SPATIAL AND TEMPORAL ENTRAINMENT OF FISH FROM HAUSER RESERVOIR, MONTANA

by

Justin Philip Spinelli

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APPROVAL

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Justin Philip Spinelli

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Dr. Alexander V. Zale

Approved for the Department of Ecology

Dr. David W. Roberts

Approved for the Division of Graduate Education

Dr. Carl A. Fox

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ABSTRACT

Management of fish populations in Hauser Reservoir, Montana, is hindered by undesirable and unpredictable downstream entrainment of fish through Hauser Dam. My objectives were to estimate spatial and temporal entrainment of fish larger than 100 mm total length through Hauser Dam and identify environmental and operational conditions influencing entrainment. I quantified entrainment using hydroacoustics at the turbine intakes from July 2007 to November 2008 and the spillway from May to July 2008. Species composition was characterized using multiple netting gears. I investigated the relationships between entrainment and conditions in the reservoir and at the dam using multiple linear regression. Total entrainment was 145,470 (95% CI = 138,144 – 152,796). About 60% of entrained fish were smaller than 220 mm. Annual entrainment from summer to autumn was higher in 2007 (N = 79,031; 95% CI = 73,861 – 84,201) than in 2008 (N = 52,513; 95% CI = 47,830 – 57,196). I applied species composition by size to the hydroacoustic data to identify entrained fish species, but many fish (N = 55,529; 95% CI = 50,337 – 60,721) could not be reliably assigned to species because concurrent net catches did not include individuals of similar size. Total entrainment was mostly made up of rainbow trout (33.3%) and walleye (30.2%). Spillway entrainment was 16% of total entrainment and was correlated with spillway discharge; turbine entrainment was not. Turbine entrainment increased from summer to autumn in both years, probably in response to autumn turnover and releases of hatchery rainbow trout. On average, 9.0% (SD = 1.2%) of hatchery fish were entrained soon after being stocked in the reservoir. Most regression models were equally ranked using Akaike Information Criterion corrected for small sample size indicating that a combination of conditions were influencing entrainment. Spatial and temporal patterns of entrainment at Hauser Dam were typical of other facilities in that entrainment varied in response to a changing combination of operational and environmental conditions. Identification of these patterns of entrainment allows managers to evaluate effects to the reservoir population and make more informed decisions.

INTRODUCTION

Fish populations in many North American reservoirs are affected by entrainment through hydroelectric facilities. Loss of fish by entrainment may hinder management to maintain recreational fisheries and reproductive populations. Hydroelectric facilities are often required to assess and mitigate their effects on aquatic biota as part of the permitting process with the Federal Energy Regulatory Committee (FERC). Entrainment of salmonid outmigrants is well understood in the Columbia and Snake River system, where outmigration is encouraged (Stieg and Iverson 1998; Coutant and Whitney 2000; Johnson and Moursund 2000; Venditti et al. 2000; Ploskey et al. 2005). However, effects of entrainment on resident reservoir species are not as well understood and are unpredictable (Stober et al. 1983; FERC 1995; Navarro et al. 1996; Petr and Mitrofanov 1998; Thurrien and Bourgeois 2000). Understanding entrainment patterns and the factors influencing them are crucial to helping managers make informed decisions and for determining cost effective methods to reduce entrainment rates.

Patterns of entrainment can be affected by season, time of day, and the distribution of fish horizontally and vertically in a water body. Entrainment at midwestern U.S. facilities was low and consistent in winter while the activity of fish was low, but increased in summer and autumn as fish became more active and juveniles emerged from nursery areas (EPRI 1992; FERC 1995). In addition, entrainment of many species at facilities across the United States was higher at night than during the day (EPRI 1992; FERC 1995; Navarro et al. 1996). For example, entrainment rates of kokanee *Oncorhynchus nerka* at Libby Dam peaked from three hours before midnight to two hours before sunrise during all seasons (Skaar et al. 1996), and largemouth bass *Micropterus salmoides* and bullheads *Ameiurus* spp. were entrained more between 1600 and 0400 hours than during other times of the day at four Michigan facilities (Navarro et al. 1996). The horizontal placement of the intakes relative to the shoreline can also be a factor as limnetic species (e.g., kokanee) are more likely to be entrained away from the shoreline whereas littoral species (e.g., yellow perch *Perca flavescens*) are likely to be entrained through intakes near shorelines (FERC 1995).

Discharge influences entrainment rates at many facilities (Coutant and Whitney 2000; Ploskey et al. 2005; Schreffler et al. 1994; Skaar et al. 1996). Entrainment rates of kokanee increased during months of high flows at Dworshak Dam, Idaho (Maiolie and Elam 1998; Stark and Maiolie 2004), and correlated positively with spillway discharge at Libby Dam, Montana (Skaar et al. 1996). Salmonids in the Columbia River delayed outmigration from forebays until they detected and aligned themselves with a downstream current (Stieg and Iverson 1998; Johnson and Moursund 2000; Venditti et al. 2000). The proportion of discharge among primary passage structures (e.g., spillway and two sluiceways) affected the horizontal distribution of entrainment across the Bonneville Dam, but not among turbines or spillgates within primary structures (Ploskey et al. 2005), suggesting the horizontal distribution of discharge may also affect entrainment rates across facilities.

Temperature and dissolved oxygen (DO) concentration dynamics play a crucial role in entrainment because they affect movements of fish. Temperature and DO dynamics influence metabolism, respiration, reproductive condition, and behavior of fishes because avoiding hypoxic conditions enhances survival of many oxygen sensitive species such as salmonids (Davis 1975). Rainbow trout *Oncorhynchus mykiss* and brown trout *Salmo trutta* selected deeper, cooler waters when surface temperatures exceeded 20ºC during summer in the Jocassee Reservoir, North and South Carolina, but only if hypolimnetic dissolved oxygen concentrations remained above 5 mg/L (Barwick et al. 2004). A decline in catch per unit effort of rainbow and Yellowstone cutthroat trout *O. clarkii bouveri* in floating gillnets when surface water temperatures reached 20ºC in two Wyoming lakes was attributed to use of cooler, deeper water (Rhea et al. 2005). In contrast, cutthroat and rainbow trout behavior in Spada Lake, Washington, was not influenced by surface water temperatures as warm as 22.5ºC and DO concentrations as low as 3.9 mg/L (Stables and Thomas 1992). Increased entrainment in four reservoirs in Michigan was attributed primarily to higher activity levels during reproduction as temperatures increased (Navarro et al. 1996). Entrainment declined when withdrawal occurred below the thermocline in two stratified reservoirs in South Carolina because fish avoided the hypoxic hypolimnion (Paller et al. 2006).

All discharge of the Missouri River flows through the hydroelectric turbines at Hauser Dam, Montana, most of the year, but when discharge exceeds turbine capacity excess water is diverted over the spillway. Typically, high discharges occur in spring as the winter snowpack melts, but in recent years drought has reduced spring runoff and river discharges have remained low. In addition, the reservoir stratifies thermally and hypolimnetic DO concentrations decline to less than 5 mg/L during summer, which appears to restrict large species to surface waters upstream of the dam (Horn 2004).

Hypoxia may influence entrainment more than discharge because discharge in the summer is relatively stable, declining slowly through autumn.

Evidence of fish entrainment at Hauser Dam was first documented in the late 1960s when rainbow trout released in Canyon Ferry Reservoir were caught by anglers in Hauser and Holter reservoirs and in the Missouri River below Holter Reservoir (Hill 1973). Hill (1973) attributed entrainment to stocking during high discharge (April through July) and recommended that fish be stocked when no spillway discharge occurred. Despite altered stocking efforts, the rainbow trout and kokanee fisheries collapsed during the mid-1990s after four consecutive years of record high river discharges (Dalbey 2001). Kokanee and rainbow trout losses were positively correlated with spillway discharge (Skaar and Humphrey 1997).

Entrainment past Hauser Dam is thought to be a major influence on the abundance of resident fish populations in Hauser Reservoir. Despite efforts by Montana Fish, Wildlife and Parks (MFWP) Region 3 managers to maintain fish populations in the reservoir, the fishery remains erratic and unsatisfactory to anglers (S. Dalbey, Montana Fish, Wildlife and Parks, personal communication). Catch rates of rainbow trout and kokanee in the reservoir have been low in recent years despite management efforts to improve the fishery through stocking (Dalbey and Humphrey 2006).

Estimating entrainment and understanding the factors that influence entrainment are crucial to fishery managers and necessary to satisfy FERC re-licensing requirements. Issues of particular interest to managers are the differences in entrainment between high and low water years and entrainment of recently stocked rainbow trout. My objectives were to (1) estimate seasonal turbine and spillway entrainment of fish larger than 100 mm total length (TL) through Hauser Dam and (2) identify environmental and operational conditions influencing entrainment through the facility.

STUDY AREA

Hauser Reservoir is formed by Hauser Dam, which is located on the Missouri River northeast of Helena, Montana (Figure 1). The reservoir is eutrophic with a surface area of 1,537 hectares, maximum depth of 21 m, and a retention time of two to eight days (Skaar and Humphrey 1997; Horn 2004). It undergoes thermal stratification from early spring through the summer and early autumn. Thermal stratification of the reservoir is weakened by its short retention time and can be disrupted following a storm event (M. J. Horn, Bureau of Reclamation, personal communication). The dam is a run-of-the-river hydroelectric facility capable of producing 19 megawatts of energy at full operation while drawing 124.6 m^3/s of water through its turbines (Figure 2). Six turbines draw water from a forebay canal on the north side of the dam (hereafter, forebay) that is 77.4 m long, 14.3 m wide, and 9.7 m deep at mean pool elevation. Average velocity of water entering the forebay was 0.84 m/s (SD = 0.08 m/s). The intakes of the turbines draw water from the forebay floor to 5.4 m below mean pool elevation and maximum discharge varies among turbines: units 1 through 4 are each capable of drawing 18.4 m^3/s, unit 5 21.2 m^3/s, and unit 6 29.7 m^3/s. All turbines are equipped with 5.1-cm trashracks extending from above mean pool elevation to the floor of the forebay.

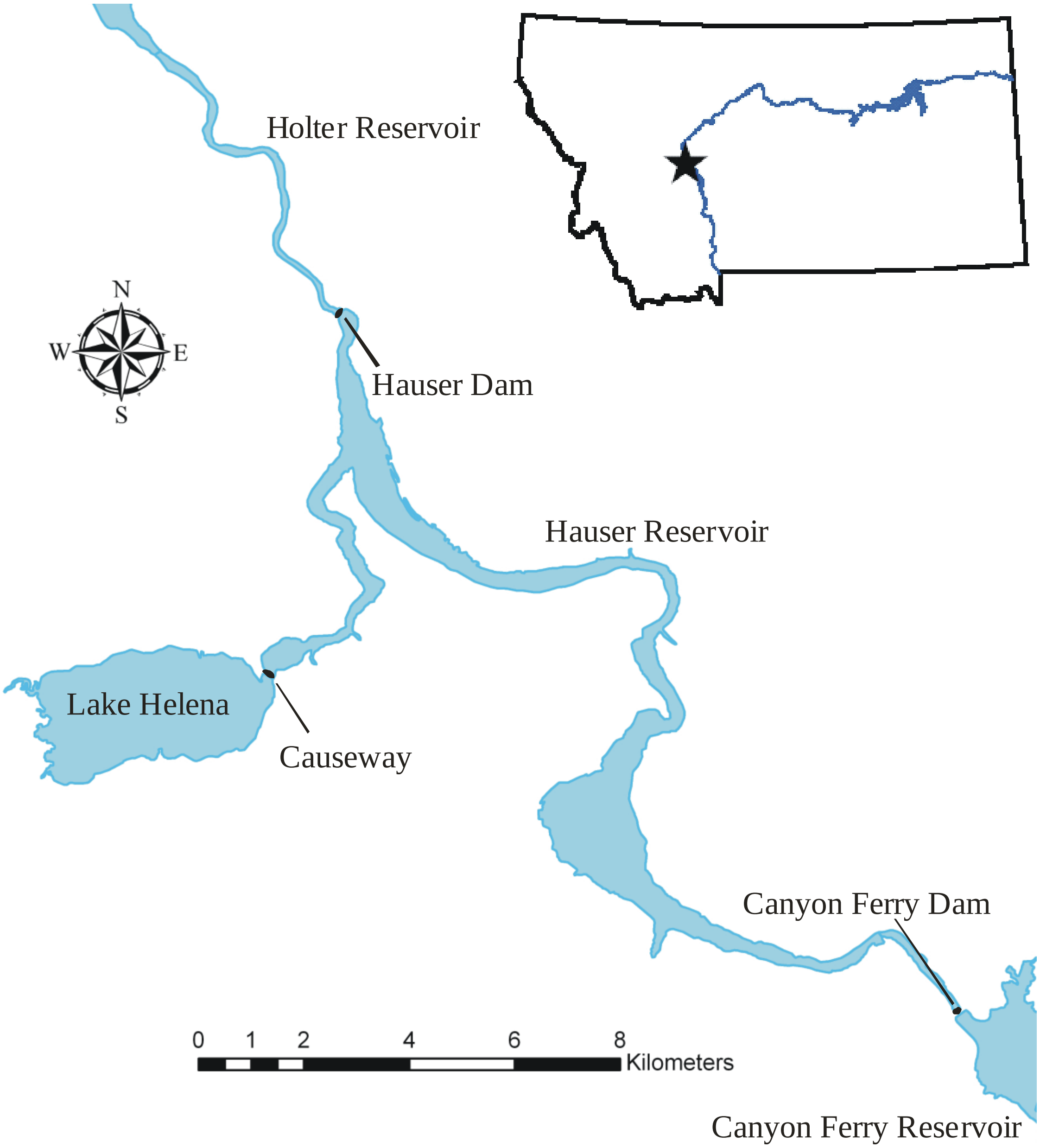


Figure 1.—Map of Hauser Reservoir, Montana (★) showing the locations of Hauser Dam and Canyon Ferry Dam.

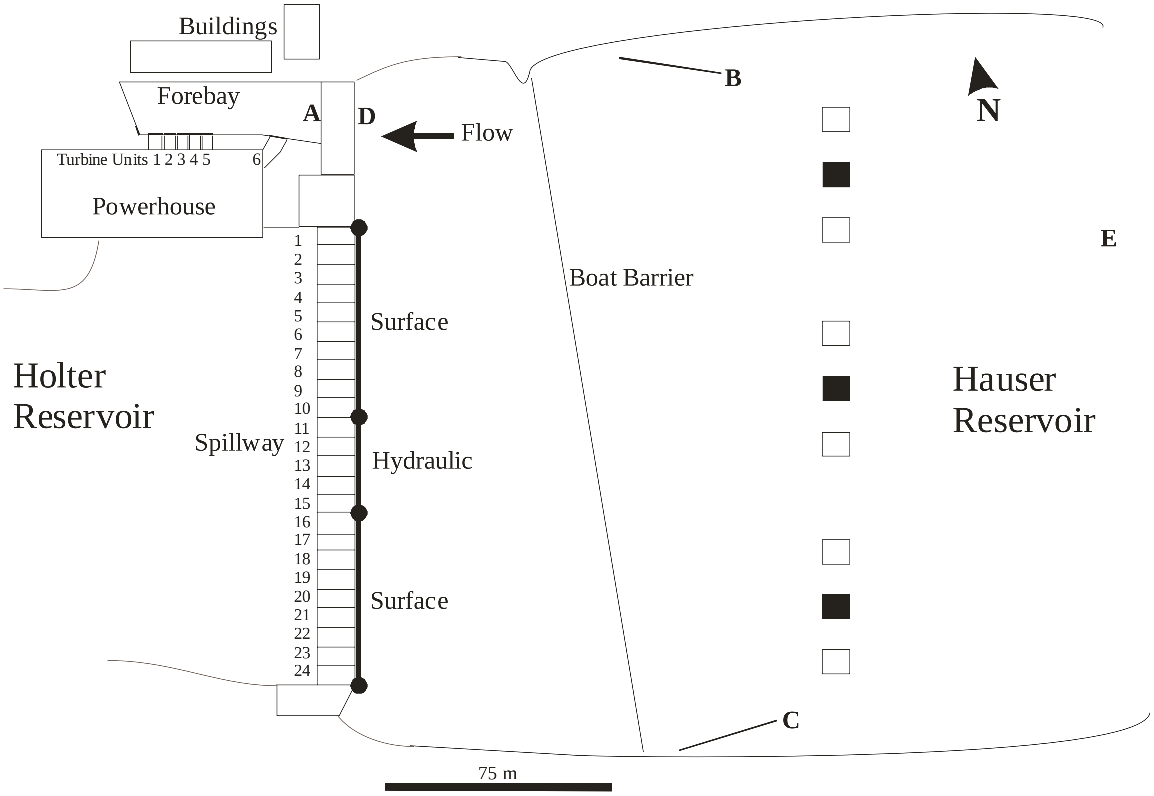


Figure 2.—Overhead diagram of Hauser Dam indicating locations of the different turbines, spillbay types, forebay netting structure (A), vertical gill net stations in 2007 (white squares) and 2008 (black squares), horizontal gill net stations north (B) and south (C), temperature datalogger station (D), and reservoir water-quality station (E).

The Hauser Dam spillway is 150 m long with a total of 24 spillbays (Figure 2). Spillbays 11 through 15 each have four hydraulic sluice gates capable of discharging up to 152.4 m^3/s of water between 2.4 m below mean pool elevation to the crest of the dam (4.2 m). Spillbays 1 through 10 and 16 through 24 are each made up of four 137.2 cm wide vertical stacks of flashboards. Each flashboard stack is made up of (from surface to dam crest) one surface board 5.1 cm thick by 91.4 cm tall, seven boards 7.62 cm thick by 30.5 cm tall, and five boards 10.2 cm thick by 30.5 cm tall. Flashboard spillbays are operated by removing one row of boards at a time from the surface to the crest of the dam, and each spillbay is capable of spilling between 64.6 m^3/s (top row only) and 2,351.8 m^3/s (all flashboards). Spill passed through hydraulic gates will be referred to hereafter as hydraulic spill and spill through flashboard gates as surface spill.

During my study, turbines discharged water continuously and spillway discharge occurred for short periods of time. Turbine units 1 through 3 and 6 were operated continuously at the maximum discharge. Unit 5 was shut down from July 23, 2007, to January 15, 2008, because of mechanical issues and maintenance. Unit 4 was shut down from February 1 to April 21, 2008, for maintenance. Hydraulic spill was low and intermittent from July 4, 2007, to May 19, 2008, occurring in response to turbine maintenance. Prolonged spillway discharge during runoff occurred from May 20 through July 20, 2008. Hydraulic spill occurred during the entire spill period and surface spill from June 2 to July 9. Only the top rows of flashboards were removed for surface spill. Spillbay 1 was used from June 2 to 25, and spillbays 23 and 24 were never used.

METHODS

Transducer Deployment and Sampling

Entrainment through turbines and the spillway were quantified separately with Hydroacoustic Technology, Inc. (HTI), Model 241 Digital Split-Beam Hydroacoustic Systems. Each system was composed of one echosounder, two transducers, two sets of transducer cables, and one desktop computer. The echosounder controlled the transmitting, receiving, amplification, and timing of signals emitted by the transducer, which is the device that creates and receives acoustic vibrations (Johnston et al. 2005). The desktop computers were loaded with programs necessary for adjusting echosounder settings (Lantastic for Windows NT/2000 [v8.0] and HTI software SOUNDER [v1.0]), and translating the information into visual representations (EchoScape [v2.2]) of the transducer beam (echograms) for analysis (Figure 3). The hydroacoustic systems were calibrated by HTI personnel using a standard tungsten-carbide sphere 38.1 millimeters (mm) in diameter to detect fish -53.6 decibels (dB) to -51.0 dB, or about 55 to 68 mm total length (TL), and larger (Love 1977; Table 1).

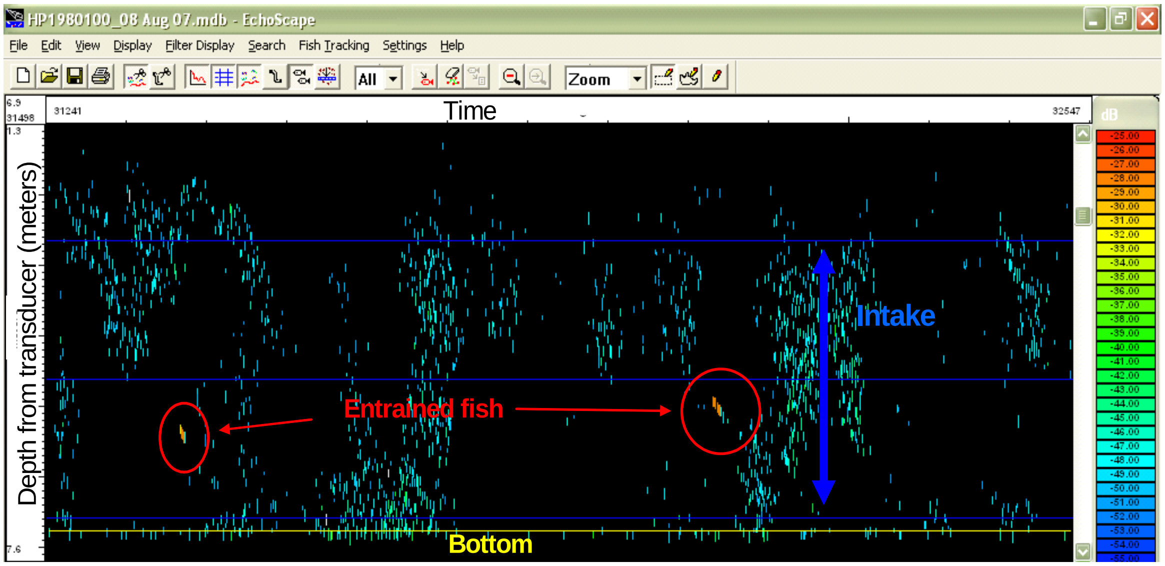


Figure 3.—Example of an echogram displayed using Echoscape (v2.2) with two entrained fish indicated.

Table 1.—Hydroacoustic system settings used to detect entrained fish at Hauser Dam from July 4, 2007 through November 13, 2008.

	Forebay		Spillway	
	unit-6	unit-3	Surface	Hydraulic
Echo sounder operating frequency (kHz)	200		200	
Transducer nominal beam width (º)	15	15	6	15
Cable length (m)	76.2	76.2	137.2	152.4
Angle off axis (º; vertical and horizontal)				
minimum	-7.5	-7.5	-3.0	-7.5
maximum	7.5	7.5	3.0	7.5
Receiver gain (dB)	-12.0	-12.0	-6.0	-6.0
Transmit power (dBW)	20.0	20.0	20.0	20.0
Adjusted TVG gain (dB)	1.24	2.20	-3.20	-2.20
Source level (dBuPa@1m)	212.43	212.43	213.99	208.37
Receiving sensitivity (40 logR; dBuPa@1m)	-163.11	-160.39	-172.54	-166.17
Transmitted pulse width (ms)	0.2	0.2	0.2	0.2
Pulse repetition rate (pings/s)	15	15	10	10
Echo pulse width acceptance bounds				
minimum (ms)	0.1	0.1	0.1	0.1
maximum (ms)	0.3	0.3	0.3	0.3

Table 1.—Continued.

	Forebay		Spillway	
	unit-6	unit-3	Surface	Hydraulic
Min on-axis echo acceptance threshold (mV)	207	283	115	105
Min on-axis echo acceptance threshold (dB)	-52.2	-53.2	-51.0	-53.6

Fish entrainment was monitored in the forebay at turbine units 3 and 6 for the entire study from July 4, 2007, through November 13, 2008. Unit 6 was monitored because it was unique among the six turbines in that it is capable of drawing more water and is located upstream of the other five turbines (Figure 2). Unit 3 was selected because it was located in the center of the five adjacent turbines and was thought to be representative of those turbines. Units 3 and 6 were monitored with a single 15º split-beam transducer at each turbine intake, pole mounted in the down-looking direction 1 m deep to avoid interference by wave action (Figure 4). The transducers were oriented 10º upstream from the trashracks to ensure the deepest edges of the transducer beams touched the forebay floor. The unit-6 transducer was mounted at the center of the intake and the unit-3 transducer was mounted between units 3 and 4 and rotated 18º to avoid interfering with the ability of the headgate to close in an emergency (Figure 5).

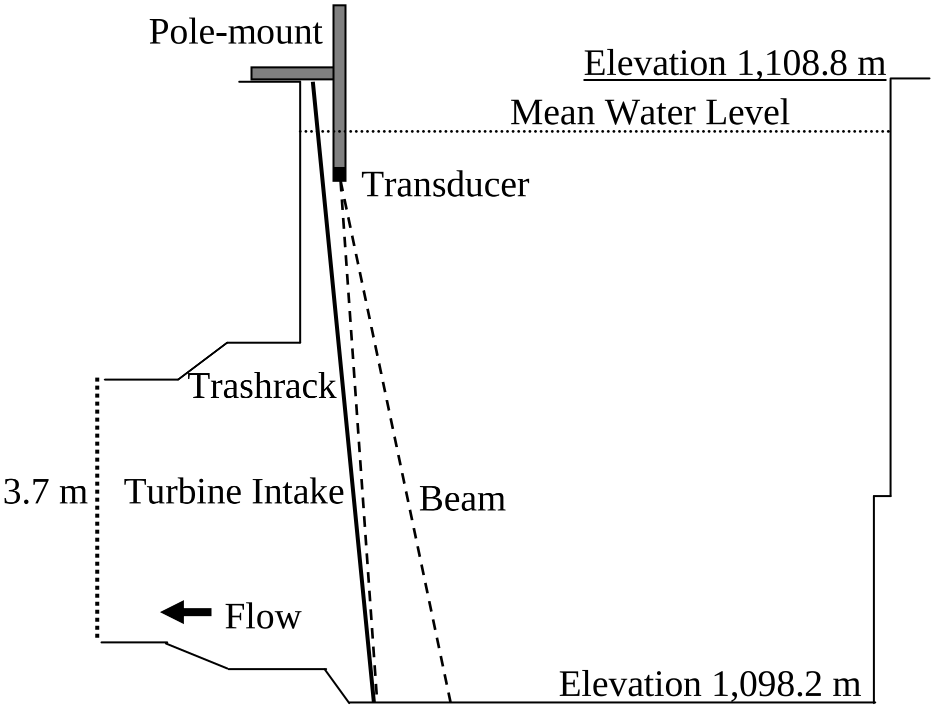


Figure 4.—Down-looking orientation of forebay transducer mounts.

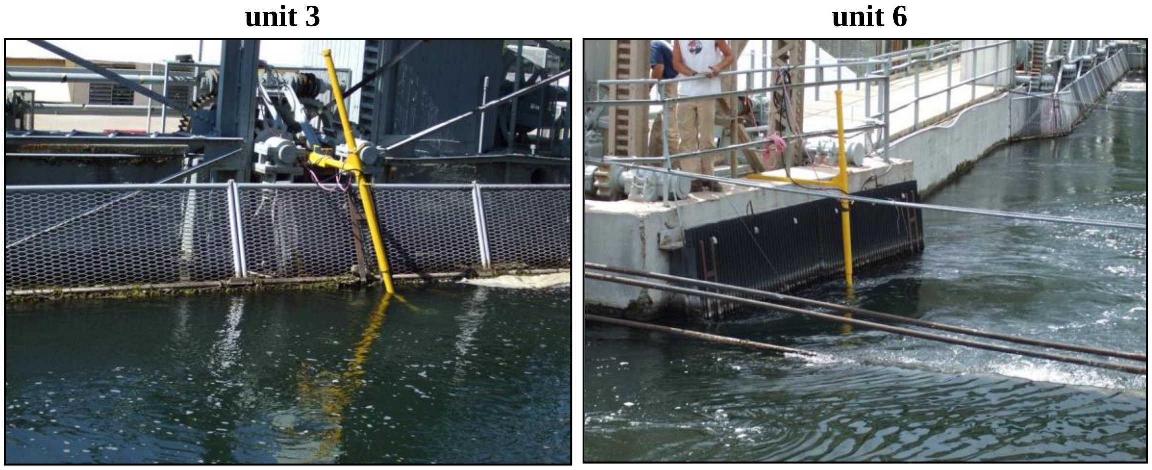

unit 3 **unit 6**

Figure 5.—Photographs of down-looking transducer mounts at turbine units 3 and 6.

I investigated the distribution of entrainment among turbine intakes hydroacoustically to verify my assumption that entrainment through unit 3 was representative of entrainment through unmonitored units (units 1, 2, 4, and 5).

Entrainment at each unmonitored unit was observed continuously for one 24-h period using a 15° transducer (previously used in the spillway) concurrently with unit 3. The additional transducer was mounted in the same orientation (Figure 5) and using the same settings (Table 1) as unit 3. Monitoring periods for unmonitored units began on October 29 (unit 5), October 30 (unit 4), November 6 (unit 2), and November 7, 2008 (unit 1). Echoes from the additional transducer did not affect monitoring at unit 3. Entrainment through unmonitored units was similar to entrainment through unit 3 for each sample day as judged by overlapping 95% confidence intervals; entrainment through unit 3 was therefore considered representative of unmonitored units (Figure 6).

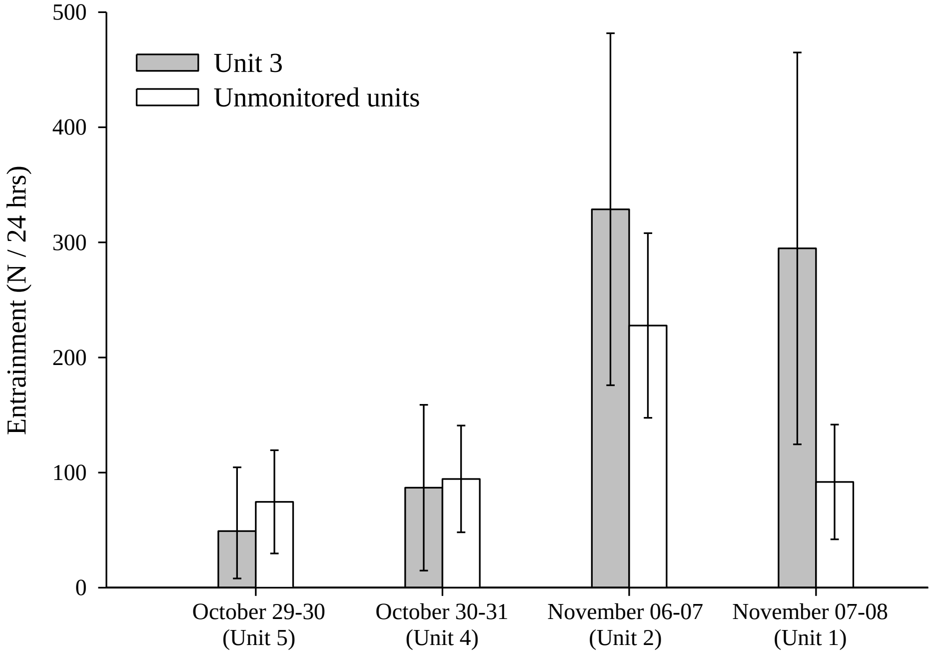
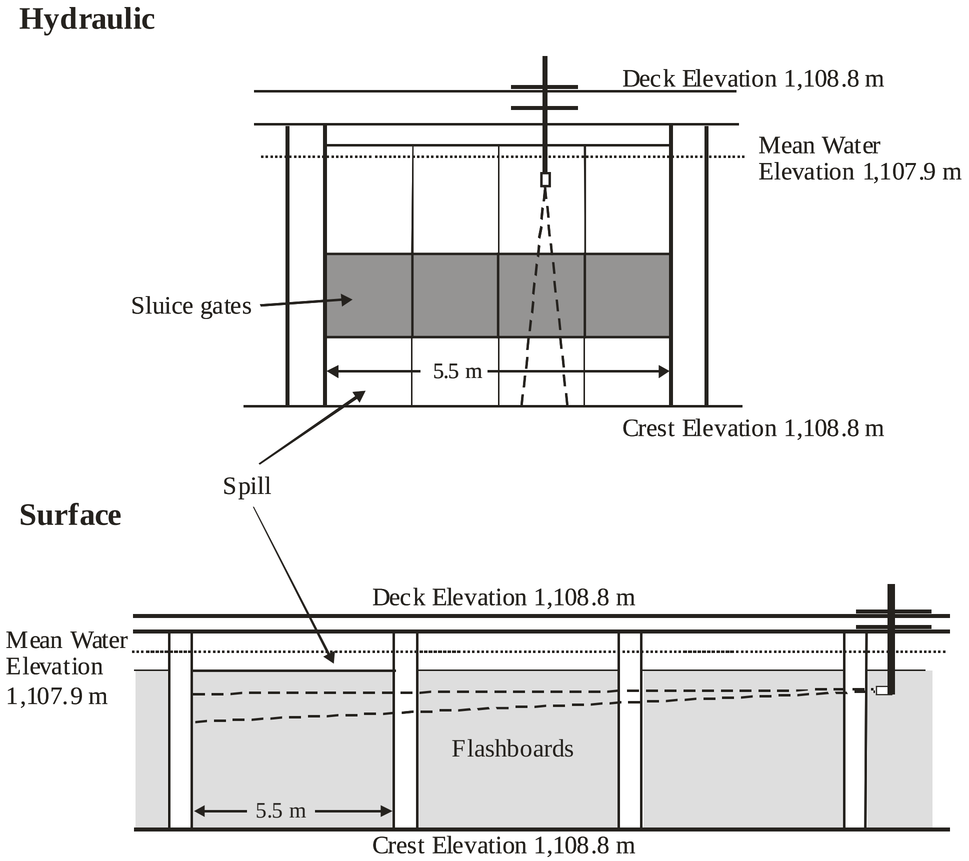


Figure 6.—Entrainment in 24 hours with 95% confidence intervals (error bars) through various turbine intakes between October 29 and November 08, 2008. Grey bars are entrainment through unit 3 and white bars are entrainment through various unmonitored intakes, which are labeled in parenthesis.

The spillway system monitored entrainment during prolonged spillway discharge from May 20 through July 20, 2008 (hereafter referred to as spill), through both hydraulic and surface spill. The spillway system included one transducer to monitor hydraulic spill and one transducer to monitor surface spill (Figure 7). Both transducers were pole-mounted 1 m deep to avoid interference by wave action. A 15º split-beam transducer mounted looking down and 3º upstream monitored hydraulic spill at the center of spillbay-15. Surface spill was monitored with a 6º split-beam transducer oriented side-looking across spillbays 6, 7, and 8, aimed 4º upstream to maximize distance while monitoring fish close the entrance of the spillbays, and 4º down to keep the expanding edge of the beam parallel to the water surface (Figure 7). Hydraulic and surface spillway entrainment were assumed to be representative of similarly configured spillbays operated during spring 2008 because no additional transducers were available to assess the spatial distribution of entrainment between spillbays.



Hydraulic

Surface

Figure 7.—Diagram of transducer setup and orientation in hydraulic and surface spillbays.

All entrained fish were counted between 0000 and 2359 hours every two days. Model 241 echosounders are not capable of operating two transducers concurrently. Each hydroacoustic system monitored entrainment with two transducers in alternating five-minute sequences for a total of 30 minutes per transducer per hour (Table 2). When an error corrupted data in any part of a sample, the following day was analyzed instead to ensure a continuous 24-h sample. Entrained fish were counted manually in hydroacoustic data files to reduce overestimation caused by milling behavior (EPRI 1992) and phantom entrainment from intermittent noise. Entrained fish were counted on alternating days to capture high and low days of entrainment that may have been missed if they were randomly selected (Derr et al. 1993). In addition, counting entrainment on alternating days resulted in a monthly sample size of 15 days, which would estimate entrainment within 9.6% to 22.0% of true entrainment 95% of the time (Johnson et al. 1994).

Table 2.—Sample schedule for one hour at turbine and spillway transducers.

		Turbine		Spillway	
Sequence	Minutes past the hour	unit 3	unit 6	Hydraulic	Surface
1	0		*X*	*X*	
2	5	*X*			*X*
3	10		*X*	*X*	
4	15	*X*			*X*
5	20		*X*	*X*	
6	25	*X*			*X*
7	30		*X*	*X*	
8	35	*X*			*X*
9	40		*X*	*X*	
10	45	*X*			*X*
11	50		*X*	*X*	
12	55	*X*			*X*

X indicates the transducer is active

Some fish that were counted in the hydroacoustic data were excluded from entrainment estimates. Fish detected with fewer than four echoes were removed from the dataset because a minimum of four echoes is necessary to accurately measure the size of entrained fish (P. Nealson, Hydroacoustic Technology, Inc., personal communication). Fish that held their position in the transducer beam and swam upstream away from turbine intakes were not included in entrainment estimates. Split-beam transducers are capable of tracking the path of a fish in three dimensions (Simmonds and MacLennan 2005). The face of the transducer is divided into four quadrants. Fish movement can be tracked in two dimensions as fish move from one quadrant of the beam to the next. The third dimension is the changing distance from the transducer as the fish moves through the beam. Directional vectors were calculated assuming the fish maintained its direction of movement after leaving the transducer beam. To be considered entrained in the turbine intakes, a fish had to reach the intake deeper than 3.5 m (2.5 m from the transducer) without moving left or right outside the intake opening (2.4 m). Fish entrained in hydraulic spill only had to be moving in the direction of flow because no milling behavior was observed. Surface spill was not directly monitored because river flow rates did not reach levels that required the removal of more than the top flashboards (0-1 m) and the transducer was mounted to maximize coverage of the entire spillbay (Figure 7). Therefore, fish were considered entrained in surface spill if they moved into the spillbay in an upwards direction towards spilling water.

Entrainment Estimation

Hydroacoustic transducers were not capable of monitoring the entire cross-sectional area of the turbine intakes or spillbays at Hauser Dam. Transducer beams are conical and are capable of sampling more area as they travel away from the transducer (Johnson et al. 2005). However, the transducer beams did not travel far enough at the dam to expand fully; thus, each entrained fish was extrapolated under the assumption that an equal distribution of fish is entrained across the turbine intakes and spillbays when integrated over time by

$$WF = \frac{W}{\left(2R + \frac{\Delta R}{2}\right) \times Tangent\left(\frac{\theta}{2}\right)},$$

where *WF* is the extrapolated count of each entrained fish observed in the transducer beam; *W* is the height of surface spillbay (4.3 m) for the side-looking orientation, or width (4.9 m) of the turbine intake or spillbay for the down-looking orientation; *R* is the initial distance from the transducer (m); Δ*R* is the change in distance from the transducer as the fish swims through the beam (m); and *Θ* is the expansion angle of the transducer in radians. For example, *WF* of fish detected 2 m from a 15º transducer was 9, but *WF* of fish detected 7 m from the same transducer was 3 because less cross-sectional area of the turbine intake was monitored.

I estimated hourly turbine and spillway entrainment every two days for 30-mm size classes (Skalski 2007). Turbine entrainment was estimated by adding entrainment through turbine units and doubled to extrapolate entrainment to one adjacent unsampled day

$$\hat{T}_{jkn} = 2\left(\hat{U}6_{jkn} + \frac{Z}{z} \times \hat{U}3_{jkn}\right),$$

where *U6* is entrainment at unit-6, *U3* is entrainment at unit-3, *j* is the hour when entrainment occurred, *k* is 24-h sample, *n* is the 30-mm size class, *Z* is the number of units operated adjacent to unit 3 (nominally, *Z* = 5), *z* is the number of monitored units (*z* = 1). Variance of turbine entrainment was estimated as

$$\hat{Var}\left(\hat{T}_{jkn}\right) = 2^2\left(\hat{Var}\left(\hat{U}6_{jkn}\right) + \left(\frac{Z}{z}\right)^2 \times \hat{Var}\left(\hat{U}3_{jkn}\right)\right).$$

Hourly spillway entrainment was estimated by adding entrainment through hydraulic and surface spillbays as

$$\hat{S}_{jkn} = 2\left(\frac{Y}{y} \times \hat{SH}_{jkn} + \frac{U}{u} \times \hat{SS}_{jkn}\right),$$

where *SH* is the entrainment in hydraulic spill, *SS* is the entrainment in surface spill, *Y* is the total number of hydraulic spillbays operated (nominally, $Y = 5$), *y* is the number of hydraulic spillbays monitored ($y = 1$), *U* is the total number of surface spillbays operated (nominally, $U = 15$), *u* is the number of surface spillbays monitored ($u = 3$). Variance of spillway entrainment was estimated as

$$\hat{Var}\left(\hat{S}_{jkn}\right) = 2^2\left(\left(\frac{Y}{y}\right)^2 \times \hat{Var}\left(\hat{SH}_{jkn}\right) + \left(\frac{U}{u}\right)^2 \times \hat{Var}\left(\hat{SS}_{jkn}\right)\right).$$

See Appendix A for hourly entrainment and variance estimation at individual turbine units and spillbays.

Species Specific Entrainment

Netted species composition (see Reservoir Fish Assemblage and Water Quality section) was calculated biweekly. The catch of each species in each gear was scaled to 100 to account for variable gear performance before combining the net catch and calculating species composition (Weaver et al. 1993). Scaling the number of fish caught in each gear was necessary to prevent gears that caught many fish (e.g., vertical gill nets) from masking patterns in gears that caught few fish (e.g., forebay trap nets). Netted species composition was then applied to turbine entrainment as

$$\hat{T}_{ujkn} = C_{un} \times \hat{T}_{jkn},$$

where C is the combined netted species composition, and u is individual species. Variance of species specific turbine entrainment was estimated as

$$\hat{Var}\left(\hat{T}_{ujkn}\right) = \left(C_{un}\right)^2 \times \hat{Var}\left(\hat{T}_{jkn}\right).$$

Species specific entrainment through the spillway was calculated as

$$\hat{S}_{ujkn} = C_{un} \times \hat{S}_{jkn},$$

and variance as

$$\hat{Var}\left(\hat{S}_{ujkn}\right) = \left(C_{un}\right)^2 \times \hat{Var}\left(\hat{S}_{jkn}\right).$$

Seasonal Entrainment

The study period was divided into seasons using the thermal dynamics in the reservoir (Figure 8). Summer was defined as the time when the reservoir was thermally stratified to turnover and the water column mixed; autumn began at turnover and ended when the water column cooled below 4ºC, which was considered the onset of winter; spring began when water temperatures warmed above 4ºC and the water column mixed regularly. Daily temperatures of water entering the forebay were recorded at 1400 hours by 10 HOBO Pendant® temperature dataloggers (Onset Computer Corp., Bourne, Massachusetts) that were spaced 1 m apart from 0.5 m (surface) to 9.5 m deep (bottom; Figure 2). Dataloggers at 1.5 m and 8.5 m were used to monitor thermal dynamics of the reservoir until August 7, 2008, when the datalogger at 1.5 m failed; the datalogger at 2.5 m was subsequently used (Figure 8). Dataloggers were suspended in the water column from a chain attached to the deck of the dam, and held in place in the water by a 56.7-kg concrete block resting on the forebay floor.

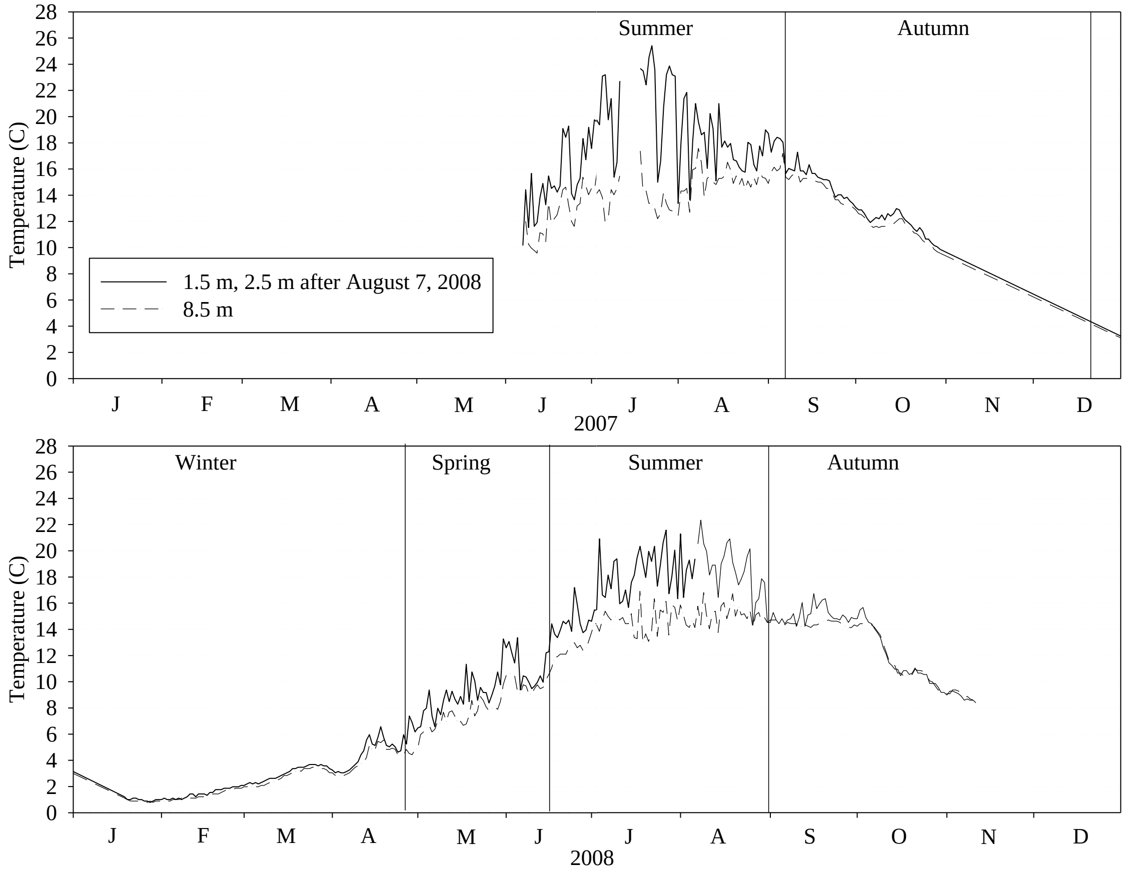


Figure 8.—Temperatures of water entering the forebay measured by HOBO Pendant® dataloggers at 1.5 m and 8.5 m from June 2007 to November 2008. After August 7, 2008, the datalogger at 1.5 m failed, and the datalogger at 2.5 m was used instead. When temperatures are the same, the water column is mixed, but when shallow water is consistently warmer than deep water the reservoir is thermally stratified.

Seasonal turbine and spillway entrainment estimates were calculated with 95% confidence intervals ($z_{95} = 1.96$) by adding species specific entrainment and variance for days, hours, and size classes (Skalski 2007). Turbine entrainment was calculated by

$$\hat{T}_{us} = \sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{T}_{ujkns} \pm z_{95} \times \left(\sqrt{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{Var}\left(\hat{T}_{ujkns}\right)}\right),$$

where *s* = season, and spillway entrainment as

$$\hat{S}_{us} = \sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{S}_{ujkns} \pm z_{95} \times \left(\sqrt{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{Var}\left(\hat{S}_{ujkns}\right)}\right).$$

I calculated the composition of identified fish entrained in the turbines in each season (Skalski 2007) as

$$\hat{P}_{us} = \frac{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{T}_{ujkns}}{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{u=1}^{U}\hat{T}_{ujkns}},$$

and variance as

$$\hat{Var}\left(\hat{P}_{us}\right) = \left(\hat{P}_{us}\right)^2 \times \left(1-\hat{P}_{us}\right)^2 \times \left(\left(\frac{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\sqrt{\hat{Var}\left(\hat{T}_{ujkns}\right)}}{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\hat{T}_{ujkns}}\right) + \left(\frac{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{u=1}^{U}\sqrt{\hat{Var}\left(\hat{T}_{ujkns}\right)}}{\sum_{j=1}^{24}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{u=1}^{U}\hat{T}_{ujkns}}\right)\right).$$

I calculated the composition of identified fish entrained in the spillway using the same procedure.

Reservoir Fish Assemblage and Water Quality

Fish were sampled with nets concurrently with hydroacoustic sampling to estimate species composition of entrained fish (Ransom and Steig 1994). Multiple gears were used to capture a more representative sample of the fish assemblage (EPRI 1992; Weaver et al. 1993; FERC 1995). Fish were netted continuously for 48 hours per week in 2007 from July to mid-October and biweekly through winter. Netting periods were extended to 72 hours in May 2008 and conducted weekly until mid-June and biweekly until November. Captured fish were held in live wells for processing, identified to species, and their total lengths measured (mm).

Forebay Trap Nets

Forebay trap nets were deployed from a custom made net deployment structure in the entrance to the forebay from December 2007 through November 2008 (Figure 9). Netting was not conducted from July to December 2007 because of technical difficulties with the forebay net structure. Each net was 6.7-m long, with a 1.5-m tall and 1.5-m wide mouth tapering to a 0.6-m long by 0.33-m diameter cod end with zippered access. The mouth of the net was heavy canvas with grommets at 15.2-cm intervals. Netting was knotted #18 1.27-cm bar-mesh from the mouth to the cod end, and the cod end was double layered 0.48-cm delta mesh. Fykes of 1.27-cm bar-mesh were added to the nets in May 2008, 3 m from the mouths with 0.3-m diameter openings. The two nets were set at two randomly selected horizontal positions across the forebay and lowered to one of five randomly chosen 1.52-m depth strata (Figure 9). Nets were checked every 6 hours, and a new horizontal position and depth were chosen for each set.

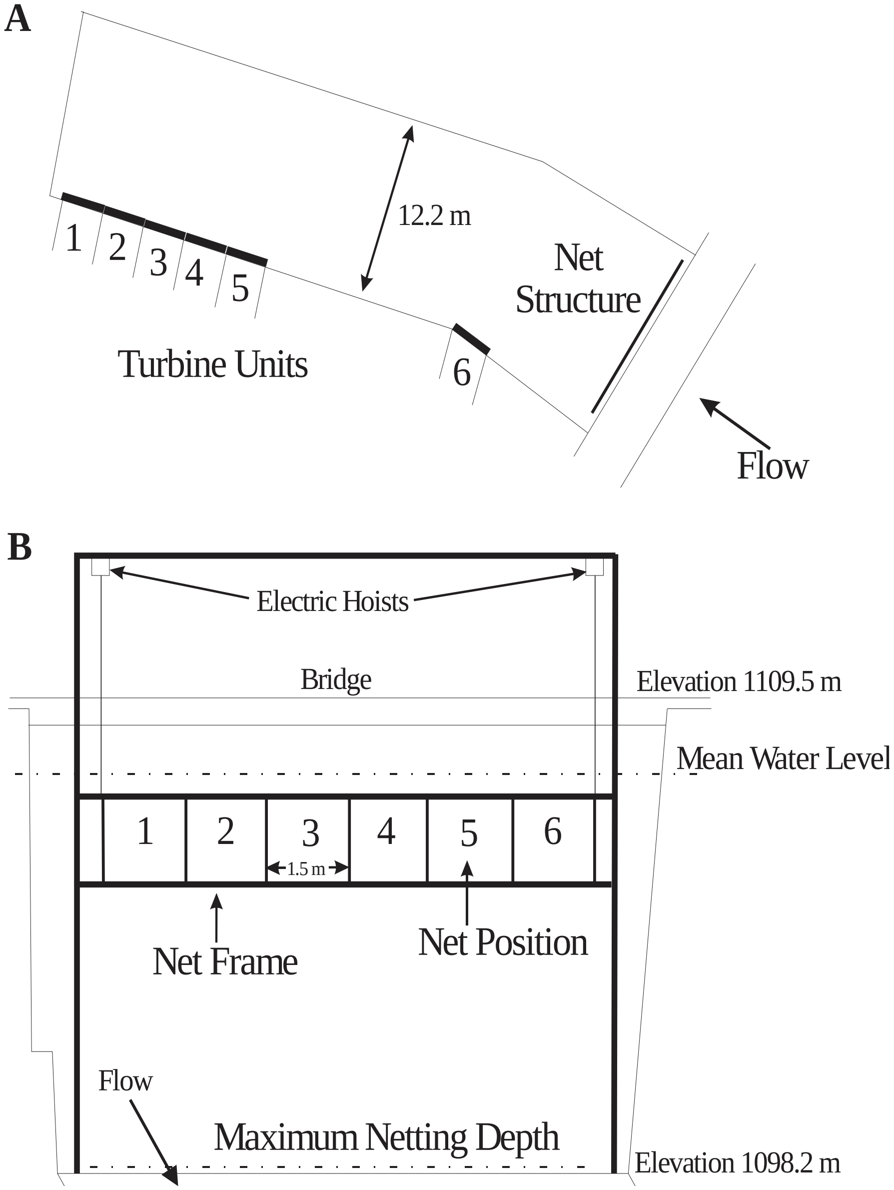


Figure 9.—Top view of the forebay indicating where forebay trap nets were deployed (A) and a drawing of the custom forebay netting structure (B). The net frame could be positioned vertically from the surface of the water to the maximum netting depth, which was about 7.6 cm from the forebay floor.

Forebay trap net capture efficiency was assessed experimentally in 2008 to attempt to explain low catch rates in nets. Capture efficiency of small (< 100 mm) salmonids and non-salmonids was evaluated because body size and shape can affect swimming ability in fish (Katopodis and Gervais 1991; Haro et al. 2004). Thus, capture efficiency of large fish (> 100 mm) is lower than small fish, and capture efficiency of salmonids is lower than for non-salmonids of the same size. Admittedly, capture efficiency trials on both sizes of fish would have been ideal because I could have evaluated the magnitude of the difference in capture efficiency. Unfortunately, large rainbow trout were not available at the hatchery and larger fish from the reservoir were difficult to obtain and keep alive in the numbers necessary (100 – 200 individuals) for multiple trials. On July 1, 2008, salmonid efficiency trials were conducted using rainbow trout obtained from the MFWP Giant Springs Trout Hatchery in Great Falls, Montana. One-hundred and seventy-nine rainbow trout were used in the salmonid efficiency trials (mean TL = 86.8 mm; SD = 9.5 mm). On September 6, 2008, a second set of efficiency trials were conducted on non-salmonids captured in Hauser Reservoir using a 0.32-cm bar-mesh beach seine 30.48-m long by 3.05-m tall. Capture efficiency trials of non-salmonids were conducted with a mixture of yellow perch (N = 90; mean TL = 61.7 mm; SD = 9.6 mm), suckers *Catostomus* spp. (N = 32; mean TL = 51.8 mm; SD = 6.6 mm), and common carp *Cyprinus carpio* (N = 3; mean TL = 50.7 mm; SD = 1.5 mm).

All fish were transported to the dam in 37.8-liter coolers and acclimated to surface water temperatures upstream of the dam before all capture efficiency trials. Transport water was replaced with reservoir water at a rate of about 3.8 liters per 12 minutes over two hours. Surface water temperature during the salmonid trials (13.8ºC) was slightly cooler than during the non-salmonid trials (14.4ºC).

Efficiency trials were conducted by releasing 29 or 30 fish into the mouth of the forebay trap net (< 30 cm upstream), which was deployed at the surface, through a 15.2-cm diameter PVC pipe. Salmonid efficiency trials (N = 6) occurred between 1420 hours on July 1 and 0330 hours on July 2 for about 120 minutes each. Non-salmonid trials (N = 6) occurred between 1500 and 1800 hours for about 20 minutes each. After each trial, all fish were removed from the net. Fewer salmonids released in the mouth of the net were captured than non-salmonids (Table 3).

Table 3.—Capture efficiency of forebay trap nets for salmonids (July 2008) and non-salmonids (September 2008) less than 100 mm total length.

Species	Trial	Number released	Number captured	Trial Duration (min)	Proportion Captured	Time of Day
Salmonids	1	30	19	118	0.63	Day
	2	29	19	117	0.66	Day
	3	29	6	105	0.21	Day
	4	29	11	119	0.38	Night
	5	30	6	105	0.20	Night
	6	30	15	117	0.50	Night
	Mean (SD)				0.43 (0.20)	
Non-salmonids	1	30	19	20	0.63	Day
	2	30	20	20	0.67	Day
	3	30	16	20	0.53	Day
	4	30	23	20	0.77	Day
	5	30	21	21	0.70	Day
	Mean (SD)				0.66 (0.08)	Day

Reservoir Gill Nets

Vertical gill nets were deployed from July to November 2007, and May to November in 2008 (Figure 2). Nets were not deployed during winter because ice prevented access to the reservoir. Six panels of 1.27, 1.90, 2.54, 3.18, 3.81, and 5.08-cm bar-mesh were strung together in a gang. Each panel was 3.6-m wide and 30.5-m tall. The gang was deployed for 8-hour sets from the surface to the bottom at one of six randomly selected stations spaced evenly across the reservoir in 2007. A new station was randomly selected for each set. Netting stations were reduced from six to three and sampled systematically in 2008 (Figure 2). Gangs were set at each station for three sets beginning at the southwest station and ending at the northeast station, to ensure equal netting coverage across the reservoir.

Horizontal gill nets were deployed from May to November in 2008 to sample the shoreline fish assemblage because shoreline and pelagic assemblages can be different, but all species may be susceptible to entrainment (FERC 1995). Nets were 29-m long by 1.6-m tall with multiple 2, 3.5, 5.0, and 7.5-cm bar-mesh panels. One net was deployed diagonally on each shoreline from the edge of the water to a depth of about 3 m concurrently with vertical gill netting (Figure 2). Diagonal net deployment sampled more of the shoreline because the sides of the reservoir are steep.

Water Quality

Water-quality profiles were conducted one time during each netting period using a hand held Hydrolab Surveyor® water quality meter with a Hydrolab Quanta® multiprobe sonde (Hach Environmental, Loveland, Colorado) from July through

November in 2007, and May through November in 2008. No vertical profiles were sampled using the Hydrolab during winter because the ice upstream of the dam was not safe to walk on. Water-quality profiles were measured at a permanent MFWP water-quality monitoring station upstream of the dam (Figure 2). Temperature (ºC), dissolved oxygen (DO; mg/L and % saturation), pH, and conductivity (µS/cm) were measured at 1-m intervals from the surface to the bottom. The Hydrolab was field calibrated for DO at the beginning of all profiles.

Hatchery Rainbow Trout Entrainment

Hatchery rainbow trout entrainment was estimated to evaluate each stocking event. Daily estimates were calculated by summing all entrained rainbow trout smaller than 280 mm total length to ensure all hatchery fish were included in the estimate. I was not able to identify the stocking event from which each fish originated. Therefore, all entrained fish were assumed to have originated from the most recent stocking event. In addition, unidentified fish that were smaller than 280 mm were included to more realistically estimate entrainment. Unidentified fish were apportioned by the proportion of identified fish smaller than 280 mm that were entrained hatchery rainbow trout. For example, 40 of 100 unidentified fish (< 280 mm) were assumed to be entrained hatchery rainbow trout when 40% of identified entrained fish (< 280 mm) were rainbow trout.

Conditions Influencing Entrainment

Multiple linear regression analysis (hereafter, regression) was used to explore the relationships between total weekly entrainment at Hauser Dam and environmental conditions and dam operations. Regression models were compared with Akaike's information-theoretic approach corrected for small sample size (AICc) to rank models by their importance to entrainment (Burnham and Anderson 1998). Both *a priori* and *a posteriori* models were compared because this analysis was strictly exploratory to identify variables that influence entrainment more than others (Table 4). Selection results were presented for only models within two distance units (ΔAICc) from the top model as they have the highest support. The relative importance of different predictors to entrainment was evaluated using AICc weights (w_i).

Table 4.—Models investigated to determine conditions that were influential to entrainment of fish at Hauser Dam in 2007 and 2008.

Model	Abbreviation
a priori	
Mean weekly spillway discharge (m^3/s)	SpillD
Mean weekly turbine discharge (m^3/s)	TurbD
Temperature above the turbine intakes (˚C)	TempAb
Dissolved oxygen below the turbine intakes (mg/L)	DObel
Temperature above (˚C) and dissolved oxygen below (mg/L) the turbine intakes	TempAb + Dobel
Thermocline depth (m)	ThermD
a posteriori	
Mean reservoir water column temperature (˚C)	mTemp
Mean reservoir water column dissolved oxygen (mg/L)	mDO
Mean reservoir water temperature (˚C) and dissolved oxygen (mg/L)	mTemp + mDO
Mean weekly photoperiod (min)	DayL
Mean minimum barometric pressure (mm Hg)	minBP
Mean maximum barometric pressure (mm Hg)	maxBP

Entrainment was analyzed separately during spill and when no spill occurred to prevent high entrainment rates associated with spillway discharge from masking less evident responses to reservoir conditions at other times of the year. Conditions in the reservoir during runoff differ from conditions during late summer and early autumn; the reservoir is cooler, thermal stratification is absent, and DO concentrations are higher during runoff. Thus, I expected that spillway discharge would influence entrainment more than any other variable during spill and that temperature and DO dynamics would be most influential when no spill occurred. In addition, regression analysis was conducted on separate size groups because large (≥ 220 mm) and small (< 220 mm) fish respond differently to environmental conditions in the reservoir (Horn et al. 2004). Winter entrainment was not explored using regression analysis because entrainment rates then were low, relatively constant, and few fish were identified.

Regression analysis was complicated by low sample size because not all fish were identified by concurrent netting. A minimum of six observations was required to avoid overfitting models (M. Taper, Montana State University, personal communication); therefore yellow perch, mountain whitefish, and most identified small fish were excluded from the analysis. In addition, small rainbow trout entrainment was not modeled because few fish were captured and identified except soon after hatchery stocking.

Entrainment During spill

Regression models of entrainment during spill were fit for weekly spillway and turbine entrainment separately to compare the influence of conditions spatially. Factors included were (1) mean weekly spillway discharge (m^3/s) measured by operators at

Hauser Dam, (2) mean weekly photoperiod (min) from the Astronomical Applications Department of the U.S. Naval Observatory, and (3) mean weekly minimum and maximum barometric pressure (mm Hg) from the National Oceanic and Atmospheric Administration (NOAA) weather station at the Helena Regional Airport. Temperature and DO were excluded from the analysis because there were not enough reservoir water quality profile observations (N = 4) during spillway discharge. Turbine discharge was also excluded because it varied less than 300 m^3/s during spring runoff.

Regression models were fit for weekly spillway and turbine entrainment separately to compare the influence of conditions spatially. Entrainment was $\log_{10}$ transformed to improve normality and make the relationship linear; regression models were fit and residuals were checked visually to satisfy the assumption that variance was constant (Kutner et al. 2005). Pearson correlation (r) was used to identify multicollinearity among predictors because only models with two or less predictors were fit; I did not fit models of collinear variables ($P < 0.10$).

Entrainment When No Spill Occurred

Turbine entrainment from July 4 to November 18, 2007, and July 21 to November 13, 2008, was analyzed separately to compare between low and high water years. I fit regression models for $\log_{10}$ transformed weekly turbine entrainment when no spill occurred using the same process as I did during spill (above). Factors included were (1) mean weekly turbine discharge (m^3/s) measured by Hauser Dam operators, (2) mean weekly photoperiod (min) from the Astronomical Applications Department of the U.S. Naval Observatory, (3) mean weekly minimum and maximum barometric pressure (mm

Hg) from the NOAA weather station at the Helena Regional Airport, (4) mean water column temperature (ºC) and (5) DO concentration (mg/L), (6) the ratio of mean water column temperature to mean water column DO, (7) mean temperature above the turbine intakes, (8) mean DO concentration below the turbine intakes, and (9) thermocline depth (m).

RESULTS

Reservoir Fish Assemblage

Composition of combined net catch (N = 2,338) was primarily rainbow trout (42.9%), white sucker (27.4%), and walleye (14.6%). Longnose sucker (5.3%), burbot (3.5%), kokanee (2.9%), and brown trout (2.5%) were captured in moderate numbers. Mountain whitefish, yellow perch, and common carp were less than 1% of the total catch.

Most net-caught fish were captured in summer and autumn in both years in vertical and horizontal gill nets (54% and 45%, respectively). Gill nets captured few fish smaller than 220 mm, of which about 3% were in horizontal and 15% were in vertical gill nets (Figure 10).

Forebay trap net catch was 1% of all fish caught in nets and most were smaller than 220 mm (Figure 10). Many fish captured in forebay nets were too small (< 100 mm) to be included in determining entrainment composition (Table 4). Small catostomids were the most common small fish captured in the nets, peaking in August and increasing in size through November (Figure 11).

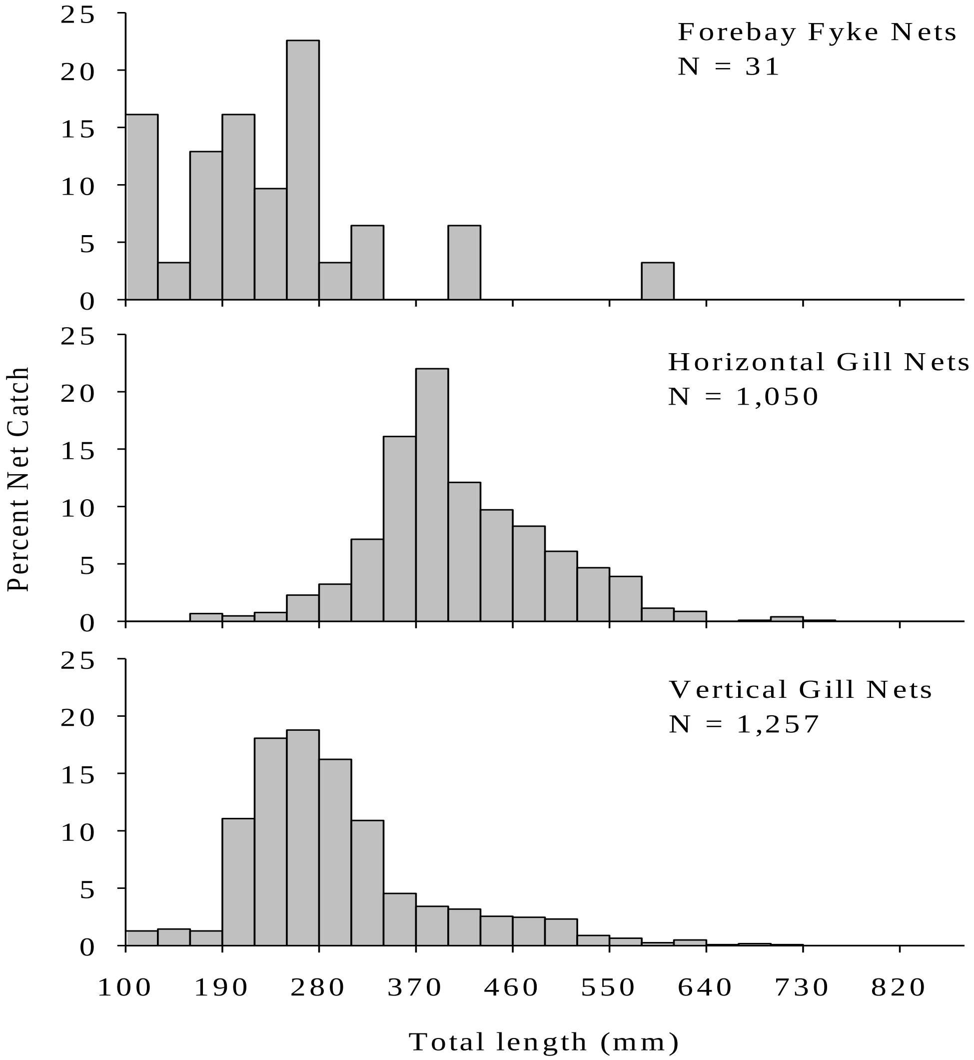


Figure 10.—Length frequency of all fish larger than 100 mm captured in multiple netting gears. Forebay nets were operated from December 2007 to November 2008, horizontal gill nets from May to November 2008, and vertical gill nets from July to November 2007 and May to November 2008.

Table 5.—Size metrics of forebay net catch smaller than 100 mm total length from May through November 2008.

		Total Length (mm)				
Species	N	Mean	SD	Min	Max	Month Captured
Catostomus spp.	102	31.0	6.01	20	54	July - November
Yellow perch	5	31.6	6.76	21	39	August
Walleye	3	44.7	14.16	36	61	May - September
Kokanee	3	73	10.82	61	82	July
Oncorhynchus spp.	1	49	--	--	--	August
Pimephales spp.	1	32	--	--	--	August

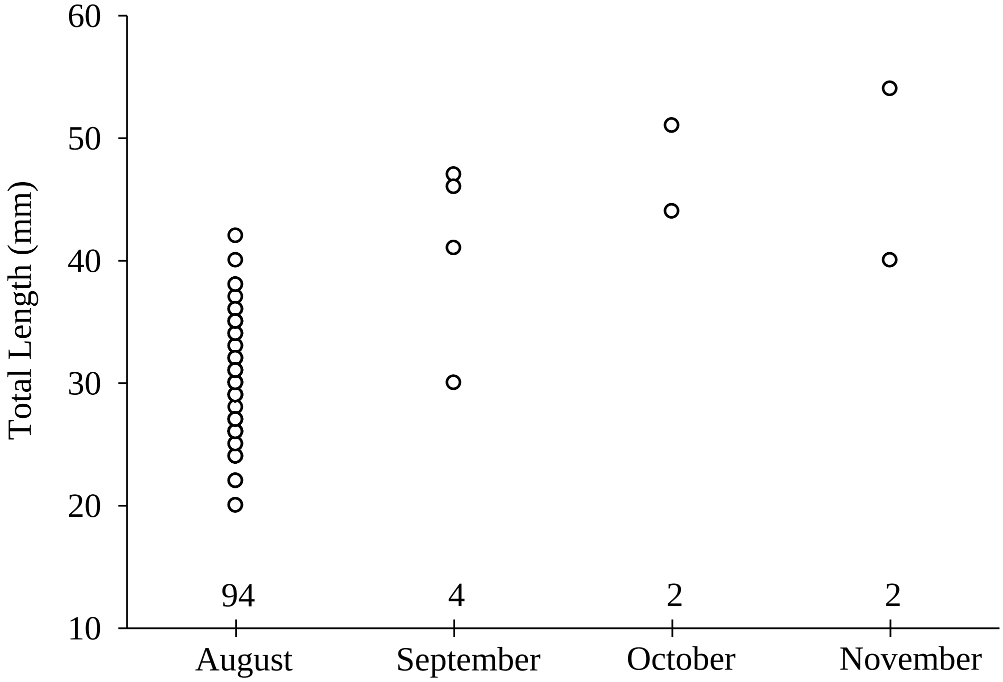


Figure 11.—Monthly catch of catostomids (< 100 mm) captured in the forebay trap net in 2008. Each circle represents an individual fish and the number is the quantity of fish captured in each month is included along the x-axis.

Seasonal Entrainment

Total estimated entrainment from July 2007 through November 2008 was 145,470 (95% CI = 138,144 – 152,796). Peak daily entrainment occurred in autumn in both years and during spill (Figure 12; Table 6). Entrainment in autumn 2007 made up 35% of total entrainment; 19% occurred in autumn 2008, and 16% during spill. Only 6% of total entrainment occurred in winter. Combined entrainment from summer to autumn was higher in 2007 (N = 79,031; 95% CI = 73,861 – 84,201) than in 2008 (N = 52,513; 95% CI = 47,830 – 57,196).

Ninety-two percent of total entrainment occurred in the turbines (Table 6). All entrainment in autumn (2007 and 2008) occurred in turbines. However, 49% of entrainment during spill was in the turbines and 51% was in the spillway in 2008.

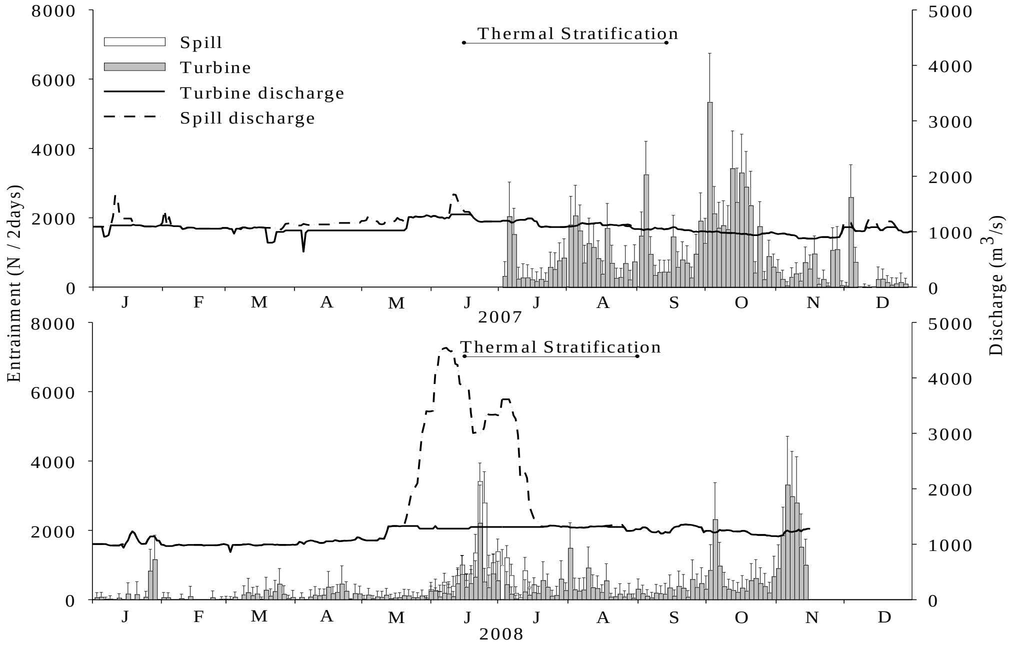


Figure 12.—Two-day entrainment estimates for all species combined (error bars are 95% confidence intervals) through the turbines and spillway between July 4, 2007, and November 13, 2008. Also included is the hydrograph for turbine and spillway discharge through Hauser Dam.

Table 6.—Estimated seasonal fish entrainment (95% confidence intervals) of Hauser Reservoir species through the turbines and spillway at Hauser Dam between July 2007 and November 2008. Percent total identified entrainment is in parentheses after the species name, and N is the number of days in a season. Seasonal entrainment was not estimated for species that were not captured in concurrent netting, and spillway entrainment was only estimated for spring and summer 2008.

	2007		2008					
	Summer (N = 68)	Autumn (N = 91)	Winter (N = 141)	Spring (N = 51)	Summer during Spill (N = 33)	Summer without Spill (N = 44)	Autumn (N = 124)	
Area of Entrainment								**TOTAL**
Rainbow trout, *Oncorhynchus mykiss* (33.3)								
Turbine	1,646	9,961	--	211	454	3,005	13,838	**29,115**
	(1,009 – 2,283)	(8,243 – 11,679)		(16 – 406)	(208 – 700)	(2,033 – 3,977)	(11,415 – 16,261)	**(25,910 – 32,320)**
Spillway				274	534			**808**
				(91 – 457)	(303 – 765)			**(513 – 1,103)**
Walleye, *Sander vitreus* (30.2)								
Turbine	2,103	17,035	--	463	2,553	910	1,262	**24,326**
	(1,330 – 2,876)	(14,847 – 19,223)		(129 – 797)	(1,628 – 3,478)	(495 – 1,325)	(806 – 1,718)	**(21,732 – 26,920)**
Spillway				13	2,863			**2,876**
				(2 – 48)	(2,139 – 3,587)			**(2,151 – 3,601)**
Kokanee, *Oncorhynchus nerka* (13.5)								
Turbine	1,336	3,417	--	52	637	30	6,089	**11,561**
	(678 – 1,994)	(2,737 – 4,097)		(5 - 196)	(292 – 982)	(10 - 67)	(4,352 – 7.826)	**(9,548 – 13,574)**
Spillway				0	590			**590**
					(246 – 934)			**(246 – 934)**
Brown trout, *Salmo trutta* (2.7)								
Turbine	633	562	--	78	303	111	123	**1,810**
	(259 – 1,007)	(284 – 840)		(13 - 187)	(10 – 649)	(19 – 203)	(22 – 224)	**(1,204 – 2,416)**
Spillway				42	621			**663**
				(8 – 104)	(211 – 1,031)			**(249 – 1,077)**

Table 6.—Continued.

	2007		2008					
	Summer	Autumn	Winter	Spring	Summer		Autumn	
	(N = 68)	(N = 91)	(N = 141)	(N = 51)	during Spill	without Spill	(N = 124)	
Area of Entrainment					(N = 33)	(N = 44)		**TOTAL**
Burbot, *Lota lota* (7.9)								
Turbine	2,705	2,313	--	46	260	10	1,221	**6,555**
	(1,794 – 3,616)	(1,550 – 3,076)		(8 – 109)	(6 – 514)	(4 – 26)	(713 – 1,729)	**(5,237 – 7,873)**
Spillway				0	549			**549**
					(265 – 833)			**(265– 833)**
Longnose sucker, *Catostomus catostomus* (4.2)								
Turbine	1,093	1,259	--	94	259	385	196	**3,285**
	(576 – 1,610)	(778 – 1,740)		(10 – 224)	(73 - 443)	(167 – 603)	(30 – 362)	**(2,495 – 4,075)**
Spillway				10	522			**532**
				(2 – 39)	(167 – 877)			**(176 – 888)**
White sucker, *Catostomus commersonii* (4.7)								
Turbine	223	371	--	236	382	1,107	1,024	**3,343**
	(25 – 421)	(183 – 559)		(32 – 440)	(179 – 585)	(578 – 1,636)	(510 – 1,538)	**(2,506 – 4,180)**
Spillway				193	683			**876**
				(66 – 320)	(396 – 970)			**(563 – 1,189)**
Mountain whitefish, *Prosopium williamsoni* (0.3)								
Turbine	8	35	--	0	3	80	71	**197**
	(2 – 30)	(3 – 111)			(1 – 11)	(1 – 209)	(7 – 210)	**(23 – 403)**
Spillway				0	55			**55**
					(11 – 143)			**(11 – 143)**

Table 6.—Continued.

	2007		2008					
	Summer	Autumn	Winter	Spring	Summer		Autumn	
	(N = 68)	(N = 91)	(N = 141)	(N = 51)	during Spill	without Spill	(N = 124)	
Area of Entrainment					(N = 33)	(N = 44)		**TOTAL**
				Yellow perch, *Perca flavescens* (2.4)				
Turbine	172	1,358	276	32	--	--	333	**2,171**
	(4 – 340)	(729 – 1,987)	(42 – 5565)	(3 – 122)			(34 – 719)	**(1,360 – 2,982)**
Spillway				0	--	--		**0**
				Common carp, *Cyprinus carpio* (0.7)				
Turbine	659	--	--	--	--	--	--	**659**
	(104 – 1,214)							**(104 – 1,214)**
Spillway				--	--			--
				Unidentified Fish				
0Turbine	17,922	14,238	8,189	2,691	2,515	2,170	3,166	**50,891**
	(15,267 – 20,577)	(11,573 – 16,903)	(6,345 – 10,033)	(1,709 – 3,673)	(1,212 – 3,818)	(955 – 3,673)	(1,220 – 5,112)	**(45,844 – 55,938)**
Spillway				1,028	3,610			**4,638**
				(519 – 1,537)	(2,506 – 4,714)			**(3,422 – 5,854)**
				TOTAL, All Species Combined				
Turbine	**28,499**	**50,532**	**8,465**	**3,903**	**7,372**	**7,813**	**27,309**	**133,893**
	(25,322 – 31,676)	**(46,454 – 54,610)**	**(6,600 – 10,330)**	**(2,799 – 5,007)**	**(6,096 – 9,530)**	**(6,096 – 9,530)**	**(23,620 – 30,998)**	**(126,754 – 141,032)**
Spillway				**1,558**	**10,019**			**11,577**
				(997 – 2,119)	**(8,476 – 11,562)**			**(9,936 – 13,218)**

Distribution of Spillway Entrainment

Spillway entrainment was first observed nine days after the spillgates opened on May 20, 2008 (Figure 13). Entrainment through hydraulic spillbays was 10.7 % of total spillway entrainment. On average, 29.2% (SD = 25.2%) of spillway entrainment was through hydraulic spill when both types of spillbay were operated.

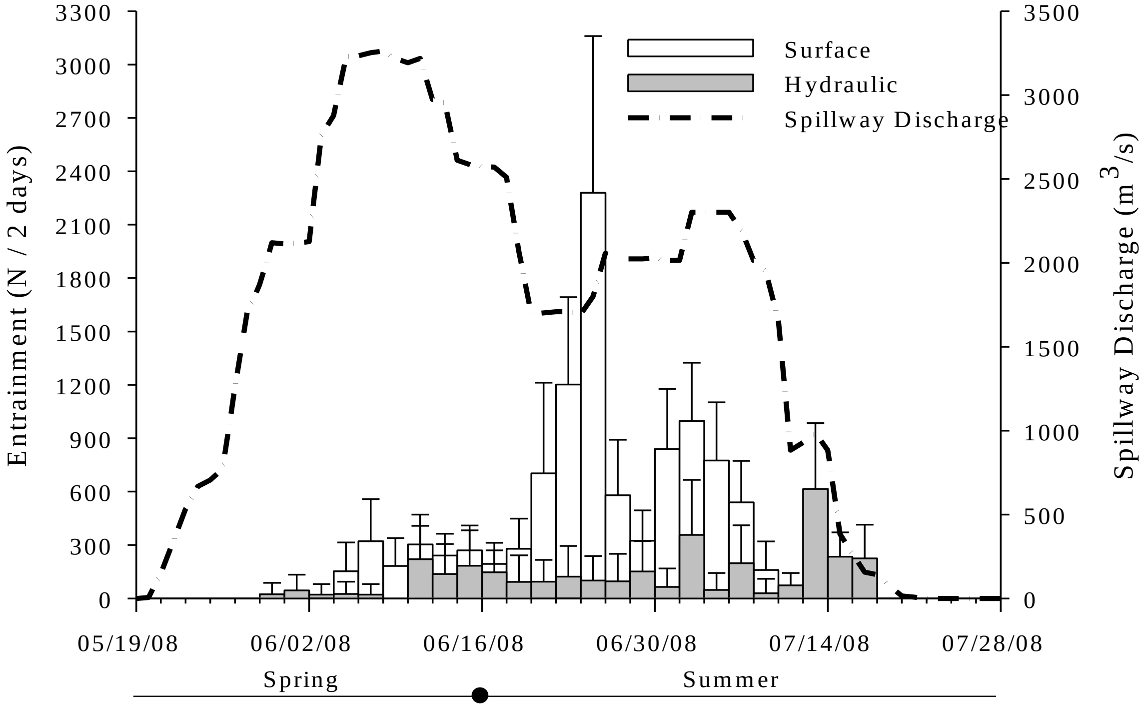


Figure 13.—Seasonal distribution of spillway entrainment between spillgate types (bars are stacked and error bars are 95% confidence intervals) from May 20 to July 20, 2008. Hydraulic spill occurred during all of runoff and surface spill occurred from June 2 to July 9.

Species Specific Entrainment

Species-specific entrainment varied seasonally in 2007 (Table 6); mean daily entrainment of more commonly entrained species (e.g., rainbow trout, walleye, and kokanee) increased from summer through autumn, but entrainment of less common species (e.g., brown trout, burbot, and longnose sucker) declined concurrently (Figure 14). Entrainment increased from winter through autumn in 2008, peaking in early summer during spill. Turbine entrainment of most species declined rapidly after spill ended in July 2008 (1) temporarily before increasing in autumn (burbot and kokanee), (2) to a low level that remained stable through autumn (walleye and brown trout), or (3) continuously through autumn (longnose sucker; Figure 14). Only rainbow trout and white sucker entrainment increased after spill ended; rainbow trout entrainment increased and white sucker entrainment declined through autumn.

Not all fish that were entrained were identified by concurrent netting. Forty percent of entrained fish were unidentified in 2007 and 2008. Most fish were unidentified in winter (97%) and spring 2008 (69%) as few fish were captured in concurrent netting. Forebay trap nets were the only gear used in winter and caught only one yellow perch and one common carp. All gears were used in spring, but vertical gill nets captured only 35 fish as strong currents during spillway discharge stretched the nets tight, probably preventing many fish from being entangled. The proportion of unidentified fish declined from summer through autumn during both years from 63% to 28% in 2007 and 31% to 12% in 2008.

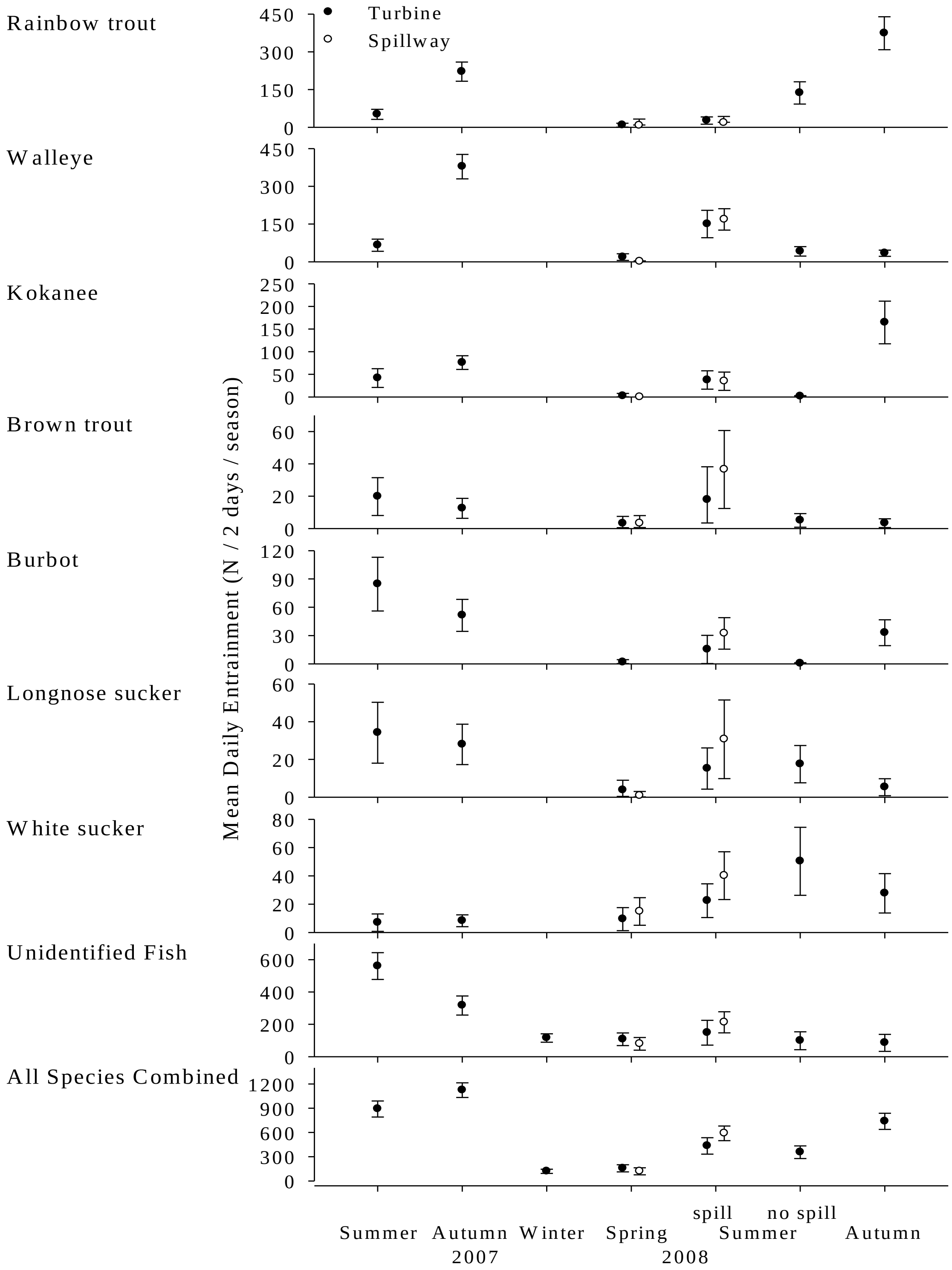


Figure 14.—Seasonal mean two-day entrainment with 95% confidence intervals of Hauser Reservoir species through the turbines (closed circles) and spillway (open circles) of Hauser Dam from July 2007 to November 2008.

Species Composition

Rainbow trout (33.3%) and walleye (30.2%) made up most of identified entrainment (Table 6) and usually made up most of entrainment in seasons when entrainment was high (i.e., autumn 2007 and spill; Figure 15). However, more kokanee than walleye were entrained in autumn 2008 (Table 6; Figure 15). Turbine and spillway entrainment of most species was similar (Figure 15) but rainbow trout were especially prevalent in spill discharge in spring 2008 and walleye were common in turbine entrainment in both spring and summer, but increased from 2% of spillway entrainment in spring to 45% in summer.

Some species appeared more susceptible to entrainment than others as judged by different relative abundances in nets versus entrainment (Figure 15). Rainbow trout were abundant in spillway entrainment in spring. Similarly, walleye appeared to be susceptible to entrainment in both the turbines and the spillway in summer 2008. Species that were more susceptible to entrainment in summer 2007 were brown trout, burbot, and kokanee. The proportion of fish in nets that were white suckers was lower than in either spillway or turbine entrainment, indicating white suckers might not be as susceptible to entrainment as other species.

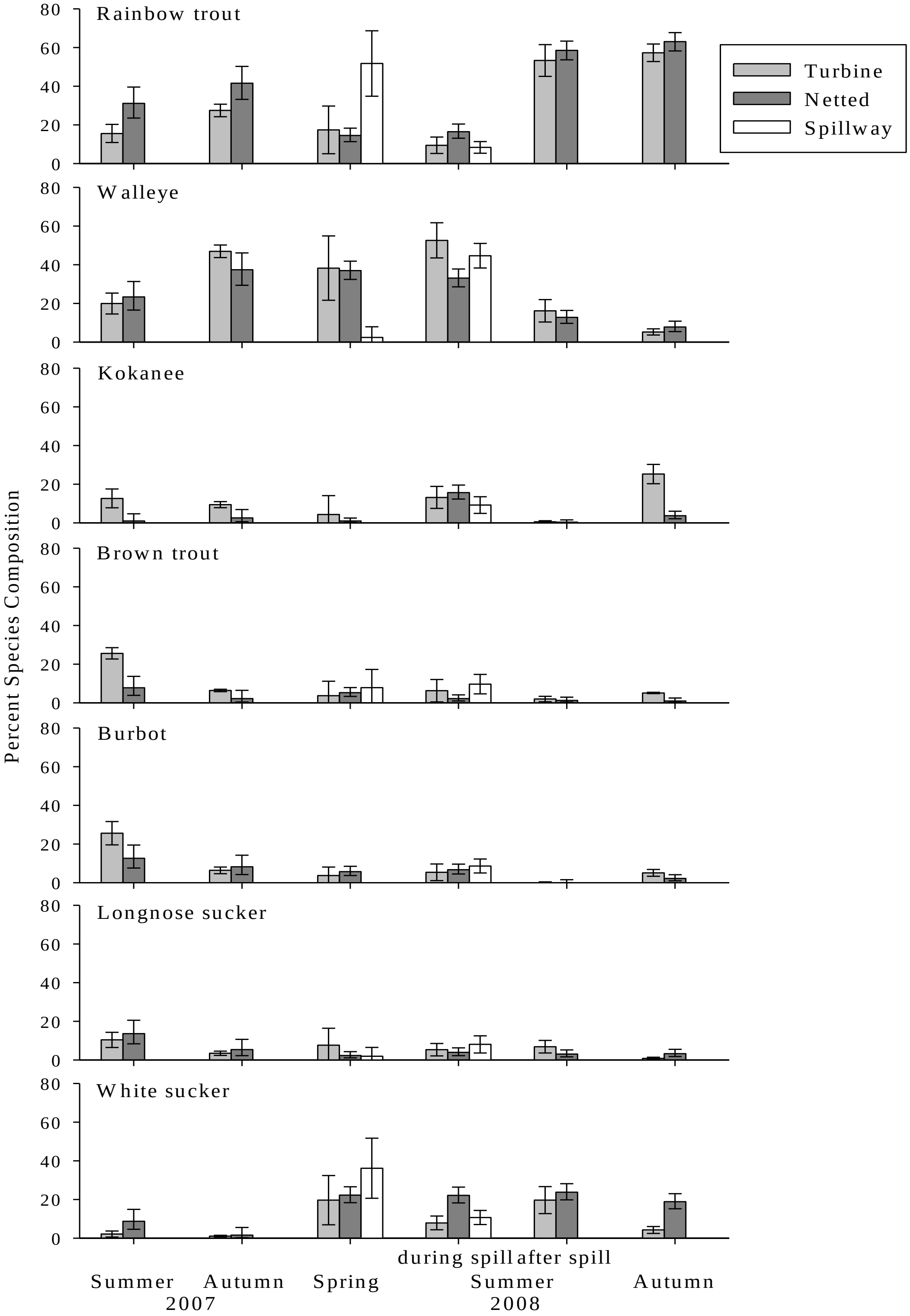


Figure 15.—Seasonal compositions (error bars are 95% CIs) of entrained fish in the turbines and spillway, and the composition of fish captured in nets in 2007 and 2008, excluding entrainment in winter.

Size Distribution

Sixty-four percent of total entrainment was made up of small fish 100 to 220 mm long and the proportion of entrainment consisting of small fish varied little seasonally (mean = 61%, SD = 7%). Most small fish that were identified in concurrent netting were rainbow trout, walleye, and kokanee (Figures 16, 17, and 18); none of the small fish entrained in the spillway in spring 2008 could be identified (Figure 18). During spill, 75% of small fish were entrained in the turbines in spring, but only 45% in summer.

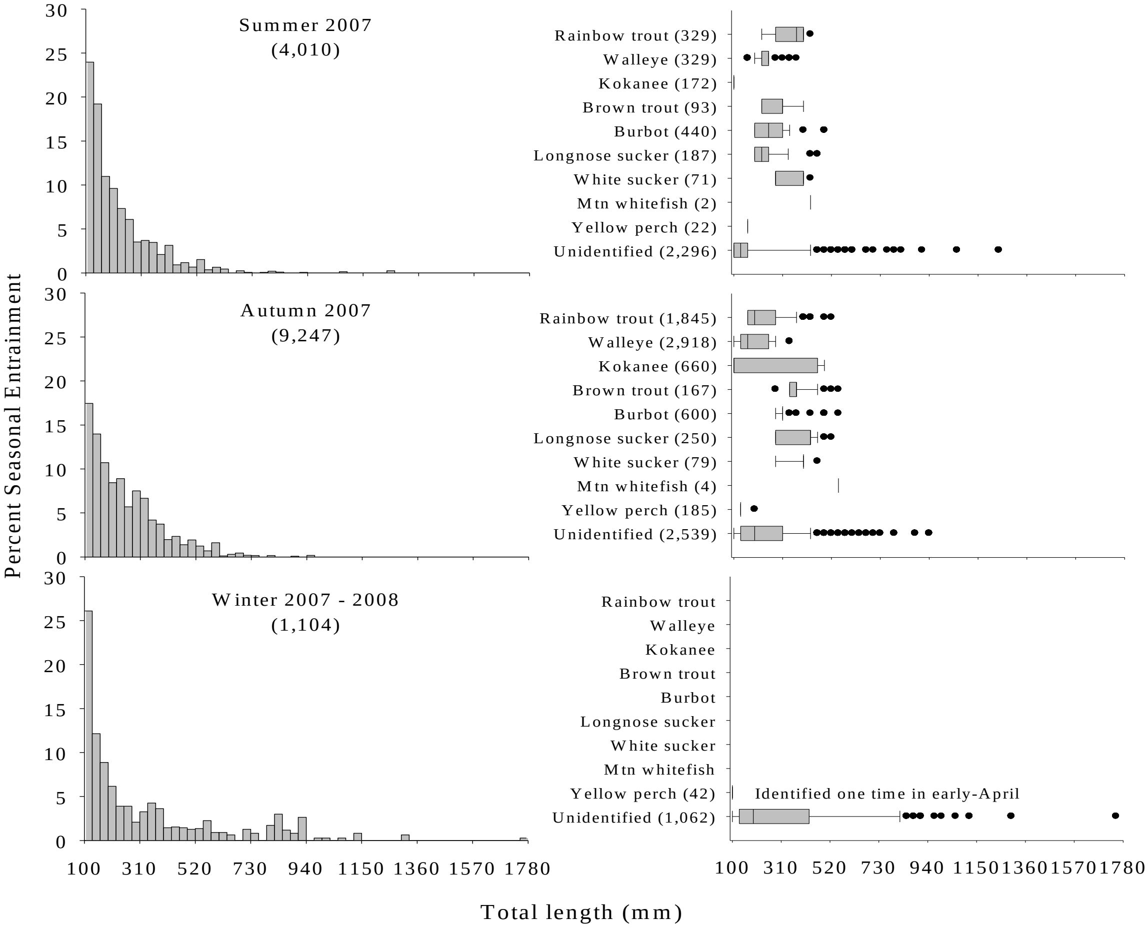


Figure 16.—Seasonal size distribution of all species combined (length-frequency plot) and the size distributions of individual species (box plot) observed by the turbine transducers from summer 2007 to winter 2007-2008. Also included in parentheses are the total extrapolated counts of entrained fish in the transducer beam (*WF*).

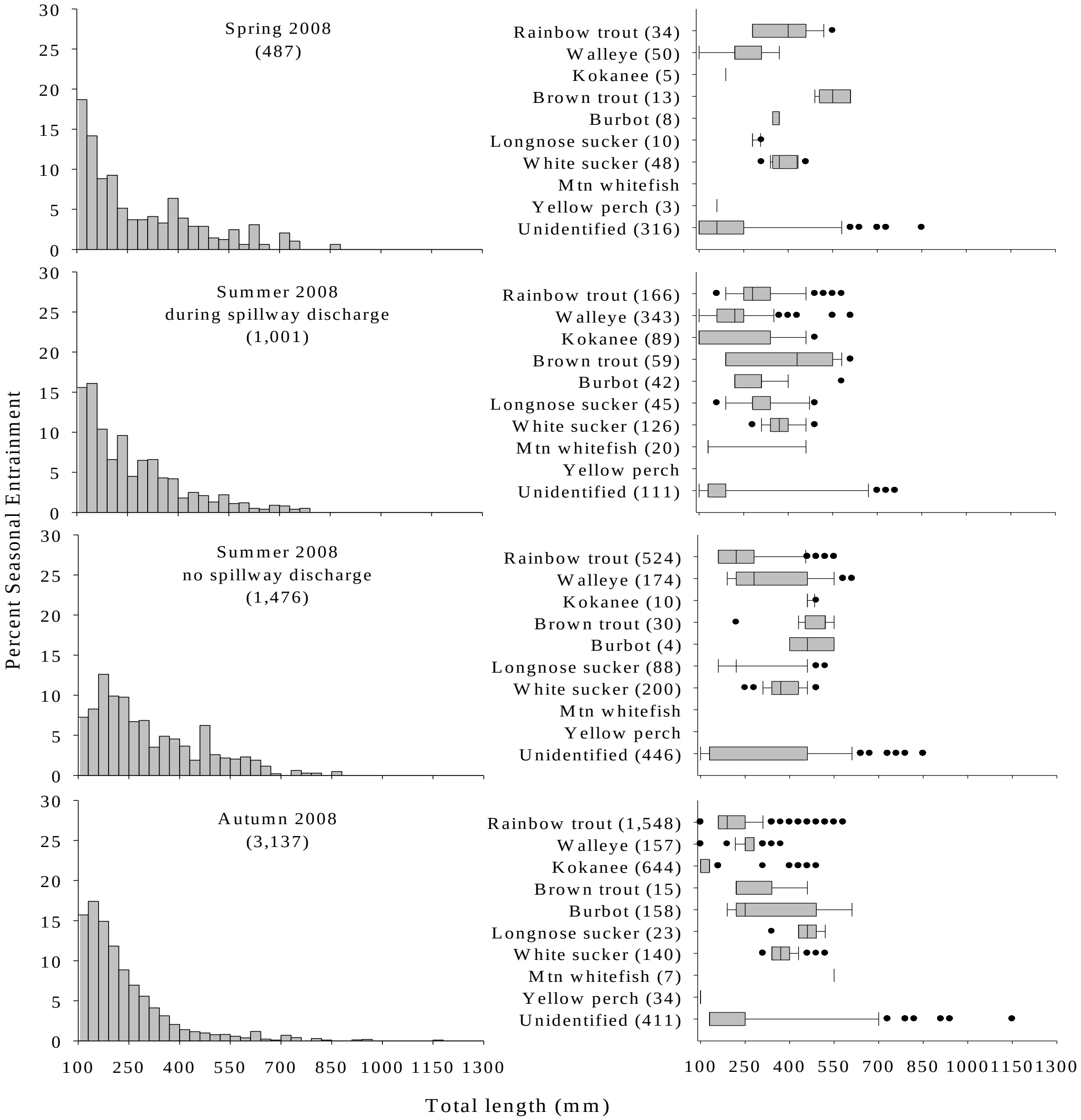


Figure 17.—Seasonal size distribution of all species combined (length-frequency plot) and the size distributions of individual species (box plot) observed by the turbine transducers from spring to autumn 2008. Also included in parentheses are the total extrapolated counts of entrained fish in the transducer beam (*WF*).

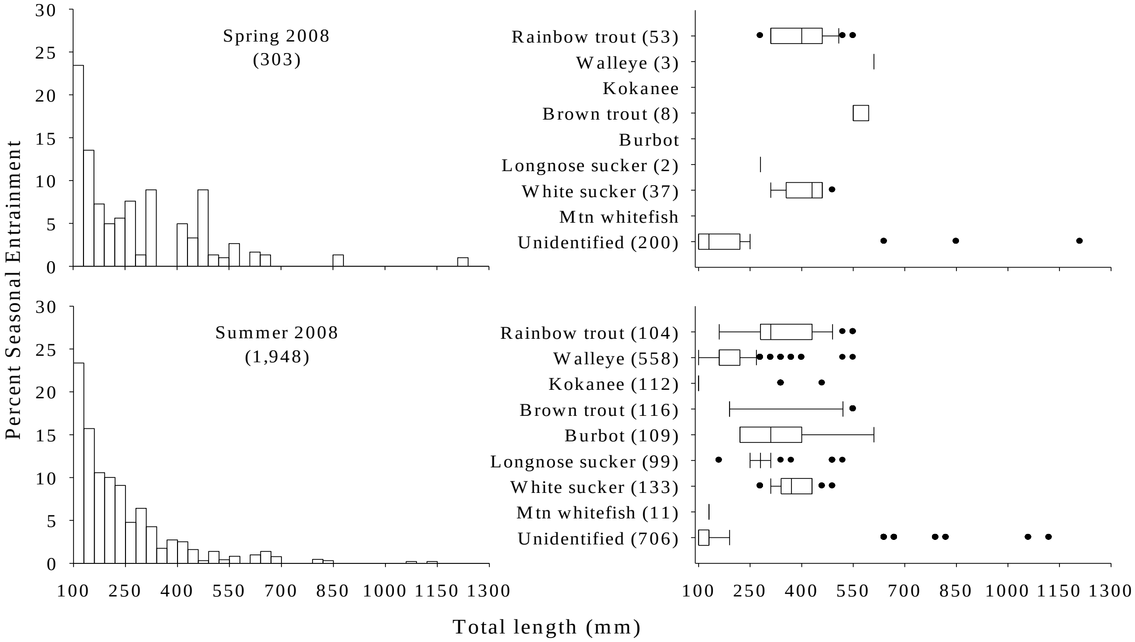


Figure 18.—Seasonal size distribution of all species combined (length-frequency plot) and the size distributions of individual species (box plot) observed by the spillway transducers from spring to summer 2008. Also included in parentheses are the total extrapolated counts of entrained fish in the transducer beam (*WF*).

Diurnal Distribution

Turbine entrainment occurred at all times of the day in all seasons, except spring 2008 when little entrainment occurred between midnight and 0200 hours (Figures 19, 20, and 21). Kokanee were the only species entrained in summer 2007 that had relatively high entrainment during the night (Figure 19). Spillway entrainment peaked during the night in both spring and summer, but a secondary peak occurred during the day in summer (Figure 22). Entrainment in the turbines during spill peaked during the day in spring and morning in summer (Figure 21).

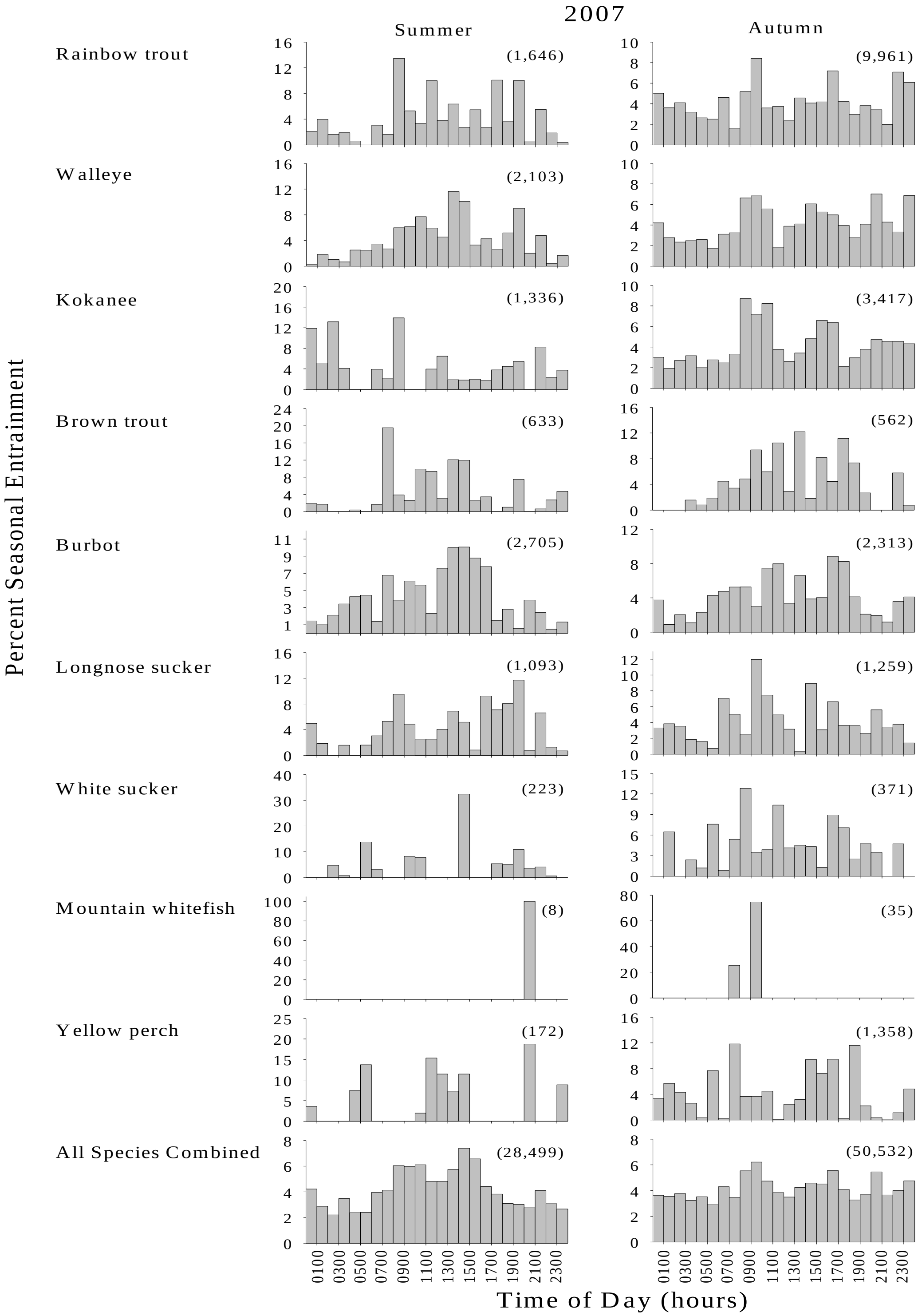


Figure 19.—Seasonal diurnal periodicity of entrainment in summer and autumn in 2007. Also included in parentheses are seasonal entrainment estimates.

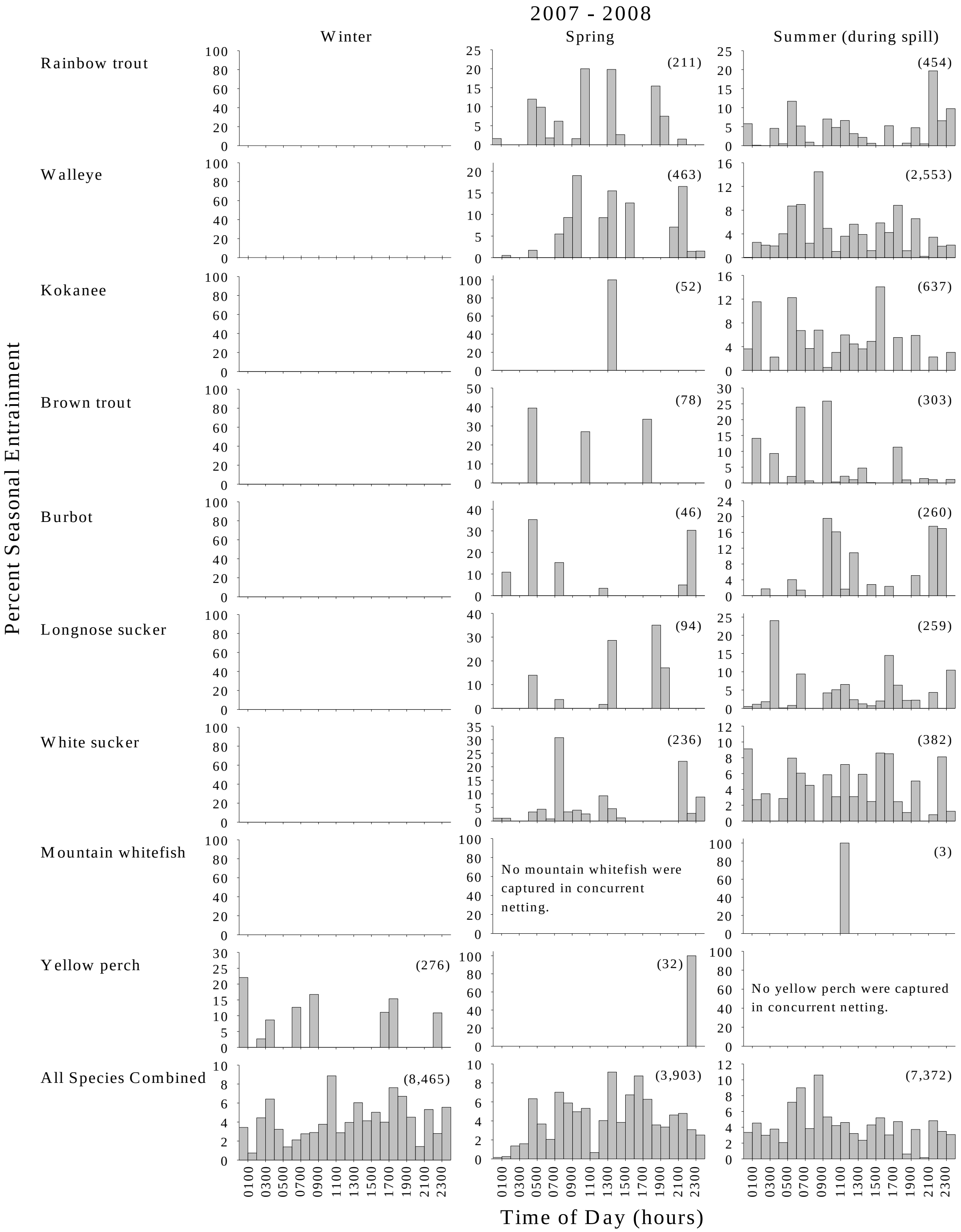


Figure 20.—Seasonal diurnal periodicity of entrainment from winter 2007-2008 to summer (during spillway discharge) 2008. Yellow perch were identified one time during winter in April; no other species was identified in winter entrainment. Also included in parentheses are seasonal entrainment estimates.

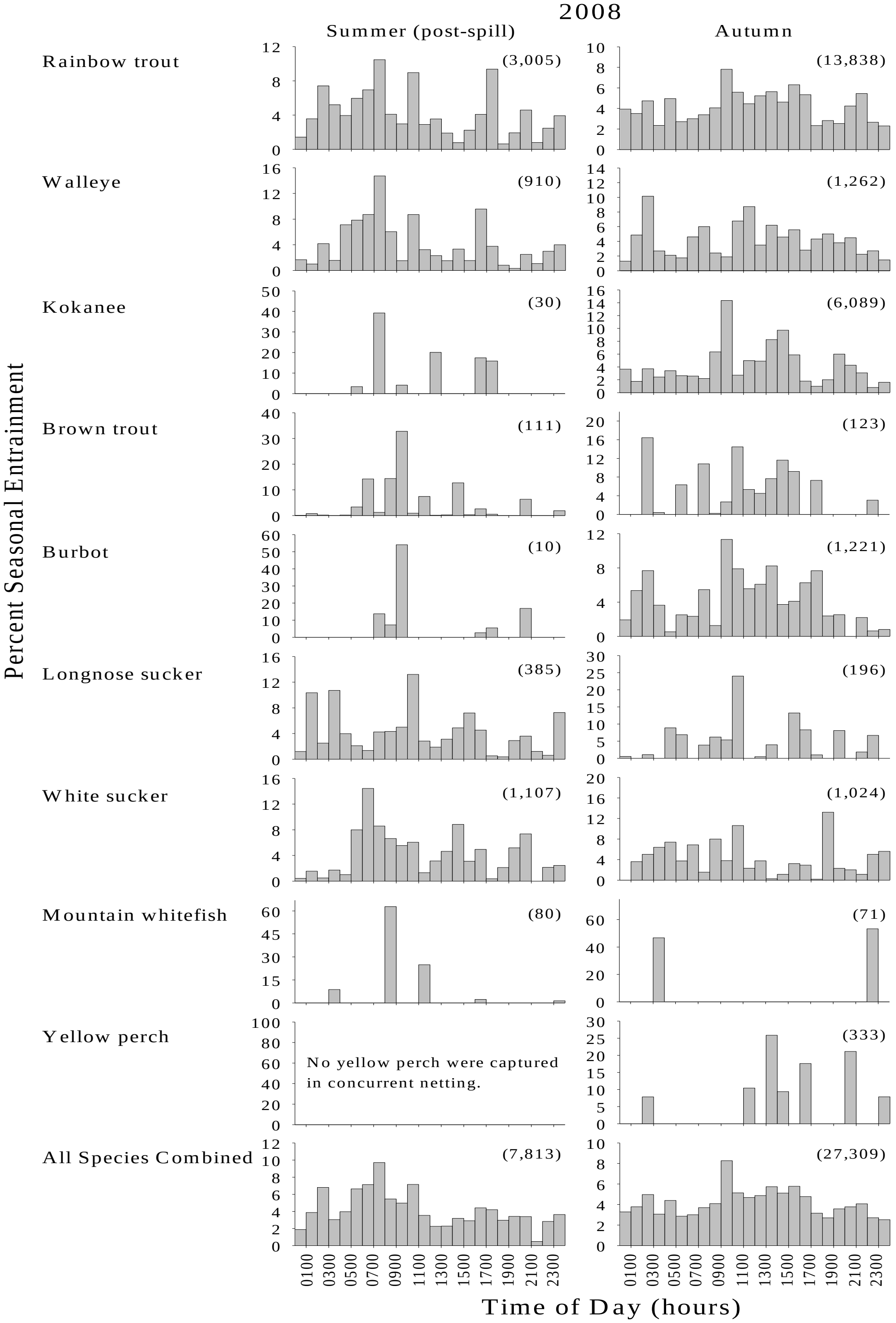


Figure 21.—Seasonal diurnal periodicity of entrainment from summer after spill ended to autumn 2008. Also included in parentheses are seasonal entrainment estimates.

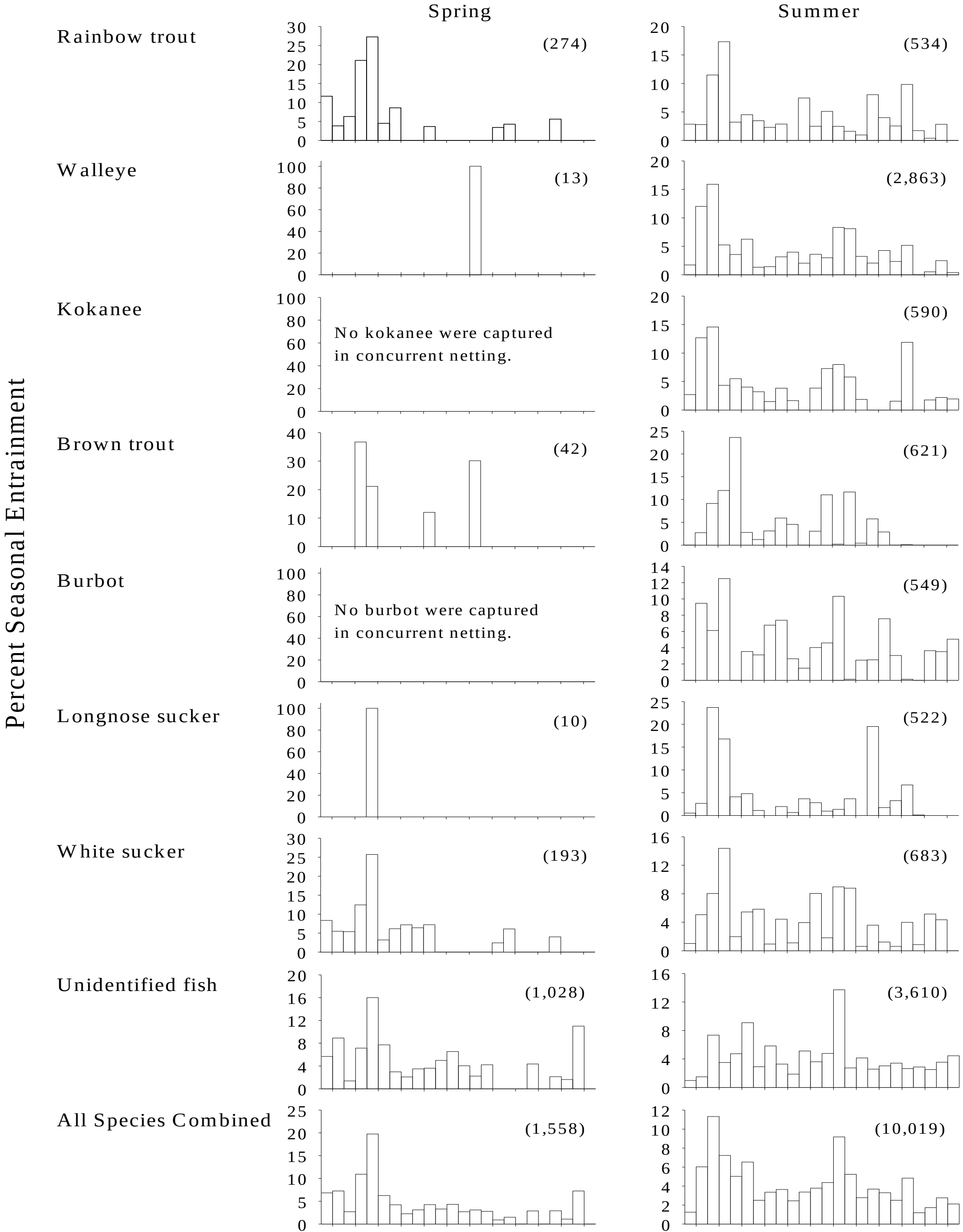


Figure 22.—Seasonal diurnal periodicity of spillway entrainment in spring and summer 2008. Burbot, kokanee, and mountain whitefish were not identified with nets in spring. Yellow perch were not identified in either season. Also included in parentheses are seasonal entrainment estimates.

Hatchery Rainbow Trout Entrainment

Recently stocked hatchery rainbow trout made up a large proportion of entrained fish in autumn 2007 (29%), summer 2008 after spillway discharge ended (75%), and autumn 2008 (59%). Stocking events included multiple releases of 6,000 to 15,000 fish over 8 to 15 days (Table 7). Hatchery rainbow trout entrainment began one to two days following the first release of each stocking event and lasted for at least one month (Figure 23). Entrainment peaked between 5 and 21 days following the first release. However, a second higher peak occurred 37 days after the first release in early November 2008.

The proportion of hatchery fish entrained from each stocking event varied from 7.6% in autumn 2007 to 9.8% in summer 2008 (Table 8). Stocking in autumn 2007 contained more, smaller fish than other events. Entrainment in winter was not estimated because no hatchery rainbow trout were captured in concurrent netting. However, entrainment of fish stocked in autumn 2007 increased from 7.6% to 13.5% when all small (< 280 mm) unidentified fish entrained in winter and spring were added, which increased mean stocking entrainment by 2.0%. Stocking in summer 2008 was split between one release on July 2 during high spill and a series of releases from July 14 to July 21 as flows rapidly declined. No fish were entrained between July 2 and July 14, 2008, and 421 (95% CI = 259 – 584) were entrained through both the turbines and spillway before spill ended on July 20, of which 64% were entrained in the spillway.

Hatchery fish were entrained (N = 1,038; 95% CI = 766 – 1,310) in August and early September 2007 before the autumn 2007 stocking (Figure 23). The source of early hatchery fish was likely Canyon Ferry stockings in spring or early summer. Entrained

Canyon Ferry hatchery fish were not estimated during other times because their numbers were confounded by releases in Hauser Reservoir.

Table 7.—Stocking times and size of stocked fish in Hauser Reservoir in 2007 and 2008.

Stocking Event	Dates of Stocking	Number of Releases	Mean Number Fish per release (SD)	Range of Mean Total Length (mm)	Mean Temperature (SD)	Total Stocked
Autumn 2007	9/25/07 – 10/09/07	11	13,123 (1,325)	175 – 183	13.0 (1.0)	144,351
Summer 2008	07/02/08 – 07/21/08	9	6,404 (1,261)	213 – 232	16.0 (3.5)	57,632
Autumn 2008	09/29/08 – 10/14/08	15	7,809 (847)	203 – 224	13.0 (2.4)	117,128

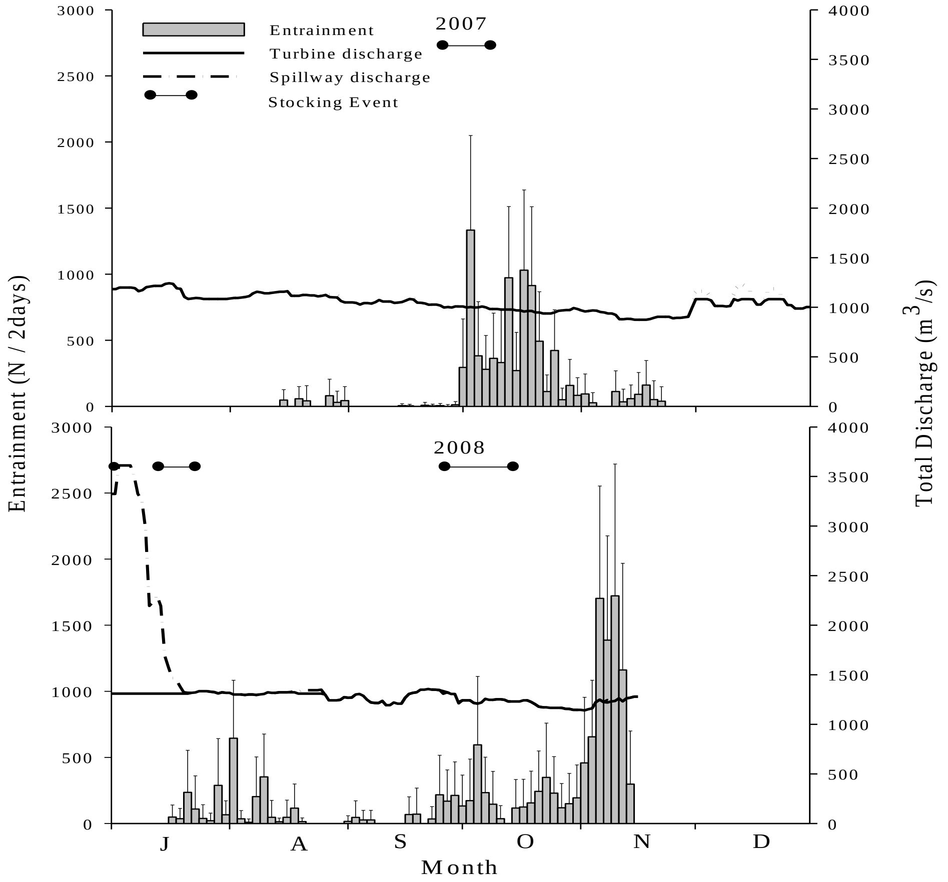


Figure 23.—Two day entrainment estimates (error bars are 95% confidence intervals) of hatchery rainbow trout (< 280 mm) in 2007 and 2008.

Table 8.—Estimated entrainment of recently stocked rainbow trout (< 280 mm) in Hauser Reservoir in 2007 and 2008.

Stocking Event	Estimated	95% CI	Percent of Stocked Fish Entrained
Autumn 2007	11,033	(9,246 – 12,820)	7.6
Summer 2008	5,546	(4,184 – 6,908)	9.6
Autumn 2008	11,477	(9,095 – 13,860)	9.8
Mean (SD)			**9.0 (1.2)**

Conditions Influencing Entrainment

Entrainment During Spill

Photoperiod and spillway discharge were the variables influencing spillway entrainment during spill (Table 9). Barometric pressure influenced turbine entrainment (Table 10). Photoperiod was the top ranked model for 85% of large (≥ 220 mm) fish and for all small (< 220 mm) fish combined that were entrained in spill (Table 9). Spillway discharge was the top ranked model for only burbot entrainment in both the spillway (Table 9) and turbines (Table 10). Spillway discharge and photoperiod were highly correlated ($r = 0.84$, $P = 0.0043$) and peak spillway discharge corresponded with the longest days of the year (Figure 24), which may have masked the importance of spillway discharge to entrainment. Turbine and spillway entrainment of most species was positively related to mean weekly spillway discharge (Tables 9 and 10). However, spillway discharge was negatively related to rainbow trout, walleye, and brown trout entrainment in turbines (Table 10). Multiple models were within two ΔAICc units of the top ranked model (i.e., equally ranked) for most species entrained in turbines (Table 10). Barometric pressure was the most frequently top-ranked model in turbine entrainment, but whether it was minimum or maximum barometric pressure that corresponded to high entrainment varied among species.

Comparisons between large and small fish were difficult because few small fish that were entrained were identified in concurrent netting. When all species were combined, photoperiod was the top ranked model for both large and small fish entrained in the spillway (Table 9) and large fish entrained in the turbines (Table 10). Photoperiod was also the top ranked model for large walleye entrained in both the spillway and turbines, but multiple models of small walleye entrainment were equally ranked as top models.

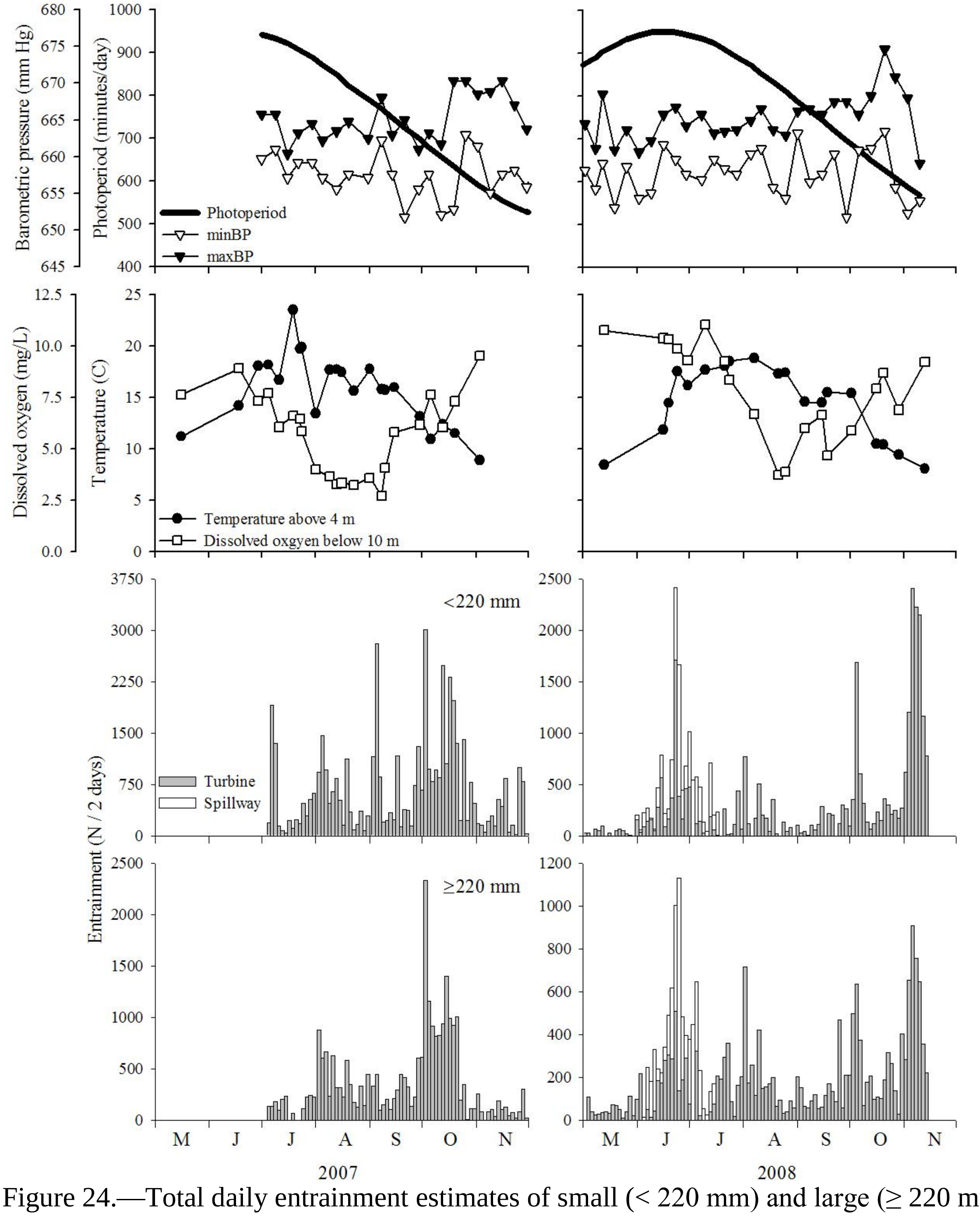


Figure 24.—Total daily entrainment estimates of small (< 220 mm) and large (≥ 220 mm) fish through the turbines and spillway from May through November 2007 and 2008 with respect to photoperiod (minutes), minimum and maximum barometric pressure, surface water temperatures above the turbine intakes (< 4 m), and hypolimnetic dissolved oxygen concentration below the turbine intakes (> 10 m). Confidence intervals for the entrainment estimates were omitted for clarity.

Table 9.—Model selection of linear regression models of weekly spillway entrainment of fish at Hauser Dam from May to July 2008. The relationships of $\log_{10}$(spillway) entrainment and spillway discharge (SpillD; m^3/s), photoperiod (DayL; min/day), and minimum (minBP) and maximum (maxBP) barometric pressure (mm Hg) were ranked according to Akaike information criterion corrected for small sample size (AICc). In addition, the table presents renormalized AICc weight (w_i), the number of parameters in the model (K), the number of weekly entrainment estimates for each species (N), percent of variation explained by the model (R^2), and model significance (*P*).

Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
	All Fish Combined					
< 220	-61.92011 + 0.06865×DayL	-5.7976	0.0000	0.7302	1	9
	-206.31486 + 0.31452×maxBP	-2.5743	3.2233	0.1457	1	
	-139.5552 + 0.21598×minBP	-1.3010	4.4966	0.0771	1	
	1.47317 + 0.00054623×SpillD	-0.3095	5.4881	0.0470	1	
≥ 220	-94.07602 + 0.10253×DayL	-13.2889	0.0000	0.9927	1	9
	0.2215 + 0.00104×SpillD	-3.4070	9.8819	0.0071	1	
	-191.99386 + 0.29235×maxBP	3.9103	17.1992	0.0002	1	
	-72.66255 + 0.11362×minBP	5.8907	19.1796	0.0001	1	
	Rainbow trout					
≥ 220	-68.4434 + 0.07462×DayL	-19.5634	0.0000	0.9432	1	9
	0.0582 + 0.0082804×SpillD	-13.9407	5.6227	0.0567	1	
	-103.00772 + 0.15746×maxBP	-0.6201	18.9433	0.0001	1	
	-36.56748 + 0.0579×minBP	0.4195	19.9829	0.0000	1	
	Walleye					
< 220	-68.75881 + 0.07546×DayL	-10.1930	0.0000	0.7376	1	6
	-313.93684 + 0.47531×maxBP	-9.2410	0.9520	0.4582	1	
	0.41543 + 0.00109×SpillD	-6.2713	3.9217	0.1038	1	
	-175.97404 + 0.27025×minBP	-1.7247	8.4683	0.0107	1	
≥ 220	-72.39819 + 0.07883×DayL	-5.3898	0.0000	0.7376	1	7
	-297.70687 + 0.45057×maxBP	-2.7368	2.6530	0.1958	1	
	0.24736 + 0.00080823×SpillD	0.0282	5.4180	0.0491	1	
	-143.29131 + 0.22019×minBP	2.0927	7.4825	0.0175	1	
	Brown trout					
≥ 220	-47.80739 + 0.0519×DayL	-18.2581	0.0000	0.9451	1	8
	-0.04826 + 0.00053256×SpillD	-12.5036	5.7545	0.0532	1	
	-294.88882 + 0.44622×maxBP	-4.4717	13.7864	0.0010	1	
	-30.0986 + 0.04713×minBP	-3.9947	14.2634	0.0008	1	

Table 9.—Continued.

Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
	Burbot					
≥ 220	-0.17176 + 0.00117×SpillD	-10.9886	0.0000	0.9222	1	6
	-64.78731 + 0.07071×DayL	-5.5932	5.3954	0.0621	1	
	-268.45681 + 0.40614×maxBP	-2.6727	8.3159	0.0144	1	
	-94.02974 + 0.14652×minBP	2.2065	13.1951	0.0013	1	
	Longnose sucker					
≥ 220	-68.69873 + 0.0746×DayL	-15.6830	0.0000	0.9958	1	7
	-191.13842 + 0.28969×maxBP	-3.1395	12.5435	0.0019	1	
	0.13627 + 0.00066744×SpillD	-2.7441	12.9389	0.0015	1	
	-124.87677 + 0.19172×minBP	-1.3161	14.3669	0.0008	1	
	White sucker					
≥ 220	-67.69667 + 0.07385×DayL	-14.8833	0.0000	0.9547	1	9
	0.18119 + 0.00077444×SpillD	-8.7266	6.1567	0.0439	1	
	-136.35885 + 0.20776×maxBP	-1.1400	13.7433	0.0010	1	
	-44.00785 + 0.06927×minBP	0.7812	15.6645	0.0004	1	

Table 10.—Model selection of linear regression models of weekly turbine entrainment of fish at Hauser Dam during spillway discharge from May to July 2008. The relationships of $\log_{10}$(turbine) entrainment and spillway discharge (SpillD; m^3/s), photoperiod (DayL; min/day), and minimum (minBP) and maximum (maxBP) barometric pressure (mm Hg) were ranked according to Akaike information criterion corrected for small sample size (AICc). In addition, the table presents renormalized AICc weight (w_i), the number of parameters in the model (K), the number of weekly entrainment estimates for each species (N), percent of variation explained by the model (R^2), and model significance (*P*).

Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
	All species combined					
< 220	2.28917 + 0.00023123×SpillD	-21.4493	0.0000	0.4834	1	13
	-8.44794 + 0.01191×DayL	-21.0655	0.3838	0.3990	1	
	-19.54215 + 0.03363×minBP	-17.3652	4.0841	0.0627	1	
	14.03941 - 0.01728×maxBP	-17.0985	4.3508	0.0549	1	
≥ 220	-54.12987 + 0.086189×minBP	-27.8741	0.0000	0.6754	1	
	-2.58889 + 0.00554×DayL	-24.7396	3.1345	0.1409	1	
	2.45611 + 0.00006466×SpillD	-23.9330	3.9411	0.0941	1	
	-16.41344 + 0.02854×maxBP	-23.8342	4.0399	0.0896	1	

Table 10.—Continued.

Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
	Rainbow trout					
≥ 220	14.86251 - 0.01388×DayL	-14.6738	0.0000	0.4056	1	10
	2.28722 - 0.00023474×SpillD	-14.5567	0.1171	0.3825	1	
	48.7886 - 0.07058×maxBP	-12.2609	2.4129	0.1214	1	
	-0.65139 + 0.00392×minBP	-11.6753	2.9985	0.0906	1	
	Walleye					
< 220	1.46493 + 0.00049413×SpillD	-5.9423	0.0000	0.4329	1	6
	-155.10085 + 0.23655×maxBP	-4.6522	1.2901	0.2271	1	
	-15.55236 + 0.01892×DayL	-4.6424	1.2999	0.2260	1	
	-106.23316 + 0.16428×minBP	-3.2735	2.6688	0.1140	1	
≥ 220	-73.05857 + 0.11412×minBP	-23.6008	0.0000	0.8092	1	12
	-41.43919 + 0.0654×maxBP	-19.2209	4.3799	0.0906	1	
	2.08254 - 0.00007245×SpillD	-18.2297	5.3711	0.0552	1	
	2.40971 - 0.0004544×DayL	-17.8244	5.7764	0.0451	1	
	Brown trout					
≥ 220	68.12431 - 0.10065×maxBP	-17.4898	0.0000	0.6036	1	8
	4.47533 - 0.00346×DayL	-14.5496	2.9402	0.1388	1	
	25.15841 - 0.03627×minBP	-14.4632	3.0266	0.1329	1	
	1.33727 - 0.0000484×SpillD	-14.3352	3.1546	0.1247	1	
	Burbot					
≥ 220	0.01894 + 0.00089663×SpillD	-21.1440	0.0000	0.9777	1	6
	-120.52174 + 0.18539×minBP	-12.4789	8.6651	0.0128	1	
	-39.05689 + 0.0432×DayL	-11.6978	9.4462	0.0087	1	
	-114.20112 + 0.17403×maxBP	-6.9753	14.1687	0.0008	1	
	Longnose sucker					
≥ 220	-70.25796 + 0.10892×minBP	-11.2401	0.0000	0.4655	1	11
	-58.13245 + 0.08963×maxBP	-9.7744	1.4657	0.2237	1	
	1.24114 + 0.00007842×SpillD	-9.1443	2.0958	0.1633	1	
	0.27842 + 0.00115×DayL	-8.9414	2.2987	0.1475	1	
	White sucker					
≥ 220	-50.20711 + 0.07912×minBP	-18.3168	0.0000	0.4936	1	11
	6.15573 - 0.00467×DayL	-16.4058	1.9110	0.1898	1	
	-11.30064 + 0.01976×maxBP	-16.0720	2.2448	0.1607	1	
	1.7920 + 0.00001521×SpillD	-16.0118	2.3050	0.1559	1	

Entrainment When No Spill Occurred

Multiple models were within two ΔAICc units of the lowest AICc ranked (best) model for most species in entrainment when no spill discharge occurred (Table 11). Minimum barometric pressure was the most common top ranked model, and weeks of low mean minimum barometric pressure corresponded with high entrainment. Minimum barometric pressure was especially important for rainbow trout entrainment as the model was top ranked in both years.

Temperature and dissolved oxygen conditions also influenced entrainment when no spillway discharge occurred. Entrainment of large fish in 2007 and all sizes in 2008 declined when hypolimnetic dissolved oxygen concentrations were lower than 6 mg/L (Figure 24). In addition, the top ranked model for large fish of all species combined was surface water temperature plus hypolimnetic dissolved oxygen (Table 11). The influence of temperature and dissolved oxygen on entrainment of most species was inconclusive because multiple models were equally ranked. However, all highly ranked models of white sucker entrainment in 2007 were of temperature and dissolved oxygen dynamics, but the relationship between white sucker entrainment and dissolved oxygen was negative in 2007 and positive in 2008 (Table 11).

Table 11.—Model selection of linear regression models of weekly turbine entrainment of fish at Hauser Dam from 2007 to 2008 when no spillway discharge occurred. The relationships between $\log_{10}$(turbine) entrainment and turbine discharge (TurbD), photoperiod (DayL), minimum (minBP) or maximum (maxBP) barometric pressure, water column temperature (mTemp), water column dissolved oxygen (mDO), temperature above the turbine intakes (TempAb), and dissolved oxygen below the turbine intakes (DObel) were ranked according to Akaike information criterion corrected for small sample size (AICc). Only models within 2 ΔAICc units of the lowest AICc ranked model were reported). In addition, the table presents renormalized AICc weight (w_i), the number of predictors in the model (K), the number of weekly entrainment estimates for each species (N), percent of variation explained by the model (R^2), and model significance (*P*).

Year	Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
		All species combined					
2007	< 220	67.25952 - 0.09731×minBP	-36.3238	0.0000	0.8861	1	16
	≥ 220	5.05105 - 0.08547×TempAb - 0.13364×DObel	-29.9049	0.0000	0.5523	2	16
2008	< 220	4.95733 - 0.00303×DayL	-16.6722	0.0000	0.4170	1	9
	≥ 220	5.30033 - 0.00205×TurbD	-25.0251	0.0000	0.1567	1	9
		22.23473 - 0.02969×minBP	-24.8492	0.1759	0.1435	1	
		2.26188 + 0.05708×mDO	-24.6413	0.3838	0.1293	1	
		2.36788 + 0.05016×DObel	-24.1643	0.8608	0.1019	1	
		3.22410 - 0.0069507×DayL	-24.0230	1.0021	0.0949	1	
		-10.66809 + 0.0201×maxBP	-23.6366	1.3885	0.0783	1	
		2.95009 - 0.0191×mTemp	-23.3806	1.6445	0.0689	1	
		2.74296 - 0.01509×ThermD	-23.2200	1.8051	0.0636	1	
		2.84998 - 0.00993×TempAb	-23.1781	1.8470	0.0622	1	
		Rainbow trout					
2007	≥ 220	99.7364 - 0.14837×minBP	-25.7531	0.0000	0.9611	1	15
2008	≥ 220	34.54244 - 0.04883×minBP	-26.6584	0.0000	0.3750	1	9
		3.38172 - 0.00128×DayL	-25.0287	1.6297	0.1660	1	
		5.95166 - 0.00278×TurbD	-24.9932	1.6652	0.1631	1	
		Walleye					
2007	< 220	119.60706 - 0.17798×minBP	-14.3341	0.0000	0.4284	1	8
		12.0492 - 0.28891×mTemp - 0.74901×mDO	-13.8216	0.5125	0.3315	2	
		7.84119 - 0.1145×TempAb - 0.49993×DObel	-12.6966	1.6375	0.1889	2	
	≥ 220	108.90354 - 0.16201×minBP	-18.7259	0.0000	0.7829	1	15

Table 11.—Continued.

Year	Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
Walleye							
2008	≥ 220	6.90197 - 0.00407×TurbD	-9.8681	0.0000	0.1556	1	9
		0.8546 + 0.11513×mDO	-9.6299	0.2382	0.1381	1	
		-31.04854 + 0.04929×maxBP	-9.1220	0.7461	0.1071	1	
		1.64414 + 0.05121×ThermD	-8.9292	0.9389	0.0973	1	
		1.19691 + 0.08231×DObel	-8.9260	0.9421	0.0971	1	
		2.25141 - 0.03922×mTemp	-8.6595	1.2086	0.0850	1	
		-4.56022 + 0.00961×minBP	-8.3385	1.5296	0.0724	1	
		1.65801 + 0.00013448×DayL	-8.3106	1.5575	0.0714	1	
		1.79777 - 0.00284×TempAb	-8.3068	1.5613	0.0713	1	
		1.14749 - 0.01781×mTemp + 0.10638×mDO	-7.9912	1.8769	0.0609	2	
Kokanee							
2007	< 220	9.68567 - 0.30574×mTemp - 0.44931×mDO	-22.2068	0.0000	0.5269	2	6
		48.42147 - 0.06965×minBP	-20.8004	1.4064	0.2608	1	
2008	≥ 220	1.99913 - 0.00118×DayL	-12.0445	0.0000	0.1493	1	6
		-18.19515 + 0.02898×maxBP	-11.3632	0.6813	0.1062	1	
		1.42308 - 0.02061×TempAb	-11.3296	0.7149	0.1044	1	
		1.42416 - 0.03662×mDO	-11.2999	0.7446	0.1029	1	
		1.17342 - 0.02732×ThermD	-11.2488	0.7957	0.1003	1	
		2.12626 - 0.00078878×TurbD	-11.1965	0.8480	0.0977	1	
		1.35049 - 0.03063×DObel	-11.1552	0.8893	0.0957	1	
		1.69304 - 0.00084393×minBP	-11.0593	0.9852	0.0912	1	
		1.14391 - 0.00048642×mTemp	-11.0588	0.9857	0.0912	1	
Brown trout							
2007	≥ 220	49.01754 - 0.071×maxBP	-33.2010	0.0000	0.4601	1	13
2008	≥ 220	55.34434 - 0.08245×minBP	-10.2944	0.0000	0.2527	1	7
		-2.2164 + 0.14792×mTemp + 0.16116×mDO	-8.8895	1.4049	0.1252	2	
		0.11364 + 0.12336×mDO	-8.7635	1.5309	0.1176	1	
		-0.16743 + 0.07852×mTemp	-8.5271	1.7673	0.1044	1	
Burbot							
2007	≥ 220	65.19479 - 0.09591×minBP	-23.8975	0.0000	0.3380	1	16
		3.81784 - 0.07616×TempAb - 0.0918×DObel	-22.7095	1.1881	0.1866	2	
		3.03298 - 0.05884×TempAb	-21.9714	1.9261	0.1290	1	
2008	≥ 220	5.68693 - 0.00642×DayL	-8.2551	0.0000	0.3162	1	7
		15.25641 - 0.01123×TurbD	-7.9414	0.3137	0.2703	1	
		-1.74329 + 0.40803×mDO	-6.7424	1.5127	0.1484	1	

Table 11.—Continued.

Year	Fish Size (mm)	Model	AICc	ΔAICc	w_i	K	N
		Longnose sucker					
2007	≥ 220	31.05544 - 0.04416×minBP	-28.0219	0.0000	0.1828	1	13
		2.3503 - 0.05767×DObel	-27.2734	0.7485	0.1258	1	
		2.51348 - 0.07266×mDO	-27.1890	0.8329	0.1206	1	
		1.35511 + 0.0497×mTemp	-26.8587	1.1632	0.1022	1	
		1.60072 + 0.02776×TempAb	-26.6929	1.3290	0.0941	1	
2008	≥ 220	26.23432 - 0.03786×minBP	-14.4580	0.0000	0.1569	1	8
		0.95704 + 0.04764×mDO	-13.7561	0.7019	0.1105	1	
		-12.43858 + 0.02065×maxBP	-13.4785	0.9795	0.0962	1	
		1.66768 - 0.00045498×DayL	-13.4655	0.9925	0.0956	1	
		1.14996 + 0.02628×DObel	-13.4312	1.0268	0.0939	1	
		1.14219 + 0.012×TempAb	-13.4277	1.0303	0.0938	1	
		1.66177 - 0.0026903×TurbD	-13.3447	1.1133	0.0900	1	
		1.24627 + 0.00566×mTemp	-13.3400	1.1180	0.0897	1	
		1.32028 + 0.00030932×ThermD	-13.3310	1.1270	0.0893	1	
		White sucker					
2007	≥ 220	2.40682 - 0.12522×mDO	-21.6352	0.0000	0.1680	1	10
		2.14843 - 0.09984×DObel	-21.5548	0.0804	0.1614	1	
		0.49705 + 0.08296×mTemp	-21.0526	0.5826	0.1255	1	
		1.67114 - 0.04478×ThermD	-20.7881	0.8471	0.1100	1	
		1.6688 + 0.03909×mTemp - 0.09175×mDO	-20.3211	1.3141	0.0871	2	
		2.12934 + 0.00093573×TempAb - 0.09886×DObel	-19.9483	1.6869	0.0723	2	
		1.16829 + 0.03009×TempAb	-19.8738	1.7614	0.0696	1	
2008	≥ 220	-2.3879 + 0.18869×mTemp + 0.20305×mDO	-15.6008	0.0000	0.6133	2	9

DISCUSSION

Seasonal Entrainment

Entrainment of resident fish at Hauser Dam appears to be low relative to other facilities in the United States. Flow-adjusted annual entrainment estimates for 43 hydropower facilities from the midwestern to eastern U.S. were calculated by dividing hourly entrainment by hydraulic capacity in thousands of cubic meters per second (kcms; FERC 1995). FERC (1995) found that entrainment ranged from 0.003 to 22.0 fish/hour/kcms (mean = 1.1; SD = 3.5). Flow-adjusted entrainment at Hauser Dam of 0.096 fish/hour/kcms was much lower than the mean entrainment rate. In addition, peak daily entrainment estimates at four northeast Michigan hydroelectric facilities with much lower hydraulic capacities than Hauser Dam (i.e., maximum capacity was 79.7 to 117.1 m^3/s lower) ranged from about 180 to 2,200 fish/day (Navarro et al. 1996). However, mean daily entrainment in autumn at Hauser Dam was 561.5 fish/day in 2007, 369.0 fish/day in 2008, and 761.7 fish/day during spill (spillway and turbine combined).

Entrainment increased seasonally from summer through autumn in 2007 and spring to autumn in 2008. Typically, seasonal entrainment increases as juvenile and age-0 fish emerge from nursery habitats (Johnson et al. 1989; FERC 1995) as up to 90% of entrained fish are smaller than 200 mm (EPRI 1992). Increased entrainment of large fish occurred after turnover. Horn (2004) found that fish activity increased in the vicinity of the dam after turnover, which may explain increasing entrainment. Most kokanee captured in concurrent netting in autumn had metamorphosed for spawning (i.e., humpshaped backs, elongated and hooked jaws, and bright red coloration) and entrained fish were likely searching for suitable spawning habitat. More walleye and rainbow trout may have been entrained in autumn as they fed on small fish migrating through the reservoir because walleye in Hauser Reservoir feed primarily on small fish in autumn (Dalbey 2001) and small fish make up a large portion of rainbow trout diets (Beauchamp 1990). Entrainment in winter and early spring was low and relatively stable before spillway discharge. Ice covered the reservoir from December 2007 to April 2008, and water temperatures reached a low of about 1ºC in late January and early February. One episode of high entrainment that occurred in late January can perhaps be attributed to cold water temperatures inhibiting the ability of fish to withstand and avoid fluctuating turbine discharges (EPRI 1992; FERC 1995; Sorenson et al. 1998). I do not have information for winter and early spring 2007, but multi-year studies have shown that entrainment at these times is consistently low and episodic in inland reservoirs of the midwestern U.S. (EPRI 1992; FERC 1995).

High turbine and spillway entrainment during runoff made up large proportions (19% and 20%, respectively) of entrainment from spring to autumn in 2008. Spillway entrainment of salmonids migrating downstream in the Columbia River system has been extensively studied and the selection of the spillway as a downstream pathway has been attributed to fish orienting themselves with bulk river flow (Coutant and Whitney 2000). The negative relationship between turbine entrainment and spillway discharge during spill and a positive relationship for spillway entrainment indicates that some species were orienting themselves with spill. High rainbow trout and kokanee entrainment is attributable to downstream migration during high runoff. Kokanee are especially susceptible to entrainment, as 95% of age-1 and age-2 kokanee were lost through Dworshak Dam during high flows in late winter and early spring (Maiolie and Elam 1998). Non-migratory species are entrained because they are not capable of avoiding strong currents (FERC 1995) or when more active in association with spawning (Navarro et al. 1996). Spillway discharge began near the end of the spawning period for walleye, which occurs from April through May in the upper Missouri reservoirs (Dalbey and Humphrey 2005). High walleye entrainment during spill most likely occurred as they searched for feeding grounds after spawning (Heidinger et al. 1989; Rassmusen et al. 2002). Entrainment of longnose and white suckers during spill was likely a result of spawning activity because individuals captured in concurrent netting displayed spawning coloration and turbercles.

Diurnal variation of turbine entrainment was relatively low, but most spillway entrainment occurred at night through surface spillbays. High entrainment at night has been observed in many species at facilities across the U.S. and was attributed to increased activity at night (EPRI 1992; FERC 1995; Navarro et al. 1996; Skaar et al. 1996; Coutant and Whitney 2000). Many fish, especially small fish, inhabit deeper waters during the day and follow prey towards the surface at night (Lucas et al. 2000; Hardiman et al. 2004) making them more susceptible to entrainment near the surface. Increased entrainment at night may have occurred as small fish migrated vertically and piscivorous species (i.e., walleye and rainbow trout) followed them.

Hatchery Rainbow Trout Entrainment

Entrainment of recently stocked fish is thought to limit the number of fish recruiting to the fishery and make management efforts unpredictable in Hauser Reservoir. Stocking efforts have been timed to avoid excess entrainment during high flows (Hill 1973; Skaar and Humphrey 1997), resulting in stable survival of released fish despite annual variation of flow conditions (Dalbey and Humphrey 2005). Low variation of entrainment among stocking events (mean = 9.0%; SD = 1.2%) indicated timing of stocking as currently executed has little effect on the rate of entrainment. Entrainment of hatchery fish in winter is unknown and though autumn 2007 entrainment doubled when winter entrainment was added, it only increased mean stocking entrainment by 2%.

Most entrainment of hatchery fish was temporary and likely a result of dispersal through the reservoir. Hatchery rainbow trout dispersal in moving waters varies in direction and distance after release (Cresswell 1981), but at least a small proportion disperse downstream (Helfrich and Kendall 1982) and can travel long distances in a short time (Bettinger and Bettoli 2002). Operational factors expected to increase entrainment such as low reservoir elevation and high discharge (McLellan et al. 2008) varied little after stocking. Reservoir elevation changed less than 30.5 cm, and most stocking avoided spill. Although a high percentage of entrainment during the last six days of spill was through the spillway, most of the entrainment from the summer stocking event occurred after spill ended.

No patterns were discernable between entrainment of hatchery fish and water temperature or DO. Autumn entrainment occurred after fall turnover when water temperatures were below 15.5ºC and DO was above 5 mg/L. Water temperatures between 17ºC and 19ºC did not appear to limit entrainment of fish stocked in summer 2008. However, entrainment of summer stocked fish may have been limited by low hypolimnetic DO concentrations (< 5.1 mg/L) because entrainment of all fish declined for a short time until turnover.

Conditions Influencing Entrainment

Identification of strong associations between entrainment and environmental and operational variables at Hauser Dam was complicated because multiple models were equally ranked within two ΔAICc units of the top model. Multiple similarly ranked models indicated the data were not sufficient to infer strong relationships between entrainment and environmental and operational variables (Burnham and Anderson 1998) and were likely a result of high weekly variability and low sample size; small magnitude changes relative to seasonal variation prevented relationships from being apparent (Rose 2000).

Spillway discharge was expected to be more influential to entrainment in the turbines and spillway during spill than either barometric pressure or photoperiod (Skaar and Humphrey 1997). However, a high correlation between spillway discharge and photoperiod resulted in both models being highly ranked. Additional entrainment information from years when spill occurred earlier and had lower discharge would identify whether spillway discharge or photoperiod is more influential to entrainment at Hauser Dam. Turbine and spillway entrainment were positively related to spillway discharge for all species during spill, except rainbow trout. The negative relationship between spillway discharge and rainbow trout entrained in turbines indicated that they were attracted to the spillway with the bulk of the river flow (Coutant and Whitney 2000; Ploskey et al. 2005).

Barometric pressure was the most common factor influencing entrainment through the turbines both during spill and when no spill occurred. Barometric pressure has been positively associated with spawning movements of rainbow trout (Peterson 1972), activity levels of black crappie *Pomoxis nigromaculatus* (Guy et al. 1992), and depth distribution of sauger *Sander canadensis* (Jeffrey and Edds 1999). Entrainment was positively associated with barometric pressure during spill, but the relationship was negative at times without spill suggesting that fish movement increased when weather conditions were unstable.

Reservoir habitat availability is restricted in the reservoir in summer when fish avoiding warm surface water temperatures encounter low hypolimnetic DO concentrations (< 5 mg/L; Skaar and Humphrey 1997; Horn 2004). I expected entrainment to increase as fish were forced into intermediate depths of the reservoir where turbines draw water for power generation (Rhea et al. 2005). Temperature and DO were seldom ranked as top models, but entrainment declined when hypolimnetic DO concentrations were below 5.1 mg/L and surface water temperatures were warmer than 15.9ºC. Entrainment can be limited when turbine withdrawal is below the thermocoline in hypoxic waters (Paller et al. 2006), but fish in Hauser Reservoir were present at depths of turbine withdrawal year-round. Low entrainment at the dam was most likely a result of fish avoiding waters upstream of the dam during warm and hypoxic conditions (Horn 2004).

Sampling Limitations

Hydroacoustics

Hydroacoustics was used to estimate entrainment at Hauser Dam because it is capable of monitoring fish behavior continuously and noninvasively (Ransom and Steig 1994; McKinstry et al. 2005); however, transducer placement and sampling regime may have biased entrainment estimates. First, entrainment estimates were calculated from fish behavior directly upstream of trashracks and spillgates. I assumed that all fish leaving the transducer beam would continue into turbine intakes and spillbays. Detected fish may have changed direction outside of the transducer beam, but I believe this is unlikely as the beams were aimed close to the entrainment area. Second, transducers were mounted in fixed locations preventing an evaluation of the spatial distribution among spillbays and turbines most of the year. Higher entrainment occurs through units farther from the forebay inlet in midwestern U.S. facilities, and spillway entrainment can vary spatially depending on the proximity to shorelines (FERC 1995). Monitoring at fixed locations may have biased estimates as more or less entrainment may have occurred in unmonitored areas. Though my investigation of the spatial variation of entrainment among turbine intakes was only a snapshot in time, I conducted it when entrainment rates were high (autumn 2008) and I should have detected a skewed distribution of entrainment if it occurred. I was unable to evaluate spatial variation among spillbays in surface and hydraulic spill because moving transducers during spill was too dangerous to attempt. Finally, entrained fish identified with gill nets may not have represented the true composition of entrainment because fish assemblages in and around facilities can be different from their impoundments (FERC 1995). Unfortunately, low catches in forebay trap nets prevented me from evaluating the differences between the fish assemblage in the forebay and those captured in reservoir gill nets.

Concurrent Netting

Despite using multiple gears to identify entrained fish, concurrent netting was ineffective at identifying about 40% of entrained fish. The inability of hydroacoustic systems to identify entrained fish is disadvantageous as periodic netting is often biased (Ransom and Steig 1994). A proportion of entrained fish were not identified because netting consistently did not capture all sizes of entrained fish, especially fish smaller than 200 mm and larger than 500 mm. Reservoir gill netting was the primary method used to identify entrained fish because forebay netting was not possible until December 2007, and few fish were captured in forebay nets in 2008.

Seasonal variation in the ability of concurrent netting to capture a representative size distribution of entrained fish was a function of the ability of gill nets to capture fish. Gill nets were not operated in winter because ice prevented access to the reservoir. Vertical gill nets were not effective at capturing fish during spill in spring and summer 2008. Strong water currents during spill stretched the gill nets tight, thus preventing fish from being entangled. When no spill occurred, sizes of fish captured in nets were more representative of entrainment. The declining number of unidentified fish from summer to autumn was probably a result of many factors that affect gear efficiency such as fish activity and density, season, and turbidity (Hubert 1996).

Forebay nets contributed little information to species identification as few fish were captured in them. Netting in the forebay was necessary because the preferred strategy of deploying nets behind the trashracks was not possible at the dam, and the alternative strategy of deploying at turbine draft tubes would have resulted in contamination by tailrace resident fish (FERC 1995; Sorenson et al. 1998). Forebay entrance water velocities were low (< 1.0 m/s) and large fish encountering the nets were easily able to avoid them (Katopodis and Gervais 1991; Haro et al. 2004). However, small fish (< 100 mm) were captured frequently in late summer, and capture efficiency trials indicated the nets are capable of capturing small fish. High summer and autumn entrainment in the midwestern U.S. was attributed to increased densities of young fish that emerged from nursery areas (FERC 1995). Though small fish were not quantified adequately in this study using forebay trap nets, they can be used in future studies of ichthyoplankton and juvenile fish entrainment.

Management Implications

Entrainment of impounded fish populations through hydroelectric facilities is a challenge faced by managers worldwide, and has faced increased attention (FERC 1995; Navarro et al. 1996; McLellan et al. 2008). The spatial and temporal patterns of entrainment at Hauser Dam were typical of other facilities in that entrainment varied seasonally, but I was not able to identify the conditions that were influencing entrainment. Typically, discharge is thought to be the primary condition influencing entrainment rate. Discharge affected entrainment at Hauser Dam only during spill, though the evidence was obscured by a high correlation between spillway discharge and photoperiod. At other times of the year, entrainment was affected by a variety of conditions, and high entrainment appeared to respond to seasonal changes associated with turnover.

Identification of spatial and temporal patterns of entrainment and the factors that affect entrainment allow managers to evaluate effects on fish populations and allocate their resources more efficiently. Strategies to reduce entrainment of recently stocked rainbow trout have been implemented by MFWP to avoid releasing fish during spillway discharge at Hauser Dam, and should continue as a high percentage of the July 2008 event was entrained through spillgates. However, losses of about 10% of stocked fish and many other fish species in autumn may warrant additional strategies to protect fish from being entrained (Appendix C). Reducing entrainment in autumn may be possible because the cross-sectional area of the forebay entrance is relatively small, the water velocity there is low, the forebay net structure is already in place and can be used to deploy fish deterrence technologies, and little aquatic vegetation capable of fouling such deterrence structures and reducing their efficiency is present in the water column (Stober et al. 1983; Michaud and Taft 2000).

REFERENCES CITED

Baldwin, C. M., and M. C. Polacek. 2002. Evaluation of limiting factors for stocked kokanee and rainbow trout in Lake Roosevelt, Washington, 1999. Report FTP 04-03. Washington Department of Fish and Wildlife, Inland Fish Investigations, Spokane.

Barwick, D. H., J. W. Foltz, and D. M. Rankin. 2004. Summer habitat use by rainbow trout and brown trout in Jocassee Reservoir. North American Journal of Fisheries Management 24:735–740.

Beauchamp, D. A. 1990. Seasonal and diel food habits of rainbow trout stocked as juveniles in Lake Washington. Transactions of the American Fisheries Society 119:475–482.

Bettinger, J. M., and P. W. Bettoli. 2002. Fate, dispersal, and persistence of recently stocked and resident rainbow trout in a Tennessee tailwater. North American Journal of Fisheries Management 22:425–232.

Burnham, K. P., and D. R. Anderson. 1998. Model selection and inference a practical information-theoretic approach. Springer-Verlag, New York.

Coutant, C. C. 1977. Compilation of temperature preference data. Journal of the Fisheries Research Board of Canada 34:739–745.

Coutant, C. C., and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. Transactions of the American Fisheries Society 129:351–380.

Cresswell, R. C. 1981. Post-stocking movements and recapture of hatchery-reared trout released into flowing waters – a review. Journal of Fish Biology 18:429–442.

Dalbey, S. R., and T. A. Humphrey. 2000. Statewide fisheries investigations. Hauser and Holter drainage fisheries management, 2000 Annual Report. Report on Projects F-78-R-6, F-113-R1. Montana Department of Fish, Wildlife and Parks, Fisheries Division, Helena.

Dalbey S. R. 2001. Statewide fisheries management. Hauser and Holter drainage fisheries management, 2001 Annual Report. Report on Projects F-113-R1, -R2, -R3. Montana Department of Fish, Wildlife and Parks, Fisheries Division, Helena.

Dalbey, S. R., and T. A. Humphrey. 2005. Statewide fisheries investigations. Hauser and Holter drainage fisheries management, Report for 2002 & 2003. Report on Projects F-113-R2, -R3, -R4. Montana Department of Fish, Wildlife and Parks, Fisheries Division, Helena.

Dalbey, S. R., and T. A. Humphrey. 2006. Statewide fisheries investigations. Hauser and Holter Reservoir drainage fisheries management, 2004 Report. Report on Projects

F-113-R2, -R3, -R4. Montana Department of Fish, Wildlife and Parks, Fisheries Division, Helena.

Davis, J. C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. Journal of the Fisheries Research Board of Canada 32:2295–2332.

Derr, J. A., H. E. Zich, R. F. Carline, and L. M. Young. 1993. Sampling protocol for estimating entrainment and turbine mortality of fish at hydropower sites. Technical Report 93-04. Statistical Consulting Center, Pennsylvania State University, University Park, Pennsylvania.

Donald, D. B. 1987. Assessment of the outcome of eight decades of trout stocking in the Mountain National Parks, Canada. North American Journal of Fisheries Management 7:545–553.

EPRI (Electric Power Research Institute). 1992. Fish entrainment and turbine mortality review and guidelines. EPRI TR-101231. Electric Power Research Institute, Palo Alto, California.

FERC (Federal Energy Regulatory Committee). 1995. Preliminary assessment of fish entrainment at hydropower projects. A report on studies and protective measures. FERC DPR-10. Federal Energy Regulatory Committee, Washington, D.C.

Guy, C. S., and M. L. Brown, editors. 2007. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Guy, C. S., R. M. Neumann, and D. W. Willis. 1992. Movement patterns of adult black crappie, *Pomoxis nigromaculatus*, in Brant Lake, South Dakota. Journal of Freshwater Ecology 7:137–147.

Hardiman, J. M., B. M. Johnson, and P. J. Martinez. 2004. Do predators influence the distribution of age-0 kokanee in a Colorado reservoir? Transactions of the American Fisheries Society 133:1366–1378.

Haro, A., T. Castro-Santos, J. Noreika, and M. Odeh. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Sciences 61:1590–1601.

Heidinger, R. C., B. L. Tetzlaff, W. T. Davin, Jr., T. Werenski, and B. Woolard. 1989. Movement of walleye in Illinois reservoirs. Final Report F-56-R. Fisheries Research Laboratory, Southern Illinois University, Carbondale, Illinois.

Helfrich, L. A., and W. T. Kendall. 1982. Movements of hatchery-reared rainbow, brook, and brown trout stocked in a Virginia mountain stream. Progressive Fish-Culturist 44:3–7.

Hill, W. J. 1973. Central Montana fisheries study. Fish management surveys. Report on Projects F-5-R-21, Job 1-b. Montana Department of Fish and Game, Helena.

Horn, M. J. 2004. Effects of releases from Canyon Ferry Dam on the limnology and fisheries of Hauser Reservoir, Montana. Technical Memorandum 8220-04-06. U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Hubert, W. A. 1996. Passive capture techniques. Pages 157–182 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Jeffrey, J. D., and D. R. Edds. 1992. Spring movements and spawning habitat of sauger (*Stizostedion canadense*) in a small Midwestern USA reservoir. Journal of Freshwater Ecology 14:385–397.

Johnson G. E., F. W. Olsen, and E. S. Kuehl. 1989. Fishery assessments at hydroelectric projects using electrofishing, nets, and hydroacoustics. Pages 796–805 *in* A. J. Eberhardt, editor. Waterpower ’89: Proceedings of the International Conference on Hydropower, Niagara Falls, New York.

Johnson, G. E., J. R. Skalski, and D. J. Degan. 1994. Statistical precision of hydroacoustic sampling of fish entrainment at hydroelectric facilities. North American Journal of Fisheries Management 14:323–333.

Johnson, R. L., and R. A. Moursund. 2000. Evaluation of juvenile salmon behaviour at Bonneville Dam, Columbia River, using multibeam techniques. Aquatic Living Resources 13:313–318.

Johnston, S. V., T. W. Steig, J. E. Ehrenberg, B. H. Ransom, P. A. Nealson, and T. C. Torkelson. 2005. Using hydroacoustics for fisheries assessment: a companion manual to the short course, version 2.2. Hydroacoustic Technology, Inc., Seattle, Washington.

Katopodis C. A., and R. Gervais. 1991. Ichthyomechanics. Freshwater Institute Central and Arctic Region. Department of Fisheries and Oceans, Winnipeg, Manitoba, Canada.

Kelso, J. R. M. 1978. Diel rhythm in activity of walleye, *Stizostedion vetreum*. Journal of Fish Biology 12:593–599.

Kutner, M. H., C. J. Nachtsheim, J. Neter, and W. Li. 2005. Applied linear statistical models, 5th edition. McGraw-Hill/Irwin, New York.

Love, R. H. 1977. Target strength of an individual fish at any aspect. Journal of the Acoustical Society of America 62:1397–1403.

Lucas, M. C., L. Walker, T. Mercer, and J. Kubecka. 2002. A review of fish behaviours likely to influence acoustic fish stock assessment in shallow temperate rivers and lakes. R&D Technical Report W2-063/TR/1. Environmental Agency, Bristol, United Kingdom.

Maiolie, M. A., and S. Elam. 1998. Kokanee entrainment losses at Dworshak Reservoir. Idaho Department of Fish and Game. Annual Progress Report to Bonneville Power Administration, Portland, Oregon.

McKinstry, C. A., M. A. Simmons, C. S. Simmons, and R. L. Johnson. 2005. Statistical assessment of fish behavior from split-beam hydro-acoustic sampling. Fisheries Research 72:29–44.

McLellan, H. J., S. G. Hayes, and A. T. Scholz. 2008. Effects of reservoir operations on hatchery coastal rainbow trout in Lake Roosevelt, Washington. North American Journal of Fisheries Management 28:1201–1213.

Michaud, D. T., and E. P. Taft. 2000. Recent evaluations of physical and behavioral barriers for reducing fish entrainment at hydroelectric plants in the upper Midwest. Environmental Science & Policy 3:S499–S512.

Navarro, J. E., and D. J. McCauley. 1996. Turbine passage at four low-head hydroelectric facilities in northeast Michigan. North American Journal of Fisheries Management 16:182–191.

Nelson, J. S., E. J. Crossman, H. Espinoza-Perez, L. T. Findley, C. R. Gilbert, R. N. Lea, and J. D. Williams. 2004. Common and scientific names of fishes from the United States, Canada, and Mexico. American Fisheries Society, Special Publication 29, Bethesda, Maryland.

Paller, M. H., D. E. Fletcher, M. M. Standora, T. B. Grabowski, T. A. Jones, S. A. Dyer, and J. J. Isely. 2006. Emigration of fish from two South Carolina cooling reservoirs. North American Journal of Fisheries Management 26:976–982.

Peterson, D. A. 1972. Barometric pressure and its effect on spawning activities of rainbow trout. Progressive Fish-Culturist 34:110–112.

Petr, T., V. P. Mitrofanov. 1998. The impact on fish stocks of river regulation in Central Asian and Kazakhstan. Lakes and Reservoirs Research and Management 3:143–164.

Ploskey, G. R., M. A. Weiland, C. R. Schilt, J. Kim, P. N. Johnson, M. E. Hanks, D. S. Patterson, J. R. Skalski, and J. Hedgepeth. 2005. Hydroacoustic evaluation of fish passage through Bonneville Dam in 2004. Report PNNL-15249. Pacific Northwest National Laboratory, Richland, Washington.

Ransom, B. H., and T. W. Steig. 1994. Using hydroacoustics to monitor fish at hydropower dams. Lake and Reservoir Management 9:163–169.

Rasmussen, P. W., D. M. Heisey, S. J. Gilbert, R.M . King, and S. W. Hewett. 2002. Estimating postspawning movement of walleyes among interconnected lakes of northern Wisconsin. Transactions of the American Fisheries Society 131:1020–1032.

Rhea, D. T., W. A. Hubert, R. S. Gangl, and R. A. Whaley. 2005. Temporal and spatial variation in relative abundance and length structure of salmonids in reservoirs: implications for monitoring. North American Journal of Fisheries Management 25:1301–1309.

Rose, K. A. 2000. Why are quantitative relationships between environmental quality and fish populations so elusive? Ecological Applications 10:367–385.

Shreffler, D. K., D. R. Geist, and W. V. Mavros. 1994. Qualitative assessment of the impacts of proposed system operating strategies to resident fish within selected Columbia River reservoirs. Prepared for the Bonneville Power Administration, Portland, Oregon. Pacific Northwest National Laboratory, Richland, Washington.

Simmonds, E. J., and D. N. MacLennan. 2005. Fisheries acoustics: theory and practice, 2nd edition. Blackwell Science Ltd., Oxford, United Kingdom.

Skaar, D., J. DeShazer, L. Garrow, T. Ostrowski, and B. Thomburg. 1996. Investigations of fish entrainment through Libby Dam, 1990–1994. Prepared for Bonneville Power Administration, Portland, Oregon. Montana Department of Fish, Wildlife and Parks, Helena.

Skaar, D., and T. Humphry. 1997. Statewide fisheries investigations. Survey and inventory of coldwater lakes. Part B: Flushing losses of hatchery rainbow trout from three mid-Missouri River reservoirs. Report on Projects F-46-R-5, Job II-f. Montana Department of Fish, Wildlife and Parks, Fisheries Division, Helena.

Skalski, J. R. 2007. Statistical analysis plan for the Boundary Dam hydroacoustic and fyke-net investigations, *draft*. School of Aquatic and Fishery Sciences, University of Washington, Seattle.

Sorenson, K. M., W. L. Fisher, and A. V. Zale. 1998. Turbine passage of juvenile and adult fish at a warmwater hydroelectric facility in northeastern Oklahoma: monitoring associated with relicensing. North American Journal of Fisheries Management 18:124–136.

Stark, E. J., and M. A. Maiolie. 2004. Dworshak Reservoir strobe light testing and entrainment monitoring. 2002 Annual Report. Idaho Department of Fish and Game Report 04-23. Prepared for Bonneville Power Administration, Portland, Oregon.

Stables, T. B., and G. L. Thomas. 1992. Acoustic measurement of trout distributions in Spada Lake, Washington, using stationary transducers. Journal of Fish Biology 40:191–203.

Stieg, T. W., and T. K. Iverson. 1998. Acoustic monitoring of salmonid density, target strength, and trajectory at two dams on the Columbia River, using a split-beam scanning system. Fisheries Research 35:43–53.

Stober, Q. J., R. W. Tyler, and C. E. Petrosky. 1983. Barrier net to reduce entrainment losses of adult kokanee from Banks Lake, Washington. North American Journal of Fisheries Management 3:331–354.

Thurrien, J., and G. Bourgeois. 2000. Fish passage at small hydro sites. Genivar Consulting Group for CANMET Energy Technology Centre, Ottawa, Ontario, Canada.

Venditti, D. A., D. W. Rondorf, and J. M. Kraut. 2000. Migratory behavior and forebay delay of radio-tagged juvenile fall Chinook salmon in a Lower Snake River impoundment. North American Journal of Fisheries Management 20:41–52.

Walburg, C. H. 1977. Loss of young fish in reservoir discharge and year-class survival, Lewis and Clark Lake, Missouri River. American Fisheries Society Special Publication 8:441–448.

Weaver, M. J., J. J. Magnuson, and M. K. Clayton. 1993. Analyses for differentiating littoral fish assemblages with catch data from multiple sampling gears. Transactions of the American Fisheries Society 122:1111–1119.

Willis, D. W., and J. L. Stephen. 1987. Relationships between storage ratio and population density, natural recruitment, and stocking success of walleye in Kansas reservoirs. North American Journal of Fisheries Management 7:279–282.

APPENDICES

APPENDIX A

CALCULATIONS FOR HOURLY ENTRAINMENT ESTIMATES

I estimated hourly turbine and spillway entrainment every two days for 30-mm size classes (Skalski 2007). Model 241 echosounders are not capable of operating two transducers concurrently. Each hydroacoustic system monitored entrainment with two transducers in alternating five-minute sequences for a total of 30 minutes per transducer per hour (Table 2). Calculations were made assuming sequences were sampled randomly.

Forebay Entrainment

Entrainment through unit-6 was calculated as

$$\hat{U}6_{jkn} = \left[\frac{A}{a} \sum_{i=1}^{a} WF_{ijkn} \right],$$

where

WF = the extrapolated count of each detected fish
$U6$ = the entrainment in turbine unit-6
i = the 5-min sequence within each hour
j = the hour when entrainment occurred
k = 2-day sample
n = the 30-mm size class
A = the possible number of five minute sequences per hour (A = 12)
a = the actual number of five minute sequences sampled per hour (a = 6),

and variance as

$$\hat{Var}\left(\hat{U}6_{jkn}\right) = \left[\frac{A^2\left(1 - \frac{a}{A}\right) s^2 WF_{jkn}}{a} \right].$$

Entrainment through unit-3 was calculated as

$$\hat{U}3_{jkn} = \left[\frac{A}{a} \sum_{i=1}^{a} WF_{ijkn} \right],$$

where

U3 = the entrainment in turbine unit 3,

and variance as

$$\hat{Var}\left(\hat{U}3_{jkn}\right) = \left[\frac{A^2\left(1 - \frac{a}{A}\right) s^2 WF_{jkn}}{a} \right].$$

Standard deviations for both turbine units were calculated as

$$s^2 WF_{jkn} = \frac{\sum_{i=1}^{a} \left(WF_{ijkn} - \overline{WF}_{jkn}\right)^2}{(a-1)},$$

where

$$\overline{WF}_{jkn} = \frac{\sum_{i=1}^{a} WF_{ijkn}}{a}.$$

Spillway Entrainment

Entrainment through the hydraulic spillbays was calculated as

$$\hat{SH}_{jkn} = \left[\frac{A}{a} \sum_{i=1}^{a} WF_{ijkn} \right],$$

where

SH = the entrainment in hydraulic spill,

and variance as

$$\hat{V}ar\left(\hat{S}H_{jkn}\right)=\left[\frac{A^{2}\left(1-\frac{a}{A}\right)s^{2}WF_{jkn}}{a}\right].$$

Entrainment through surface spillbays was calculated as

$$\hat{S}S_{jkn}=\left[\frac{A}{a}\sum_{i=1}^{a}WF_{ijkn}\right],$$

where

SS = the entrainment in surface spill,

and variance as

$$\hat{V}ar\left(\hat{S}S_{jkn}\right)=\left[\frac{A^{2}\left(1-\frac{a}{A}\right)s^{2}WF_{jkn}}{a}\right].$$

Standard deviation for spillway entrainment was calculated as

$$s^{2}WF_{jkn}=\frac{\sum_{i=1}^{b}\left(WF_{ijkn}-\overline{WF}_{jkn}\right)}{\left(a-1\right)},$$

where

$$\overline{WF}_{jkn}=\frac{\sum_{i=1}^{b}WF_{ijkn}}{a}.$$

APPENDIX B

PREDICTOR VARIABLES FOR MODEL SELECTION

Descriptive statistics of conditions influencing entrainment of fish during spill and when no spill occurred.

		2007					2008				
Variable	Abbreviation	N	Mean	SD	Minimum	Maximum	N	Mean	SD	Minimum	Maximum
Entrainment During Spill											
Mean weekly spillway discharge (m^3/s)	SpillD						9	1738.1	995.3	170.4	2964.2
Mean weekly turbine discharge (m^3/s)	TurbD						9	1302.5	15.5	1280.2	1328.3
Mean weekly photoperiod (min)	DayL						9	937.3	11.7	918.1	950.0
Mean minimum barometric pressure (mm Hg)	minBP						9	657.4	2.8	653.0	661.7
Mean maximum barometric pressure (mm Hg)	maxBP						9	663.7	2.2	660.7	666.7
Entrainment When No Spill Occurred											
Mean weekly spillway discharge (m^3/s)	SpillD	19	0.5	2.2	0.0	9.5	17	2.1	6.9	0.0	28.5
Mean weekly turbine discharge (m^3/s)	TurbD	19	1054.6	89.8	894.0	1209.1	17	1262.0	55.8	1151.1	1337.8
Temperature above the turbine intakes (°C)	TempAb	16	15.5	3.7	8.9	23.5	10	14.5	3.9	8.1	18.8
Dissolved oxygen below the turbine intakes (mg/L)	DObel	16	5.6	1.9	3.2	9.5	10	6.5	1.9	3.7	9.2
Mean reservoir water column temperature (°C)	mTemp	16	13.5	1.9	8.9	15.4	10	12.8	2.7	7.6	15.0
Mean reservoir water column dissolved oxygen (mg/L)	mDO	16	6.7	1.5	4.5	9.7	10	7.7	1.8	5.3	11.0
Thermocline depth (m)	ThermD	16	1.7	2.8	0.0	9.0	10	2.3	2.7	0.0	7.1
Mean weekly daylength (min)	DayL	19	769.2	123.5	572.7	942.6	17	740.5	110.6	568.1	908.6
Mean minimum barometric pressure (mm Hg)	minBP	19	657.5	3.2	651.8	662.9	17	657.9	3.6	651.8	663.4
Mean maximum barometric pressure (mm Hg)	maxBP	19	664.8	3.1	660.4	670.3	17	666.2	3.4	659.1	674.6

APPENDIX C

LITERATURE REVIEW OF ENTRAINMENT PROTECTION TECHNOLOGIES

INTRODUCTION

Many North American reservoirs are inhabited by fish populations that are affected by entrainment through hydroelectric facilities. Loss of fish by entrainment may hinder management to provide a successful fishery to anglers and maintain reproductive populations. Entrainment protection technologies that have been developed and implemented to reduce entrainment include physical screening (Stober et al. 1983; Michaud and Taft 2000) and behavioral stimuli such as strobe lighting (Nemeth and Anderson 1992; Ploskey and Johnson 2001; Johnson et al. 2005), electricity (Hyman et al. 1975; Kynard and O’Leary 1993), sound (Popper and Carlson 1998; Sand et al. 2001), and bubble curtains (Patrick and Christie 1985; Sager et al. 2000). Physical screening is effective at protecting fish from being entrained, but maintenance can be costly depending on the debris loading and biological growth that can accumulate on and damage screens (Stober et al. 1983; Michaud and Taft 2000). Behavioral technologies work inconsistently to redistribute fish at hydroelectric facilities and are considered experimental (Popper and Carlson 1998; Coutant 2001). However, several field tests of various technologies have been effective at reducing entrainment (Hyman et al. 1975; Stark and Maiolie 2004; Sonny et al. 2006).

PHYSICAL PROTECTION

Physical protection structures are the most common method for excluding fish and other organisms from entering water intakes and are present at almost all facilities (FERC 1995). Laboratory and field evaluations of physical barriers have been summarized by a number of authors (AIC 2005; FERC 1995; Taft 2000; Whitney et al. 1997). Types of physical barriers exist for different life-stages of fish and water conditions include low-velocity fish screens, high-velocity fish screens, louvers and angled bar racks, and barrier nets.

Low-velocity fish screens

Low velocity fish screens are installed in areas where water velocities are relatively low to reduce impingement and injury by diverting fish into downstream bypasses (FERC 1995) or cooling intakes (Taft 2000). They are usually directed towards the protection of icthyoplankton and juvenile fish. Screen mesh size is usually small (< 12 mm; AIC 2005). Types of low-velocity screens used at hydroelectric facilities are fine-mesh traveling screens and wedge-wire screens equipped with a debris removal apparatus such as traveling brushes, high-pressure backwash, or air-burst systems (FERC 1995). Mortality and injury of juvenile salmonids at low-velocity screens ranges from 1% to 32%; such screens are up to 90% effective at diverting fish into bypasses (FERC 1995).

Traveling screens have been developed at many facilities to carry impinged organisms to the surface where they are spray-washed into a collection system and safely released (Taft 2000). Traveling screens are only effective for protecting fish from entrainment when they are used in concert with other physical barriers (Taft 2000). Fine mesh traveling screens capture fish eggs and larvae in 0.5 to 1.0 mm mesh (Taft 2000). Taft (2000) concluded that survival in such screens is largely species and life-stage specific. These screens have proven reliable and do not experience unusual clogging or cleaning problems at cool water intake structures.

Wedge-wire screens have small screen slot sizes (larger than fine-mesh screens), low water velocities at their slot openings, and are designed to function passively where water currents are moving perpendicularly to the face of the screens (Taft 2000). A forebay wedge-wire screen tested at Priest Rapids Dam in 1989 reduced the number of juvenile salmonids in the test gatewell to 10% of adjacent gatewells, but was abandoned after the frame proved too difficult to maneuver and periphyton accumulation led to unacceptable head loss (Ransom and Malone 1990, cited by Whitney et al. 1997). Two full scale installations of wedge-wire screens at cooling water intake structures with 6.4 and 10.0 mm slot openings have been effective, though clogging by debris and biological growth is a concern (Taft 2000).

High-Velocity Fish Screens

High-velocity fish screens are used where approach velocities exceed capabilities of low-velocity screens (FERC 1995). These screens have typically been used to divert downstream migrating salmonids into bypasses and collection devices and reduce mortality in turbines. Eicher screens are designed for penstocks where intake velocities exceed 0.7 m/s and can be tilted to flush debris (FERC 1995). An Eicher screen in a 3-m diameter penstock at the Elwha Hydroelectric Project in Washington was effective at diverting more than 98% of steelhead *Oncorhynchus mykiss*, coho *O. kisutch*, and Chinook *O. tshawytscha* salmon smolts at velocities from 0.4 to 0.7 m/s (EPRI 1992). Survival of salmon smolts exceeded 99% in penstock water velocities as high as 1.8 m/s at the Puntledge Project in British Columbia, Canada (Smith 1997, cited by Taft 2000).

Modular inclined screens (MIS) are a recent design used in water intakes with low or high approach velocities (FERC 1995; Taft 2000). They were effective at reducing mortality of juvenile channel catfish *Ictalurus puctatus*, brown trout *Salmo trutta*, coho salmon, chinook salmon, and Atlantic salmon *Salmo salar* smolts to less than 1% at water velocities ranging from 0.61 to 3.0 m/s (Taft 2000). However, they were not as effective for American shad *Alosa sapidissima* and blueback herring *A. aestivalis* at water velocities over 1.8 m/s. They have not been installed at any hydroelectric facilities (AIC 2005; Taft 2000).

Louvers and Angle Bar Racks

Louver and angle bar rack protection systems consist of an array of evenly spaced, vertical slats aligned across a channel at an angle leading towards a bypass (Taft 2000). They create a turbulence zone in front of the panels that fish avoid. Louvers to divert juvenile fish have been successfully applied under carefully controlled flow conditions at pump intakes and irrigation diversions (Whitney et al. 1997). Louvers are commonly 80% to 95% effective at diverting fish away from irrigation diversion intakes under a wide variety of conditions (Taft 2000). Effectiveness of trash racks modified with louvers at a hydroelectric facility at Sullivan Dam on the Willamette River varied from 40% to 80% (Stone and Webster 1986, cited by Whitney et al. 1997).

Barrier Nets

Barrier nets for entrainment reduction and guiding fish into bypasses have had variable success. Barrier nets at Brownlee and Wanapum dams on the Columbia River were ineffective at guiding fish for downstream passage because fish swam through and around the nets (Whitney et al. 1997). However, a barrier net in Banks Lake, Washington, reduced entrainment of adult kokanee; it successfully retained 96% of the population and reduced entrainment of adult yellow perch *Perca flavescens*, longnose sucker *Catostomus catostomus*, lake whitefish *Coregonus clupeaformis*, and other species (Stober et al. 1983). Exclusion efficiency increased when the net was anchored tangentially to the shoreline, leadline anchors were moved upstream on longer leads, and a skirt of netting was added to the bottom of the net (Stober et al. 1983). A 4.02-km long net barrier installed at a pumped storage plant on Lake Michigan in 1989 reduced entrainment of five salmon species *Oncorhynchus* spp., yellow perch, rainbow smelt *Osmerus mordax*, alewife *Alosa pseudoharengus*, and bloater *Coregonus hoyii* by 80% to 96% (Reider et al. 1997, cited by Taft 2000).

The success of barrier nets is often complicated by water currents, debris, and biological loading. Net testing at Wanapum dam was discontinued because the net was inefficient, was difficult to anchor, and required frequent cleaning (Whitney et al. 1997).

Barrier nets are viable options for reducing entrainment at cooling water intake structures when debris, biological loading, and water velocities are low (< 0.3 m/s) (Taft 2000). For example, a net installed in front of traveling screens at a power station on the Patuxent River successfully reduced excess seasonal impingement; fouling was controlled by regularly changing net panels (Loos 1986, cited by Taft 2000). Loading on the barrier net in Banks Lake, Washington, was successfully cleaned every 3 weeks from July to September by spray-washing the net as it was drawn over a floating barge, though the net submerged when periphyton growth in summer increased drag on it (Stober et al. 1983). Microbial action can also be used if nets are stored on the bottom of the reservoir (Michaud and Taft 2000).

BEHAVIORAL PROTECTION

Behavioral technologies have been developed to emit audible, acoustic, and visual stimuli that act to attract or deter fish from certain areas. Several of these technologies have been installed and tested at hydroelectric facilities to prevent fish from being entrained or to guide them towards downstream passage structures. No single technology is a “silver bullet” to prevent entrainment of fish. Some of the inconsistencies with behavioral technologies are species and sight specific (Popper and Carlson 1998; Coutant 2001). Primary behavioral technologies are electrical barriers, air bubble curtains, strobe lighting, and acoustic barriers.

Electrical Barriers

Electrical barriers have been used to affect the distributions of fish in laboratory (Stewart 1981) and field settings (Palmisano 1988). Atlantic salmon smolts and dabs *Limanda limanda* repeatedly avoided an electrical barrier (Stewart 1981). Adult salmon were successfully diverted to a trap by creating an electrical barrier across a river (Palmisano 1988). Electrical barriers have been used successfully to prevent migration of a variety of species through irrigation canals (Clarkson 2004), weirs (Maceina et al. 1999; Verrill et al. 1995), and small streams (Savino et al. 2001; Swink 1999) but have been used with limited success to prevent impingment and entrainment (Hyman et al. 1975; Kynard and Oleary 1993). Electrical barriers were somewhat effective for guiding American shad to bypasses but not for excluding fish from entering the turbine intakes at the Holyoke Dam on the Connecticut River (Kynard and O’Leary 1993). Installation of an electrical barrier inside intakes of a nuclear power plant on the Connecticut River reduced some species by 20%; a barrier upstream of the intakes was more effective than intake barriers at excluding small fish (< 150 mm), but the results were inconsistent for most species (Hyman et al. 1975). In both studies, fish encountering electric barriers were immobilized and drifted downstream (Hyman et al. 1975; Kynard and O'Leary 1993).

Electrical fields do not appear to be a viable option for preventing downstream entrainment at hydroelectric facilities. Fish are not able to detect and avoid the electric fields before entering them. Sensitivities of fish to electrical fields are highly variable and more sensitive species may be immobilized. Immobilized fish may then be drawn further into the area of concern where they may be killed or passively entrained. Electric barriers are more effective in shallow canals to prevent upstream movement.

Air Bubble Curtains

The use of air bubble curtains has not been widely reported. They have been tested, but not applied, in field settings (Popper and Carlson 1998). Atlantic salmon smolts and dabs in the laboratory and sea-cages passed through air bubble curtains when trials exceeded 20 minutes (Stewart 1981). Gizzard shad, alewife, and rainbow smelt avoided an air bubble curtain in the laboratory, but the curtain was more effective when used with strobe lighting (Patrick and Christies 1985). White perch *Morone americana*, spot *Leiostomus xanthurus*, and menhaden *Brevoortia tyrannus* showed little avoidance of air bubbles until strobe lights were applied (Sager et al. 2000). The utility of air bubble curtains for protecting fish from entrainment at Hauser Dam is unknown because the technology has not been adequately tested in the field. However, air bubbles may be a useful and relatively cheap addition to other behavioral technologies such as strobe lights.

Strobe Lights

Strobe lights have been successfully used to influence the behavior of fish in laboratory (Nemeth and Anderson 1992; Ploskey and Johnson 2001) and field (Stark and Maiolie 2004; Johnson et al. 2005; McKinstry et al. 2005; Hamel et al. 2008) applications. Forty-five to ninety percent of test coho and Chinook salmon remained at least 6.5 m away from strobe lights (Nemeth and Anderson 1992). Similarly, Chinook salmon, smallmouth bass, and northern pikeminnow avoided strobe lighting under laboratory conditions (Amaral et al. 2001). Field applications of strobe lights have showed similar results. Strobe lights redistributed fish at the Hiram M. Chittenden Locks Project in Seattle, Washington, and reduced entrainment by 75% (Johnson et al. 2005). Kokanee and rainbow trout avoided the lighted area within 10 m of active strobe lights (McKinstry et al. 2005). Strobe lights significantly reduced densities of fish by 72% to 100% ($P < 0.0001$) at night in Spirit Lake and Lake Pend Oreille, Idaho, and fish remained 30 m to 136 m away from the lights (Maiolie et al. 2001). When the same system was used at Dworshak Dam, Idaho, the density of fish near the strobe lights declined from 253 fish/hectare to 83 fish/hectare and mean distance from the lights increased from 8.7 m to 31.2 m (Stark and Maiolie 2004). Rainbow smelt *Osmerus* *mordax* repeatedly avoided strobe lights of variable intensities during all tests (nighttime only) at Lake Oahe Dam, South Dakota, from June through October remaining 6 m to 21 m from the lights (Hamel et al. 2008). Habituation did not appear to occur for rainbow smelt tested for 4 hours (Hamel et al. 2008) and kokanee tested for 6 hours (Maiolie et al. 2001).

Strobe light effectiveness appears to be governed by the species and site specific factors, which may override the tendency of some species to avoid lights. Northern pikeminnow responded to light stimulus less than both Chinook salmon and smallmouth bass, and all species were more sensitive at night (Amaral et al. 2001). Amaral et al. (2001) concluded that ambient light during the daytime reduced the effectiveness of the strobe lights because turbidity remained similar for all trials during the study. Strobe lighting at Grand Coulee Dam had little effect on the distribution of fish during the daytime; ambient light and higher discharges may have overridden their tendency to avoid intense light (McKinstry et al. 2005). Turbidity can affect the ability of strobe lights to alter the distributions of fish in an area. The distance that kokanee moved away from strobe lights in Spirit Lake and Lake Pend Oreille was positively correlated with the transparency of the water ($r^2 = 0.69$, $N = 6$) and varied from 2.8 m to 17.5 m (Maiolie et al. 2001). Strobe lights appear to be a viable option for protecting fish from being entrained at hydroelectric facilities. However, they may not be effective during the daytime or in turbid water.

Acoustic Barriers

Most studies employing sound to affect fish behavior were unsuccessful largely because many species are not sensitive to sound (Popper and Carlson 1998). High-frequency ultrasound has been inconsistent when used to guide many species in field tests (e.g. rainbow trout, walleye, and yellow perch), though variable avoidance was observed in cage experiments (EPRI 1998). However, applications of high-frequency ultrasound have successfully reduced entrainment of blueback herring (Nestler et al. 1992) and alewives (Dunning et al. 1992; Ross et al. 1993, 1996). Application of 80–150 kHz sound elicited statistically significant avoidance responses by blueback herring in cage studies at the Richard B. Russell Dam on the Savannah River and successfully repelled fish away from the dam at night in field evaluations (Nestler et al. 1992). Alewives exposed to a variety of frequencies in cage experiments exhibited consistent avoidance responses to frequencies ranging from 110–150 kHz, but some fish appeared to acclimate to the sound stimulus after being repeatedly exposed to it (Dunning et al. 1992). An ultrasound system emitting 190 dB in a frequency band from 122–128 kHz successfully reduced entrainment of spawning alewives on average 85% at the James A. FitzPatrick Nuclear Power Plant on Lake Ontario near Oswego, New York; some fish either avoided the system or were in poor condition and unable to avoid the stimulus and were impinged (Ross et al. 1993). The system was modified to improve coverage of the acoustic barrier and entrainment was reduced 84% under all conditions (Ross et al. 1996). However, some fish were nevertheless impinged confirming suspicions that poor condition was affecting the ability of some fish to avoid the intakes (Ross et al. 1996).

Application of low-frequency infrasound to repel fish may be more effective than ultrasound because fish detect it as kinetic energy similar to that made by predators (Sand et al. 2001). Laboratory testing elicited repeated avoidance responses by juvenile Atlantic salmon at frequencies from 5–10 Hz (Knudsen et al. 1992, 1994) and by Chinook salmon and rainbow trout at 10 Hz (Knudsen et al. 1997). Pacific salmonids encountering the barrier repeatedly continued to avoid it indicating that a barrier would be effective when encountered more than once (Knudsen et al. 1997). Atlantic salmon smolts avoided a 1.5 m inlet in the laboratory when 10 Hz infrasound was used, but not 150 Hz (Sand et al. 2001). However, infrasound was less successful in laboratory experiments on juvenile Chinook and coho salmon at frequencies from at 10–35 Hz (Ploskey and Johnson 2001). Ploskey and Johnson (2001) speculated that poor harmonics minimized startle responses of fish more than 3.5 m from the device. Infrasound elicited weak responses by juvenile Chinook salmon, brook trout, and rainbow trout exposed to 10–14 Hz for 5 to 15 seconds and fish appeared to acclimate to the sound (Mueller et al. 2001). Chinook salmon did not respond to frequencies ≤ 60 Hz, but northern pikeminnow avoided all frequencies except 20 Hz in cage tests at Roza Dam on the Yakima River, Washington (Amaral et al. 2001). An array of more than 20 sound projectors creating frequencies from 60–600 Hz was successful at reducing entrainment of over 24 families of estuarine fish by 59.6% in five cooling water intakes drawing about 25.1 m^3/s (Maes et al. 2004). Cyprinids stayed up to 10 m away from an infrasound projector in Lake Borrevann, Norway, reducing entrainment at two 5.2 m tall by 6 m long intakes with water velocities of 0.17–0.28 m/s by more than 80% (Sonny et al. 2006).

Habituation was not observed in either brief, acute exposures or prolonged exposures at night.

Acoustic barriers may be an effective means to prevent entrainment of fish at Hauser Dam. Infrasound appears to be more promising than ultrasound because it relies on the ability of a fish to feel rather than hear the stimulus. However, the sensitivity of fish to sound stimuli is variable and habituation has been observed in experimental settings.

CONCLUSION

Effective fish protection at Hauser Dam will likely require the integration of multiple behavioral technologies. Concurrent multiple stimuli can provide adequate protection across a range of environmental variables (Popper and Carlson 1998). Though experimental, both strobe lighting and infrasound have been effective at reducing entrainment of a variety of species at hydroelectric facilities. Strobe lighting was especially effective for salmonids, but the light stimulus may not be as effective during the daytime or when the water is turbid. Infrasound has also been effective for multiple species, but each species responds to different frequencies of sound and habituation to the stimulus has been observed.

Behavioral technologies are still considered experimental and their effectiveness often relies on site-specific conditions. Thus, investigation of the effectiveness of strobe lighting, infrasound, or a combination of both is necessary before proceeding with full scale deployment. Deployment of behavioral technologies from the existing forebay net structure in autumn may be the most cost effective strategy for reducing entrainment at Hauser Dam. The existing forebay structure could be used for deployment with little additional modification and the small cross-sectional area of the forebay entrance can be easily covered. Autumn deployment may be more cost effective than year-round operation because entrainment in general is high in autumn and most hatchery rainbow trout are entrained then also.

REFERENCES CITED

AIC (Acres International Corporation). 2005. Fish entrainment and mortality study: volume 1. Report FERC No. 2216. Prepared for the New York Power Authority, New York.

Amaral, S. V., F. C. Winchell, and T. N. Pearsons. 2001. Reaction of Chinook salmon, northern pikeminnow, and smallmouth bass to behavioral guidance stimuli. American Fisheries Society Symposium 26:125–144.

Clarkson, R. W. 2004. Effectiveness of electrical fish barriers associated with the central Arizona project. North American Journal of Fisheries Mangement 24:94–105.

Dunning, D. J., and Q. E. Ross. 1992. Alewives avoid high-frequency sound. North American Journal of Fisheries Management 12:407–416.

EPRI (Electric Power Research Institute). 1992. Fish entrainment and turbine mortality review and guidelines. EPRI TR-101231. Electric Power Research Institute, Palo Alto, California.

EPRI (Electric Power Research Institute). 1998. Review of downstream fish passage and protection technology evaluations and effectiveness. TR-109483. Electric Power Research Institute, Palo Alto, California.

FERC (Federal Energy Regulatory Committee). 1995. Preliminary assessment of fish entrainment at hydropower projects. A report on studies and protective measures. FERC DPR-10. Federal Energy Regulatory Committee, Washington, D.C.

Hamel, M. J., M. L. Brown, and S. R. Chipps. 2008. Behavioral responses of rainbow smelt to in situ strobe lights. North American Journal of Fisheries Management 28:394–401.

Hyman, M. A. M., W. H. Mowbray, and S. B. Saila. 1975. The effects of two electrical barriers on the entrainment of fish at a freshwater nuclear power plant. Pages 205–237 *in* S. B. Saila, editor. Fisheries and energy production: a symposium. Lexington Books, Lexington, Massachusetts.

Johnson, P. N., K. Bouchard, and F. A. Goetz. 2005. Effectiveness of strobe lights for reducing juvenile salmonid entrainment into a navigation lock. North American Journal of Fisheries Management 25:491–501.

Knudsen. F. R., P. S. Enger, and O. Sand. 1994. Avoidance responses to low frequency sound in downstream migrating Atlantic salmon smolt, *Salmo salar*. Journal of Fish Biology 45:227–233.

Knudsen, F. R., P. S. Enger, and O. Sand. 1992. Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. Journal of Fish Biology 40:523–534.

Knudsen, F. R., C. B. Schreck, S. M. Knapp, P. S. Enger, and O. Sand. 1997. Infrasound produces flight and avoidance responses in Pacific juvenile salmonids. Journal of Fish Biology 51:824–829.

Kynard, B., and J. O'Leary. 1993. Evaluation of a bypass system for spent American shad at Holyoke Dam, Massachusetts. North American Journal of Fisheries Management 13:782–789.

Loos, J. L. 1986. Evaluation of benefits to PEPCO of improvements in the barrier net and intake screens at Chalk Point Station between 1984 and 1985. Prepared for Environmental Affairs Group, Water and Land Use Department, Potomac Electric Power Company, Washington, D.C.

Maceina, M. J., J. W. Slipke, and J. M. Grizzle. 1999. Effectiveness of three barrier types for confining grass carp in embayments of Lake Seminole, Georgia. North American Journal of Fisheries Management 19:968–976.

Maiolie, M. A., B. Harryman, and B. Ament. 2001. Response of free-ranging kokanee to strobe lights. American Fisheries Society Symposium 26:27–35.

Maes, J., A. W. H. Turnpenny, D. R. Lambert, J. R. Nedwell, A. Parmentier, and F. Ollevier. 2004. Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. Journal of Fish Biology 64:938–946.

McKinstry , C. A., M. A. Simmons, C. S. Stevens, and R. L. Johnson. 2005. Statistical assessment of fish behavior from split-beam hydro-acoustic sampling. Fisheries Research 72:29–44.

Meuller, R. P., D. A. Neitzel, and B. G. Amidan. 2001. Evaluation of infrasound and strobe lights for eliciting avoidance behavior in juvenile salmon and char. American Fisheries Society Symposium 26:79–89.

Michaud, D. T., and E. P. Taft. 2000. Recent evaluations of physical and behavioral barriers for reducing fish entrainment at hydroelectric plants in the upper Midwest. Environmental Science & Policy 3:S499–S512.

Nemeth, R. S., and J. J. Anderson. 1992. Response of juvenile coho and Chinook salmon to strobe and mercury lights. North American Journal of Fisheries Management 12:684–692.

Nestler, J. M., G. R. Ploskey, and J. Pickens. 1992. Responses of blueback herring to high-frequency sound and implications for reducing entrainment at hydropower dams. North American Journal of Fisheries Management 12:667–683.

Palmisano, A. N., and C. V. Burger. 1988. Use of a portable electric barrier to estimate chinook salmon escapement in a turbid Alaskan river. North American Journal of Fisheries Management 8:475–480.

Patrick, P. H., and A. E. Christie. 1985. Responses of fish to a strobe light/air-bubble barrier. Fisheries Research 3:157–172.

Ploskey, G. R., and P. N. Johnson. 2001. Effectiveness of strobe lights and an infrasound device for eliciting avoidance by juvenile salmon. American Fisheries Society Symposium 26:37–56.

Popper, A. N., and T. J. Carlson. 1998. Application of sound and other stimuli to control fish behavior. Transactions of the American Fisheries Society 127:673–707.

Ransom, B.H., and K.M. Malone. 1990. Hydroacoustic evaluation of the sluiceway at Wanapum Dam in passing juvenile salmon and steelhead trout during spring 1990. Hydroacoustic Technology, Inc., Report to Grant County Public Utility District No. 2, Ephrata, Washington.

Reider, R. H., D. D. Johnson, P. Latvaitis, J. A. Gulvas, E. R. Guilfoos. 1997. Operation and maintenance of the Ludington Pumped Storage Project barrier net. Fish Passage Workshop sponsored by Alden Research Laboratory, Conte Anadromous Fish Research Laboratory, Electric Power Research Institute, and Wisconsin Electric Power Company, Milwaukee, Wisconsin.

Ross, Q. E., and D. J. Dunning. 1993. Response of alewives to high-frequency sound at a power plant intake on Lake Ontario. North American Journal of Fisheries Management 13:291–303.

Ross, Q. E., and D. J. Dunning. 1996. Reducing impingement of alewives with high-frequency sound at a power plant intake on Lake Ontario. North American Journal of Fisheries Management 16:548–559.

Sager, D. R., C. H. Hocutt, and J. R. Stauffer Jr. 2000. Avoidance behavior of *Morone americana*, *Leiostomus xanthurus* and *Brevoortia tyrannus* to strobe light as a method of impingement mitigation. Environmental Science & Policy 3:S393–S403.

Sand, O., P. S. Enger, H. E. Karlsen, and F. R. Knudsen. 2001. Detection of infrasound in fish and behavioral responses to intense infrasound in juvenile salmonids and European silver eels: a minireview. American Fisheries Society Symposium 26:186–193.

Savino, J. F., D. J. Jude, and M. J. Kostich. 2001. Use of electrical barriers to deter movement of round goby. American Fisheries Symposium 26:171–182.

Smith, L. W., and D. J. Ferguson. 1979. Cleaning and clogging tests of passive intake screens in the Sacramento River, California. Proceedings of the Passive Intake Screen Workshop, Chicago, Illinois.

Sonny, D., F. R. Knudsen, P. S. Enger, T. Kvernstuen, and O. Sand. 2006. Reactions of cyprinids to infrasound in a lake and at the cooling water inlet of a nuclear power plant. Journal of Fish Biology 69:735–748.

Stark, E. J., and M. A. Maiolie. 2004. Dworshak Reservoir strobe light testing and entrainment monitoring. Idaho Department of Fish and Game Report 04-23. Prepared for Bonneville Power Administration, Portland, Oregon.

Stewart, P. A. M. 1981. An investigation into the reactions of fish to electrified barriers and bubble curtains. Fisheries Research 1:3–22.

Stober, Q. J., R. W. Tyler, and C. E. Petrosky. 1983. Barrier net to reduce entrainment losses of adult kokanee from Banks Lake, Washington. North American Journal of Fisheries Management 3:331–354.

Stone and Webster Engineering Corporation. 1986. Assessment of downstream migrant fish protection technologies for hydroelectric application. Report AP-4711. Prepared for Electric Power Research Institute, Palo Alto, California.

Swink, W. D. 1999. Effectiveness of an electrical barrier in blocking a sea lamprey migration on the Jordan River, Michigan. North American Journal of Fisheries Management 19:397–405.

Taft, E. P. 2000. Fish protection technologies: a status report. Environmental Science & Policy 3:S349–S359.

Verrill, D. D., and C. R. Berry, Jr. 1995. Effectiveness of an electrical barrier and lake drawdown for reducing common carp and bigmouth buffalo abundances. North American Journal of Fisheries Management 15:137–141.

Whitney, R. R., L. D. Calvin, M. W. Erho, Jr., and C. C. Coutant. 1997. Downstream passage for salmon at hydroelectric projects in the Columbia River Basin: Development, installation, and evaluation. Report No. 97-15. Prepared for the Northwest Power Planning Council, Portland, Oregon.