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Turbulence Investigation and Reproduction for Assisting Downstream Migrating Juvenile Salmonids, Part II of II

Effects of Induced Turbulence on Behavior of Juvenile Salmon

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Effects of Induced Turbulence on Behavior of Juvenile Salmon

Draft Report of Research

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Executive Summary

Passage through dams is a major source of mortality of anadromous juvenile salmonids because some populations must negotiate up to eight dams in Columbia and Snake rivers. Dams cause direct mortality when fish pass through turbines, but dams may also cause indirect mortality by altering migration conditions in rivers. Forebays immediately upstream of dams have decreased the water velocity of rivers and may contribute substantially to the total migration delay of juvenile salmonids. Recently, Coutant (2001a) suggested that in addition to low water velocities, lack of natural turbulence may contribute to migration delay by causing fish to lose directional cues. Coutant (2001a) further hypothesized that restoring turbulence in dam forebays may reduce migration delay by providing directional cues that allow fish to find passage routes more quickly (Coutant 2001a). Although field experiments have yielded proof of the concept of using induced turbulence to guide fish to safe passage routes, little is known about mechanisms actually causing behavioral changes.

To test hypotheses about how turbulence influences movement and behavior of migrating juvenile salmonids, we conducted two types of controlled experiments at Cowlitz Falls Dam, Washington. A common measure of migration delay is the elapsed time between arrival at, and passage through, a dam. Therefore, for the first set of experiments, we tested the effect of induced turbulence on the elapsed time needed for fish to traverse through a raceway and pass over a weir at its downstream end (time trial experiment). If turbulence helps guide fish to passage routes, then fish should pass through the raceway quicker in the presence of appropriately scaled and directed turbulent cues. Second, little is known about how the physical properties of water movement provide directional cues to migrating juvenile salmonids. To examine the feasibility of guiding fish with turbulence, we tested whether directed turbulence could guide fish into one of two channels in the raceway, and subsequently cause them to pass disproportionately over the weir where turbulent cues were aimed (guidance experiment). Last, we measured and mapped water velocity and turbulence during the experiments to understand water movement patterns and the spatial distribution of turbulence in the raceways.

For both the time trial and guidance experiments, we found that small water jets and propellers (hereafter referred to as props) created directed turbulence relative to the control where no turbulence was induced. We found that the treatments affected the spatial pattern of water velocity and turbulence. For the control, water velocities were low, uniform, and moved in a downstream direction with very little turbulence. Compared to the control, the jet and prop treatments altered the direction of water velocity diagonally across raceway and downstream. Relative to controls, the jet and prop treatments also induced substantial turbulence as was indicated by turbulent kinetic energy (TKE), turbulent intensity (TI), and strain. The props affected water velocities and turbulence over a larger area of the raceway than the jet treatments, although the magnitude of velocity and turbulence was generally similar between the two treatments. Water velocity vectors indicated that both props and jets induced a recirculating eddy pattern, but the props appeared to induce higher-velocity eddies. These differences in eddies were likely caused by differences in motive water between jets and props, where the jets draw water from the flume and the props draw water directly from the raceway.

For the time trial experiments, we found that the treatments, time of day (day or night), and light and turbidity affected passage times of juvenile coho salmon. For coho salmon, we found that jet treatments caused fish to pass through the raceway in significantly less time than for either props or control treatments (daytime only). For night trials with coho salmon, there was no significant difference in passage times between jet and control treatments, but passage times for both were significantly less than for props. For Chinook salmon, we found that passage times were substantially longer during the night, compared to the day. For both day and night, passage times of Chinook salmon for prop and jet trials were significantly longer than controls. We used a combined measure of light and turbidity (log[light]/turbidity) as an index of light levels experienced by fish after being attenuated by water of different turbidities. For coho salmon during the night, we found an inverse relationship between passage times and the light index, but during the day we found that passage times were positively related to the light index. For Chinook salmon, we found passage times were inversely related to the light index regardless of the day or night, which caused passage times to be longer during the night.

For the guidance experiment, we tested whether directed turbulence could guide fish into one of two channels in the raceway, and subsequently cause them to pass disproportionately over the weir where turbulent cues were aimed. For this test we used three treatments; turbulence aimed at the north channel, turbulence aimed at the south channel, and no induced turbulence (control). Although we found a statistical difference between some treatments, we found little evidence that the turbulence treatments provided a consistent directional guidance to influence the proportion of fish passing through the north weir. A mean of 36% of fish (SE=0.06) passed through the north weir for the controls, 54% of fish (SE=0.05) passed through the north weir for the north treatment, and 53% of fish (SE=0.04) passed through the north weir for the south treatment. We found treatments were significantly different at a significance level of alpha=0.10. Multiple comparisons (Tukey's HSD test) conducted at a significance level of 0.10 showed that the south treatment was significantly different than controls, but there was no significant difference between north and south treatments, nor between control and north treatments. In addition, we found no consistent relation of proportional passage through the north weir with ambient light levels, turbidity, or the light index.

We found that many factors affected the behavior of juvenile salmon in response to turbulence. During the time trial experiment, we observed high trial-to-trial variation in passage times, but that much of this variation could be explained by time of day, ambient light levels, and turbidity. We also found differences between juvenile Chinook salmon and coho in their response to these environmental variables. Last, we observed other behavioral differences between species such as schooling observed with coho salmon, but not Chinook salmon. Overlaid on variation caused by environmental factors was the effect of turbulence treatments, the direction of which differed between species and treatment. We suspect that these behavioral differences may have been caused by differences in the degree of smoltification of juvenile Chinook and coho salmon, rather than by innate differences between species. If physiological status differed between species, then degree of smoltification could explain fish response to turbulence. For the guidance experiment, we showed that turbulence treatments affected the proportion of fish passing through each channel, but that the direction of the effect was inconsistent between the north and south treatments. It is possible that turbulence in general provided a form of cover that distributed fish more evenly in the raceway, relative to the control where fish passed preferentially through one channel. Our experiments highlight the complexity of fish behavior and the difficulty of prescribing general guidelines for the application of induced turbulence. Nonetheless, under some circumstances induced turbulence had desirable effects on fish behavior that could be applied to field scenarios to reduce migration delays and guide fish to safe passage routes.

Introduction

As juvenile salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) migrate from their natal streams to the ocean, they are subject to mortality from both natural and anthropogenic sources. Passage through dams is a major source of direct mortality because some populations must negotiate up to eight dams in Columbia and Snake rivers (Nehlsen et al. 1991). Dams cause direct mortality such as passage through turbines (Schoenemen et al. 1961; Mathur et al. 1996), but dams may also cause indirect mortality by altering migration conditions in rivers. For instance, dams increase the cross-sectional area of rivers, thereby reducing water velocities and increasing travel times of juvenile salmonids. Decreased travel rates may indirectly reduce survival by causing increased opportunity for avian and piscivorous predators (Poe et al. 1991; Vigg et al. 1991; Petersen 1994; Ward 1995; Collis 2001), greater energy expenditure per unit distance traveled (Congleton 2002), reversal of smoltification (i.e., residualism; Sims et al. 1978; Raymond 1979; Zaugg 1981; Viola and Schuck 1995; Bennett 1992), and delayed arrival to the estuary (Zaugg 1985; Budy et al. 2002).

Migration delay in forebays immediately upstream of dams may contribute substantially to the total migration delay, relative to delays incurred during migration through reservoirs. Venditti et al. (2000) and Plumb et al. (2003) showed that median migration rates of juvenile salmonids in the reservoir ranged from about 10 km/d to 40 km/d, but migration rates through dam forebays were less than 10 km/d and often approached zero during periods of low flow. These researchers identified two important behaviors that likely contributed to slow migration rates through forebays. First, in the forebay fish were observed to travel back and forth numerous times along the face of the dam, indicating they were searching for a suitable passage route (Venditti et al. 2000). Second, a high proportion of fish were observed traveling a considerable distance upstream after arriving at the dam (14 km for Venditti et al. 2000, 9.6 km for Plumb et al. 2003). One hypothesis explaining this behavior proposes that slow water velocities near dams cause fish to lose their directional cues to travel downstream (Coutant 2001a; ISAB 2003).

Coincident with reduced water velocities in reservoirs is a lack of turbulence that fish normally experience in natural river systems. Recently, Coutant (2001a) suggested that in addition to low water velocities, lack of natural turbulence may contribute to the loss of directional cues observed in behavior of migrating fish near dams. Fish detect changes in velocity using multiple senses including the lateral line, inner ear, vision, and tactile sensations (Montgomery et al. 1997; 2000). Superficial neuromasts in the lateral line detect magnitude and direction of flow, and allow fish to detect changes in flow over different parts of the body (Montgomery et al. 1997; 2000). Because turbulence is variation in water velocity over space and/or time, lack of turbulence may reduce the ability of fish to detect changes in flow velocity and direction, thereby contributing to the loss of directional cues.

Recently, Coutant (2001a) hypothesized that restoring turbulence in dam forebays may reduce migration delay by providing directional cues that allow fish to find passage routes more quickly. Coutant (2001a) proposed that the natural turbulence of rivers could be mimicked using a series of water jets or propellers (hereafter referred to as props) aimed downstream and towards safe routes of passage. Field research using "induced turbulence" techniques have shown promise in positively affecting fish migration behavior. Darland et al. (2001a) showed that turbulence induced with large props succeeded in altering approach paths of fish from the north side of a dam forebay to the south side of the forebay. In a subsequent experiment, Darland et al. (2001b) showed that induced turbulence aimed toward surface collection entrances increased the number of juvenile salmonids passing via the surface collection system, relative to a control without induced turbulence.

Although these field experiments yield proof of the concept of using induced turbulence to guide fish to safe passage routes, little is known about mechanisms actually causing behavioral changes. First, little research has measured turbulence in combination with fish behavior. In field settings, measuring and mapping the spatial distribution of turbulence is difficult because of the large scale of dam forebay environments. Second, species-specific responses, physiological status of fish, implementation design of jets or props, and the structure, scale, and magnitude of induced turbulence may determine how fish respond behaviorally. Moreover, in the field fish respond to multiple environmental factors such as weather, time of day, season, discharge, and dam operations, which makes it difficult to identify causal mechanisms of fish response to induced turbulence.

To test hypotheses about how turbulence influences movement and behavior of migrating juvenile salmonids, we conducted two types of controlled experiments at Cowlitz Falls Dam, Washington. Migration delay is one consequence of the inability of fish to locate safe routes of passage through dams. A common measure of migration delay is the elapsed time between arrival at, and passage through, a dam. Therefore, for the first set of experiments, we tested the effect of induced turbulence on the elapsed time needed for fish to traverse through a raceway and pass over a weir at its downstream end. If turbulence helps guide fish to passage routes, then fish should pass through the raceway quicker in the presence of appropriately scaled and directed turbulent cues. Second, little is known about how the physical properties of water movement provide directional cues to migrating juvenile salmonids. To examine the feasibility of guiding fish with turbulence, we tested whether directed turbulence could guide fish into one of two channels in the raceway, and subsequently cause them to pass disproportionately over the weir where turbulent cues were aimed. Last, we measured and mapped water velocity and turbulence during the experiments to understand water movement patterns and the spatial distribution of turbulence in the raceways.

Methods

Study Area

We conducted our study at Cowlitz Falls Dam on the Cowlitz River, a tributary to the Lower Columbia River in Southeast Washington. The Cowlitz River drains into the Columbia River about 70 km downstream of Portland, Oregon and its headwaters are located near Mount Ranier, Mount Adams, and Mount Saint Helens, Washington. Cowlitz Falls Dam is the uppermost of three dams on the Cowlitz River. Cowlitz Falls Dam has a fish collection facility to collect and transport juvenile anadromous salmonids around the lower two dams, one of which lacks fish collection facilities. During the juvenile salmonid migration discharge at Cowlitz Falls Dam normally ranges from 1,500

ft^3s^{-1} to 10,000 ft^3s^{-1}, and temperature ranges from 10 °C to 16 °C. Turbidity in the Cowlitz River fluctuates with air temperature due to glacial runoff from Mount Ranier and normally ranges between 10 and 30 NTUs (nephelometric turbidity units).

Cowlitz Falls Dam was an excellent site to conduct our experiments for a number of reasons. First, we considered the origin of fish to be an important factor in how migrating juvenile salmonids might respond to turbulence. Naturally reared, juvenile fish exposed to ambient levels of river turbulence and collected during their normal seaward migration may react differently to turbulence than hatchery-reared fish exposed to lower levels of turbulence in raceways. The Cowlitz River supports three species of naturally reared anadromous salmonids – steelhead *Oncorhynchus mykiss*, coho salmon *Oncorhynchus kisutch*, and Chinook salmon *Oncorhynchus tshawytscha*, whereas at most other potential study sites, only hatchery-reared juvenile salmonids were available as experimental subjects. Second, we were able to conduct experiments with both coho salmon and Chinook salmon because their run-timings were distinct, with coho migrating in June and July and Chinook migrating in August. Last, the fish collection facility provided a source of fish and had a suitable raceway in which to conduct our experiments.

Environmental Conditions

To quantify the effect of environmental variation on movement of fish through the raceway, we collected data on a number of physical parameters. We collected ambient light levels at the beginning of each experiment using a light meter (Radiometer/Photometer, International Light Inc., Model IL 1400A). We also obtained records of daily temperature and turbidity from Washington Department of Fish and Wildlife (WDFW) personnel, who operated the fish collection facility. Because fish may use both visual and turbulent cues to negotiate the raceway, we conducted experiments during both day and night when visual cues would be maximized and minimized, respectively.

Time Trial Experiments

The turbulence experiments were conducted in a concrete raceway at Cowlitz Falls Dam. The raceway was located outdoors at the fish collection facility at Cowlitz Falls Dam. The raceway was 15.1 m long and 2.44 m wide with a slope of 1.5% and average water depth of 0.84 m (Figure 1). The raceway was oriented in an east-west direction with the water running from west to east. Due to this orientation, the south wall cast a shadow into part of the raceway during much of the day. Ambient river water was obtained from the fish collection facility and fed into the upstream end of the raceway via a flume. A fish holding and acclimation area was installed in the raceway using perforated aluminum panels (Figure 1). To smooth the flow and create uniform velocities in the raceway, additional perforated panels were placed on the upstream end of the holding area.

Because little is known about the appropriate scale or structure of turbulence to which fish respond, we created turbulence using two types of devices following the approach of Hotchkiss (2002). First, we used oscillating hot tub jets with a nozzle diameter of 1.5 cm. Depending on the experiment, either two or three jets were run in-series and were powered by 1.5 hp electric centrifugal pump (Dayton Inc.) operating at 3,450 rpm (rotations per minute) and pumping 50-60 gpm (gallons per minute). The jets were configured to oscillate in the downstream direction. Second, we used variable-speed electric trolling motors (HVT Motorguide, 32 lb thrust, 12 volts) to drive a 36°-pitch, 4-blade, 11.7-cm diameter prop. All motors were operated at the lowest speed setting during the experiments.

Raceway setup

We tested the effect of three treatments on passage times of juvenile salmon: turbulence induced with jets, turbulence induced with props, and a control (no induced turbulence). We installed three jets and three props along the north wall of the raceway (Figure 1). The jets and props were angled downstream to create a plume of turbulence that cut diagonally across the raceway.

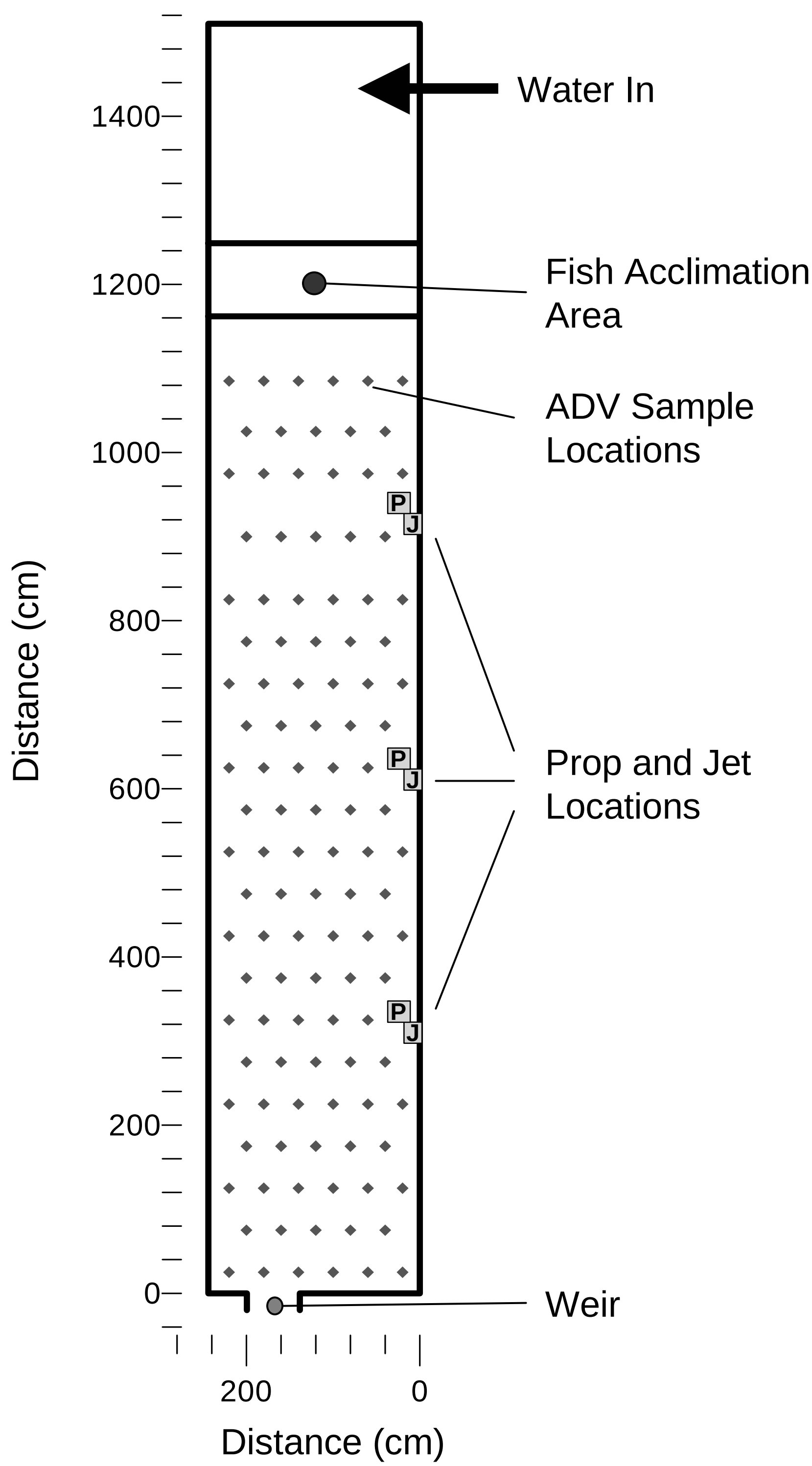

Figure 1. — Schematic of the raceway time trial experiment conducted at Cowlitz Falls Dam during 2002. Shown are the raceway dimensions; locations of the props (P), jets (J), weir, water input, and fish acclimation area; and locations of water velocity samples measured using the acoustic Doppler velocimeter (ADV).

To determine the effect of turbulence on passage time through the raceway, we measured the time it took fish to pass over a weir at the downstream end of the raceway. The weir was a 0.61-m wide sharp-crested weir constructed of 2x4-in lumber and was located south of the center of the raceway (Figure 1). During the time trial experiments water height over the weir was maintained at 13.5 cm corresponding to a discharge of 2 ft^3s^{-1}. Connected to the downstream end of the weir was a separator rack constructed of 1-in PVC pipe with 1-cm spacing. Water, but not fish, passed through the separator rack. The separator rack was connected to a catch bucket (100 L) to collect fish once they passed over the weir. To identify when each fish passed over the weir, the separator rack was filmed during the experiments with a video camera and recorded with a time-lapse VCR. To record fish passing over the weir at night but minimize visible light that might affect fish behavior, we used an infrared lens over an incandescent bulb, which illuminated the separator rack.

Running the time trials

We planned to conduct 10 time trials for each treatment (control, jet, prop); however, for coho salmon, we were able to run 11 control, 10 jet, and 10 prop trials. For Chinook salmon we ran 8 control, 8 jet, and 7 prop trials. Each day, we conducted one day trial and one night trial. The order of conducting the three treatments was randomly assigned within day trials and night trials. Each trial was conducted as follows: 25 fish were obtained from the fish collection facility and held overnight to recover from the stress of handling and anesthesia. Following the recovery period, fish were introduced to the acclimation area of the raceway by gently tipping their holding bucket into the raceway. Fish were allowed 3 h to acclimate to the raceway before beginning each trial.

Just prior to starting each trial, the jets or props were turned on (for treatments), the video recorder was started, light levels were recorded, the fish were released by removing the downstream perforated panels of the acclimation area, and their release time was recorded. Each trial was run for 5 – 6 h, during which time care was taken not to disturb the experiments. At the end of each trial, fish that passed over the weir were counted from the catch bucket, the raceway was drained, and the number of fish remaining in the raceway was recorded.

Data analysis

To analyze data from the time trial experiments, videos of the separator rack connected to the weir were reviewed and the time that each fish passed the weir was recorded. For each fish, we then calculated passage time through raceway as the elapsed time from the start of the trial to the time of passage. During review of the videos, we noted that fish were passing over the weir in distinct groups, indicating schooling behavior in the raceway. To quantify this behavior, we assigned fish to a group if the time between passage of consecutive fish was <5 s. If the time between consecutive fish was >5 s, the fish was assigned to a new group. This allowed us to quantify the prevalence of schooling behavior and passage of groups of fish by plotting a frequency distribution of group sizes.

We used analysis of covariance to understand which factors explained the most variation in passage times of juvenile coho and Chinook salmon. We constructed an ANCOVA model with the fixed effects of TREATMENT (control, jet, prop) and TIMEOFDAY (day, night). Ambient light levels and turbidity likely interact by altering light levels experienced by fish in the raceway after the light was attenuated by water of different turbidities. To understand how light and turbidity affected passage times of juvenile coho salmon, we used a combined index of ambient light and turbidity (log[light levels] ÷ turbidity). This index was included as a covariate in the ANCOVA model and provided a relative measure of the light levels experienced by fish in the raceway. In addition to these main effects, we tested all possible interactions between factors. The passage times of coho and Chinook salmon violated several of the assumptions necessary for using parametric analysis to statistically compare the treatments. Specifically, passage time distributions were skewed and variances of passage times between some groups differed by an order of magnitude. To normalize the distribution and stabilize the variance, we log-transformed passage time data to prior to statistical analysis.

Guidance Experiment

Raceway setup

For our second experiment, we tested whether directed turbulence could guide fish to pass over one of two weirs in the raceway. We used plywood to divide the raceway into two 2.45-m long channels directly upstream of the weir (Figure 2). Each channel was equipped with a 0.45-m wide weir located 0.15 m from the center divider. We installed two oscillating jet nozzles on each side of the raceway 4.5 m upstream of the weirs (Figure 2). We used only jets for this experiment based on preliminary findings of the time trial experiment showing that coho passed through the raceway quickest during the jet treatments. During the experiments, water height over the weirs was maintained at 11 cm, corresponding to a discharge of 1.06 ft^3s^{-1} through each weir. A separator rack and catch bucket was attached to the downstream end of each weir to catch fish after passing through the raceway. A tarp was suspended about 6 m above the raceway to shade the raceway and reduce shadows that could affect which weir fish passed through. However, the tarp did not completely eliminate a shadow cast along the south side of the raceway during the daytime.

Running the raceway guidance experiment

We used three treatments to test the effect of the turbulence on guidance of fish through the raceway: turbulence aimed at the north channel, turbulence aimed at the south channel, and a control with no induced turbulence. For the north treatment, the south jet was aimed across the raceway at the north channel and the north jet was aimed directly downstream towards the north channel. The jets were switched for the south treatment (i.e., north jet aimed at south channel, south jet aimed directly downstream).

To test the effect of turbulence on guidance of fish, we compared the number of fish passing through each of the channels during the treatments. We conducted 10 trials for each treatment between August 14 and August 24, 2002. We used only juvenile Chinook salmon for this experiment because juvenile coho salmon were not available. The order of conducting the three treatments was randomly assigned within day and night trials. Each trial was conducted as follows: 18-25 fish were obtained from the fish

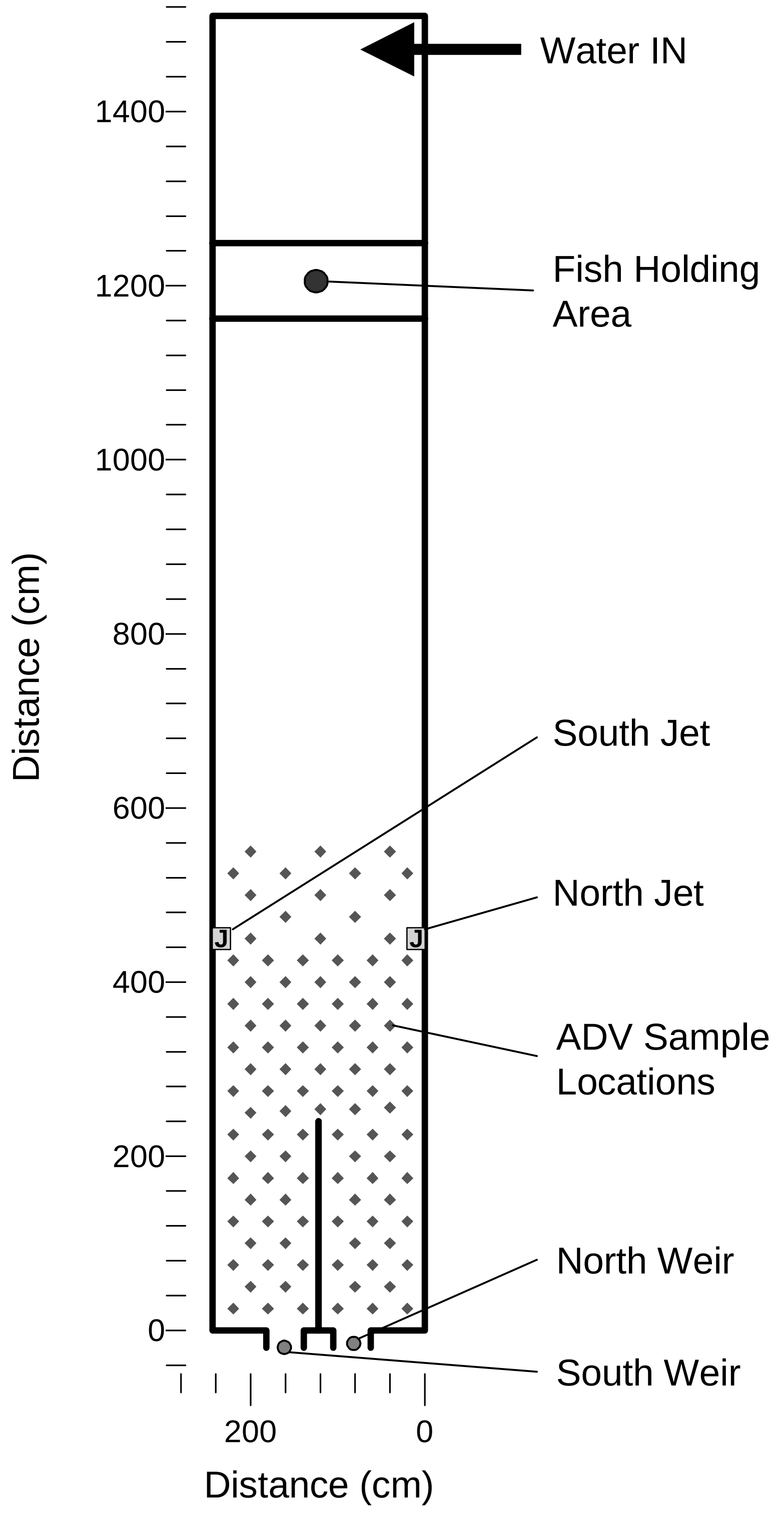

Figure 2. — Schematic of the raceway guidance experiment conducted at Cowlitz Falls Dam during 2002. Shown are the raceway dimensions; locations of the jets (J), weirs, water input, and fish acclimation area; and locations of water velocity samples measured using the acoustic Doppler velocimeter (ADV).

collection facility and held overnight to recover from stress of handling and anesthesia. Following the recovery period, fish were introduced to the acclimation area of the raceway by gently tipping their holding bucket into the raceway. Fish were allowed 2 h to acclimate to the raceway before beginning each trial. Just prior to starting each trial, the jets were turned on (for treatments), light levels were recorded, and the fish were released by removing the downstream perforated panels of the acclimation area. Each trial was run for 3 h, during which time care was taken not to disturb the experiments. Following the trials, the number of fish passing over each weir was counted from the catch buckets, the raceway was drained, and the number of fish remaining in the raceway was recorded.

Data analysis

To determine the effect of turbulence on guiding fish through the channels, we tested the null hypothesis of no difference among treatments in the proportion of fish passing through the north channel. We used each trial as replicates and used analysis of variance (ANOVA) with TREATMENT (control, north, south) and TIMEOFDAY (day and night) as class factors to test for differences in the mean proportion of fish passing through the north channel. We also plotted the proportion of fish passing through the north channel against ambient light levels, turbidity, and the light index to determine whether light levels or turbidity affected passage through the north or south channels.

Quantifying Velocity and Turbulence

To quantify the effect of the treatments on water velocity and turbulence, we measured velocity and turbulence using an Acoustic Doppler Velocimeter (ADV, SonTek Instruments). The ADV was deployed from a rigid sampling frame to minimize movement of the ADV probe, which could introduce noise into the instantaneous velocity measurements. For the time trial experiments, we collected 116 point samples for each treatment with the sample points arranged in a grid pattern (Figure 1). For the guidance experiment, we collected 105 point samples for each treatment with the point samples arranged in a grid pattern (Figure 2). Each sample was collected for 2 min with velocity readings in each direction (x, y, and z) collected every 0.25 s. Water velocity samples were collected at half the water's depth, the depth at which props and jets were deployed. Each 2-min sample was filtered to exclude data points where the correlation among beams was <90%. We calculated strain, turbulent intensity, turbulent kinetic energy, and mean velocities in each direction. To examine the effects of the treatments on velocity and turbulence patterns, we mapped velocity and turbulence parameters using the Kriging method to interpolate values between sampling points.

Turbulent Kinetic Energy (TKE) was calculated as:

$$TKE = 0.5\left(\sum\frac{\left(U_i - \overline{U}\right)^2}{n} + \sum\frac{\left(V_i - \overline{V}\right)^2}{n} + \sum\frac{\left(W_i - \overline{W}\right)^2}{n}\right)$$

Where U_i, V_i, and W_i is the instantaneous water velocity at time *i* in the streamwise, transverse, and vertical directions, respectively; $\overline{U}$, $\overline{V}$, and $\overline{W}$ are the mean velocities of each two-minute sample for each direction; and *n* is the number of observations in each two-minute sample.

Turbulent intenstity was calculated for each component as

$$\overline{TI(x)} = \frac{\sum_{i=1}^{n}\sqrt{\left(U_i - \overline{U}\right)^2}}{n}$$

$$\overline{TI(y)} = \frac{\sum_{i=1}^{n}\sqrt{\left(V_i - \overline{V}\right)^2}}{n}$$

$$\overline{TI(z)} = \frac{\sum_{i=1}^{n}\sqrt{\left(W_i - \overline{W}\right)^2}}{n}$$

Where $\overline{TI(x)}$, $\overline{TI(y)}$, and $\overline{TI(z)}$ are mean turbulent intensities in the streamwise, transverse, and vertical directions, respectively. For examining the effect of treatments, we mapped only the total mean turbulent intensity, which was calculated as

$$\overline{TI} = \frac{\overline{TI(x)} + \overline{TI(y)} + \overline{TI(z)}}{3}$$

We also calculated strain, which is the change in velocity over the distance between adjacent sampling points. Strain can be calculated in any direction, but we calculated change in the streamwise velocity over the transverse direction; or

$$\frac{d\overline{U}}{dy} = \frac{\overline{U_i} - \overline{U_{i-1}}}{Y_i - Y_{i-1}}$$

Where $d\overline{U}$ is change mean streamwise velocity, *dy* is the transverse distance between adjacent sampling locations, and Y_i is the location of each sample.

Results

Environmental conditions

Since experiments were conducted outdoors and used ambient river water, environmental conditions varied during our experiments. Weather during the experiments ranged from cloudy and rainy days to sunny and clear days. These weather variations affected water turbidity, water temperature, and ambient light levels. Water temperatures increased in early July, was stable from mid-July through early August, and ranged from 11°C to 17.5°C (Figure 3a). Turbidity varied substantially during the experiments and ranged from 5.73 NTU to 38.9 NTU (Figure 3a). Ambient light levels during the day varied by an order magnitude from 539 lumens/ft^2 (lm/ft^2) on a cloudy day to 10,700 lm/ft^2 on a clear, sunny day (Figure 3b). Ambient light levels at night varied by four orders of magnitude from 0.001 lm/ft^2 on a clear, moonless night to 6.2 lm/ft^2 on a moonlit night (Figure 3b).

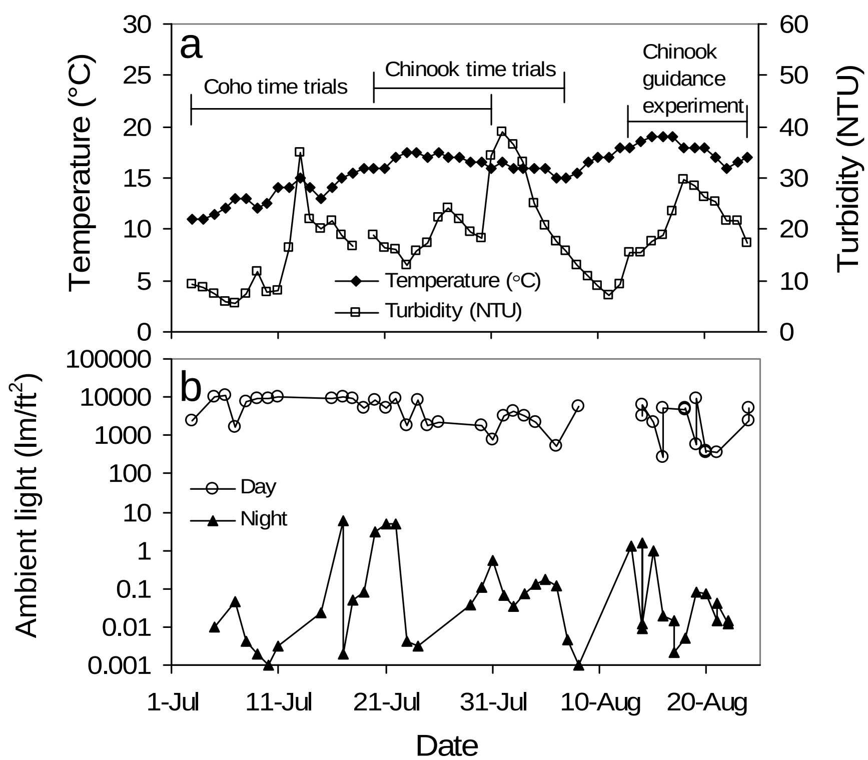

Figure 3. — Ambient environmental conditions during the turbulence raceway experiments conducted at Cowlitz Falls Dam during 2002. Shown are water temperature (top), turbidity (top), light levels during the day (bottom), and light levels during the night (bottom).

Time trial experiments

Water velocity and turbulence

For all water velocity and turbulence parameters, we found substantial differences among the control, jet, and prop treatments. Mean values for all parameters were higher for jet and prop treatments, compared to controls (Table 1). Mean velocity, TI, and strain values for treatments were approximately double that of the controls. Both jet and prop treatments also substantially increased the variation among sampling points for all parameters (Table 1). Although the prop and jet treatments did not affect minimum values of parameters, maximum values of all parameters were much higher than controls (Table 1). Comparing jets and props, props had higher mean values for all parameters, likely because they affected a larger area of the raceway than the jets (Figures 4-7). In contrast, jets had a higher maximum velocity and strain than props, which may have been caused by the small, localized jet of water.

Table 1. — Summary of velocity and turbulence parameters collected during the time trial experiments conducted at Cowlitz Falls Dam during 2002.

Parameter	Mean	Standard deviation	Minimum	Maximum
Mean velocity magnitude (cm/s)				
Control	2.2	1.6	0.17	9.1
Jet	4.1	4.4	0.15	29.4
Prop	4.7	4.6	0.30	26.8
Turbulent kinetic energy (cm^2/s^2)				
Control	6.3	3.3	2.4	23.4
Jet	15.5	18.0	3.1	113.1
Prop	25.7	25.2	3.6	146.9
Mean turbulent intensity (cm/s)				
Control	1.4	0.3	0.9	2.9
Jet	2.3	1.0	1.1	6.8
Prop	2.9	1.3	1.3	7.8
Strain (dU/dy, cm/s/cm)				
Control	0.043	0.041	0.000	0.211
Jet	0.093	0.124	0.001	0.682
Prop	0.096	0.099	0.000	0.546

We found that the treatments affected the spatial pattern of water velocity and turbulence. For the control, water velocities were low, uniform, and moved in a downstream direction with very little turbulence (Figures 4,5,6, and 7). Compared to the control, the jet and prop treatments altered the direction of water velocity diagonally across raceway and downstream (Figure 4). Relative to controls, the jet and prop treatments also induced substantial turbulence as was indicated by TKE, TI, and strain (Figures 5, 6, and 7). The props affected water velocities and turbulence over a larger area of the raceway than the jet treatments, although the magnitude of velocity and turbulence was generally similar between the two treatments (Figures 4,5,6, and 7). Water velocity vectors indicated that both props and jets induced a recirculating eddy pattern, but the props appeared to induce higher-velocity eddies, especially for the prop furthest upstream in the raceway (Figure 4). These differences in eddies were likely caused by differences in motive water between jets and props, where the jets draw water from the flume and the props draw water directly from the raceway.

Coho salmon time trials

For coho salmon, we ran 11 control, 10 jet, and 10 prop trials between July 3 and July 30, 2002. Most fish passed over the weir during the trials: for 22 of the trials, all 25 fish passed over the weir, and for the remaining 9 trials 1 – 3 fish per trial did not pass over the weir. During analysis of the videos, we were not able to positively identify and record passage times for all fish that passed over the weir. On average, we recorded passage times for 23 (standard deviation, SD = 2.4) of the 25 fish in each trial. Overall, we released 772 fish into the raceway; 14 fish did not pass over the weir, 706 fish were identified in the videos, and 50 fish could not be identified in the video.

After fish were released, they began passing the raceway within 30 min. After beginning the trials, the first fish passed over the weir in a median of 23 min (range = 6 – 92 min) for the control trials, 16 min (range = 4 – 24.3) for jet trials, and 26 min (range = 15 – 56 min) for prop trials. For the control and jet trials conducted at night, fish began passing the weir sooner than for trials conducted during the day (Table 2). However, for the prop trials, we observed little difference in the time for the first fish to pass the weir (Table 2).

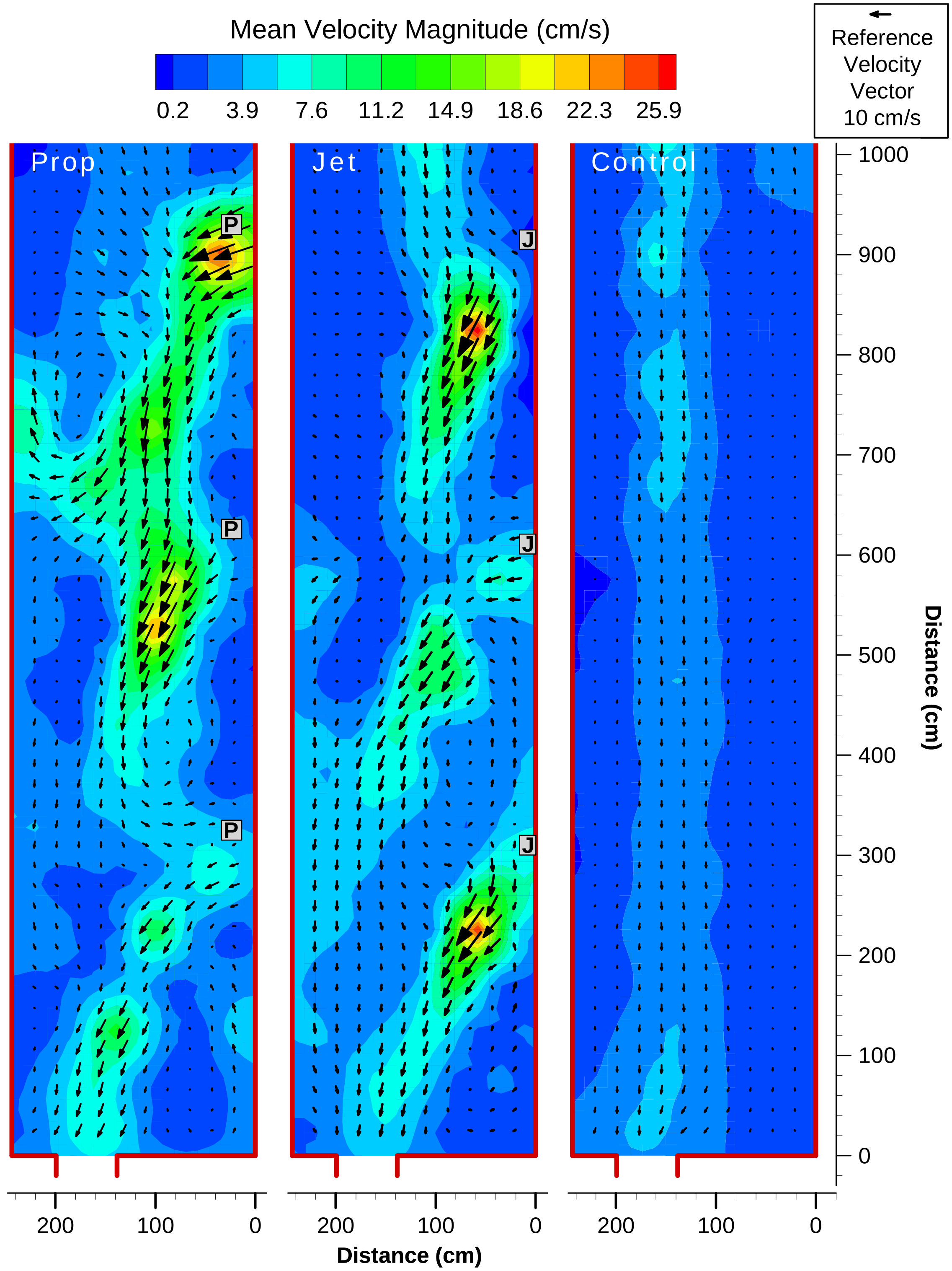

Figure 4. — Mean water velocities during time trial experiments for prop, jet, and control treatments. Colored contours show the velocity magnitude, vectors show the direction of water flow, and size of the vectors also indicates water velocity magnitude.

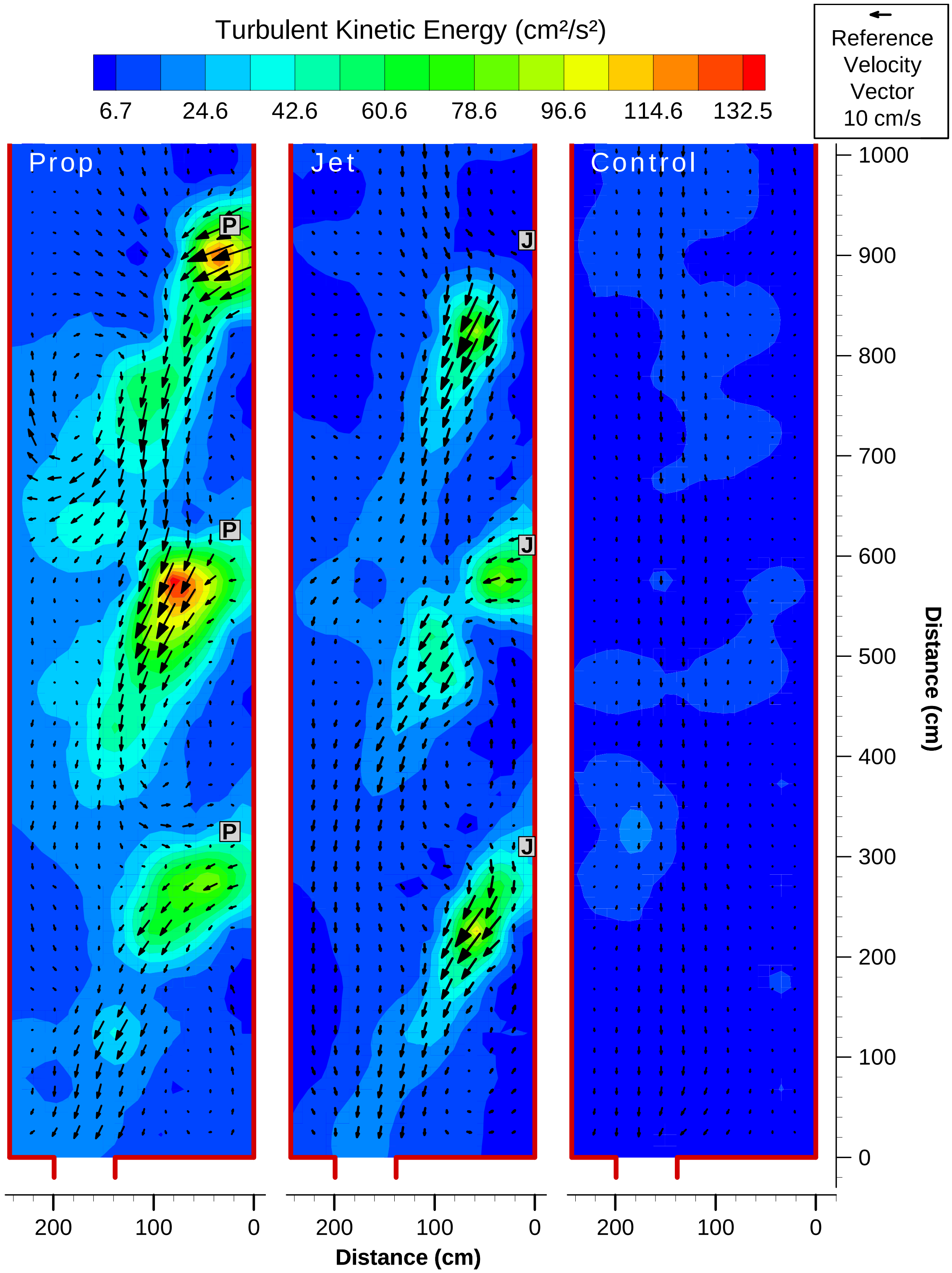

Figure 5. — Turbulent kinetic energy during time trial experiments for prop, jet, and control treatments. Colored contours show the velocity magnitude, vectors show the direction of water flow, and size of the vectors also indicates water velocity magnitude.

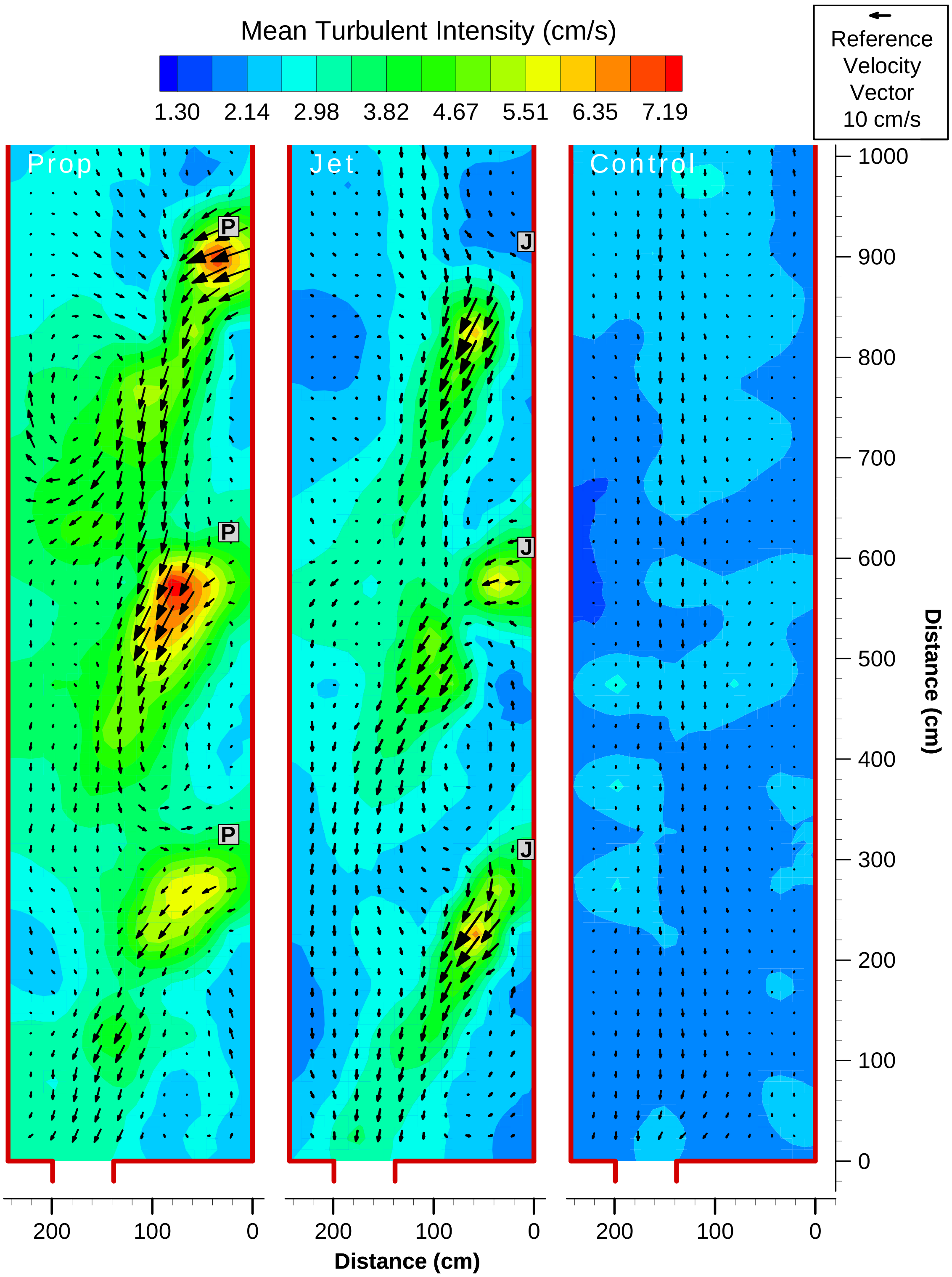

Figure 6. — Mean turbulent intensity during time trial experiments for prop, jet, and control treatments. Colored contours show the mean turbulent intensity, vectors show the direction of water flow, and size of the vectors indicates water velocity magnitude.

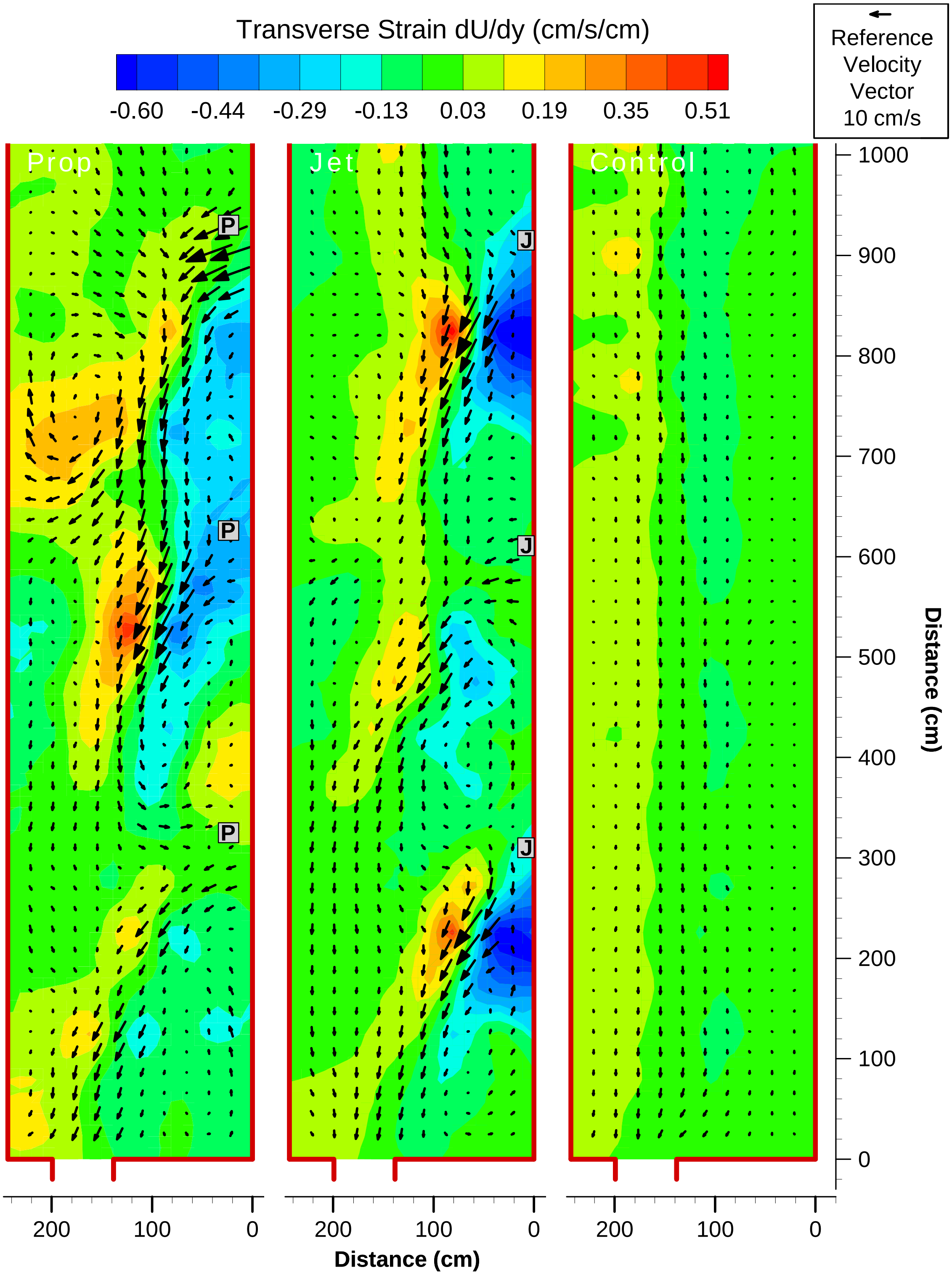

Figure 7. — Strain (calculated as change in streamwise velocity, dU, in the transverse direction, dy) during time trial experiments for prop, jet, and control treatments. Colored contours show strain, vectors show the direction of water flow, and size of the vectors indicates water velocity magnitude.

Table 2. — Descriptive statistics of the time (min) after the start of each trial for the first juvenile coho salmon to pass over the raceway weir.

Treatment	Time of day	Number of trials	Mean	Median	Standard deviation	Range
Control	Day	6	34.6	22.2	31.3	8.9 – 92.4
	Night	5	9.8	9.3	2.8	5.7 – 12.4
Jet	Day	5	16.8	18.3	6.5	6.9 – 24.3
	Night	5	12.1	10.2	6.6	4.2 – 21.2
Prop	Day	5	35.3	26.6	15.6	21.8 – 56.1
	Night	5	27.7	25.0	11.3	14.5 – 44.0

We found that juvenile coho salmon passed over the weir in distinct groups and were more likely to pass the weir in groups during the day than at night. During the day, 81% (296 of 367) of the fish passed over the weir in groups of 2 or more fish. In contrast, during the night only 26% (89 of 339) of the fish passed over the weir in groups of two or more fish. During the day, group sizes ranged from 2 to 17 fish, but at night group sizes ranged from 2 to 6 fish (Figure 8). These data indicate that schooling and passing the weir in groups diminishes during the night. There were no apparent differences among treatments in number of fish passing over the weir in groups.

After the first fish began passing the raceway, most of the other fish followed quickly behind. However, some fish took much longer to pass the raceway, resulting in skewed distributions of their passage times (Figure 9). In addition, although fish began passing the raceway quicker at night, overall, passage times were more spread out at night (Table 3, Figure 9). These distributions could have arisen from fewer fish passing in groups during the night compared to the day. By examining median passage times for day and night, we found passage times were shorter at night for control trials, about the same for jet trials, and longer during the night for prop trials (Table 3).

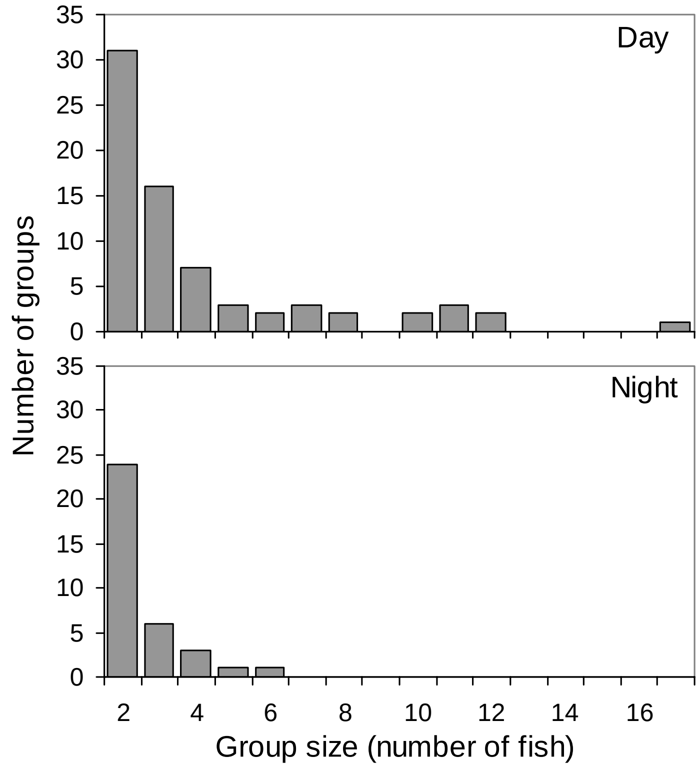

Figure 8. — Frequency distribution of group sizes for juvenile coho salmon that passed over the raceway weir in groups. Fish were assigned to a group if the time of weir passage between consecutive fish was <5 s and assigned to new group if the time between consecutive fish was >5s.

Table 3. — Descriptive statistics of raceway passage times from time of release to weir passage (minutes) for coho salmon.

Time of day	Treatment	Number of fish	Mean	Median	Standard deviation	Range
Day	Control	134	44.6	29.1	33.7	8.9 – 226.5
	Jet	116	25.1	22.3	12.5	6.9 – 131.8
	Prop	117	41.0	36.2	14.6	21.8 – 73.3
Night	Control	119	31.6	18.9	32.9	5.7 – 166.9
	Jet	109	38.2	24.3	51.6	4.2 – 309.2
	Prop	111	67.3	46.9	75.7	14.5 – 497.1

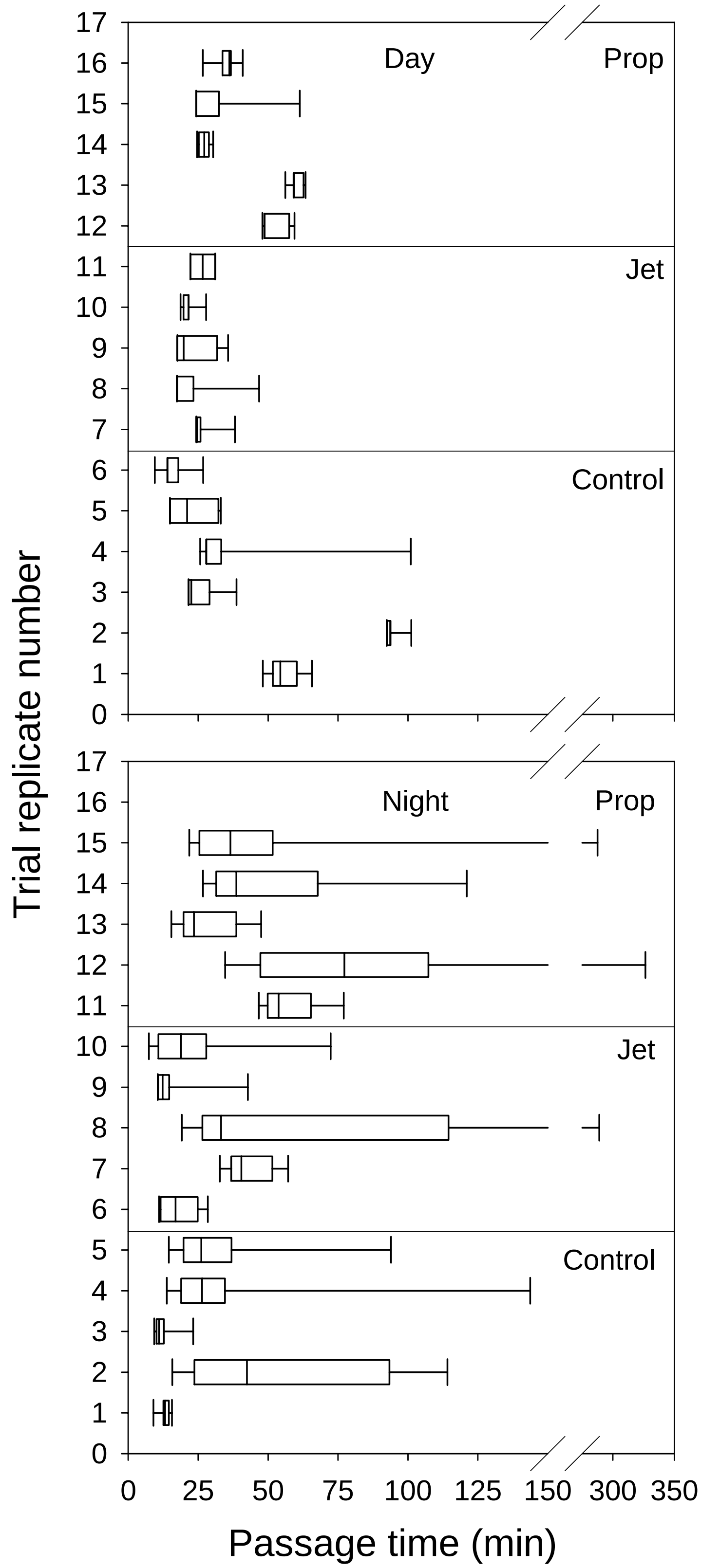

Figure 9. — Box plots of passage times for each time trial of coho salmon. The line through the box represents the median, the box represents the 25th to 75th percentiles, and the whiskers represent the 5th to 95th percentiles of the passage time distributions.

Three factors accounted for 88% of the variation explained by theANCOVA model (Table 4). However, overall the ANCOVA model explained only 10% of the total variation in passage times of juvenile coho salmon. Although the model explained a small proportion of the total variation, travel time distributions of juvenile salmon are typically characterized by high variation due to random diffusion.(Zabel and Anderson 1997). Nonetheless, we found a number of factors significantly affected passage times of juvenile coho salmon. An interaction between the light index and time of day explained the most variation, followed by the effect of treatments and the light index. None of the interactions terms with treatment were significant (Table 4) at the $\alpha = 0.05$ level, but the interaction of treatment and light index was significant at the $\alpha = 0.10$ level.

Table 4. — ANCOVA model results for testing the effects of treatment, time of day, and the light index on the passage times of juvenile Coho salmon during the raceway experiments at Cowlitz Falls Dam, 2002.

Source of variation	DF	Sum of squares	Mean square	*F*-value	*P*-value	Proportion of explained variation	r^2
LIGHTINDEX*TIMEOFDAY	1	21.6	21.6	58.8	<0.0001	0.634	0.063
TREATMENT	2	5.5	2.7	7.5	0.0006	0.161	0.016
LIGHTINDEX	1	2.9	2.9	7.9	0.0052	0.085	0.008
LIGHTINDEX*TREATMENT	2	2.0	1.0	2.7	0.0693	0.058	0.006
LIGHTINDEX*TREATMENT*TIMEOFDAY	2	1.4	0.7	1.9	0.1452	0.042	0.004
TREATMENT*TIMEOFDAY	2	0.6	0.3	0.8	0.4316	0.018	0.002
TIMEOFDAY	1	0.1	0.1	0.3	0.6042	0.003	0.000

The interaction between the light index and time of day suggested light and turbidity affected passage times of coho salmon, but that the effect of light and turbidity on passage times depended on the time of day (Table 4). During the night, passage times for all treatments were inversely related to the light index, but during the day passage times were positively related to the light index (Figure 10). The shortest passage times for all treatments occurred at the highest values of the light index at night and the lowest values during the day. For night trials, each treatment had a similar response to light and turbidity levels, but during the day, passage times were shortest for the jet treatment regardless of light and turbidity levels.

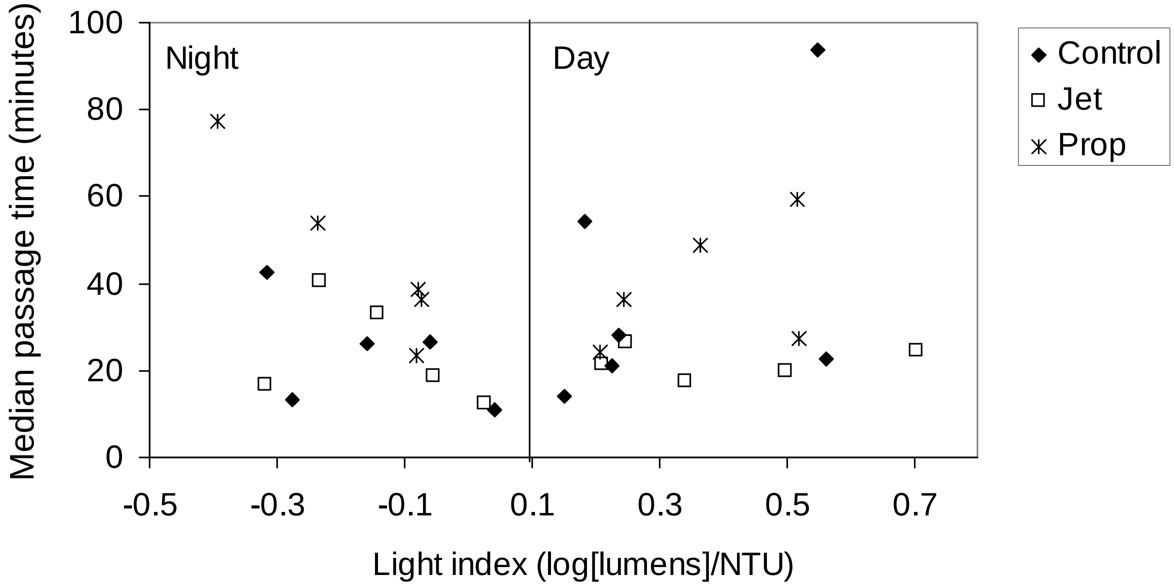

Figure 10. — Median passage times for control, jet, and prop trials as a function of the light index. The light index was calculated as logarithm of light levels divided by turbidity to estimate the combined effect of both light and turbidity on passage times of juvenile coho salmon.

The significant interactions prevented interpretation of treatment effects in the ANCOVA model. Therefore, to test the effect of the treatments on passage times, we conducted multiple comparisons between treatments (Tukey's HSD test), for the day and night separately. We did not use covariates because all treatments experienced similar light and turbidity levels (Figure 10). During the day, passage times for the jet trials (median = 22.3 min) were significantly less ($P < 0.05$) than those of both the control (median = 29.1 min) and prop trials (median = 36.2 min; Table 3). However we found no significant difference ($P > 0.05$) in passage times between prop and control trials. At night, there was no significant difference ($P > 0.05$) in passage times between jet (median = 24.3) and control trials (median = 18.9), but passage times for both the jet and control trials were significantly less ($P < 0.05$) than those of the prop trials (median = 46.9 min; Table 3).

Chinook salmon time trials

For Chinook salmon, we ran 8 control, 8 jet, and 7 prop trials between July 20 and August 8, 2002. In contrast to coho salmon trials where most fish passed over the weir during the trials, for only two trials did all Chinook salmon pass over the weir. For the remaining 22 trials 1 – 7 fish did not pass over the weir during the trials. More Chinook salmon did not pass over the weir during the jet and prop trials compared to the controls. A mean of 2.3 (SD=1.7) fish per trial remained in the raceway following control trials compared to means of 3.5 (SD=2.1) fish per trial for the jet and 3.7 (SD=2.7) fish per trial for the prop treatments. As with trials for coho salmon, we were not able to identify passage times in the videos for an average of 2.6 fish per trial (SD=2.6) that passed over the weir. Over all trials, we released 574 Chinook salmon in the raceway; 72 fish did not pass over the weir, 442 fish were identified in the videos passing over the weir, and 60 fish could not be identified in the videos.

As with coho salmon, Chinook salmon also began passing over the weir within 30 min of release. After beginning the trials, the first Chinook salmon passed over the weir in a median of 16 min (range = 13 – 31 min) for the control trials, 29 min (range = 13 – 70 min) for the jet trials, and 30 min (range = 26 – 58 min) for the prop trials. For the control trials fish began passing over the weir sooner during the day compared to night, but for both jet and prop trials fish began passing over the weir in similar amounts of time between day and night (Table 5).

Table 5. — Descriptive statistics of the time (min) after the start of each trial for the first juvenile Chinook salmon to pass over the raceway weir.

Treatment	Time of day	Number of trials	Mean	Median	Standard deviation	Range
Control	Day	4	14.6	13.6	2.2	13.2 – 17.8
	Night	4	22.3	22.3	7.3	13.3 – 31.3
Jet	Day	4	27.2	26.8	11.8	13.1 – 42.1
	Night	4	40.3	34.1	20.8	23.1 – 70.0
Prop	Day	3	30.8	31.4	3.9	26.6 – 34.3
	Night	4	35.3	28.5	15.2	26.3 – 58.0

In contrast to Coho salmon, we found little evidence of schooling behavior during passage of Chinook salmon over the weir. During the day, 18% (39 of 214) of Chinook salmon passed over the weir in groups of two or more fish, and during the night only 7% (16 of 228) of fish passed over the weir in groups of two or more fish (Figure 11). Group sizes for Chinook salmon were smaller than for coho salmon, with group sizes ranging between 1 – 4 fish per group.

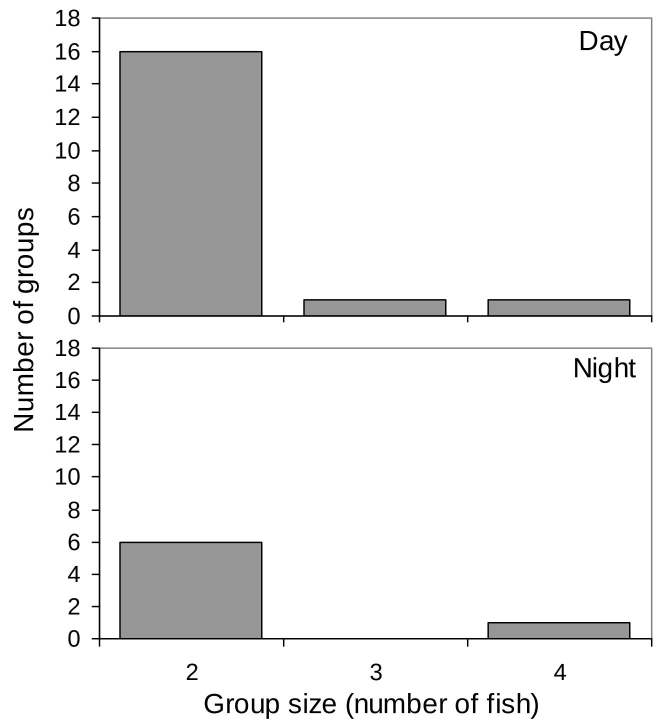

Figure 11. — Frequency distribution of group sizes for juvenile Chinook salmon that passed over the raceway weir in groups. Fish were assigned to a group if the time of weir passage between consecutive fish was <5 s and assigned to new group if the time between consecutive fish was >5s.

As with coho salmon, we found that passage time distributions of juvenile Chinook salmon were skewed and varied substantially among trials (Figure 12). However, in contrast to coho salmon, Chinook salmon took much longer to pass through the raceway overall, and longer at night relative to the day. Depending on the treatment, median passage times of Chinook salmon ranged from 39.6 min to 82.7 min during the day, but from 123.4 to 200.6 min at night (Table 6). In comparison, median passage times of Coho salmon never exceeded 46.9 min.

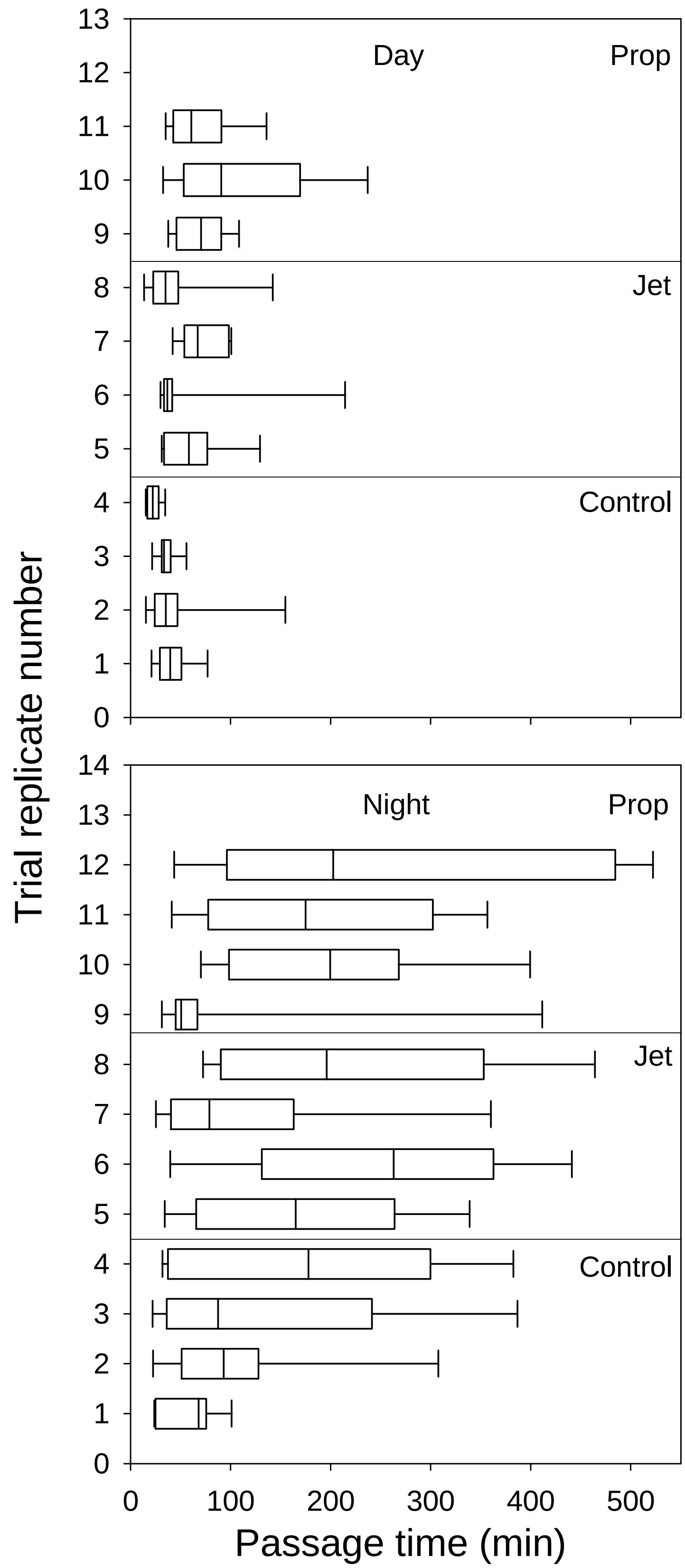

Figure 12. — Box plots of passage times for each time trial of Chinook salmon. The line through the box represents the median, the box represents the 25th to 75th percentiles, and the whiskers represent the 5th to 95th percentiles of the passage time distributions.

Table 6. — Descriptive statistics of raceway passage times from time of release to weir passage (minutes) for juvenile Chinook salmon.

Time of day	Treatment	Number of fish	Mean	Median	Standard deviation	Range
Day	Control	86	39.6	32.2	36.3	13.2 – 260.0
	Jet	68	60.0	42.1	44.2	13.2 – 257.1
	Prop	60	82.7	76.1	49.8	26.6 – 238.6
Night	Control	84	123.4	81.9	115.3	13.3 – 464.6
	Jet	69	191.8	168.1	137.2	23.1 – 520.2
	Prop	75	200.6	185.4	151.5	26.3 – 526.5

We found that both treatments and the light index significantly affected the passage times of Chinook salmon . Of the variation explained by the model, treatments accounted for 40% and the light index accounted for 38% of this variation (Table 6). In contrast to coho salmon, passage times of Chinook salmon were inversely related to the light index over both day and night (Figure 13). This relation caused passage times to be longer at night than during the day (Table 6). There was no significant interaction between treatment and time of day (Table 6), which allowed us to interpret significant main effects. Multiple comparisons (Tukey's HSD test) showed that passage times of controls were significantly less ($P < 0.05$) than both prop and jet treatments, and those of jet treatments were significantly less ($P > 0.05$) than prop treatments (Table 6, Figure 12).

Table 7. — ANCOVA model results for testing the effects of treatment, time of day, and the light index on the passage times of juvenile Chinook salmon during the raceway experiments at Cowlitz Falls Dam, 2002.

Source of variation	DF	Sum of squares	Mean square	*F*-value	*P*-value	Proportion of explained variation	$r2$
TREATMENT	2	8.5	4.2	7.97	0.0005	0.404	0.023
LIGHTINDEX	1	7.9	7.9	14.83	0.0001	0.376	0.021
TIMEOFDAY	1	1.6	1.6	3.02	0.0827	0.077	0.004
TREATMENT*TIMEOFDAY	2	1.3	0.7	1.25	0.2865	0.064	0.004
LIGHTINDEX*TREATMENT	2	1.3	0.6	1.23	0.2924	0.063	0.004
LIGHTINDEX*TREATMENT*TIMEOFDAY	2	0.3	0.2	0.33	0.7189	0.017	0.001
LIGHTINDEX*TIMEOFDAY	1	0.0001	0.0001	0	0.9861	0.000	0.000

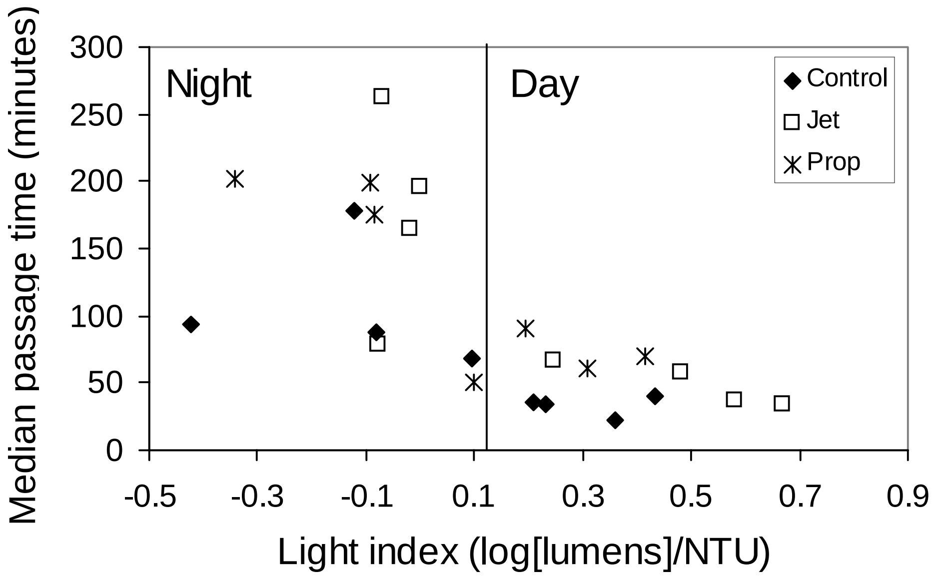

Figure 13. — Median passage times for control, jet, and prop trials as a function of the light index. The light index was calculated as logarithm of light levels divided by turbidity to estimate the combined effect of both light and turbidity on passage times of juvenile Chinook salmon.

Guidance Experiment

Water velocity and turbulence

For all water velocity and turbulence parameters, we found that the treatments succeeded in directing water towards the channel where jets were aimed. Mean values for all parameters were higher for both treatments, compared to controls (Table 8). Both treatments also substantially increased the variation among sampling points for all parameters (Table 8). Although the treatments did not affect minimum values of parameters, maximum values of all parameters were much higher than controls (Table 8). Comparing north and south treatments, the north treatment had higher mean values for all parameters (Figures 14-17).

Table 8. — Summary of velocity and turbulence parameters collected during the guidance experiments conducted at Cowlitz Falls Dam during 2002. For the north treatment the south jet was aimed towards the north channel, and vice versa for the south treatment.

Parameter	Mean	Standard deviation	Minimum	Maximum
Mean velocity magnitude (cm/s)				
Control	3.5	1.4	0.33	6.9
North	4.7	5.7	0.14	34.6
South	4.1	3.3	0.07	17.6
Turbulent kinetic energy (cm^2/s^2)				
Control	7.4	3.2	2.9	23.7
North	18.1	23.5	3.2	148.1
South	16.4	16.7	3.5	95.5
Mean turbulent intensity (cm/s)				
Control	1.6	0.3	1.1	2.4
North	2.4	1.3	1.1	7.7
South	2.4	1.0	1.1	6.2
Strain (dU/dy, cm/s/cm)				
Control	0.032	0.026	0.000	0.129
North	0.106	0.141	0.001	0.600
South	0.070	0.077	0.000	0.365

We found that the treatments affected the spatial pattern of water velocity and turbulence. For the control, water velocities were low, uniform, and moved in a downstream direction with very little turbulence (Figures 14,15, 16, and 17). Compared to the control, the north and south treatments altered the direction of water velocity diagonally across raceway and downstream (Figure 14). Relative to controls, treatments also induced substantial turbulence as was indicated by TKE, TI, and strain (Figures 15, 16, and 17). The north treatment affected a larger area of the raceway than the south treatment. This difference may have arisen because the jets were powered by one pump and implemented in series. Therefore, since the south jet (aimed at the north channel) was the last in the series, it likely had higher discharge than the north jet.

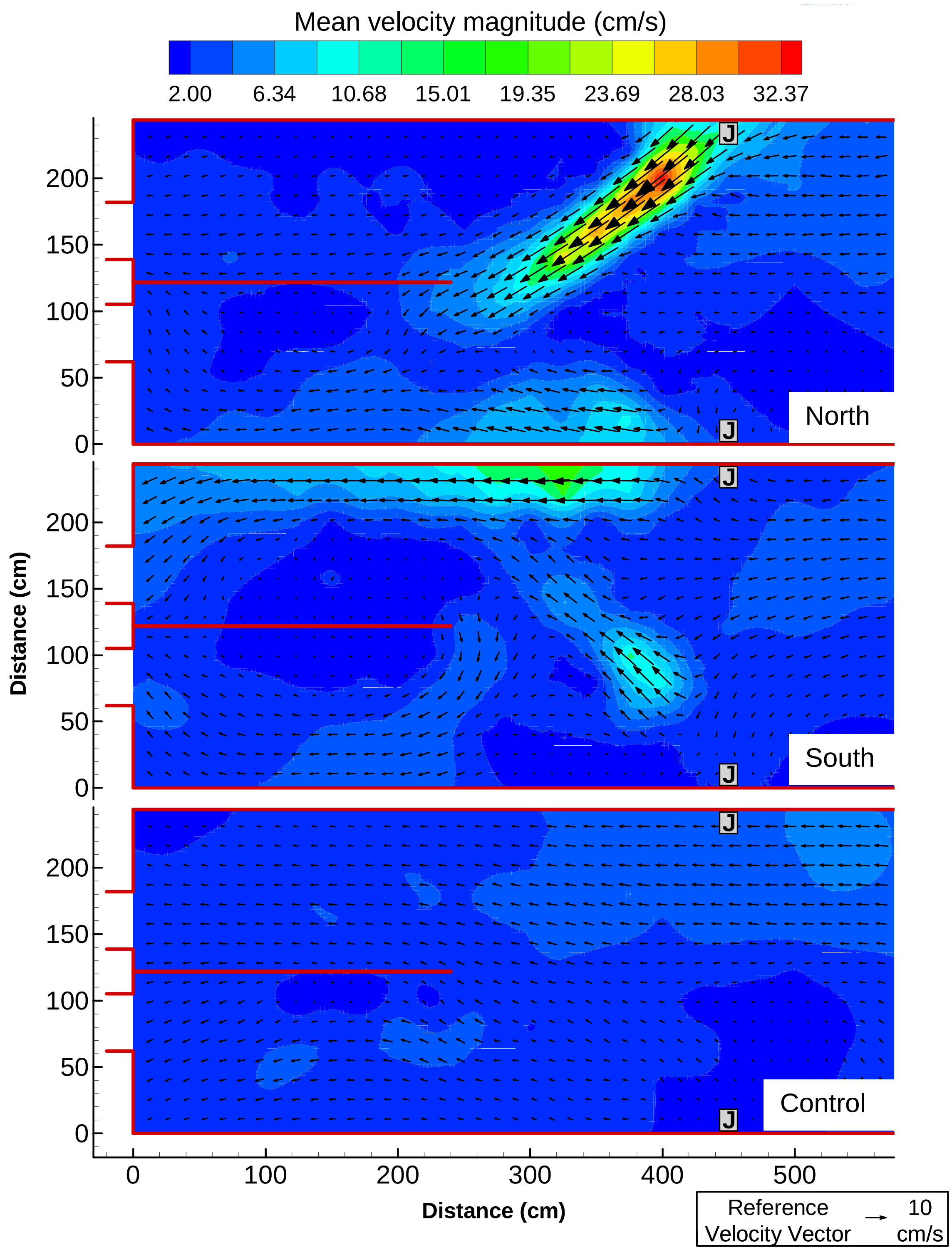

Figure 14. — Mean water velocities during guidance experiments for north, south, and control treatments. Colored contours show the velocity magnitude, vectors show the direction of water flow, and size of the vectors also indicates water velocity magnitude.

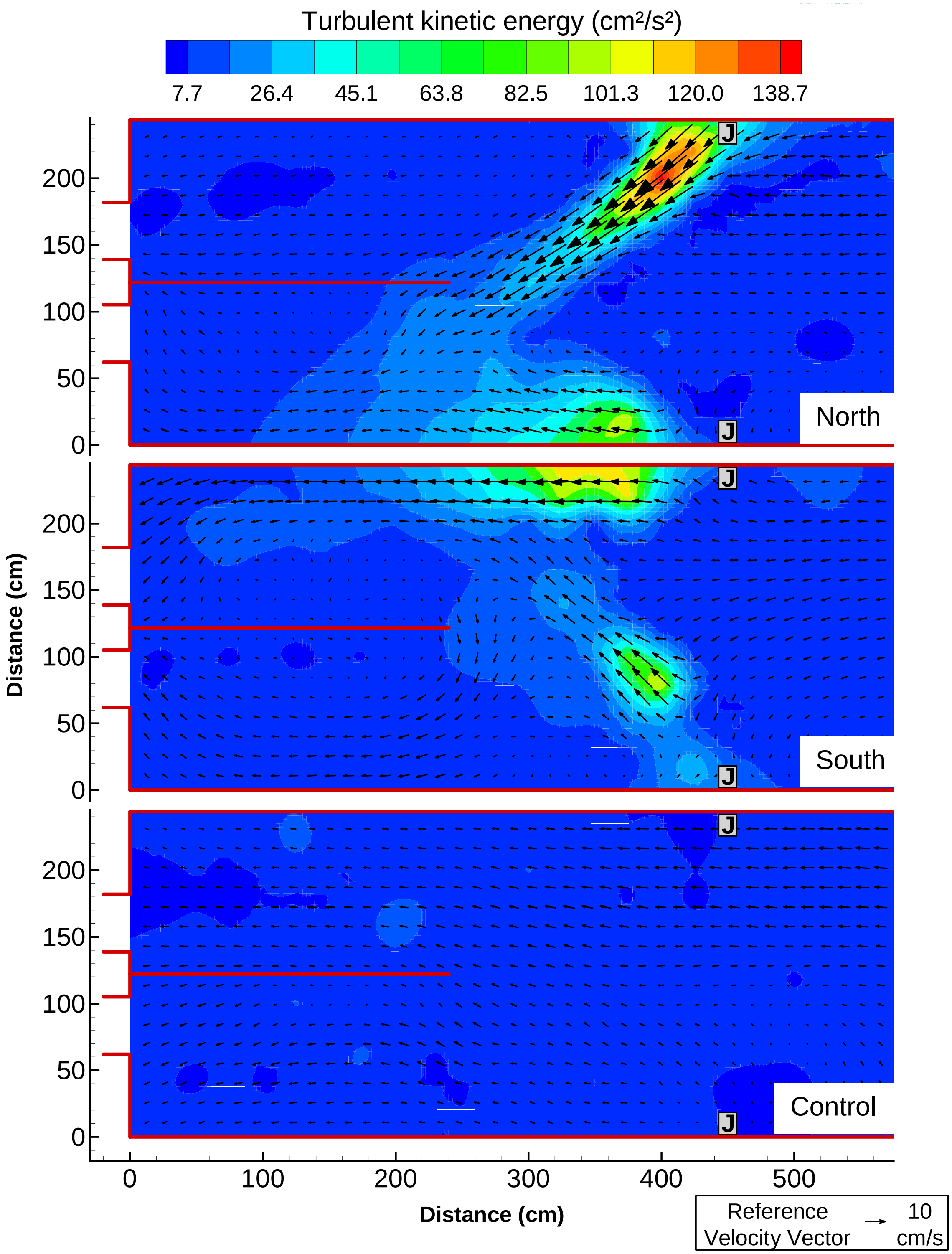

Figure 15. — Turbulent kinetic energy during guidance experiments for north, south, and control treatments. Colored contours show turbulent kinetic energy, vectors show the direction of water flow, and size of the vectors indicates water velocity magnitude.

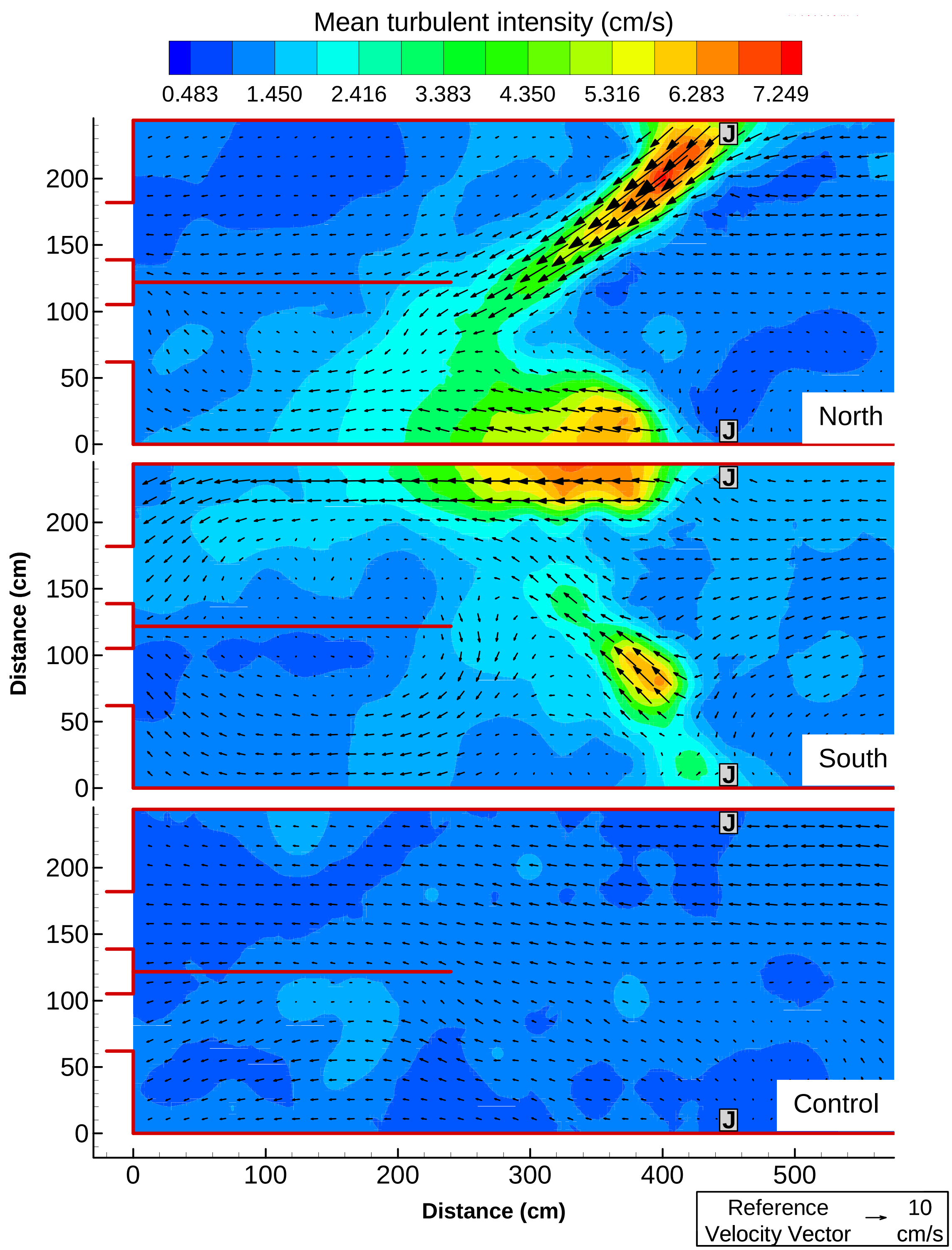

Figure 16. — Mean turbulent intensity during guidance experiments for north, south, and control treatments. Colored contours show the mean turbulent intensity, vectors show the direction of water flow, and size of the vectors indicates water velocity magnitude.

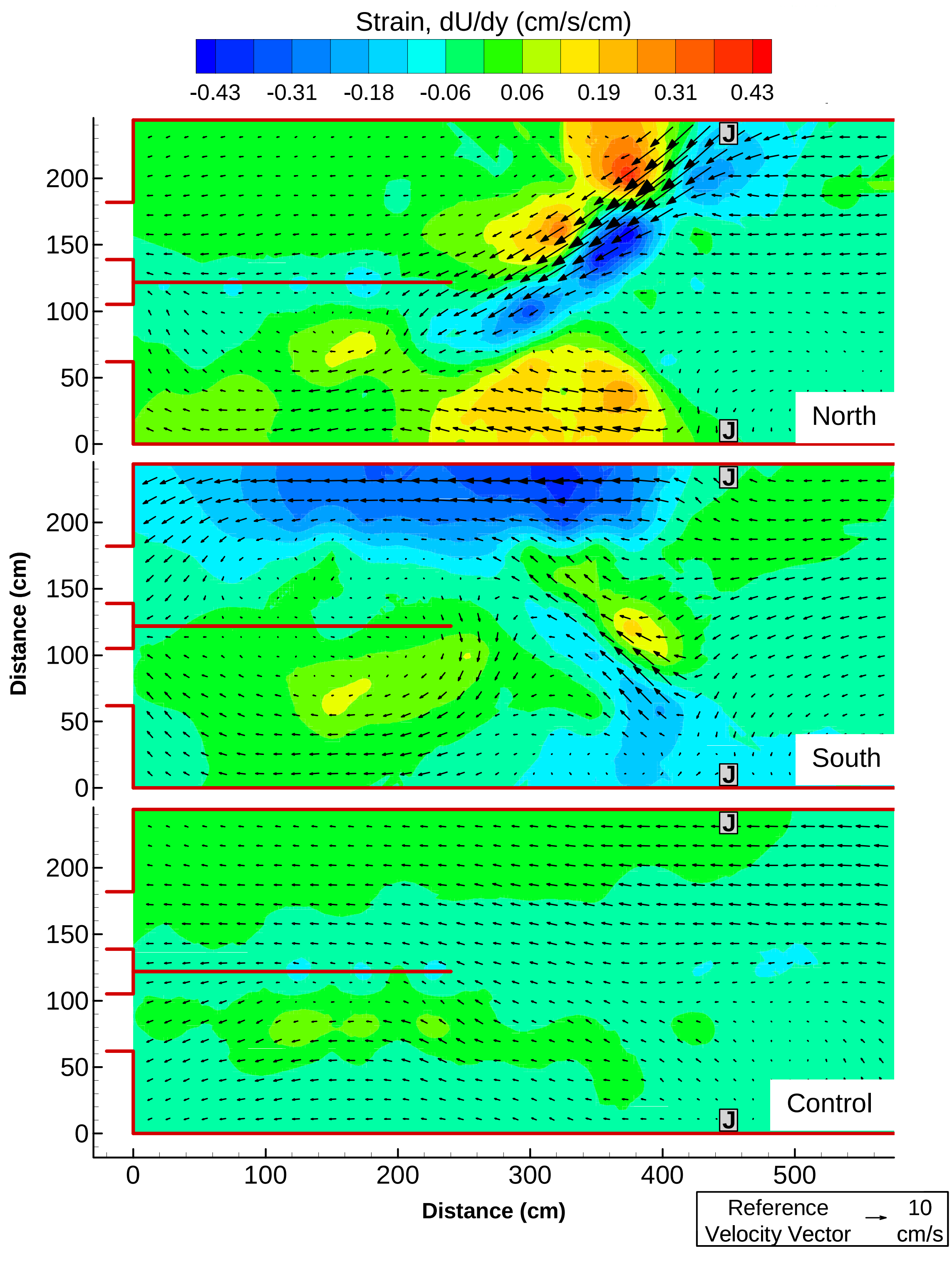

Figure 17. — Strain (calculated as change in streamwise velocity, dU, in the transverse direction, dy) during guidance experiments for north, south, and control treatments. Colored contours show strain, vectors show the direction of water flow, and size of the vectors indicates water velocity magnitude.

Chinook salmon guidance

For the guidance experiment, we conducted 10 trials for each treatment between August 14 and August 24, 2002. Between 24% and 85% of the juvenile Chinook salmon passed through the raceway during the 3-h duration of each trial. However, we excluded one trial (north treatment during night) from data analysis because only 2 of the 20 fish for this trial passed over the weirs during the 3-h trial duration. On average, 60% of fish for control trials, 58% of fish for north trials, and 40% of fish for south trials passed the raceway during the 3-h trial duration. A higher proportion of fish in the raceway passed over the weirs for day trials (mean = 50%) compared to night trials (mean = 40%).

Although we found a statistical difference between some treatments, we found little evidence that the turbulence treatments provided a consistent directional guidance to influence the proportion of fish passing through the north weir. A mean of 36% of fish (SE=0.06) passed through the north weir for the controls, 54% of fish (SE=0.05) passed through the north weir for the north treatment, and 53% of fish (SE=0.04) passed through the north weir for the south treatment. We found no significant time of day effect (day, night) on the proportion of fish passing through the north weir ($F_{[1,23]}$=2.21, P=0.15) and no significant interaction between time of day and treatment ($F_{[2,23]}$=0.48, P=0.62). We found treatments were significantly different at a significance level of alpha=0.10 but not at alpha=0.05 ($F_{[2,23]}$=3.21, P=0.059). Multiple comparisons (Tukey's HSD test) conducted at a significance level of 0.10 showed that the south treatment was significantly different from controls, but there was no significant difference between north and south treatments, or between control and north treatments. In addition, we found no consistent relation of proportional passage through the north weir with ambient light levels, turbidity, or the light index (Figure 18).

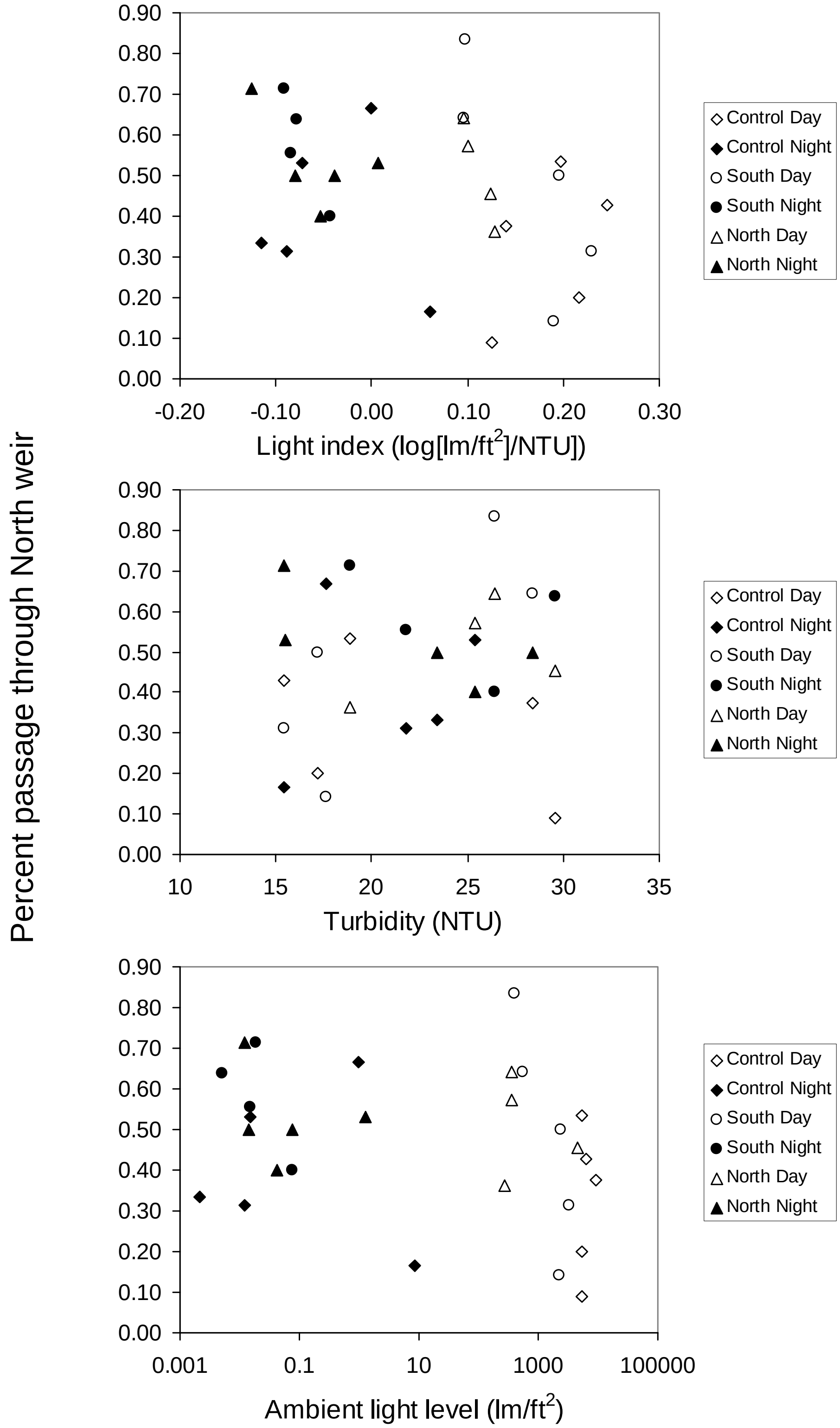

Figure 18. — Scatter plots of percent of fish passing through the north weir plotted against ambient light levels, turbidity, and the light index during raceway guidance experiments conducted at Cowlitz Falls Dam during 2002.

Discussion

Based on the findings of Hotchkiss (2002) in his investigation of turbulence in streams and the results of Darland et al. (2001) in their study of induced turbulence to improve fish guidance, we designed several experiments to further investigate the response of fish to turbulence in a partially controlled environment. In the first experiment we determined the downstream passage time of juvenile salmonids when we introduced turbulence into the flows in experimental raceways. In a second set of fish guidance experiments, we determined if turbulent flows from one side of the raceway to the other resulted in guidance along the path of the turbulence. In our design considerations, we selected our study site at Cowlitz Falls Dam, Washington because of the availability of naturally migrating juvenile salmonids and the close proximity of the raceways to the source of river water and experimental fish. In making this selection, we recognized that we would have less control over variables such as light levels, turbidity, and seasonal variation. However, we also considered the consistent water source, availability of in-river migrating fish, and the experimental environment to be ideal for our experiments.

We found that several factors affected the behavior of juvenile salmon in response to turbulence. During the time trials of the passage experiment, we observed high trial-to-trial variation in passage times, but found that much of this variation could be explained by time of day, ambient light levels, and turbidity. We also found differences between the responses of juvenile Chinook and coho salmon to these environmental variables. Last, we observed other behavioral differences, such as schooling among coho salmon exposed to turbulence, but not Chinook salmon. Overlaid on effect of species-specific and environmental factors was the effect of turbulence treatments. Turbulence form jets led to the quickest passage times for coho salmon (daytime only), but induced turbulence (both jets and props) caused juvenile Chinook salmon to remain in the raceway longer than control treatments.

Differences in the structure of turbulence created by jets and props apparently affected the passage times of juvenile coho salmon. With jet-induced turbulence, passage times of juvenile coho salmon were either less than (day) or similar to controls (night) and were less than passage times of fish exposed to prop-induced turbulence. Jet-induced turbulence differed in a number of ways from prop-induced turbulence. First, water plumes emitted from the jets oscillated in a circular fashion, which may have produced consistent periodic fluctuations in water velocity similar to small-scale vortices shed from natural obstructions in rivers. Second, Hotchkiss et al (2002) showed that small, oscillating jets produced eddies of similar length scales as boulder obstructions in natural streams. Eddy length scales could be an important attribute of turbulence affecting behavior of migrating juvenile salmonids. Eddies with similar length scales as juvenile salmon (≈10 cm) may be detected as variations in flow magnitude and direction along the body of fish and could be used to orient and guide fish. Eddy length scales larger than the size of the fish, however, would not be detected as velocity differences along the body. This may cause fish to orient in the general direction of flow at its specific location within the eddy causing circular movement that could disorient fish (Odeh et al. 2002) or delay downstream movement.

In contrast to the jets, props created turbulence with different characteristics than observed in natural rivers. Hotchkiss (2002) showed that small props created strain and eddy length scales that were substantially less than occurred in natural gravel-bed rivers, whereas jets produced strain and eddy length scales similar to natural rivers. Although we observed larger and stronger eddy patterns with the prop, it is likely that smaller-scale eddy lengths were also issued directly from the prop, since we used props very similar to those of Hotchkiss (2002). Thus, at fine scales in the raceway, fish would have been exposed to eddies smaller than occur in natural rivers. In addition, the eddy patterns observed at larger scales in the raceway could have delayed fish passing through the raceway. Our findings support hypotheses of other workers suggesting that the structure of turbulence is an important factor driving behavioral responses of fish to turbulence. Mimicking the turbulence of natural gravel-bed rivers appears to elicit a more favorable behavioral response from juvenile salmon that could be used to guide fish quickly and safely to passage routes at dams.

Several differences we observed between coho and Chinook salmon may be associated with smoltification or parr-smolt transformation, rather than distinct differences associated with the species. Juvenile salmon undergo smoltification in preparation for the seaward migration and ocean entry. Attributes associated with smoltification may explain some of the patterns in behavior that we observed during the experiments. Smoltification and the onset of the seaward migration is accompanied by an increased disposition to migrate, increased buoyancy, and increased schooling behavior. Other characteristics that change this transformation are possible changes in visual acuity and increased silvering to reduce predation risk in a pelagic environment. We did not measure any of the physiological measures (i.e., gill ATPase, thyroxine) that may have indicated the degree of smoltification in juvenile salmonids in our study. At the time of emigration past Cowlitz Falls Dam, juvenile coho are age 1+ and average 120 mm fork length, most juvenile Chinook salmon emigrate as age 0+ and are much smaller than coho, averaging 113 mm fork length. Based on this knowledge about our experimental animals we believe that juvenile Chinook salmon may have been in the early stages of smoltification (relative to coho salmon) since they display life history attributes similar to ocean-type Chinook where juveniles emigrate as age 0+ and rear as they move slowly downstream. If the status of smoltification differed between species, then differences in behavior and disposition to migrate that usually accompanies smoltification may explain the differences we observed in fish response to turbulence.

Downstream migrating smolts may respond differently to turbulence than individuals that have yet to undergo the parr-smolt transformation. Downstream displacement is disadvantageous for parr maintaining station in an ideal location for feeding and rearing in a stream environment. In contrast, maintenance of station is disadvantageous to smolts that must quickly migrate downstream and enter the ocean environment. For example, parr are typically less buoyant than smolts, which is hypothesized to assist parr in maintaining station in the stream, whereas higher buoyancy is hypothesized to facilitate downstream displacement in smolts (Saunders 1965). In much the same way, turbulence may be used by parr to help them orient and maintain station in the water column, but used in an opposite fashion by smolts to facilitate downstream movement (Coutant 2001).

We observed schooling among coho salmon in the experiments, but not Chinook salmon and this provides additional evidence that juvenile Chinook salmon may have been less smolted than coho salmon. When rearing in streams many juvenile salmon maintain territories and display agonistic behavior towards other individuals (McMahon and Holtby 1992). As smoltification advances, juveniles abandon their territories and develop schooling behavior during the downstream migration (Brett and Alderace 1958; McMahon and Holtby 1992; McCormick et al. 1998). Turbulence may have provided a form of cover to less-smolted juvenile Chinook salmon, causing them to orient and maintain station in the raceway to avoid downstream displacement. In contrast, more advanced smoltification in coho salmon may have caused coho to pass through the raceway in similar (night) or less (day) time when fish were exposed to turbulence. However, it is difficult to reach a definitive conclusion about whether the behavioral differences we observed were species-specific responses or whether they were due to differences in smoltification.

We found that the combination of light levels and turbidity had different effects on passage times of coho and Chinook salmon. For coho salmon, we observed a negative relation of passage time with light and turbidity during night, but a positive relation during the day. Thus, at both the lowest and highest light index levels, juvenile coho salmon took the longest to pass through the raceway. At intermediate levels of the light index, perhaps replicating light levels during crepuscular periods, coho salmon had the shortest passage times through the raceway. In contrast, we found that Chinook salmon passage times were negatively related the light index, with the lowest passage times occurring at combinations of high ambient light levels and low turbidities, typically occurring during the day.

Understanding vision in fish is useful in attempting to interpret different fish behavior as light levels varied. Vision is one of the primary senses aiding orientation of fish to their stream environment (Arnold et al. 1974). For example, fish use vision to detect displacement in their environment from fixed reference points such as stream substrate (Jones 1963). However, vision is also a primary sense that predators use to capture prey (i.e., reaction distance). Vogel and Beauchamp (1999) showed that both light levels and turbidity affected reaction distance of lake trout to forage fish, suggesting that both light levels and turbidity affect predation risk. Juvenile salmon must trade off the benefit of moving from one location to another with the risk of predation during movement. How fish balance this trade off could depend on the degree of smoltification and how fish are driven by different motivations to move to new locations.

For juvenile Chinook salmon that may have been in early stages of smoltification, fish may have been driven more by risk of predation and locating an optimal habitat to maintain station than by motivation to migrate downstream. Consequently, during the day with high light levels and low turbidities, when relative risk of predation is high, the fish's primary motivation may have been to seek cover. Because of absence of cover in the raceway, juvenile Chinook salmon may have moved through the raceway quickly to seek a new location that would subsequently minimize predation risk. In contrast, at night when the combined effect of light and turbidity was lowest, predation risk was minimized, possibly resulting in less motivation to move quickly through raceway. Likewise, in the presence of turbulence, the raceway more closely replicated a natural stream environment, which may provided a form of cover that was perceived to have lower predation risk, ultimately resulting in longer passage times through the raceway during the turbulence treatments.

For coho salmon in an advanced stage of smoltification, their primary motivation is to move downstream quickly while minimizing predation risk. The light index provided a measure of the relative field of vision for fish in the raceway. Therefore, quick movement through the raceway during intermediate light and turbidity levels may have resulted from the optimal tradeoff where visual cues could be used to aid downstream movement during periods when predation risk would be relatively low. At low light levels during night, risk of predation is minimized, but so are visual cues to guide downstream movement, causing fish to take longer to negotiate the raceway. In contrast, during high light levels and low turbidities, although visual cues to guide downstream movement are maximized, predation risk is also higher, which may have caused juvenile coho salmon to take longer to move through raceway.

In the guidance experiments we demonstrated that turbulence treatments could change the proportion of fish guided over a weir compared to control conditions. However, we were concerned when we found that 64% of the fish passed over the south weir during control conditions when we expected closer to 50%. In our analysis we found two factors that may have could have caused more fish to pass through the south weir during the experiment. We found slightly higher water velocities for control treatments along the south side of the raceway compared to the north side (Figure 14). Furthermore, we had shaded the raceway to eliminate a shadow that was cast along the south side of the raceway leading to the south weir, but the shading did not completely eliminate the shadow. Comparing the control group between day and night, we found that during the night 60% of the fish passed the south weir and during the day 67% passed the south weir. These differences suggest that fish passage may have been biased toward the south weir by light levels during the day and by slightly higher water velocities during day and night.

Had the turbulence treatments consistently guided fish towards the channel where turbulence was aimed, we would have expected the proportion of fish passing through each weir to differ from the controls. Thus, for the north treatment, we would have expected a higher proportion than controls passing through the north channel (e.g., >36%). Our findings were in line with expectations for the north treatment, where 54% (+18% over the control condition) of fish passed through the north channel with turbulent flow compared to 36% during the control treatment. However, for the south treatment, 47% of fish passed through the south channel compared to the control treatment when 64% passed through the south weir. The south treatment appeared to have little effect, but why? We believe the north treatment was effective because the turbulent plume had mean water velocities up to four fold greater, turbulent kinetic energy up to three fold greater, mean turbulent intensity up to three fold greater, and strain up to two fold greater than the plume characteristic of the south treatment. The results indicate that a certain level of turbulence was necessary to overcome the ambient light and low flow conditions characteristic of the raceway during control treatments. The north treatment was effective at this but the south treatment failed.

Our study highlights the complexity of juvenile salmon behavior, which makes it difficult to derive general guidelines for application of induced turbulence in dam forebays. Nonetheless, we were able to explain much of the variation in behavior and provide findings that should be useful to guide future research. First, both species tested here responded to turbulence, but the nature of the response appeared to depend on their smoltification development and ambient environmental factors. Although we can not rule out the possibility that the behavioral differences we observed were species-specific, evidence suggests coho salmon may have been at a more advanced stage of smoltification, relative to Chinook salmon. Thus, field studies with multiple species and life stages should recognize the diversity of possible responses to turbulence. Second, the structure of turbulence was an important factor and suggests that replicating the turbulence of natural stream environments is most likely to elicit a favorable response from juvenile salmonids. Both the oscillating nature of the jets and their ability to create eddy length scales and strain similar to natural streams may have been the mechanisms affecting juvenile salmon behavior. These findings suggest that arrays of numerous smaller jets rather than few large jets may better replicate natural turbulence. However, future research should measure turbulence of different sized jets at a range of discharge to identify the combinations that best replicates natural turbulence. Knowing which combinations produces natural turbulence will benefit field applications where site-specificity may dictate the scale of the implementation. Last, response to turbulence will be affected by other environmental and site-specific factors. In this respect, researchers should consider these factors and use turbulence in combination with other behavioral guidance mechanisms (for example, artificial lights or shading) to elicit the desired behavioral response from juvenile salmon (sensu Coutant 2001b). Our experiments highlight the complexity of fish behavior and the difficulty of prescribing general guidelines for the application of induced turbulence. Nonetheless, under some circumstances induced turbulence had desirable effects on fish behavior that could be applied to field scenarios to reduce migration delays and guide fish to safe passage routes.

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