powerplant is restricted by site dynamics—flow conditions near the dam and power supply availability at the opposite bank. To determine lateral fish passage across a portion of the forebay, a dual-head multibeam sonar (DHMS) system was deployed in 2003. These sonar heads ensonified an area from just below the water's surface to under the barge and extended out to 30 m (Figure G.1). The position of the multibeam sonar heads also allowed us to determine if the response to the strobe lights extended to the region behind the lights.
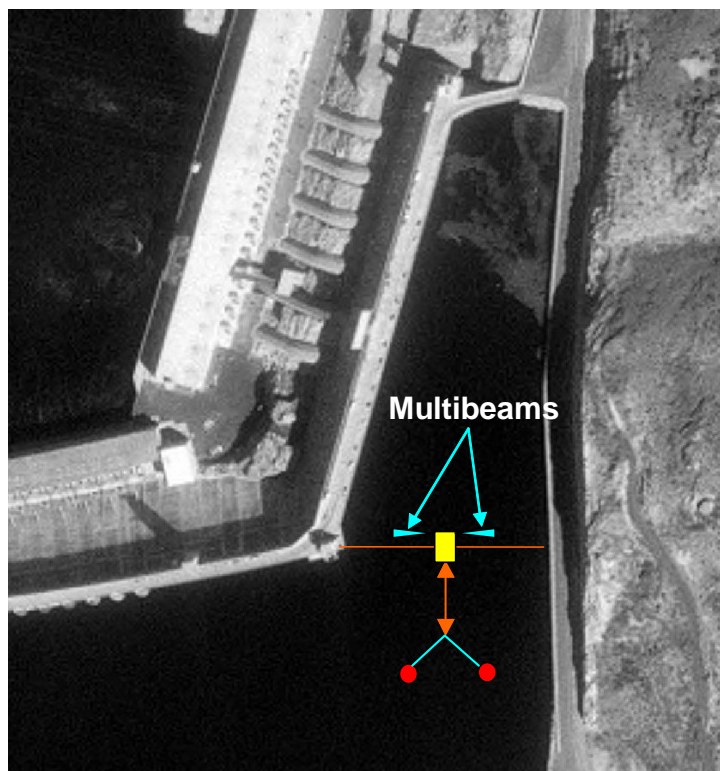

Figure G.1.   Location of Two Multibeam Sonar Systems in the Forebay of the Third Powerplant, Grand Coulee Dam, 2003

G.1 Methods

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

Data collected from the DHMS were processed using Battelle's tracking software, Mtrack (version 3_8b). The software filtered out permanent structures and grouped targets together based on their proximity in space, time, and angle units. Manual processing was used to make the final determination of fish tracks. Only a subset of the data was processed through the final selection. These files were randomly selected from the time period 15 minutes before and after the hour. This time period was selected to sample the hourly shift between lights off and on during the 1-hr on/off treatment. Additionally, more files were selected from nighttime because previous studies have shown the response to lights occurs predominantly during that period. Approximately 16% of the multibeam files were tracked manually, with 54% from periods of maximum darkness and 5% during daylight hours.

Prior to processing, the data files were preprocessed through a series of programs that split the single file into two separate binary files according to sonar head orientation from which we created the quality control and manual processing files. After manual processing, the files were processed further to remove blank lines and fish targets with fewer than six returns (pings). Fish positions were calculated within the forebay in two planes, depth, and distance from the sonar head. Distance from the sonar head is distance across the forebay with the sonar heads location defined as the zero position.

G.2 Results

More than 20,500 fish targets were detected by the multibeam sonar between June 4 and August 1, 2003. The average numbers of fish detected per hour during the daytime and night when the lights were on and off are presented in Figure G.2. Data for the 1-hr on/off treatment were included in the totals for lights on and for lights off. The difference in counts between day and night is the result of unequal processing—only 5% of the day files were processed compared to more than 50% of the night files. There is a distinct difference between lights on and off at night, with more than twice as many fish detected when the lights were on compared to when the lights were off. There was no apparent difference during the day between lights on and off; however, the sample size was very small. Overall there was no *statistical* difference in the number of fish detected on either side of the forebay (184/day on the dam side versus 166/day on the right bank side) (t-test, $p = 0.46$).

(a) Kongsberg Simrad Mesotech Ltd., Port Coquitlam, British Columbia, Canada.
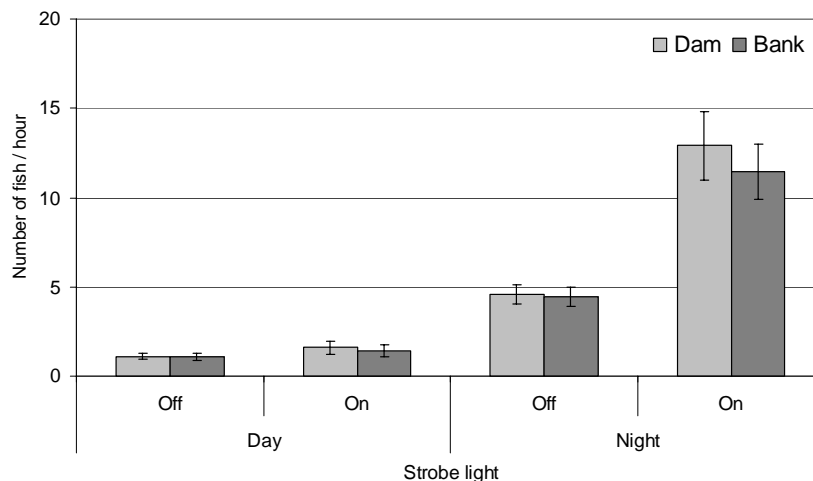
Figure G.2. Average Number of Fish Detected per Hour by Two Multibeam Sonar Heads in the Forebay of the Third Powerplant at Grand Coulee Dam Between June 4 and August 1, 2003. One sonar head ensonified the region toward the dam, while the other was oriented toward the right bank. Bars represent standard errors.

The spatial distribution of fish targets was determined for 3-m^2 areas. Contour plots of the counts are shown in Figure G.3 for fish detected during the day and in Figure G.4 for fish detected at night. The numbers for the day samples are very small and should be interpreted with caution.

The nighttime distributions (Figure G.4) appear to indicate that, when the lights are on, fish are located above and to the side of the lights (lights are 15 m deep). When the lights are off, fish continue to be oriented toward the surface but at a much reduced density.

Processing the multibeam data was complicated by the presence of noise. This could inflate the number of fish detected and the region where they are detected. Much of the noise was due to deflections off the light frame under daytime flow conditions. This may have produced the apparent concentration of fish under the sonar heads during the day (i.e., at 27 m depth, as evidenced by the lower left plot in Figure G.3).

Results appear to indicate that during the day and at night, when the lights are off, the distribution of fish was fairly uniform across the forebay. At night, when the lights were on, fish, behind the lights, were concentrating above the lights and to the side.

G.3 Reference

Perry RW, MJ Farley, GS Hansen, DJ Shurtleff, and DW Rondorf. 2003. *Using 3D Acoustic Telemetry to Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington, 2002.* Annual Report 2002 to U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Dam Side   Lights Off   Bank Side
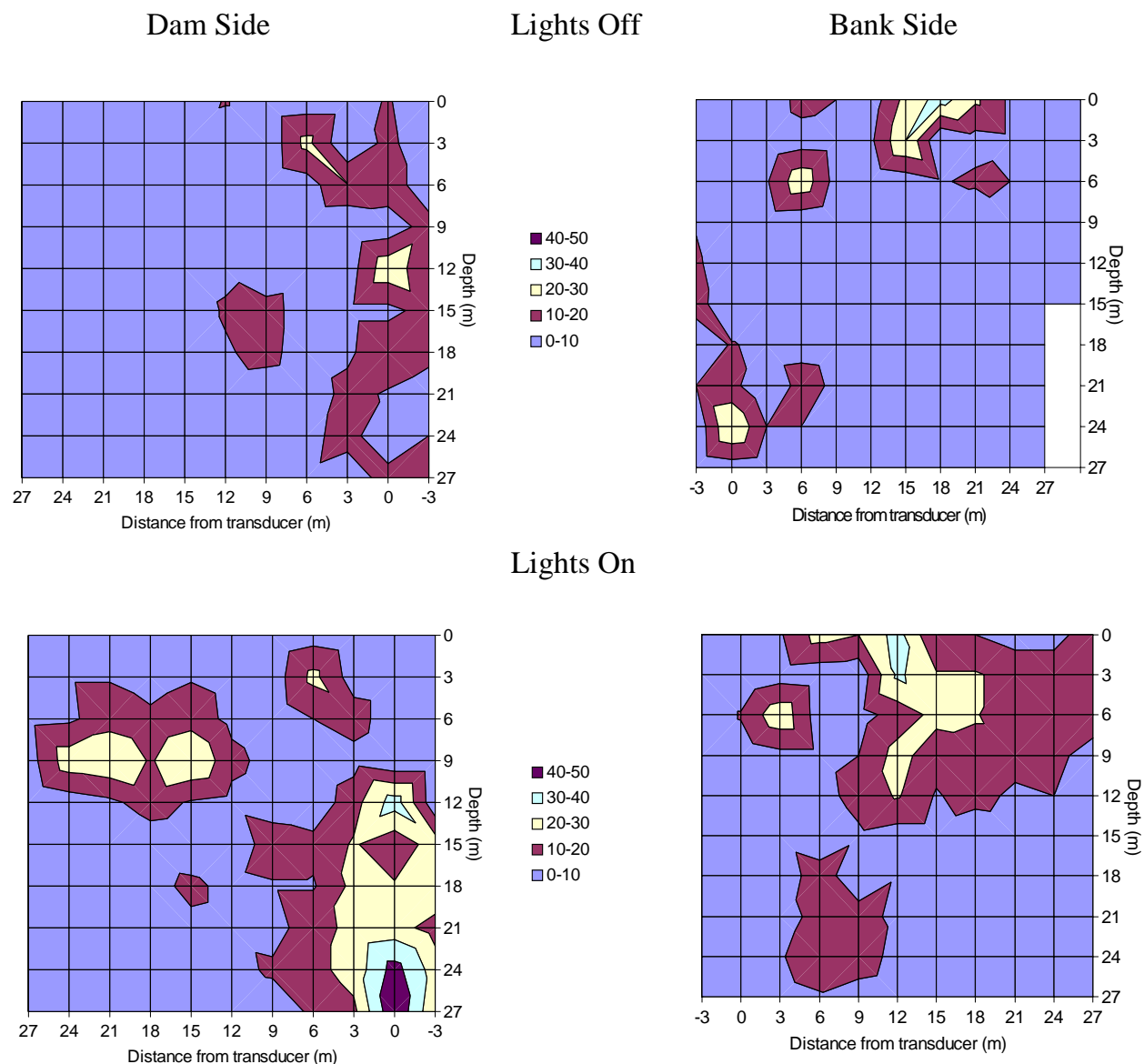

Lights On

Figure G.3.   Distribution of Fish Detected by Two Multibeam Sonar Heads During the Day Between June 4 and August 1, 2003. One multibeam sonar head was pointed toward the dam (Dam Side) and the other toward the right bank (Bank Side).

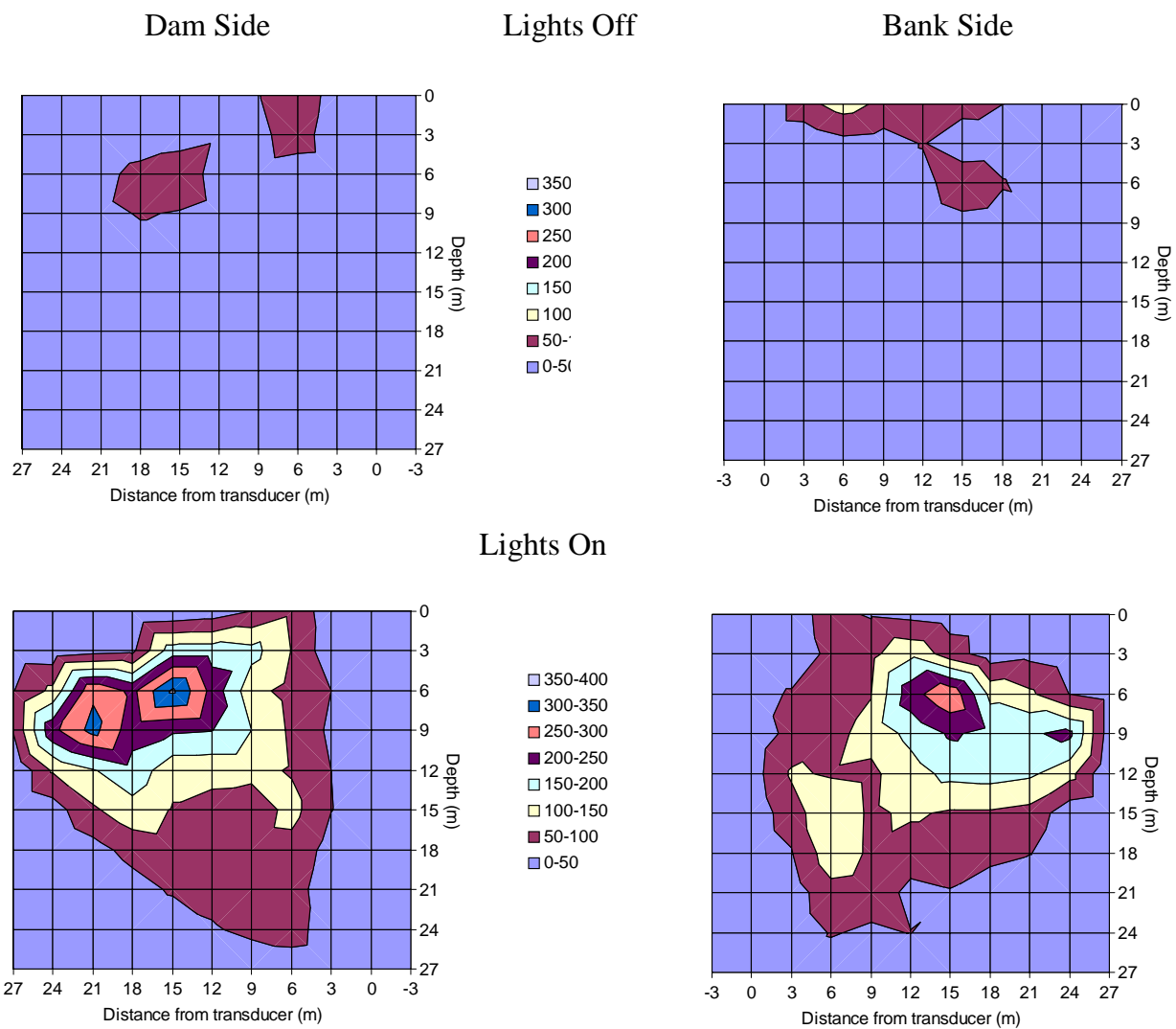Dam Side   Lights Off   Bank Side

Lights On

Figure G.4.   Distribution of Fish Detected by Two Multibeam Sonar Heads at Night Between June 4 and August 1, 2003. One multibeam sonar head was pointed toward the dam (Dam Side) and the other toward the right bank (Bank Side).

Appendix H

Graphs Used in the Analysis of Arrival Rates for 24-Hour Treatments, Swimming Direction Angle, Swimming Effort, and Water Flow

Appendix H

Graphs Used in the Analysis of Arrival Rates for 24-Hour Treatments, Swimming Direction Angle, Swimming Effort, and Water Flow

Graphs in this appendix are in support of analysis presented in Section 4, Results and Discussion.

H.1   Arrival Rates for 24-Hour Treatments

Calculated arrival rates shown in Figures H.1 through H.5 were based on the regression slope of the cumulative arrival over each day from 8 a.m. to 8 a.m. the following day. The counting interval for determining the rate was one-half hour. Values are subject to greater variability when fewer fish are counted.

The general pattern repeated over all the blocks was that there was little to no difference in arrival rates between strobe lights off and strobe lights on during daylight hours. At night, count rates when strobe lights were on exceeded count rates when lights were off. On some days, the count rate with lights off around sunset was higher than when lights were on (see results for Blocks 2, 6, 8, 10, 11, 12, and 14).
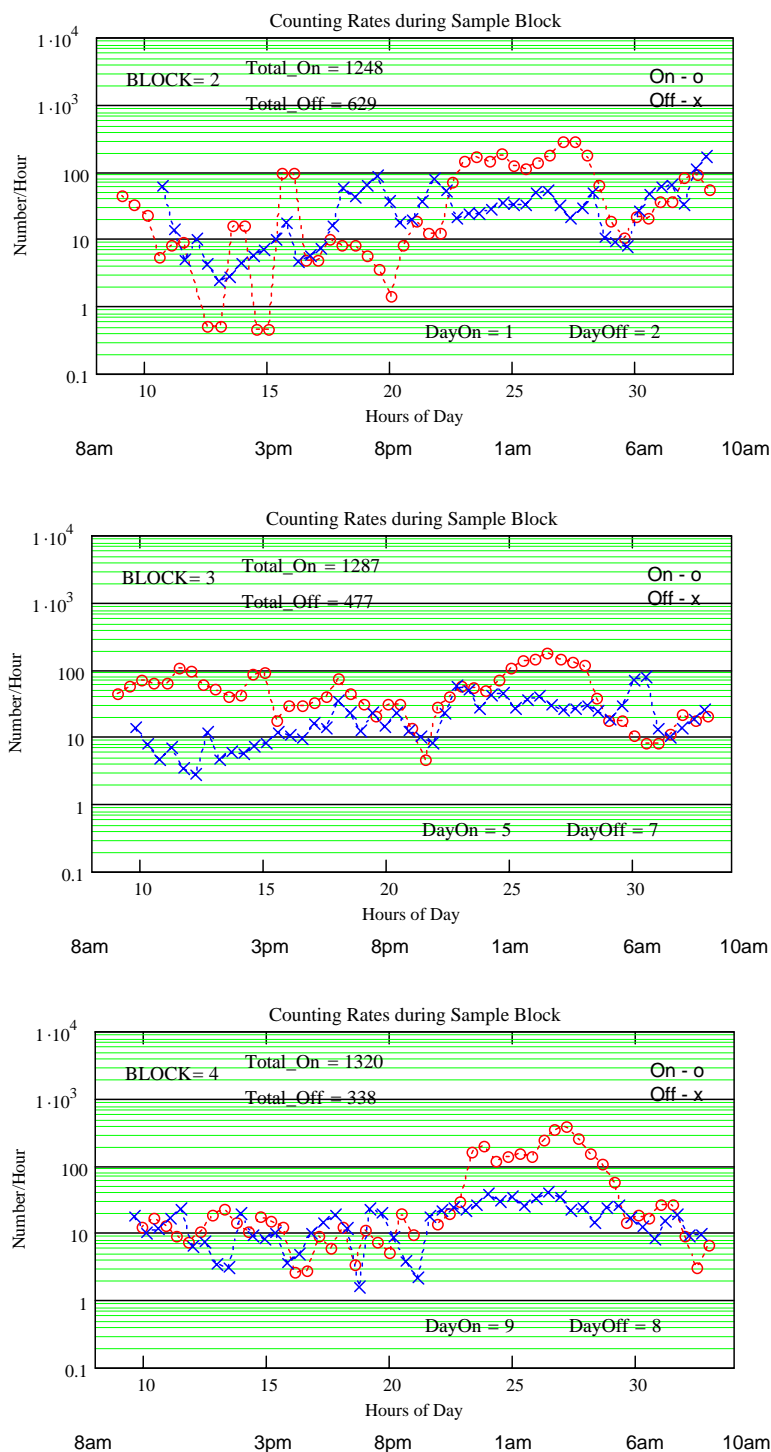
Figure H.1. **Arrival Rates for Fish Detected During 24-hr Light Treatments for Blocks 2 (June 17–19, 2003) through 4 (June 24–26, 2003). Totals refer to number of fish detected. DayOn and DayOff refer to the study day numbered from June 17. Red indicates arrivals when strobe lights are on; blue represents arrivals when strobe lights are off.**

H.2

Figure H.2.   **Arrival Rates for Fish Detected During 24-hr Light Treatments for Blocks 5 (June 28–30, 2003) through 7 (July 5–7, 2003). Totals refer to number of fish detected. DayOn and DayOff refer to the study day numbered from June 17. Red indicates arrivals when strobe lights are on; blue represents arrivals when strobe lights are off.**

Figure H.3.　Arrival Rates for Fish Detected During 24-hr Light Treatments for Blocks 8 (July 8–10, 2003) through 10 (July 15–17, 2003). Totals refer to number of fish detected. DayOn and DayOff refer to the study day numbered from June 17. Red indicates arrivals when strobe lights are on; blue represents arrivals when strobe lights are off.
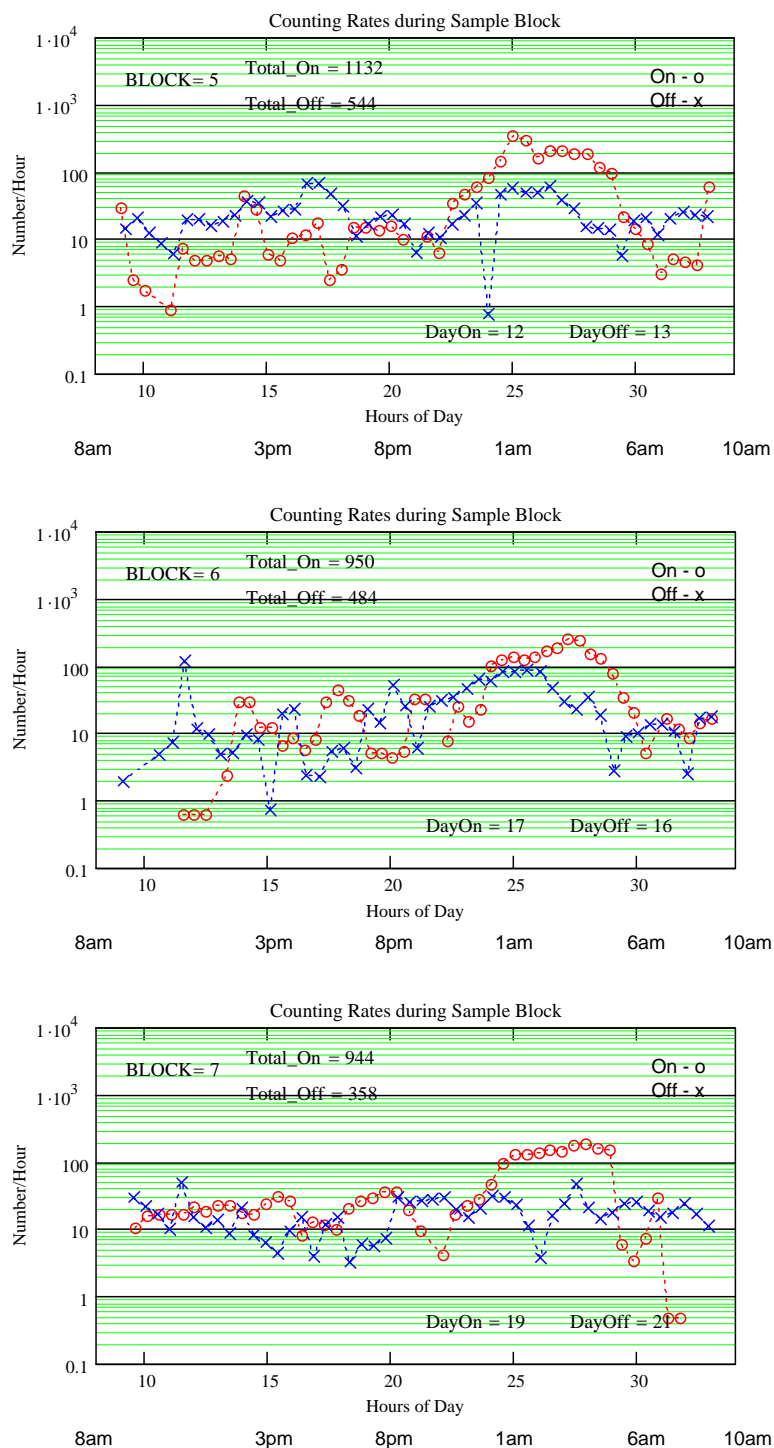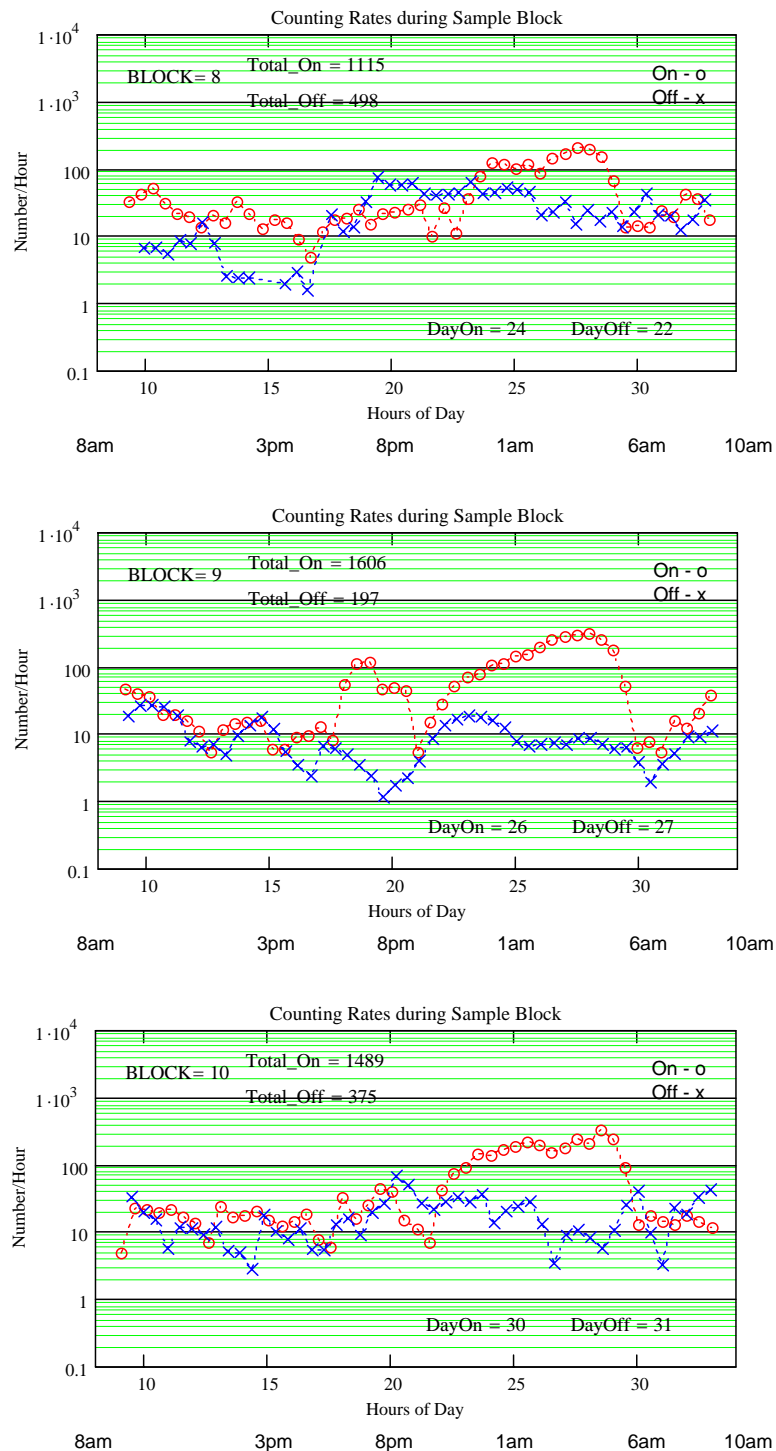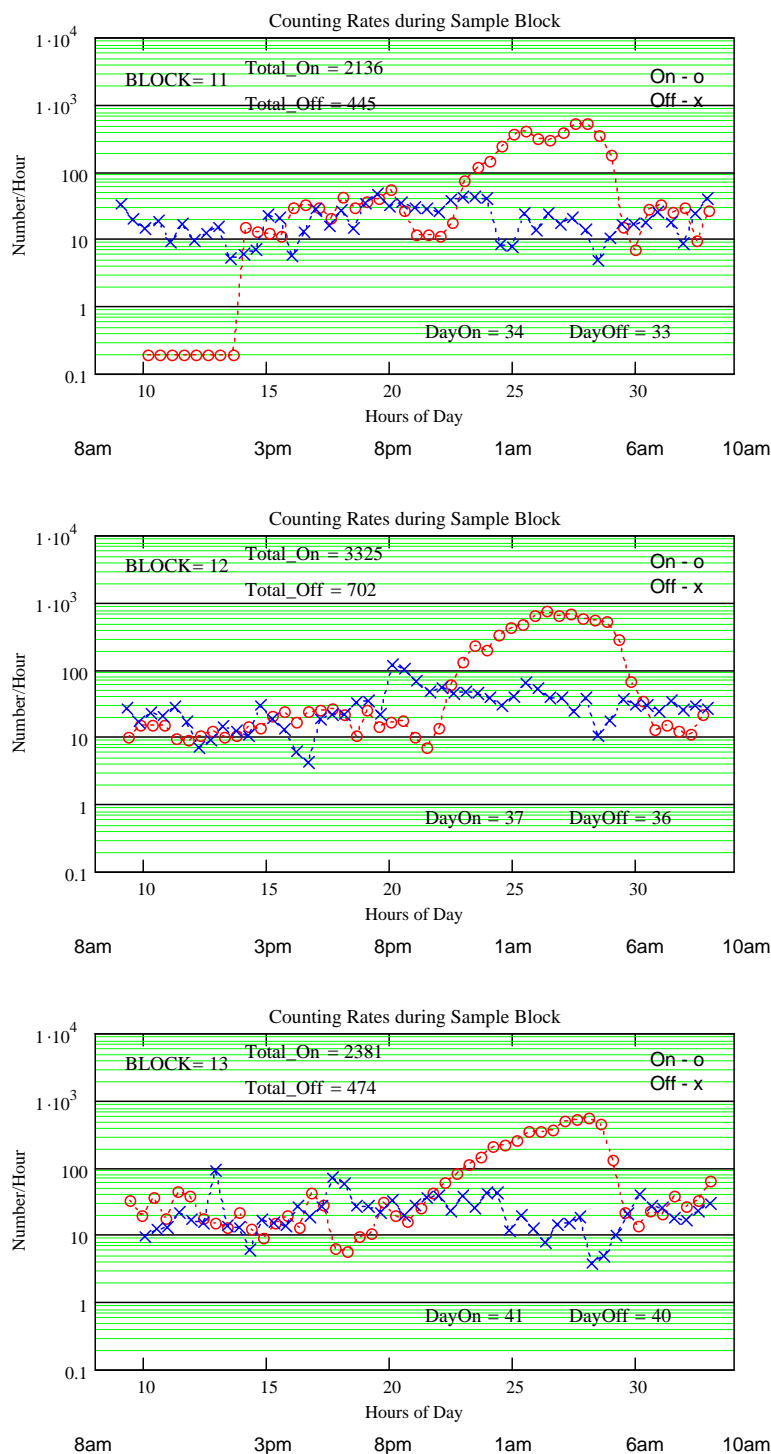
Figure H.4.   Arrival Rates for Fish Detected During 24-hr Light Treatments for Blocks 11 (July 19–21, 2003) through 13 (July 26–28, 2003). Totals refer to number of fish detected. DayOn and DayOff refer to the study day numbered from June 17. Red indicates arrivals when strobe lights are on; blue represents arrivals when strobe lights are off.
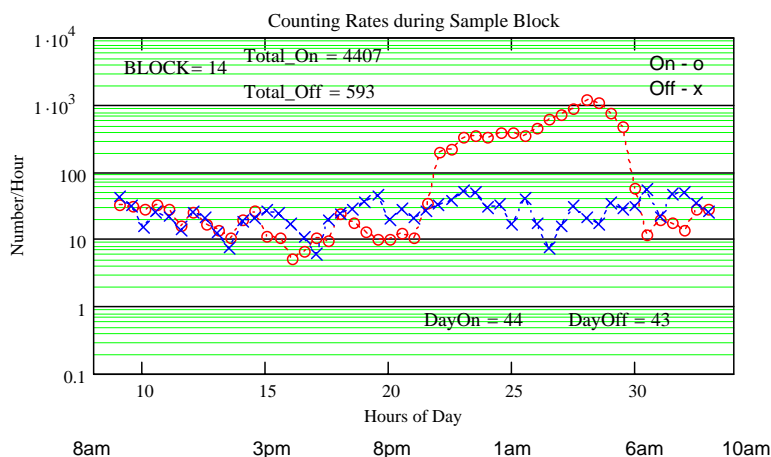
Figure H.5.   Arrival Rates for Fish Detected During 24-hr Light Treatments for Block 14 (July 29–31, 2003). Totals refer to number of fish detected. DayOn and DayOff refer to the study day numbered from June 17. Red indicates arrivals when strobe lights are on; blue represents arrivals when strobe lights are off.

H.2   Fish Swimming Direction

Figures H.6 through H.9 show the angular direction of movement for all fish targets at each splitbeam transducer location. The angular direction is the angle between the displacement velocity vector and the downstream flow 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, and upstream, into the forebay, is at 180°. The angular direction for a fish headed directly downstream would be zero. The inner concentric rings indicate the percentage probability distribution. The continuous 24-hr light treatment is first (Figures H.6 and H.7), followed by the 1-hr on/off treatment (Figures H.8 and H.9). In each set, the results for the strobe-lights-on treatment are shown in red; lights-off results are in black. The transducer beams are numbered 0, 3, 2, 1, and 10 from upstream to down-stream, respectively, along the centerline of the lights. Two transducers were aimed slightly upstream and to either side of the centerline of the lights at the location of the ADCP (see Figure D.2, Appendix D). The transducer pointing toward the dam is number 20, and the transducer aimed toward the right bank is number 30. One transducer, at 18 m from the strobe lights (number 3), experienced a malfunction in its multiplexer during the study period, preventing estimation of swimming direction. Therefore, data from that transducer were not included in this analysis.

When the lights were on at night, the fish were generally headed across the forebay, toward either the dam or the right bank (i.e., angular directions of 90º and 270º, respectively) for all locations. When the lights were off at night, the distribution of angular directions was in all directions, indicating the fish were moving equally in all directions. For fish detected during the daytime, the primary direction of movement again was to either side of the forebay.

Day   **Night**

Figure H.6.   **Swimming Direction for Fish Detected by Splitbeam Transducers 10 (6 m from lights), 1 (10 m from lights), 2 (14 m from lights), and 0 (22 m from lights) During the Day and at Night When the Strobe Lights Were On (Red) and Off (Black) for 24 Hours. Note the scales are not consistent.**

H.7

Day   Night

Figure H.7.   **Swimming Direction for Fish Detected by Splitbeam Transducers 20 (6 m from lights oriented toward the dam) and 30 (6 m from lights oriented toward the right bank) During the Day and at Night When the Strobe Lights Were On (Red) and Off (Black) for 24 Hours. Note the scales are not consistent.**
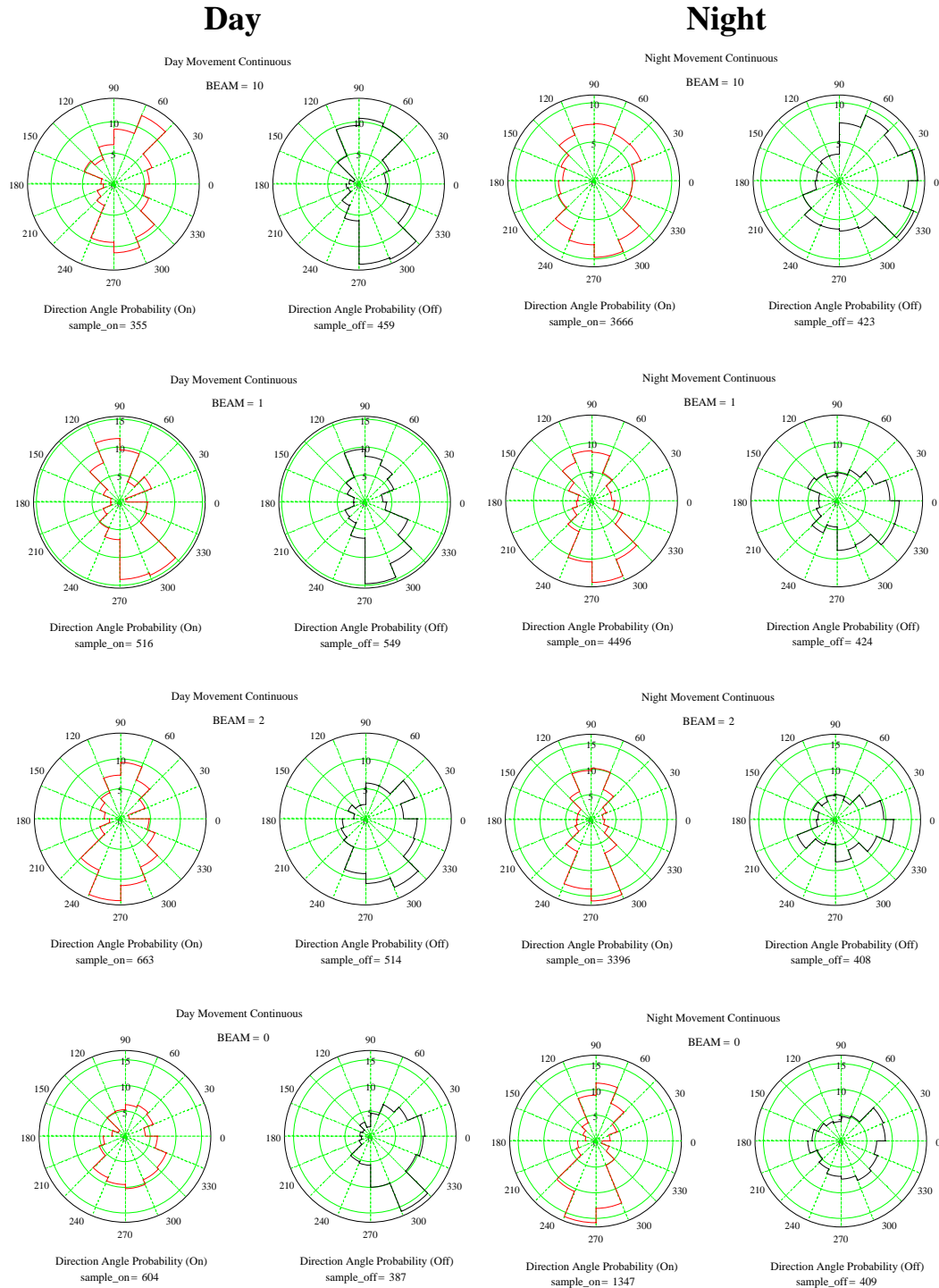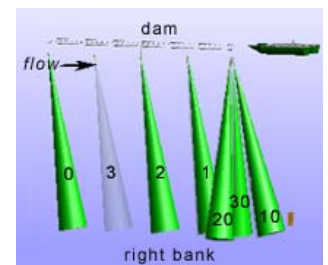
Day　　　　　　　　　　　　　　　　**Night**

Figure H.8. **Swimming Direction for Fish Detected by Splitbeam Transducers 10 (6 m from lights), 1 (10 m from lights), 2 (14 m from lights), and 0 (22 m from lights) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 1 Hour. Note the scales are not consistent.**
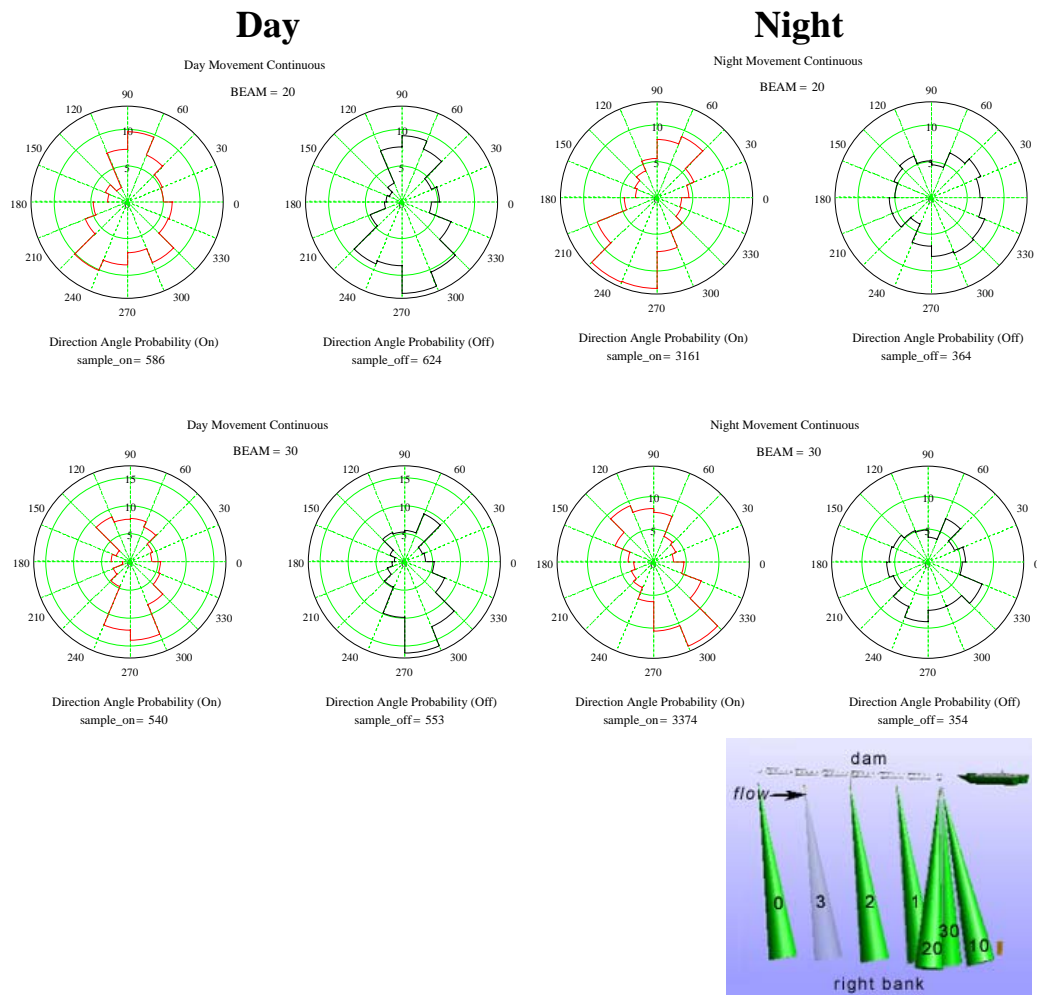
Day   Night

Figure H.9.   **Swimming Direction for Fish Detected by Splitbeam Transducers 20 (6 m from lights oriented toward the dam) and 30 (6 m from lights oriented toward the right bank) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 1 Hour. Note the scales are not consistent.**
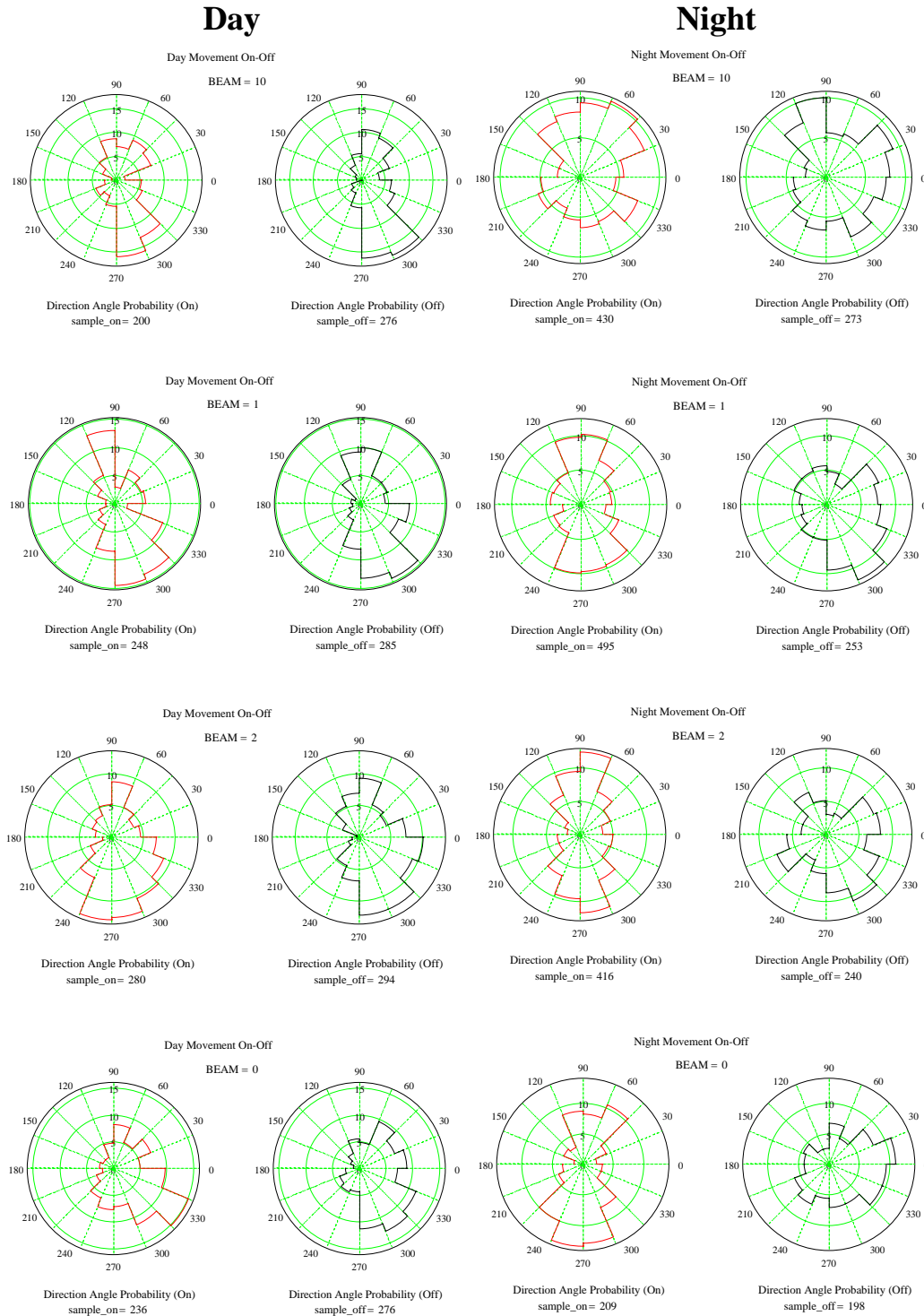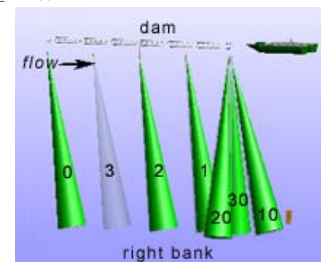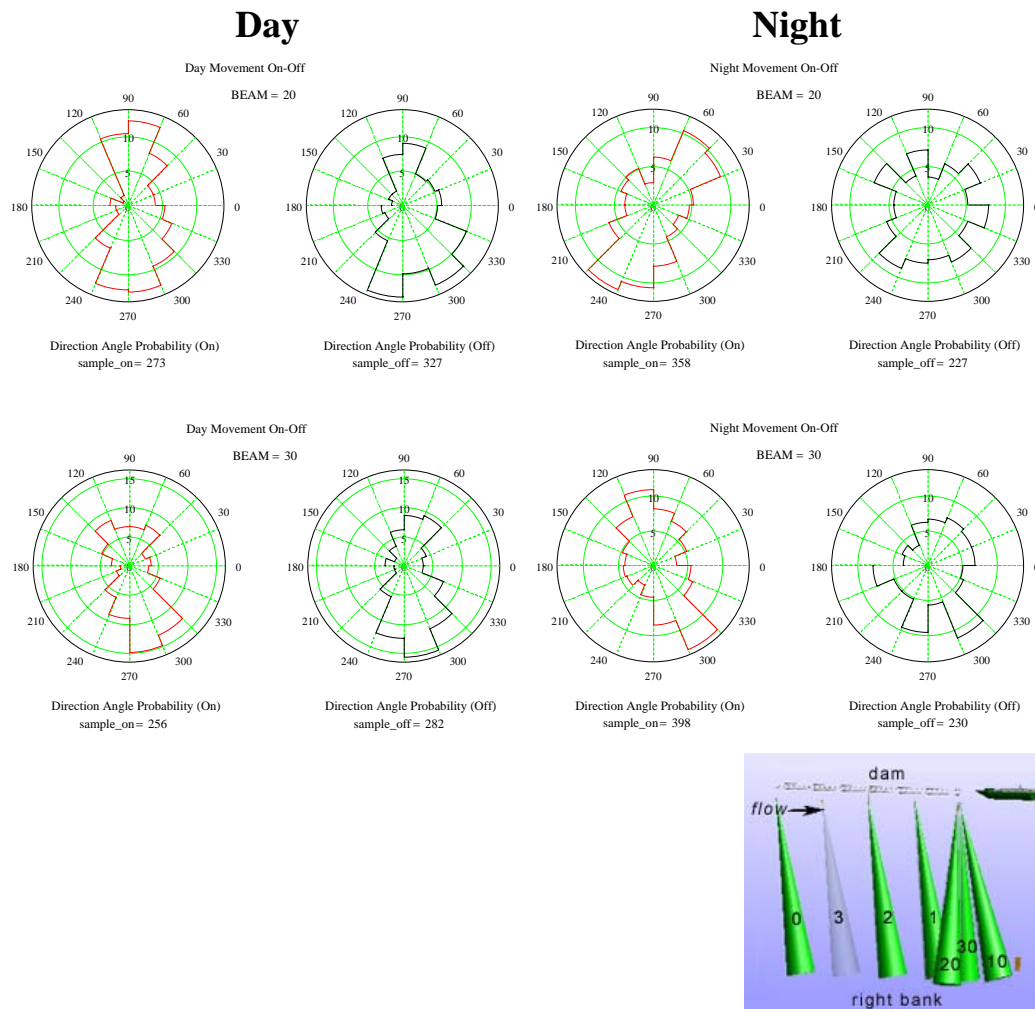
H.3   Fish Swimming Effort

Figures H.10 through H.15 show the swimming effort of fish detected by the seven splitbeam transducers upstream of the strobe lights. The direction in which a fish was swimming as measured by the splitbeam hydroacoustic system was the true direction of movement with respect to a fixed reference frame. By subtracting water velocity from the overall swimming velocity, the effort the fish expends 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 velocity was measured at the same location as the three splitbeam transducers closest to the strobe lights using an ADCP (see Appendix D).

Wind rose histograms are used to show the distribution of fish swimming effort. Swimming effort is shown by both the direction of movement (direction angle probability) and swimming velocity (velocity median magnitude). In these figures, downstream is at zero degrees, the dam is at 90º, and upstream, into the forebay, is at 180°. The angular direction for a fish headed directly downstream would be zero. The inner concentric rings on the direction angle indicate the percentage probability distribution. The rings on the velocity magnitude histogram are speeds in meters per second. The continuous 24-hr light treatment is first (Figures H.10 through H.12), followed by the 1-hr on/off treatment (Figures H.13 through H.15). In each set, lights-on results are in red, lights-off in black. One transducer, at 18 m from the strobe lights (transducer 3), experienced a malfunction in its multiplexer during the study period, preventing estimation of swimming direction and effort. Therefore, data from that transducer were not included in this analysis.

Fish swimming effort during the daytime was generally upstream in opposition to the flow. This response was apparent under both lights-on and lights-off treatments. At night under low flow conditions, swimming effort was dependent on the light treatment. When lights were on, swimming effort was across the forebay, toward either the dam or the right bank. This response was evident for fish detected by all six splitbeam transducers. For fish detected by the splitbeam closest to the lights (i.e., transducer 10 at 6 m), there is somewhat more variability than at either the next transducer upstream (i.e., transducer 1 at 10 m) or for the other two transducers at 6 m (i.e., transducers 20 and 30). When the lights were off at night, there was no dominant direction of swimming effort.

Day

Night

Day Swimming Effort Continuous

Night Swimming Effort Continuous

BEAM = 10

BEAM = 10

Direction Angle Probability (On)

Direction Angle Probability (Off)

Direction Angle Probability (On)

Direction Angle Probability (Off)

Velocity Median Magnitude (On)

Velocity Median Magnitude (Off)

Velocity Median Magnitude (On)

Velocity Median Magnitude (Off)

sample_on = 186

sample_off = 280

sample_on = 1.852×10^3

sample_off = 274

Day Swimming Effort Continuous

Night Swimming Effort Continuous

BEAM = 1

BEAM = 1

Direction Angle Probability (On)

Direction Angle Probability (Off)

Direction Angle Probability (On)

Direction Angle Probability (Off)

Velocity Median Magnitude (On)

Velocity Median Magnitude (Off)

Velocity Median Magnitude (On)

Velocity Median Magnitude (Off)

sample_on = 211

sample_off = 315

sample_on = 2.257×10^3
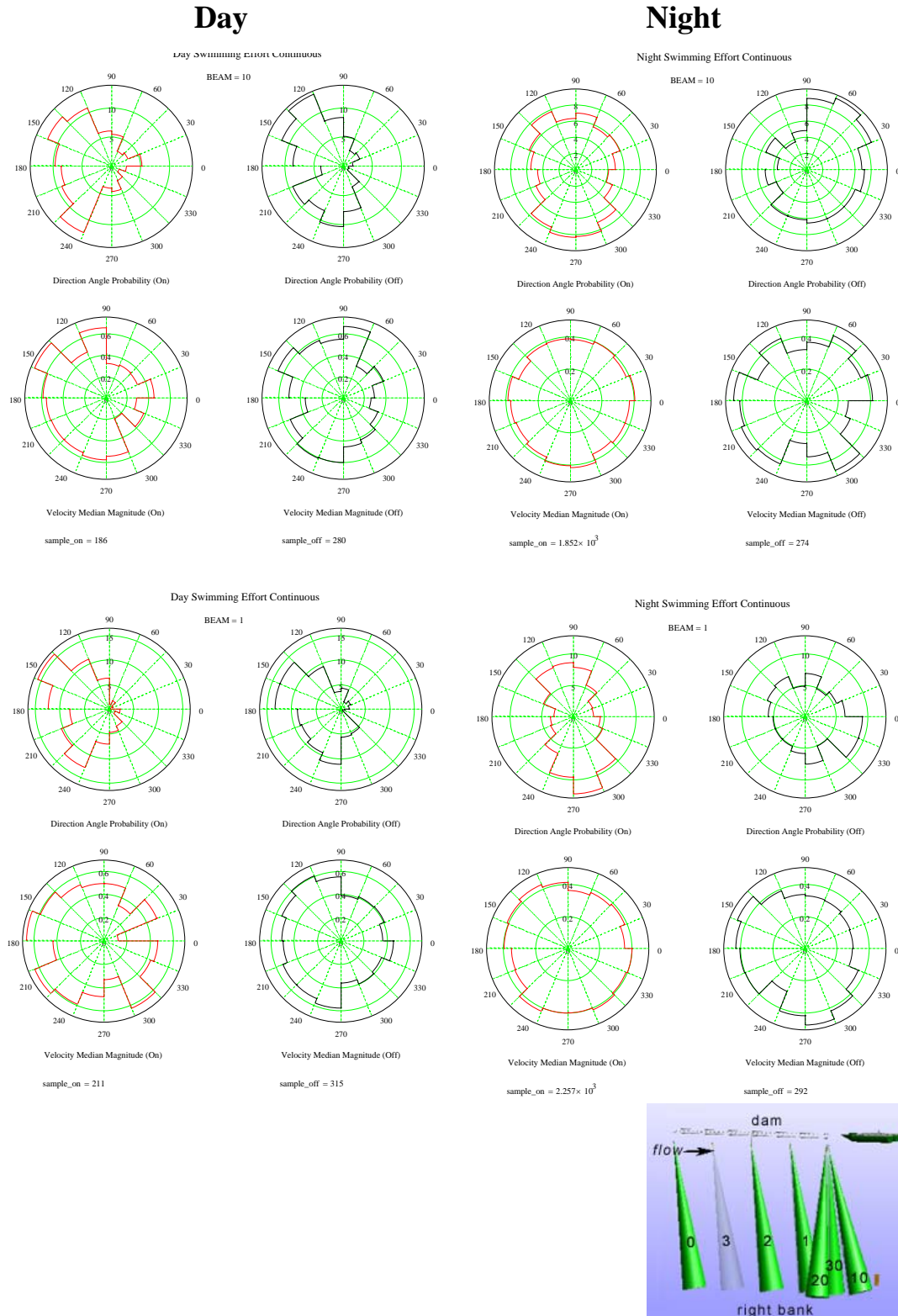
sample_off = 292

Figure H.10. Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 10 (6 m from lights) and 1 (10 m from lights) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 24 Hours. Effort direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

H.12

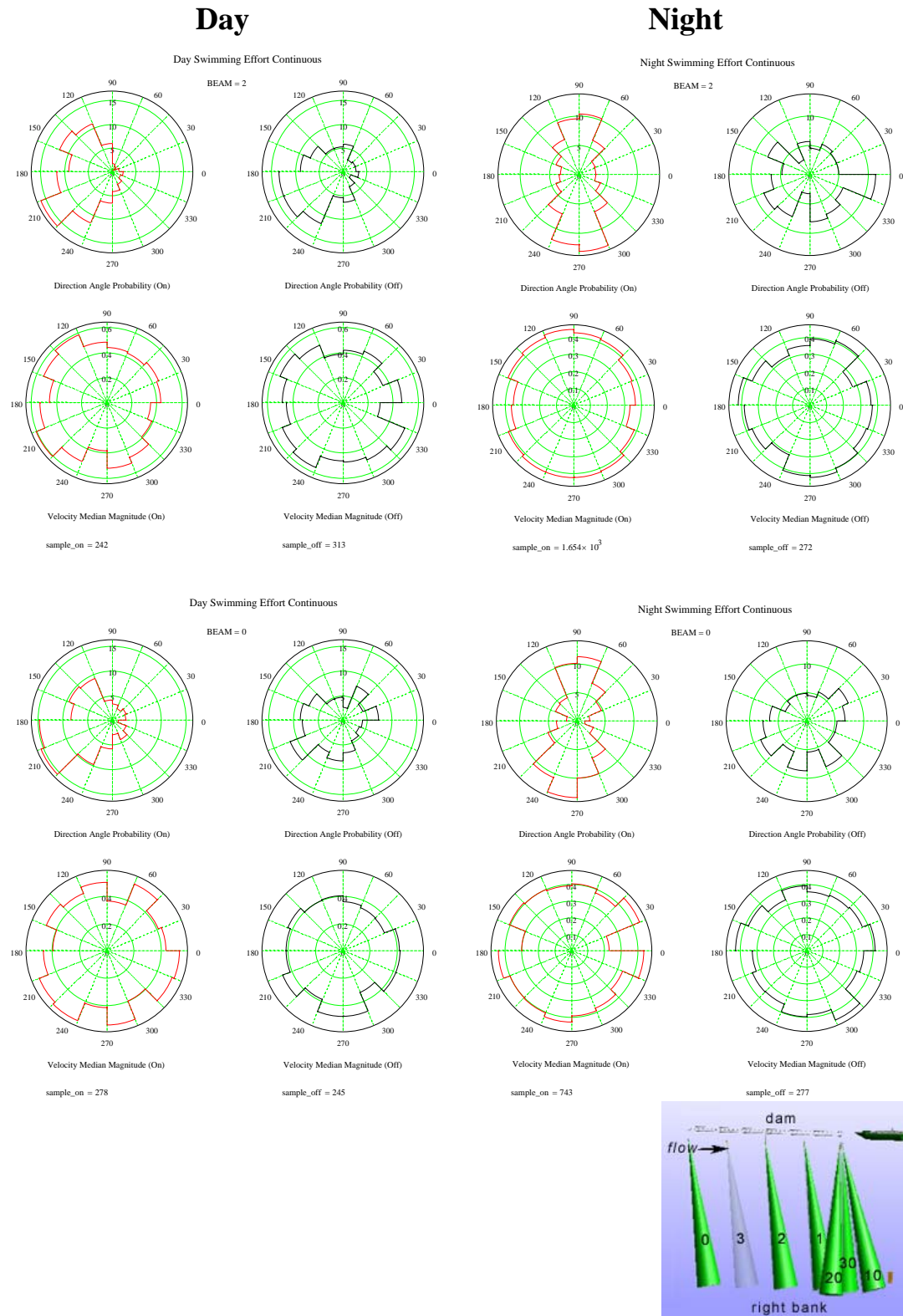# Day   # Night

Figure H.11. Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 2 (14 m from lights) and 0 (22 m from lights) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 24 Hours. Effort direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

Day   # Night

Figure H.12. Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 20 (6 m from lights, dam side) and 30 (6 m from lights, right bank side) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 24 Hours. Effort direction is the upper histogram, velocity (m/s) is the lower histogram.
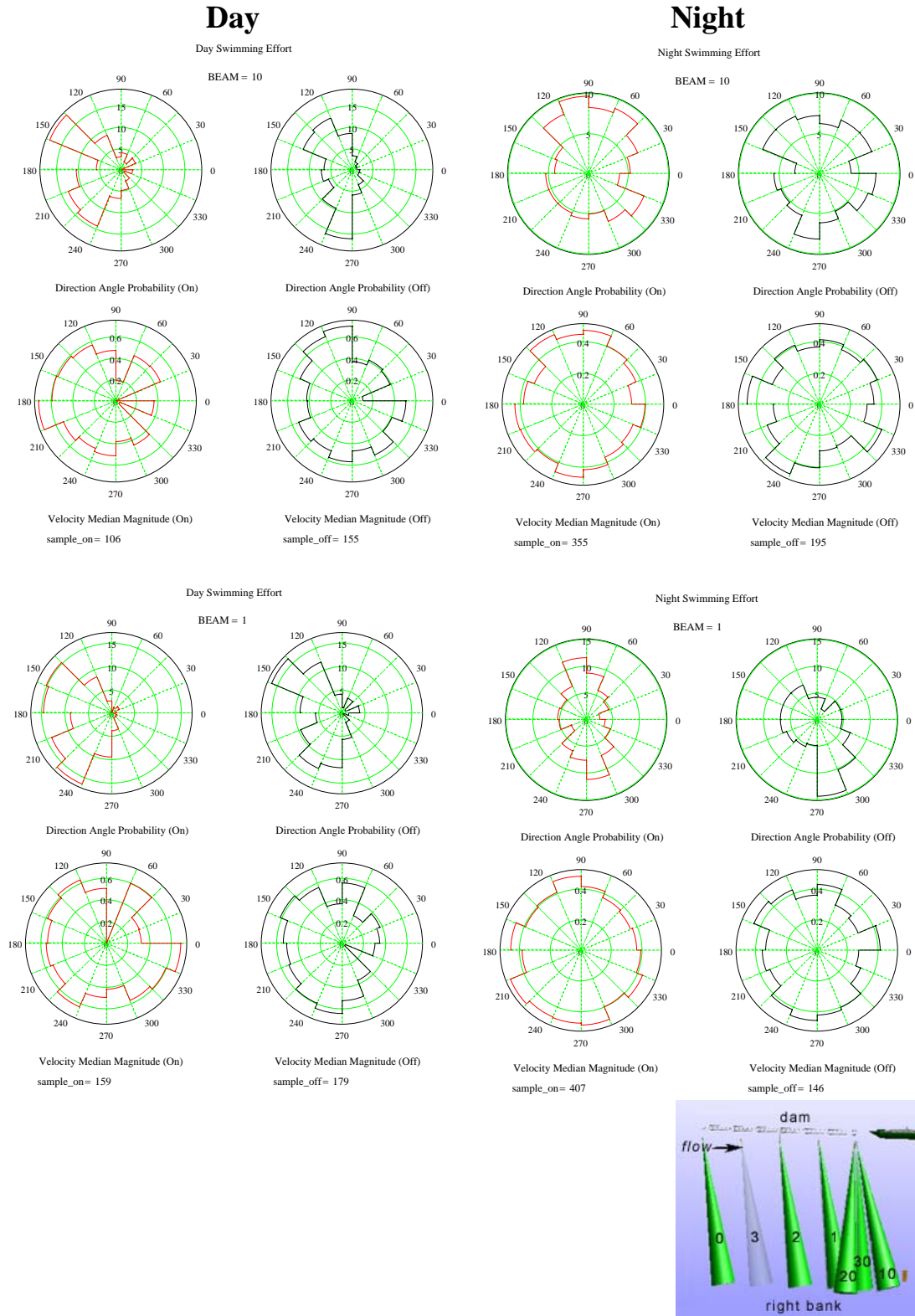
Day **Night**

Figure H.13. Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 10 (6 m from lights) and 1 (10 m from lights) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 1 Hour. Effort direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

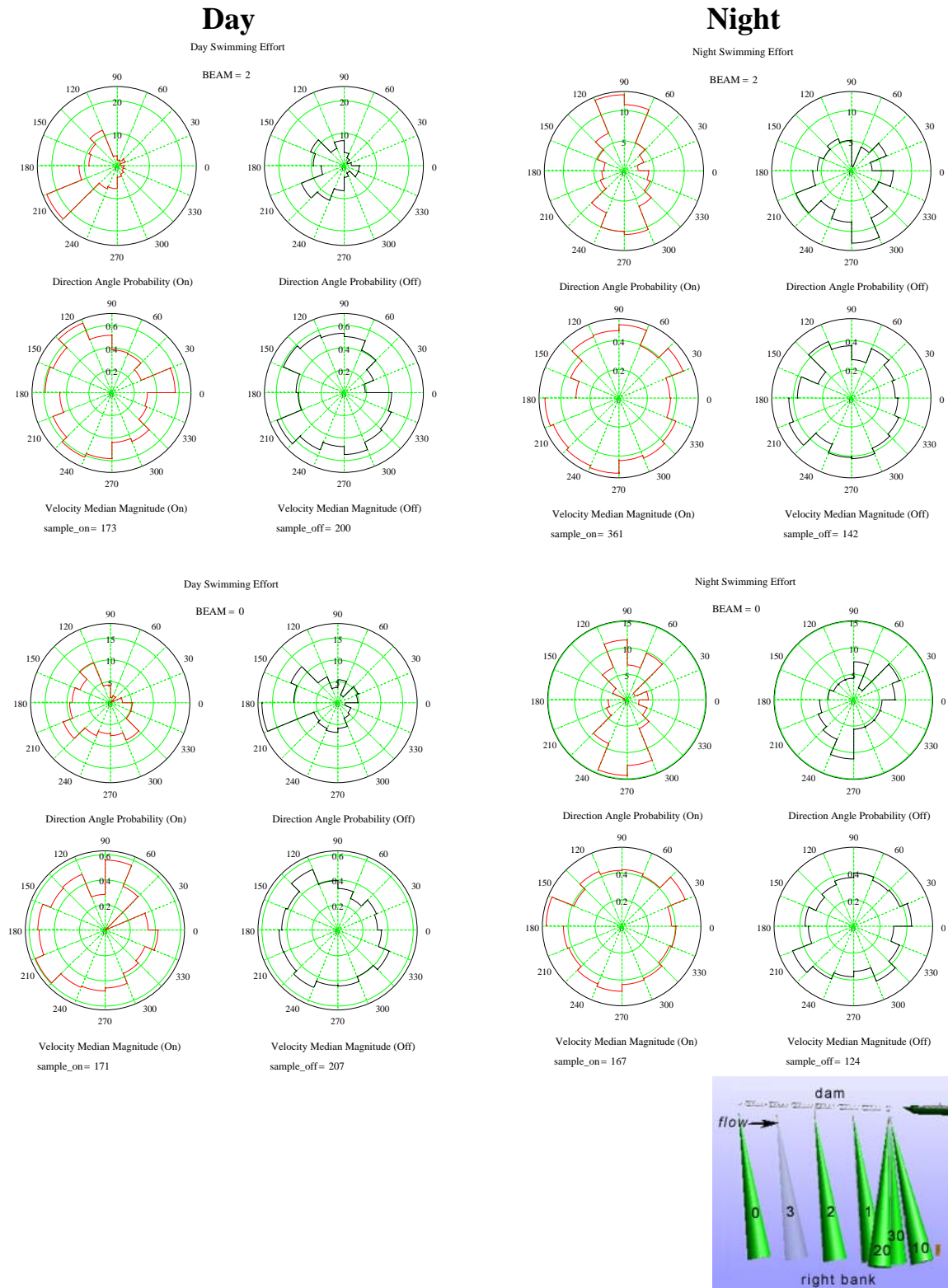## Day   Night

Figure H.14. Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 2 (14 m from lights) and 0 (22 m from lights) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 1 Hour. Effort direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

H.16

Day

Night

Figure H.15. **Swimming Effort (direction and speed) for Fish Detected by Splitbeam Transducers 20 (6 m from lights, dam side) and 30 (6 m from lights, right bank side) During the Day and at Night When the Strobe Lights Were On (red) and Off (black) for 1 Hour. Effort direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.**
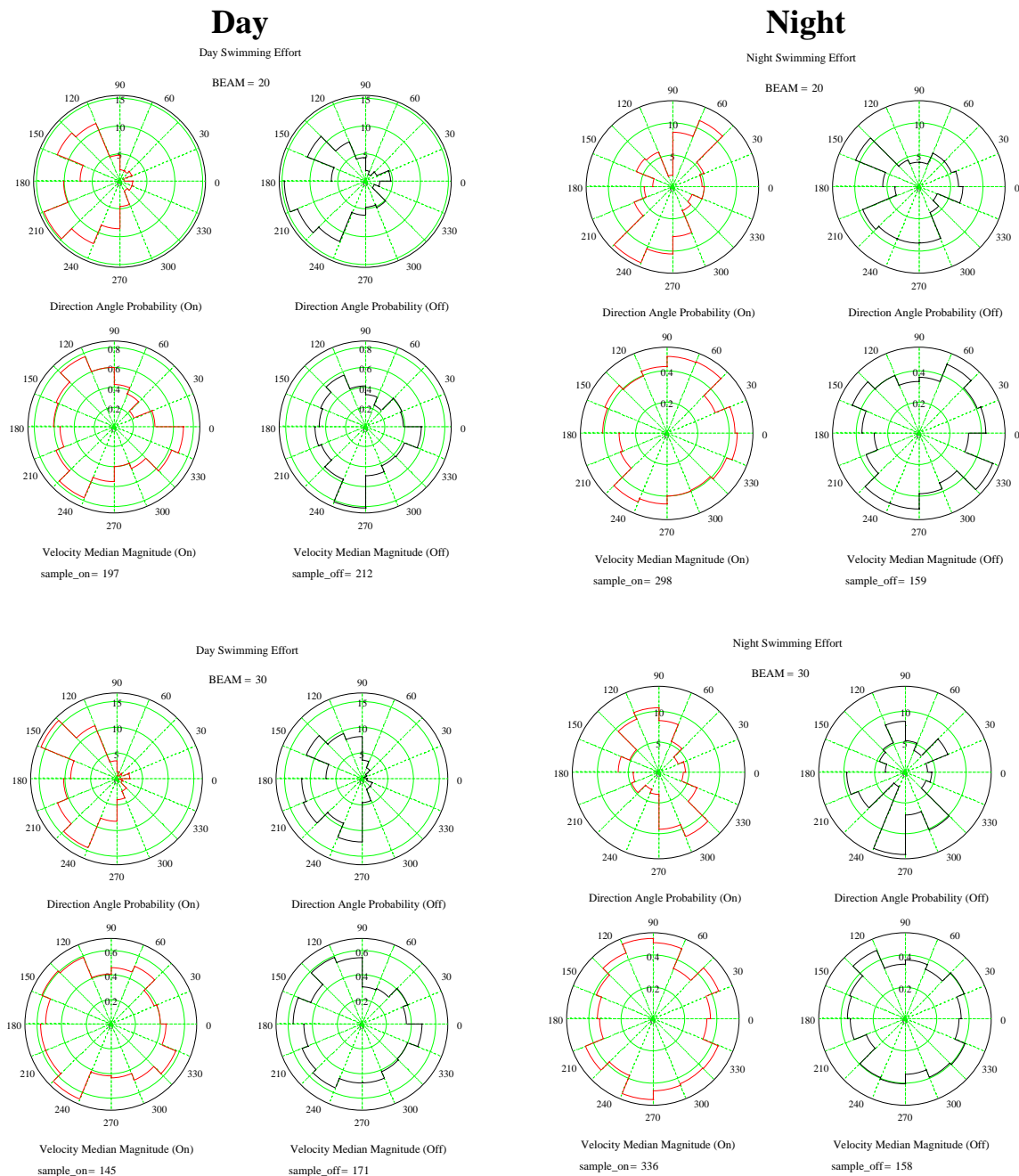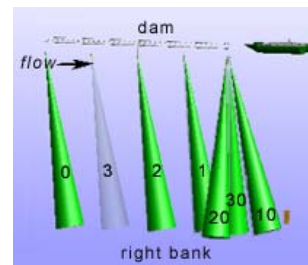
H.4   Water Flow

Figures H.16 through H.18 are histograms of water flow in the vicinity of each splitbeam transducer. Water velocity was measured using an ADCP at 6 m from the strobe lights, at the same location as the three splitbeam transducers (see Appendix D). However, the water flows depicted in these graphs are the flows when fish were present (i.e., these are the flows that were used to calculate the fishes' swimming effort). Flows are presented only for the 24-hr continuous on and 24-hr continuous off treatments.

A wind rose histogram is used to show the distribution of water flow at each transducer. Both the direction of flow (direction angle) and velocity (velocity magnitude) are shown. In these figures, down-stream is at zero degrees, the dam is at 90º, and upstream, into the forebay, is at 180°. The inner concentric rings on the direction angle indicate the percentage probability distribution. The rings on the velocity magnitude histogram are speeds in meters per second. In each set, results for lights-on are presented in blue, results for lights-off in black. One transducer, at 18 m from the strobe lights (transducer 3), experienced a malfunction in its multiplexer during the study period, preventing estimation of swimming direction and effort. Therefore, data from that transducer were not included in this analysis.

During the daytime, the dominant direction of water flow in the forebay of the third powerplant was downstream and slightly toward the right bank. The velocity magnitude was the highest (maximum 0.8 m/s) at the splitbeam transducer closest to the light frame (i.e., 6 m) (Figure H.16) and lowest (maximum < 0.4 m/s) at the transducer farthest from the lights (i.e., 22 m) (Figure H.17).

At night, there appears to be a paradox where flows are high when the lights are off, and low when the lights are on. This arose because the flows in these figures were selected for the times that fish were present. It appears that when lights were on at night, and flows were low (i.e., < 0.1 m/s), a lot of fish were detected in the vicinity of the splitbeam transducers. However, when lights were off, fish were more likely to be present when the flows were higher. Thus, at night, when the lights were off and flows were low, few fish were present in the region of the transducers. As flows increased, more fish passed through this region. These flows were still below those found during the daytime (i.e., 0.15 m/s compared to between 0.4 and 0.8 m/s during the daytime).

Day   **Night**
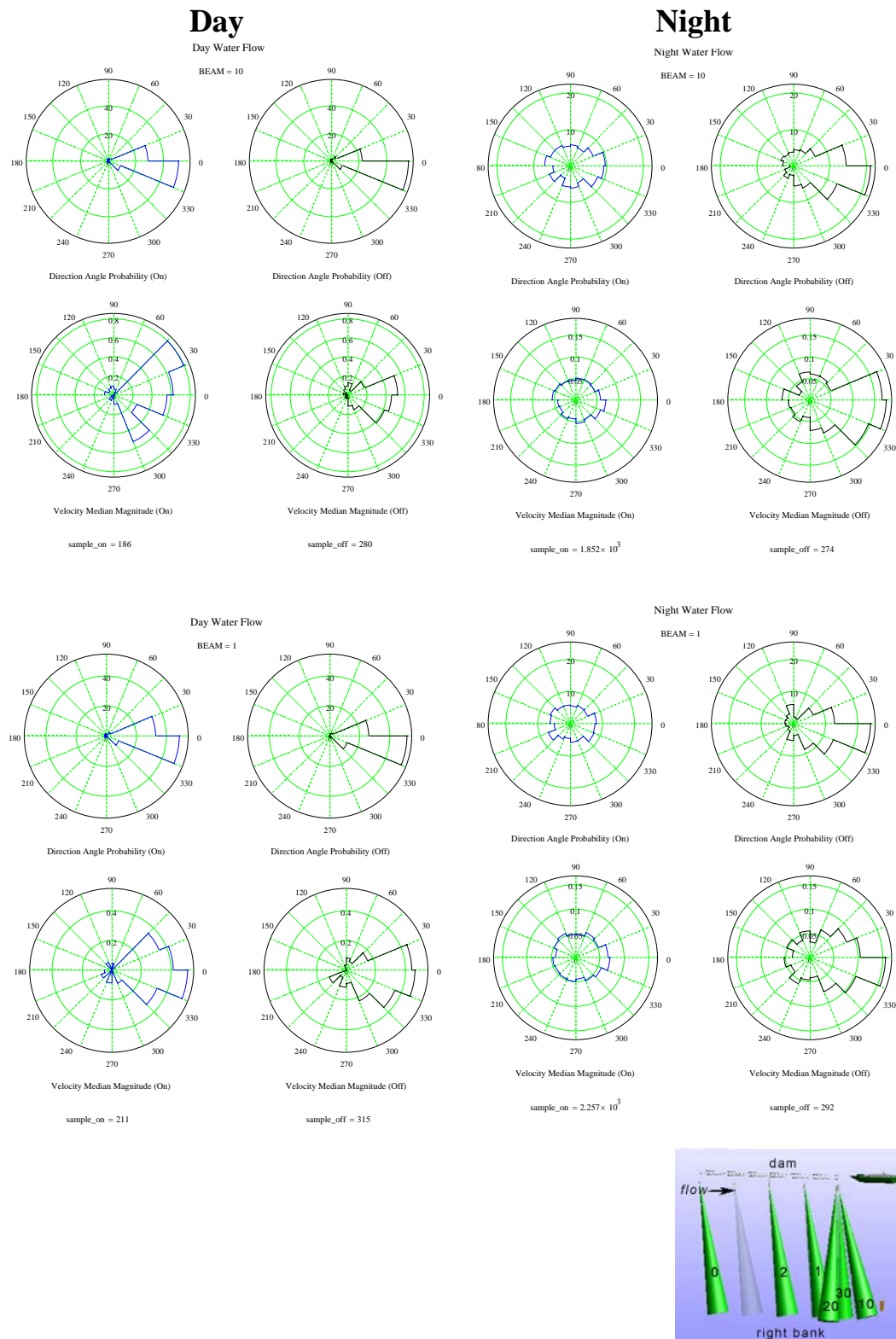

Figure H.16. Water Flow at Splitbeam Transducers 10 (6 m from lights) and 1 (10 m from lights) During the Day and at Night When the Strobe Lights Were On (blue) and Off (black) for 24 Hours. Direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

Day   Night

Day Water Flow   Night Water Flow

BEAM = 2   BEAM = 2

Direction Angle Probability (On)   Direction Angle Probability (Off)   Direction Angle Probability (On)   Direction Angle Probability (Off)

Velocity Median Magnitude (On)   Velocity Median Magnitude (Off)   Velocity Median Magnitude (On)   Velocity Median Magnitude (Off)

sample_on = 242   sample_off = 313   sample_on = 1.654×10^3 sample_off = 272

Day Water Flow   Night Water Flow

BEAM = 0   BEAM = 0

Direction Angle Probability (On)   Direction Angle Probability (Off)   Direction Angle Probability (On)   Direction Angle Probability (Off)

Velocity Median Magnitude (On)   Velocity Median Magnitude (Off)   Velocity Median Magnitude (On)   Velocity Median Magnitude (Off)

sample_on = 278   sample_off = 245   sample_on = 743   sample_off = 277
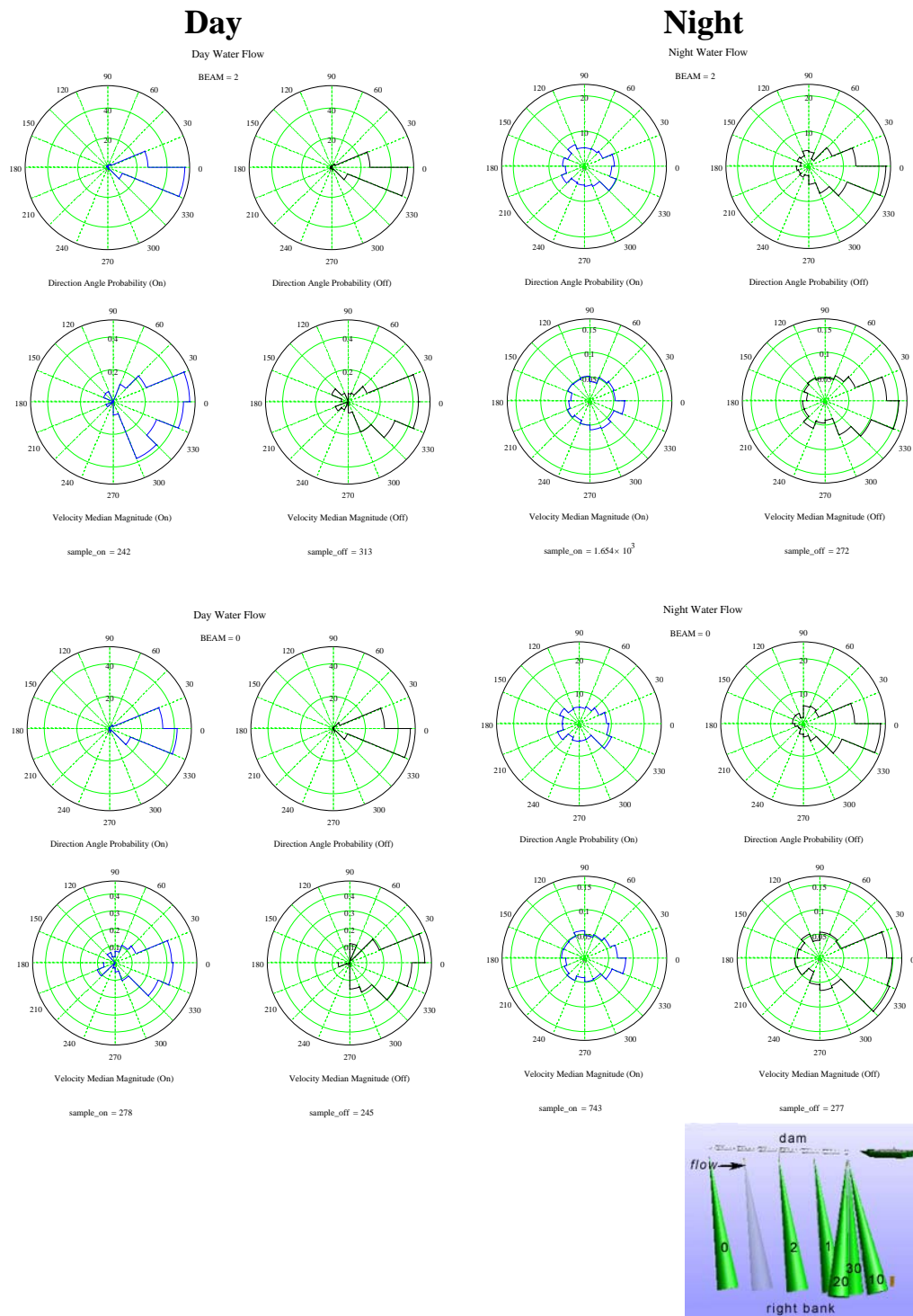

Figure H.17. Water Flow at Splitbeam Transducers 2 (14 m from lights) and 0 (22 m from lights) During the Day and at Night When the Strobe Lights Were On (blue) and Off (black) for 24 Hours. Direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.

H.20

Figure H.18. **Water Flow at Splitbeam Transducers 20 (6 m from lights, dam side) and 30 (6 m from lights, right bank side) During the Day and at Night When the Strobe Lights Were On (blue) and Off (black) for 24 Hours. Direction is the upper histogram, velocity (m/s) is the lower histogram. Note the scales are not consistent.**
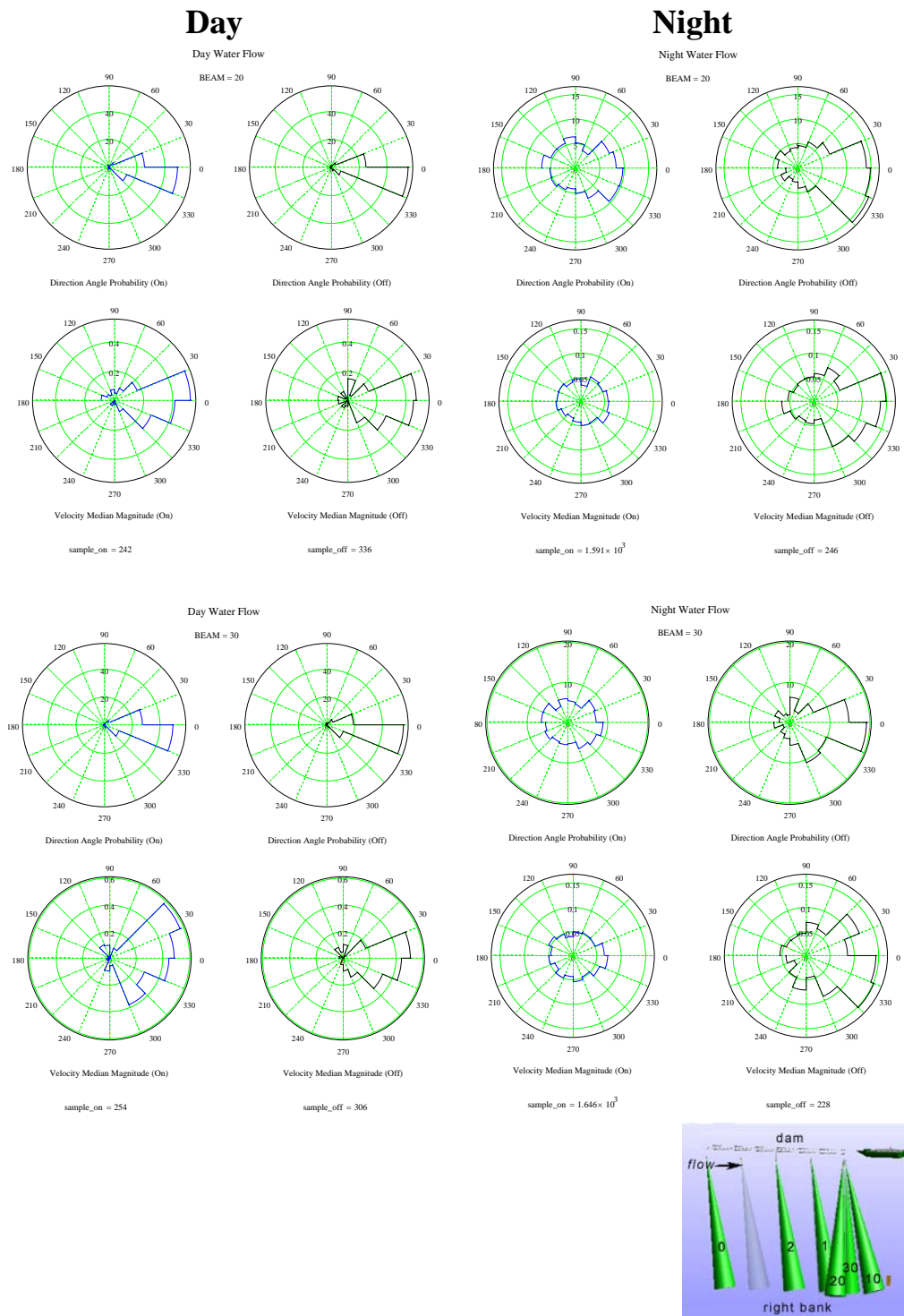
Appendix I

Zooplankton Sampling and Analysis

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Zooplankton Sampling and Analysis

One possible explanation for the positive response of fish to strobe lights in 2002 was that fish "may be keying in on illuminated prey in the vicinity of the strobe lights" (Johnson et al. 2003). To test this explanation, study researchers recommended that *"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"* (Johnson et al. 2003).

This appendix describes a preliminary experiment and offers recommendations for follow-on work.

In 2003, the collection of zooplankton was designed as a pilot study to determine the frequency and location of the sampling effort needed at the study site to estimate zooplankton abundance. The pilot study yielded very limited data on species composition and abundance, but enough information was gathered, along with improving our field and laboratory techniques, to develop a more rigorous study in 2004.

I.1   Materials and Methods

Zooplankton were sampled at night from the strobe light study barge. Additional samples were taken during the daytime in the forebay near the barge. All samples were collected with a 118-micron mesh vertical tow plankton net with radius of 10 cm and a height of 66.3 cm (Figure I.1). Vertical tows were made from a depth of 30 m.

The nighttime collection consisted of three samples taken under three different light conditions (all lights off, 3 lights on, and 6 lights on) for a total of nine samples on the night of July 11. These nine samples were taken between 12:00 a.m. to 2:30 a.m. on a clear night with a nearly full moon. This nighttime collection was divided into three sampling periods of 30 minutes for each light condition, beginning with all lights off, followed by 3 lights on, and ending with 6 lights on. Between each 30-minute sampling period, the lights operated for a 30-minute adjustment period.

Because of the strong water flow during daytime hours, the five daytime samples were taken from a boat drifting between the right attachment buoy and the barge (Figure 3.2). These samples were taken every Friday except July 4 between 9:00 a.m. and 11:00 a.m. beginning on June 20 and ending on July 25.

Organisms in each tow were preserved in individual bottles containing 10 ml of 37% formaldehyde. Samples were transferred to PNNL in Richland and prepared for identification according to American Public Health Association standard methods (APHA 1998). Zooplankton identification was done to test

Figure I.1.   Vertical Tow Plankton Net

equipment and determine needs for 2004; thus, identification was done to only subclass or order level using taxonomic keys by Thorp and Covich (2001). An Olympus SX-PP dissecting microscope was used in identification.

   Density was calculated for each sample using a formula similar to that used by Cichosz et al. (1999). Zooplankton densities (number of organisms per cubic meter) were calculated for each individual tow using the formula

$$D = \frac{C \times V'}{V'' \times V'''} \qquad\qquad (I.1)$$

where D = density (number of organisms per cubic meter)
        C = number of organisms counted
        V' = volume of concentrated subsample
        V'' = volume of counted subsample
        V''' = volume of entire sample.

I.2   Results

   The data showed a generally greater density of zooplankton under the barge near the light frame under all light conditions sampled at night compared to the forebay location upstream of the barge that was sampled during the daytime (Figure I.2). There may also be a very slight difference between three
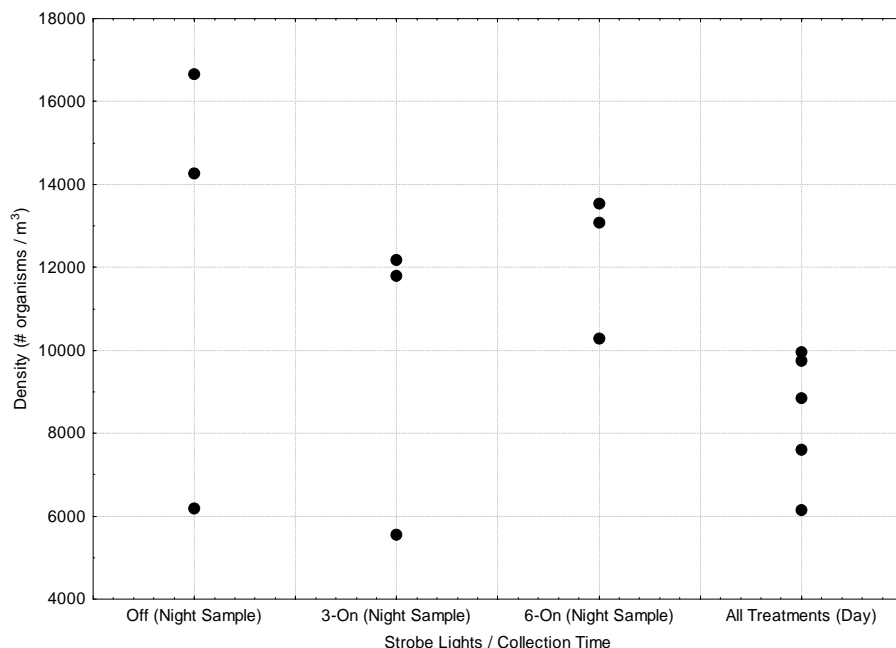
Figure I.2.   Density of Zooplankton Sampled at Night from the Barge under Three Strobe Light Conditions (Lights Off, 3 Lights On, and 6 Lights On) and During the Day Upstream of the Barge Under All Strobe Light Conditions at Grand Coulee Dam, 2003

light conditions; however, the number of samples was too small to confirm this. The density of the forebay samples is similar to and slightly higher than densities found by Cichosz et al. (1999), but more sampling should be done next year to confirm this.

Identification showed that 99% of the samples consisted of *Daphnia* and Copepoda, similar to the 97% found by Cichosz et al. (1999).

I.3   Recommendations

As mentioned previously, this pilot study was to test the sampling system and offer a preliminary assessment of zooplankton near the light frame. This pilot study provided us with sufficient information to design a rigorous study in 2004.

Recommendations for the 2004 study include

- a thorough review of the multiple studies done on plankton sampling in Lake Roosevelt by the Spokane Tribe and Eastern Washington University

- sampling and analysis of zooplankton near the light frame under various light conditions and at different times

- sampling and analysis of zooplankton from standard sampling sites within the third powerplant forebay.

I.4 References

American Public Health Association, American Water Works Association, Water Environment Federation. 1998. "10200 – Plankton." In *Standard Methods for the Examination of Water and Wastewater*, 20th ed. American Public Health Association, Washington, D.C.

Cichosz TA, JP Shields, and K Underwood – Spokane Tribe of Indians. 1999. *Lake Roosevelt Monitoring/Data Collection Program – 1997 Annual Report*. DOE/BP-32148-3, Bonneville Power Administration, Portland, Oregon. Available at http://www.efw.bpa.gov/Environment/EW/EWP/DOCS/REPORTS/RESIDENT/R32148-3.pdf (24 November 2003).

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

Thorp JH and AP Covich. 2001. *Ecology and Classification of North American Freshwater Invertebrates*, 2nd ed. Academic Press, San Diego, California.