Using 3D Acoustic Telemetry to Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington

Chief Joseph Kokanee Enhancement Feasibility Study

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Using 3D Acoustic Telemetry to Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington, 2002

Annual Report for 2002

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Using 3D Acoustic Telemetry to Assess the Response of Resident Salmonids to Strobe Lights in Lake Roosevelt, Washington, 2002

Annual Report for 2002

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Executive Summary

In 1995, the Chief Joseph Kokanee Enhancement Project was established to mitigate the loss of anadromous fish due to the construction of Chief Joseph and Grand Coulee dams. The objectives of the Chief Joseph Enhancement Project are to determine the status of resident kokanee (*Oncorhynchus nerka*) populations above Chief Joseph and Grand Coulee dams and to enhance kokanee and rainbow trout (*Oncorhynchus mykiss*) populations. Studies conducted at Grand Coulee Dam documented substantial entrainment of kokanee through turbines at the third powerhouse.

In response to finding high entrainment at Grand Coulee Dam, the Independent Scientific Review Panel (ISRP) recommended investigating the use of strobe lights to repel fish from the forebay of the third powerhouse. Therefore, our study focused on the third powerhouse and how strobe lights affected fish behavior in this area. The primary objective of our study was to assess the behavioral response of kokanee and rainbow trout to strobe lights using 3D acoustic telemetry, which yields explicit spatial locations of fish in three dimensions. Our secondary objectives were to 1) use a 3D acoustic system to mobile track tagged fish in the forebay and upriver of Grand Coulee Dam and 2) determine the feasibility of detecting fish using a hydrophone mounted in the tailrace of the third powerhouse.

Within the fixed hydrophone array located in the third powerhouse cul-de-sac, we detected 50 kokanee and 30 rainbow trout, accounting for 47% and 45% respectively, of the fish released. Kokanee had a median residence time of 0.20 h and rainbow trout had a median residence time of 1.07 h. We detected more kokanee in the array at night compared to the day, and we detected more rainbow trout during the day compared to the night.

In general, kokanee and rainbow trout approached along the eastern shore and the relative frequency of kokanee and rainbow trout detections was highest along the eastern shoreline of the 3D array. However, because we released fish near the eastern shore, this approach pattern may have resulted from our release location. A high percentage of rainbow trout (60%) approached within 35 m of the eastern shore, while fewer kokanee (40%) approached within 35 m of the eastern shore and were more evenly distributed across the entrance to the third powerhouse cul-de-sac area.

During each of the strobe light treatments there were very few fish detected within 25 m of the strobe lights. The spatial distribution of fish detections showed relatively few tagged fish swam through the center of the array where the strobe lights were located. We detected 11 kokanee and 12 rainbow trout within 25 m of the strobe lights, accounting for 10% and 18% respectively, of the fish released. Both species exhibited very short residence times within 25 m of the strobe lights No attraction or repulsion behavior was observed within 25 m of the strobe lights. Directional vectors of both kokanee and rainbow trout indicate that both species passed the strobe lights by moving in a downstream direction and slightly towards the third powerhouse.

We statistically analyzed fish behavior during treatments using a randomization to compare the mean distance fish were detected from the strobe lights. We compared treatments separately for day and night and with the data constrained to three distances from the strobe light (< 85m, < 50 m, and < 25 m). For kokanee, the only significant randomization test (of 10 tests) occurred with kokanee during the day for the 3-On treatment constrained to within 85 m of the strobe lights, where kokanee were significantly further away from the strobe lights than during the Off treatment (randomization test, $P < 0.004$, Table 1.5). However, one other test had a low P-value ($P = 0.064$) where kokanee were closer to the lights during the 3-On treatment at night within 85 m of the strobe lights compared to the Off treatment. For rainbow trout, none of the 11 tests were significant, but one test had a low P-value ($P = 0.04$), and fish were further away from the strobe lights during the 6-On treatment, within 50 m, during the day (Table 1.5).

During 2002, it is unclear whether tagged fish truly had little response to the strobe lights, or whether too few fish near the strobe lights and short residence times prevented us from detecting a behavioral response to the strobe lights. Although fish tended to be slightly further away from the strobe lights during 3-On and 6-On treatments compared to the Off treatment, only one of the 21 statistical tests indicated that these differences were significant. However, within 25 m of the strobe lights we may have had little power to detect a difference due to the few fish available for statistical comparison.

We detected 32 kokanee and 7 rainbow trout in the tailrace of Grand Coulee Dam, accounting for 30% and 12%, respectively of the fish released. Of the fish detected in the tailrace, 100% of the rainbow trout and 59% (19 of 32) of kokanee were detected in the forebay array. For kokanee detected on the tailrace hydrophone, their mean depth in the 3D array was considerably deeper than kokanee that were not detected on the tailrace hydrophone.

During the 10 mobile tracking sessions we detected 14 of 173 fish tagged and released for the strobe light study; 7 of 106 kokanee and 7 of 67 rainbow trout. Although 42 % of the fish detected were only detected once, 2 kokanee and 1 rainbow trout were detected 6 times. There were 37 detections for the 14 individual fish.

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Acknowledgments

A special thanks to Tim Peone with the Spokane Tribal Fish Hatchery and Mitch Combs with the Sherman Creek Hatchery for supplying fish and tagging facilities. Thanks to Bob Johnson, at the Pacific Northwest National Laboratory, for his role in the organization and operation of the strobe light study; the Bureau of Reclamation for coordinating the use of the dam facilities (especially Jan Schrader and Steve Sauer), and the Spring Canyon National Park for the use of dock space. We would like to acknowledge our colleagues at the Columbia River Research Laboratory, U.S. Geological Survey, for their assistance and support. This study was supported by the Bonneville Power Administration, Environment, Fish and Wildlife Department, Portland, Oregon (Project # 1995-001-02; Contract # 00004767).

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Chapter 1

Movement and Behavior of Kokanee and Rainbow Trout Near Strobe Lights in the Forebay of Grand Coulee Dam

Introduction

The Chief Joseph Kokanee Enhancement Project was established in 1995 to mitigate the loss of anadromous fish due to the construction of Chief Joseph and Grand Coulee dams. This project operates through cooperative agreements between the Confederated Tribes of the Colville Indian Reservation, Spokane Indian Tribe, and Washington Department of Fish and Wildlife. The objectives of the Chief Joseph Enhancement Project are to determine the status of resident kokanee *Oncorhynchus nerka* populations above Chief Joseph and Grand Coulee dams and to enhance kokanee and rainbow trout *Oncorhynchus mykiss* populations. To determine the status of kokanee populations, the Chief Joseph Enhancement Project estimated entrainment of fish through turbines at the dams, fish escapement at spawning sites, survival rates of naturally produced kokanee, the genetic status of naturally produced stocks, and impacts of hatchery production and sport fishing on naturally produced stocks.

Studies conducted at Grand Coulee Dam documented substantial entrainment of kokanee through turbines at the third powerhouse. Using hydroacoustic technology, BioSonics Inc. (2000) estimated that over 1.5 million fish were entrained during the four-year study. The third powerhouse entrained the most fish, and at times, entrainment rates exceeded 200 fish/h. In comparison, the left and right powerhouses had entrainment rates up to only 20 fish/h.

High entrainment rates at the third powerhouse were attributed to numerous factors. The third powerhouse has higher generation and discharge capacity than the other powerhouses. Total generating capacity for the dam is 6,809 mega watts, and the third powerhouse accounts for 62% of this generating capacity. In addition, turbine intakes at the left and right powerhouses are only 5.5 m in diameter, whereas the turbine intakes of the third powerhouse are 12.2 m in diameter. The high capacity of these turbines can create high flow and strong currents in the forebay cul-de-sac. Furthermore, the depth of the turbine intakes at the third powerhouse is approximately 30 m shallower than those of the left and right powerhouse. These factors may have contributed to high entrainment at the third powerhouse, relative to the left and right powerhouses.

Having established that entrainment at Grand Coulee Dam was sacrificing efforts to enhance the Lake Roosevelt fishery, the project's scope was modified to develop strategies to reduce entrainment at Grand Coulee Dam. The Independent Scientific Review Panel (ISRP) recommended the investigation of strobe lights to repel fish from the forebay of the third powerhouse at Grand Coulee Dam.

Both laboratory and recent field studies have shown that strobe lights can elicit an avoidance response from fish. Most studies in controlled environments have shown that juvenile salmonids avoid strobe lights (Nemeth and Anderson 1992, Ploskey and Johnson 2001, Mueller et al. 2001). Recent field studies in Idaho found that free-ranging kokanee exhibited significant avoidance of strobe lights (Maiolie et al. 2001). Another recent field application found that strobe lights dispersed juvenile salmon from a culvert intake at the Hiram M. Chittenden Locks in Seattle, Washington (Johnson et al. 2001).

The primary objective of our study was to assess the behavioral response of kokanee and rainbow trout to strobe lights. We conducted our study in conjunction with Battelle (Johnson et al. 2003), which used hydroacoustic techniques to assess the response of resident fish to strobe lights. We used 3D acoustic telemetry, which yields explicit spatial locations of fish in three dimensions. Our sampling methods complement those of Johnson et al. (2003) for two reasons. First, hydroacoustic methods are able to obtain very high sample sizes of fish targets within the vicinity of the strobe lights, but for 3D telemetry, the expense of transmitters limits size of the sampled population. Second, 3D acoustic telemetry allows us to estimate species-specific responses to the strobe lights, whereas hydroacoustic methods are unable to differentiate among fish species. Secondary objectives included 1) mobile tracking tagged fish with 3D acoustic telemetry in the forebay, upriver of Grand Coulee Dam and Banks Lake and 2) to determine the feasibility of detecting tagged fish in the tailrace to confirm entrainment of tagged fish through the turbines.

Study Area

Grand Coulee Dam is located on the Columbia River in northeast Washington. Construction started in December 1933 and ended in 1942, but construction of the third powerhouse began in 1967 and was completed in 1980. The impoundment forming Franklin D. Roosevelt Lake (hereafter referred to Lake Roosevelt) is 243 km long and has a surface area of 33,306 ha. The dam axis is 1,592 m long and contains over 9 million cubic meters of concrete. The dam consists of a pump generator plant with six 4.3 m diameter penstocks, left and right powerhouses each with nine 5.5 m diameter penstocks, a 509 m spillway with 11 drum gates, and the third powerhouse with six 12.2 m diameter penstocks. The total generating capacity of the third powerhouse is 4,222 mega watts, and the left and right powerhouses together generate 2,587 mega watts.

Our study focused on the third powerhouse, an area known to have high fish entrainment (Figure 1.1). The third powerhouse is located on the east wing of the dam, which creates a cul-de-sac in the forebay. In front of the third powerhouse, the maximum depth of the forebay is 54.8 m and the penstock openings are 2.4 m above the bottom of the cul-de-sac.

Methods

Strobe Light Study Design

The behavioral response of acoustic-tagged kokanee and rainbow trout to strobe lights was monitored between June 8 and July 23, 2002 in the cul-de-sac area of the third powerhouse of Grand Coulee Dam (Figure 1.1). The strobe light system consisted of six strobe lights (Flash Technology Inc, Franklin, Tennessee) set to a flash rate of 360 flashes/min. The strobe lights were lowered from a barge to a depth of about 15 m and oriented horizontally upriver (Johnson et al. 2003). This application of strobe lights differs from our study in 2001, where only three strobe light were used at a depth of 10 m (Simmons et al. 2002).

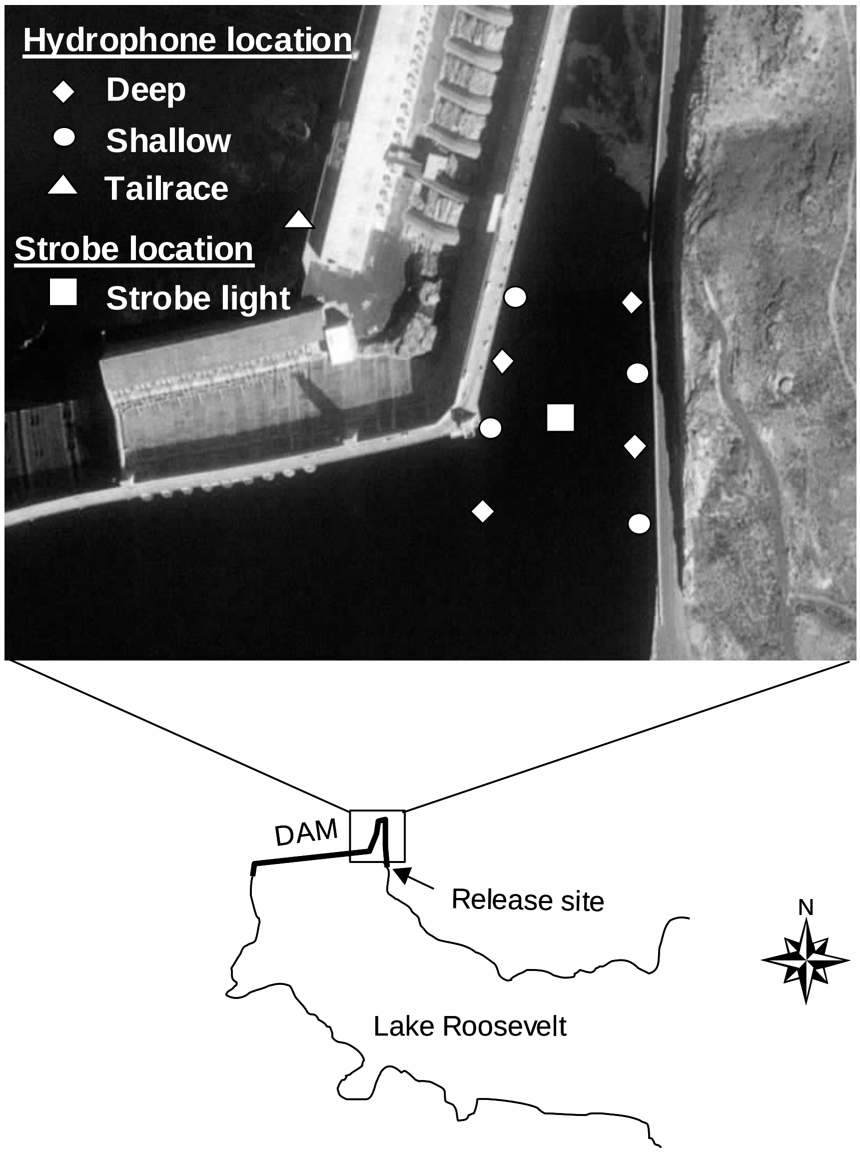

Figure 1.1. — Schematic showing the locations of the release site, the hydrophone array (◊ and ○), and the strobe light array (□) near the third powerhouse cul-de-sac of Grand Coulee Dam during 2002.

Movement patterns of tagged fish were monitored under a randomized block design with two treatments and a control to test the effects of strobe lights on fish behavior. Treatments consisted of 24 h periods of the strobe lights on low intensity (three strobe lights on, 3-On), the strobe lights on high intensity (six strobe lights on, 6-On), or the strobe lights off. The order of the treatments was randomized within each three-day block. We collected data from June 8 to July 23, 2002, but we did not process the data collected after July 4, 2002 due to lightening damage to the acoustic equipment and strobe lights. Therefore, we used 8 complete blocks of data for analysis (Table 1.1).

Table 1.1. — Randomized block schedule of strobe light treatments for the blocks used in data analysis.

Block number	Date	Treatment
7	06/08/02	3-On
	06/09/02	Off
	06/10/02	6-On
8	06/11/02	6-On
	06/12/02	Off
	06/13/02	3-On
	06/14/02	Calibration
9	06/15/02	Off
	06/16/02	3-On
	06/17/02	6-On
10	06/18/02	3-On
	06/19/02	6-On
	06/20/02	Off
	06/21/02	Calibration
11	06/22/02	Off
	06/23/02	6-On
	06/24/02	3-On
12	06/25/02	Off
	06/26/02	6-On
	06/27/02	3-On
	06/28/02	Calibration
13	06/29/02	Off
	06/30/02	6-On
	07/01/02	3-On
14	07/02/02	6-On
	07/03/02	Off
	07/04/02	3-On

Fish Tagging and Release Schedule

We tagged and released 106 kokanee and 67 rainbow trout over 15 releases between June 6 and July 7, 2002. Fish were collected and tagged at the Spokane Tribal Hatchery using techniques described by Adams et al. (1998a). Prior to tagging, fish were held for 12 – 17 h in a raceway with constant flowing water. A fish was anesthetized with tricaine methanesulfonate (MS-222; 70 mg/L) in a 19 L bucket until losing equilibrium (about 90 s). The fish's fork length was measured to the nearest millimeter, and its weight was measured to the nearest 0.1 g. The fish was then placed ventral side up on a soft foam pad with an elongated groove cut in the center. The foam pad was coated generously with a slime coat protectant (Stress Coat, Aquarium Pharmaceuticals, Inc.). The fish was supplied with a continuous, controlled flow of anesthetic solution (MS-222, 20 mg/L) through surgical tubing placed in the fish's mouth.

Due to size differences between kokanee and rainbow trout, we used two different sizes of 3D acoustic transmitters (hereafter referred to as tags) to monitor fish behavior at Grand Coulee Dam in 2002. Since kokanee were smaller than rainbow trout, we used a smaller transmitter with kokanee. On average, kokanee measured 182.4 mm fork length (SD = 18.5) and weighed 72.4 g (SD = 23.6). For kokanee we used 3D tags that were 6.8 mm wide by 18 mm in diameter, weighed 1.5 g, had a battery life of 16 d, and represented 2.1% of the fish's weight (Model 795-E, Hydroacoustic Technology Inc. (HTI)). Rainbow trout measured an average of 249.3 mm (SD = 29.7) and weighed 212.9 g (SD = 56.4). For rainbow trout we used 3D tags (Model 795-F) that were 9 mm long by 18 mm in diameter, weighed 2.2 g, had a battery life of 24 d, and represented 1.0% of the fish's weight (HTI Inc.).

To implant the transmitter, a 10-mm incision was made parallel to the mid-ventral line beginning 3 mm anterior to the pelvic girdle and 3 mm away from the mid-ventral line. The incision was just deep enough to penetrate the peritoneum. The tag was then gently inserted into the body cavity and a liquid antibiotic, oxytetracycline (100 mg/mL), was pipetted into the incision at a dosage of 50 mg/kg body weight. The incision was then closed using absorbable Vicryl sutures (4-0 coated Vicryl with a taper RB-1 needle). Three simple, interrupted, evenly spaced stitches were placed across the incision, and then swabbed with a small amount of antibiotic ointment (containing bacitracin zinc, neomycin sulfate, and polymyxin B sulfate). After the second stitch was completed, anesthetic flow was switched to oxygenated fresh water to initiate recovery. Immediately after surgery, fish were placed in a 662.5 L tank supplied with oxygen and a continuous flow of fresh water.

Following tagging, fish were transported to the release site. During transportation, bottled oxygen was supplied to the tank at a rate of approximately 200 ml/min. To allow fish to recover from surgery, they were held in the tank for 24 – 32 h prior to release. The fish were supplied with running reservoir water and air stones, and the water temperature was monitored. There were no mortalities prior to release. Following the holding period, fish were released into the reservoir at a randomly selected day (1000 hours) or night (2200 hours) release time. For the first two releases, fish were released from a boat near the Boat Restricted Zone buoy line. The third release occurred at Spring Canyon, and the remaining 12 releases occurred at the BOR boat ramp.

3D Acoustic Telemetry System

The acoustic telemetry system is a passive acoustic device where the hydrophones listen for the sound waves emitted by an acoustic transmitter. The acoustic telemetry system consisted of a model 290 receiver equipped with 8 hydrophones (hereafter referred to as an array) that formed a volume of coverage (HTI Inc., Seattle, Washington). The 3D coverage of the hydrophone array encompassed a volume 183 m wide by 503 m long by 52 m deep near the third powerhouse of Grand Coulee Dam. Signals received by the array were time-synchronized to geo-reference the transmitter in three dimensions (northing, easting, and elevation). Each hydrophone had a detection range of 330°, which provided an almost omni-directional receiving field except for a 30° blind spot behind the tip of the hydrophone. The receiver had an internal computer and hard drive linked to each channel and was networked to a separate monitoring computer. Signals received from the hydrophones were recorded via HTI's Acoustic Tag software onto the hard drive of the monitoring computer in hour-long files named by the given Julian date and time. Files were downloaded and backed-up daily.

The eight hydrophones were deployed in the cul-de-sac area of the third powerhouse of Grand Coulee Dam (Figure 1.1) and were set to monitor a known range of tag signals. Tags transmitted at a frequency of 307.2 kHz with a pulse width of 2.0 ms and unique pulse code that identified individual tags. The algorithm for three-dimensional positioning required that the four hydrophones used in the calculations were located in different planes. Therefore, we deployed four hydrophones at the bottom of the forebay and mounted four hydrophones at the surface. The position of each hydrophone was measured using traditional survey techniques with a Nikon Laser Surveyor Total Station (model DTM-10).

During 2002, we mounted a hydrophone in the tailrace to test the feasibility of detecting tagged fish in the tailrace of Grand Coulee Dam. We mounted this hydrophone near turbine units 21 and 22 (Third Powerhouse) to determine if we could verify entrainment of tagged fish and if we could detect tagged fish in the tailrace that passed the dam via routes other than the third powerhouse. The additional hydrophone was placed in the tailrace of the third powerhouse, was not included as part of the forebay array, and only determined presence or absence of fish in the tailrace.

Accurate position estimates required that the speed of sound be measured throughout the water column because temperature substantially affects the speed of sound. The HTI hydrophones were programmed to measure and record temperature at each hydrophone four times daily. We also measured speed of sound profiles in the forebay of the third powerhouse using sound velocimeters (Smart Sensor model RS-485, Applied Microsystems Ltd., Sidney, British Columbia, Canada).

Data Collection and Processing

We deployed two test tags in the hydrophone array to determine the precision of the 3D telemetry system. Test tags were deployed from the strobe light barge in the center of the array at 3 m and 10 m deep. We estimated precision as the median of the range in locations of the fixed tags for 1-minute periods. Estimating precision over 1-minute periods accounts for movement of the strobe barge since the barge probably moved little over short time spans. We could not obtain estimates of accuracy during

2002 because the strobe barge moved substantially over the study period. Although a GPS monitored barge movement, the tags were an unknown distance downstream of the barge, which prevented an estimation of accuracy. We assume that accuracy of the 3D system during 2002 was similar to that measured in 2001 (Perry et al. 2003).

Data processing involved two steps. First, the acoustic record of each tag on each of the eight hydrophones was manually proofed using HTI's Mark Tags Software. Raw data must be manually proofed to exclude acoustic noise and multipath. Multipath occurs when sound waves emitted from the transmitter are reflected off underwater objects such as the dam and bottom surfaces. For data quality and control, we developed standardized protocols for proofing raw data files. Manually proofing files is the most labor-intensive step of the data processing procedures. Second, following manual proofing, files must be processed in HTI's Acoustic Tag program to track acoustic echoes. This procedure uses a hyperbolic algorithm to solve for the transmitter's 3D position. In addition, a time-stamp is calculated so that the transmitter is referenced in both space and time.

Data Analysis

To examine fish behavior in the third powerhouse cul-de-sac and in response to the strobe lights, we focused our analysis in two areas. First, we analyzed fish behavior within the entire 3D array, a volume much larger than is affected by the strobe lights. Second, we narrowed the spatial scale of the analysis to focus on fish behavior in the area affected by the strobe lights and to examine the response of fish to the strobe light treatments. At both spatial scales, we analyzed spatial and temporal patterns of movement. In addition, we include the time of day (day or night) as a factor in our analysis because fish behavior and their response to the strobe light may be dependent on the time of day.

To analyze movement patterns within the hydrophone array, we examined spatial patterns of fish detections and residence time of tagged fish within the hydrophone array. To examine spatial trends in fish movement, we divided the array into a grid of 3x3 m cells (x and y planes only). We then calculated the number of detections in each cell and the average depth of detections in each cell. This analysis allowed us to identify areas of high or low concentrations of fish detections. The average depth of detections in each cell allowed us to determine spatial trends in the depth of fish. Residence times within the array were calculated by summing the time between consecutive detections. We also calculated the vertical distribution of fish within the hydrophone array because vertical distribution could affect whether fish come close enough to the strobe lights to be affected by the treatments. Another important consideration for future application of strobe lights is how fish approach the third powerhouse cul-de-sac. To determine where fish first entered the third powerhouse cul-de-sac, we extracted the first detection of each fish and plotted a frequency histogram of locations across the entrance the cul-de-sac (from the corner of the third and right powerhouse to the eastern shoreline).

To evaluate fish movement in response to the strobe light treatments, we restricted our analysis to the area where fish movements may have been affected by the strobe lights. First, within 25 m of the strobe lights we examined movement patterns, directional vectors, residence times, and vertical distributions of fish near the strobe lights. This spatial scale was consistent with Johnson et al. (2003), who also examined movement patterns within 25 m of the strobe lights. Next, we statistically compared treatments at a number of spatial scales where fish movement could be affected by the lights. To determine the maximum distance that fish could detect light emitted from the strobe lights, we conducted a light extinction analysis using data from Johnson et al. (2003). This analysis was not intended as an exhaustive, rigorous measure of light attenuation from the strobe lights, but was intended to provide a rough measure for restricting statistical analysis to locations where fish movements may have been influenced by the strobe light.

The strobe light emits intense light, but light levels decline exponentially as light moves through water. Johnson et al. (2003) showed that relative illumination from the strobe light declined from about 1850 relative light intensity units at 2 m from the strobe light to about 100 relative light intensity units at 15 m from the strobe light. However, light visible to fish would likely travel much further than 15 m from the strobe lights. Maximum feeding rates of salmonids usually occur at light levels of about 3.4 lx, which corresponds to light levels near the surface during dawn and dusk (Koski and Johnson

2002). Therefore, we calculated the distance at which light levels from the strobe lights would attenuate to about 3.4 lx using the following equation for light attenuation:

$$I_z = I_0 e^{-\eta z}$$

where I_z is the light intensity at distance Z from the strobe light, I_0 is the light intensity emitted from the strobe light, and η is the extinction coefficient which depends on the wavelength of light and water clarity. Using data from Johnson et al. (2003) on light levels at a range of distances from the strobe light, we calculated η and I_0 using linear regression analysis on log-transformed light levels. We then used these parameters in the above equation to calculate the distance, Z, at which light emitted from the strobe lights attenuated to 3.4 lx. Based on this analysis, at 85 m from the strobe light, light levels would be about 3.4 lx and should be detectable by fish.

Statistical analysis of 3D telemetry data is difficult because the data often violates the assumptions of standard statistical analyses. Fish detections are often spatially and temporally autocorrelated because a fish's spatial location at time *t* depends on its location at *t*-1. Furthermore, response of fish to environmental conditions (e.g., day/night, water velocity) can lead to further autocorrelation in the spatial distribution of fish detections. When data are autocorrelated, observations are not independent which violates a critical assumption of standard parametric analysis. Using standard statistical analysis on this data could result in inflation of the Type I error rate, where differences are determined significant when in fact, they are not. Therefore, we developed a randomization test to compare the effects of the strobe light treatments on fish behavior.

Fish may either be attracted to, repelled from, or not influenced by strobe lights. If fish were attracted to the strobe lights, then they would likely move closer to the lights compared to the Off treatment. Conversely, if fish were repelled, they would stay further away from the strobe lights compared to when the lights were Off. To test this hypothesis, we calculated the mean distance of fish detections from the strobe lights during the treatments. For analysis, we used only data upstream of the strobe light, since the strobe light was aimed upstream. To account for responses of fish to different light levels, we ran statistical tests on data constrained to within 85 m (the maximum distance that fish were likely to detect the strobe light), 50 m, and 25 m (the distance that corresponds to analyses of Johnson et al. 2003). Lastly, we conducted separate tests for day and night because ambient light levels may affect fish's response to the strobe light. In summary, we compared mean distance of fish for each On treatment to the Off treatment for each species, day/night, and distance from strobe (< 85 m, < 50 m, < 25 m) combination.

Our randomization test assessed the null hypothesis of no difference between treatments in the mean distance of fish from the strobe lights. Under the null hypothesis of a randomization test, an observation is just as likely to have occurred during any treatment (Anderson 2001). Therefore, to conduct the test we randomly assigned each fish's movement path to a treatment. A movement path, consisting of a time series of spatial coordinates of a tagged fish, may be randomly exchanged among treatments. However, we chose not to randomly exchange individual detections among treatments because an individual detection is inextricably linked to the other detections in the movement path. Thus, individual detections cannot be exchanged among treatments.

To conduct the randomization test, first the test statistic was calculated as the difference between treatment means. After randomly exchanging the movement paths among the on and off treatment, we recalculated the mean distance of fish from the strobe lights and the difference between treatment means. We repeated this procedure 10,000 to create a null distribution of differences between treatment means. The two-tailed p-value of the randomization test was calculated as the proportion of absolute values in the null distribution greater than the test statistic (i.e., the observed difference between treatment means). Lastly, because we conducted six paired tests for each day/night and distance (<85 m, <50 m, and <25m) combination, we used a Bonferroni correction to maintain the Type-I error rate at 0.05 over all six tests. With the Bonferroni correction, each test was considered significant at the $\alpha = 0.05$ level when the p-value was less than $0.05 \div 6 = 0.008$.

Results

Discharge and Dam Operations

Relative to our 2001 study (Perry et al. 2003), discharge at Grand Coulee Dam was high during our study period in 2002. Between June 7 and July 5, 2002, the mean daily discharge through the dam was 175,305 ft^3/s. At the third powerhouse, the mean daily discharge was 116,338 ft^3/s, 66% of the total discharge (Figure 1.2). Mean hourly discharge for the third powerhouse ranged from 75,197 ft^3/s to 139,063 ft^3/s, and was highest during mid-day (Figure 1.3). Spill greater than 500 ft^3/s occurred during 55% of the study period (Figure 1.4).

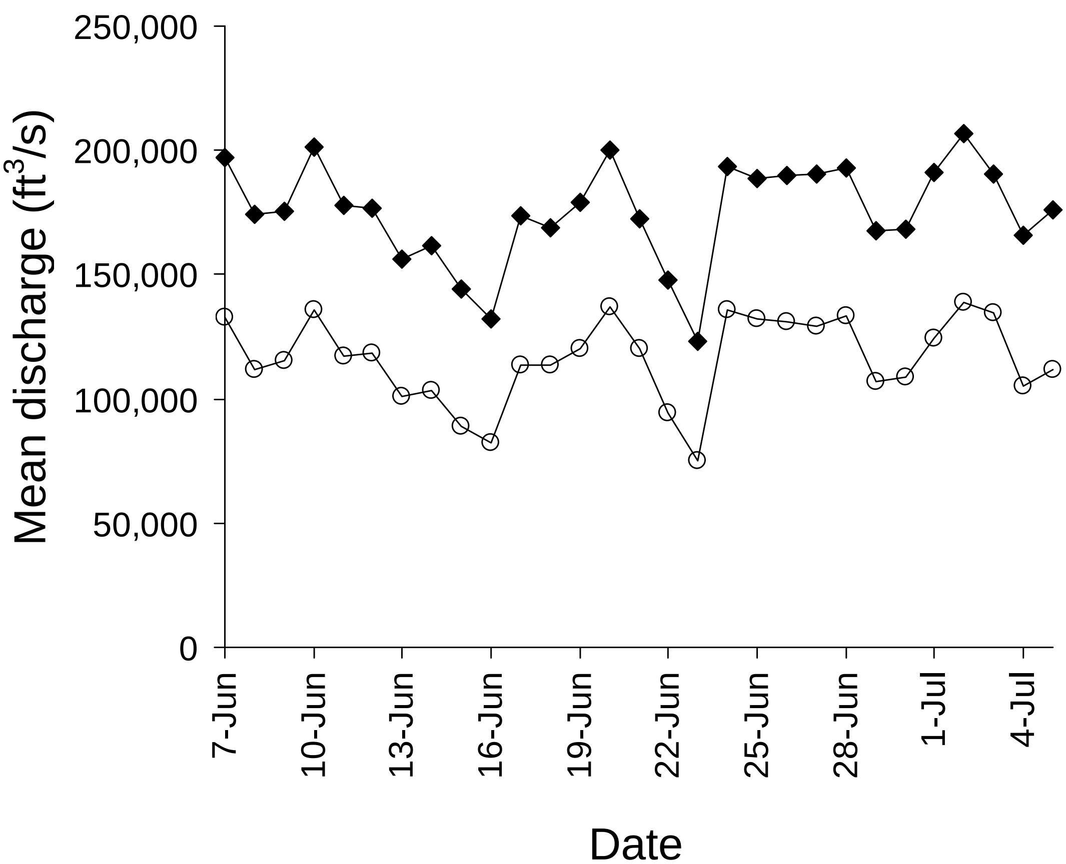

Figure 1.2. — Mean daily discharge at Grand Coulee Dam (◆) and the third powerhouse (O) between June 7 and July 5, 2002.

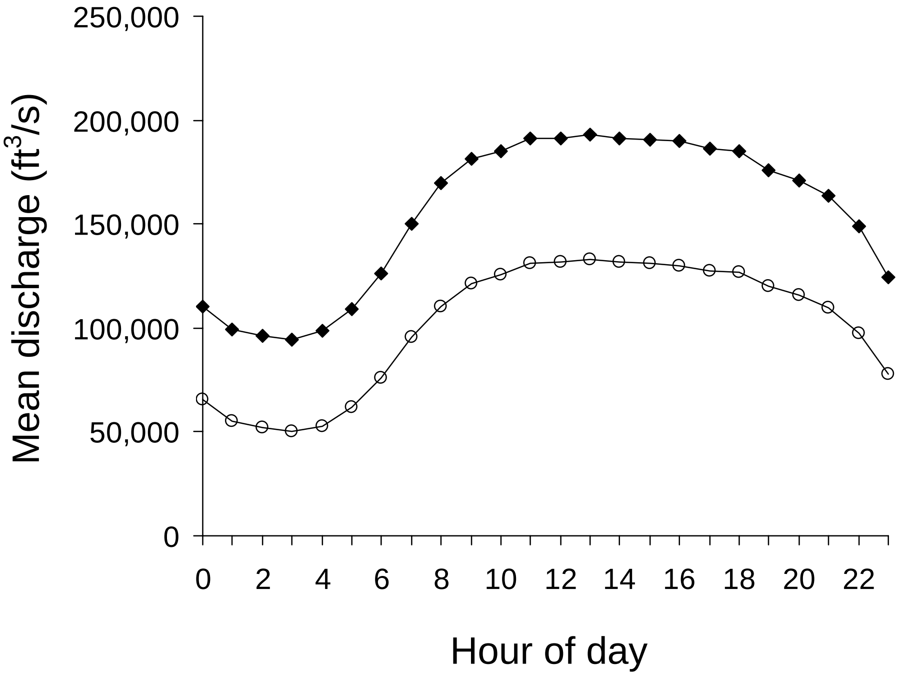

Figure 1.3. — Mean hourly discharge at Grand Coulee Dam (◆) and the third powerhouse (O) between June 7 and July 5, 2002.

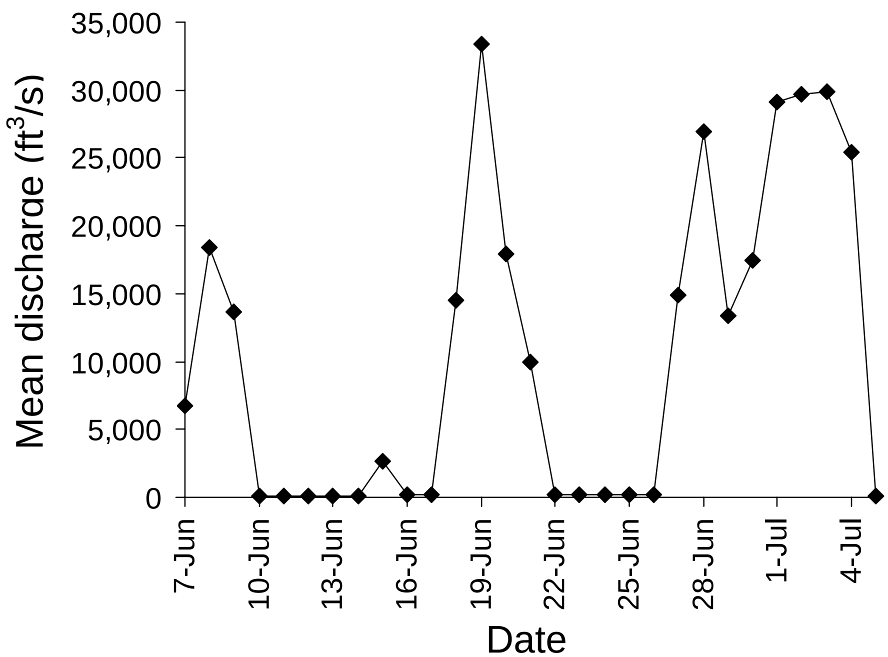

Figure 1.4. — Mean daily spill discharge at Grand Coulee Dam between June 7 and July 5, 2002.

Precision of the 3D Telemetry System

The precision of the test tag at a depth of 3 m was better than that of the test tag at 10 m deep, but this was likely due to greater movement of the 10-m tag (Table 1.2). In the northing, easting, and depth of both test tags, the median range in locations was less than 1 m, except for precision in the depth of the 10-m tag.

Table 1.2. — The precision of 3D telemetry system during 2002 in the third powerhouse forebay of Grand Coulee Dam. Precision was measured using fixed tags mounted to the strobe light barge at a depth of 3 m and 10 m. Precision was estimated as the median of the range in spatial locations over 1-minute periods.

Tag depth	Northing (m)	Easting (m)	Depth (m)
3 m	0.44	0.26	0.67
10 m	0.87	0.61	1.43

Fish Movements Within the Hydrophone Array

We detected 50 kokanee and 30 rainbow trout within the 3D array, accounting for 47% and 45% respectively, of the fish released. Nearly equal percentages of each species were detected, but we found large differences between species in the number of detections and residence time within the 3D array. Kokanee had a median of 373 detections per fish (range 10 – 2,097), whereas rainbow trout had a median of 3,726 detections per fish (range 39 – 29,538). The residence times of kokanee were shorter and more variable than rainbow trout (Figure 1.5). Kokanee had a median residence time of 0.20 h (range 0.01 – 3.57 h), whereas rainbow trout had a median residence time of 1.07 h (range 0.06 – 30.68 h). The residence time distributions of both species were skewed to the right (Figure 1.5).

We expected the number of fish detected during the day and night to be proportional to the number of day and night hours. Although night hours comprised only 38% of the 24-hour day, 64% (32 of 50) of the tagged kokanee were detected during the night while only 48% (24 of 50) were detected during the day. The number of tagged kokanee in the 3D array peaked after dark and decreased through the night (Figure 1.6). For rainbow trout, we detected fewer tagged fish in the 3D array during the night

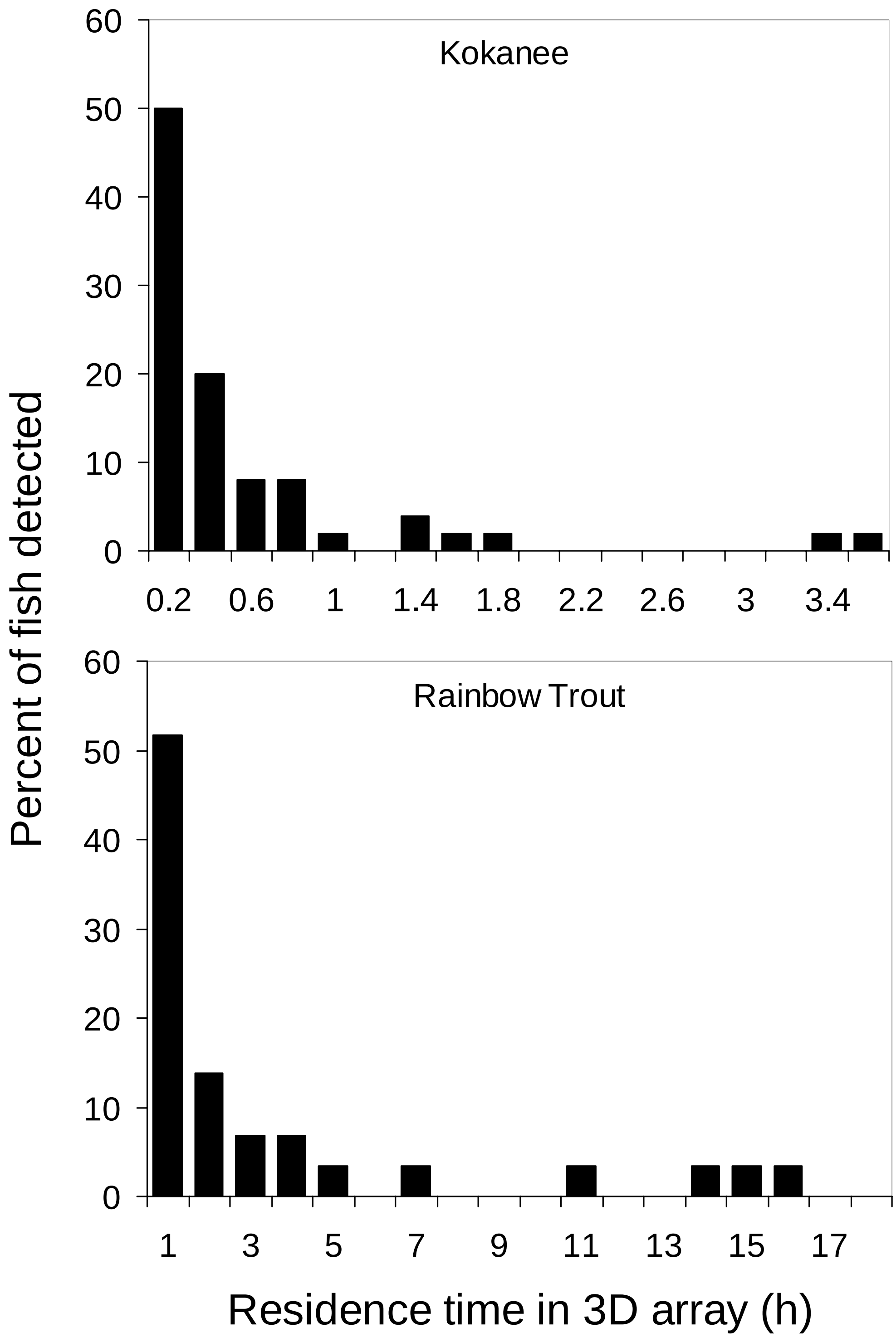

Figure 1.5. — Residence time distributions of kokanee and rainbow trout within the 3D array in the third powerhouse forebay of Grand Coulee Dam, 2002. Note the difference in x-axis scales of kokanee and rainbow trout. One rainbow trout with a residence time of 30.68 hours is not shown.

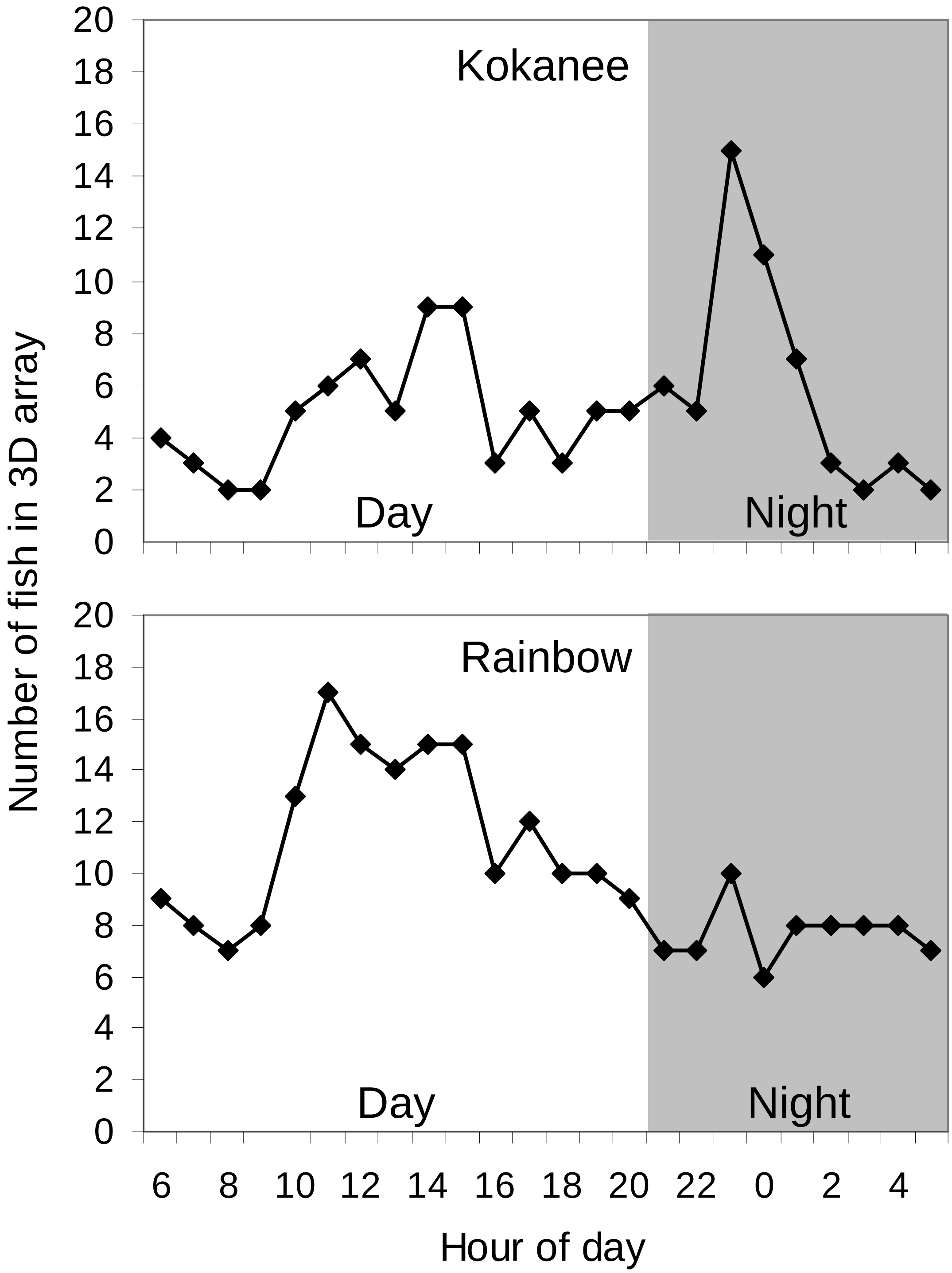

Figure 1.6. — The number of kokanee and rainbow trout detected during each hour of the day in the 3D array at Grand Coulee Dam, 2002.

compared to the day, as was expected (Table 1.3). During the day, 83% (25 of 30) of rainbow trout were detected in the 3D array compared to 57% (17 of 30) at night. The number of tagged rainbow trout in the 3D array peaked in mid-day and decreased through the night. We also expected residence times during the day and night to be proportional to the number of day and night hours, but we found no significant difference between day and night residence times of both species (Wilcoxon rank sums test, $P > 0.05$ for both species, Table 1.3).

Table 1.3. — Descriptive statistics of day and night residences times (h) of kokanee and rainbow trout in the 3D array at Grand Coulee Dam, 2002.

Time of day	Number of fish	Mean	Median	Range	Standard deviation
		Kokanee			
Day	24	0.55	0.17	0.01 - 3.23	0.88
Night	32	0.32	0.22	0.03 - 1.54	0.31
		Rainbow Trout			
Day	25	3.26	1.27	0.003 – 16.9	4.43
Night	17	2.18	0.57	0.0 – 13.7	3.47

In general, kokanee and rainbow trout approached the third powerhouse cul-de-sac via the eastern shore, the highest concentration of detections occurred along the eastern shore, and very few detections occurred near the center of the 3D array where the strobe light was located. Although 170 m is the distance across the entrance of the third powerhouse cul-de-sac, 60% (18 of 30) of tagged rainbow trout and 40% (20 of 50) of tagged kokanee were first detected within 35 m of the eastern shore (Figure 1.7). This distribution may have resulted from our release location near the east shore of the cul-de-sac. Nonetheless, relative to first detections of rainbow trout, those of tagged kokanee were more evenly distributed across the entrance to the third powerhouse cul-de-sac (Figure 1.7). Once fish entered the cul-de-sac, a high concentration of detections occurred along the eastern shore, indicating that fish spent the most time along that shore (Figure 1.8 – Figure 1.11, see Appendix 1 for movement paths of individual fish). In particular, the northeast corner of the 3D array exhibited the highest concentration of

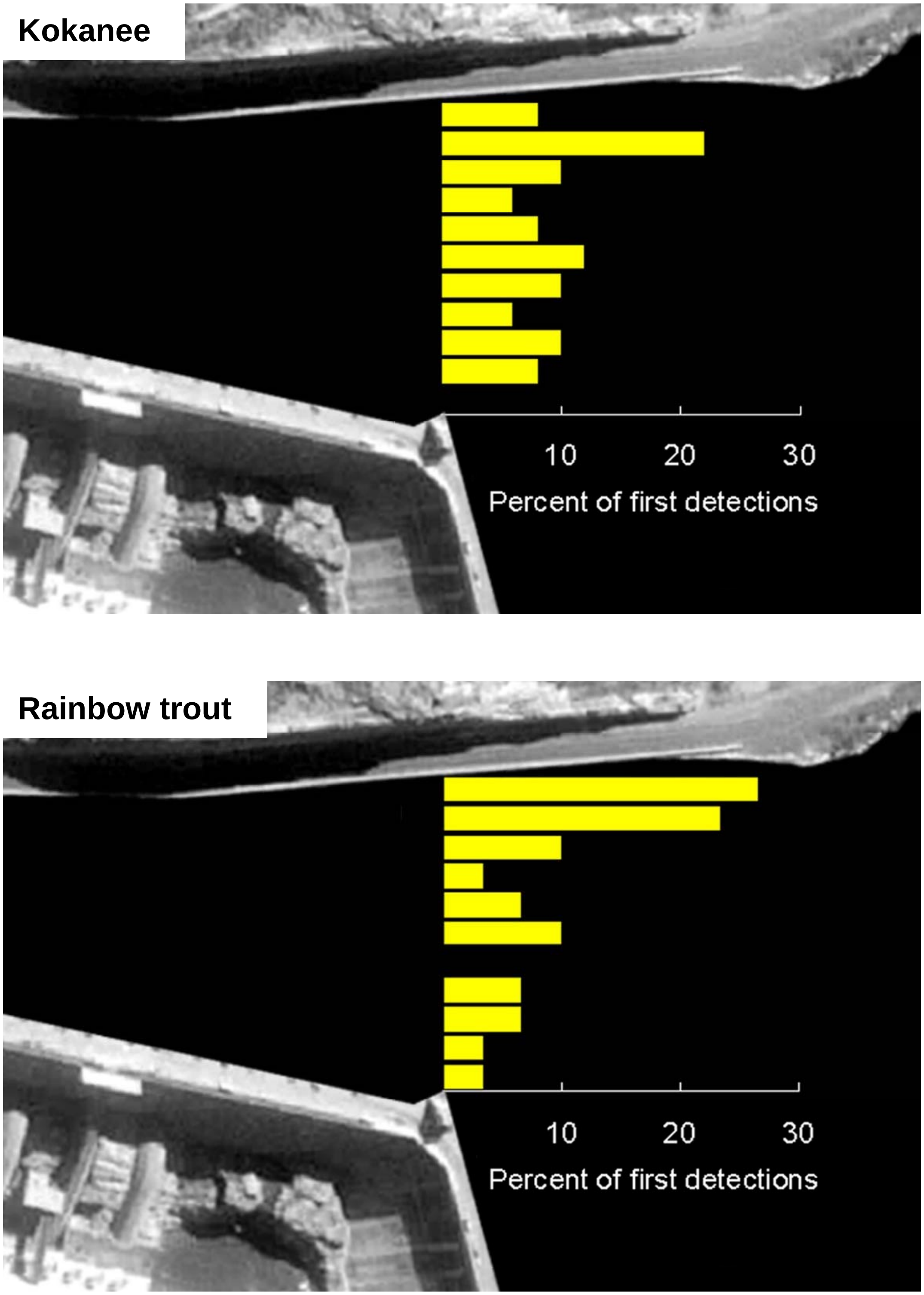

Figure 1.7. — The distribution of first detections across the entrance of the third powerhouse cul-de-sac at Grand Coulee Dam during 2002 for kokanee and rainbow trout.

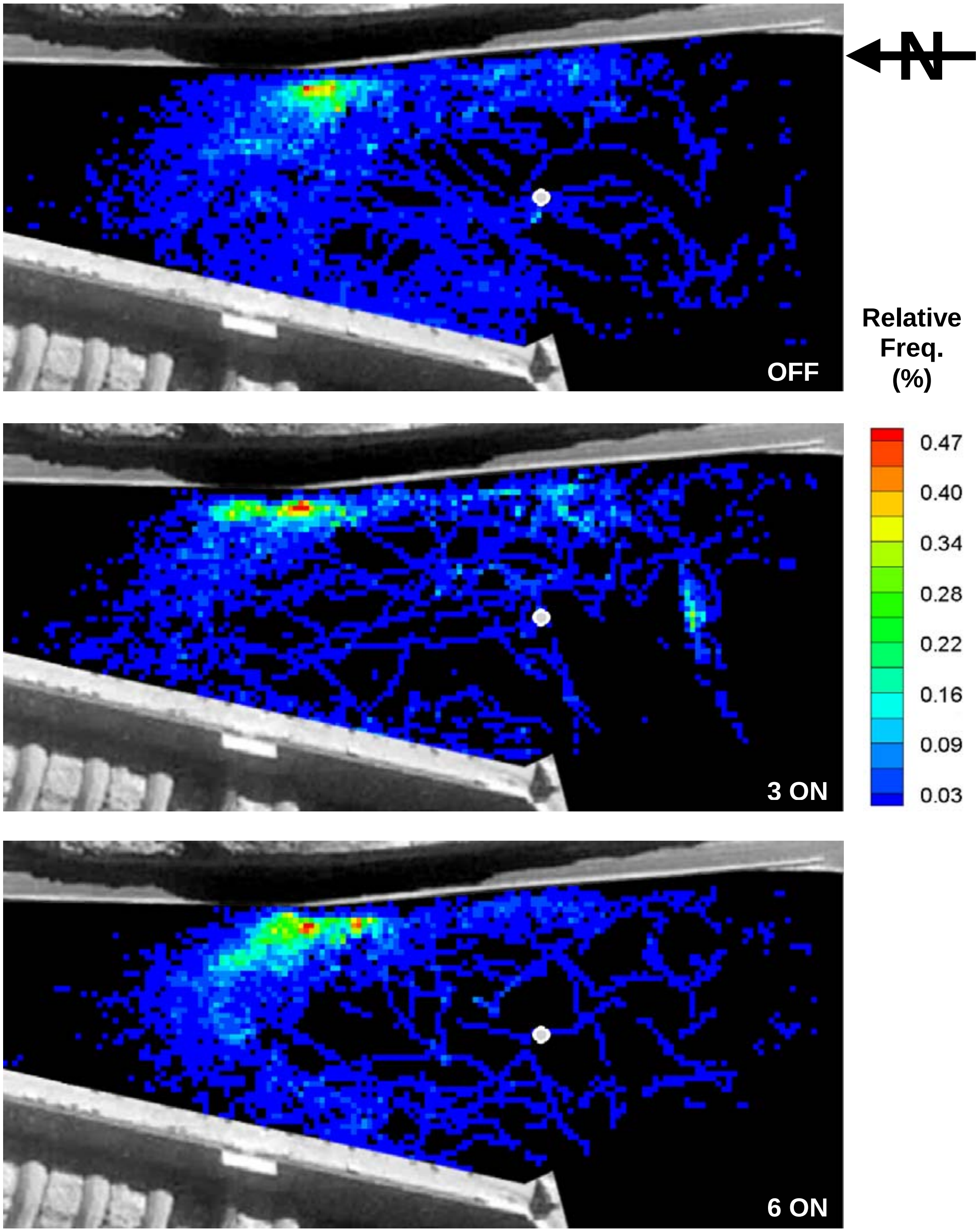

Figure 1.8 — Percent of total detections in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam during 2002 for rainbow trout during the day for strobe light treatments Off (n = 18), 3-On (n = 12), and 6-On (n = 7). The gray circle marks the location of strobe light.

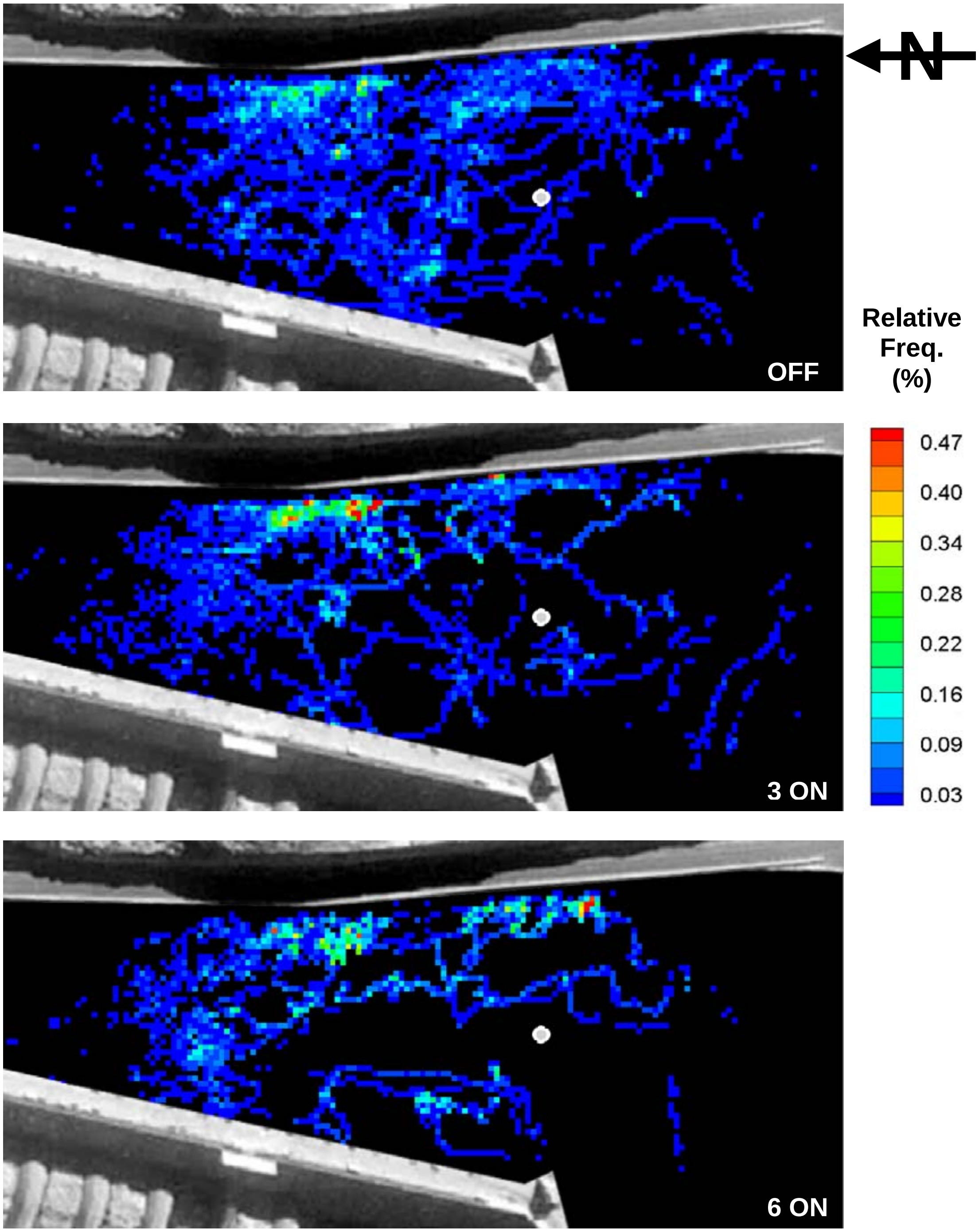

Figure 1.9. — Percent of total detections in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam during 2002 for rainbow trout during the night with strobe light treatments Off (n = 8), 3-On (n = 14), and 6-On (n = 6). The gray circle marks the location of strobe light.

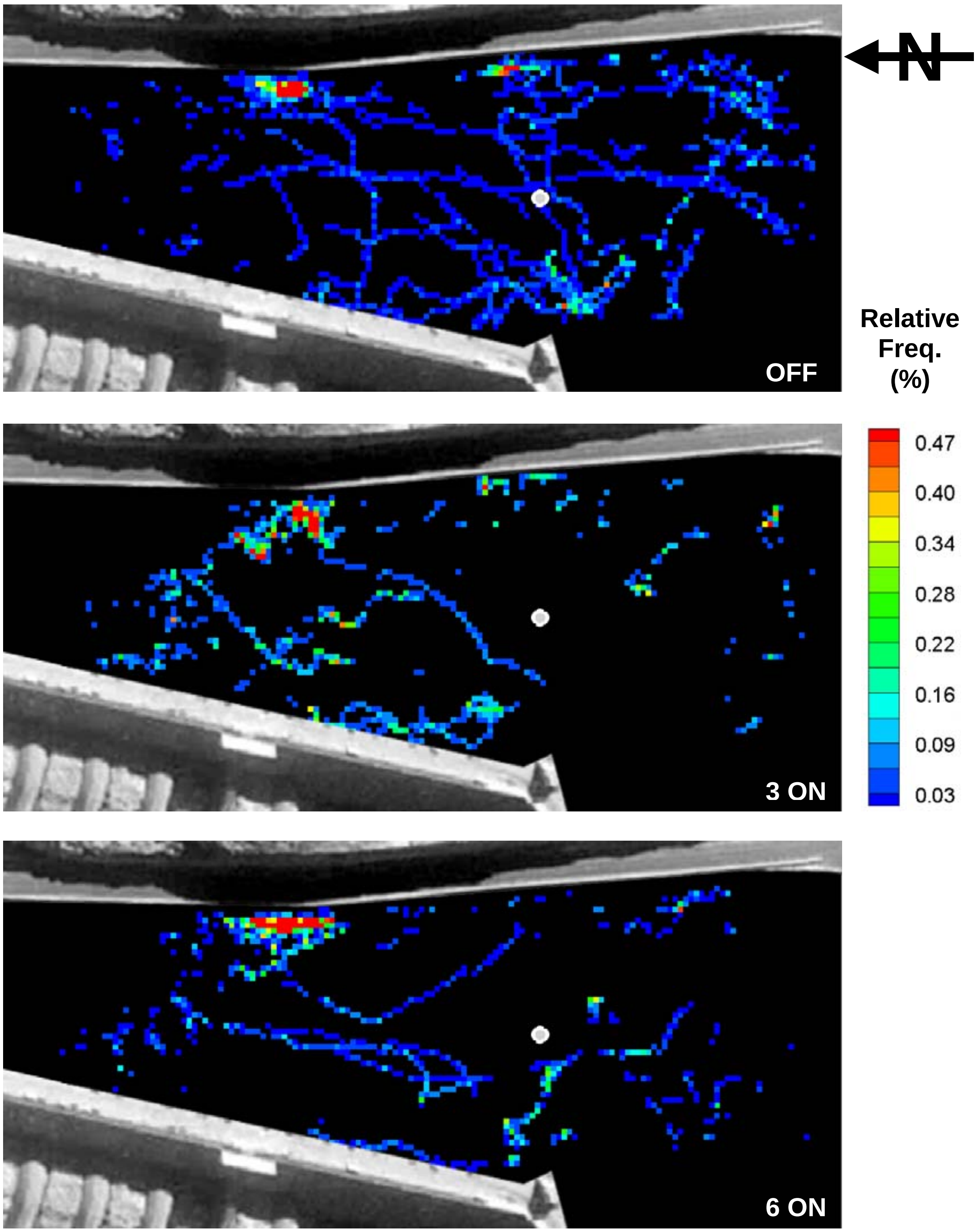

Figure 1.10. — Percent of total detections in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam during 2002 for kokanee during the day with strobe light treatments Off (n = 15), 3-On (n = 7), and 6-On (n = 6). The gray circle marks the location of strobe light.

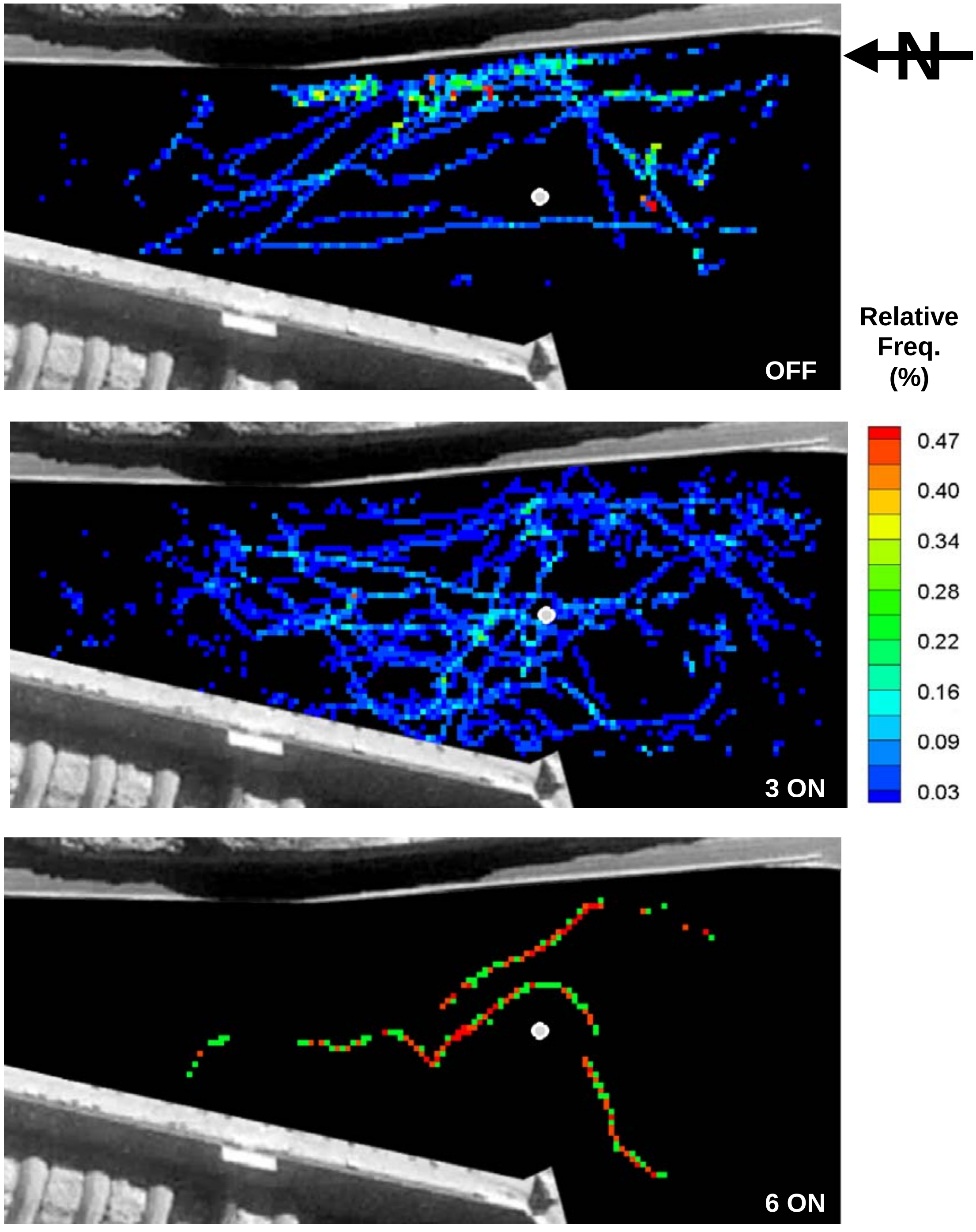

Figure 1.11. — Percent of total detections in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam during 2002 for kokanee during the night with strobe light treatments Off (n = 14), 3-On (n = 17), and 6-On (n = 3). The gray circle marks the location of strobe light.

detections for both species. For kokanee, the high concentration of detections in the northeast corner was observed only during the day, but this pattern was observed during both day and night for rainbow trout (Figure 1.8 – Figure 1.11).

Overall, most rainbow trout were shallower than kokanee and we found few patterns in the spatial distribution of fish depths. For rainbow trout, 83% (25 of 30) were shallower than 15 m (i.e., strobe light depth), whereas 48% (24 of 50) of kokanee were shallower than 15 m (Figure 1.12). Kokanee were deeper during the day (median depth = 14.8 m) than during the night (median depth = 9.8 m); however for rainbow trout we observed little difference in the depth between day (median depth = 3.1 m) and night (median depth = 3.0 m). We found few consistent patterns in the spatial distribution of fish depths, but spatial distributions clearly showed that most kokanee were deeper than rainbow trout (Figure 1.13 – Figure 1.16). Also, kokanee concentrated in the northeast corner of the 3D array during the day were shallower than kokanee detected in other areas of the 3D array (Figure 1.15).

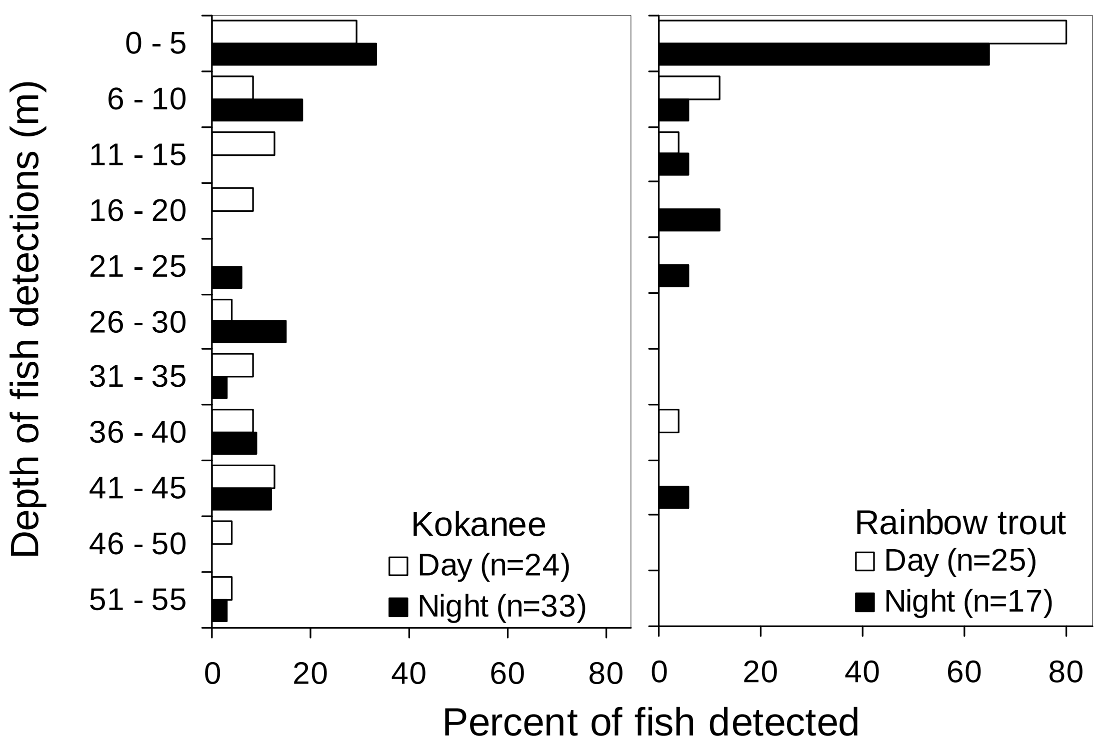

Figure 1.12. — Vertical distribution of kokanee and rainbow trout in the 3D array in the third powerhouse cul-de-sac of Grand Coulee Dam in 2002 during the day and night.

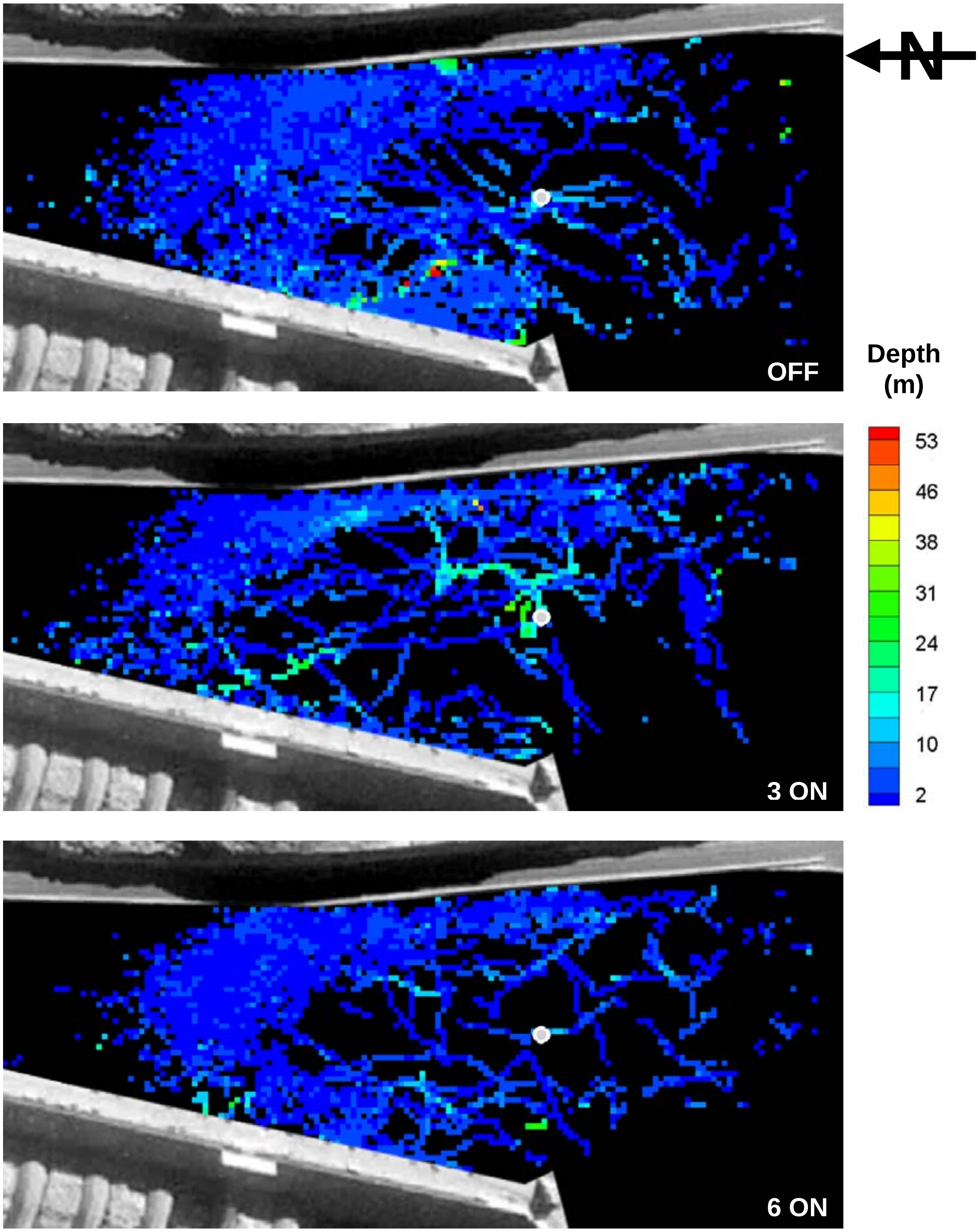

Figure 1.13. — Spatial distribution of rainbow trout depths in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam in 2002 during the day with strobe light treatments Off (n = 18), 3-On (n = 12), and 6-On (n = 7). The gray circle marks the location of strobe light.

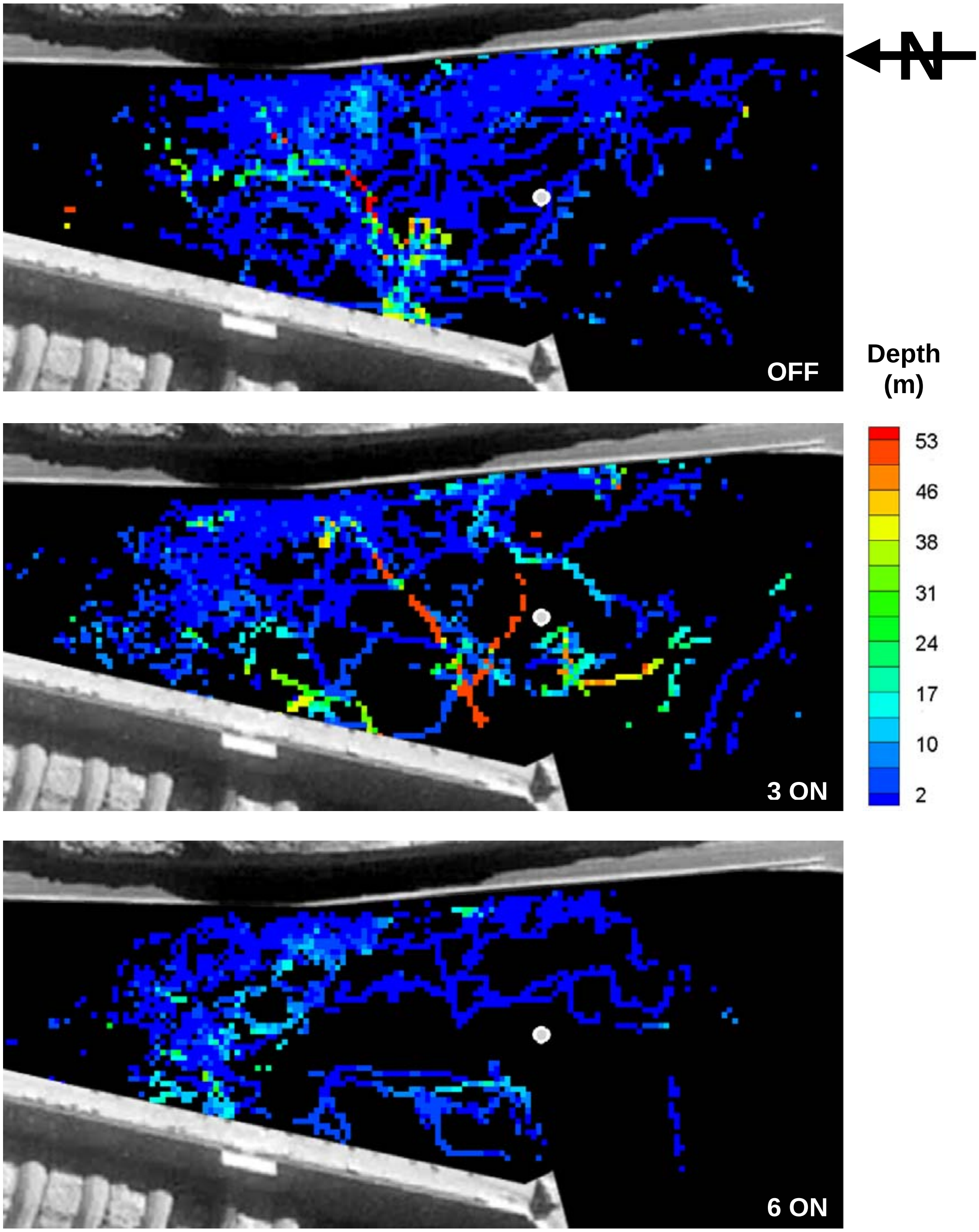

Figure 1.14. — Spatial distribution of rainbow trout depths in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam in 2002 during the night with strobe light treatments Off (n = 8), 3-On (n = 14), and 6-On (n = 6). The gray circle marks the location of strobe light.

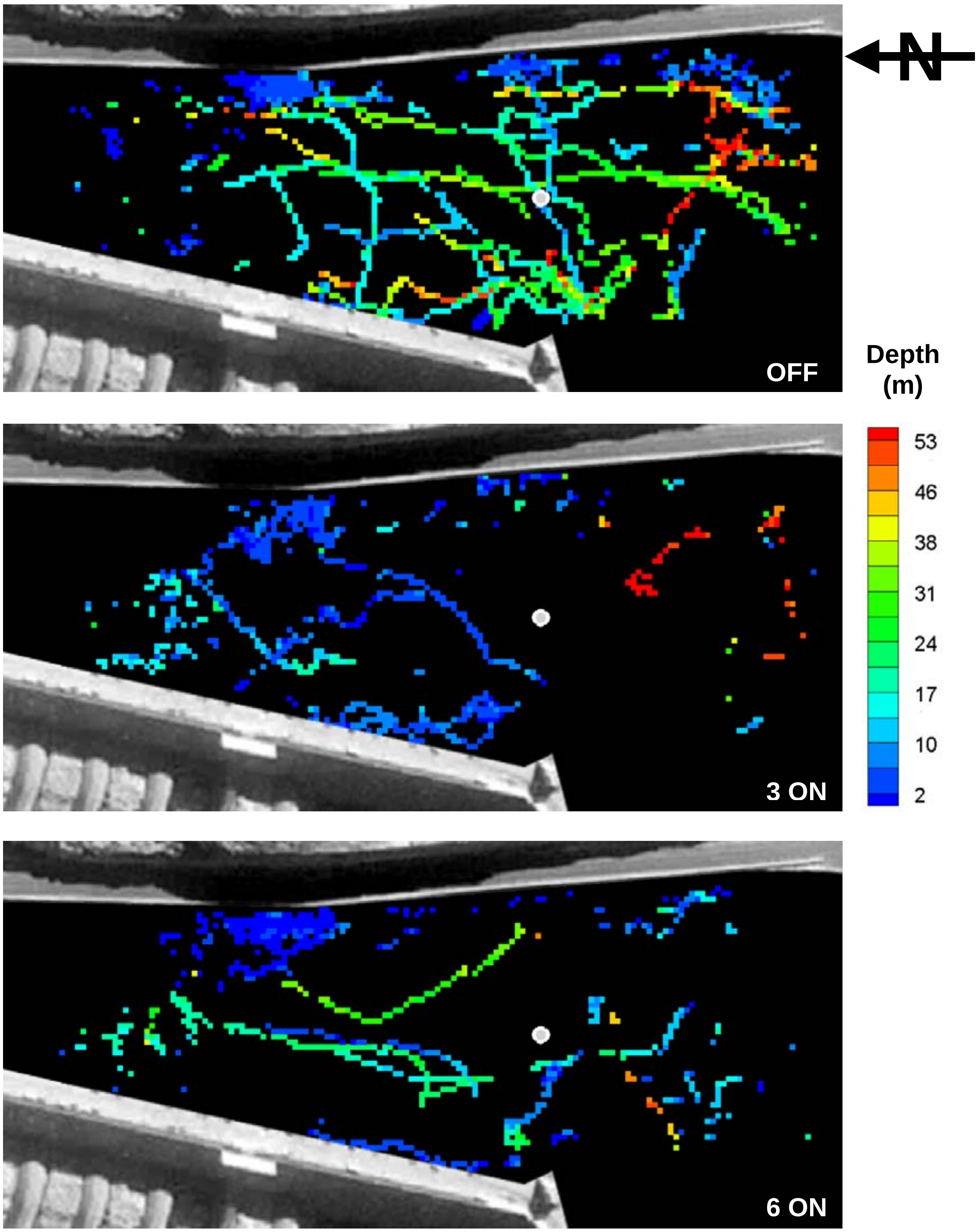

Figure 1.15. — Spatial distribution of kokanee depths in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam in 2002 during the day with strobe light treatments Off (n = 15), 3-On (n = 7), and 6-On (n = 6). The gray circle marks the location of strobe light.

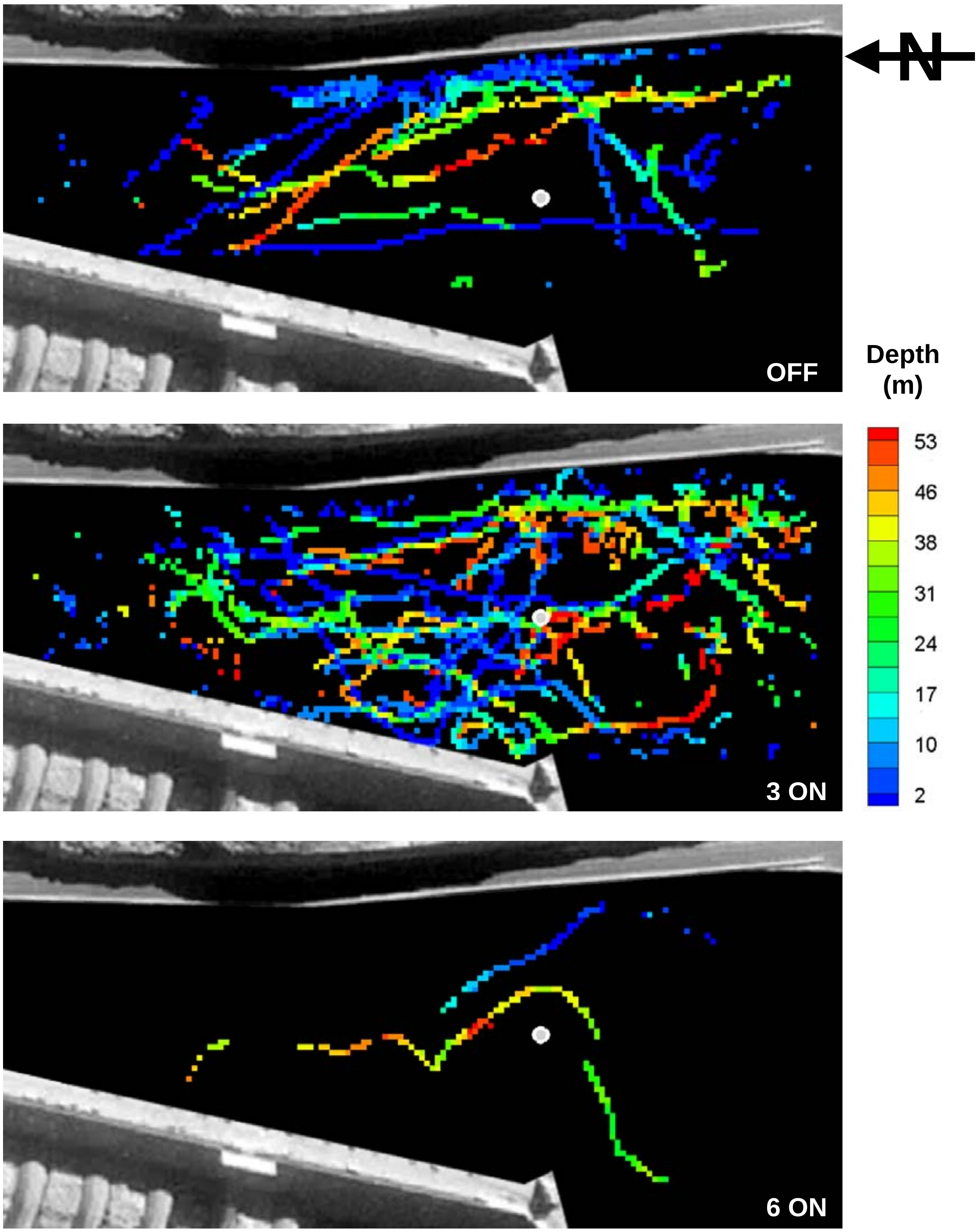

Figure 1.16. — Spatial distribution of kokanee depths in 3x3 m bins in the third powerhouse cul-de-sac of Grand Coulee Dam in 2002 during the night with strobe light treatments Off (n = 14), 3-On (n = 17), and 6-On (n = 3). The gray circle marks the location of strobe light.

Fish Behavior Near the Strobe Lights

We detected few tagged fish within 25 m of the strobe lights during each of the treatments, tagged fish spent little time within 25 m of the strobe lights, and most fish near the strobe lights were moving in a downstream direction. For kokanee, 0 – 3 fish were detected during any one treatment, while 0 – 7 rainbow trout were detected during any treatment within 25 m of the strobe lights (Table 1.4). Both species exhibited short residence times within 25 m of the strobe lights, and the small sample sizes precluded statistical comparison of these residence times (Table 1.4). From the movement patterns of fish near the strobe lights, we observed neither attraction nor repulsion behavior (Figures 1.17 and 1.18). Directional vectors of both kokanee and rainbow trout near the strobe lights indicated that both species were moving in a downstream direction and towards the third powerhouse (Figures 1.19 and 1.20).

Table 1.4. — Summary of residence time (minutes) within 25 m of the strobe lights for tagged kokanee and rainbow trout during the day and night and during each of the three strobe light treatments at Grand Coulee Dam during 2002.

Time of day	Strobe light treatment	Number of fish	Mean	Median	Range	Standard deviation
			Kokanee			
Day	Off	3	1.3	0.7	0.4 to 2.9	1.3
	3-On	0	---	---	---	---
	6-On	2	0.2	0.2	0.1 to 0.3	0.1
Night	Off	2	0.6	0.6	0.2 to 1.1	0.2
	3-On	3	3.6	2.3	0.2 to 8.4	4.2
	6-On	1	9.9	9.9	-	-
			Rainbow trout			
Day	Off	6	2.0	1.2	0.0 to 6.0	2.2
	3-On	7	1.3	0.7	0.4 to 5.5	1.8
	6-On	1	1.9	1.9	-	-
Night	Off	3	2.1	1.8	1.4 to 3.0	0.8
	3-On	2	1.2	1.2	0.9 to 1.5	0.4
	6-On	0	---	---	---	---

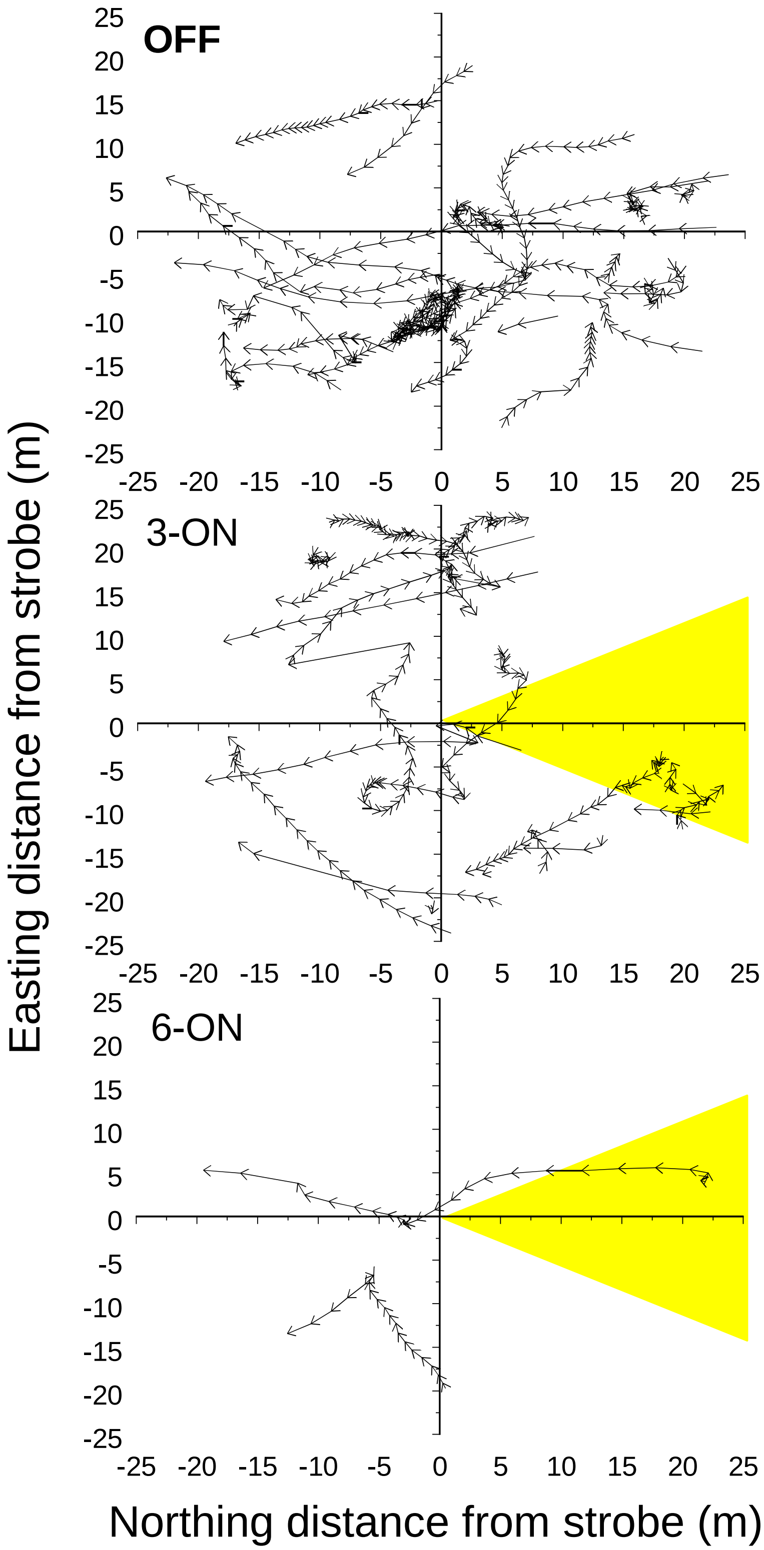

Figure 1.17. — Movement patterns of rainbow trout within 25 m of the strobe light during treatments, Off (n = 9), 3-On (n = 9), and 6-On (n = 1). Arrows are directional vectors and the strobe light is located at the origin. The yellow shaded area approximates the location of the strobe light beam.

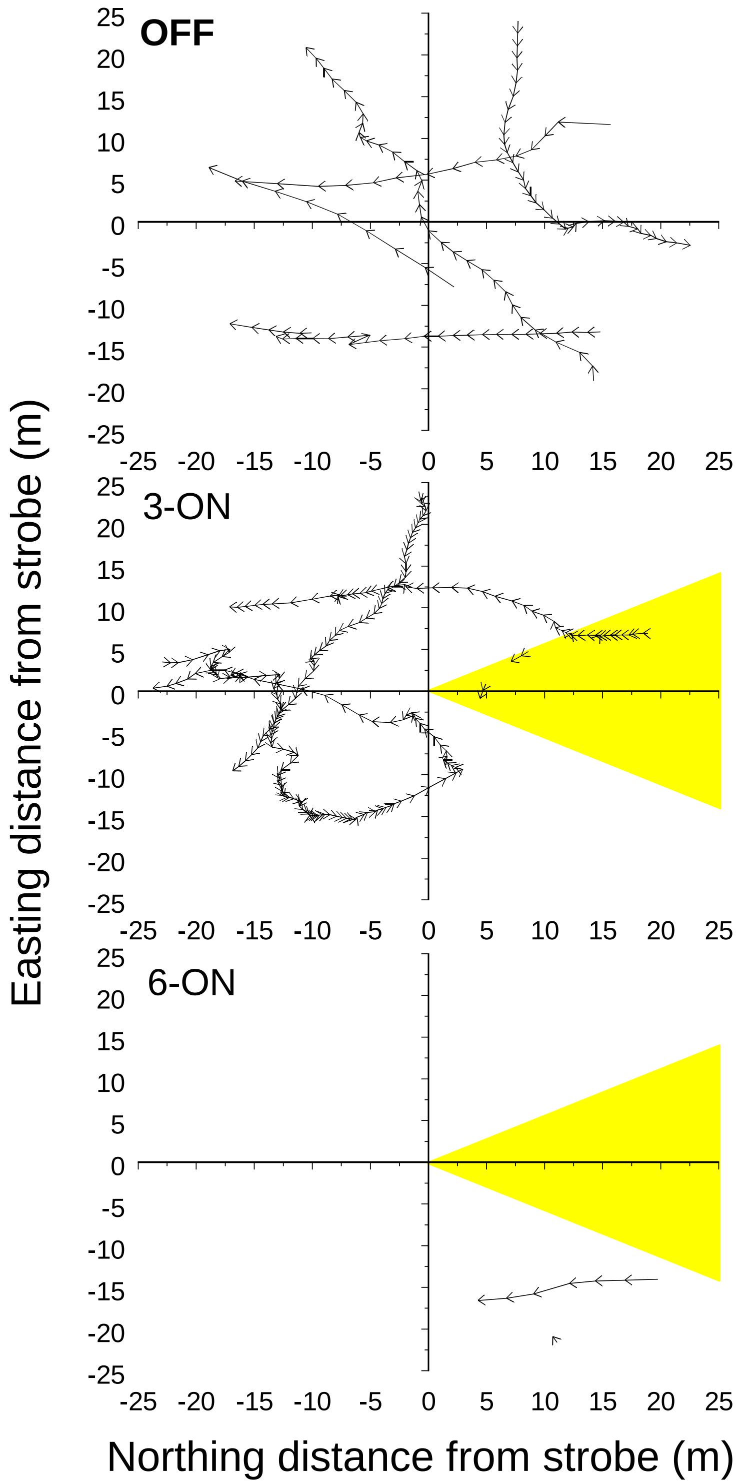

Figure 1.18. — Movement patterns of kokanee within 25 m of the strobe lights during treatments, Off (n = 5), 3-On (n = 3), and 6-On (n = 3). Arrows are directional vectors and the strobe light is located at the origin. The yellow shaded area approximates the location of the strobe light beam.

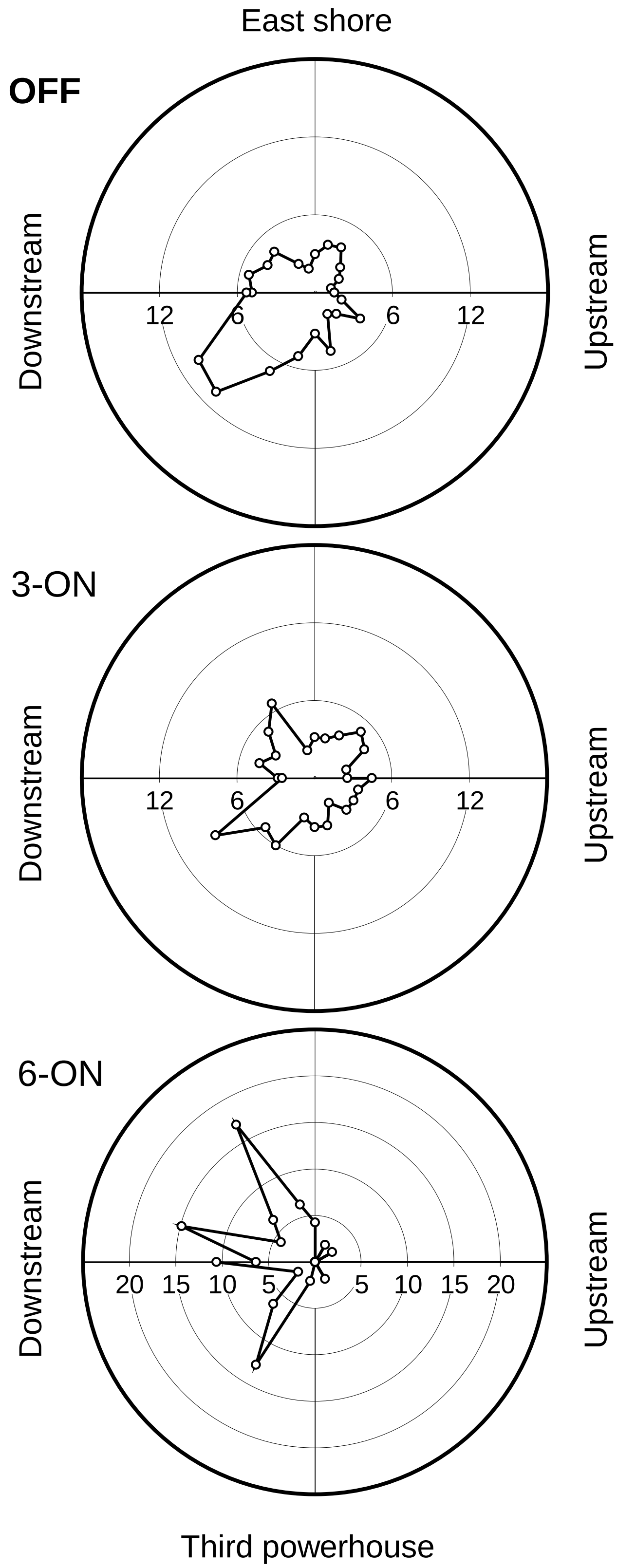

Figure 1.19. Polar distribution plots of the movement directions of rainbow trout detected within 25 m of the strobe lights at Grand Coulee Dam during 2003. The x-axis shows the percent of movement directions.

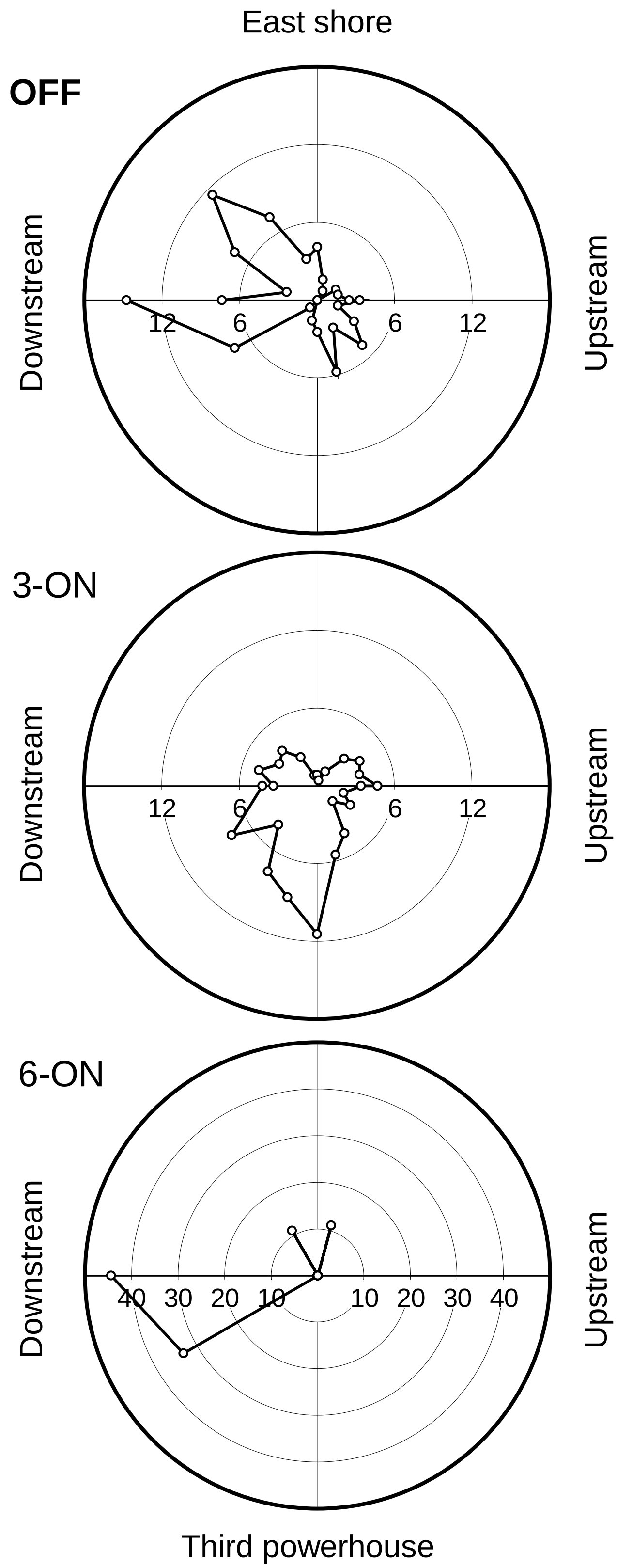

Figure 1.20. Polar distribution plots of the movement directions of kokanee detected within 25 m of the strobe lights at Grand Coulee Dam during 2003. The x-axis shows the percent of movement directions.

In general, we detected the fewest fish near the strobe lights (< 25m) during the 6-On treatment, but this was not likely a treatment effect. Rather, fewer fish passed near the strobe lights during the 6-On treatment because of differences among treatments in the number of fish within the 3D array. For example, 26 rainbow trout were detected in the entire 3D array during both the Off and 3-On treatments, but only 13 were detected during the 6-On treatment. Thus, fewer tagged fish were available to pass near the strobe lights during the 6-On treatment compared to the other treatments.

Analysis of the mean distance of fish detections from the strobe light showed that under most treatment scenarios (i.e., among treatments, day and night, and within 85 m, 50 m, and 25 m from strobe lights) the mean distance of fish was farther away from the strobe lights during the 3-On and 6-On treatments (Table 1.5). However, On and Off treatment differences tended to be small and nearly all randomization tests were not significant (Table 1.5). For kokanee, the only significant randomization test occurred with kokanee during the day for the 3-On treatment constrained to within 85 m of the strobe lights, where kokanee were significantly further away from the strobe lights than during the Off treatment (randomization test, $P < 0.004$, Table 1.5). However, one other test had a low P-value ($P = 0.064$) where kokanee were closer to the lights during the 3-On treatment at night within 85 m of the strobe lights compared to the Off treatment. For rainbow trout, none of the 11 tests were significant, but one test had a low P-value ($P = 0.04$), and fish were significantly further away from the strobe lights during the 6-On treatment, within 50 m, during the day (Table 1.5).

Table 1.5. Mean distance of fish detections from the strobe lights during treatments, day and night, and within 85 m, 50 m, and 25 m from the strobe lights at Grand Coulee Dam during 2002. P-values are from a randomization test comparing each On treatment (3-On, 6-On) to the Off treatment.

Detections used in analysis	Time of day	Treatment	Number of fish	Number of detections	Mean distance (m) from strobe	P-value
			Kokanee			
< 85 m from strobe	Day	OFF	9	936	57	
		3-ON	6	92	75	0.004
		6-ON	5	240	48	0.347
	Night	OFF	12	799	68	
		3-ON	15	1078	56	0.064
		6-ON	2	111	58	0.311
< 50 m from strobe	Day	OFF	7	249	34	
		3-ON	1	140	34	0.582
		6-ON	2	7	37	0.926
	Night	OFF	3	67	38	
		3-ON	9	453	38	0.884
		6-ON	2	43	42	0.896
< 25 m from strobe	Day	OFF	3	59	16	
		3-ON	0	0	---	---
		6-ON	2	9	21	0.372
	Night	OFF	1	12	22	
		3-ON	3	45	20	0.575
		6-ON	0	0	---	---
			Rainbow trout			
< 85 m from strobe	Day	OFF	12	2002	66	
		3-ON	9	2043	63	0.702
		6-ON	6	1008	65	0.971
	Night	OFF	7	1784	67	
		3-ON	9	877	56	0.241
		6-ON	4	1055	71	0.735
< 50 m from strobe	Day	OFF	9	304	27	
		3-ON	8	2363	32	0.301
		6-ON	5	219	39	0.040
	Night	OFF	4	212	30	
		3-ON	4	385	35	0.292
		6-ON	1	116	37	0.676
< 25 m from strobe	Day	OFF	5	144	14	
		3-ON	6	100	17	0.611
		6-ON	1	14	17	0.658
	Night	OFF	3	102	20	
		3-ON	2	63	21	0.798
		6-ON	0	0	---	---

Tailrace Detections

We detected 32 kokanee and 7 rainbow trout in the tailrace of Grand Coulee Dam, accounting for 30% and 12%, respectively of the fish released. Of the fish detected in the tailrace, 100% of the rainbow trout and 59% (19 of 32) of kokanee were detected in the forebay array, suggesting that tagged kokanee may have passed the dam through routes other than the third powerhouse or passed undetected through the third powerhouse. It is likely that we did not detect all entrained fish on the tailrace hydrophone because only one hydrophone was mounted in the tailrace, which likely had a limited detection range. For kokanee detected on the tailrace hydrophone, their mean depth in the 3D array was considerably deeper than kokanee that were not detected on the tailrace hydrophone (Table 1.6).

Table 1.6. — Descriptive statistics of the depth (m) of fish within the 3D array (forebay) that were detected on the tailrace hydrophone and fish that were not detected on the tailrace hydrophone at Grand Coulee Dam during 2002.

Species	Detection In Tailrace?	Number of fish	Mean	Median	Range	Standard deviation
Kokanee	Yes	19	26.3	28.3	1.0 – 45.8	16.5
	No	31	16.6	7.8	0.1 – 53.0	16.2
Rainbow	Yes	7	7.8	3.2	2.4 – 35.8	12.4
Trout	No	23	6.8	3.5	0.2 – 42.4	9.5

Discussion

Behavioral patterns of tagged fish during our 2002 strobe light study differed substantially from the strobe light study we conducted in 2001 (Perry et al. 2003). Within the 3D array, we detected a lower proportion of tagged rainbow trout than during 2001. Although there were similar species-specific patterns between years (e.g., kokanee residence times were shorter in both years than rainbow trout) we found that residence times and the number of fish detected near the strobe lights were both lower in 2002 than in 2001. Furthermore, fewer fish in 2002 were detected near the center of the array. These between-year differences in fish behavior may have been influenced by the relatively high discharge during 2002. We also found that the vertical distribution of fish may have influenced their passage routes through the dam, which could also be a function of discharge. In addition to assessing the behavioral response of fish to the strobe lights, our data provides important information on fish behavior within the third powerhouse cul-de-sac that can be used to guide future strobe light implementation.

Between years, we observed many similar species-specific behavioral patterns such as vertical distribution of fish and residence times. During both years, kokanee were distributed throughout the water column and a high proportion of tagged kokanee were deeper than rainbow trout. Also for both 2001 and 2002, rainbow trout were restricted to the shallower depths, with very few fish being detected below 25 m. Rainbow trout had residence times 4.5 times longer than kokanee in 2002, which followed similar patterns in residence times between species in 2001 (Perry et al. 2003). Lastly, in both years we detected more tagged rainbow trout in the 3D during the day than the night, but in contrast, more tagged kokanee were detected at night in comparison to day. These similarities in behavioral patterns among years may be species-specific characteristics that occur regardless of environmental conditions, such as changes in discharge.

Although many patterns were similar between years, we observed differences in the magnitude of residence times and the number of tagged fish detected near the strobe lights. Residences times of kokanee were less than residence times of rainbow trout in both 2001 and 2002; however, both species exhibited shorter residence times in 2002. The decrease in median residence time from 2001 to 2002 was proportional to the increase in the mean discharge from 2001 to 2002. Mean discharge in 2002 was 4.4 times greater than the discharge in 2001. Median residence times in 2002 were 4.5 times shorter than in 2001 for kokanee and 5 times shorter than in 2001 for rainbow trout. Thus, the increase in discharge could have caused shorter residence times by quickly entraining fish into the turbines. Alternatively, higher discharge could have reduced travel times if fish quickly moved across the array, to the downstream end of the cul-de-sac. Another difference between years was the high concentration of detections near the northeastern corner of the array observed during 2002, but not 2001. Furthermore, relative to 2001, we found an absence of detections in the center of the array and near the strobe lights during 2002. These spatial patterns may be attributed to changes in velocity in the center of the cul-de-sac caused by higher discharge in 2002. High velocities near the center of the cul-de-sac may have influenced fish to stay away from the center of the cul-de-sac and to seek refugia in lower velocity regions near the edges of the cul-de-sac where a high concentration of detections was observed. Although the release location may have affected approach paths, most fish were released from the same location in both 2001 and 2002, suggesting that other factors influenced the difference in spatial distributions between 2001 and 2002.

Our data suggests that the vertical distribution of fish may influence where fish pass through the dam, or which fish are prone to entrainment. For rainbow trout, which were surface-oriented, fish may be more prone to passing through the spillway during years of high spill discharge such as occurred in 2002. Of the rainbow trout released, in 2002 we detected 32% percent fewer rainbow trout than in 2001, when little spill discharge occurred. Also, as indicated by mobile tracking (See Chapter 2), rainbow trout were detected along both shores of the forebay. Although circumstantial, the spatial distribution of rainbow trout in the forebay as indicated by mobile tracking, their lower detection rates in 2002, and the higher spill discharge (which occurred at the surface) suggests that a higher proportion of tagged rainbow trout could have passed through the spillway in 2002. For kokanee, which were distributed throughout the water column, we found that deeper fish had a higher likelihood of being entrained through the turbines compared to kokanee that were shallow. For example, kokanee detected on the tailrace hydrophone had a median depth of 28 m in the forebay, whereas kokanee not detected on the tailrace hydrophone were shallower and had a median depth of 8 m in the forebay.

Of the few fish detected within 25 m of the strobe lights, nearly all of the fish were moving in a downstream direction. Both the absence of detections in the center of the array near the strobe lights and the downstream movement of fish that were detected near the strobe lights may be due to relatively high velocities observed in this area during 2002. Acoustic Doppler Current Profiler (ADCP) data collected by Johnson et al. (2003) indicated that velocities in the region of the strobe light were between 60 and 90 cm/s during mean flows of 2002 (116,338 ft^3/s). However, at flows of about 60,000 ft^3/s at the third powerhouse, Johnson et al. (2003) found that velocities near the strobe light were < 20 cm/s. Because mean flow at the third powerhouse in 2001 (26,209 ft^3/s) was much less than 60,000 ft^3/s, we can infer that water velocities were likely less than 20 cm/s near the strobe barge in 2001. These differences in velocities between years could have caused some of the differences we observed between years in the spatial distribution of fish. At low discharge and velocities, fish would be more likely to meander through the center of the array and to pass near the strobe lights, as was observed in 2001 (Perry et al. 2003). In contrast, high discharge and velocities could have caused the patterns we observed in 2002, where there was an absence of tagged fish in high velocity areas and higher detection densities along the edges of the array, where velocities were probably lower. In particular, the high concentration in the northeast corner of the array may have been caused by an eddy, which would have provided a velocity refuge for fish.

Although attraction (Perry et al. 2003) and repulsion (Maiolie et al. 2001, Ploskey and Johnson 2001) of fish from strobe lights has been documented in some studies, we found little evidence of either response during 2001. During 2001, we found individual fish (both kokanee and rainbow trout) that were clearly attracted to the strobe lights (Perry et al. 2003). Furthermore, during 2002 Johnson et al. (2003) found higher fish counts during the On treatments than the Off treatment, and they suggested that fish may have been attracted to the general region of the strobe lights to feed on prey items. During 2002, it is unclear whether tagged fish truly had little response to the strobe lights, or whether too few fish near the strobe lights and short residence times prevented us from detecting a behavioral response to the strobe lights. Although fish tended to be slightly further away from the strobe lights during 3-On and 6-On treatments compared to the Off treatment, only one of the 21 statistical tests indicated that these differences were significant. In addition, one of the other tests that had a low P-value, but the mean distance of detections was closer to the strobe lights during the On treatment. Lastly, within 25 m of the strobe lights we may have had little power to detect a difference due to the few fish available for statistical comparison.

In addition to response of fish to strobe lights, our data provides valuable information on approach paths, where fish spent the most time, and how fish were spatially distributed near the third powerhouse cul-de-sac. This additional information is critical for guiding future decisions for the strobe light study design or in the case that strobe lights are fully implemented. With high concentrations of fish along the eastern shoreline during both 2001 and 2002, it may be advantageous to position the strobe light near the eastern shoreline or along an edge of the cul-de-sac. Placing the strobe lights along the eastern shore will intercept fish movements during low flow (2001) and higher flow (2002) and any behavioral response to the strobe light would be more readily detected. However, the release location of tagged fish may influence their approach paths. Moreover, orienting strobe lights vertically over a greater range of depths may intercept more kokanee, which are fairly evenly distributed throughout the water column.

Chapter 2

Mobile Tracking 3D Acoustic Tagged Fish

Introduction

Mobile tracking with radio telemetry or acoustic telemetry has been useful in determining fish movements outside of fixed arrays. Although mobile tracking is widely used in radio telemetry, mobile tracking using a 3D acoustic telemetry system is relatively new. Having determined the feasibility of acoustic mobile tracking at Grand Coulee Dam in 2001, we found that acoustic mobile tracking provided useful information on fish behavior. Specifically, during 2002 we identified locations of fish outside the fixed array, in the forebay and upstream of Grand Coulee Dam.

Mobile tracking performed in 2001 at Grand Coulee Dam identified where tagged fish congregated outside the fixed array. This helped to identify areas of interests for mobile tracking in 2002, which included: the boat restricted zone (hereafter BRZ) of the third powerhouse outside the fixed array, outside the BRZ and upstream (reservoir), within the BRZ in front of the Banks Lake Pumping Station (pumping station), and within Banks Lake reservoir (Banks Lake). We mobile tracked in Banks Lake and in front of the Banks Lake Pumping Station to evaluate whether fish were transported to Banks Lake via the reservoir pumps. Tracking within the third powerhouse determined whether fish were holding in this area, but outside of our fixed array. Last, we tracked within the reservoir to determine if tagged fish were holding in other areas upstream of the dam.

Methods

The mobile acoustic telemetry system consisted of a boat-mounted model 290 receiver (Hydroacoustic Technology, Inc. (HTI) Seattle, Washington) equipped with five hydrophones. The acoustic system was linked with a Trimble NT 3000 GPS (Trimble Navigation Limited, Sunnyvale, California). The acoustic receiver and GPS were time-synchronized, which enabled us to georeference (northing and easting) fish positions following the post processing of the data. The hydrophones were mounted horizontally, 0.2 meters apart from each other and were suspended from the bow of the boat at a depth of 0.6 to 0.9 meters deep. The hydrophones were set to various gains to provide different detection ranges. To determine the detection range, we traveled toward a fixed acoustic tag and measured the distance at which the tag was first detected on each hydrophone. Distances were determined using the Trimble NT 3000 GPS (Trimble Navigation Limited, Sunnyvale, California) and a Bushnell Model 20-0500 laser rangefinder (Bushnell Performance Optics, Overland Park, Kansas). Lower gain settings result in smaller detection ranges. Conversely, at higher gain settings, the tag can be detected at longer distances from the boat (Figure 2.1).

Mobile tracking was conducted in Banks Lake, near the pumping station, the third powerhouse, and the reservoir between July 16 and July 22, 2002. These areas were mobile tracked with an emphasis on Banks Lake and additional mobile tracking near the third powerhouse cul-de-sac and outside the BRZ. Each area was mobile tracked in random boat paths (maximum coverage was attempted, Figure 2.2) for three hours per area both during the day and night (Table 2.1).

Table 2.1. — Mobile tracking schedule at Grand Coulee Dam between July 16 and July 22, 2002. Night mobile tracking was conducted between 1900 and 08:00 hours and Day mobile tracking was conducted between 0800 and 1900 hours.

Date	Location	Diel Period
07/16/02	Banks Lake	Day
07/16/02	Outside BRZ	Night
07/17/02	Pumping Station	Day
07/18/02	Third Powerhouse	Day
07/18/02	Banks Lake	Night
07/19/02	Pumping Station	Day
07/21/02	Pumping Station	Day
07/21/02	Banks Lake	Night
07/22/02	Outside BRZ	Day
07/22/02	Banks Lake	Night

Data Collection and Processing

Unlike radio telemetry, fish with 3D acoustic tags cannot be actively pinpointed while mobile tracking in the field because the hydrophones we used were not directional (but directional hydrophones are available). Therefore, we post-processed the data to identify time and location where a fish was detected. If fish were detected on several hydrophones, we only used detections on the lowest gain hydrophone which yielded the minimum distance of the tagged fish from the boat. To associate acoustic pings with a geo-referenced location, we matched the time that a fish was detected to the GPS location of the boat at the time of detection. Each fish was assigned only one location for each hour of mobile tracking.

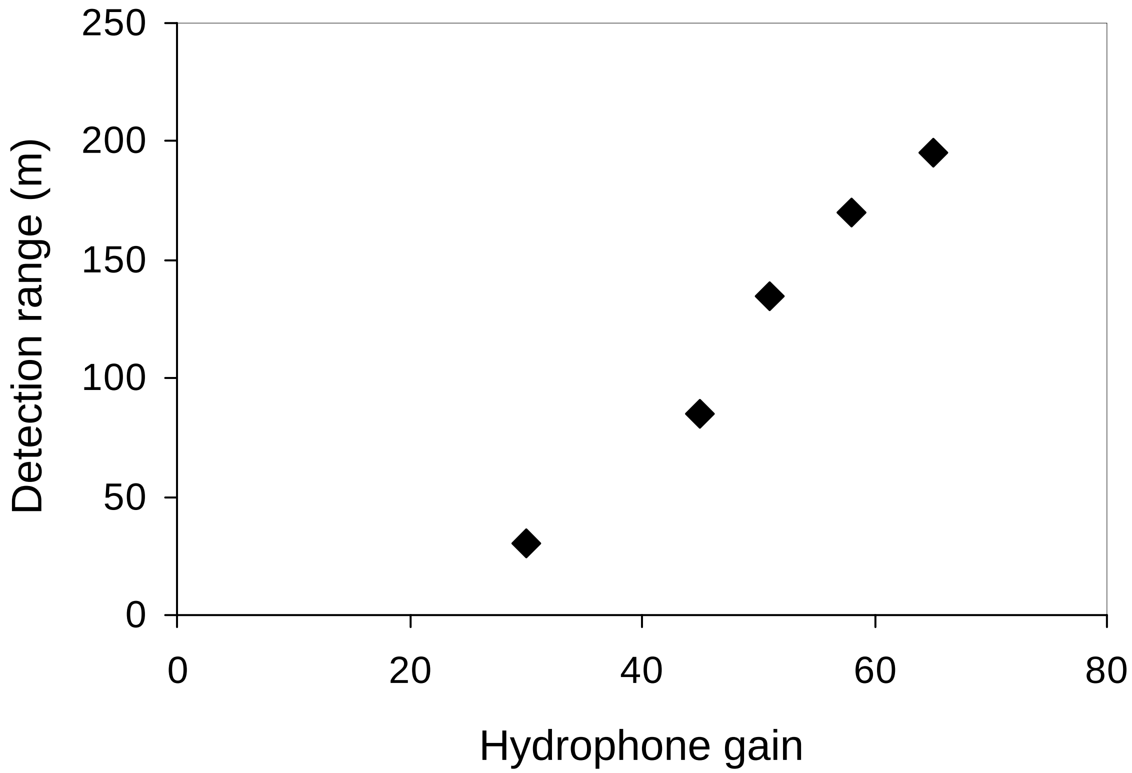

Figure 2.1. — The relation between hydrophone gain and the distance (m) that a tag could be detected from the boat for mobile tracking at in Lake Roosevelt near Grand Coulee Dam in 2002.

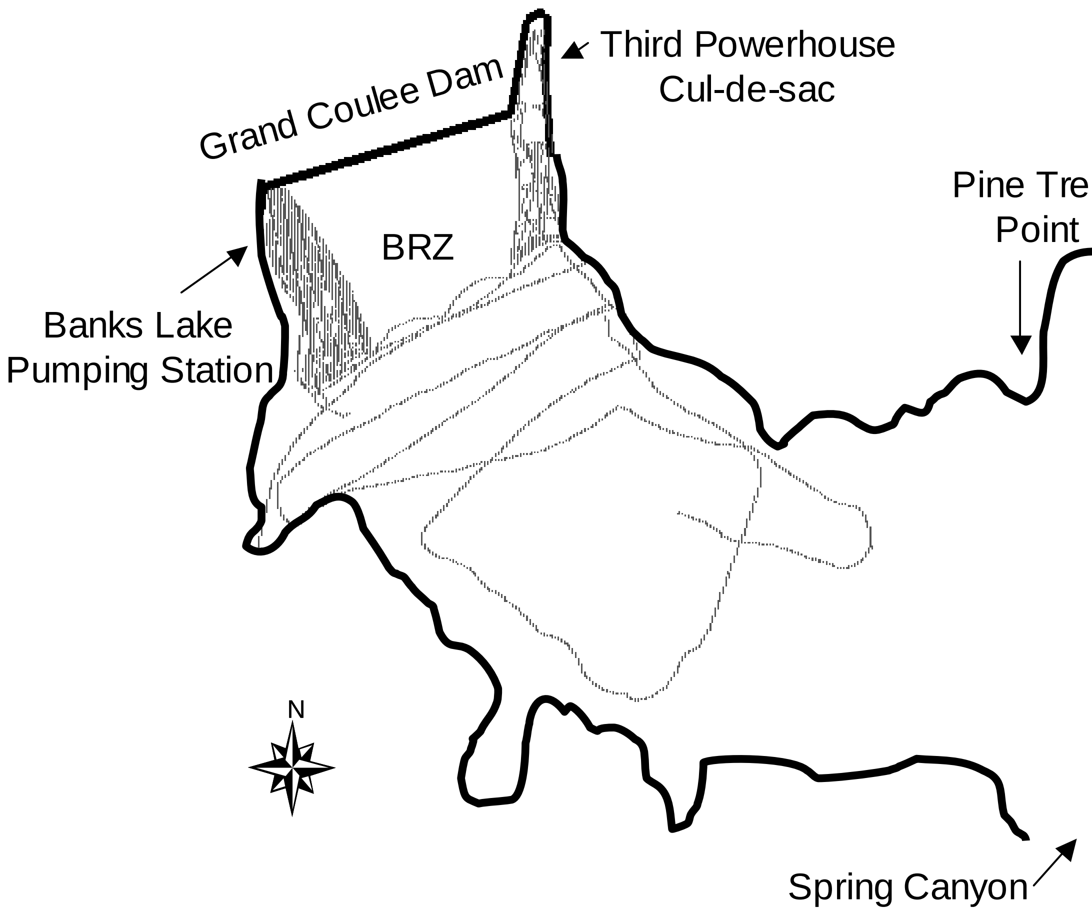

Figure 2.2. — Schematic of mobile tracking area showing location of GPS tracks during mobile tracking at Grand Coulee Dam, 2002.

Results

During the 10 mobile tracking sessions we detected 14 of 173 fish tagged and released for the strobe light study; 7 of 106 kokanee and 7 of 67 rainbow trout (Figure 2.3). Although 42% of the fish detected were only detected once, 2 kokanee and 1 rainbow trout were detected 6 times. There were 37 detections for the 14 individual fish. In contrast to 2001, where 65-75% of fish detections were detected between 126 and 325 m (Perry et al., 2001), 43% of fish detections were between 36 and 85 m of the tracking boat (Figure 2.4).

The majority of fish detected during mobile tracking (71%, 5 kokanee and 5 rainbow) were outside the BRZ near the east and west shorelines of the reservoir. The northeastern shoreline and third powerhouse cul-de-sac comprised 71% (10 of 14) of all fish and 100% of the kokanee (Figure 2.5). There were a few detections near the Banks Lake pumping station, and no detections were observed in the four tracking period in Banks Lake. We found no differences between day and night because only one night tracking was conducted in Lake Roosevelt and 8 fish were located (5 kokanee and 3 rainbow trout).

Discussion

Although we detected equal numbers of kokanee and rainbow trout during mobile tracking, we found that kokanee were concentrated along the eastern shoreline and rainbow trout were spread through the reservoir. Of the number of each species released, we detected 7% of the kokanee and 10% of the rainbow trout. We covered a large area of the reservoir compared to the fixed array in the third powerhouse cul-de-sac area and were able to identify species-specific areas where fish were located throughout the reservoir. During 2001 most fish were detected in the pumping station, but in 2002 we detected only one rainbow near the pumping station; however, less effort was spent mobile tracking near the pumping station during 2002. Generally, both kokanee and rainbow trout in 2001 were spread throughout the reservoir, while in 2002 we found that all of the kokanee were congregated along the eastern shoreline and rainbow trout were spread throughout the reservoir. No kokanee were detected near the third powerhouse in 2001, though during 2002 we expanded our survey efforts to include inside the third powerhouse cul-de-sac and detected many kokanee near this area.

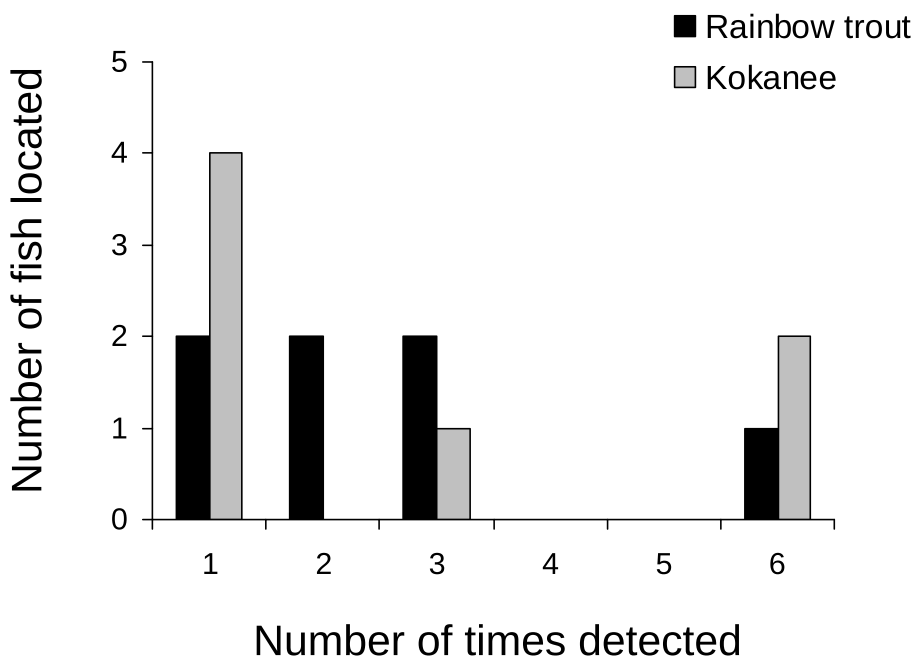

Figure 2.3. — Detection summary of 14 fish (7 kokanee and 7 rainbow trout) located during 10 mobile tracking periods in Lake Roosevelt, 2002.

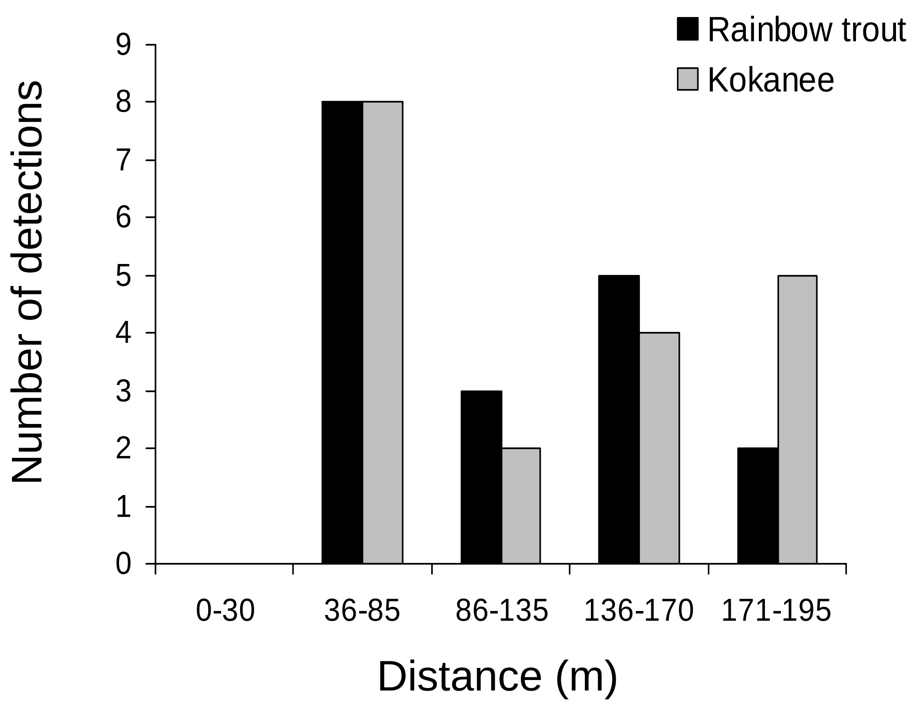

Figure 2.4. — Number of fish locations for kokanee and rainbow trout at a given detection range from the tracking boat during 10 mobile tracking periods in Lake Roosevelt, 2002.

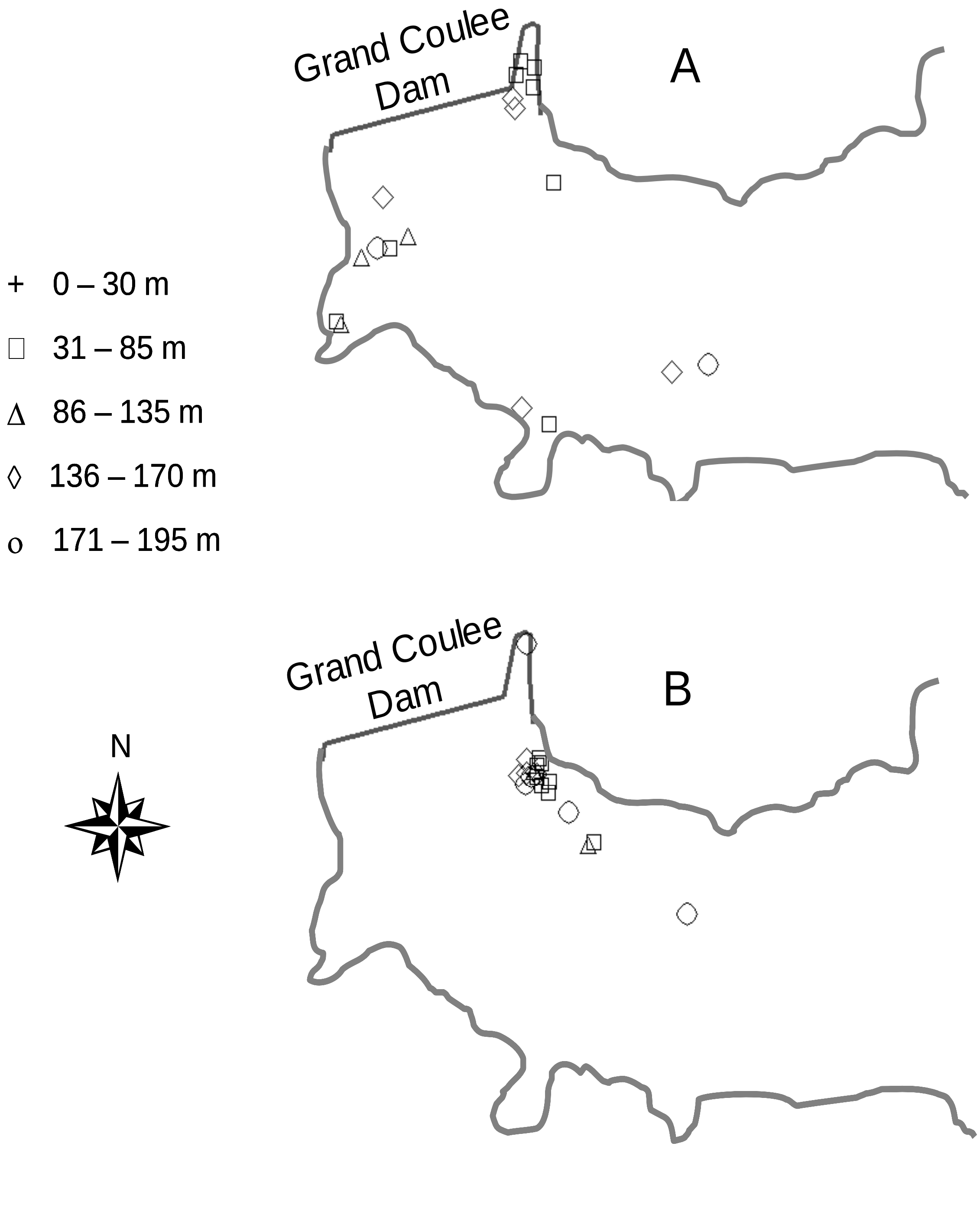

Figure 2.5. — Schematic showing fish locations for rainbow trout (A) and kokanee (B) detected during 10 mobile tracking periods in Lake Roosevelt, 2002.

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Appendix 1: Movement Paths of Individual Fish

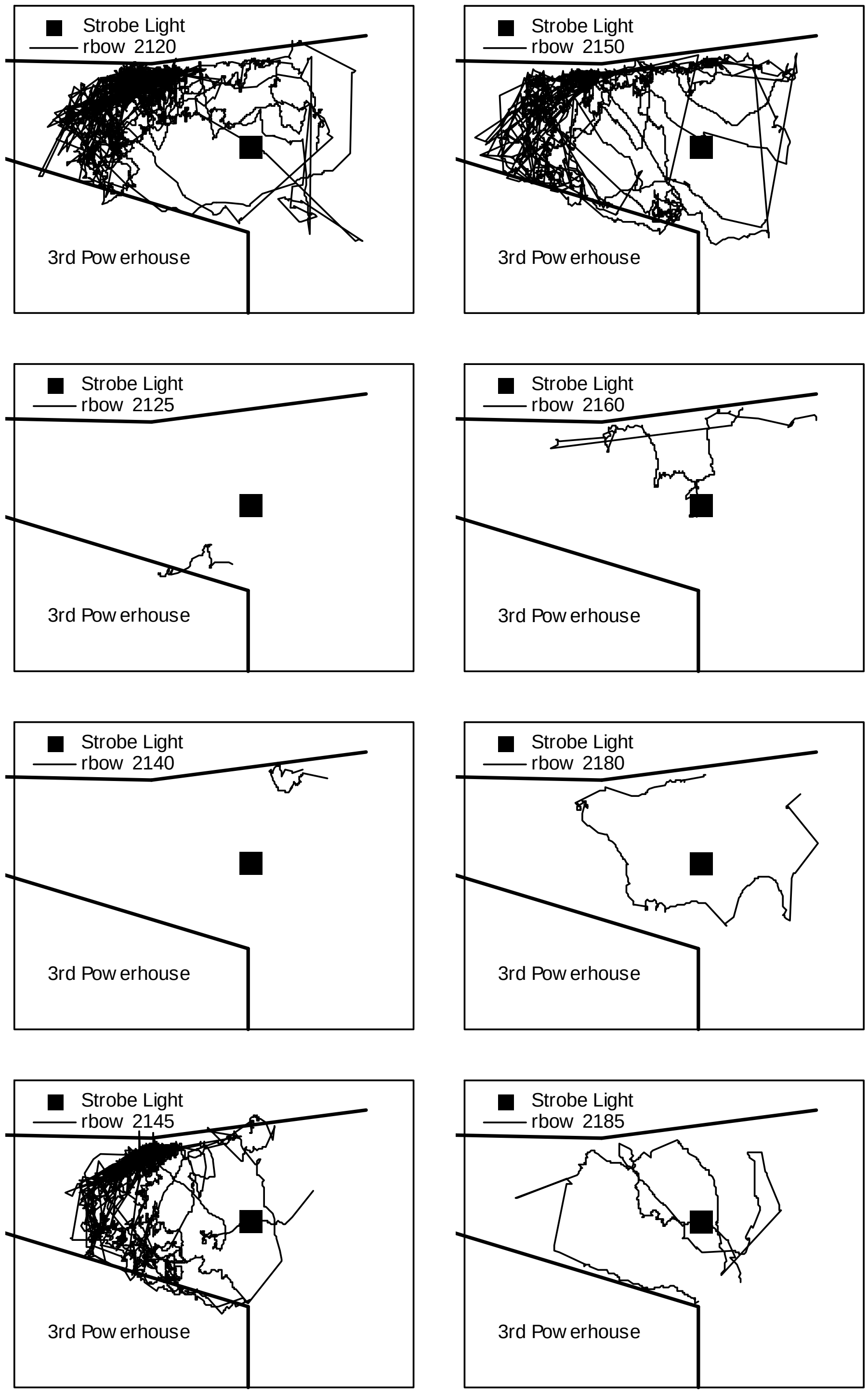

Figure A1.1. — Movement paths of individual tagged rainbow trout (rbow) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

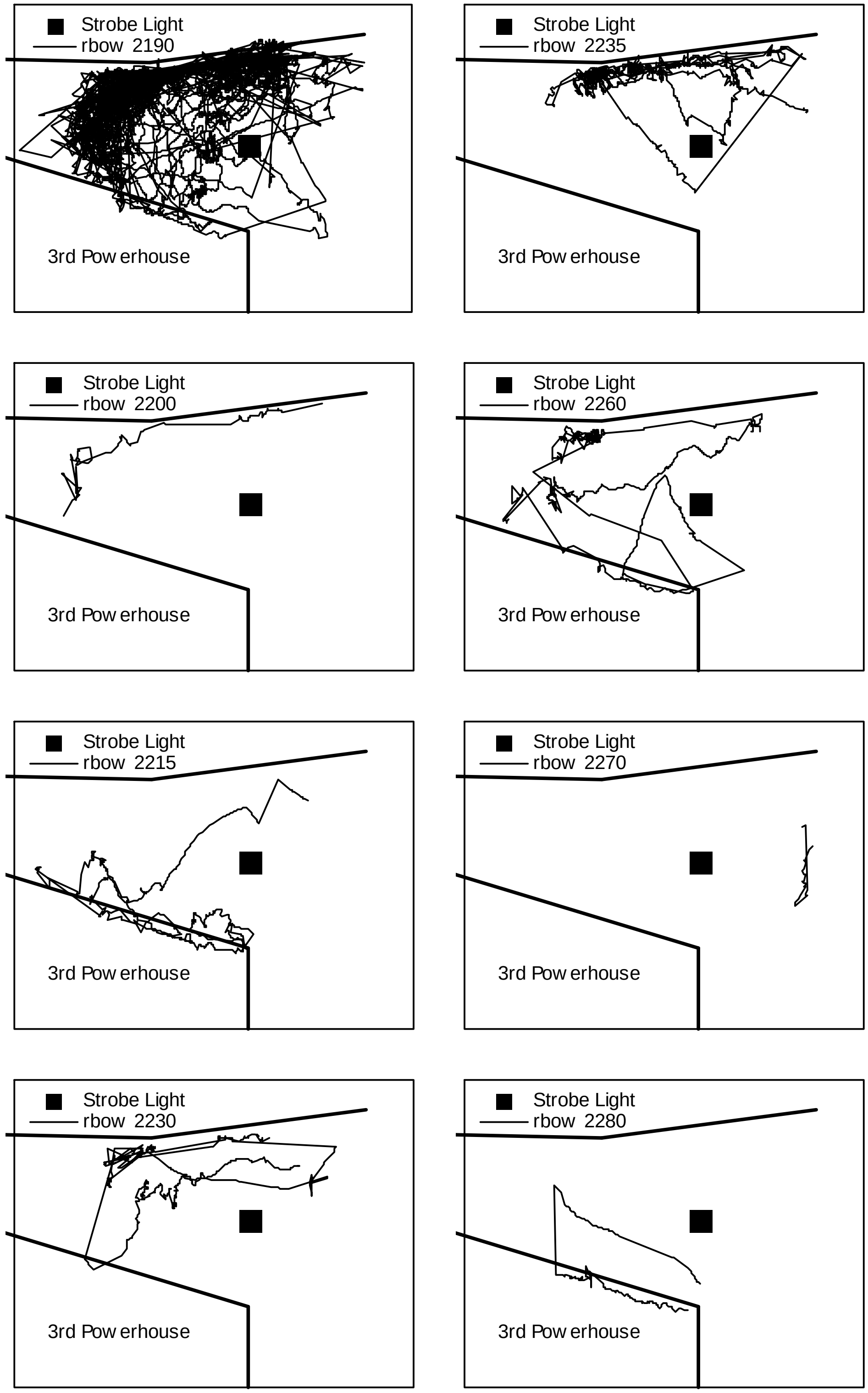

Figure A1.1 continued. — Movement paths of individual tagged rainbow trout (rbow) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

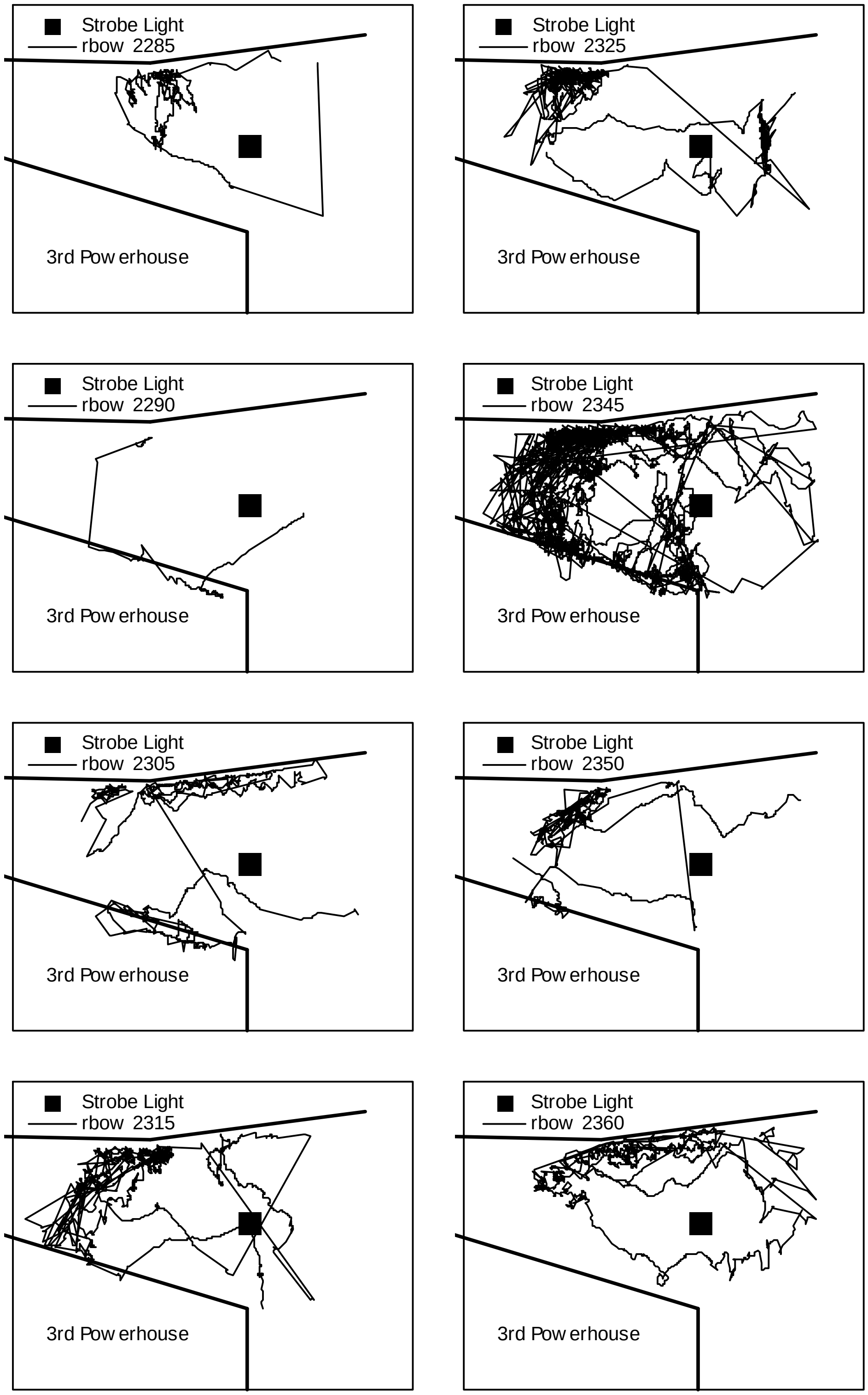

Figure A1.1 continued. — Movement paths of individual tagged rainbow trout (rbow) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

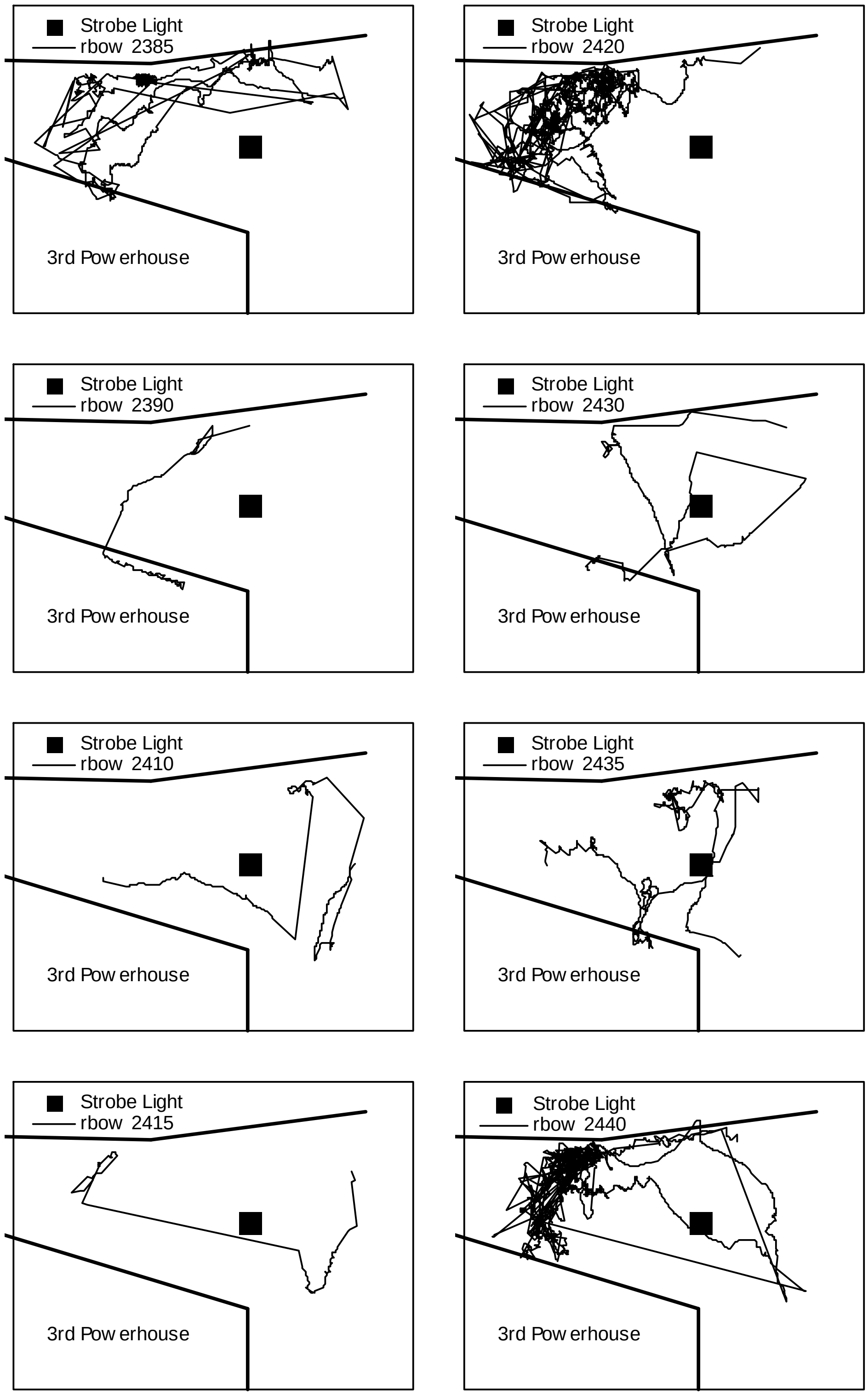

Figure A1.1 continued. — Movement paths of individual tagged rainbow trout (rbow) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

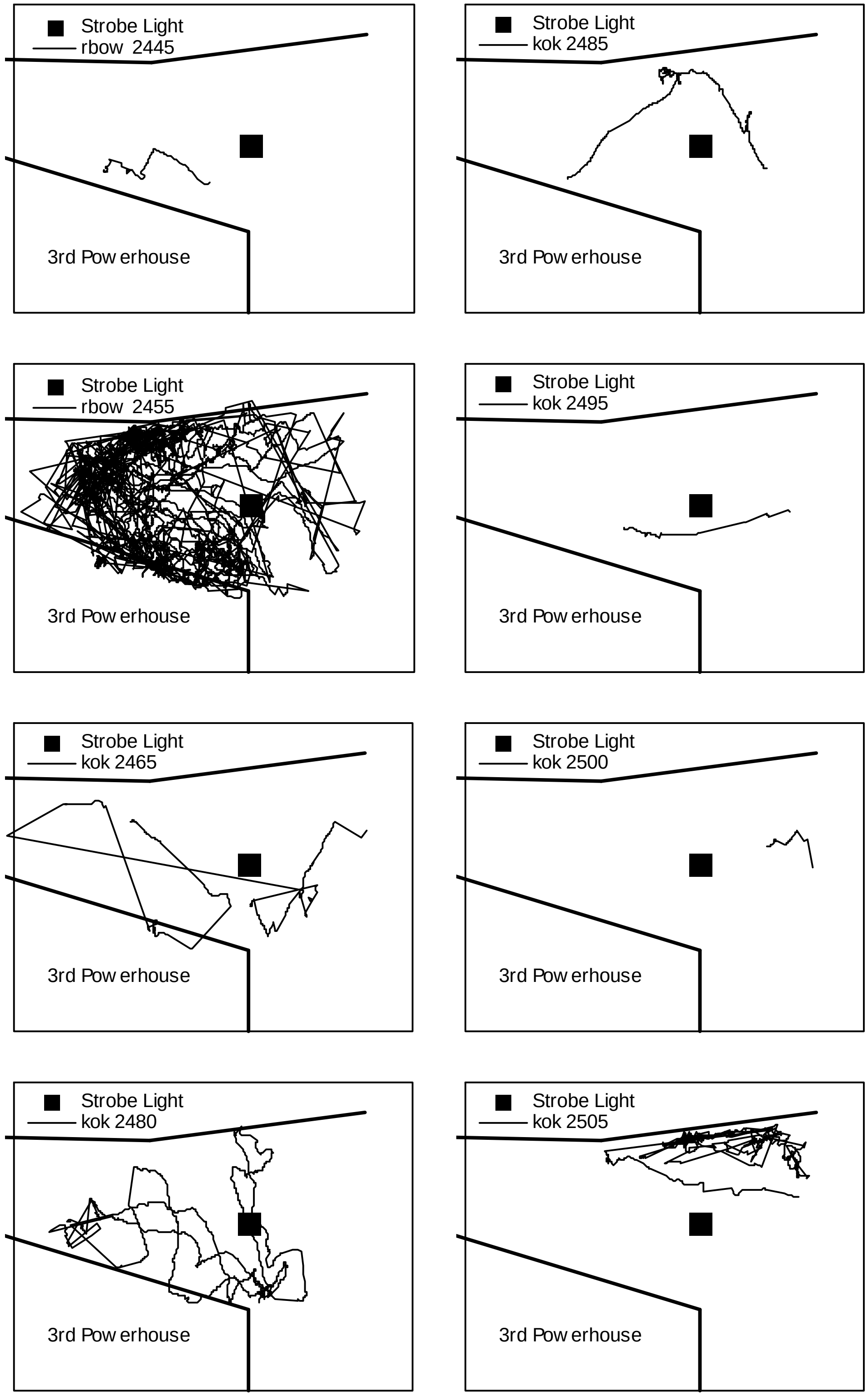

Figure A1.1 continued. — Movement paths of individual tagged rainbow trout (rbow) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

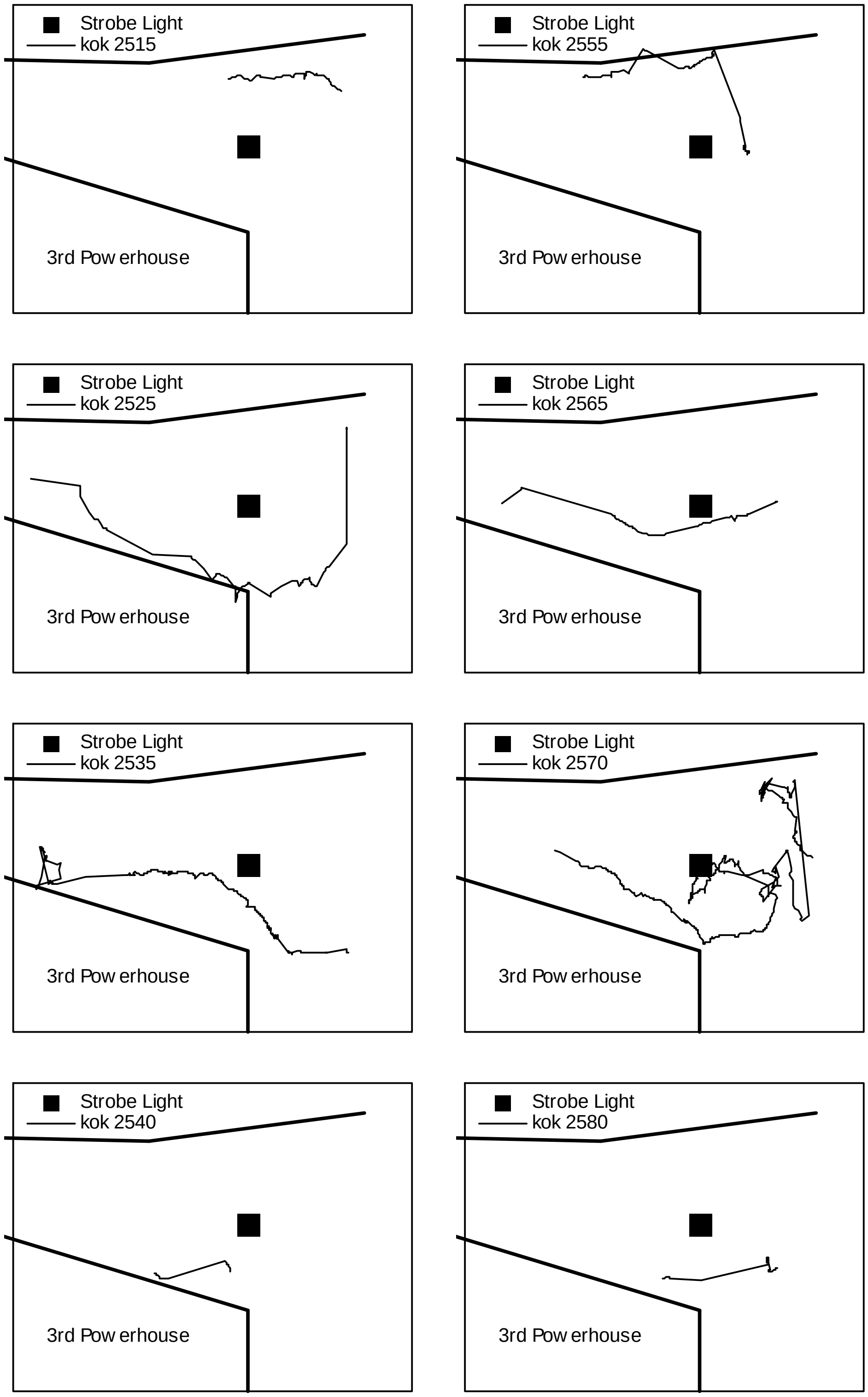

Figure A1.2. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

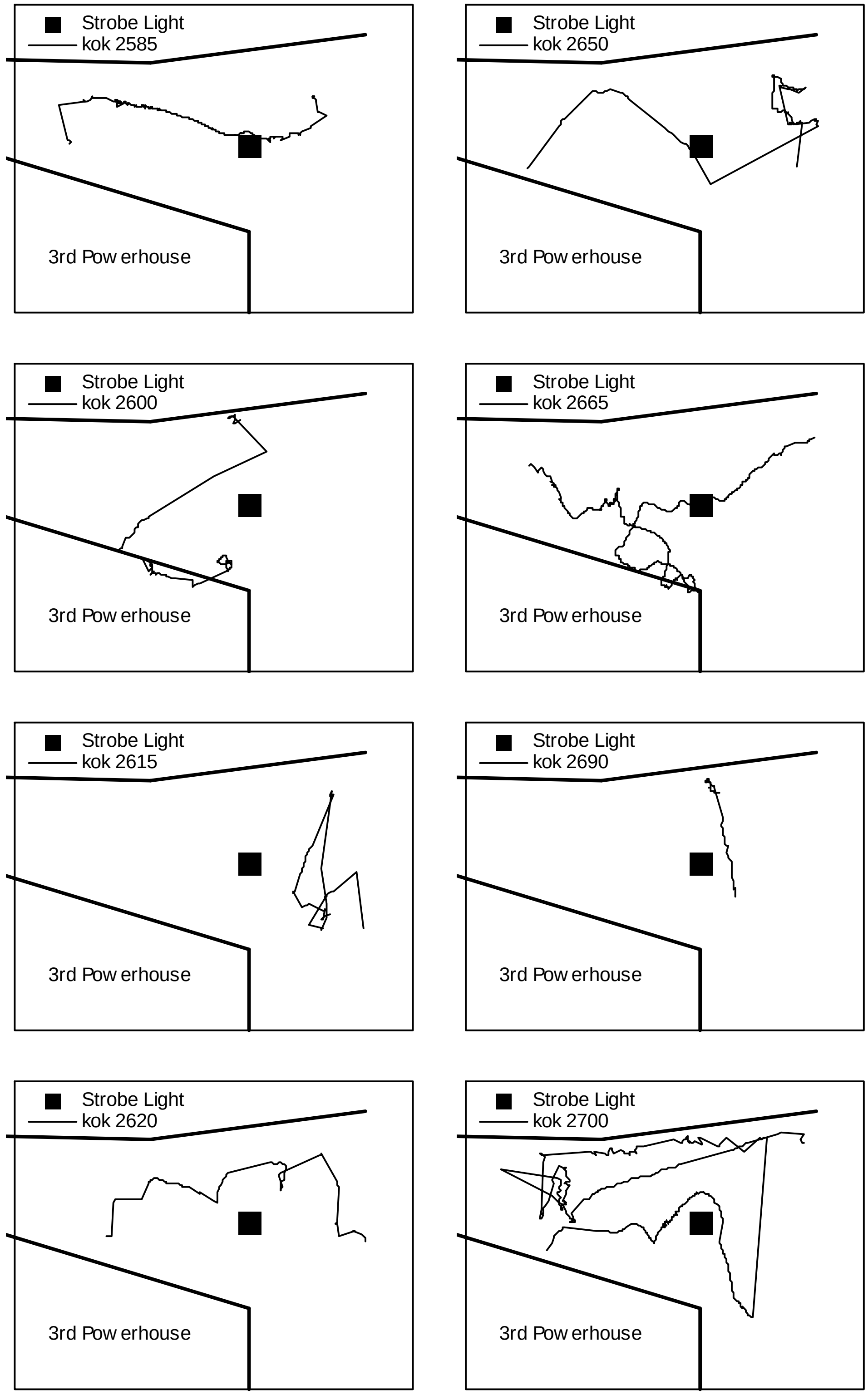

Figure A1.2 continued. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

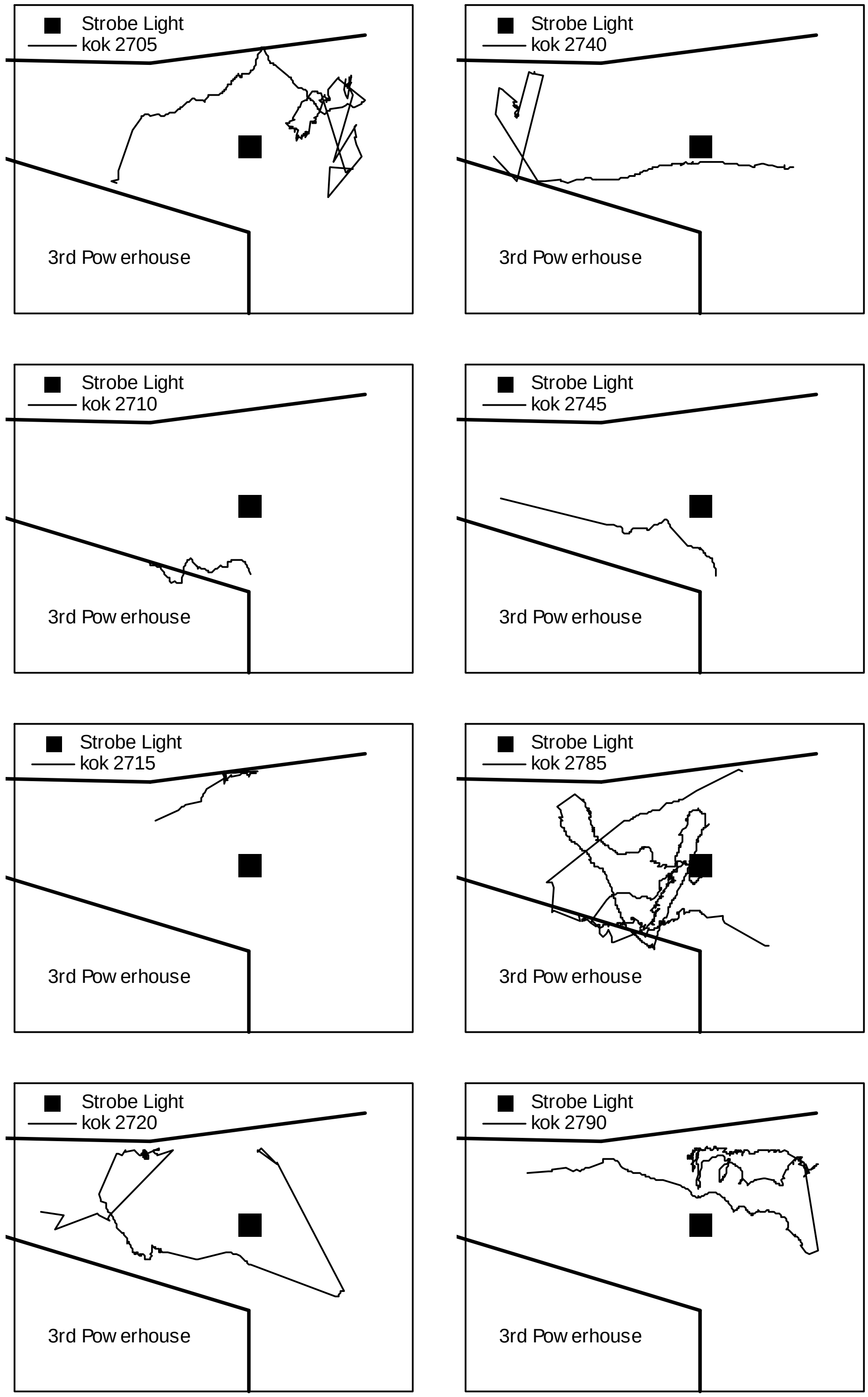

Figure A1.2 continued. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

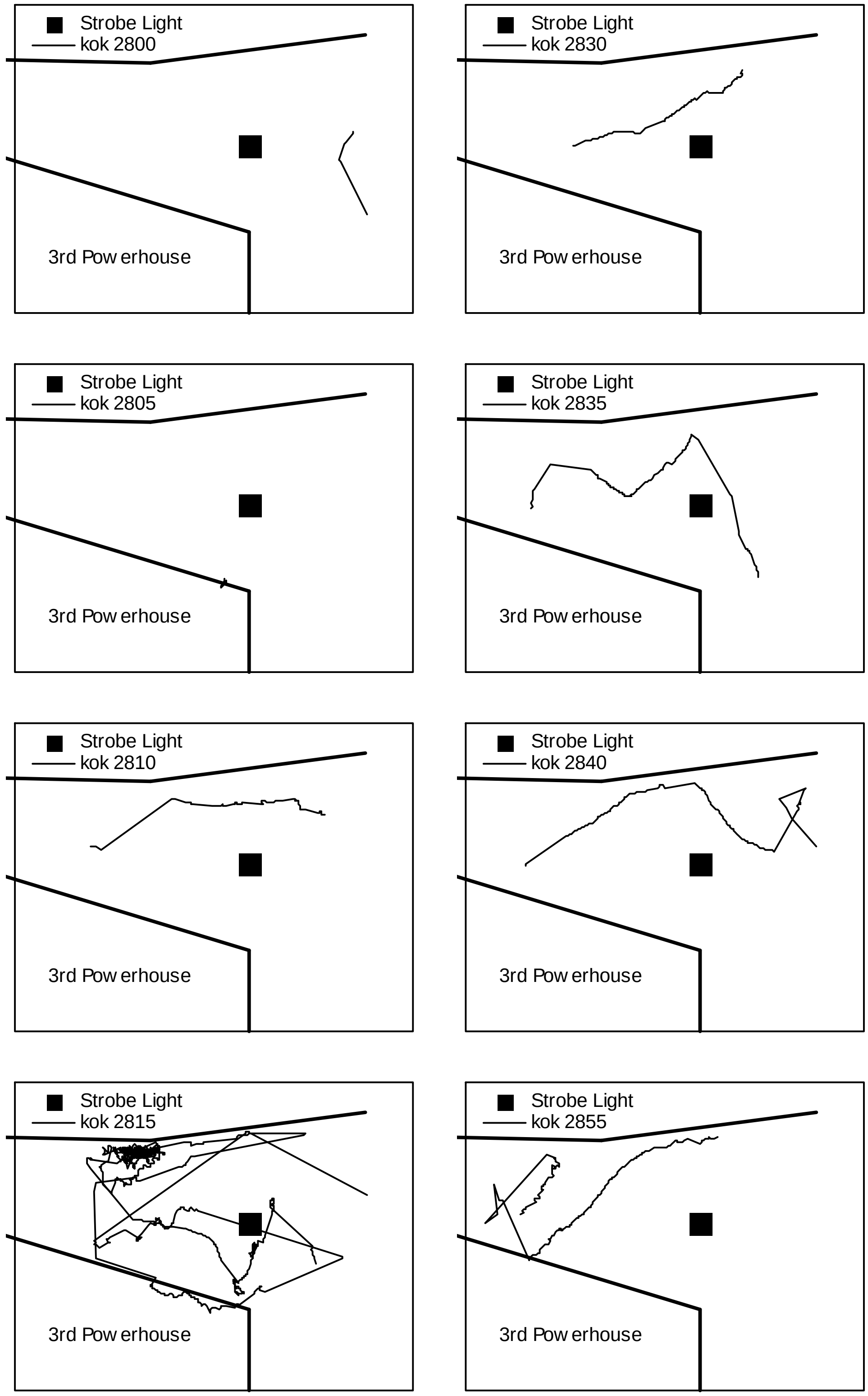

Figure A1.2 continued. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

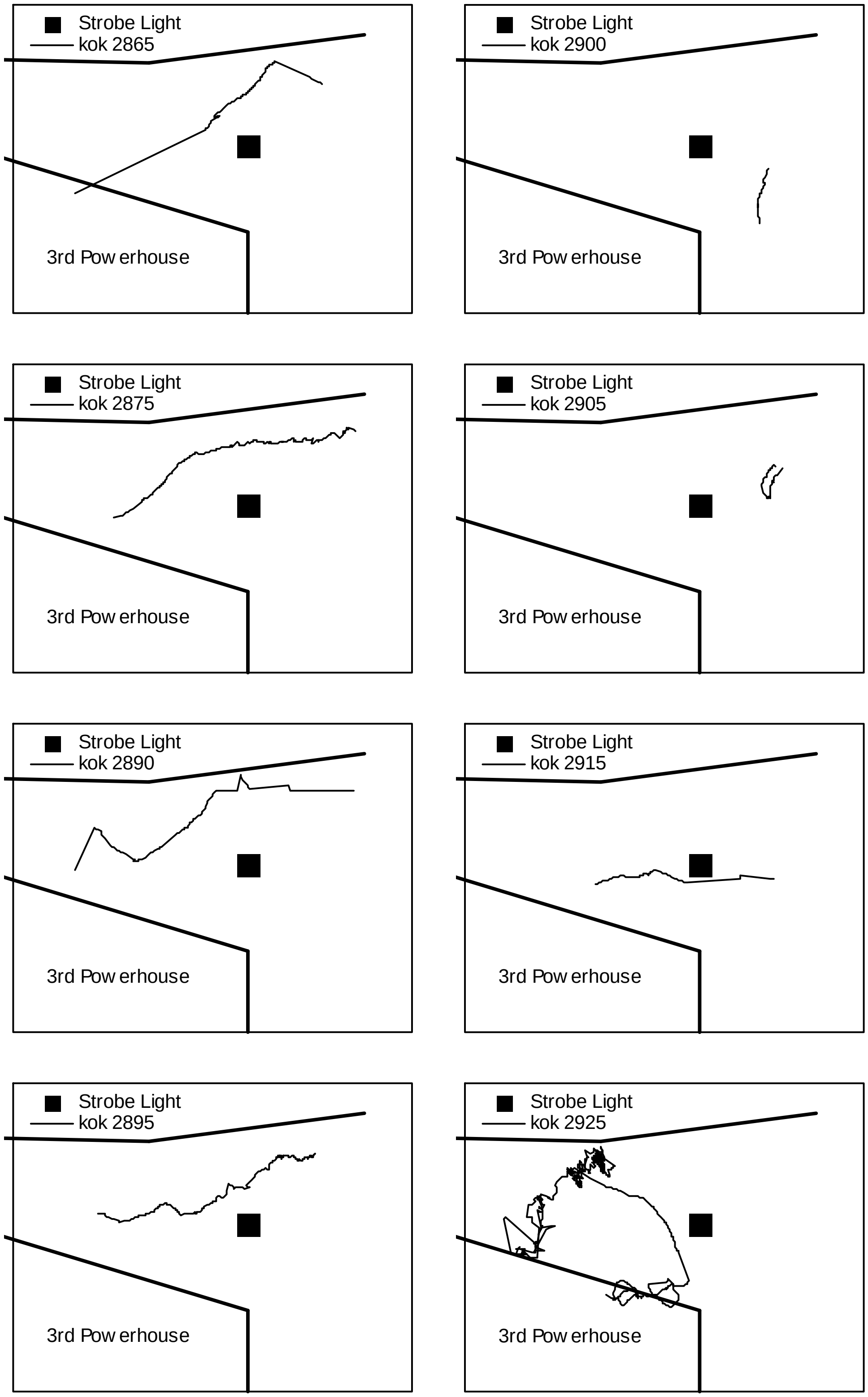

Figure A1.2 continued. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

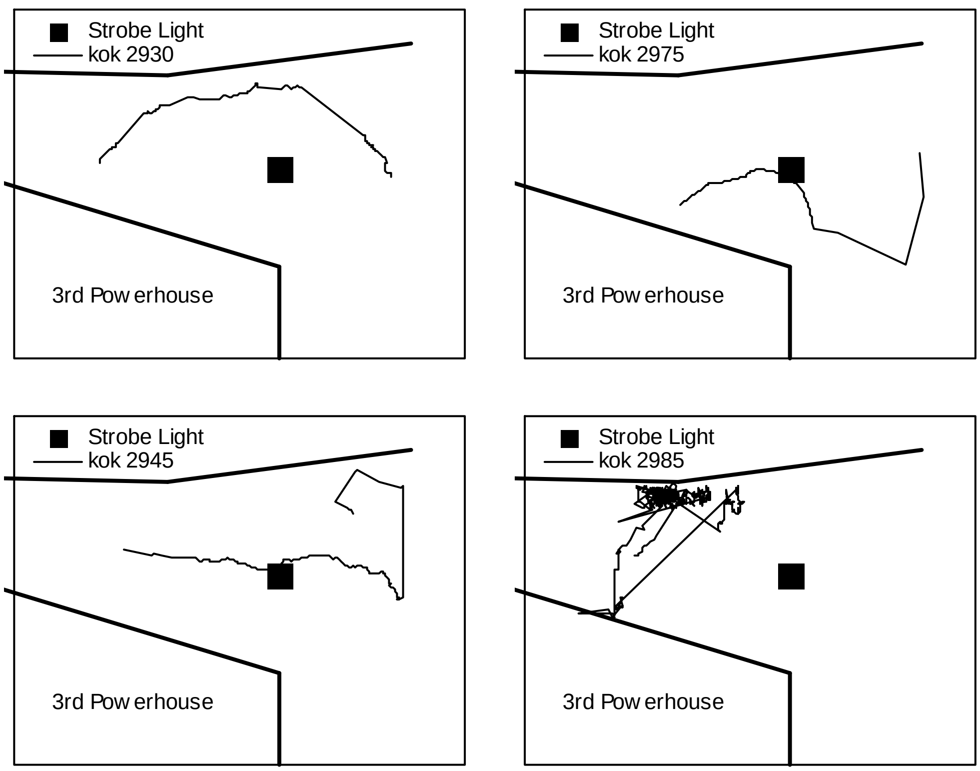

Figure A1.2 continued. — Movement paths of individual tagged kokanee (kok) in the 3D hydroacoustic array near the third powerhouse cul-de-sac at Grand Coulee Dam, 2002. The black square shows the location of the strobe lights.

Appendix 2: Detection and Residence Time Summaries

Table A2.1. — The residence time of kokanee and rainbow trout for the entire 3D array during 2002.

Strobe treatment	Number of fish	Mean	Median	Range	Standard deviation
Kokanee					
Off	29	0.35	0.18	0.01 to 2.93	0.57
3-On	24	0.39	0.24	0.03 to 1.54	0.39
6-On	9	0.47	0.17	0.03 to 3.07	0.98
Rainbow Trout					
Off	26	1.91	1.10	0.0 to 7.32	2.31
3-On	26	1.17	0.56	0.01 to 3.86	1.15
6-On	13	2.98	2.86	0.28 to 6.74	2.30

Table A2.1 — Summary of the number of detections within 25 m of the strobe lights for tagged kokanee and rainbow trout during the day and night and during each of the three strobe light treatments at Grand Coulee Dam during 2002.

Time of day	Strobe light treatment	Number of fish	Mean	Median	Range	Standard Deviation
			Kokanee			
Day	Off	3	30.7	15.0	8.0 to 69.0	33.4
	3-On	0	-	-	-	-
	6-On	2	4.5	4.5	2.0 to 7.0	3.5
Night	Off	2	14.0	14.0	5.0 to 23.0	12.7
	3-On	3	79.0	52.0	5.0 to180.0	90.6
	6-On	1	212.0	212.0	-	-
			Rainbow trout			
Day	Off	6	52.0	31.0	1.0 to163.0	59.6
	3-On	7	35.4	17.0	8.0 to152.0	51.7
	6-On	1	47.0	47.0	-	0.0
Night	Off	3	49.7	45.0	39.0 to 65.0	13.6
	3-On	2	29.0	29.0	24.0 to 34.0	7.1
	6-On	0	-	-	-	-

Appendix 3: Fish Release Summary

Table A3.1. — Release summary for acoustic-tagged rainbow trout released into Lake Roosevelt in 2002.

Release	Date	Release time	Number released	Mean length (mm)	Mean weight (g)
1	6/6/02	10:14	5	202.8	198.3
2	6/8/02	23:02	5	247.0	192.1
3	6/10/02	23:45	5	246.2	198.0
4	6/14/02	10:21	5	246.8	195.1
5	6/16/02	22:12	5	244.6	189.6
6	6/18/02	18:00	5	231.2	175.3
7	6/20/02	10:30	5	242.8	195.4
8	6/22/02	10:00	5	260.4	230.4
9	6/25/02	10:05	4	225.5	145.9
10	6/27/02	10:00	4	267.3	244.5
11	6/29/02	22:20	4	279.0	242.6
12	7/1/02	10:18	3	258.0	235.8
13	7/3/02	21:50	4	263.8	247.1
14	7/5/02	10:10	4	256.8	230.6
15	7/7/02	21:45	4	267.0	272.1

Table A3.2. — Release summary for acoustic-tagged kokanee released into Lake Roosevelt in 2002.

Release	Date	Release time	Number released	Mean length (mm)	Mean weight (g)
1	6/6/02	10:14	7	188.9	75.0
2	6/8/02	23:02	7	176.4	62.6
3	6/10/02	23:45	7	175.9	61.1
4	6/14/02	10:21	7	197.9	85.1
5	6/16/02	22:12	7	196.4	96.6
6	6/18/02	18:00	7	190.3	87.0
7	6/20/02	10:30	7	178.0	65.6
8	6/22/02	10:00	7	179.1	69.5
9	6/25/02	10:05	6	186.3	81.5
10	6/27/02	10:00	7	175.3	60.6
11	6/29/02	22:20	7	189.3	79.7
12	7/1/02	10:18	7	189.3	81.4
13	7/3/02	21:50	8	168.5	55.7
14	7/5/02	10:10	8	181.3	72.3
15	7/7/02	21:45	7	163.0	52.8