Evaluation of Juvenile Salmonid Gatewell Egress Using Updated Orifice Lighting Treatments at McNary Dam, 2010

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EXECUTIVE SUMMARY

Artificial lighting is currently being used in varying applications and intensities for illumination of gatewell exits at U.S. Army Corps of Engineers hydroelectric projects to decrease delays for bypassed fish on the Snake and Columbia Rivers. While previous studies have shown a variable response to light across salmonid species, the literature suggests that improvements can often be made in fish passage if light intensity, wavelength, and/or directionality are optimized.

In 2010, Pacific Northwest National Laboratory (PNNL) designed a light ring system for illuminating the orifice entrance in a gatewell. Staff from the Pasco Research Station of the National Marine Fisheries Service, NOAA, collaborated with PNNL on the design, fabrication, and installation of a track system for the light. The track system was used to lower, retrieve, and position the light ring over the orifice entrance. The light ring was deployed and tested on an existing 30.5-cm orifice in gatewell 6B (south orifice) at McNary Dam during 2010.

We evaluated three levels of light intensity (50 lux, 300 lux, and reference (light off, with <1 lux) to determine whether there was a difference in gatewell egress associated with each treatment. The light ring directed most of the light inward and produced a glow that projected outward into the gatewell. Intensity could be adjusted by an external control module. Prior to each test, a light meter was used to measure illuminance and adjust output to meet the designated treatment schedule. Changing turbidity levels required adjustment of light output to meet the required treatment conditions.

Using a hose, we released groups of PIT-tagged fish behind the trash rack for entrainment into the gatewell of turbine unit 6B. During each light treatment, tagged fish moved volitionally out of the gatewell, passing through the orifice and into a flume, where two in-line PIT-tag detectors recorded their passage. We released fish for one light treatment per day, during both day and night diel periods, and monitored detections for each group over a 12-h period.

For each release group, we estimated mean passage time (gatewell egress) from release until first detection at the PIT-tag monitors on the downstream side of the test orifice. Passage distribution was modeled using time-to-event methods. The models included three factors: *week* (1-6), *diel period* (day/night), and *light treatment* (300 lux, 50 lux, and reference or light off); and three covariates (*fork length*, *turbidity*, and turbine unit *flow*). Akaike's Information Criterion (AIC) was used to determine which set of

factors and covariates were best supported by the data. Prediction of 50% passage was estimated for each cohort from the model-averaged individual estimates.

Both orifice light treatments decreased delay in the gatewell and improved egress for yearling and subyearling Chinook, sockeye salmon, and juvenile steelhead under most conditions. Sample sizes for coho salmon were insufficient for analysis. Differences in passage-time distribution between the two light treatments (50 and 300 lux) were minimal. The magnitude of delay between the 50- and 300-lux treatments and the reference (light off) treatment was greater for fish released in the evening than for those released in the morning, indicating that the orifice light was less effective during daytime due to ambient light. By covering the gatewells, egress for illuminated orifices during the daytime could be improved. The 50- and 300-lux treatments also provided a significant reduction in passage delay during periods of high turbidity, which occurred during the end of May and early June.

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INTRODUCTION

A primary focus of recovery efforts for depressed stocks of Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* in the Columbia River Basin has been assessing and improving fish passage conditions at dams (Williams 2008). Juvenile bypass has been identified as a viable alternative for increasing survival and fish passage efficiency at hydroelectric dams on the Snake and Columbia Rivers (Muir et al. 2001). However, the condition of migrating juvenile salmonids diverted from turbines into juvenile bypass systems (JBSs) at hydroelectric projects is an ongoing concern because the operating criteria for turbines or the JBS may influence passage timing as well as injury or mortality rates.

Contemporary fish bypass systems consist of numerous components, including diversion screens, flumes, barrier screens, orifices, and fish sampling and holding facilities. At McNary Dam, for example, extended-length submersible bar screens guide fish upward and away from turbine intakes. Guided fish then enter gatewells, where vertical barrier screens confine fish near underwater orifices. Fish pass through one of two orifices into a collection channel, which extends along the length of the powerhouse. From the collection channel, fish can either be returned to the river below the dam, diverted to holding raceways for transport, or diverted for tagging or examination within the juvenile fish facility. Each component of this system may contribute to delay in the downstream migration of juvenile salmonids.

At McNary Dam, two studies found considerable delay associated with gatewell egress. Beeman and Maule (2001) found that juvenile spring Chinook salmon *O. tshawytscha* spent 83% and steelhead spent 96% of their total time in the JBS within the upper 11 m of the gatewell. Axel and Dey (2001) found similar results for subyearling Chinook salmon at McNary Dam, with gatewell residence accounting for 90-98% of total passage time through the JBS. Since the majority of passage delay within the JBS is in the gatewell, modifications that reduce gatewell residence time have the greatest opportunity to decrease passage times for bypassed fish.

Artificial lighting in gatewell orifices is currently being utilized, to varying degrees, at all Columbia and Snake River projects operated by the United States Army Corps of Engineers (USACE). While previous studies have shown a variable response to light for each salmonid species (Rainey 1985; Fields 1966; Hoar 1957; Puckett and Anderson 1988), the literature suggests that improvements can be made with respect to orifice passage efficiency if light intensity, wavelength, and/or directionality can be optimized so that juvenile salmonids find the orifice more readily.

Mueller and Simmons (2008) evaluated the current orifice lighting system at Bonneville Powerhouse II and determined that light output at the orifice entrance measures less than 1 lux. Their review suggested that the minimum luminance at an orifice entrance should be 200-300 lux. In this report, we detail the continuation of that work, in collaboration with Bob Mueller of Pacific Northwest National Laboratories (PNNL), in order to determine whether gatewell egress time can be reduced by increasing luminance at the orifice entrance.

The 2008 Federal Columbia River Power System Biological Opinion calls for screened bypass system modifications at Bonneville Powerhouse II to improve fish guidance efficiency and reduce gatewell residence time (NMFS 2008, Reasonable and Prudent Alternative 18). In addition, the 2008 BiOp stipulates continued evaluation of modifications and configurations for safe fish passage (RPA 54). This study was conducted in part to address these directives and determine if an updated orifice lighting system (tested at McNary Dam) would provide additional benefit for migrating juvenile salmonids passing Bonneville Powerhouse II.

METHODS

Study Area

The focal point of this study was McNary Dam on the Columbia River (rkm 470) in southeast Washington State (Figure 1). This dam has three major passage routes for migrating juvenile fish: the spillway (including two top-spillbay weirs), the powerhouse (14 Kaplan turbines), and a juvenile bypass system (JBS). The powerhouse is 433.4 m long, and each turbine unit intake is outfitted with extended-length submersible bar screens, which guide fish out of the turbine intake into gatewells. In the gatewells, fish are confined by vertical barrier screens to an area near a submerged orifice leading to the fish collection channel. There are two submerged orifices providing access to the collection channel, but only one of these is open at a time.

Orifice openings are operated from the bypass channel by an air-operated slide gate, and each measures 30.5-cm in diameter. After the orifice draws fish out of the gatewells and into the collection channel, they are diverted into a 91.4-cm-diameter transport pipe. The centers of the two orifices are 1.1-m from the north and south ends of the gate slot at elevation 100.6 m above mean sea level (msl). Normal operating pool for the reservoir varies between elevations 102.1 and 103.6 m, averaging 102.9 m msl. The normal gatewell drawdown due to turbine loading is 30.5 cm, resulting in an average orifice submergence of 2 m below the gatewell surface. McNary Dam was selected for this study because of existing experimental PIT-tag detection facilities between the gatewell orifice exit and the collection channel.

Light Design

The light array used for testing was designed by PNNL and was composed of three rings of LEDs with 12 lights per ring (Figure 2). The inner ring directed light at a 30° angle inward, towards the orifice; the middle ring produced light at a 90° angle; and the outer ring directed light at a 45° angle outward, into the gatewell. A research team consensus determined that for the initial year of evaluation, we would test only the inner ring, in order to limit the large range of variables that would need to be considered by introducing varying angles of light. The LEDs had a beam angle of 115°, and each light ring was wired on an individual circuit for flexibility in light intensity output. At a distance of 30.5 cm from the light array, the lowest light level projected using only the inner ring was approximately 1 lux, and the highest level was 400 lux.

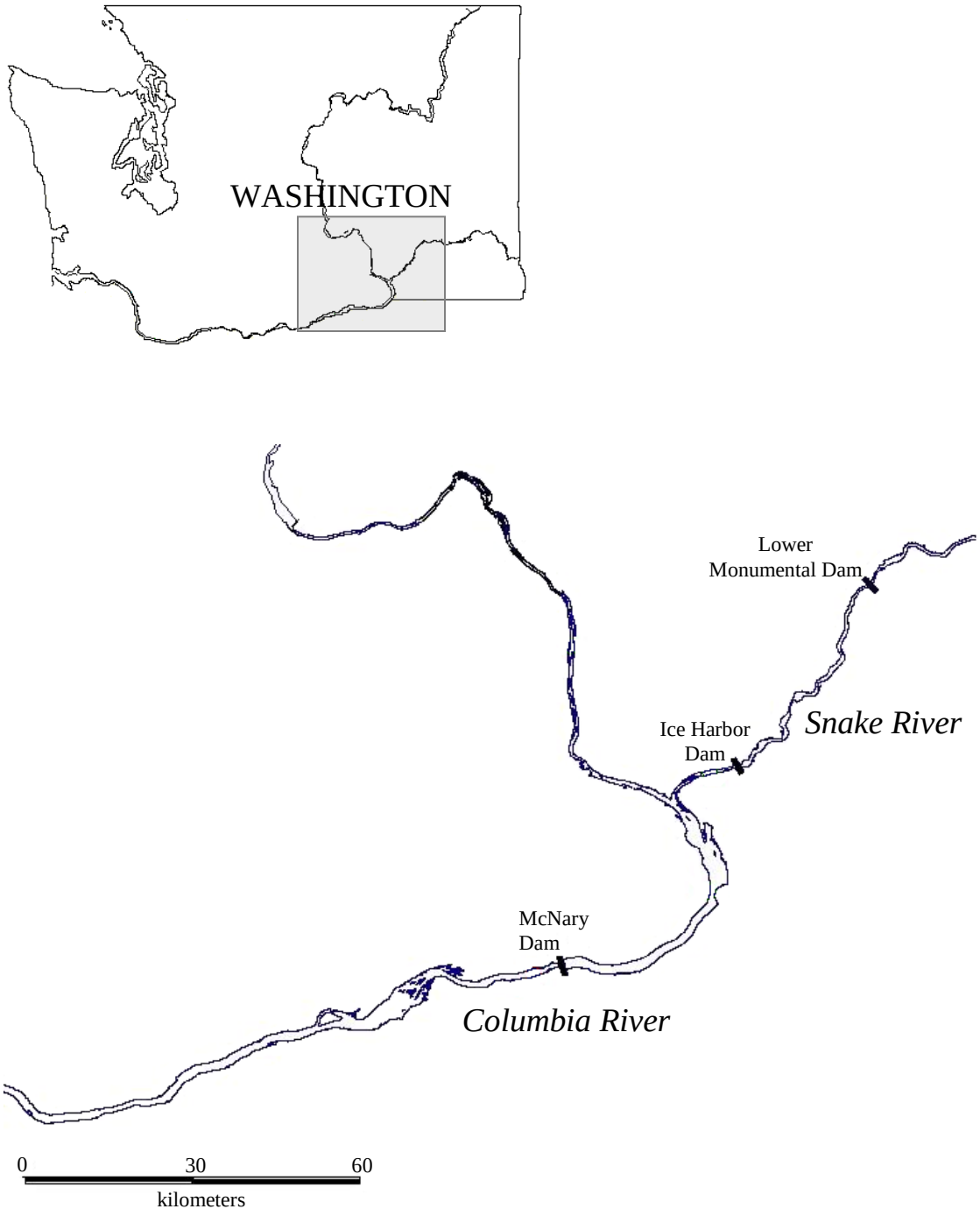

Figure 1. Study area showing location of McNary Dam, 2010.

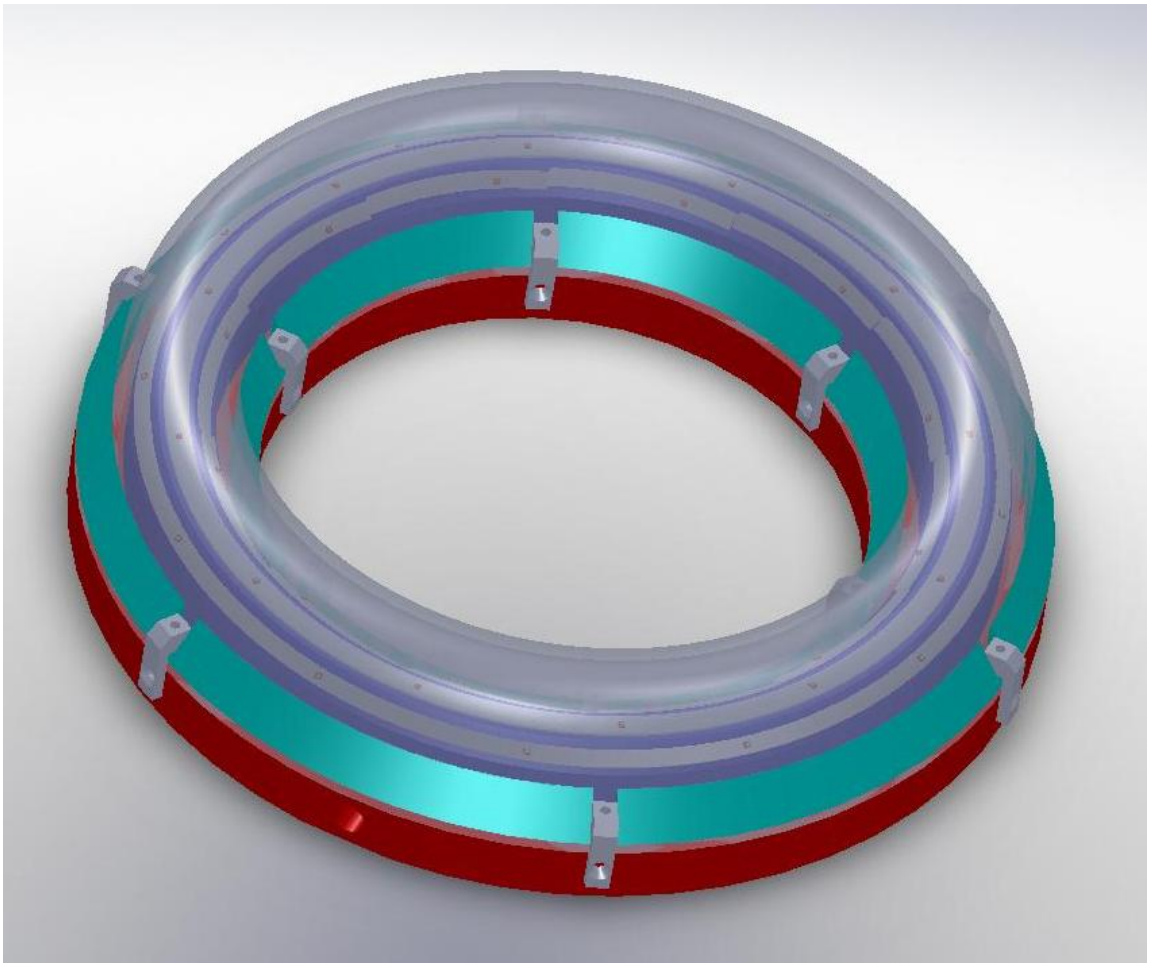

Figure 2. Orifice light ring developed and constructed to evaluate juvenile salmonid passage response to light intensity at McNary Dam, 2010. (Image courtesy of Jake Tucker, PNNL).

The light ring was developed with white light-emitting diodes (LEDs), which have peak wavelengths of 450 and 550-600 nm and a color-corrected temperature range of 3700-5000 Kelvin. This provided a neutral white color and a balanced wavelength that was near that of the peak optimal spectral response of juvenile salmonids (Loew and Lythgoe 1978; Bowmaker and Knuz 1987; Parkyn and Hawryshyn 2000).

A frame system was constructed and installed in gatewell 6B at McNary Dam in order to guide the orifice light ring into position (Figure 3). This frame held the light ring flush with the concrete as it was lowered into position over the orifice. As the orifice was opened, the light ring abutted the concrete wall to provide minimal disruption of flow. The assembled light ring was pressure tested for leaks in a test tank by PNNL prior to installation at McNary Dam. The external light sensor and data logger were also tested prior to deployment.

Figure 3. Orifice light ring being lowered into position at McNary Dam during track installation when the gatewell was dewatered. Under normal conditions the light ring would be 2 m under water.

Fish Collection, Tagging, and Release

We collected river-run yearling Chinook, coho *O. kisutch*, and sockeye *O. nerka* salmon and juvenile steelhead at the McNary Dam smolt collection facility from 3 May to 8 June 2010. River-run subyearling Chinook salmon were collected from 7 June to 15 July 2010. We tagged only fish that did not have any gross injury or deformity, were not previously PIT tagged, and were at least 65 mm in length. Fish were anesthetized with tricaine methanesulfonate (MS-222) and sorted in a recirculating anesthetic system.

PIT tags were purchased from Digital Angel Corp.[1] Each tag measured 12.5 mm in length by 2.1 mm in diameter, with a weight of 0.1 g in air. Average total volume for each tag was 43.3 mm^3.

Fish were PIT tagged using techniques described by Prentice et al. (1990a,b). Immediately following tagging, fish were transferred through a water-filled 10.2-cm pipe to a 935-L holding tank that was maintained with flow-through river water. Fish were held a minimum of 20 h for recovery and determination of post-tagging mortality. After the post-tagging recovery period, holding tanks were driven to the release location at the forebay deck of gatewell 6B. All holding tanks were aerated with oxygen during transport.

Fish were released through a 10.1-cm diameter release hose. The hose was connected to the holding tank with its terminus positioned just below the intake ceiling, approximately 2.5 m downstream from the gatewell 6B trashrack (Figure 4). We released groups of fish for one light treatment (300 or 50 lux or light off) twice per day at 0600 and 1800 PDT. One light-treatment condition was tested each week of the study. This provided six different tests, each with a unique lighting level and diel period, for each week. Thus, each week was considered a study replicate, and the 6 weeks provided temporal replication over the smolt migration season.

Prior to each release, the lighting treatment was established at either 50, 300, or <1 lux (light off), as determined by a light meter positioned 30.5 cm from the center axis of the light ring. Once the treatment condition was established, the light meter was raised out of the water, the south orifice was opened, and the north orifice was closed in gatewell 6B. Fish were released, and the time of release was recorded as the start of the test for calculating the time until gatewell egress.

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

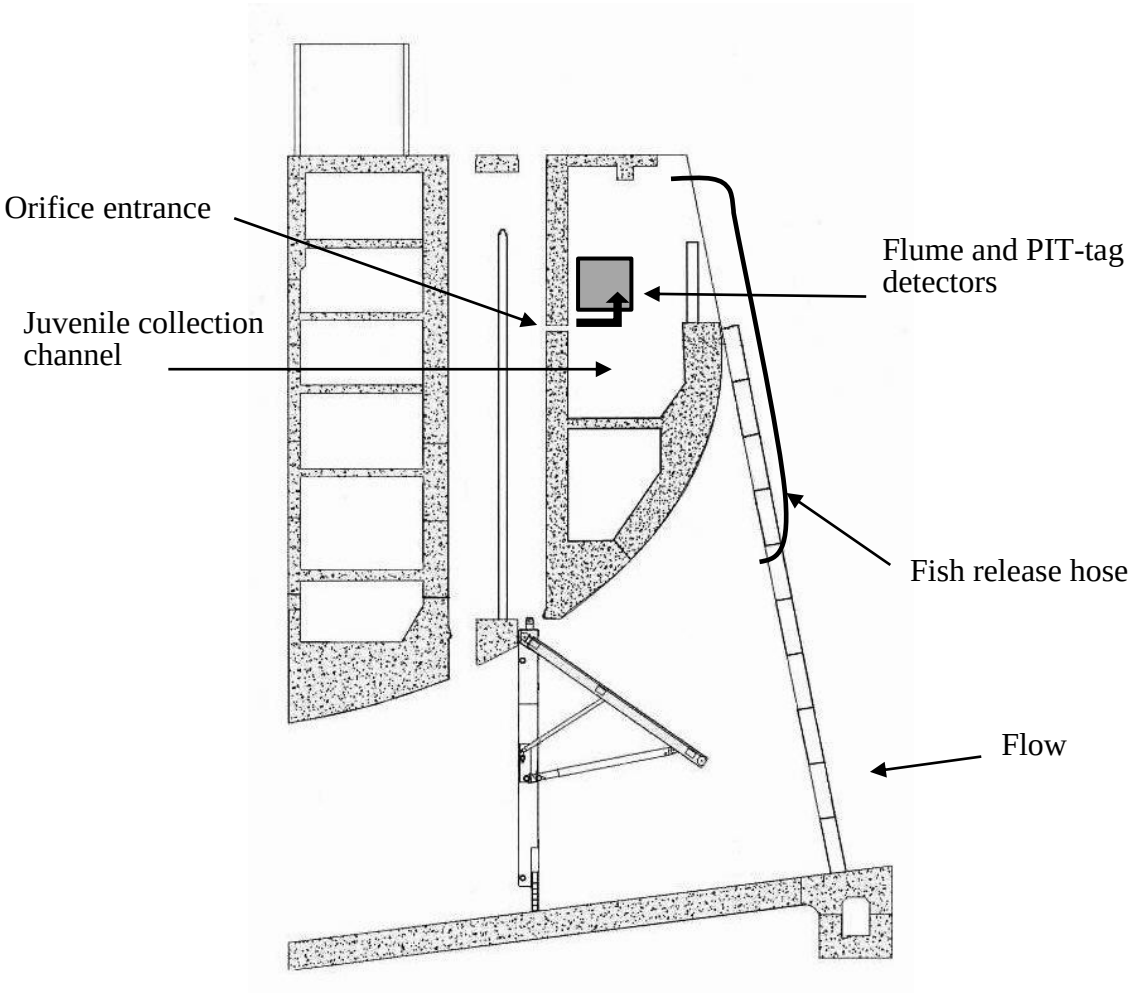

Figure 4. Cross-sectional view of McNary Dam showing fish release hose, orifice entrance, flume, and PIT-tag detection locations.

Data Analysis

The primary research question was whether different levels of light in the orifice would affect the passage rate of juvenile salmonids through the bypass system. To address this question, we conducted a statistical analysis that compared passage distributions under different light-treatment conditions. To evaluate passage, we used a class of statistical procedures developed to analyze "time-to-event" data (Lawless 1982; Tableman and Kim 2004). In this study, the "event" of interest was passage of fish through the orifice, and thus time-to-event was the time each individual fish required to complete a passage event after it was released, defined as t_i. Benefits of this type of analysis are that it 1) considers the entire distribution of fish, and is thus more powerful than methods that reduce the data to means or medians, and 2) accounts for fish that did not complete the event during the study period. Data from these fish were "censored," although still included in the analysis (to avoid bias toward shorter travel time).

To determine passage times for each fish, a flume located downstream from the orifice trap in gatewell 6B (south orifice) was fitted with PIT-tag monitors to interrogate test fish as they exited the gatewell via the orifice. Gatewell egress time, t_i, was calculated as the difference between release time and time of detection in the flume. Each test was conducted for a 12-h period, and detections after 12 h were considered "right-censored" at 12 h for the purpose of forming egress time distributions (see description below).

Fish that were not detected on the flume monitors were omitted from analysis because their passage time could not be measured. Study fish were not detected for a variety of reasons: they may have been able to swim away from intake 6B, they may have passed through the gap at the top of the intake screen, or orifices might have been cycled by USACE staff before fish passed through, in which case they passed via an unmonitored route. We assumed that the probability of non-detection, and the passage distribution of non-detected fish, was not related to treatment (Hosmer et al. 2008).

For each release group, we estimated median passage time from release until first detection in the PIT-tag detectors on the flume of the orifice trap. Estimates were made by modeling passage distributions. Although we were primarily interested in the effects of light treatment, we included other variables in our model selection process that might influence passage time. The models (see below) included the three factors of *week* (1-6), *diel period* (day/night), and light *treatment* (300 or 50 lux, or light off); and three covariates of *length*, *turbidity*, and unit *flow*, as well as two-way interactions between factors.

Turbidity was measured in nephelometric turbidity units (NTU) using a YSI 6920 V2 Sonde with a 6136 optical turbidity probe. Turbidity levels were logged throughout the study in order to compare environmental conditions with observed results. Time to passage was censored at 12 h, when the next treatment was implemented. We censored the data from these fish because even though we had records of when they actually passed, their passage timing was potentially impacted by the subsequent treatment. Data from these fish contributed to passage information until the time they were censored; although we did not know their real passage time, we did know that it occurred after more than 12 h. To have omitted them from analysis would have biased the passage distribution estimates downward (toward a shorter passage time).

The analysis was based on the survivor function, $S(t)$, which described the proportion of individuals that had not passed by time t. Note that $S(t)$ is always 1.0 when $t = 0.0$ (beginning of a release for a given treatment), and decreases through time to 0.0. The shape of $S(t)$ is based on a parametric model, wherein the factors and covariates included determine how quickly $S(t)$ declines from 1.0 to 0.0. In the simplest case, $S(t)$ is modeled as a negative exponential function, and the predictor variables determine its rate of decline. The probability distribution function, $f(t)$, determines the probability of passage during a specified time period, and is derivable from $S(t)$ (Lawless 1982; Tableman and Kim 2004; Hosmer et al. 2008).

To relate the model to the data, this distribution can be expressed as

$$\log(t_i) = \beta_0 + \beta_1 \cdot x_{1,i} + \ldots \beta_n \cdot x_{n,i} + \sigma z_i$$

where $\{\beta_0, \beta_1, \ldots, \beta_n\} = \beta$ is a vector of regression coefficients; $\{x_1, x_2, \ldots, x_n\} = x$ is a vector of factors, factor interactions, and covariates; z_i is a residual from the specified distribution; and σ is a scale parameter (Tableman and Kim 2004).

Thus σ and Z determine the shape of the survival distribution and the form of the probability distribution function, $f(t)$, while the regression coefficients, factors, and covariates determine the relative passage rates among individuals in a cohort. We used the exponential distribution to describe passage data because this type of data is expected to be "right-tailed" (i.e., a majority of fish pass early, with a smaller proportion straggling behind).

To estimate model parameters and determine model fits, the likelihood must be specified. The general form of the likelihood function for a sample of size, *n*, when data are censored is:

$$L(t_i, C_i, \delta_i) = \prod_{i=1}^{n} f(t_i)^{\delta_i} S(C_i)^{1-\delta_i}$$

where t_i was the recorded time of passage for individual *i*, C_i was the time of censoring (i.e., 12 h), and $\delta_i = 1$ for an individual *i* whose passage time was less than 12 h, and $\delta_i = 0$ for an individual whose passage time was censored (Lawless 1982). Estimates of model parameters were obtained using maximum likelihood methods (Hosmer et al. 2008; Tableman and Kim 2004).

The candidate set of models for this study was all models from the largest (including all factors, all two-way interactions between factors, and all covariates) to the smallest (only *week*). Since *week* was essentially a blocking or nuisance factor in this analysis, we included it in all models. All models that included interactions also included corresponding main effects.

We compared models using Akaike's Information Criterion corrected for sample size (AICc; Burnham and Anderson 2002). AICc was calculated as twice the log estimated likelihood function adjusted for sample size (number of PIT-tagged fish) and number of model parameters. We obtained $AICc_i$ for each model *i* in the candidate set. We then computed differences from the minimum value (of the candidate set of models) as $\Delta_i = AICc_i - AICc_{min.}$ Next, we computed AICc weights for the *i*th model as

$$w_i = \frac{\exp\left(-\frac{1}{2}\Delta_i\right)}{\sum_{i=1}^{13} \exp\left(-\frac{1}{2}\Delta_i\right)}$$

Each w_i was interpreted as the weight of evidence supporting model *i* among our set of models (Burnham and Anderson 2002). In addition, predicted values were "model-averaged" by making estimates for each model and then constructing a weighted average across models using AICc weights. For instance, we estimated median passage time under a specified model by determining the value of *t* such that $S(t) = 0.5$. We then determined the model-averaged by median by taking a weighted average (across models) of the estimated medians.

RESULTS

Tagging and Release

River-run yearling Chinook, and sockeye salmon, and juvenile steelhead of mixed origin were collected, PIT-tagged, and released at the McNary Dam smolt collection facility from 3 May to 8 June 2010 (Tables 1 and 2). We were unable to collect and tag sufficient numbers of coho salmon to obtain meaningful information on gatewell egress. River-run subyearling Chinook salmon of mixed origin were collected, PIT-tagged, and released from 7 June to 15 July 2010 (Tables 1 and 2). Handling and tagging mortality for the evaluation (tagged and non-tagged fish) was 1.2% overall.

Table 1. Total number by species of fish tagged and released for evaluating gatewell egress during light treatments at McNary Dam, 2010.

Release time (PDT)	Yearling Chinook salmon	Steelhead	Sockeye salmon	Subyearling Chinook salmon
0600	1,591	1,154	1,763	2,512
1800	1,612	1,130	1,839	2,478
Totals	3,203	2,284	3,602	4,990

Table 2. Mean fork length (FL) and standard deviation (σ) by species for fish tagged and released to evaluate gatewell egress timing under different orifice light treatments at McNary Dam, 2010. Sample sizes used for length are less than the numbers tagged because not all fish were measured at tagging.

	Yearling Chinook salmon	Steelhead	Sockeye salmon	Subyearling Chinook salmon
Number	3,097	2,260	3,493	4,985
Mean FL (mm)	148.7	214.7	105.4	106.9
σ	17.0	28.4	11.8	8.7

Project Operations and Environmental Conditions

Mean turbidity throughout the study was relatively low, at 3.2 NTU (range 1.6-6.5 NTU). During the subyearling Chinook release period, turbidity averaged 6.8 NTU and peaked at 20.3 NTU on 12 June (Figure 5). In general, increases in turbidity during the study were correlated with increases in river flow. Water temperature ranged from 10.7-19.7°C during the entire study.

Mean turbine discharge for the test unit (Unit 6) during the yearling Chinook collection and release period (4 May-7 June) was 10.1 kcfs (range 7.1-12.3 kcfs; Figure 6). During the subyearling Chinook release period, mean turbine discharge in Unit 6 was higher, averaging 11.4 kcfs (range 9.2-12.3 kcfs). Mean total river flow throughout the study was 250.4 kcfs (range 148.4-387.0 kcfs).

On 12 May there was a maintenance issue which required shutting down the collection channel and all water to the juvenile fish facility. As a result, we had to release all of the tagged fish for the planned 300-lux treatment at 5:39 am. When the maintenance crew had completed work, we were able to collect and tag fish for the reference or light-off treatment. These fish were released on 14 May at 0600.

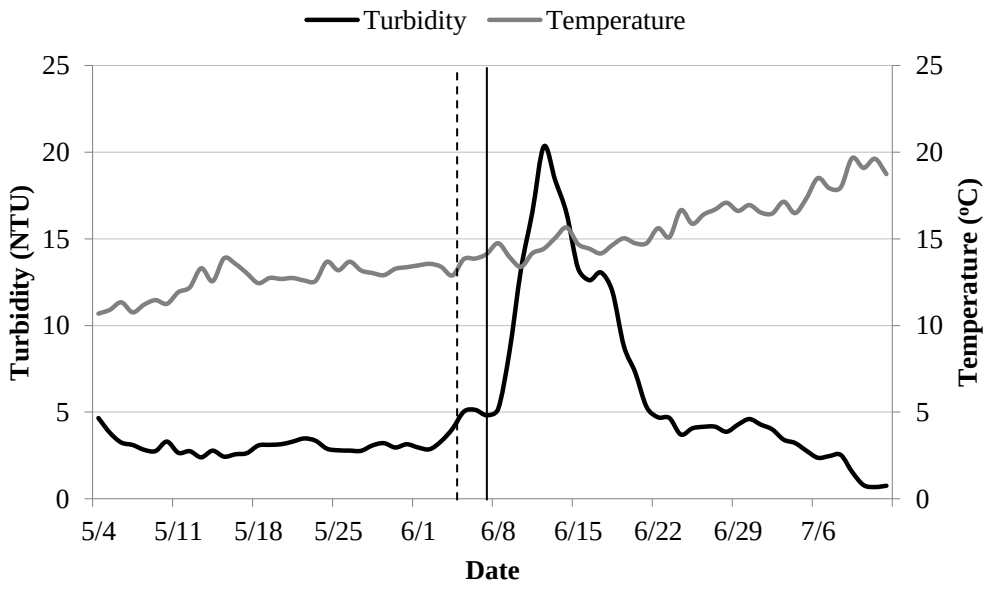

Figure 5. Turbidity and water temperature at McNary Dam near turbine intake 6B during the 2010 orifice lighting study. Solid line indicates end of yearling study period; dotted line indicates start of subyearling period.

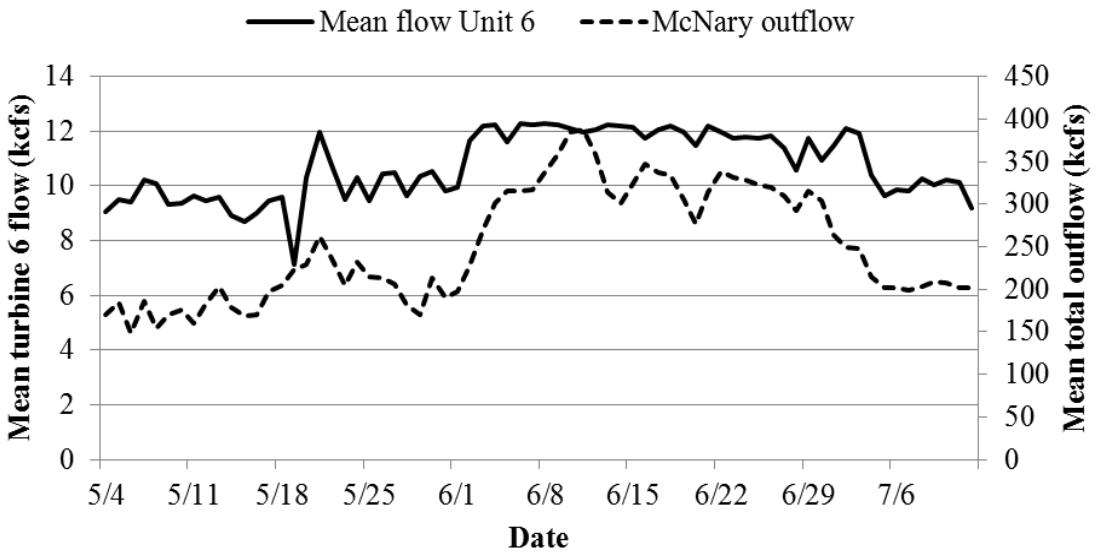

Figure 6. Mean daily turbine discharge for turbine unit 6 and mean daily outflow for McNary Dam during the 2010 orifice lighting study.

Yearling Chinook Salmon

During the 300-lux treatment, we observed shorter passage times for yearling Chinook salmon released in the evening (1800) than for those released in daytime (0600), with 18% more evening fish exiting the orifice within the first 3 h of release (Figure 7). Results for the 50-lux treatment also resulted in 18% more fish exiting the gatewell within the first 3 h for evening releases compared to morning releases, though the rate of passage was slightly reduced. In comparison, the reference treatment (light off) yielded lower passage rates than either light treatment during both daytime and evening release periods, with a higher number of fish remaining in the gatewell after the 12-h test period had ended.

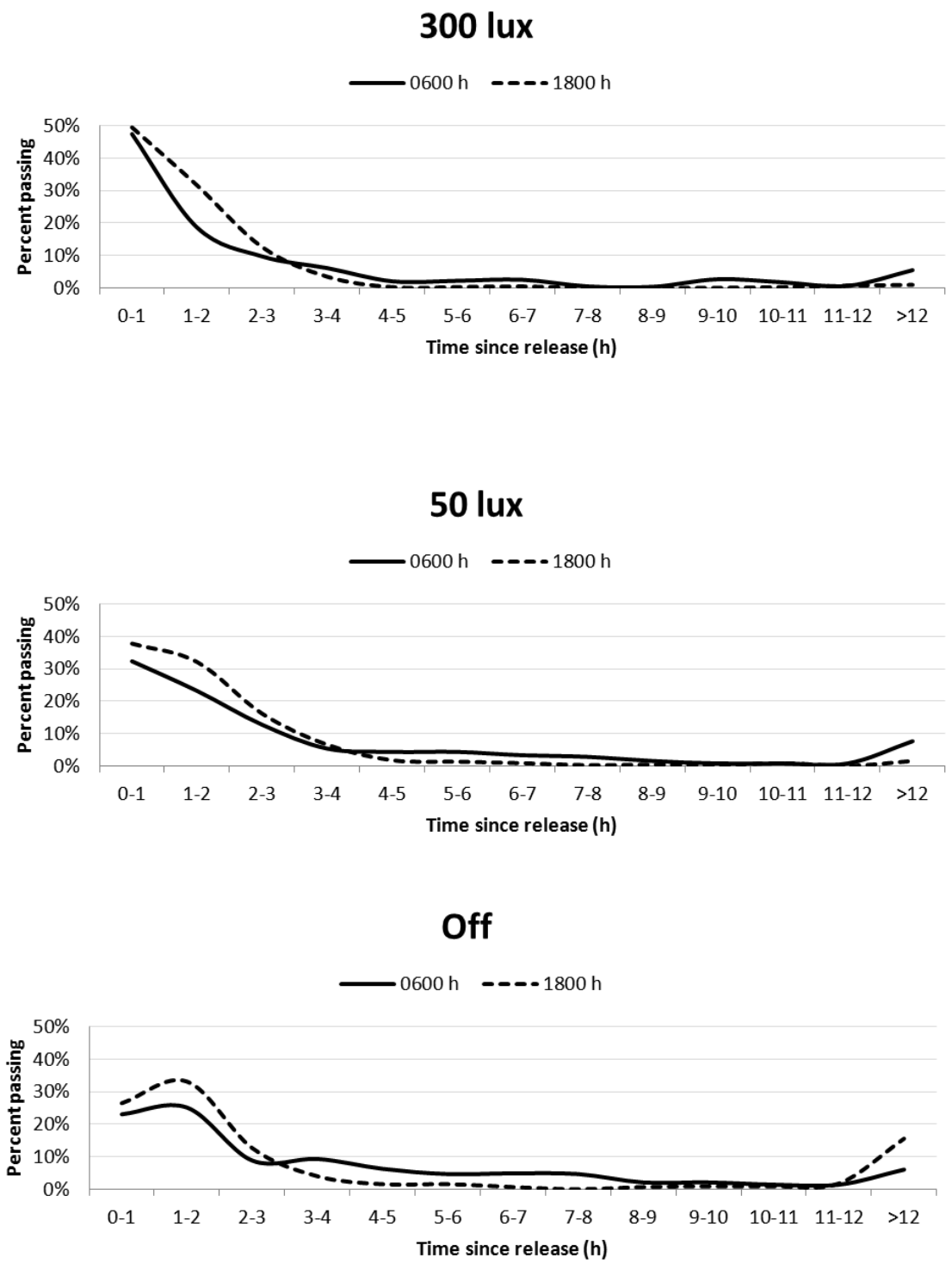

Figure 7. Percent passage of yearling Chinook salmon plotted against time since release during the 300-lux (upper panel), 50-lux (middle panel), and reference or light off (lower panel) orifice light treatments at McNary Dam, 2010.

Estimated mean (of weekly median) gatewell egress time for yearling Chinook salmon from morning releases was 1.8 h (95% CI, 1.5-2.1) during the 300-lux treatment, 2.6 h (2.0-3.2) during the 50-lux treatment, and 3.2 h (2.6-3.8) during the reference (light off) treatment (Figure 8). Fish released after 1800 h displayed shorter egress times overall, with median gatewell egress averaging 1.0 h (95% CI, 0.8-1.2) during the 300-lux treatment, 1.2 h (0.9-1.5) during the 50-lux treatment, and 2.7 h (2.2-3.2) during the reference (light off) treatment (Table 3).

The time-to-event model best supported by the data using AIC ranking included all factors, all interactions between factors, and the covariates *turbidity* and *length* (Appendix Table 1). The same model without the interaction between *week* and *diel period* was also well supported. Model-averaged results from the top 3 best fitting models are shown in Figure 9. In general, the differences between the 300- and 50-lux treatments were minimal, while the reference (light off) condition produced longer travel times except for daytime releases during weeks 3 and 4. Light treatments were most effective at night or when turbidity increased.

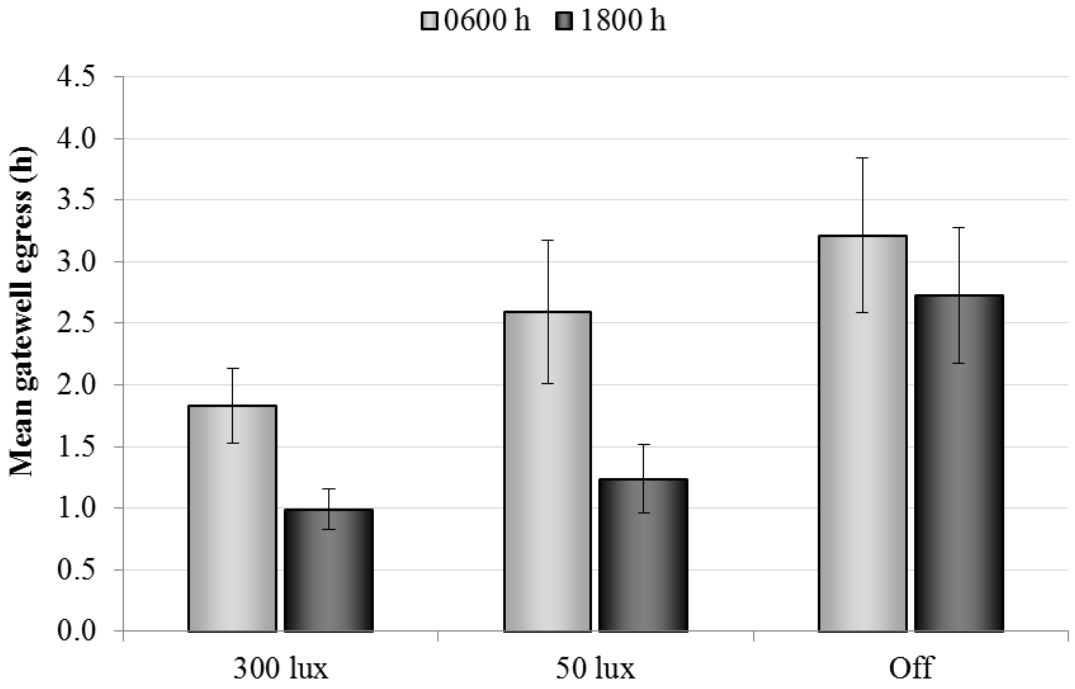

Figure 8. Estimated mean (of weekly median) gatewell egress during daytime (0600) and nighttime (1800) releases of yearling Chinook salmon under three different light treatments in Unit 6B at McNary Dam, 2010. Whiskers indicate 95% CIs.

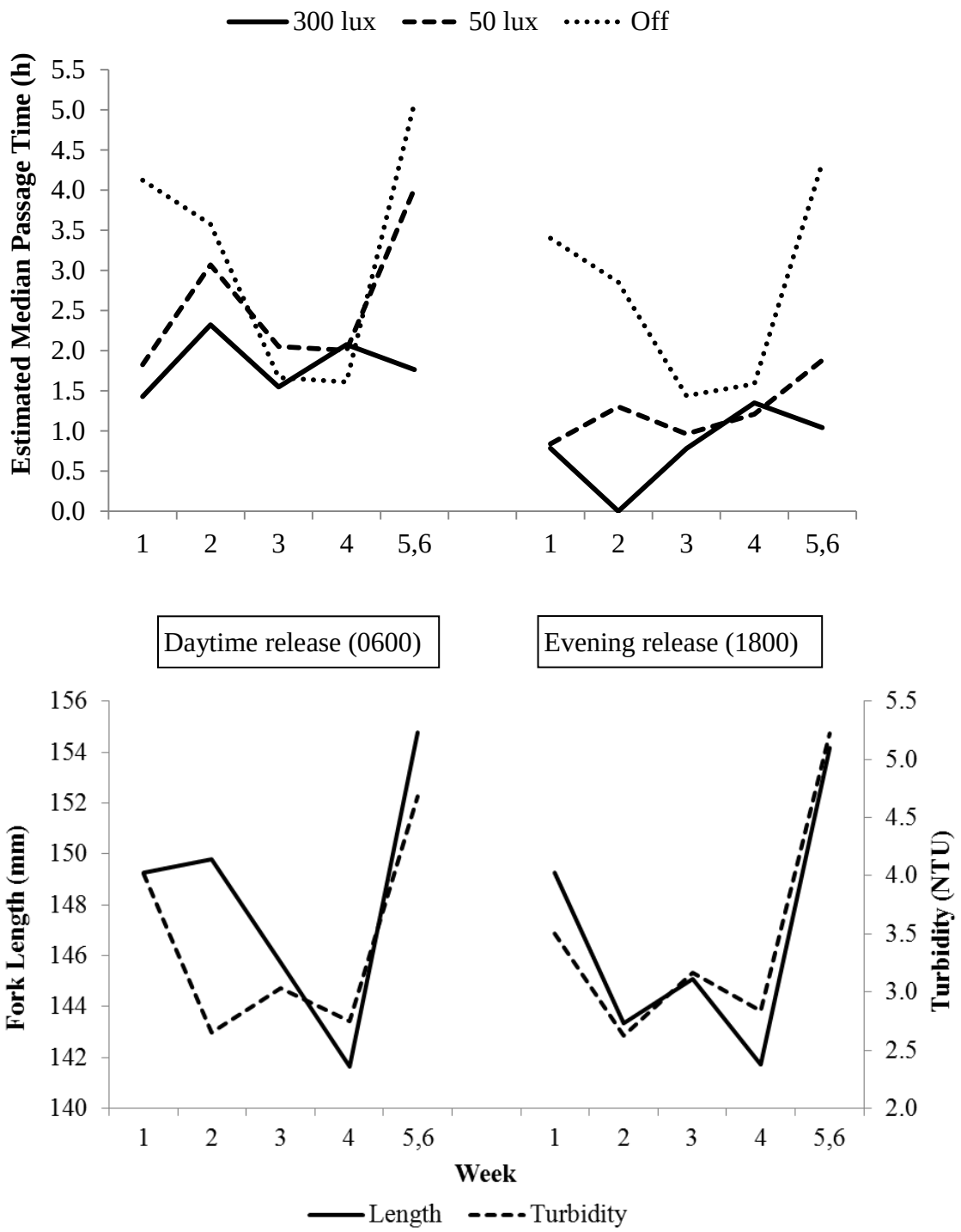

Figure 9. Upper panel shows estimated median gatewell egress by week using model-averaged data for yearling Chinook salmon in Unit 6B at McNary Dam during three different lighting treatments and two diel release periods, 2010. Lower panel shows the covariates *fork length* and *turbidity*, which factored heavily in AICc model selection.

Table 3. Numbers of yearling Chinook salmon released and detected by treatment and release time within the gatewell at McNary Dam, 2010.

		Release date	Number released	Number detected	Percent detected
Low intensity (~50 lux)					
a.m. release	Week 1	5/4/2010 6:40	105	100	95
	Week 2	5/11/2010 6:30	104	91	88
	Week 3	5/19/2010 6:22	109	104	95
	Week 4	5/27/2010 6:14	31	26	84
	Week 5	6/2/2010 6:25	74	71	96
	Week 6	6/10/2010 6:13	29	26	90
p.m. release	Week 1	5/4/2010 18:15	110	97	88
	Week 2	5/11/2010 18:13	122	108	89
	Week 3	5/19/2010 18:15	112	103	92
	Week 4	5/27/2010 18:10	42	39	93
	Week 5	6/2/2010 18:05	75	69	92
	Week 6	6/10/2010 18:10	15	15	100
Reference (light off)					
a.m. release	Week 1	5/5/2010 6:30	103	89	86
	Week 2	5/14/2010 6:09	101	79	78
	Week 3	5/20/2010 6:24	100	93	93
	Week 4	5/26/2010 6:25	105	95	90
	Week 5	6/4/2010 6:14	93	73	78
	Week 6	6/9/2010 6:14	36	26	72
p.m. release	Week 1	5/5/2010 18:14	107	99	93
	Week 2	5/14/2010 18:00	100	68	68
	Week 3	5/20/2010 17:59	103	99	96
	Week 4	5/26/2010 18:15	106	93	88
	Week 5	6/4/2010 18:10	101	49	49
	Week 6	6/9/2010 18:15	16	15	94
High intensity (~300 lux)					
a.m. release	Week 1	5/6/2010 6:25	103	96	93
	Week 2	5/12/2010 5:39	209	189	90
	Week 3	5/18/2010 6:23	118	103	87
	Week 4	5/25/2010 6:55	103	93	90
	Week 5	6/3/2010 6:18	106	96	91
	Week 6	6/8/2010 6:11	66	61	92
p.m. release	Week 1	5/6/2010 18:00	108	96	89
	Week 2	**All fish released in a.m. due to unit outage**			
	Week 3	5/18/2010 18:05	122	109	89
	Week 4	5/25/2010 18:05	119	94	79
	Week 5	6/3/2010 18:00	102	97	95
	Week 6	6/8/2010 18:10	48	40	83

Juvenile Steelhead

During the 300-lux treatment, we observed shorter passage times for juvenile steelhead released in the evening (1800) than for those released in the daytime (0600), with 23% more evening fish exiting the orifice within the first 3 h of release (Figure 10). We also saw nearly 11% of the daytime releases remain in the gatewell beyond the 12-h test period, as opposed to 2% of the evening releases. Under the 50-lux treatment, 19% more fish from the evening releases exited the gatewell within the first 3 h compared to fish from the daytime releases. The reference (light off) treatment, in comparison, yielded lower passage rates than either light treatment during either diel release period, with similar rates of fish remaining in the gatewell after the 12-h test.

Estimated mean (of weekly median) gatewell egress time for juvenile steelhead released during daytime periods was 2.7 h (95% CI, 2.1-3.3) under the 300-lux treatment, 2.1 h (1.7-2.5) under the 50-lux treatment, and 2.7 h (2.1-3.3) under the reference (light off) treatment (Figure 11). Fish released during nighttime periods displayed shorter egress times for the lighted treatments, with average medians of 1.4 h (95% CI, 1.1-1.7) under the 300-lux treatment, 1.3 h (1.0-1.6) under the 50-lux treatment, and 2.6 h (2.0-3.2) under the reference treatment (Table 4). The percent of steelhead detected was lower than that for salmon because their larger size allowed them to escape the intake flow entrainment more readily.

The best-fitting model based on AIC rank included *week*, *diel period*, and *treatment*, interactions between *treatment* vs. *week* and *treatment* vs. *diel period*, and no covariates (Appendix Table 2). Model-averaged results that used the top 4 best-fitting models indicated a similarity in passage times between treatments, except that passage time was longer for nighttime releases during the reference (light off) treatment (Figure 12). Passage times decreased through the study period for all treatments except during the last week, when passage time for the reference (light off) treatment was much longer. This corresponded with an increase in turbidity, but was not supported strongly in the modeling results.

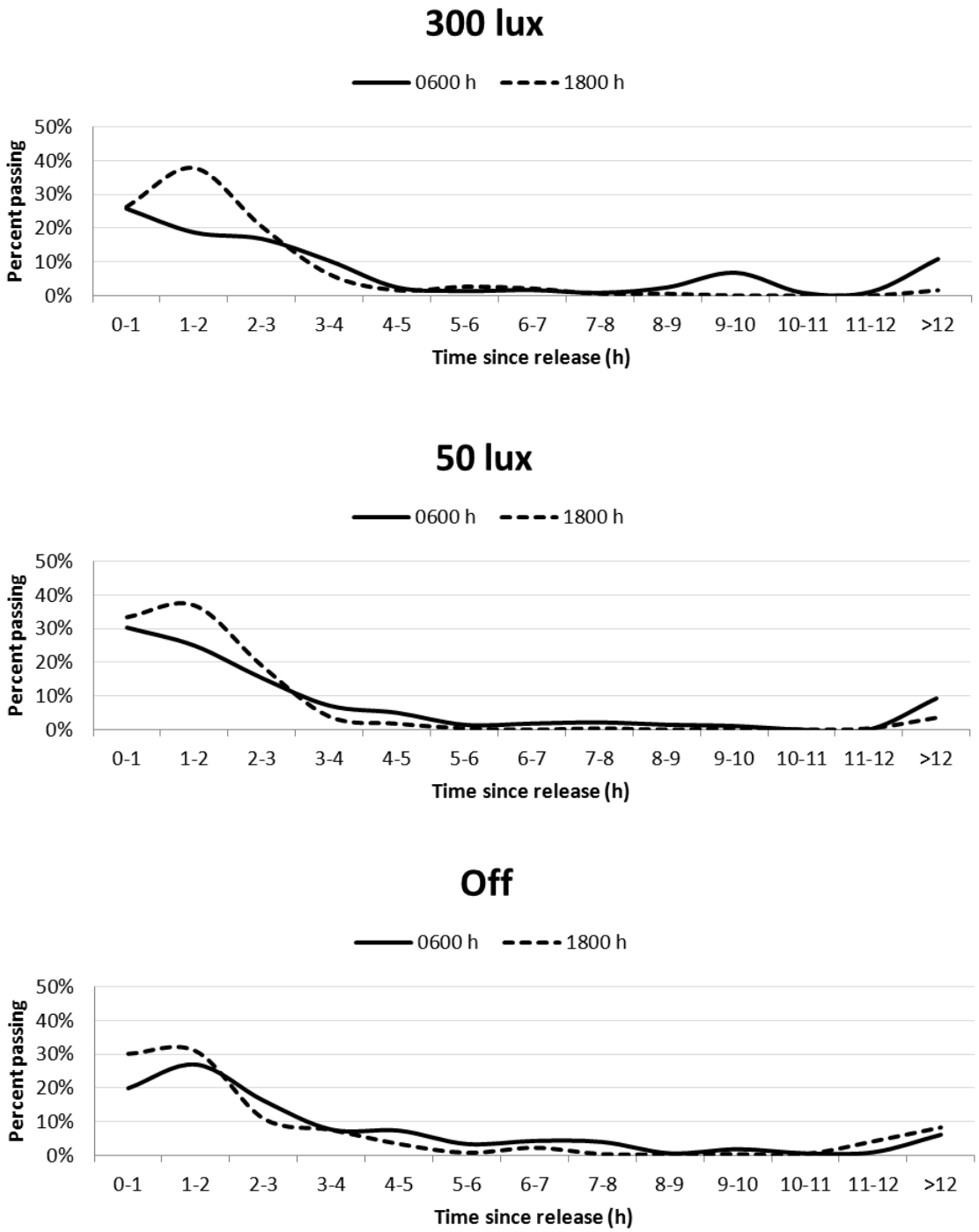

Figure 10. Percent passage of juvenile steelhead plotted against time since release during the 300-lux (upper panel), 50-lux (middle panel), and reference (lower panel) orifice light treatments at McNary Dam, 2010.

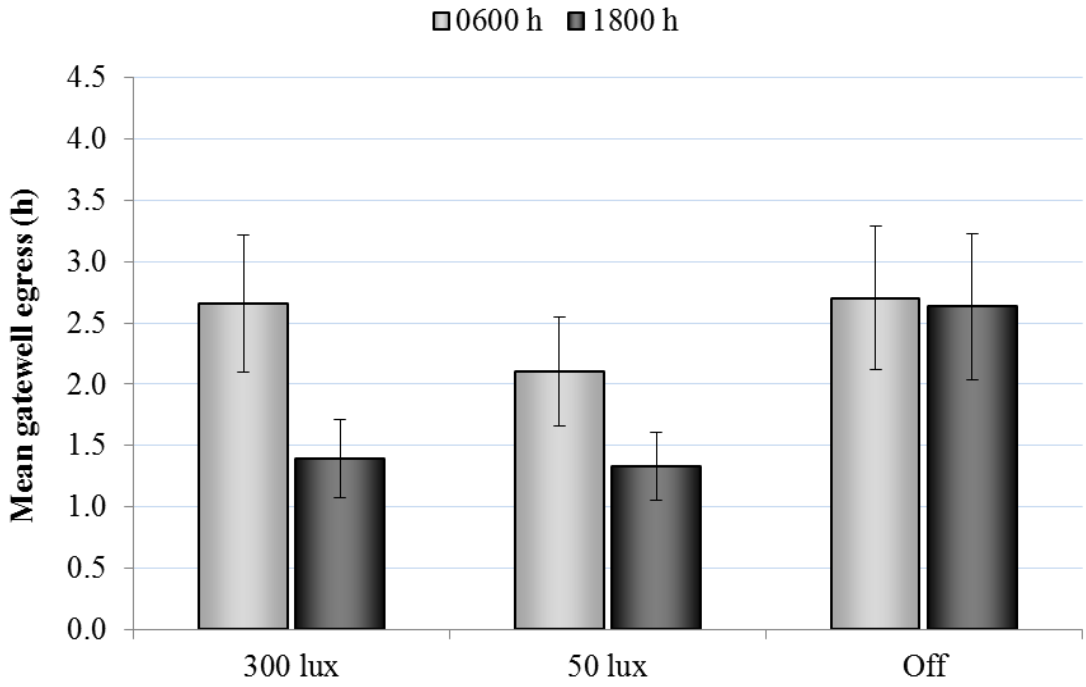

Figure 11. Estimated mean (of weekly median) gatewell egress during daytime (0600) and nighttime (1800) releases of juvenile steelhead under three different light treatments in Unit 6B at McNary Dam, 2010. Whiskers indicate 95% CIs.

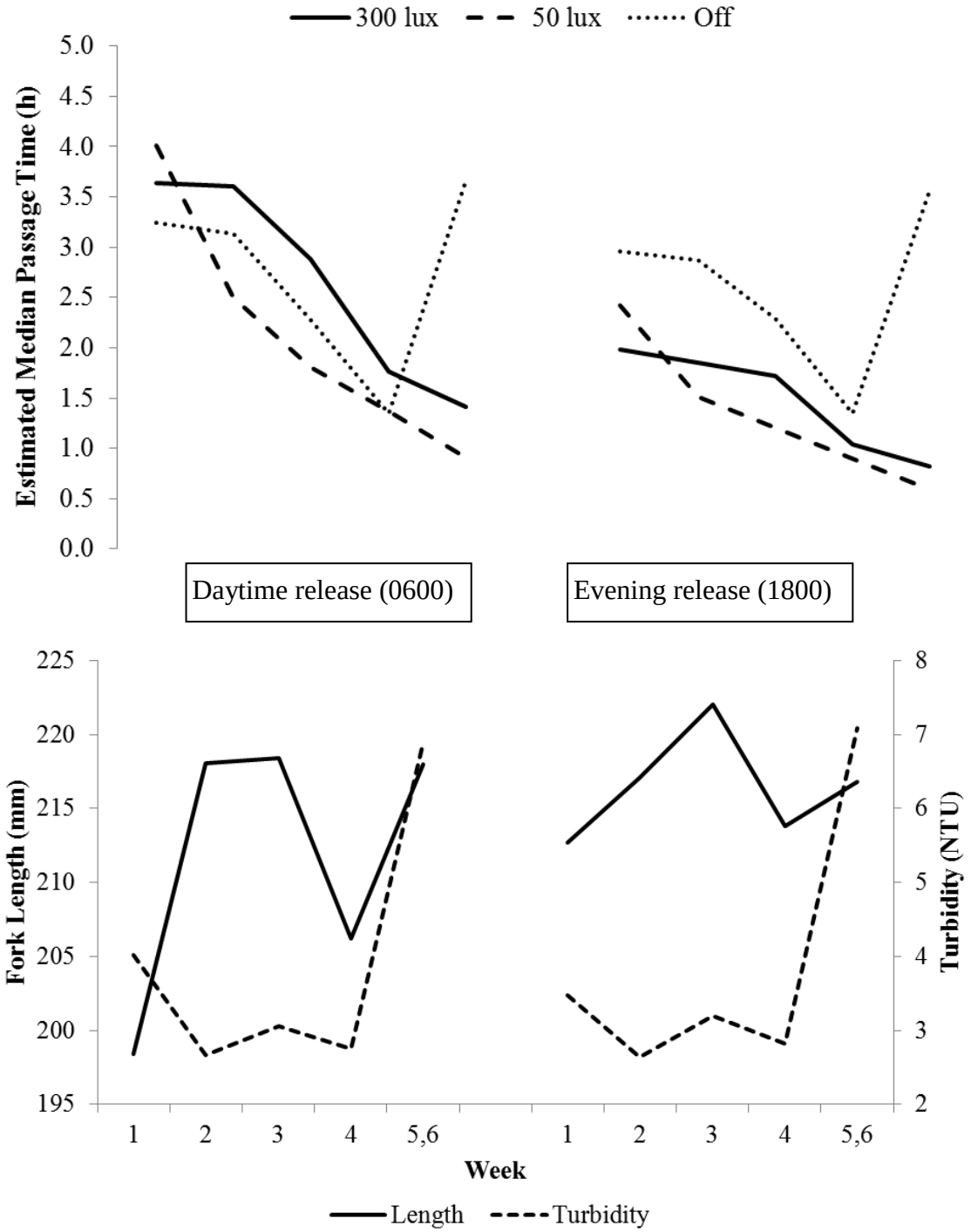

Figure 12. Upper panel shows estimated median gatewell egress by week using model-averaged data for juvenile steelhead during three different orifice light treatments in unit 6B at McNary Dam, 2010. Lower panel shows how turbidity, and to a lesser extent fork length, factored in the AICc model selection.

Table 4. Numbers of juvenile steelhead released and detected by treatment and release time within the gatewell at McNary Dam, 2010.

		Release date	Number released	Number detected	Percent detected
Low intensity (~50 lux)					
a.m. release	Week 1	5/4/2010 6:40	100	77	77
	Week 2	5/11/2010 6:30	63	52	83
	Week 3	5/19/2010 6:22	109	91	83
	Week 4	5/27/2010 6:14	57	33	58
	Week 5	6/2/2010 6:25	4	4	100
	Week 6	6/10/2010 6:13	24	23	96
p.m. release	Week 1	5/4/2010 18:15	98	66	67
	Week 2	5/11/2010 18:13	94	73	78
	Week 3	5/19/2010 18:15	106	83	78
	Week 4	5/27/2010 18:10	57	39	68
	Week 5	6/2/2010 18:05	14	7	50
	Week 6	6/10/2010 18:10	20	16	80
Reference (light off)					
a.m. release	Week 1	5/5/2010 6:30	51	44	86
	Week 2	5/14/2010 6:09	76	44	58
	Week 3	5/20/2010 6:24	101	86	85
	Week 4	5/26/2010 6:25	96	83	86
	Week 5	6/4/2010 6:14	49	40	82
	Week 6	6/9/2010 6:14	34	29	85
p.m. release	Week 1	5/5/2010 18:14	56	40	71
	Week 2	5/14/2010 18:00	65	30	46
	Week 3	5/20/2010 17:59	88	83	94
	Week 4	5/26/2010 18:15	103	73	71
	Week 5	6/4/2010 18:10	41	33	80
	Week 6	6/9/2010 18:15	7	6	86
High intensity (~300 lux)					
a.m. release	Week 1	5/6/2010 6:25	101	75	74
	Week 2	5/12/2010 5:39	203	150	74
	Week 3	5/18/2010 6:23	58	50	86
	Week 4	5/25/2010 6:55	100	66	66
	Week 5	6/3/2010 6:18	9	7	78
	Week 6	6/8/2010 6:11	21	20	95
p.m. release	Week 1	5/6/2010 18:00	100	69	69
	Week 2	**All fish released in a.m. due to unit outage**			
	Week 3	5/18/2010 18:05	47	37	79
	Week 4	5/25/2010 18:05	93	56	60
	Week 5	6/3/2010 18:00	22	16	73
	Week 6	6/8/2010 18:10	17	12	71

Sockeye Salmon

Under the 30-lux orifice light treatments, we observed shorter passage time for sockeye salmon released during nighttime (1800) than for those released during daytime (0600), with 28% more nighttime-released fish exiting the orifice within 3 h of release (Figure 13). Under the 50-lux light treatments, 39% more fish exited the gatewell within 3 h during nighttime treatments than during daytime treatments, though the rate of passage during the first hour was slightly lower for nighttime releases. The reference treatment, in comparison, yielded considerably lower passage rates than either light treatment during both the daytime and nighttime release periods, with more residuals left in the gatewell after the test had ended. Daytime releases under the reference conditions (light off) had the longest passage timing, with 24% left in the gatewell after 12 h.

Estimated mean (of weekly median) gatewell egress for sockeye salmon during morning releases was 2.9 h (95% CI, 2.3-3.5) under the 300-lux treatment, 3.7 h (2.9-4.5) at the 50-lux treatment, and 7.3 h (5.4-9.2) during the reference treatment (Figure 14). Fish released after 1800 h displayed shorter egress times with 0.9 h (95% CI, 0.7-1.1) under the 300-lux treatment, 0.8 h (CI, 0.6-1.0) at the 50-lux treatment, and 3.4 h (2.6-4.2) during the reference (light off) treatment (Table 5). The reference release during week 2 exhibited a lower detection percentage, which was a result of the orifice being closed prior to the entire release group had exited the unit. This affected both the daytime and evening releases.

The best-fitting model using AICc ranking included all three factors, all interactions between factors, and the covariates *turbidity* and *length* (Appendix Table 3). Model-averaged results using the top 3 models indicated variability in passage times between treatments by week (Figure 15). The reference (light off) treatment produced longer gatewell egress time, especially at night. Gatewell egress times decreased over the study period, except for the reference treatment in week 6 (the last week). This longer timing was significantly correlated with higher turbidity, and the relationship was supported strongly in the modeling results.

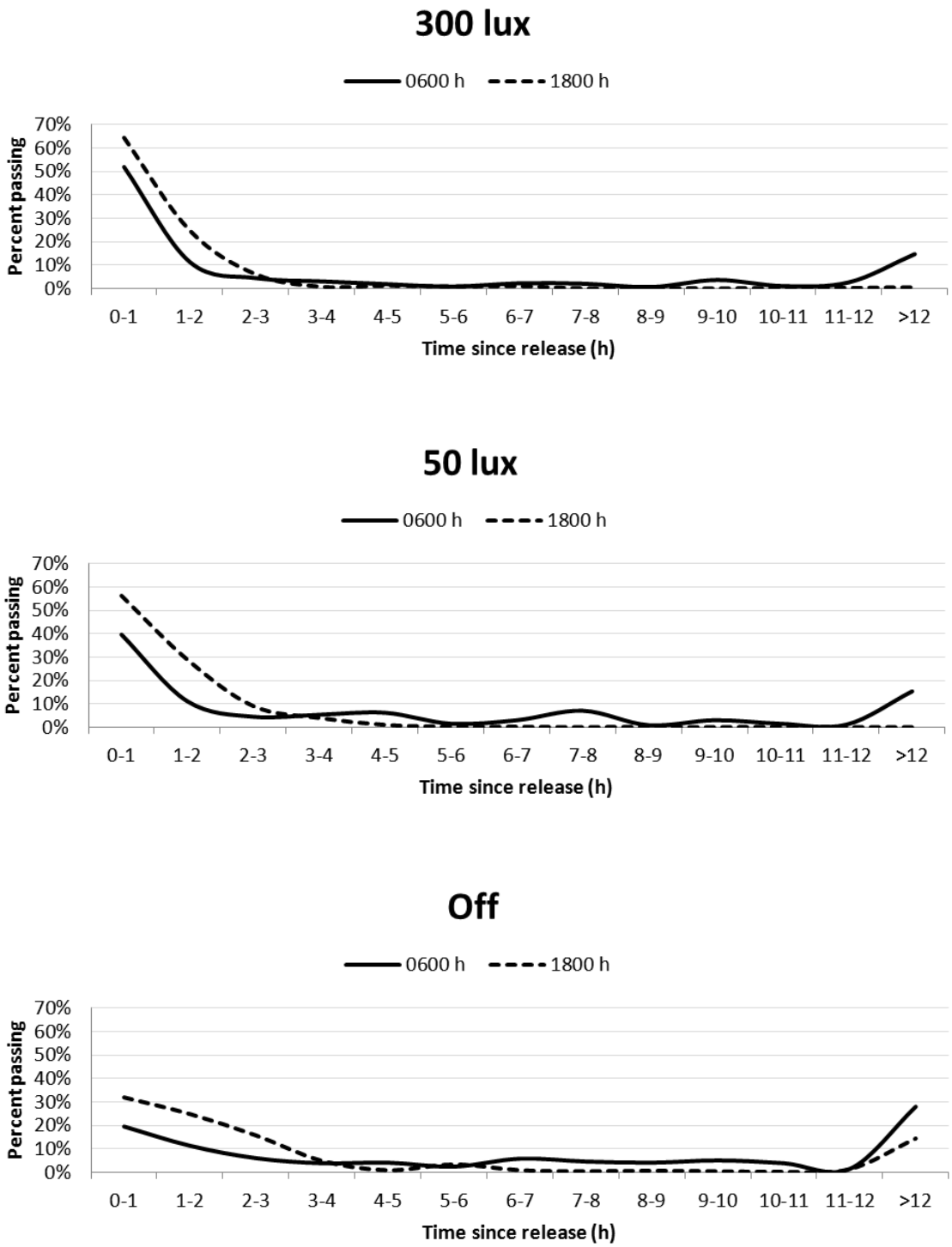

Figure 13. Percent passage of sockeye salmon plotted against time since release during the 300-lux (upper panel), 50-lux (middle panel), and reference (light off) orifice light treatments at McNary Dam, 2010.

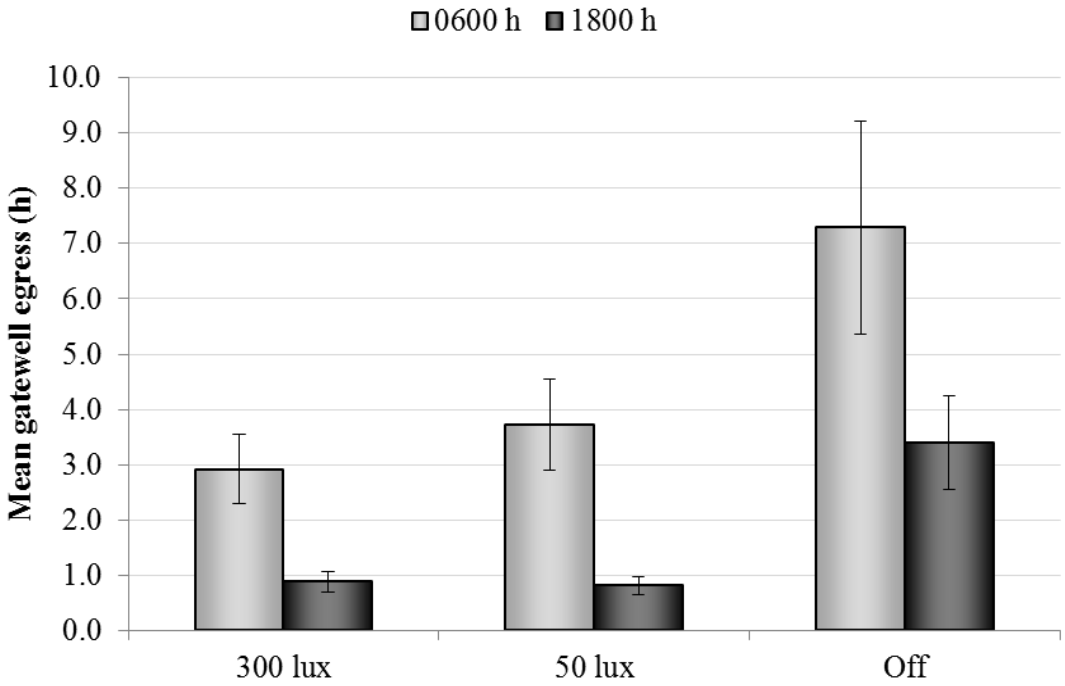

Figure 14. Estimated mean (of weekly median) gatewell egress during daytime (0600) and evening (1800) releases of sockeye salmon under three different light treatments in Unit 6B at McNary Dam, 2010. Whiskers indicate 95% CIs.

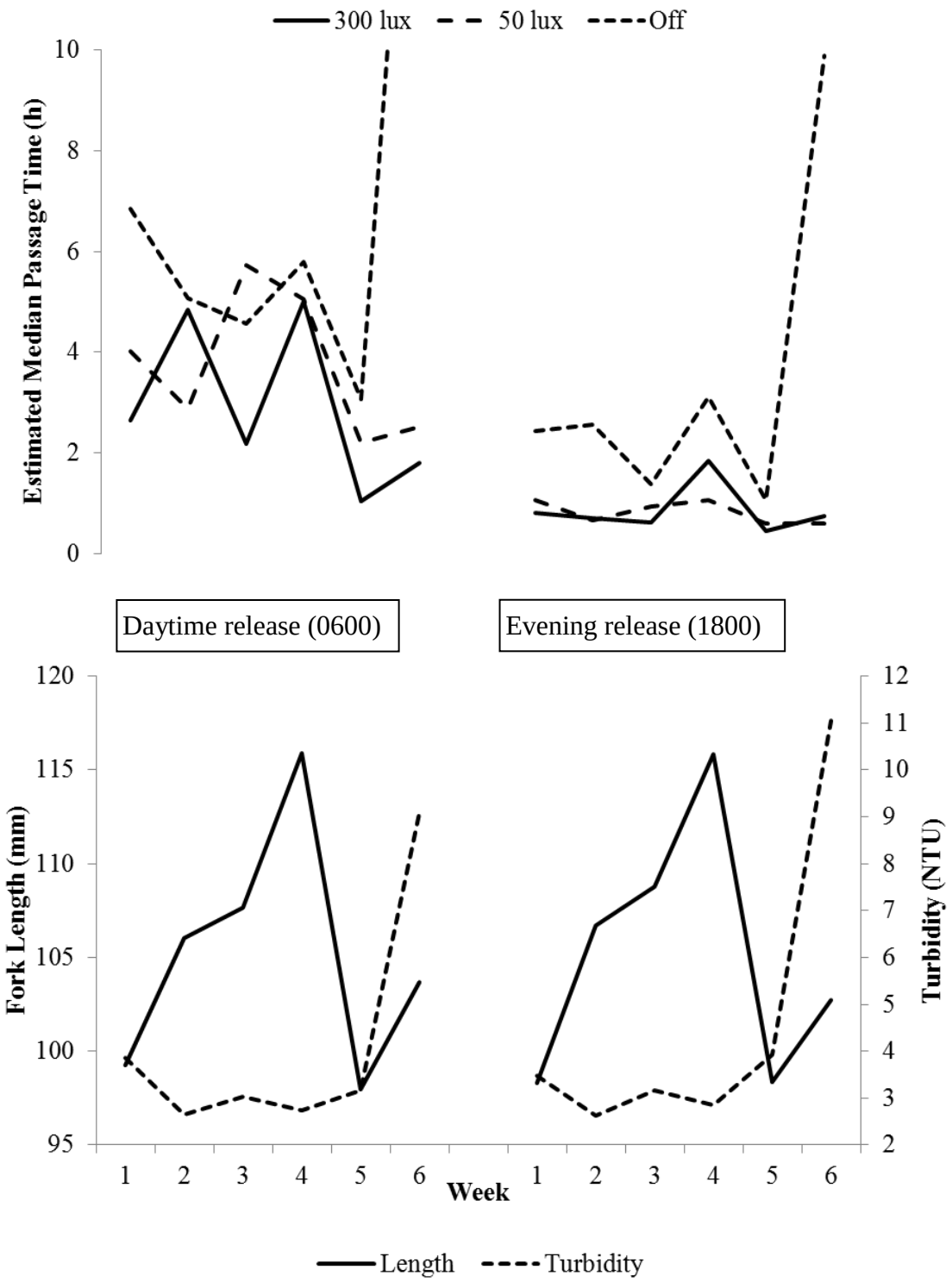

Figure 15. Upper panel shows estimated median gatewell egress by week using model-averaged data for sockeye salmon during three different lighting treatments. Lower panel shows the extent to which *turbidity*, and to a lesser degree *fork length*, factored in the AICc model selection.

Table 5. Numbers of sockeye salmon released and detected by treatment and release time within the gatewell at McNary Dam, 2010.

		Release date	Number released	Number detected	Percent detected
Low intensity (~50 lux)					
a.m. release	Week 1	5/4/2010 6:40	66	46	70
	Week 2	5/11/2010 6:30	102	81	79
	Week 3	5/19/2010 6:22	103	77	75
	Week 4	5/27/2010 6:14	105	74	70
	Week 5	6/2/2010 6:25	111	106	95
	Week 6	6/10/2010 6:13	105	85	81
p.m. release	Week 1	5/4/2010 18:15	94	80	85
	Week 2	5/11/2010 18:13	110	74	67
	Week 3	5/19/2010 18:15	108	87	81
	Week 4	5/27/2010 18:10	102	85	83
	Week 5	6/2/2010 18:05	104	92	88
	Week 6	6/10/2010 18:10	104	88	85
Reference (light off)					
a.m. release	Week 1	5/5/2010 6:30	100	87	87
	Week 2	5/14/2010 6:09	114	41	36
	Week 3	5/20/2010 6:24	96	65	68
	Week 4	5/26/2010 6:25	92	77	84
	Week 5	6/4/2010 6:14	109	71	65
	Week 6	6/9/2010 6:14	105	74	70
p.m. release	Week 1	5/5/2010 18:14	105	92	88
	Week 2	5/14/2010 18:00	100	46	46
	Week 3	5/20/2010 17:59	101	79	78
	Week 4	5/26/2010 18:15	102	89	87
	Week 5	6/4/2010 18:10	110	82	75
	Week 6	6/9/2010 18:15	99	63	64
High intensity (~300 lux)					
a.m. release	Week 1	5/6/2010 6:25	100	77	77
	Week 2	5/12/2010 5:39	209	134	64
	Week 3	5/18/2010 6:23	87	61	70
	Week 4	5/25/2010 6:55	75	57	76
	Week 5	6/3/2010 6:18	97	81	84
	Week 6	6/8/2010 6:11	98	87	89
p.m. release	Week 1	5/6/2010 18:00	101	95	94
	Week 2	**All fish released am due to unit outage**			
	Week 3	5/18/2010 18:05	100	81	81
	Week 4	5/25/2010 18:05	77	59	77
	Week 5	6/3/2010 18:00	106	95	90
	Week 6	6/8/2010 18:10	105	83	79

Subyearling Chinook Salmon

During the 300-lux treatment, we observed shorter passage times for subyearling Chinook salmon released during evening (1800) than during daytime (0600) diel periods, with 39% more evening-released fish exiting the orifice within the first 3 h (Figure 16). Results during the 50-lux treatments were similar, with 34% more fish exiting the gatewell within the first 3 h for evening than for morning (0600) releases; however, the overall rate of passage rate during the 50-lux treatment was considerably lower than that during the higher intensity treatment. The reference treatment, in comparison, yielded considerably lower passage rates than either light treatments during either diel release period, with higher rates of fish remaining in the gatewell. For both morning and evening releases during the reference (light off) treatment, more than 37% of the fish remained within the gatewell beyond the conclusion of the 12-h test.

Estimated mean (of weekly median) gatewell egress for subyearling Chinook salmon during daytime releases was 6.2 h (95% CI, 4.8-7.5) during the 300-lux treatment, 7.0 h (95% CI, 5.5-8.6) during the 50-lux treatment, and 13.9 h (95% CI, 9.6-18.2) during the reference (light off) treatment (Figure 17). Fish released after 1800 h displayed shorter egress times with average median passage times of 1.1 h (95% CI, 0.9-1.3) for the 300-lux treatment, 1.4 h (95% CI, 1.2-1.6) for the 50-lux treatment, and 8.5 h (95% CI, 6.3-10.7) for the reference treatment (Table 6). Reference treatment fish released during week 3 displayed very low detection rates, but this was a result of the orifice being closed before the entire release group had exited the unit. This closure affected detection rates for both the day and evening release groups.

The time-to-event model best supported using AICc rank included all three factors, all interactions between factors, and the covariates *turbidity* and *flow* (Appendix Table 4). Model-averaged results of the top 2 models indicated a minimal difference between the two light treatments, while the reference (light off) treatment resulted in longer travel times for both daytime and nighttime release groups (Figure 18). The light treatment was most effective at night and when turbidity was higher.

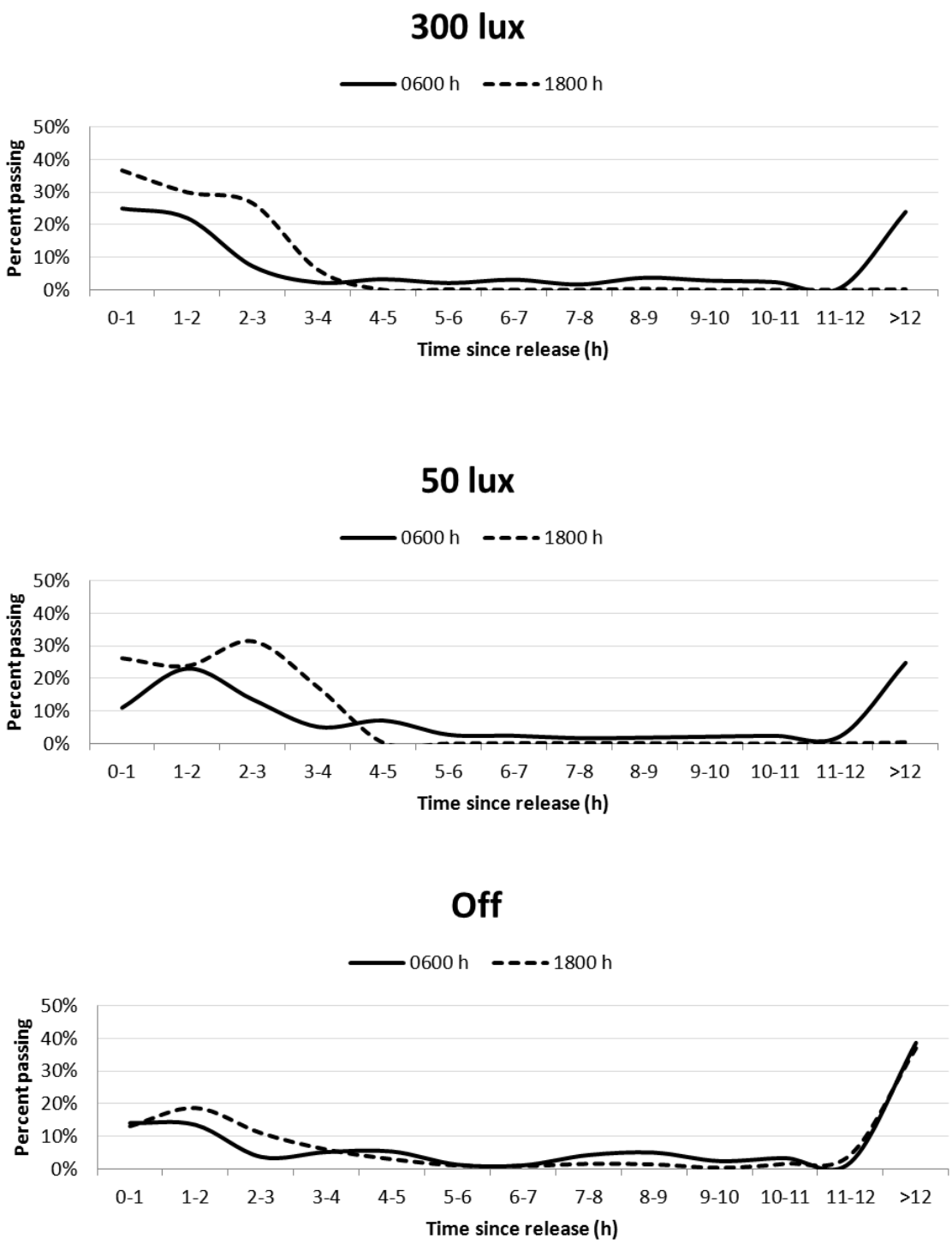

Figure 16. Percent passage of subyearling Chinook salmon plotted against time since release during the 300-lux (upper panel), 50-lux (middle panel), and reference (light off) orifice light treatments at McNary Dam, 2010.

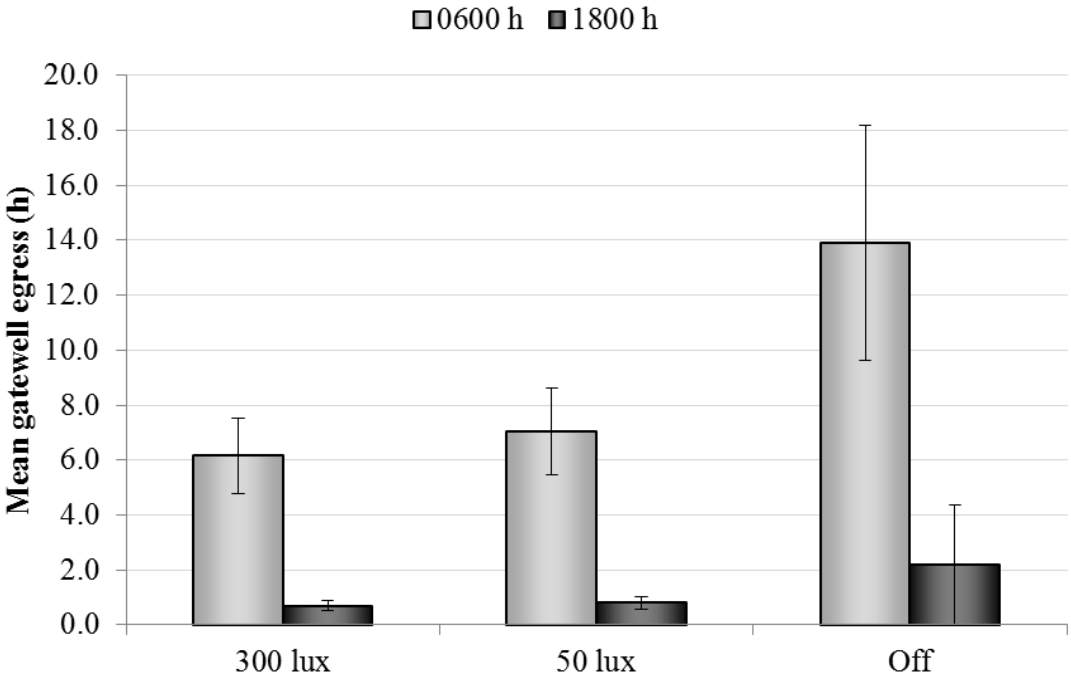

Figure 17. Estimated mean (of weekly median) gatewell egress during daytime (0600) and evening (1800) releases of subyearling Chinook salmon under three different light treatments in Unit 6B at McNary Dam, 2010. Whiskers indicate 95% CIs.

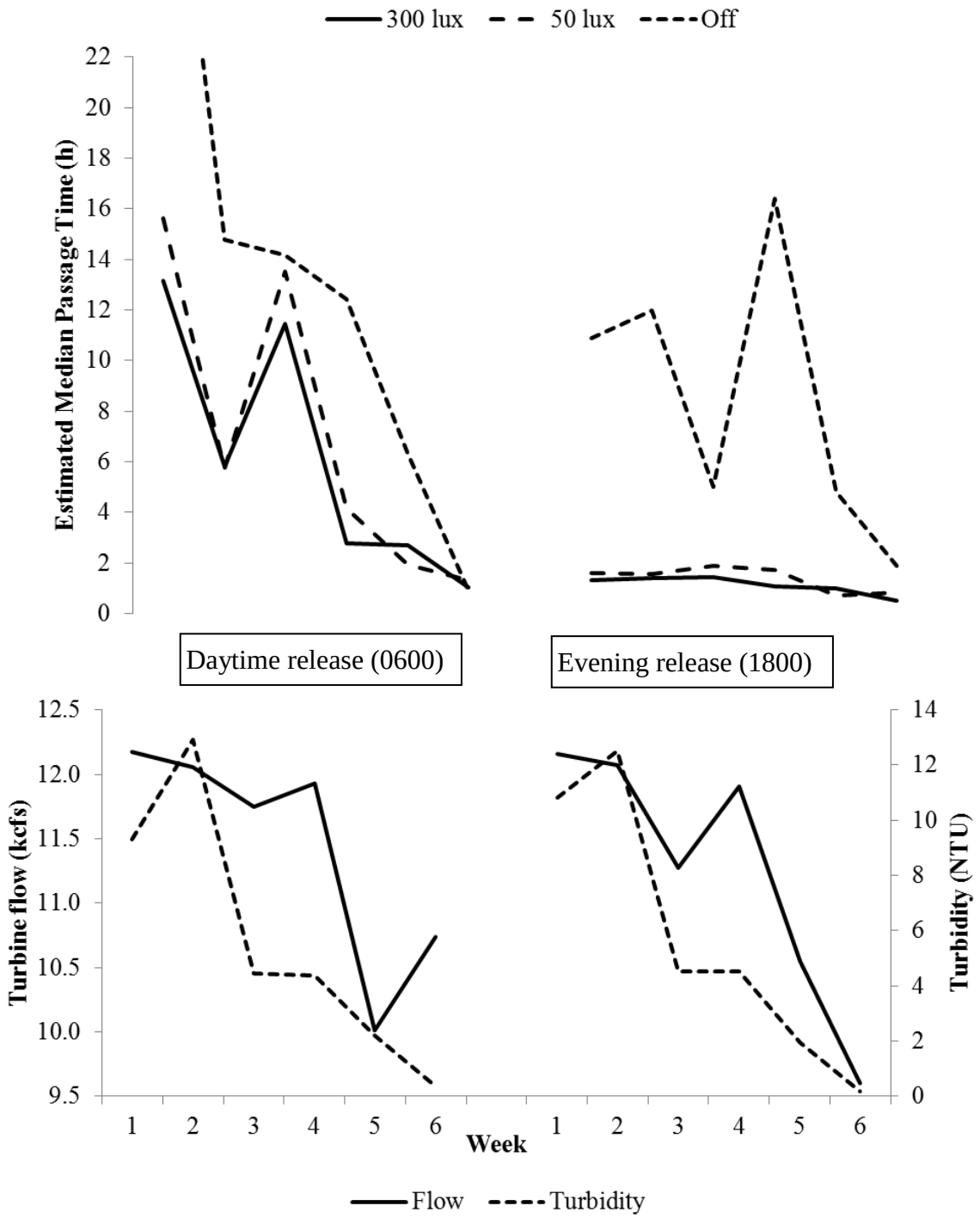

Figure 18. Upper panel shows estimated median gatewell egress by week using model-averaged data for subyearling Chinook salmon during three different orifice light treatments in Unit 6B at McNary Dam, 2010. Lower panel shows the extent to which *turbidity* and unit *flow* factored in AICc model selection.

Table 6. Numbers of subyearling Chinook salmon released and detected by treatment and release time within the gatewell at McNary Dam, 2010.

		Release date	Number released	Number detected	Percent detected
Low intensity (~50 lux)					
a.m. release	Week 1	6/10/2010 6:13	106	87	82
	Week 2	6/16/2010 6:15	149	115	77
	Week 3	6/22/2010 6:20	152	127	84
	Week 4	7/1/2010 6:20	151	121	80
	Week 5	7/9/2010 6:15	152	108	71
	Week 6	7/15/2010 6:14	147	111	76
p.m. release	Week 1	6/10/2010 18:10	103	84	82
	Week 2	6/16/2010 18:10	145	130	90
	Week 3	6/22/2010 18:15	155	135	87
	Week 4	7/1/2010 18:00	149	122	82
	Week 5	7/9/2010 18:00	152	122	80
	Week 6	7/15/2010 18:05	146	133	91
Reference (light off)					
a.m. release	Week 1	6/9/2010 6:14	85	65	76
	Week 2	6/15/2010 6:21	130	103	79
	Week 3	6/24/2010 6:17	149	27	18
	Week 4	6/30/2010 6:15	151	116	77
	Week 5	7/7/2010 6:15	151	124	82
	Week 6	7/17/2010 6:19	155	106	68
p.m. release	Week 1	6/9/2010 18:15	104	78	75
	Week 2	6/15/2010 18:40	119	87	73
	Week 3	6/24/2010 18:05	151	16	11
	Week 4	6/30/2010 18:10	148	126	85
	Week 5	7/7/2010 18:00	148	136	92
	Week 6	7/17/2010 18:05	157	130	83
High intensity (~300 lux)					
a.m. release	Week 1	6/8/2010 6:11	99	78	79
	Week 2	6/17/2010 6:26	112	95	85
	Week 3	6/23/2010 6:10	150	131	87
	Week 4	6/29/2010 6:28	151	121	80
	Week 5	7/8/2010 6:18	152	129	85
	Week 6	7/16/2010 6:05	165	122	74
p.m. release	Week 1	6/8/2010 18:10	103	89	86
	Week 2	6/17/2010 18:00	110	97	88
	Week 3	6/23/2010 18:24	150	129	86
	Week 4	6/29/2010 18:06	150	129	86
	Week 5	7/8/2010 18:00	146	124	85
	Week 6	7/16/2010 18:20	155	116	75

DISCUSSION

The presence of light in the orifice at McNary Dam generally decreased gatewell egress time for juvenile salmonids. While there were minimal differences between the 300- and 50-lux treatments, both provided a significant reduction in egress time compared to the reference (light off) treatment for most species released during both daytime and nighttime periods. A previous study found similar results and concluded that light in the orifices at Little Goose Dam increased passage rates for Chinook salmon, but appeared to have little effect on passing steelhead (Harmon and Park 1980). Our findings were similar for steelhead released in daytime periods. However, for steelhead released at night, both light treatments provided significantly shorter egress time.

Both light treatments also resulted in sizable reductions in gatewell egress time for sockeye salmon. Sockeye salmon have been shown to be highly susceptible to descaling (Martinson et al. 2010), and delay in the turbulent environment of the gatewell could increase descaling and injury rates. For subyearling Chinook salmon, delay in any area may lead to increased mortality (Richter and Kolmes 2005; Budy et al. 2002; Vigg and Burley 1991) due to exposure to higher water temperatures during the summer. Expedited passage of migrating juvenile salmonids is important to minimize descaling, injury, and stress-related impacts that may occur in the bypass system, particularly for species likely to encounter elevated water temperature and decreasing river flows.

Extensive delay within juvenile fish collection systems can also affect survival and overall fish health. Maule et al. (1988) found that stress levels in fish caused by different elements within the JBS have a cumulative effect, and that for yearling Chinook salmon, additional time spent in the bypass system can potentially depress the immune system and compromise the ability to cope with stresses. Therefore, any reduction in delay in the JBS should reduce the total stress experienced by fish and diminish impacts on fish health. The best opportunity for reducing passage delay associated with the JBS is to reduce gatewell residence time (Beeman and Maule 2001; Axel and Dey 2001).

In this study, we did not evaluate covered gatewells, so the effectiveness of light treatments may have been reduced by ambient light, particularly during the day. Future evaluations should evaluate the effectiveness of covering gatewells in order to reduce ambient light during the daytime, when greater proportions of juvenile salmonids remained in the gatewell beyond the 12-h test. Orifice passage occurred more readily at night for all treatments, with morning releases of yearling Chinook salmon and juvenile steelhead spending nearly twice as much time in the gatewell before passage, on average.

Beeman and Maule (2001) determined that most of their radio-tagged juvenile steelhead and yearling Chinook salmon passed through the gatewell to the collection channel during the evening, regardless of release time. While the orifice lights tested in this study offer prospective improvement in passage time of yearling Chinook salmon and steelhead during daytime hours, they offer and even greater benefit for sockeye and subyearling Chinook salmon. A combination of covered gatewells and adequate lighting at the orifice entrance (within 50-300 lux) could reduce delay by several hours for fish passing through the JBS.

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APPENDIX

Model Selection

Appendix Table 1. Model selection process statistics for yearling Chinook salmon based on Akaike's Information Criterion adjusted for sample size (AICc). Data was modeled using an exponential distribution. Models are listed in order from lowest AICc to highest. Delta AICc is the difference in AICc from the lowest model. Weight is the relative value of the model versus the others. Abbreviations: Wk, *week;* Dp, *diel period*; Tr, *treatment*; Len, *length*; Tur, *turbidity*; Flo, *flow*.

Model components	Log likelihood	Para-meters	Δ AICc	Weight
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len × Tur	-5006.0	24	0.0	0.44
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) Len × Tur	-5010.5	20	0.9	0.28
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) + (Dp × Tr) × Len × Tur × Flo	-5005.9	25	1.9	0.17
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len × Tur × Flo	-5010.5	21	2.9	0.11
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) × Len × Tur	-5025.3	22	34.5	0.00
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) × Len × Tur × Flo	-5025.3	23	36.5	0.00
Wk + Dp + Tr + (Wk × Tr) × Len × Tur	-5032.4	18	40.6	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len	-5032.8	19	43.4	0.00
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) + (Dp × Tr) × Len	-5028.7	23	43.4	0.00
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) + (Dp × Tr) × Len × Flo	-5028.6	24	45.3	0.00
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) + (Dp × Tr) × Tur	-5042.3	23	70.5	0.00
Wk + Dp + Tr + (Wk × D) + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-5042.1	24	72.3	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Tur	-5048.0	19	73.8	0.00
Wk + Dp + Tr + (Wk × Tr) × Len	-5055.5	17	84.8	0.00
Wk + Dp + Tr + (Wk × Tr) × Tur	-5067.1	17	108.1	0.00
Wk + Dp + Tr + (Wk × D) + (Dp × Tr) × Len × Tur × Flo	-5074.5	17	122.8	0.00
Wk + Dp + Tr + (Wk × D) + (Dp × Tr) × Len × Tur	-5077.0	16	125.8	0.00
Wk + Dp + Tr + (Dp × Tr) × Len × Tur	-5083.2	12	130.1	0.00
Wk + Dp + Tr + (Wk × Tr)	-5086.6	16	145.0	0.00
Wk + Dp + Tr × Len × Tur	-5105.3	10	170.2	0.00
Wk + Tr + (Wk × Tr) × Len × Tur	-5106.8	17	187.3	0.00
Wk + Tr + (Wk × Tr) × Len	-5127.3	16	226.3	0.00
Wk + Dp + Tr × Len	-5134.4	9	226.4	0.00
Wk + Dp + Tr	-5157.0	8	269.7	0.00
Wk + Tr + (Wk × Tr)	-5156.2	15	282.2	0.00
Wk + Tr	-5226.2	7	406.0	0.00
Wk + Dp	-5271.2	6	494.0	0.00

Appendix Table 2. Model selection process statistics for juvenile steelhead based on Akaike's Information Criterion adjusted for sample size (AICc). Data was modeled using an exponential distribution. Model in the first row has the lowest AICc. Delta AICc is the difference in a model's AICc from the lowest one. Weight is the relative value of the model versus the others. Abbreviations: Wk, *week;* Dp, *diel period*; Tr, *treatment*; Len, *length*; Tur, *turbidity*; Flo, *flow*.

Model components	Log likelihood	Para-meters	Δ AICc	Weight
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr)	-3296.9	18	0.0	0.28
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len	-3296.6	19	1.4	0.14
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Tur	-3296.6	19	1.4	0.14
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (D × Tr)	-3293.7	22	1.7	0.12
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Flo	-3296.9	19	2.0	0.10
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len	-3293.4	23	3.1	0.06
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur	-3293.5	23	3.3	0.05
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-3296.6	20	3.5	0.05
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Flo	-3293.7	23	3.7	0.04
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-3293.5	24	5.4	0.02
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr)	-3301.8	20	13.8	0.00
Wk + Dp + Tr + (Wk × Tr)	-3306.5	16	15.1	0.00
Wk + Tr + (Wk × Tr)	-3324.9	14	47.8	0.00
Wk + Dp + Tr + (Wk × Dp) + (Dp × Tr)	-3329.7	14	57.5	0.00
Wk + Dp + Tr + (Dp × Tr)	-3334.3	10	58.5	0.00
Wk + Dp + Tr + (Wk × Dp)	-3337.9	12	69.7	0.00
Wk + Dp + Tr	-3343.9	8	73.6	0.00
Wk + Dp	-3367.9	6	117.6	0.00
Wk + Tr	-3366.9	7	117.7	0.00
Wk	-3391.2	5	162.1	0.00

Appendix Table 3. Model selection process statistics for sockeye salmon based on Akaike's Information Criterion adjusted for sample size (AICc). Data was modeled using an exponential distribution. Model in the first row has the lowest AICc. Delta AICc is the difference in a model's AICc from the lowest one. Weight is the relative value of the model versus the others. Abbreviations: Wk, *week;* Dp, *diel period*; Tr, *treatment*; Len, *length*; Tur, *turbidity*; Flo, *flow*.

Model components	Log likelihood	Para-meters	Δ AICc	Weight
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len × Tur	-4729.3	28	0.0	0.42
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur	-4730.9	27	1.0	0.25
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len × Tur × Flo	-4729.2	29	1.9	0.17
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-4730.8	28	2.9	0.10
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len	-4733.4	27	6.1	0.02
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr)	-4734.9	26	7.1	0.01
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len × Flo	-4733.2	28	7.8	0.01
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len	-4739.7	22	8.5	0.01
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Flo	-4734.7	27	8.7	0.01
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr)	-4740.9	21	8.9	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len × Tur	-4739.4	23	9.9	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Tur	-4740.6	22	10.3	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len × Flo	-4739.6	23	10.3	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Flo	-4740.8	22	10.7	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Len × Tur × Flo	-4739.2	24	11.7	0.00
Wk + Dp + Tr + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-4740.5	23	12.1	0.00
Wk + Dp + Tr + (Wk × Tr)	-4758.5	19	40.0	0.00
Wk + Dp + Tr + (Wk × Dp) + (Wk × Tr)	-4753.9	24	41.0	0.00
Wk + Dp + Tr + (Wk × Dp) + (Dp × Tr)	-4872.7	16	262.4	0.00
Wk + Dp + Tr + (Dp × Tr)	-4886.0	11	278.8	0.00
Wk + Dp + Tr + (Wk × Dp)	-4887.8	14	288.5	0.00
Wk + Dp + Tr	-4905.0	9	312.8	0.00
Wk + Dp +	-5135.2	7	769.3	0.00
Wk + Tr + (Wk × Tr)	-5141.5	18	804.0	0.00
Wk + Tr	-5309.0	8	1118.8	0.00
Week	-5474.0	6	1444.8	0.00

Appendix Table 4. Model selection process statistics for subyearling Chinook salmon based on Akaike's Information Criterion adjusted for sample size (AICc). Data was modeled using an exponential distribution. Model in the first row has the lowest AICc. Delta AICc is the difference in a model's AICc from the lowest one. Weight is the relative value of the model versus the others. Abbreviations: Wk, *week;* Dp, *diel period*; Tr, *treatment*; Len, *length*; Tur, *turbidity*; Flo, *flow*.

Model components	Log Likelihood	Para-meters	Δ AICc	Weight
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur × Flo	-6787.9	28	0.0	0.55
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Flo	-6789.1	27	0.4	0.45
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Tur	-6797.7	27	17.7	0.00
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) Dp × Tr)	-6799.3	26	18.8	0.00
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) + (Dp × Tr) × Len	-6798.9	27	20.0	0.00
Wk + Dp + Tr (Wk × Dp) + (Dp × Tr) × Tur × Flo	-6852.3	18	108.6	0.00
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr) × Tur × Flo	-6860.5	26	141.1	0.00
Wk + Dp + Tr (Wk × Dp) + (Wk × Tr)	-6873.3	24	162.7	0.00
Wk + Dp + Tr (Wk × Tr) + (Dp × Tr) × Tur × Flo	-6880.2	23	174.5	0.00
Wk + Dp + Tr (Wk × Dp) + (Dp × Tr)	-6898.8	16	197.6	0.00
Wk + Dp + Tr (Wk × Tr) + (Dp × Tr)	-6915.0	21	239.9	0.00
Wk + Dp + Tr (Wk × Dp)	-6970.9	14	337.6	0.00
Wk + Dp + Tr (Dp × Tr)	-7012.4	11	414.6	0.00
Wk + Dp + Tr (Wk × Tr)	-7018.0	19	442.0	0.00
Wk + Dp + Tr	-7102.7	9	591.3	0.00
Wk + Tr (Wk × Tr)	-7361.7	18	1127.5	0.00
Wk + Tr	-7455.3	8	1294.5	0.00
Wk + Dp	-7667.9	7	1717.7	0.00
Week	-7867.3	6	2114.5	0.00