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SNAKE RIVER FALL CHINOOK SALMON LIFE HISTORY INVESTIGATIONS

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SNAKE RIVER FALL CHINOOK SALMON LIFE HISTORY INVESTIGATIONS
ANNUAL REPORT 2009

Prepared by:

Kenneth F. Tiffan
U.S. Geological Survey
Western Fisheries Research Center
Columbia River Research Laboratory
5501A Cook-Underwood Rd. Cook, Washington 98605

William P. Connor
U.S. Fish and Wildlife Service
Idaho Fishery Resource Office
P.O. Box 18 Ahsahka, ID 83520

Brian J. Bellgraph
Pacific Northwest National Laboratory
P.O. Box 999
Richland, Washington 99352

Rebecca A. Buchanan
Columbia Basin Research
School of Aquatic and Fisheries Sciences
University of Washington
1325 Fourth Avenue, Suite 1820
Seattle, Washington 98101

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U.S. Department of Energy
Bonneville Power Administration
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Portland, OR 97208-3621

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Executive Summary

In 2009, we used radio and acoustic telemetry to evaluate the migratory behavior, survival, mortality, and delay of subyearling fall Chinook salmon in the Clearwater River and Lower Granite Reservoir. We released a total of 1,000 tagged hatchery subyearlings at Cherry Lane on the Clearwater River in mid-August and we monitored them as they passed downstream through various river and reservoir reaches. Survival through the free-flowing river was high (>0.85) for both radio- and acoustic-tagged fish, but dropped substantially as fish delayed in the Transition Zone and Confluence areas. Estimates of the joint probability of migration and survival through the Transition Zone and Confluence reaches combined were similar for both radio- and acoustic-tagged fish, and ranged from about 0.30 to 0.35. Estimates of the joint probability of delaying and surviving in the combined Transition Zone and Confluence peaked at the beginning of the study, ranging from 0.323 ($\widehat{SE}$ =NA; radio-telemetry data) to 0.466 ($\widehat{SE}$ =0.024; acoustic-telemetry data), and then steadily declined throughout the remainder of the study. By the end of October, no live tagged juvenile salmon were detected in either the Transition Zone or the Confluence. As estimates of the probability of delay decreased throughout the study, estimates of the probability of mortality increased, as evidenced by the survival estimate of 0.650 ($\widehat{SE}$ =0.025) at the end of October (acoustic-telemetry data). Few fish were detected at Lower Granite Dam during our study and even fewer fish passed the dam before PIT-tag monitoring ended at the end of October. Five acoustic-tagged fish passed Lower Granite Dam in October and 12 passed the dam in November based on detections in the dam tailrace; however, too few detections were available to calculate the joint probabilities of migrating and surviving or delaying and surviving. Estimates of the joint probability of migrating and surviving through the reservoir was less than 0.2 based on acoustic-tagged fish. Migration rates of tagged fish were highest in the free-flowing river (median range = 36 to 43 km/d) but were generally less than 6 km/d in the reservoir reaches. In particular, median migration rates of radio-tagged fish through the Transition Zone and Confluence were 3.4 and 5.2 km/d, respectively. Median migration rate for acoustic-tagged fish though the Transition Zone and Confluence combined was 1 km/d.

We radio tagged 84 smallmouth bass and six channel catfish in the Confluence reach and later detected 48 bass and 1 catfish during mobile tracking. Predators were primarily located along shorelines in the Confluence, but a couple of smallmouth bass did swim into the Clearwater River. Most radio-tagged subyearlings that we determined to be dead were also located in shoreline areas suggesting that predation could account for some of the mortality we observed.

Our total dissolved gas (TDG) monitoring in the lower Clearwater River showed a cyclic pattern of low (~102%) TDG in the morning and higher (~110%) TDG in the late afternoon. Using a compensation depth of 1 m, we found that 15.4% (3.9 ha) of the lower 13 km of the

Clearwater River would not provide fish with an opportunity for depth compensation in a low-flow year. Water temperatures in the Clearwater River showed diel variations of about 2°C, and generally ranged from 10-12°C during summer flow augmentation. The Clearwater River generally showed little thermal variation while our tagged fish were at large, whereas the Snake River at the downstream boundary of the Confluence was thermally heterogeneous until mid-September. In the unimpounded Clearwater River, simulated water velocities ranged from about 1.3 to 1.5 m/s before flow augmentation ended, and were about 0.6 m/s thereafter. By comparison, velocities at the Clearwater River mouth were about 0.3 m/s during flow augmentation, and about 0.1 m/s thereafter.

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CHAPTER ONE

Migration Delay and Survival of Juvenile Fall Chinook Salmon in the Vicinity of the Confluence of the Snake and Clearwater Rivers

Kenneth F. Tiffan
U.S. Geological Survey
Columbia River Research Laboratory
5501A Cook-Underwood Rd.
Cook, Washington 98605

William P. Connor
U.S. Fish and Wildlife Service
Idaho Fishery Resource Office
P.O. Box 18
Ahsahka, ID 83520

Brian J. Bellgraph
Geoffrey A. McMichael
William A. Perkins
Marshall C. Richmond
Katherine A. Deters
Evan V. Arntzen
P. Scott Titzler
Ben J.Goodman
Pacific Northwest National Laboratory
P.O. Box 999
Richland, Washington 99352

Rebecca A. Buchanan
Columbia Basin Research
School of Aquatic and Fisheries Sciences
University of Washington
1325 Fourth Avenue, Suite 1820
Seattle, Washington 98101

Introduction

The Snake River upper reach, Snake River lower reach, Grande Ronde River, and Clearwater River are recognized as the four major spawning areas of Snake River Basin natural fall Chinook salmon *Oncorhynchus tshawytscha* upstream of Lower Granite Reservoir (Figure 1; ICTRT 2007). Though treated as one population, temperature during incubation and early rearing fosters life history diversity among the juveniles produced in these major spawning areas (Connor et al. 2002, 2003). Young fall Chinook salmon in the Snake River upper reach emerge and begin seaward movement earliest in the year followed by fish from the Snake River lower reach, Grande Ronde River, and Clearwater River. Of the four spawning areas, young fall Chinook salmon from the Clearwater River have the most diverse life history. Some of the juveniles meet the seasonal requirements to become actively migrating subyearling smolts and enter the ocean in their first summer of life. Others move downstream gradually, increase their downstream movement rate in the fall, pass Bonneville Dam, and then winter in freshwater or the Columbia River Estuary (Figure 1). A portion of the Clearwater River juveniles begin seaward migration as subyearlings, but eventually lose their disposition to actively migrate and winter in reservoirs formed by the Federal Columbia River Power System. The fish that winter in reservoirs grow to fork lengths >170 mm and enter the ocean as yearlings. They are referred to as reservoir-type juveniles (Connor et al. 2005).

Understanding the juvenile life history diversity of Clearwater River fall Chinook salmon juveniles is critical to the recovery of the Snake River Basin fall Chinook salmon population. In 2007, Arnsberg et al. (2010; hereafter Arnsberg et al.) collected data that exemplified the life history diversity of young fall Chinook salmon in the Clearwater River. During June through the first week of August, Arnsberg et al. seined subyearlings rearing along the shorelines of the free-flowing Clearwater River (Figure 2). All subyearlings 60-mm fork length and longer (N = 943) were implanted with passive integrated transponders (PIT tags; Prentice et al. 1990) and released back to the river. Subyearlings that were PIT-tagged had a mean fork length of 68 ± 8 mm. A total of 11 of the PIT-tagged fish were eventually recaptured in the free-flowing reaches. The mean residence time (i.e., the number of days that elapsed between initial tagging and recapture) was 6 ± 4 d. This suggests that after growing to 60 mm the fish spent about one week in the free flowing reaches before moving downstream. After moving downstream, the subyearlings traverse a 6-km long reach where the river transitions from a free-flowing to an impounded state. We refer to this area as the "Transition Zone" that includes both riverine and impounded habitat (Figure 2). The impounded portion makes up the Clearwater River arm of Lower Granite Reservoir. Arnsberg et al. sampled the Transition Zone from the last week of July to the end of August 2007. In contrast to the free-flowing river, the seine was set at starting points well off shore. A total of 743 subyearlings were captured in the Transition Zone at an average fork length of 103 ± 12 mm. Of these, four had been initially tagged and released from 26 to 40 d earlier in the free-flowing reaches upstream. Three of the subyearlings were recaptured 29 d after

they were initially captured and tagged in the Transition Zone. These findings confirmed that some subyearlings dispersed from the free-flowing reaches and then spent up to one month or more in the Transition Zone where they continued to grow.

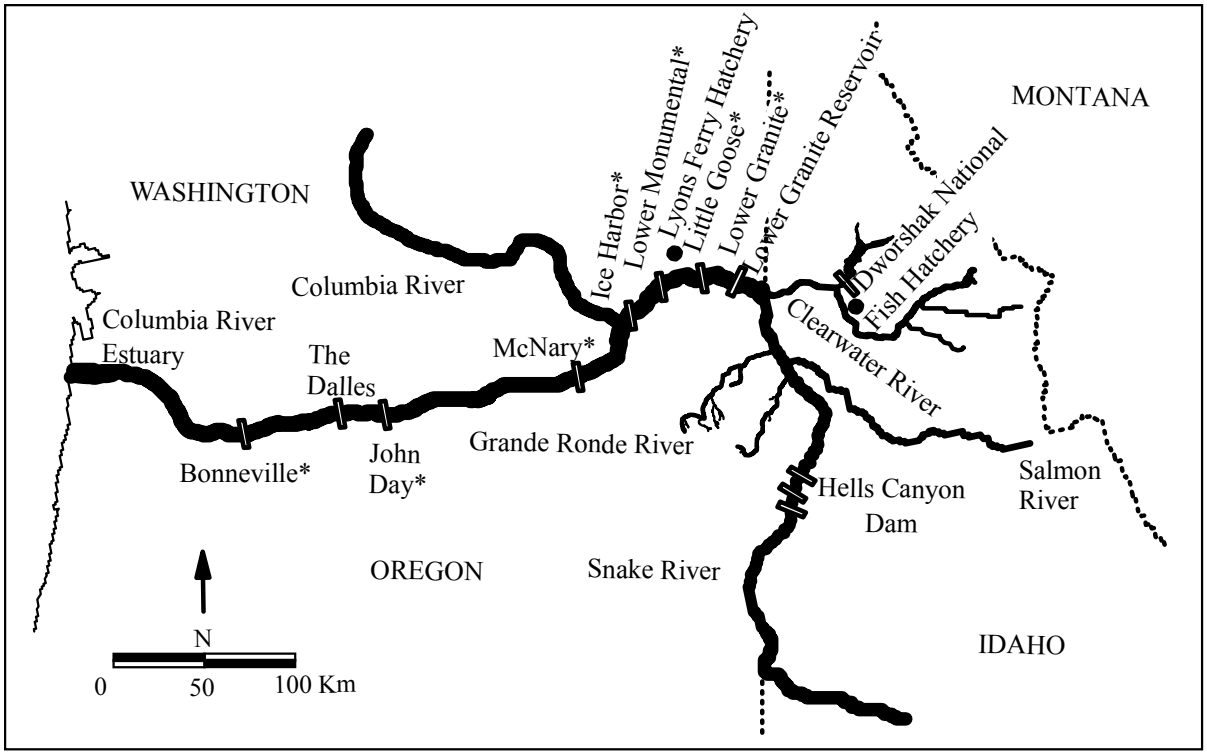

Figure 1.—The Snake River upper reach (Hells Canyon Dam to the Salmon River), Snake River lower reach (Salmon River to upper end of Lower Granite Reservoir), Grande Ronde River, and Clearwater River where fall Chinook salmon spawn. The Federal Columbia River Power System including the dams equipped with juvenile fish bypass and PIT-tag detection systems (denoted by asterisks) as well as the location of Lyons Ferry Hatchery where the hatchery fall Chinook salmon used for the study were initially cultured are also shown.

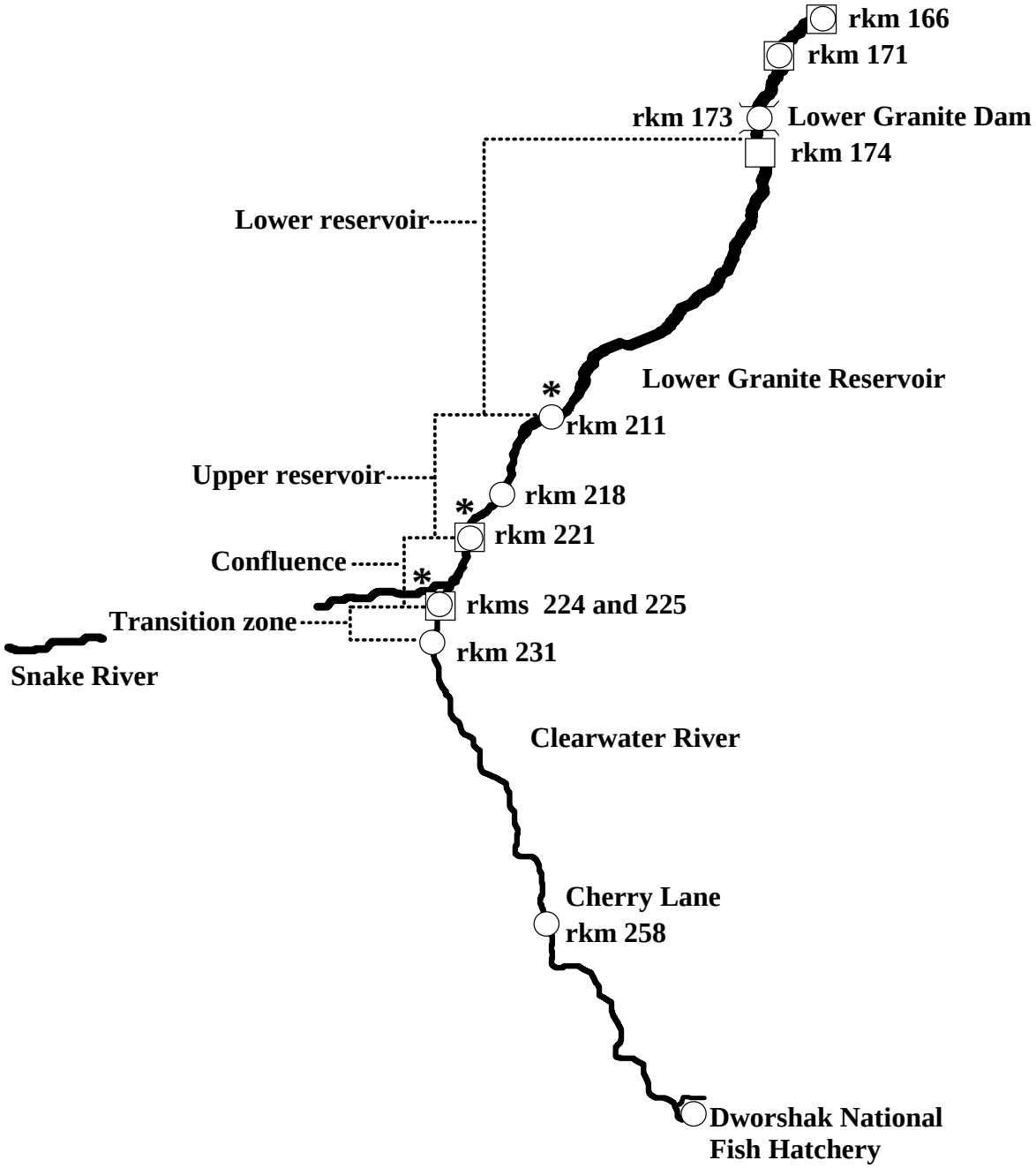

Figure 2.—The study area in 2009 including the reaches of the Clearwater River and Lower Granite Reservoirs where radio (circles) and acoustic (squares) tag detection equipment was stationed, thermographs were located (*), Dworshak National Fish Hatchery where hatchery fall Chinook subyearlings were reared and tagged, and Cherry Lane where the tagged fish were released. Arnsberg et al. (2010) sampled the upper free-flowing reach, lower free-flowing reach, and the Transition Zone in 2007. Locations are shown in river kilometers (rkm).

In 2007, we used radio and acoustic telemetry to more fully evaluate the migratory behavior, survival, mortality, and delay of subyearling fall Chinook salmon in the Clearwater River and Lower Granite Reservoir. Monthly releases of radio- and acoustic-tagged hatchery subyearlings made from May through October (~95 fish /month) showed that fish traveled relatively rapidly in the free-flowing river (>50 km/d), but then slowed substantially (<5 km/d) and delayed in the Transition Zone and Confluence (Figure 2). This behavior was most prevalent during the summer and continued into the fall. Estimates of the joint probability of migration and survival were lowest in the Transition Zone for fish released in June and lowest in the Confluence for fish released in July and August. Radio-tagged fish released in August showed the greatest delay in the Transition Zone, whereas acoustic-tagged fish released in September showed the greatest delay in the Transition Zone and Confluence reaches. Across the monthly release groups from July through September, the probability of delaying in the Transition Zone and surviving there declined throughout the study, and mortality of radio-tagged fish was highest in the Transition Zone during June, July, and August.

Given our findings from 2007, we focused our 2009 field efforts to better understand the migration delay and survival of juvenile fall Chinook salmon in the Transition Zone and Confluence from July through September. Our objective was to identify trends over time in probabilities of the following events: (1) survival and migration out of the study area, (2) migration delay and survival within the study area, and (3) mortality within the study area. The joint probability of survival and migration was estimated in multiple river reaches extending to the Lower Granite Dam forebay. The probabilities of migration delay and mortality were estimated only for the reaches surrounding the Transition Zone and Confluence of the Clearwater and Snake rivers.

Methods

Data Collection

Study area.—The upstream boundary of our study area in 2009 was Cherry Lane on the Clearwater River (approximately 258 river kilometers [rkm] from the Snake River mouth). The downstream boundary of our study area was the Lower Granite Dam tailrace (rkm 173 from the Snake River mouth; Figure 2). The precise downstream boundary of the study area was slightly different for radio-tagged fish (Figure 3) than for acoustic-tagged fish (Figure 4). Both types of telemetry technologies used a final pair of receivers in the Lower Granite Dam tailrace (Figure 4). We divided the study area into reaches based on a combination of the location of tag detection equipment (described later). Reaches were defined to be the stretches of river between adjacent detection arrays from which survival would subsequently be estimated. There were seven reaches used for analysis of radio-telemetry data in 2009 (Figure 3). Reach 1 ("Free-

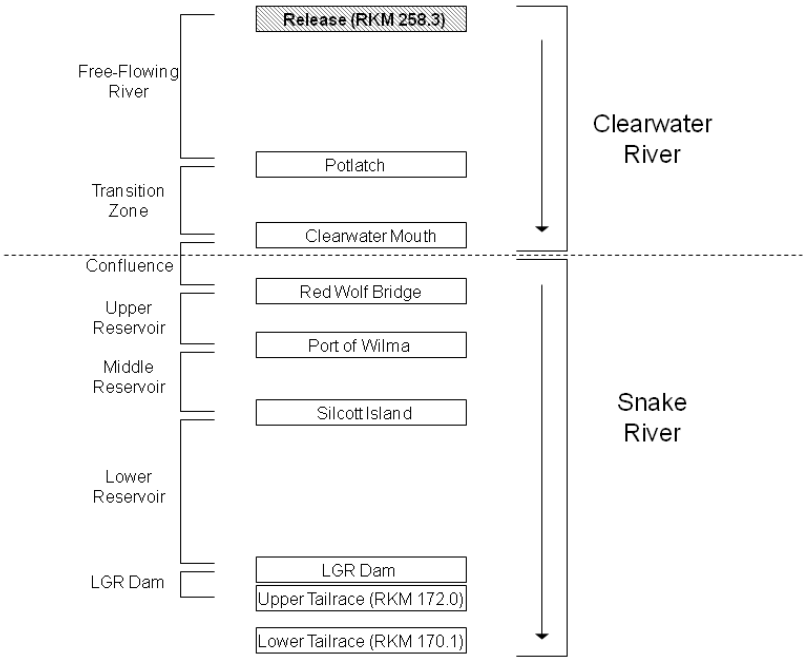

Figure 3.—Release site and locations of radio telemetry survival lines. The release site is at Cherry Lane on the Clearwater River, near the Nez Perce Tribal Hatchery.

Flowing River") extended from the release site at Cherry Lane to Potlatch. Reach 2 ("Transition Zone") extended from Potlatch to the Clearwater River mouth. Reach 3 ("Confluence") extended from the Clearwater River mouth to Red Wolf Bridge. Reach 4 ("Upper Reservoir") extended from Red Wolf Bridge to the Port of Wilma. Reach 5 ("Middle Reservoir") extended from the Port of Wilma to Silcott Island. Reach 6 ("Lower Reservoir") extended from Silcott Island to Lower Granite Dam. Reach 7 ("LGR Dam") extended from Lower Granite Dam to the first tailrace array about 1 km downstream. The probabilities of survival and detection could not be estimated separately in the final reach between the two tailrace arrays, so this reach was not included in the results. In instances where very few fish were detected at the downstream arrays, it was necessary to restrict the study area still further.

Four reaches were used in the analysis of acoustic-telemetry data and varied from that of the radio-telemetry reaches (Figures 3 and 4). The first reach ("Free-Flowing River") extended from the release site to Potlatch, and coincided closely with Reach 1 from the radio-telemetry study. The second reach was the combined "Transition Zone-Confluence", extending from Potlatch to Red Wolf Bridge, and was approximately the same region as Reaches 2 and 3 from the radio-telemetry study (Figure 4). The third acoustic reach was the "Reservoir", extending from Red Wolf Bridge to the Lower Granite Dam Forebay, and was approximately the same region as the combined Upper, Middle, and Lower Reservoir (Reaches 4-6) from the radio-

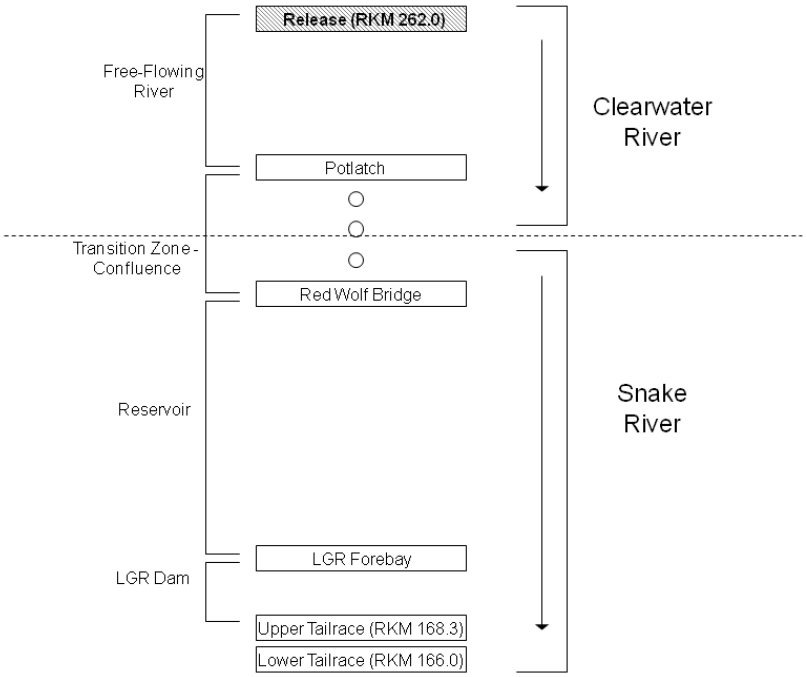

Figure 4.—Release site and locations of acoustic survival lines and intrareach detection nodes (indicated by circles). The release site is near Cherry Lane on the Clearwater River, near the Nez Perce Tribal Hatchery. The number and location of the intrareach nodes is not to scale.

telemetry study. The last acoustic reach was "LGR Dam", extending from the forebay to the first tailrace receiver, and approximately the same length and location as the seventh radio-telemetry reach (Figure 3 and 4). In instances where very few fish were detected at the downstream arrays, it was necessary to further restrict the study area.

Fish source and culture.—In 2009, we intended to collect run-at-large subyearlings from the Transition Zone of the Clearwater River for radio and acoustic tagging to better represent the natural population. Efforts to collect and tag fish in the Transition Zone in 2008 were thwarted by elevated total dissolved gas (TDG) levels in the river and mortality associated with handling and holding stress and gas bubble trauma (GBT). To avoid this problem in 2009, we intended to collect fish from the river during July and then transport them to the Nez Perce Tribal Hatchery for holding in degassed water to dissipate any dissolved gas before tagging. These efforts were not successful, therefore, we used Lyons Ferry Hatchery origin subyearlings that we held at the Dworshak National Fish Hatchery in case problems arose during collection, holding, and tagging. Acquisition of these hatchery subyearlings for our 2009 releases was coordinated under *U.S. v. Oregon*.

Hatchery subyearlings were reared in two 2-m^3 circular tanks containing 16,014 L of 10ºC hatchery water supplied at 60 L/min. We began feeding fish with No. 1.2 BioDiet growth formula and ended with No. 1.5 BioDiet growth formula. Rations were controlled so that fish were approximately 90 mm by the beginning of August. The water volume in the tank was increased to 1,926 L as the fish grew to a maximum density of 0.013 kg/L. We withheld feed 48 h prior to tagging.

Subyearling tagging and release.—We tagged subyearlings with combinations of either PIT tags and radio tags or PIT tags and acoustic tags on 12 and 13 August 2009 at the Dworshak National Fish Hatchery. We surgically implanted subyearlings with coded radio tags (Lotek Wireless, Inc., Newmarket, Ontario) and PIT tags following the methods of Adams et al. (1998; Table 1). The tags we used (model NTC-M-2) measured 12 mm long, 5 mm wide, weighed 0.43 g in air, had a pulse interval of 10 s, and had a life expectancy of 42 d. Antenna length was 16 cm. For all tagged fish, the ratio of tag weight to fish weight did not exceed 5% (range 2.2 to 5%). Immediately after surgery, the fish were placed into a 1,182-L tank on a fish transport truck that was constantly supplied with 10.0–12.0ºC hatchery water. Fish density in the tank did not exceed 0.005 kg/L. From 16 to 24 h after surgery, we trucked the hatchery subyearlings to Cherry Lane on the Clearwater River (Figure 2). During each 40-min trip to Cherry Lane, oxygen in the tank was kept near 100% saturation. The hatchery subyearlings were acclimated to ambient river temperature (9.9-10.0°C) by gradually draining the tank using a gasoline-powered water pump to gradually replace the water in the tank with river water at a maximum rate of 2ºC per hour. Only one fish died post-tagging on the first day of tagging in 2009 and this tag was used in another fish on the second day. A total of 500 PIT- and radio-tagged fish were released at Cherry Lane; half on 13 August and half on 14 August. Grand mean fork length at release was 102.6 mm (range 90-118 mm) and mean weight was 11.8 g (range 8.6 to 19.8 g).

Acoustic-tagged subyearlings were double-tagged with a PIT tag and a Juvenile Salmon Acoustic Telemetry System (JSATS) transmitter (McMichael et al. 2010; Table 1). The same three surgeons performed surgeries each day. Fish were anesthetized with 80 mg of tricaine methanesulfonate/L of water until stage 4 anesthesia was reached (i.e., total loss of equilibrium). Fork length and weight of each fish were measured after they were anesthetized. Fish were then placed on a foam surgery platform for tag implantation. All fish were implanted with 60-d transmitters (mean weight in air = 0.438 g, SD = 0.01 g, N = 562) manufactured by Advanced Telemetry Systems (Isanti, Minnesota). All transmitters had a 6-s pulse repetition interval (PRI). PolyAqua was applied to the foam pad to help maintain the fish's slime coat and reduce scale loss. Maintenance anesthetic (40 mg MS-222/L of water) was gravity-fed to fish during surgery (about 2 to 3 min) by a small tube inserted in the mouth. Anesthetic-free water was also available to the surgeon and could be adjusted to maintain proper sedation. A 7-mm incision was made parallel and about 2 mm proximal to the ventral midline. The tags were inserted into the peritoneal cavity, and the incision was closed with two simple, interrupted sutures using 5-0

Monocryl (monofilament manufactured by Ethicon, Rahway, New Jersey). Immediately after surgery, tagged fish were allowed to recover in the fish hauling tank described previously for at least 15 h and then released into the Clearwater River at Cherry Lane as described for radio-tagged fish. The range in the ratio of tag weight to fish weight was 2.0 to 5.1%. There were no post-tagging mortalities of acoustic-tagged fish before to release. All surgical and handling procedures of acoustic-tagged juvenile fall Chinook salmon were approved by the Institutional Animal Care and Use Committee at the Pacific Northwest National Laboratory under Protocol no. 2009-05.

Table 1.—Tagging data for groups of radio- and acoustic-tagged hatchery fall Chinook salmon (FC), smallmouth bass (SMB), and channel catfish (CC) released in 2009. All fall Chinook salmon were released at Cherry Lane (rkm 258) on the Clearwater River, and all smallmouth bass and channel catfish were released between Snake River kilometer 221 and 224 (3-km section downstream of the Clearwater River confluence). Only 35 of the 59 smallmouth bass tagged on 22 July had acoustic tags. No channel catfish were acoustic tagged.

Tag date	Release date	*N*	Species	Mean FL (mm±SD)	Mean weight (g±SD)	Tag life (days)
			Radio tags			
12 Aug	13 Aug	250	FC	102.3±5.0	11.6±1.9	42
13 Aug	14 Aug	250	FC	103.1±4.5	12.0±1.8	42
			Acoustic tags			
12 Aug	13 Aug	250	FC	103.5±5.3	11.2±2.0	60
13 Aug	14 Aug	250	FC	102.3±5.1	11.4±1.9	60
			Radio and acoustic tags			
16 Jul	16 Jul	25	SMB	247.2±43.4	229.0±116.6	60/120
22 Jul	22 Jul	59	SMB	246.0±45.4	227.7±143.4	60/120
22 Jul	22 Jul	6	CC	256.3±51.0	254.7±169.6	60

Predator tagging and release.—Given the spatial patterns of subyearling mortality that we observed in 2007, we speculated that some of this might have been due to predation. In 2009, we collected predators in the Confluence reach and implanted them with radio and acoustic tags that were not used in 2008 (Table 1). Fish were collected by angling in the Confluence from Red Wolf Bridge (rkm 221) to the mouth of the Clearwater River (rkm 224). Collected predators were held in net pens up to 24 h before being tagged. Fish were surgically implanted with coded radio tags (model NTC-3-L; Lotek Wireless, Inc., Newmarket, Ontario) following the methods of Adams et al. (1998). The tags measured 15.0 mm long, 4.5 mm in diameter, weighed 0.85 g in air, and had a life expectancy of 42 d. Antenna length was 16 cm. For all tagged fish, the ratio of tag weight to fish weight did not exceed 5%. Most predators

were also implanted with an acoustic tag (JSATS; Advanced Telemetry Systems, Isanti, Minnesota) that had a mean weight in air of 0.829 g (SD = 0.117 g, N = 59) and a life expectancy of 120 d. After tagging, fish were released at their location of capture after a 20 min recovery period.

Radio tag life.—We measured radio tag life (d) of 50 transmitters at the USGS's Columbia River Research Laboratory. Activated transmitters were placed in 0.6-m-diameter circular tanks that were maintained at 17ºC. Groups of 10 transmitters were placed in five different metal cans to minimize transmitted radio signals from interfering with each other. A receiver logged the radio tag signals for a total of 70 d, a point at which most tags had expired. The life of tags used in predators was not measured.

Acoustic tag life.—We measured JSATS acoustic tag life (d) at the Pacific Northwest National Laboratory's Aquatic Research Laboratory in Richland, Washington. Active transmitters with a 60-d battery life (N = 46) were placed in a 1.8-m-diameter circular tank during the test. Each transmitter was placed into an individual water-filled bag and suspended from a buoy that freely rotated in the tank to maximize the probability of detection for each transmitter and to simulate a live fish. Transmitters were monitored and signal waveforms recorded 24 h/d with an acoustic receiver from the activation date (17 August 2009) until all tags had expired. Waveform data were processed approximately weekly to determine the number of active tags throughout the study period and to determine dates of expiration for each transmitter. No tag life study was performed on 120-d tags implanted into salmon predators because a survival analysis was not performed on these fish.

Detecting radio-tagged fish.—Radio-tagged smolts were detected at fixed antenna arrays ("radio survival lines") located throughout the Clearwater River downstream of the release site at Cherry Lane, and in the Snake River between the mouth of the Clearwater River and Lower Granite Dam (LGR; Figure 2). Two survival lines were located in the LGR tailrace. Four- or nine-element Yagi antennas were used at each site in conjunction with a Lotek SRX 400 receiver (Lotek Wireless, Inc., Newmarket, Ontario). One or two receivers were deployed at each fixed detection site to maximize coverage of the river channel. Receivers were powered by 12-V batteries and solar panels. Receivers recorded the tag code, signal strength, and the time and date of each signal emitted by the tag (i.e., every 10 s) while in the vicinity of the receivers. Data from receivers were downloaded twice a week from August through mid-October.

Radio-telemetry data were processed to remove erroneous data records and produce a final dataset for analyses. Detection records were first arranged in sequential order by time and date. Records that did not fit a logical sequence in space or time, those with low signal strength, or represented by a single observation at a detection site were considered false positives and removed from further consideration. Acceptable detection data were typified by high signal

strengths, multiple records at a detection site, and progression of detections as fish moved downstream.

Mobile tracking crews monitored radio-tagged subyearlings three times a week from release in early August through early October in the Transition Zone and Confluence reaches. Mobile tracking was conducted from a boat equipped with a 3-element Yagi antenna, and a Lotek SRX400 receiver. In the Transition Zone, a total of 136 parallel transects were established perpendicular to the shoreline in 50-m intervals from the mouth of the Clearwater River (rkm 224) to the Potlatch Mill (~rkm 231). This ensured complete coverage of the Transition Zone during tracking. In the Confluence, a total of 64 parallel transects were established perpendicular to the shoreline in 50-m intervals from Redwolf Bridge (rkm 221) to the mouth of the Clearwater River (rkm 224). On each day of tracking, a GPS was used to navigate each transect beginning with the downstream-most transect in each reach. Receivers were set to continuously log any radio tags detected from subyearlings and predators. GPS units were also set to log the location of the boat every 3 s. Fish locations were ultimately determined by selecting the GPS point that corresponded to the highest signal power for a detected fish.

Detecting acoustic-tagged fish.—Eighteen acoustic telemetry receiving nodes (JSATS Model N201, Sonic Concepts, Inc., Bothell, Washington) were deployed around the confluence of the Snake and Clearwater rivers (Figure 5) and near Lower Granite Dam (Figure 6). Two nodes were deployed in the Clearwater River about 5.3 km upstream from the confluence in a line that ran perpendicular to shore, referred to as the Potlatch array, to detect fish entering the study site. An array of two nodes (Red Wolf Bridge array) was deployed in the Snake River about 2.7 km downstream from the confluence to estimate survival of fish migrating through the Confluence reach of the Snake and Clearwater rivers. Nine "intra-reach" nodes (six in the Clearwater and three in the Snake) with non-overlapping detection ranges were deployed in the thalweg to detect and determine fate (i.e., migration and survival, delay and survival, or mortality) of fish as they migrated downstream through the Snake/Clearwater Confluence. Because nodes had a maximum detection range of about 200–300 m and the river width is generally less than 600 m in this area, a single node deployed in the middle of the channel was likely able to detect fish across most of the river width. In addition to the nodes deployed around the confluence of the Snake and Clearwater rivers, a survival array of three nodes was deployed in the forebay of Lower Granite Dam (LGR Forebay array) about 0.3 km upstream from the dam, and a survival array of two nodes was deployed about 5.5 to 6.0 km downstream of the dam (LGR Tailrace array; Figure 6).

Each node consisted of a receiver powered by lithium batteries and one 15-s beacon transmitter. Node rigging typically included three buoys, an acoustic release mechanism (Model 111, InterOcean Systems, Inc., San Diego, California), anchor line, and anchor. The node was attached to the acoustic release with a 1.5-m-long section of 12.5-mm-diameter braided nylon

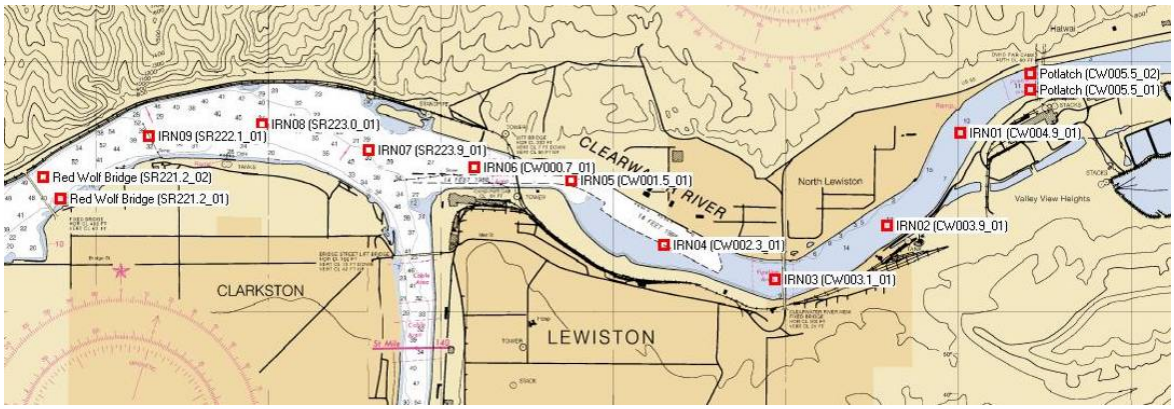

Figure 5.—Approximate locations of acoustic receiving nodes (red squares) in the Snake River (SR; enters at bottom center) and Clearwater River (CW; enters at right) in 2009. The Potlatch and Red Wolf Bridge arrays were used for survival analyses. Intra-reach nodes (IRN) were located between survival lines. Labels in parentheses indicate the river (SR or CW), river kilometer from the mouth (e.g., 223.9), and individual receiver number from the left to right bank (e.g., _01, _02, etc.).

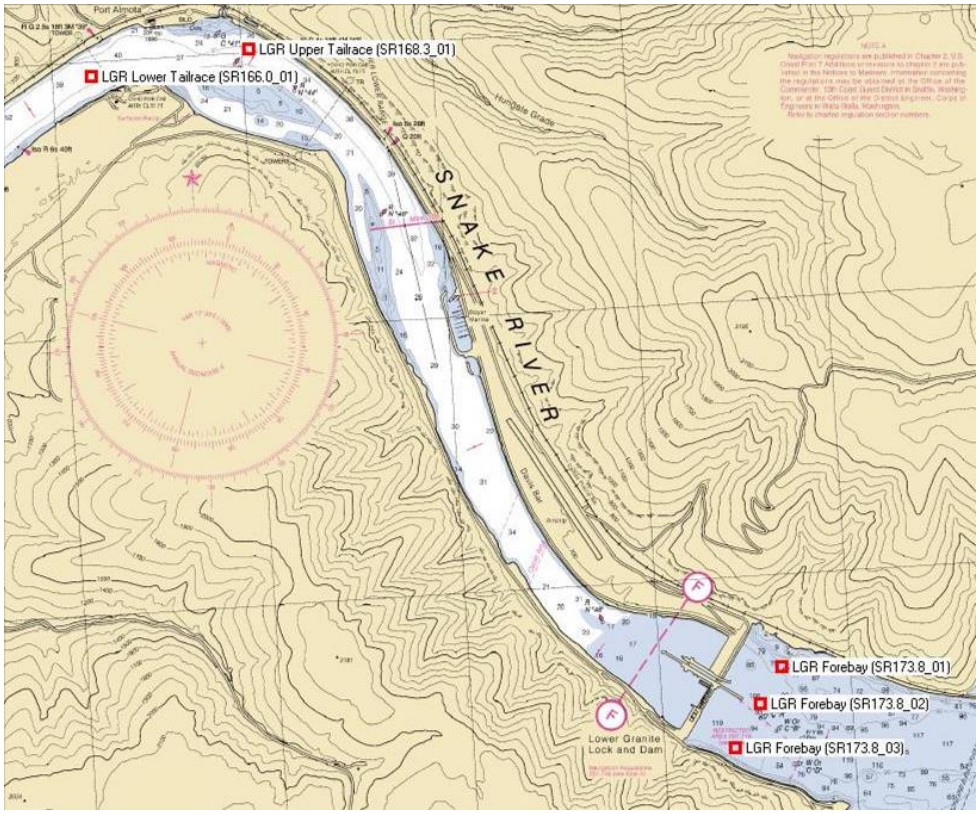

Figure 6.—Approximate locations of acoustic receiving nodes (red squares) in the Snake River (SR; enters in bottom right corner) near Lower Granite Dam (LGR), 2009. The LGR Forebay and LGR Upper/Lower Tailrace arrays were used for survival analyses. Labels in parentheses indicate the river (SR), river kilometer from the mouth (e.g., 116.0), and individual receiver number from the left to right bank (e.g., _01, _02, etc.).

rope threaded with three yellow buoys (Model BL-6, 16.5 x 12.4 cm, 1.45 kg buoyancy each; Bao Long Industrial, Ltd., Taipei, Taiwan) for extra buoyancy. The releasing end of the acoustic release held a 10-cm-diameter galvanized steel ring incorporated into the top end of a shock-corded mooring (anchor line) made from 9.5-mm-diameter Samson Tenex line. The length of the anchor line was dependent on water depth at the deployment location. A 3.7-m anchor line was used at locations greater than 12 m deep and a 1.5-m line was used at locations less than 12 m deep. The anchor end of the rope was secured to a 27-kg steel anchor using a 4.8-cm shackle. For shallow-water moorings (<5 m), the node was attached directly to the acoustic release, which was attached directly to the anchor. Depending on the mooring configuration used, the hydrophone was positioned about 1 to 7 m above the river or reservoir bottom.

Acoustic nodes were serviced (i.e., data downloaded and batteries replaced) about once every three weeks between deployment on 20 July 2009 and recovery on 10 and 11 December 2009. To recover nodes, the boat was positioned near the node waypoint, and an acoustic transducer (Model 1100E, InterOcean Systems Inc. San Diego, California) was used to activate the acoustic release, thereby detaching the node assembly from the anchor, causing the node assembly and acoustic release to rise to the water surface. Once at the surface, the node and release were collected and brought into the boat. An external LED light on the node housing was activated to verify that data were being recorded at the time of recovery. Battery packs were then replaced, and data were downloaded from an onboard Compact Flash (CF) card (SanDisk Extreme III 1.0 GB) to a laptop computer. Data were examined cursorily to determine if the node functioned properly during deployment. Nodes with potential problems were removed from service and replaced with a spare. Activating the node for redeployment entailed first connecting the node to a laptop computer and monitoring real-time data collection by the receiver. The receiver's onboard clock was then synchronized to the laptop clock, which was synchronized each day to the "true" time obtained from a satellite-linked handheld global positioning system (GPS) unit. Three detections by the receiver of the beacon transmitter were required to ensure functionality of the node before redeployment. A blank CF card was inserted into the node, data collection was resumed, and the node was resealed for deployment. The external LED light was again checked to ensure that the receiver was powered and recording data, and the node was returned to the water at approximately the same location as recovery. All mechanical components were also checked for wear and replaced if necessary during the servicing. Time, water depth (meters), and location coordinates of the node were recorded using Fugawi Marine ENC GPS software (Northport Systems Inc., Toronto, Ontario) during deployment.

Data collected by the acoustic receivers were recorded to a single text file and were subjected to a series of standardized quality control procedures. Physical data (i.e., date, time, barometric pressure, water temperature, tilt, and battery voltage) were written to the data file

every 15 s. Detections of transmitters were recorded in real time as they were received. Additional recorded information included TagID (unique code of each transmitter), time stamp, RSSI (receive signal strength indicator), and RxThreshold (a calculated measure of noise). Data file names from each acoustic receiver were labeled with the acoustic receiver location, and a copy was archived. Files were then processed to correct clock anomalies and to filter out false-positive detections (detections of TagIDs that did not meet criteria to be considered a valid detection). The filtering program recorded a valid detection if a minimum of four detections were received in 120 s and the time spacing of the latter three detections from the initial detection closely matched a multiple of the pulse-rate interval of the transmitter. After the data were filtered, additional quality control checks were applied to remove detections of tag codes that did not match fish released for the study or detections that occurred prior to the date of release, if any.

Total dissolved gas monitoring.—We monitored TDG and the distribution of water temperatures in the lower Clearwater River from April through August 2009. The goals of this task were 1) to determine whether TDG in the Clearwater River where juvenile fall Chinook salmon were collected and potentially tagged differed from that in the main-stem areas due to incomplete mixing or significant temperature differences (e.g., due to solar input or groundwater discharge), and 2) to evaluate the potential risk of TDG to fish in the lower Clearwater River based on the incidence of GBT in fish caught in 2008. We recorded TDG concentrations at the right bank, mid-channel, and left bank at three monitoring locations throughout the lower Clearwater River (CL-1, CL-2, and CL-3; Figure 7). Data from three U.S. Army Corps of Engineers (USACE)-owned gauges in the Clearwater River (LEWI, PECK, and DWQI; Figure 7) were also collected for comparison. Hydrolab Model 5 MiniSonde sensors (MS5; Hach Environmental, Loveland, Colorado) were used to monitor water quality. At each monitoring location, one MS5 sensor was programmed to record data using a 30-min interval for approximately 2-d each month during April through August 2009. Each MS5 included sensors to monitor dissolved oxygen, specific conductance, depth, TDG, and temperature. Sensor failure corrupted the data collected from CL-2 during July 2009, and these data were omitted. Data from CL-2 were also unavailable from June 2009 because the buoy was stolen and the sensor could not be recovered. Detailed manufacturer specifications, accuracies, and sensor resolutions during deployment are listed in Table A.1.

Temperature data were collected in two different ways to evaluate Clearwater River conditions. First, "temperature spot checks" were used to determine the spatial distribution of temperature differences. Temperature data were collected from several vertical positions in the water column at multiple channel positions near each of the three monitoring stations (CL-1, CL-2, and CL-3; Figure 7). These data were collected each month immediately following TDG sensor retrieval. Second, we collected temperature data every 30 min at the same times and locations that TDG monitoring data were collected.

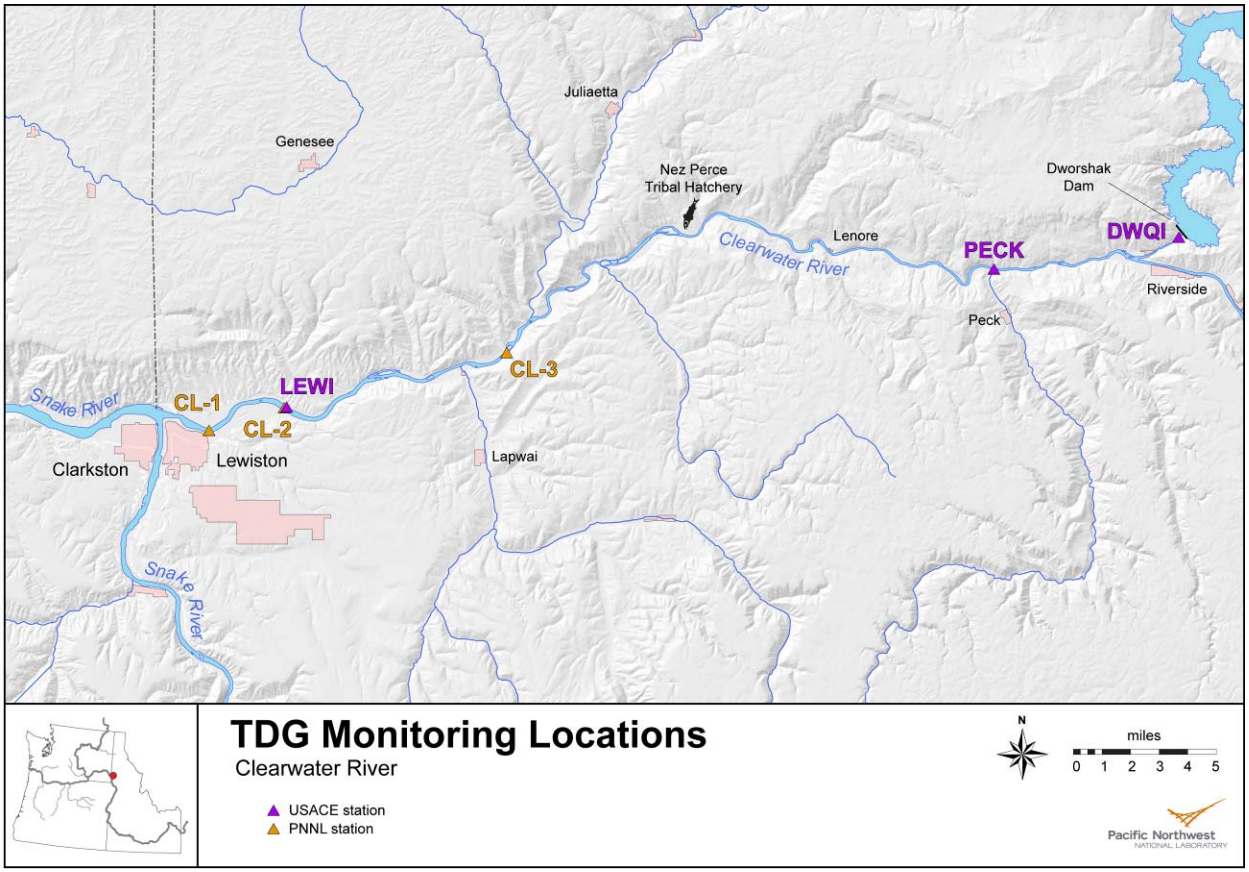

Figure 7.—Location of total dissolved gas monitoring locations from April through August 2009 (PNNL station) and permanent gas monitoring stations operated by the U.S. Army Corps of Engineers (USACE station). Tagged study fish in 2009 were released just downstream of the Nez Perce Tribal Hatchery.

Hydrodynamic data.— Hydrodynamic and water quality monitoring data were collected during the 2009 field season using methods similar to those described in the 2007–2008 report (Tiffan et al. 2009a) and the 2008–2009 report (Tiffan et al. 2009b). Six vertical strings of temperature loggers were deployed in Lower Granite Reservoir and in the Clearwater and Snake rivers upstream of their confluence (Figure 8). The three bridge-mounted temperature logger strings (LGR1, LGR2, and LGR3) were deployed 13 May 2009, and the three open-water temperature logger strings (LGR4, LGR5, and LGR6) were deployed on 14 May 2009. All six sites began measurements at 2400 hours on 16 May 2009. All temperature logger strings ran from 16 May 2009 through 15 January 2010. All temperature logger strings were recovered by 15 January 2010. One-hundred forty-four mobile acoustic Doppler current profiler (ADCP) transects (Figure 9) and 141 conductivity-temperature-depth (CTD) casts (Figure 10) were made from May through November 2009 throughout Lower Granite Reservoir and in the Clearwater and Snake rivers upstream of their confluence.

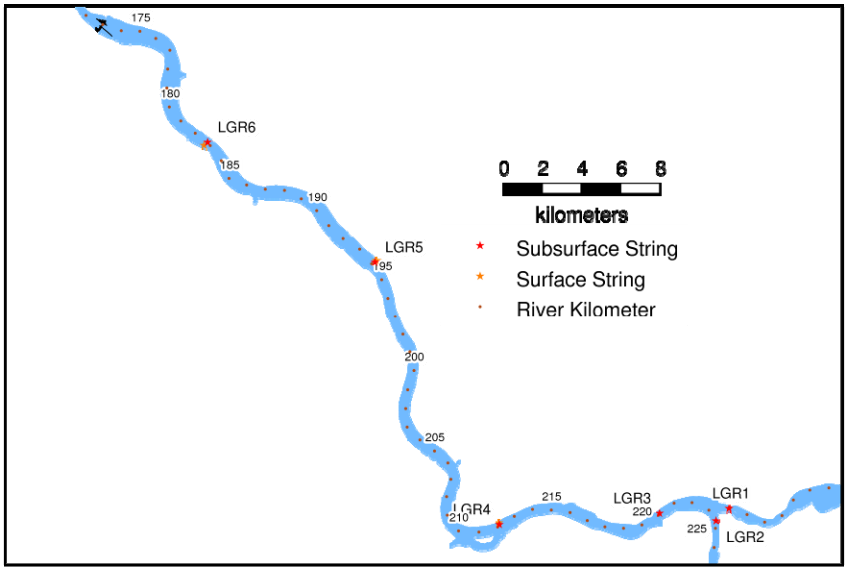

Figure 8.—Temperature logger string locations throughout Lower Granite Reservoir (LGR) for the 2009–2010 field season. Three-digit numbers labeled next to river indicate river miles from the confluence of the Snake and Columbia rivers.

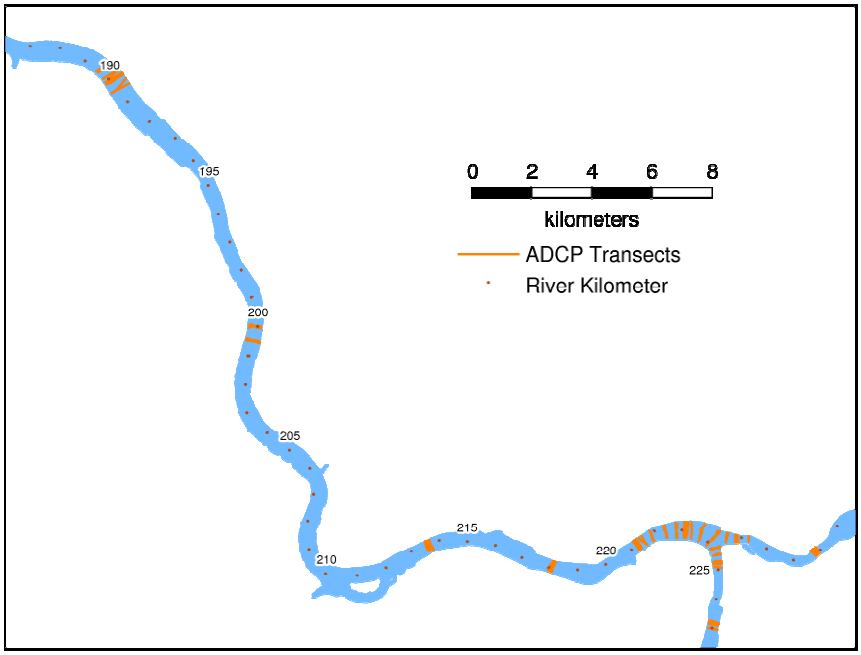

Figure 9.—Mobile acoustic Doppler current profiler (ADCP) transect locations during the 2009–2010 field season. Three-digit numbers labeled next to river indicate river miles from the confluence of the Snake and Columbia rivers.

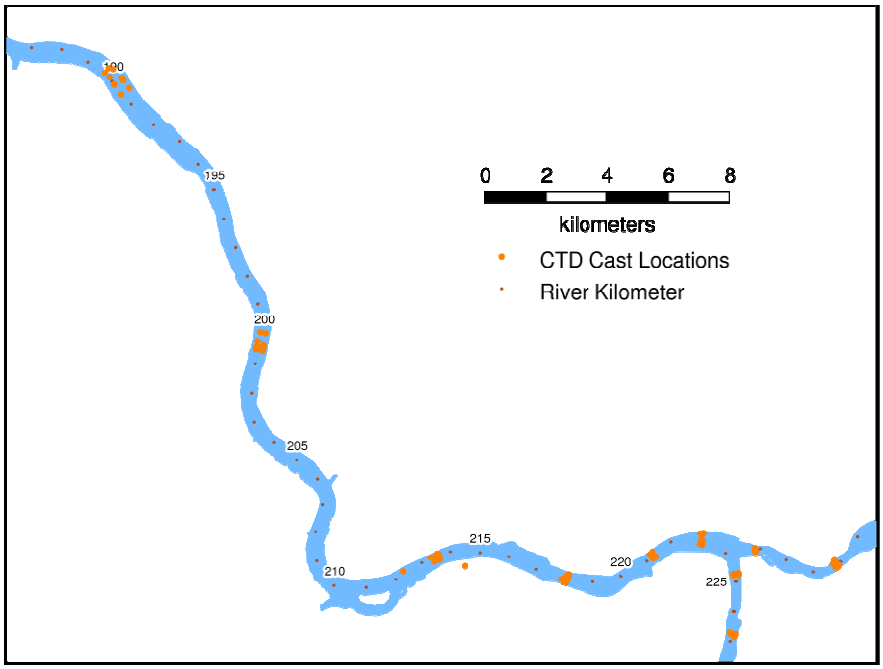

Figure 10.—Locations of conductivity-temperature-depth (CTD) casts performed in the 2009–2010 field season. Three-digit numbers labeled next to river indicate river miles from the confluence of the Snake and Columbia rivers.

Discharge data were collected from the gauges operated by the U.S. Geological Survey (USGS) in the Snake and Clearwater rivers. Clearwater River discharge was collected near Spalding, Idaho, at gauge no. 13342500, Dworshak Dam discharge was collected from gauge no. 13341000, and Snake River discharge was collected from gauge no. 13334300 near Anatone, Washington.

Data Analyses

Sampling and detection design.—A single release of 1,000 tagged smolts was made at Cherry Lane in the Clearwater River, near the Nez Perce Tribal Hatchery over a period of two days in mid-August, 2009. All detection periods for a given tag group (radio- or acoustic-tagged) began on the first day of release (13 August 2009) and varied in length, with each period lasting approximately a multiple of seven days. For example, the first detection period was from the time of release to the end of the first week, the second period was from the time of release through the end of the second week, and so on (Table 2). Thus, earlier detection periods were contained in all later detection periods. The length of the longest detection period for each release group depended on the expected and observed tag life. The radio tags were expected to last 42 d, and were observed to last an average of at least 56.1 d (median = 65.6 d). Fifteen tags were still alive on day 70, when the tag-life study was discontinued. Thus, we used radio-tag detections through day 65 (i.e., through 15 October 2009). The acoustic tags were expected to

last 60 d, and were observed to last an average of 94.9 d (median = 96.83 d). The longest detection period for acoustic tags lasted 80 d (i.e., through 30 October 2009). These detection periods used an increment of approximately a week, which was necessary for estimation of the migratory delay and mortality parameters of radio-tagged fish using the mobile tracking sampling design.

Table 2.—Detection periods and their ending dates for radio-tag and acoustic-tag release groups. Each detection period began on the first day of release, 13 August 2009. All dates are in 2009.

Detection Period	Radio-Tag Group	Acoustic-Tag Group
1	22 August	22 August
2	29 August	29 August
3	3 September	3 September
4	11 September	11 September
5	19 September	19 September
6	25 September	25 September
7	3 October	3 October
8	10 October	10 October
9	15 October	17 October
10		24 October
11		30 October

Fate determination.—Fate determination consisted of characterizing the fate of the subyearling Chinook salmon in the release groups within each reach on various temporal scales. Final fate at the end of the study characterized the state of the tagged fish at the end of the life of the tag (65 days for radio tags, and 80 days for acoustic tags). The intermediate fate analysis characterized fate at approximately weekly increments from the time of release throughout the study. On each temporal scale and for each reach, the main question to be answered was:

- What proportion of the fish migrated out of the reach during the given time period?

Additional questions focused on fish that did not migrate out of the reach:

- What proportion delayed (i.e., residualized) in the reach and survived there until the end of the given time period?

- What proportion died within the reach before the end of the given time period?

These questions were answered by estimating the following parameters:

- ϕ = joint probability of surviving and migrating out of the reach during the detection period

- ψ = joint probability of delaying migration and surviving in the reach through the end of the detection period
- μ = probability of dying in the reach before the end of the detection period

For each reach, the probabilities of migrating and surviving (ϕ), delaying migration and surviving (ψ), and dying (μ) are mutually exclusive and sum to 1. Their relative contributions to the fate of a fish can be represented in a pie chart (Figure 11). Due to limitations of the sampling design, however, the probability of delay (ψ) and mortality (μ) could be estimated only for the reaches between Potlatch and Red Wolf Bridge (i.e., Transition Zone and Confluence). These two reaches were analyzed separately using mobile tracking data from radio tags, and jointly using intrareach nodes detections from acoustic tags. In general, the joint probability of migrating and surviving (ϕ) was estimable for each reach from the release point to Lower Granite Dam (Figure 4). In some cases, the migration and survival probability (ϕ) was estimable for fewer reaches because of insufficient detections at the downstream arrays.

Fate determination for each detection period was performed using detections of either radio or acoustic tags at fixed arrays throughout the study area, and from mobile tracking of radio tags and intrareach node detections of acoustic tags between Potlatch and Red Wolf Bridge. Statistical methods were the same for each detection period. The analytic approach is described here for a single release group.

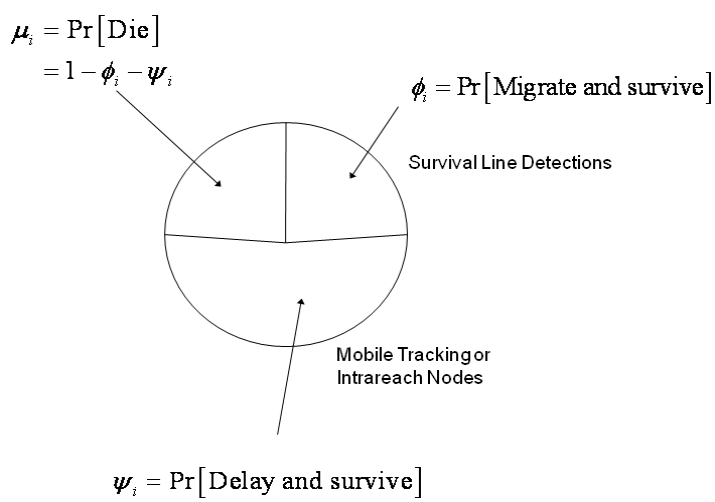

Figure 11.—Relationship between ϕ (joint probability of migrating and surviving), ψ (joint probability of delaying and surviving), and μ (probability of death) in a single reach i and detection period, and for a single release group (radio-tag or acoustic-tag).

For a single tagged release group of size R, the detections at the survival lines for the given telemetry technology (8 lines for radio tags [Figure 3], 5 lines for acoustic tags [Figure 4]) were organized into detection histories for each detection period. The detection histories were analyzed using the single release-recapture model (Skalski et al. 1998) to estimate ϕ_{iG}, the joint probability of migrating and surviving through reach i ($i = 1,\ldots,7$ for radio tags, and $i = 1,\ldots,4$ for acoustic tags) and tag group G (G = radio [R] or acoustic [A]) within the detection period, conditional on getting to that reach during the detection period.

The parameter ψ_{iG} was also estimated, where ψ_{iG} is the joint probability of delaying migration in Reach i and surviving there until the end of the detection period, conditional on arriving in that reach during the detection period for fish in tag group G (Figure 12). The parameter ψ_{2A} was estimated for the Transition Zone-Confluence using acoustic-telemetry data, whereas the two parameters ψ_{2R} and ψ_{3R} were estimated for the Transition Zone and Confluence, respectively, using radio-telemetry data. Whether radio- or acoustic-telemetry data were used, estimating ψ_{iG} first required estimating the number of live tagged fish that were present in reach i at the end of the detection period, N_{iG} (described below). The parameter ψ_{iG} was estimated as the ratio of the estimated number of live fish in the reach at the end of the detection period $\left(\widehat{N}_{iG}\right)$ to the estimated number of fish that entered the reach during the detection period:

$$\widehat{\psi}_{2G} = \frac{\widehat{N}_{2G}}{R\hat{\phi}_{1G}}$$

and

$$\widehat{\psi}_{3G} = \frac{\widehat{N}_{3G}}{R\hat{\phi}_{1G}\hat{\phi}_{2G}}.$$

The variance of $\widehat{\psi}_{iG}$ was estimated using the Delta Method (Seber 2002, pp.7-9).

The probability of death within the detection period in reach i for tag group G (μ_{iG}, $i = 2, 3$ for radio-telemetry data, and $i = 2$ for acoustic-telemetry data), conditional on arriving in reach i during the detection period, was estimated as

$$\widehat{\mu}_{iG} = 1 - \hat{\phi}_{iG} - \widehat{\psi}_{iG}.$$

The variance of $\widehat{\mu}_{iG}$ was estimated using the Delta Method.

The number of live radio-tagged fish present in a given reach at the end of a time period $\left(\widehat{N}_{iR}\right)$ was estimated using the mobile tracking samples of radio tags. Detections from the

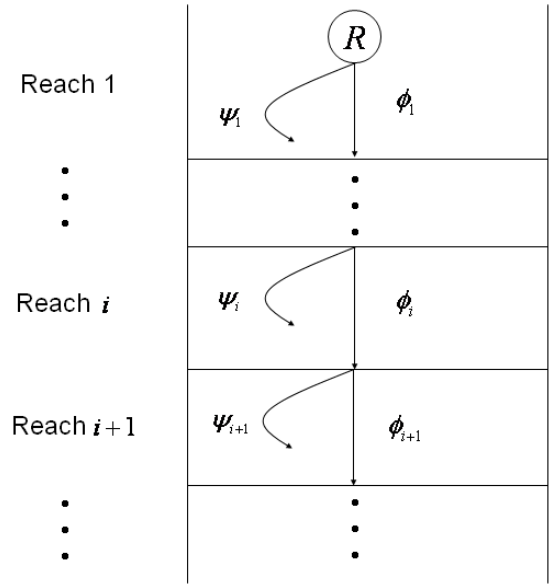

Figure 12.—Migration and delay parameters estimated from a single release (R) for a single detection period and tag group. The parameter ϕ_i is the joint probability of migrating and surviving through reach i, for $i = 1,\ldots,7$ for radio-tagged fish, and $i = 1,\ldots,4$ for acoustic-tagged fish. The parameter ψ_i is the probability of delaying migration and surviving in reach i ($i = 1,\ldots,7$ for radio-tagged fish and $i = 1,\ldots,4$ for acoustic-tagged fish) to the end of the detection period. The parameter ψ_i was estimable only for the Transition Zone and Confluence for the 2009 study.

mobile tracking samples were organized into detection histories and analyzed using the Manly-Parr method (Seber 2002, pp. 233-236) if three samples were available, or the Lincoln-Petersen method (Seber 2002, pp. 59-61) if only two samples were available.

The number of live acoustic-tagged fish present in acoustic reach 2 (Transition Zone-Confluence) at the end of a given time period $\left(\widehat{N}_{2A}\right)$ was estimated using detections on the individual receivers ("intrareach nodes") located throughout the reach using the methods of Buchanan et al. (2009) and summarized here. Two temporal subsamples of the intrareach node detections were taken during the last day or two of every time period. Detections from live fish were identified using a quantitative decision rule (see below). Detections of live fish from these subsamples were organized into detection histories representing the two subsamples. The number of live acoustic-tagged smolts present in the reach at the end of the time period was estimated using the Lincoln-Petersen model (Seber 2002, pp. 59-61). Three temporal

subsampling scenarios of the intrareach node detections were considered (Table 3). The three scenarios gave similar results, so Scenario 1 was used for reporting of results.

Table 3.—Temporal subsampling scenarios used to sample the detections on the intrareach acoustic receivers ("intrareach nodes") in order to estimate the abundance of live acoustic-tagged smolts in the Transition Zone-Confluence reach at the end of each detection period. Scenario 1 was used in reporting results.

Scenario	First Sample	Second Sample
1	Last Day, 0600-1200	Last Day, 1800-2400
2	Next to Last Day, 0600-1200	Last Day, 0600-1200
3	Next to Last Day, 1200-1800	Last Day, 1200-1800

Mortality decision rule.— The estimation of migration delay and mortality probabilities for any given reach and detection period from radio-telemetry data depended on mobile tracking in that reach at the end of the detection period, and on distinguishing between detections of live fish and those of dead fish. A fish was determined to be alive if it had a diffuse spatial pattern of locations over time, indicative of movement throughout the study area, or if it was subsequently detected at downstream detections sites after being mobile tracked (Figure 13). A fish was determined to be dead if it was repeatedly detected in the same location over numerous weeks with no subsequent detection of the tag elsewhere. Such locations usually showed a tight, clustered pattern (Figure 13).

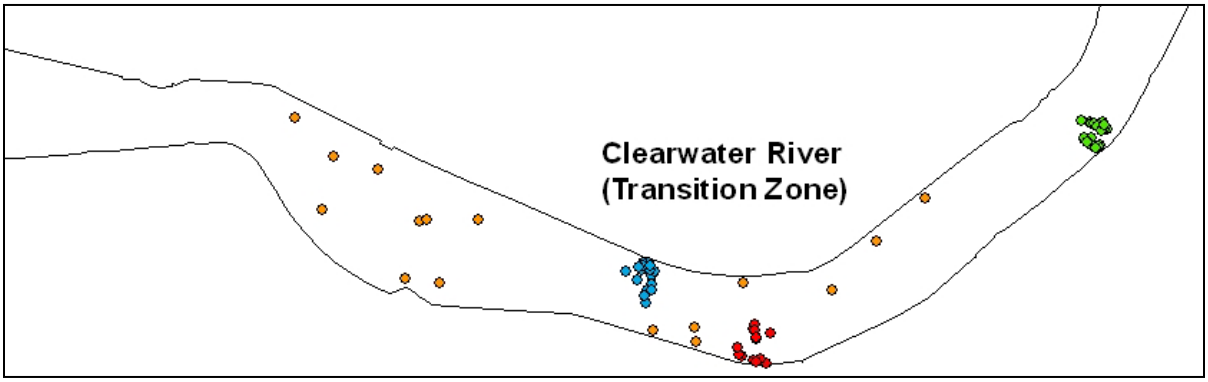

Figure 13.—Examples of the spatial patterns of fish locations used to determine if radio-tagged subyearlings were alive (orange circles) or dead (blue, red, and green circles) in 2009.

Estimation of the abundance of live acoustic-tagged smolts present in acoustic reach 2 at the end of each time period depended on the ability to distinguish between detections of live fish and detections of dead fish. The determination of whether a detection came from a live or dead fish was based on a series of decision rules. First, if a tag was subsequently detected at a different node, then the detection under consideration was assumed to have come from a live fish. Thus, only at the "final node" for a tag can the fish be assumed dead. The classification of a fish as live or dead at its final node was based on two measures: (a) the delay or "gap" in time between the first detection at the fish's final node and the last detection at its penultimate node (or, the "ultimate gap"), and (b) the length of time the fish's tag was detected at its final node (or, the "ultimate duration"). A fish with a short "ultimate gap" was assumed to be alive at its final node, because it had been moving shortly before arrival at that node. Similarly, a fish with a short "ultimate duration" was determined to be alive, because it moved on from its final node shortly after arrival there. Thus, a fish with either a short ultimate gap or a short ultimate duration was classified as alive. However, a fish with a long ultimate gap and a long ultimate duration was assumed to be dead, because it had not recently moved before reaching its final node, and it did not move or leave its final node within the time expected of a live fish.

The decision rules described above depend on two parameters: the "ultimate gap" that a dead fish may have, and the "ultimate duration" that a dead fish may have. Any fish with shorter gaps or shorter durations than these minimum values was assumed to be alive at its final node. To determine the appropriate minimum value of the ultimate gap for dead fish, we examined the distribution of observed gaps for known live fish. In particular, we measured the temporal delay for each pair of consecutive detection events at separate nodes, prior to arrival at the final node. By focusing on gaps prior to the ultimate gap, we effectively restricted the distribution to gaps for live fish. We took the 95th percentile (12.63 hr) of the distribution of gaps for live fish as the minimum gap for dead fish; any fish whose ultimate gap was greater than this minimum might be classified as dead, depending on the duration of its detection event at its final node. Similarly, to determine the duration time for dead fish, we examined the distribution of the detection duration for known live fish, and used the 95th percentile of that distribution (58.84 hr) as the duration threshold for dead fish. We further analyzed detections from nodes in shallow water separately from those in deep water in order to account for potential differences in detection ranges in shallow and deep water. Fish classified as dead at their final node were assumed dead upon arrival.

The decision rule to determine dead or alive is summarized below:

Step 1. Was the tag subsequently detected at a different node? If yes, then the tag came from a live fish. If no, then go to Step 2.

Step 2. Was the tag detected recently at a different node? In other words, was the gap between detection events short (i.e., <12.63 hr)? If yes, then the tag came from a live fish. If no, then go to Step 3.

Step 3. Was the tag detected for a short duration at the last detection location (i.e., <58.54 hr)? If yes, then the tag came from a live fish. If no, then the tag came from a dead fish.

Tag life.—Tag life was accounted for in estimation of ϕ_{iG} (i.e., the joint probability of migration and survival) using the methods of Townsend et al. (2006). Briefly, for each tag group G, an auxiliary likelihood was estimated from the tag-life study, modeling the probability of tag survival through time. The auxiliary likelihood was used to predict the probability of a tagged fish having a working tag upon arrival at each survival line, according to the average time observed between tag activation and arrival at the survival line. This "live tag" probability was used to adjust the probability of detection at each survival line and thus adjust estimates of ϕ_{iG} for the possibility of tag failure. The tag survival parameters were estimated using maximum likelihood, and variances were estimated using the bootstrap. The tag survival model used was the 4-parameter vitality model (Li and Anderson, 2009).

Travel time and migration rate.—Individual travel time from the release point to each detection array was calculated for all tagged fish detected at the array in question, as well as travel time through each reach. Because of insufficient detections at the LGR tailrace array, travel time was reported only to the LGR forebay array for radio-tagged fish, and to the LGR tailrace for acoustic-tagged fish. Migration rate was defined as travel distance divided by travel time. All travel time observations were converted to migration rates. Downstream migration rates were compared among reaches to identify spatial trends.

TDG compensation depths.—We calculated compensation depths during the highest TDG concentration measured in 2009 and during a relatively low-water year to understand the area of river available for migrating juvenile salmon to escape elevated TDG concentrations. Water surface profiles were extracted from the hydrodynamic simulation model (see *Estimated Discharge and Velocity* section) and used to compute depth based on Clearwater River bathymetry data collected in 2009 (Tiffan et al. 2009b). Clearwater River discharge on the day of highest TDG concentration in 2009 was used to estimate river depth on that day. The 90th percentile exceedence flow (calculated from the average monthly discharge exceeded 90% of the time since 1995) was used to represent a low-water year. Barometric pressure on the day of highest TDG concentration in 2009 was collected from the LEWI TDG gauge (Figure 7
Figure 7).

Temperature.—Temperature measurements collected in 10-min intervals by individual loggers were averaged by hour. Hourly statistics—the minimum, maximum, and depth-averaged

temperature over the profile—were computed from the vertical profile at each temperature string. The difference between the temperature at a given depth and the minimum for the profile was computed and used to visualize vertical thermal variation.

Estimated discharge and velocity.—To provide localized estimates of time-varying discharge and velocity, the Modular Aquatic Simulation System 1D (MASS1), a one-dimensional cross-section–averaged hydrodynamic model, was applied to the study area. An existing configuration of MASS1 was used for this study (see Rakowski et al. 2003), which included the Snake River downstream of the USGS Anatone gauge (no. 13334300) and the Columbia River downstream of Priest Rapids Dam. In general, the spatial resolution was 0.8 km everywhere except in the immediate tailrace of the dams where the resolution was 0.4 km (0.25 mi). Hourly dam operations data (stage and discharge) and daily tributary discharge were applied as boundary conditions. A 15-min computational step was used, and results were saved at 1-h intervals. In previous studies, Snake River dams were represented using a stage boundary condition and artificial lateral inflows were computed to ensure accurate discharge (Richmond et al. 2000; Rakowski et al. 2003). In the MASS1 configuration for this study, the proportional, integral, derivative (PID) feedback boundary condition described by Perkins et al. (2002) was used to represent dam operations.

The most-downstream reach of the Clearwater River in the study area is subjected to the backwater effects of Lower Granite Dam. To quantify this backwater effect, estimated cross-sectional average velocities and discharges were extracted from MASS1 simulations at locations near the Clearwater–Snake confluence, which is affected by backwater from Lower Granite Dam, and compared to an upstream unimpounded reach of the Clearwater River. However, because cross-sectional velocity is variable in the Clearwater River (due to variable cross-section area), we calculated a general velocity magnitude using reach-length-weighted averages of cross-sectional velocity computed from Clearwater rkm 10.3 to 12.6 and from the mouth to rkm 1.8 (Figure B.8). Lower Granite Dam backwater also affects Clearwater River discharge near the mouth (Figure B.9). When Clearwater River discharges are low, in the fall and winter, variation in pool stage causes sizeable discharge differences relative to an upstream location.

Water particle travel time.—Water particle travel time was computed through the Confluence reach from Clearwater rkm 7.5 to Red Wolf Bridge (Snake rkm 221). For this reach, a simulated particle was released at the upstream location every hour from 1 June 2009 through 1 March 2010. The downstream progress of the particle was computed at 5-min intervals using a linearly interpolated velocity (in both space and time) from the MASS1 hydrologic model simulation results. The particle position was saved at 15-min intervals.

Results

A total of 500 radio-tagged and 500 acoustic-tagged subyearling fall Chinook salmon were released at Cherry Lane on the Clearwater River on 13 and 14 August 2009. Of the 500 radio-tagged fish, 445 were detected on at least one of the radio survival lines before the end of the radio-telemetry study (i.e., by 15 October 2009). Of the 500 acoustic-tagged fish, 397 were detected on at least one of the acoustic survival lines before the end of the acoustic-telemetry study (i.e., by 30 October 2009). Only 2 of the 500 radio-tagged fish and 17 of the 500 acoustic-tagged fish were detected in the Lower Granite Dam tailrace, approximately 96 rkm from the release point. Some acoustic-tagged fish from 2009 were detected downstream of Lower Granite Dam and during periods outside the primary study season. Thirty-five juvenile fall Chinook salmon tagged in 2009 (6.6% of total) were detected downstream of Lower Granite Dam in fall 2009 (n = 33) or spring 2010 (n = 2) based on PIT tag detections at juvenile bypass facilities or detection by JSATS acoustic receivers not associated with this project (located in the main-stem Columbia River). Three fish were detected only by acoustic receivers in the Lower Granite Dam tailrace and were not detected by PIT tag detectors during Lower Granite Dam passage.

Juvenile salmon showed both downstream and upstream swimming behaviors while in the Transition Zone (Figure 14). Downstream-only movement was found at the first acoustic survival line at Potlatch (Clearwater rkm 5.5; Figure 14, top panel). The frequency of upstream movements by fish increased at each consecutive acoustic receiver moving downstream towards the confluence. Near the confluence at Clearwater River rkm 2.3 (acoustic receiver IRN04, Figure 14), net movements fluctuated between upstream or downstream movements throughout the season; however, net movements shifted to primarily downstream on 15 September concurrent with the end of summer flow augmentation (Figure 14, bottom panel).

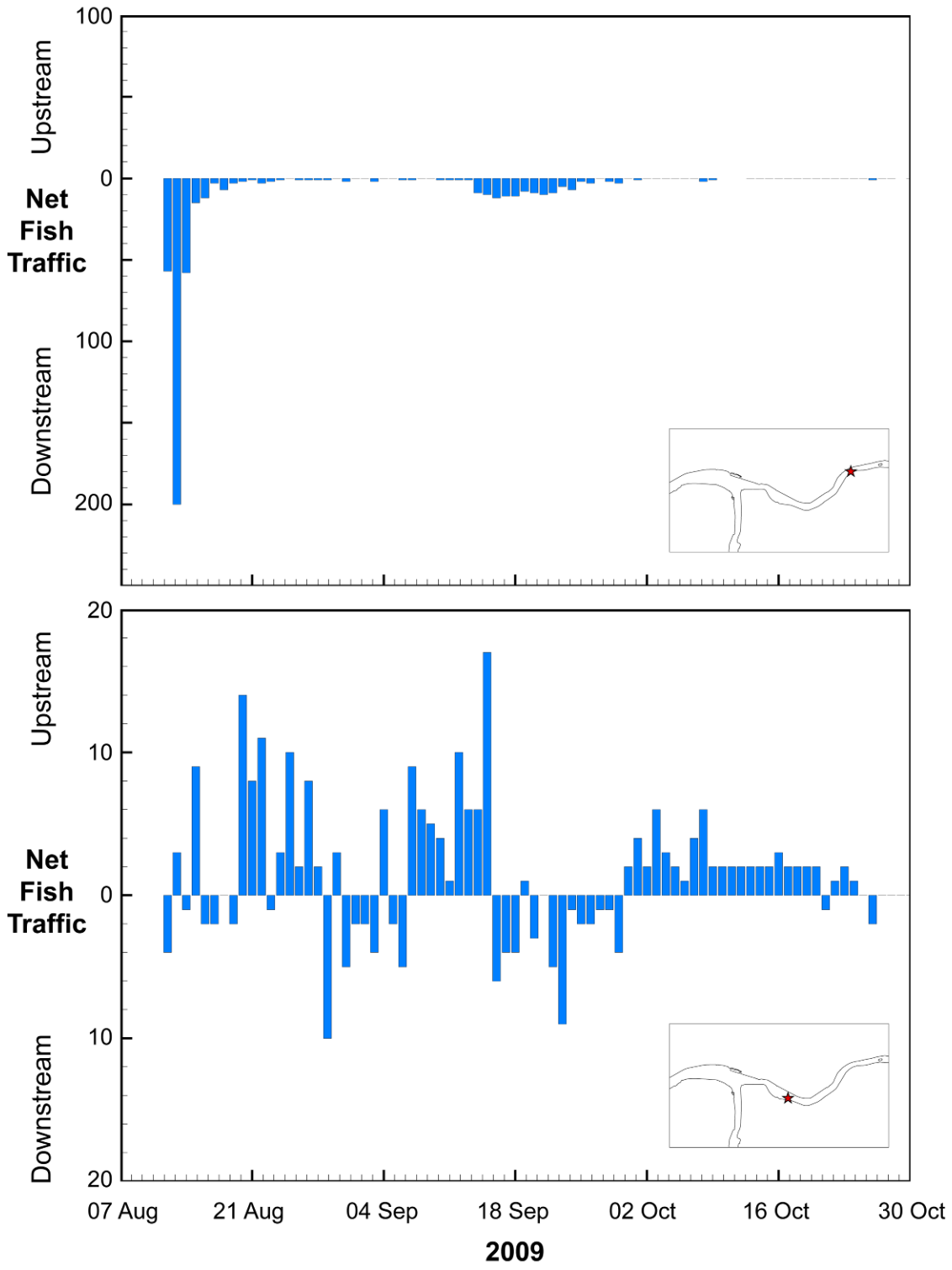

Figure 14.—Net upstream and downstream movements (i.e., Net Fish Traffic) of acoustic-tagged study fish at the Potlatch survival array (Clearwater rkm 5.5; top panel) and at the IRN04 intrareach node (Clearwater rkm 2.3, bottom panel) during the 2009 study season. Figure insets show the location of acoustic receivers in the Clearwater River.

Tag Life

The tags in the radio tag-life study began dying within a week of tag activation, and half of the radio tags in the tag-life study had died by day 66 (Figure 15). Although this was past the expected tag-life, the early failure of many of the tags meant that it was necessary to adjust estimates of the joint probability of migration and survival (ϕ) for tag failure. This need was obvious when arrival times of the tagged study fish at the radio survival lines were compared to the tag-life survival curve (Figure 16), where it is seen that many tagged fish arrived after a large proportion of the radio tags had failed.

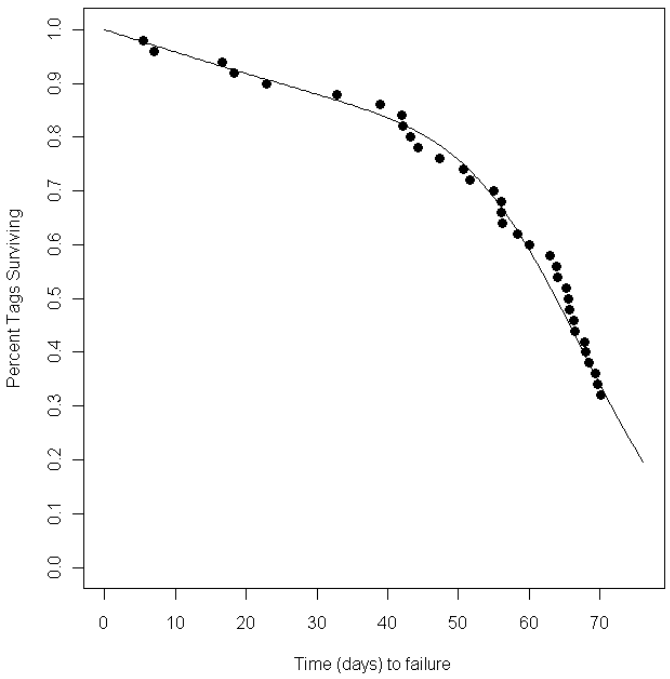

Figure15.—Observed and fitted time to failure for radio tags in the radio tag-life study. The fitted survival curve is based on the vitality model of Li and Anderson (2009).

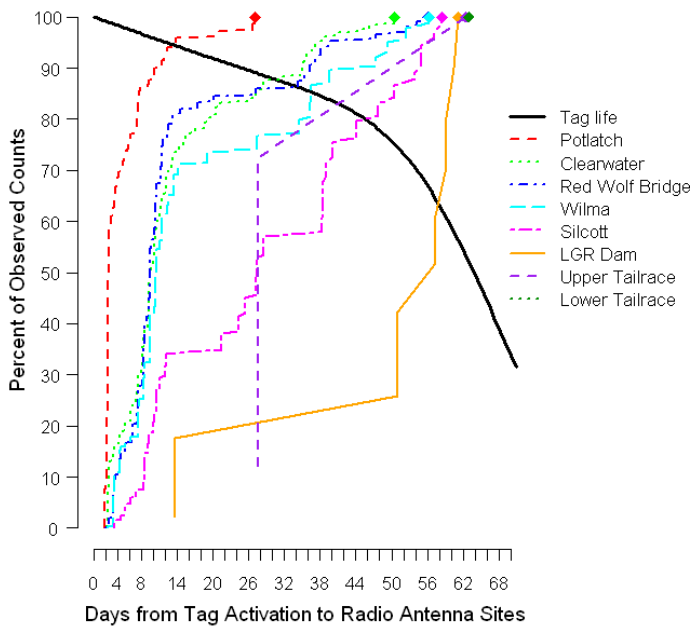

Figure 16.—Arrival distribution of radio-tagged fish at radio survival lines, and fitted tag survival curve for radio tags.

The tags in the acoustic tag-life study had less variable survival, with the first tag dying on day 62, and 50% of the tags dead by day 97 (Figure 17). It was nevertheless necessary to adjust estimates of the joint probability of migration and survival for tag failure, however, because tags continued to arrive at the acoustic survival lines after the tags in the tag-life study had begun to die (Figure 18). However, the adjustment for acoustic-tag failure was smaller than the adjustment for radio-tag failure (compare Figure 17 and 18). No effect of tagger was observed on estimates of the joint probability of migration and survival for acoustic-tagged salmon (P=0.6125).

Fate Determination

Estimation of the joint probability of migration and survival (ϕ) was possible for each release group, reach, and detection period that had sufficient detections at each array to yield informative estimates (i.e., confidence intervals for ϕ that did not cover the entire interval from 0 to 1). If fish from the release group either stopped migrating or died before reaching the downstream arrays, this meant that estimates of the migration and survival probability through a given reach may be unavailable for that release group, or may be available only for later periods. Additionally, the estimation of delay (ψ) and mortality (μ) probabilities for any given reach and period was dependent on mobile tracking in that reach at the end of the period for radio-tagged fish, and on the presence of intrareach nodes for acoustic-tagged fish. Mobile tracking of

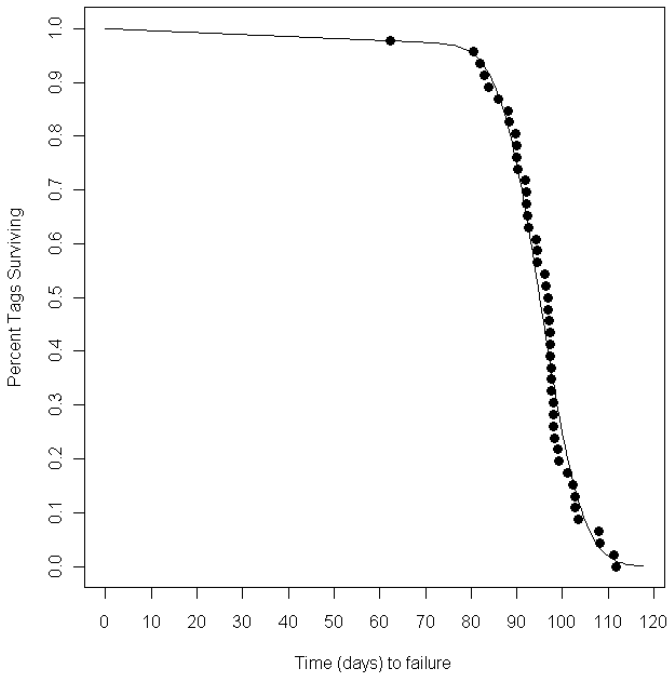

Figure 17.—Observed and fitted time to failure for acoustic-telemetry tags in the acoustic tag-life study. The fitted survival curve is based on the vitality model of Li and Anderson (2009).

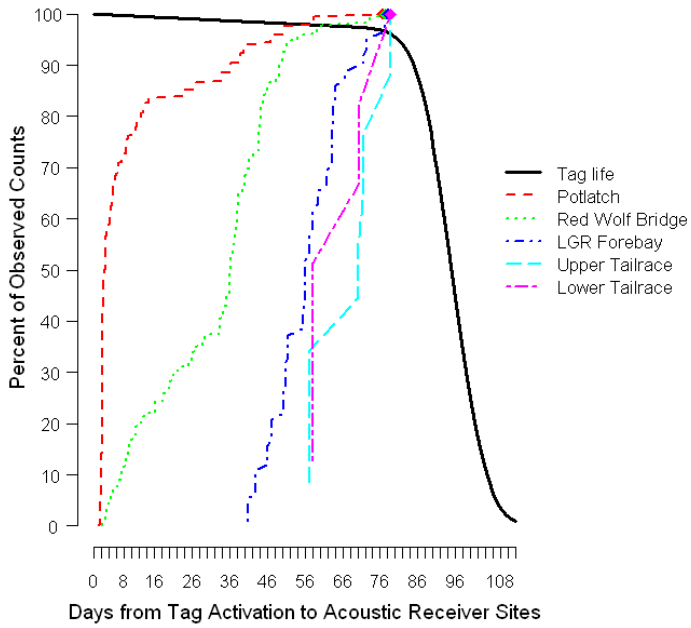

Figure 18.—Arrival distribution of acoustic-tagged fish at acoustic survival lines, and fitted tag-life curve for acoustic-telemetry tags.

radio tags was performed only in the Transition Zone (Potlatch to Clearwater Mouth) and Confluence (Clearwater Mouth to Red Wolf Bridge). Intrareach nodes were located throughout the same region, but with no acoustic survival line separating the Transition Zone and Confluence, estimates of the probabilities of delay and mortality from acoustic data are for those two reaches combined.

The first reach ("free-flowing river") extended from the release site at Cherry Lane to the first survival line at Potlatch for both radio- and acoustic-tagged salmon. Only the joint probability of migration and survival (ϕ) was estimable for this reach. For both types of tags, the estimated probability of migrating and surviving through this reach was consistently high throughout the study, ranging from 0.858 ($\widehat{SE}$ =0.026; acoustic tags) to 0.909 ($\widehat{SE}$ =0.015; radio tags) at the end of the study (Figure 19). The slight peak in the estimates from the acoustic tags in the second detection period (ending 29 August) implies that some fish migrated out of the reach early in the study, subsequently re-entered the reach, and did not exit downstream during the study period.

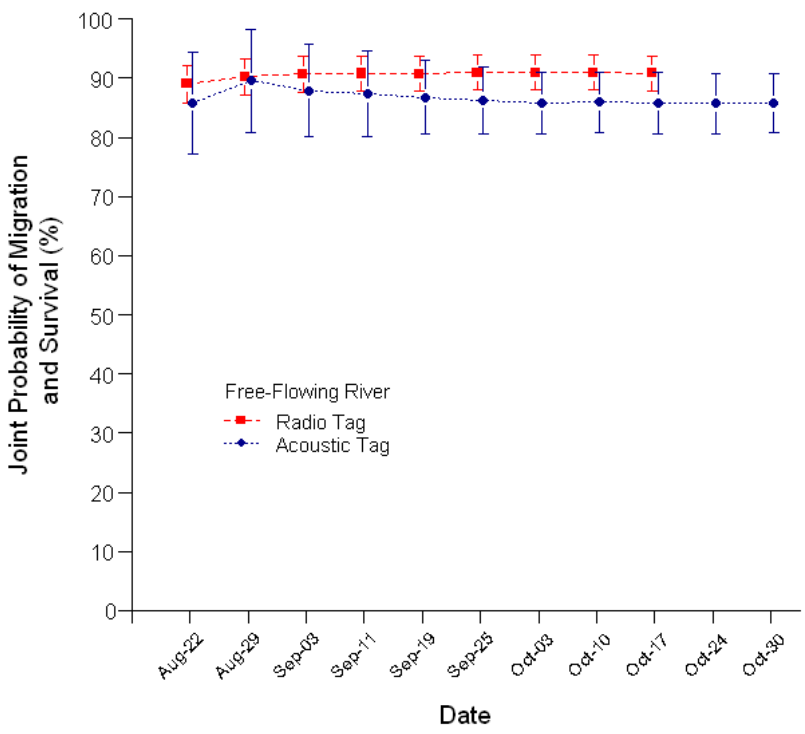

Figure 19.—Estimates of the joint probability of migration and survival (ϕ) through the Free-Flowing Reach (between the release site at Cherry Lane and Potlatch) for both radio-tagged and acoustic-tagged smolts.

The next reach was the Transition Zone, which extended from Potlatch to the mouth of the Clearwater River. This reach was monitored by mobile tracking radio-tagged fish. Mobile tracking of radio-tagged smolts was performed in this reach from August through early October, providing estimates of the joint probability of migrating and surviving (ϕ), the joint probability of delaying and surviving (ψ), and the probability of mortality (μ). Throughout the study, the estimated probability of migrating and surviving increased slightly, with a final estimate of 0.751 ($\widehat{SE}$ =0.024) at the end of the study in mid-October (Figure 20). The probability of delaying and surviving was estimated to be 0.314 ($\widehat{SE}$ =0.015) in the first week of the study, and declined steadily throughout the study, with a final estimate of 0.029 ($\widehat{SE}$ =0.004) in early October, during the last week of mobile tracking in this reach (Figure 20). Conversely, the probability of mortality was estimated to be low (0.075, $\widehat{SE}$ =0.029) in the first week of the study, with a jump to 0.183 ($\widehat{SE}$ =0.024) between the first and second weeks of the study. After the second week, the estimated probability of mortality was stable through the end of the study, with a final estimate of 0.220 ($\widehat{SE}$ =0.024) in early October (Figure 20).

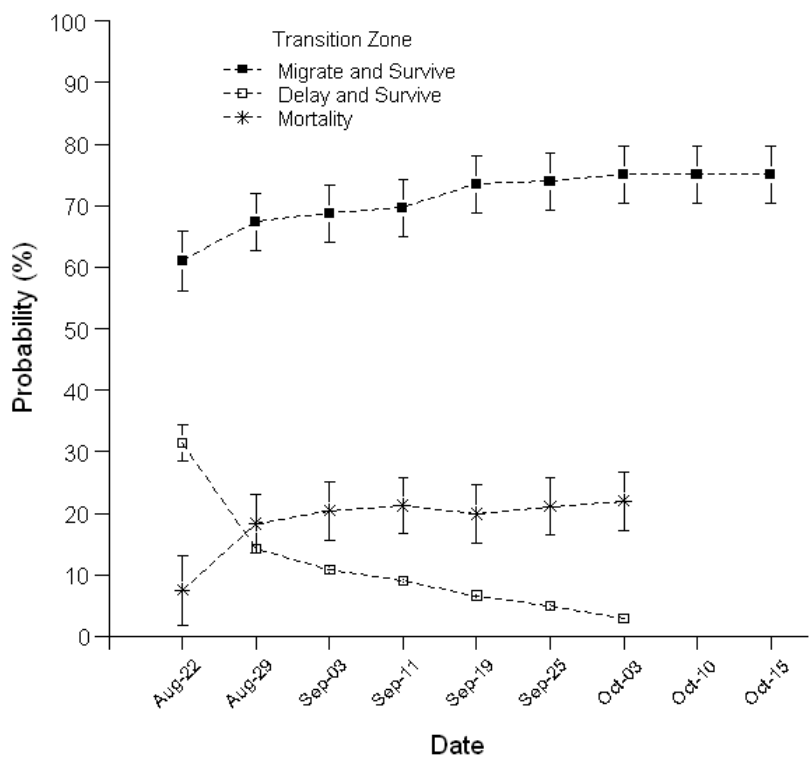

Figure 20.—Estimates of the joint probability of migrating and surviving (ϕ), the joint probability of delaying and surviving (ψ) , and the probability of mortality (μ) in the Transition Zone, from Potlatch to the mouth of the Clearwater River, based on radio-tag data.

The third reach was the Confluence, which extended from the mouth of the Clearwater River to Red Wolf Bridge on the Snake River a distance of 4.0 river kilometers. This reach was monitored by radio tags. The estimated probability of migrating and surviving through this reach was more stable and somewhat lower than for the Transition Zone, with a final estimate of 0.520 ($\widehat{SE}$ =0.029) at the end of the study in mid-October (Figure 21). Mobile tracking in the Confluence detected very few tags, resulting in very low estimates of the joint probability of delay and survival. The highest estimate of the joint probability of delaying and surviving in the Confluence was 0.015 ($\widehat{SE}$ =NA) in the first week; by early October, there were no fish detected delaying in the Confluence (Figure 21). With the estimates of delay and survival so low, the estimates of mortality were correspondingly high, with a final estimate of 0.489 ($\widehat{SE}$ =NA) in early October (Figure 21).

Together, the Transition Zone and the Confluence were monitored by both radio tags and acoustic tags. The joint probability of migrating and surviving through the combined Transition Zone and Confluence increased slightly from 0.300 ($\widehat{SE}$ =0.023) in the first week to 0.359 ($\widehat{SE}$ =0.024) in the second week of radio-telemetry data, and was then stable throughout the end of the radio-telemetry study (Figure 22). No estimate of the joint probability of migrating and surviving through this reach was available from acoustic-telemetry data until late September, because no acoustic-tagged fish were detected downstream of this reach (i.e., detected in the Lower Granite Dam forebay) until then. From late September until late October when the acoustic-telemetry study ended, the joint probability of migrating and surviving through the Transition Zone and Confluence, estimated from acoustic-tagged fish, increased only slightly from 0.299 ($\widehat{SE}$ =0.024) in September to 0.341 ($\widehat{SE}$ =0.025) in October (Figure 22).

Estimates of the joint probability of delaying and surviving in the combined Transition Zone and Confluence peaked at the beginning of the study, ranging from 0.323 ($\widehat{SE}$ =NA; radio-telemetry data) to 0.466 ($\widehat{SE}$ =0.024; acoustic-telemetry data), and then steadily declined throughout the remainder of the study. By the end of October, no live tagged juvenile salmon was detected in either the Transition Zone or the Confluence (Figure 22). As estimates of the probability of delay decreased throughout the study, estimates of the probability of mortality increased, with a final estimate of 0.650 ($\widehat{SE}$ =0.025) at the end of October (acoustic-telemetry data, Figure 22). As expected from the estimates of the probability of delay, estimates of the numbers of live radio-tagged and acoustic-tagged subyearlings present in the Transition Zone and Confluence peaked early in the study (Figure 23), and then declined throughout the study period.

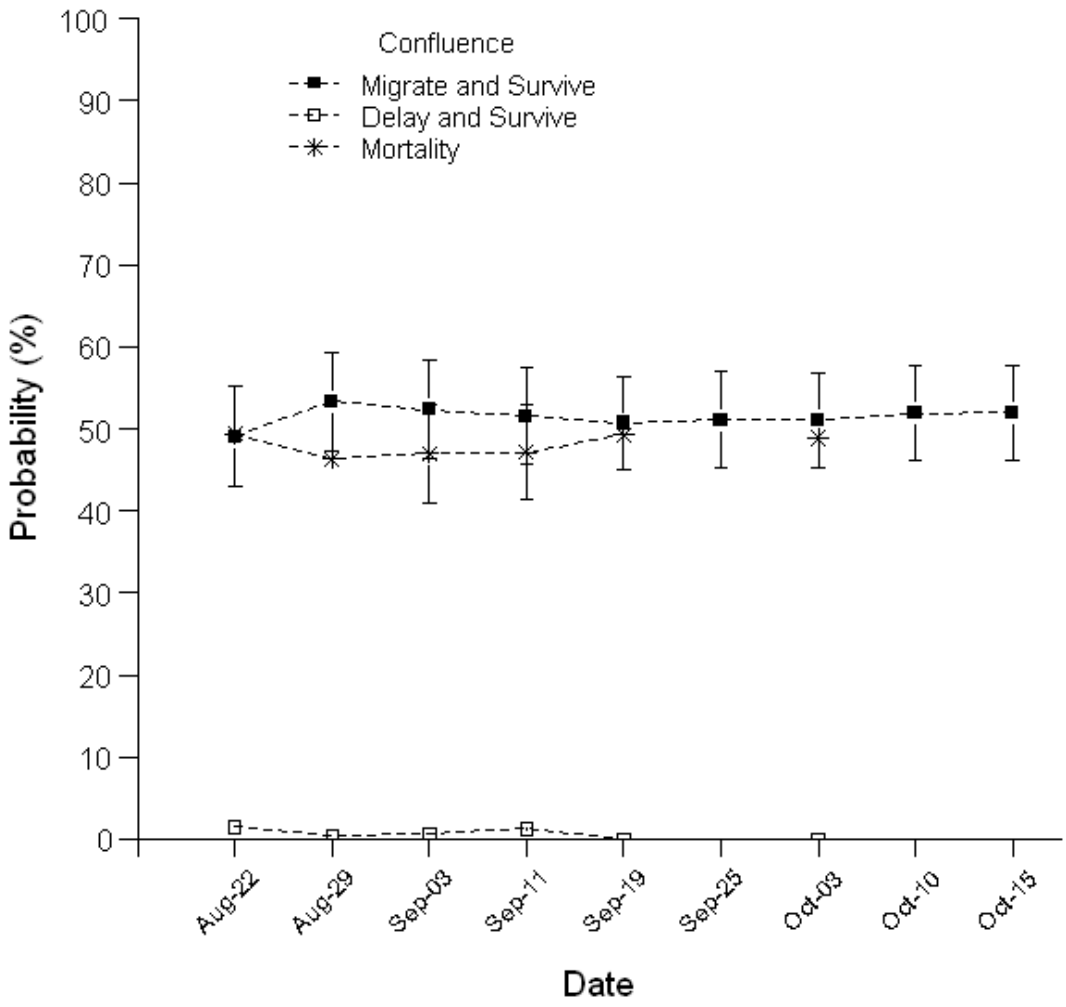

Figure 21.—Estimates of the joint probability of migrating and surviving (ϕ), the joint probability of delaying and surviving (ψ), and the probability of mortality (μ) in the Confluence, from the mouth of the Clearwater River to Red Wolf Bridge on the Snake River, based on radio-telemetry data.

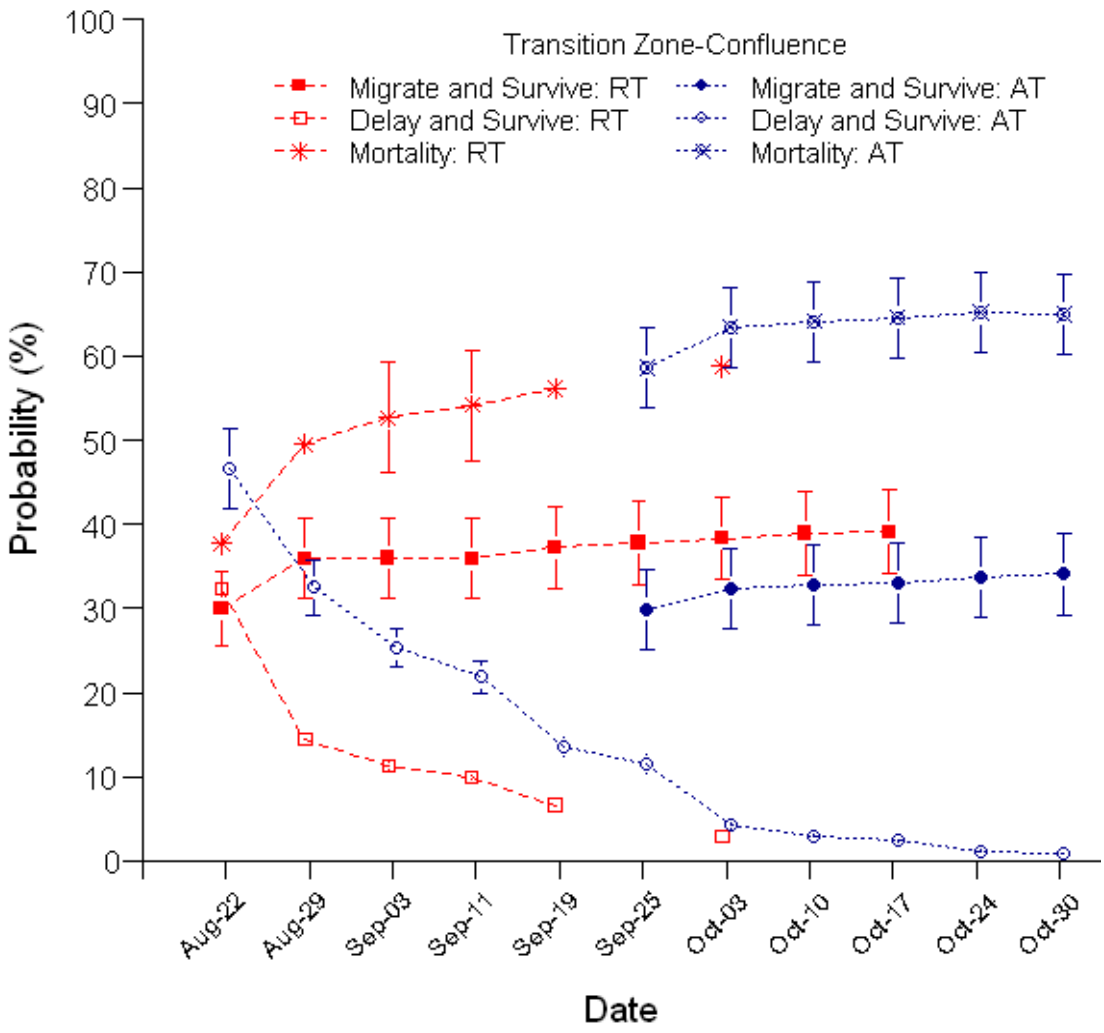

Figure 22.—Estimates of the joint probability of migrating and surviving (ϕ), the joint probability of delaying and surviving (ψ), and the probability of mortality (μ) in the combined reaches of the Transition Zone and Confluence, from Potlatch to Red Wolf Bridge on the Snake River, based on radio-telemetry data and acoustic-telemetry data.

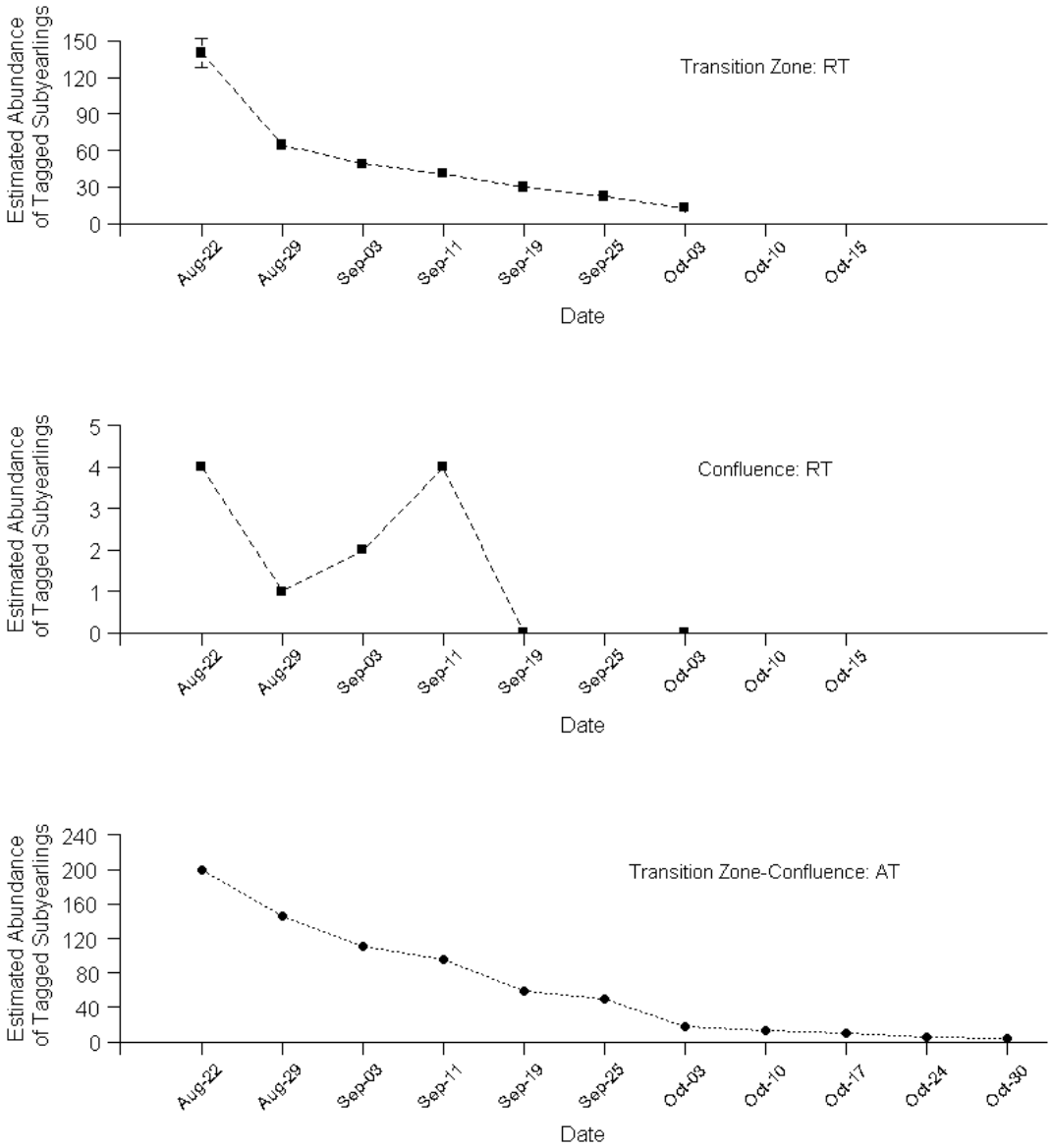

Figure 23.—Estimated abundance of tagged subyearlings present in the Transition Zone ($\widehat{N}_{2R}$, radio-telemetry data, top panel), Confluence ($\widehat{N}_{3R}$, radio-telemetry data, middle panel), and combined Transition Zone-Confluence ($\widehat{N}_{2A}$, acoustic-telemetry data, bottom panel) reaches throughout the study.

The Upper Reservoir extended from Red Wolf Bridge to the Port of Wilma, and was monitored by radio tags. Estimates of the joint probability of migrating and surviving through this reach increased slightly throughout the study, from 0.582 ($\widehat{SE}$ =0.101) in late August to 0.702 ($\widehat{SE}$ =0.080) in mid-October (radio-telemetry data, Figure 24). The Middle Reservoir extended from the Port of Wilma to Silcott Island, and was monitored only by radio tags. Estimates of the joint probability of migrating and surviving through this reach increased from 0.208 ($\widehat{SE}$ =0.051) in late August to 0.422 ($\widehat{SE}$ =0.093) in mid-October (radio-telemetry data; Figure 25). Only eight radio-tagged fish were detected downstream of Silcott Island during the study, resulting in high uncertainty in the estimates through the Middle Reservoir. The Lower Reservoir extended from Silcott Island to Lower Granite Dam. Only six radio-tagged fish were detected on the antennas at the dam, and none of these fish was subsequently detected on either of the tailrace radio antennas. This prevented estimation of the joint probability of migration and survival through either the Lower Reservoir or past the dam itself based on radio-telemetry data. However, 24 acoustic-tagged fish were detected on the acoustic survival line in the forebay, and 17 of these fish were subsequently detected on the hydrophones in the tailrace late in the study period. These detections provided estimates of the joint probability of migrating and surviving throughout Lower Granite Reservoir and past the dam itself. Until mid-October, no fish were detected exiting the reservoir. From mid-October through late October, the estimated probability of migrating through the reservoir increased from 0.087 ($\widehat{SE}$ =0.024) to 0.168 ($\widehat{SE}$ =0.031; Figure 26). The estimated probability of migrating and surviving past Lower Granite Dam and into the tailrace also increased through the month of October, from 0.084 ($\widehat{SE}$ =0.080) in the second week of October to 0.210 ($\widehat{SE}$ =0.084) at the end of the month (Figure 27). Overall, the joint probability of migrating and surviving from release at Cherry Lane to the Lower Granite Dam tailrace by the end of October was estimated to be 0.010 ($\widehat{SE}$ =0.005; acoustic-telemetry data).

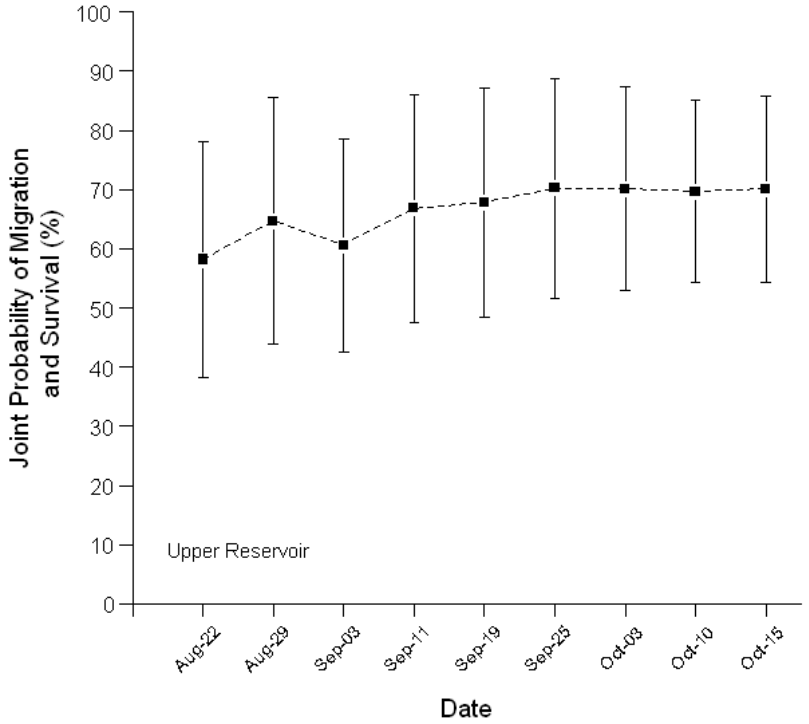

Figure 24.—Estimates of the joint probability of migrating and surviving (ϕ) through the Upper Reservoir, from Red Wolf Bridge to the Port of Wilma, based on radio-telemetry data.

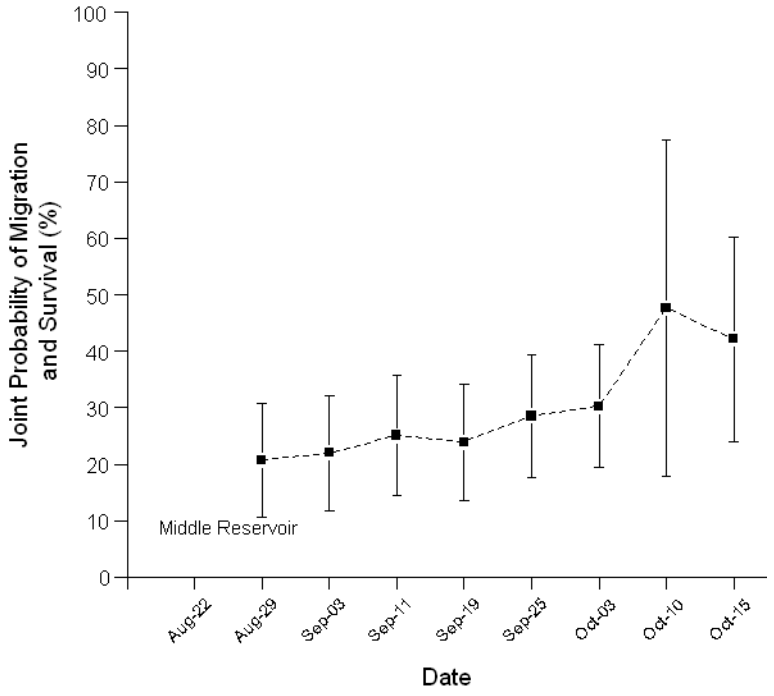

Figure 25.—Estimates of joint probability of migrating and surviving (ϕ) through the Middle Reservoir, from the Port of Wilma to Silcott Island, based on radio-telemetry data.

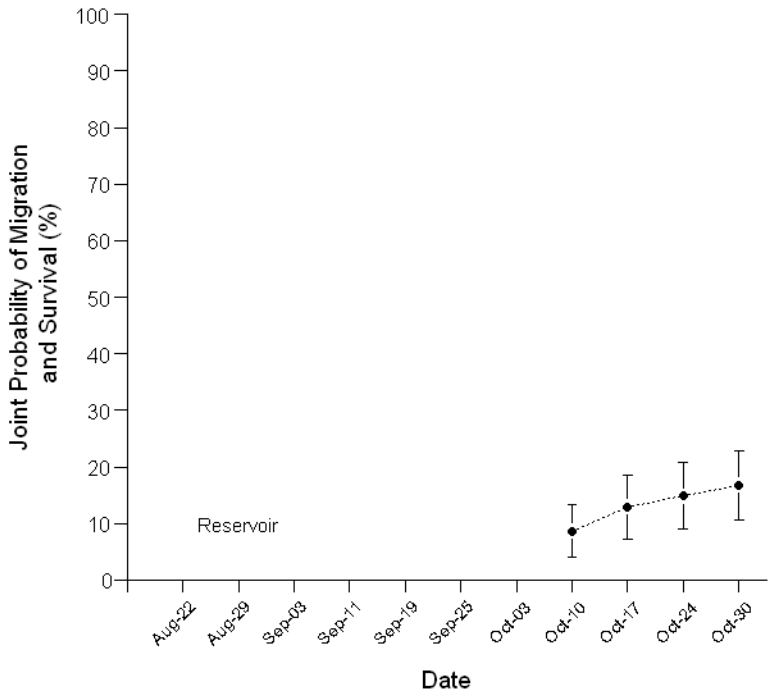

Figure 26.—Estimates of the joint probability of migrating and surviving (ϕ) through the Lower Granite Dam Reservoir, from Red Wolf Bridge to the Lower Granite Dam Forebay, based on acoustic-telemetry data.

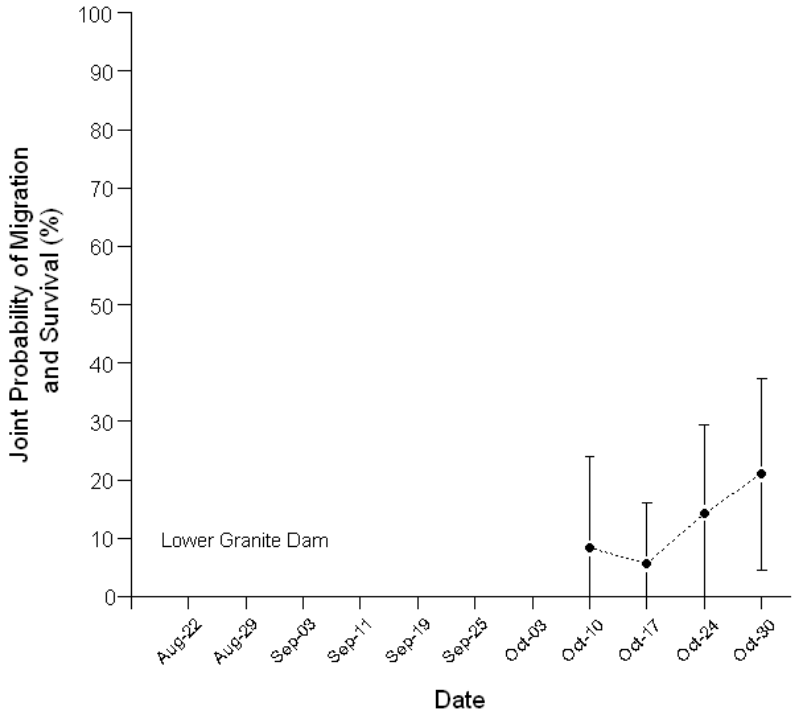

Figure 27.—Estimates of the joint probability of migrating and surviving (ϕ) past Lower Granite Dam, based on acoustic-telemetry data.

Detection Probabilities

Detection probability estimates for the acoustic survival line at Potlatch ranged from 0.8290 (SE=0.0432) to 0.8896 (SE=0.0260) over the study period (Table 4). At Red Wolf Bridge, Lower Granite forebay, and the upper tailrace survival line, all detection probability estimates were 1.0000 (Table 4). We used the estimated detection probability at Red Wolf Bridge during September-October to calculate the probability that acoustic-tagged fish migrated and survived through the Transition Zone-Confluence reach during August and September. These calculations showed that the probability of migrating and surviving during this period (for acoustic-tagged fish) ranged from 0.1540 (SE=0.0189) in the first week of the study (13 August – 22 August 2009) to 0.2617 (SE=0.0227) through 25 September 2009. In later detection periods, the estimated probability of migration and survival through the Transition Zone-Confluence ranged from 0.2987 (SE=0.0237) by 3 October 2009, to 0.3409 (0.0245) by 30 October 2009 (Figure 22).

For radio tags, estimated detection probabilities at Potlatch ranged from 0.9656 (SE=0.0112) to 0.9715 (SE=0.0093) over the study period (Table 5). At the Clearwater mouth survival line, detection probability estimates ranged from 0.9510 (SE=0.0169) to 0.9744 (SE=0.0126), whereas at Red Wolf Bridge, estimated detection probability ranged from 0.9633 (SE=0.0208) to 1.0000 (SE=0.0000). At the Port of Wilma, the estimated detection probability was lower, ranging from 0.5938 (0.0868) to 0.6669 (Se=0.1028), whereas at Silcott, estimated detection probabilities ranged from 0.7526 (SE=0.2206) to 1.0000 (Table 5). Because very few radio-tagged fish were detected at the Lower Granite Dam or tailrace survival lines, the estimates of a detection probability of 1.0000 at Silcott should be interpreted with caution.

Table 4.—Estimated detection probability (and standard error) for acoustic-tagged fish at acoustic survival lines, for each detection period.

Detection Period	Potlatch	Red Wolf	LGR Forebay	Upper Tailrace
1	0.8485 (0.0441)	NA	NA	NA
2	0.8290 (0.0432)	NA	NA	NA
3	0.8452 (0.0395)	NA	NA	NA
4	0.8556 (0.0371)	NA	NA	NA
5	0.8673 (0.0319)	NA	NA	NA
6	0.8750 (0.0292)	1.0000 (0.0000)	NA	NA
7	0.8841 (0.0273)	1.0000 (0.0000)	NA	NA
8	0.8857 (0.0269	1.0000 (0.0129)	1.0000 (0.0446)	1.0000 (0.0447)
9	0.8865 (0.0267)	1.0000 (0.0105)	1.0000 (0.0445)	1.0000 (0.0447)
10	0.8881 (0.0264)	1.0000 (0.0000)	1.0000 (0.0000)	1.0000 (0.0000)
11	0.8896 (0.0260)	1.0000 (0.0000)	1.0000 (0.0000)	1.0000 (0.0000)

Table 5.—Estimated detection probability (and standard error) for radio-tagged fish at radio telemetry survival lines, for each detection period.

Detection Period	Potlatch	Clearwater Mouth	Red Wolf	Wilma	Silcott	LGR Dam	Upper Tailrace
1	0.9656	0.9692	1.0000	0.6470	NA	NA	NA
	(0.0112)	(0.0151)	(0.0000)	(0.1159)			
2	0.9693	0.9742	0.9718	0.6190	1.0000	NA	NA
	(0.0101)	(0.0127)	(0.0196)	(0.1060)	(0.0000)		
3	0.9667	0.9744	0.9719	0.6669	1.0000	NA	NA
	(0.0104)	(0.0126)	(0.0196)	(0.1028)	(0.0000)		
4	0.9704	0.9744	0.9733	0.6156	1.0000	NA	NA
	(0.0097)	(0.0126)	(0.0186)	(0.0954)	(0.0000)		
5	0.9715	0.9565	0.9743	0.6162	1.0000	NA	NA
	(0.0093)	(0.0161)	(0.0179)	(0.0953)	(0.0445)		
6	0.9686	0.9510	0.9633	0.5938	1.0000	NA	NA
	(0.0098)	(0.0169)	(0.0208)	(0.0868)	(0.0000)		
7	0.9690	0.9515	0.9647	0.6175	1.0000	NA	NA
	(0.0097)	(0.0167)	(0.0200)	(0.0833)	(0.0000)		
8	0.9686	0.9521	0.9661	0.6244	0.7526	NA	NA
	(0.0098)	(0.0165)	(0.0192)	(0.0768)	(0.2206)		
9	0.9694	0.9514	0.9639	0.6240	0.8493	NA	NA
	(0.0095)	(0.0167)	(0.0204)	(0.0779)	(0.1412)		

Travel Time and Migration Rate

Travel time and downstream migration rates for a given reach could be measured only for those tagged fish that were detected both entering and exiting the reach. Thus, the upstream reaches had more observations of travel time and migration rate than the downstream reaches. Travel time of radio-tagged subyearlings through the Free-Flowing River reach (from Cherry Lane to Potlatch) ranged from 0.20 to 25.55 d, with most fish passing through the reach within 5 d (Figure 28a, 29). Most acoustic-tagged fish also traveled swiftly through this reach (Figure 30a, 31). Migration rate (km/d) through this reach ranged from 1.07 km/d to 139.80 km/d (median = 36.27 km/d) for radio-tagged fish, and ranged from 0.44 km/d to 163.90 km/d (median = 43.30 km/d) for acoustic-tagged fish. Travel time of radio-tagged fish through the Transition Zone ranged from 0.11 to 48.38 d, with an average of 4.99 d (Figure 28b, 29); migration rate through this reach ranged from 0.12 to 54.05 km/d, with a median of 3.43 km/d (Figure 32). Travel through the Confluence tended to be somewhat faster, with an average travel time of 2.26 d (Figure 28c, 29) and a median migration rate of 5.20 km/d for radio-tagged fish (Figure 32). The travel time of acoustic-tagged fish through the combined Transition Zone-Confluence

ranged from 0.26 to 74.49 d, with an average of 18.60 d (Figure 30b, 31). This resulted in a median migration rate of 1.03 km/d for acoustic-tagged subyearlings through the Transition Zone-Confluence (Figure 32). Nearly all of the radio-tagged fish observed passing through the Upper Reservoir traveled out of it within 2 d (Figure 28d, 29), with a median migration rate of 27.99 km/d (Figure 32). Travel through the Middle Reservoir was slightly lower, with an average travel time of 7.41 d (Figure 28e, 29) and a median migration rate of 6.43 km/d for radio-tagged fish (Figure 32). The 5 radio-tagged subyearlings observed departing the Lower Reservoir passed through that region in an average of 19.34 d (Figure 28f, 29), with a median migration rate of 1.98 km/d (Figure 32). Acoustic-tagged fish passed through the entire reservoir in an average of 24.64 d (Figure 29c, 30), with a median migration rate of 1.98 km/d (Figure 32). The 5 acoustic-tagged subyearlings observed in the Lower Granite Dam tailrace passed the dam in an average of 15.61 d (Figure 29d, 30), with a median migration rate of 0.30 km/d (Figure 32).

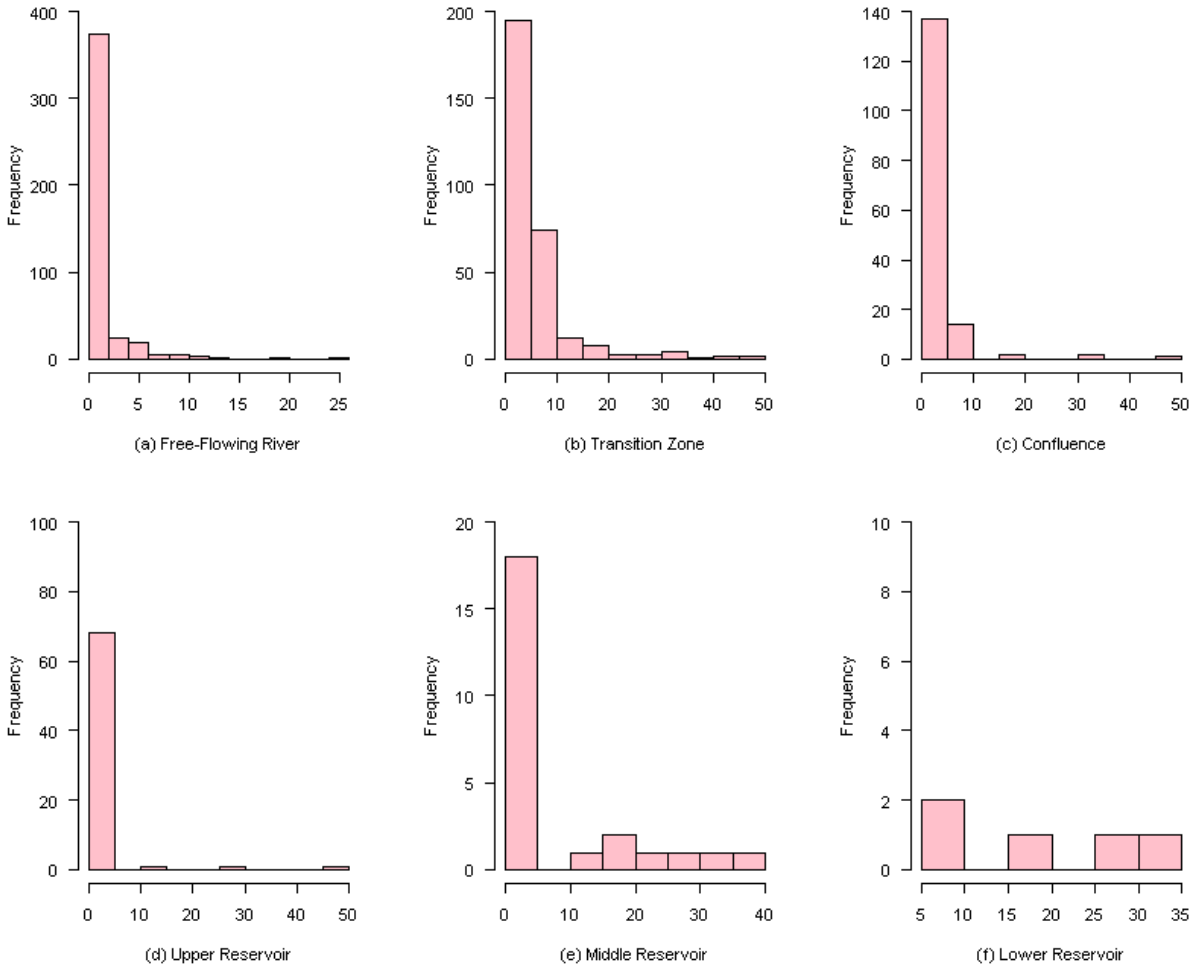

Figure 28.—Observed travel times (d) for radio-tagged subyearling Chinook salmon.

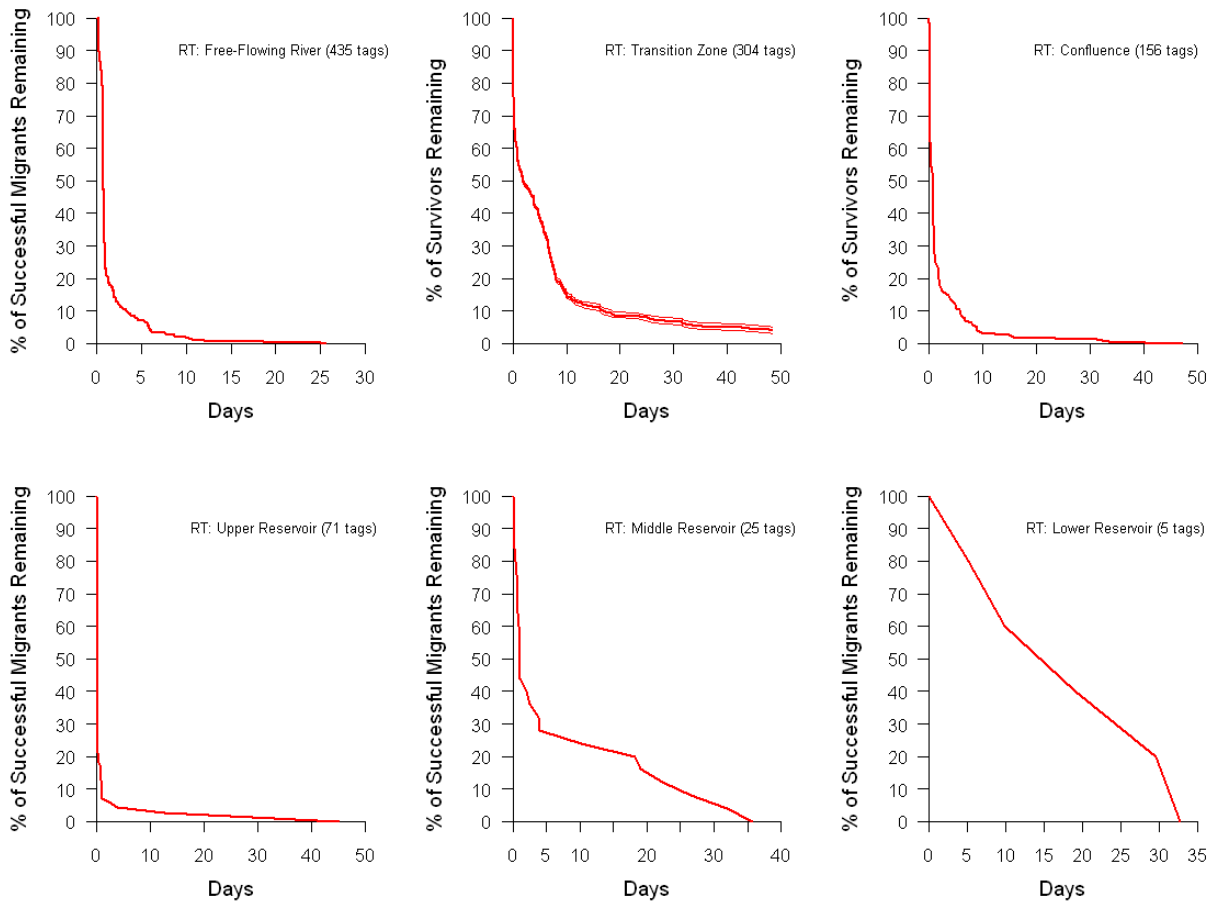

Figure 29.—The percent of radio-tagged subyearlings spending various amount of time in different study reaches in 2009. This information is closely related to that in Figure 28, but is shown a different way.

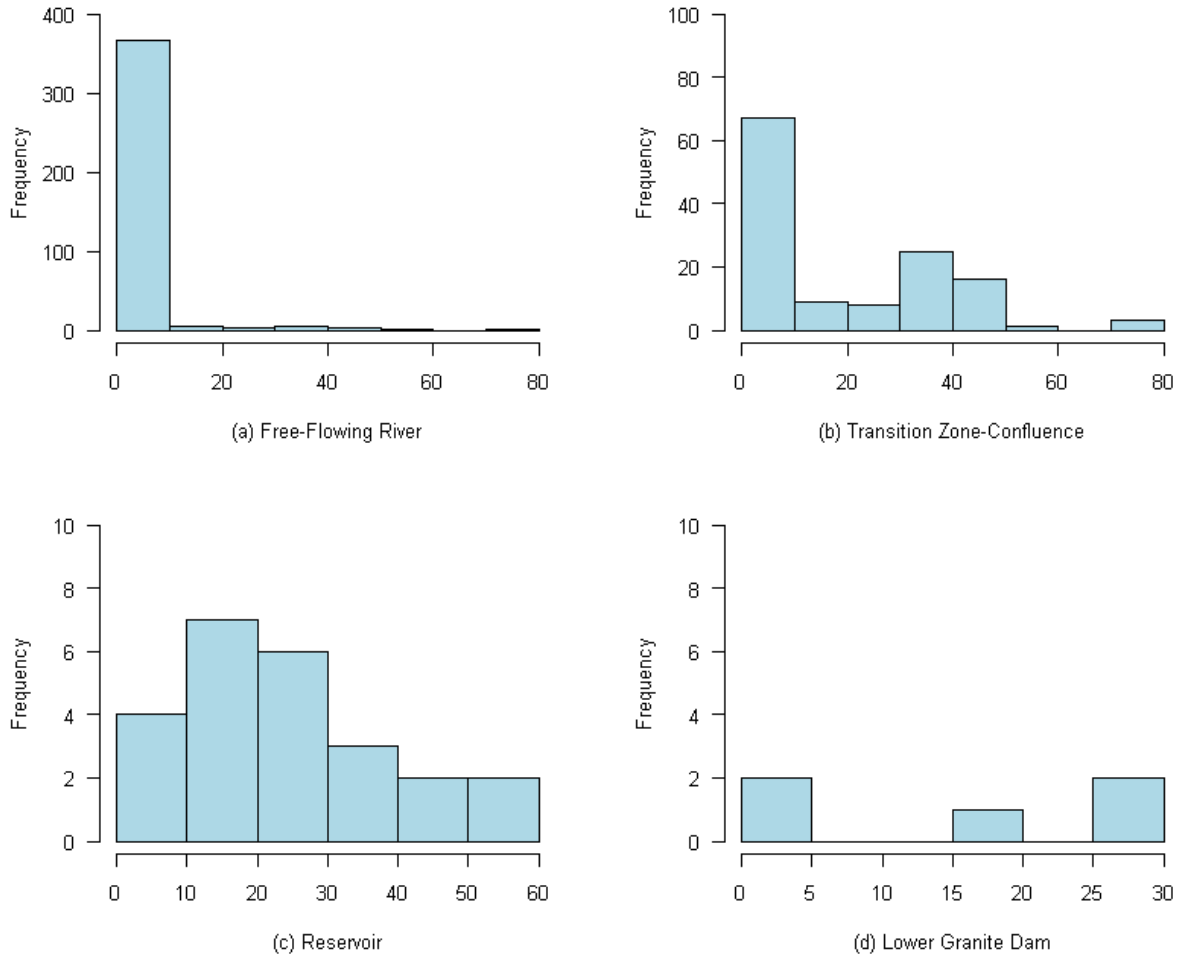

Figure 30.—Observed travel times (d) for acoustic-tagged subyearling Chinook salmon.

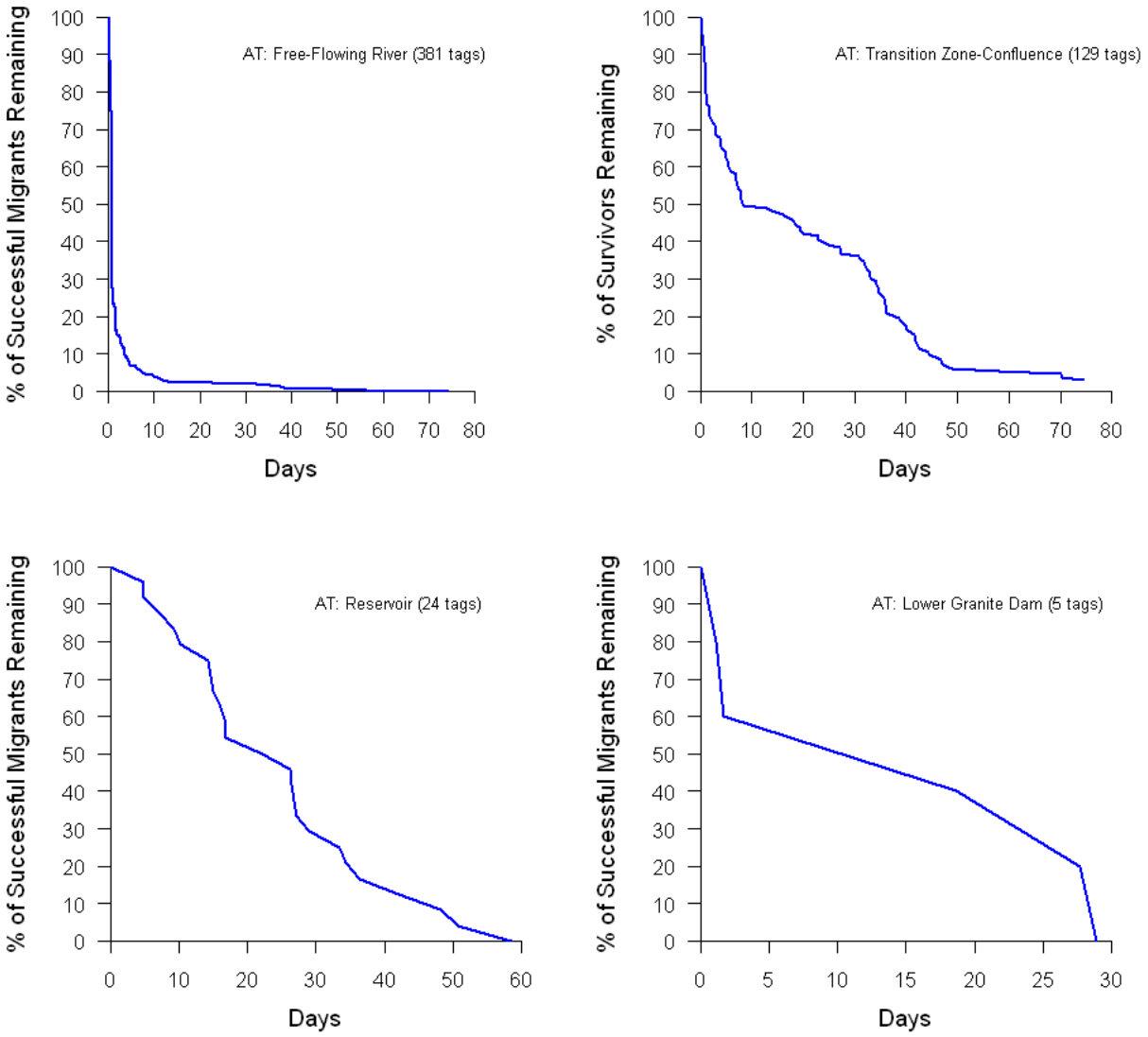

Figure 31.—The percent of acoustic-tagged subyearlings spending various amount of time in different study reaches in 2009. This information is closely related to that in Figure 30, but is shown a different way.

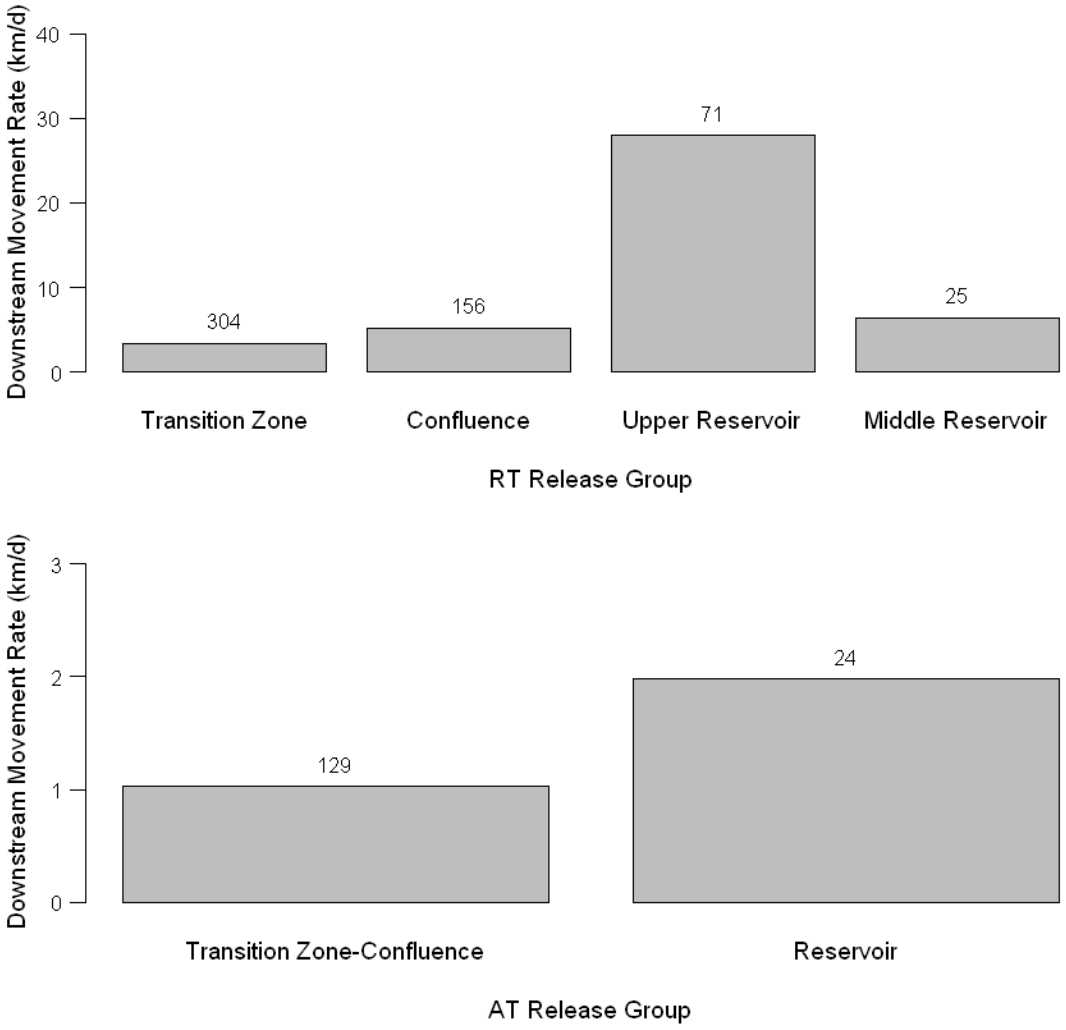

Figure 32.—Median downstream migration rate (km/d) in the study reaches for radio-tagged (RT, top panel) and acoustic-tagged (AT, bottom panel) hatchery fall Chinook salmon subyearlings in 2009. Numbers above bars indicate the number of fish with migration rate observations for the reach.

Predator Locations

We detected 48 of the 84 (57%) radio-tagged smallmouth bass during mobile tracking in 2009. We only detected one of the six channel catfish that we tagged. Most fish were detected along the shorelines of the Confluence where they were initially collected for tagging (Figure 33). Most fish did not show much movement within the Confluence, however seven smallmouth bass were detected below Red Wolf Bridge (the lower boundary of the Confluence) and one bass was detected in the Snake River above the Confluence on one tracking excursion. Nine smallmouth bass entered the Clearwater River and moved as far as 1 km upstream, and one fish swam 3 km upstream. Sixty of the smallmouth bass we radio tagged were also implanted with an acoustic tag. We detected 34 (56%) of these fish on acoustic receivers located in the Confluence, and none were detected in the Clearwater River. Only nine of the 34 (26%) fish were detected on more than one acoustic receiver. Movements of these nine fish ranged from 0.9 to 2.7 km (between receivers at Snake rkm 221.2 and rkm 223.9). Most radio-tagged subyearlings that we determined to be dead were located along shorelines in the same areas occupied by smallmouth bass, particularly in the Confluence where most predators were tagged (Figure 33).

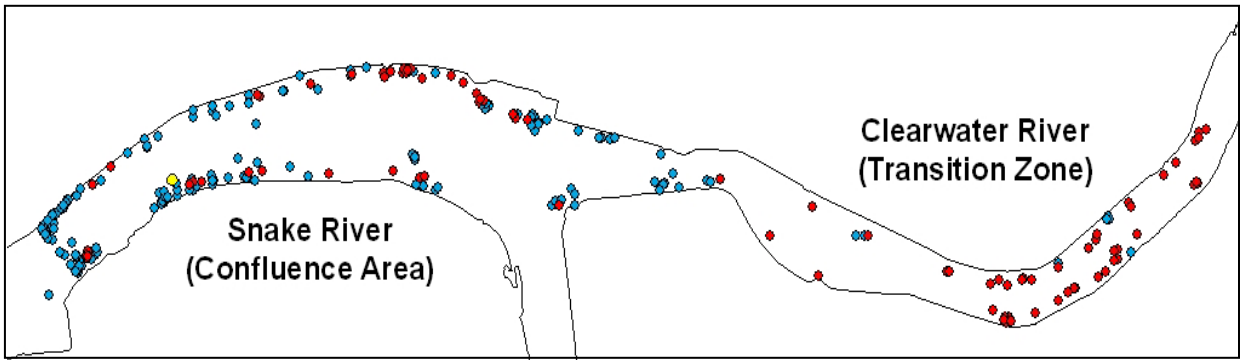

Figure 33.—Locations of predators (blue circles) and dead radio-tagged subyearlings (red circles) in the Confluence and Transition Zone in 2009. The yellow circle represents the only radio-tagged channel catfish located in 2009.

Total Dissolved Gas and Temperature Monitoring

Total dissolved gas monitoring.—The maximum hourly TDG during this study was 111.1% at the LEWI and PEKI gauges and 115.6% at the DWQI gauge (Figure 34). The peak of average daily TDG for the entire study period varied from 107% to 112% among these sites. At PNNL monitoring locations, peak hourly TDG ranged from 110.1% at CL-1 to 110.8% at CL-3 in August 2009 (Figure 34). In general, there was good agreement between PNNL and USACE sensors during all months of data collection (Figures A.1 through A.4). PNNL sensors CL-1 and CL-2 were located close to the USACE LEWI gauge, and results from CL-1, CL-2, and LEWI tracked closely. Sensor CL-3 was located several miles upstream of the LEWI gauge, and although results from that location are still similar to results from the LEWI gauge, the influence of upstream TDG concentrations (e.g., those recorded at PEKI) is apparent in the response at CL-3 (Figures A.1 - A.4). The TDG fluctuated daily and was highest late in the afternoon and lowest in the early morning (Figure 34 and A.1- A.4). During April through June, TDG levels were generally highest at upstream monitoring locations as a result of Dworshak Dam operations (Figures A.1 – A.3). During July and August, TDG was elevated at downstream locations compared to Dworshak Dam, regardless of operations there (Figures A.4 and 34). Additional detailed results for all sampling periods can be found in Appendix A.

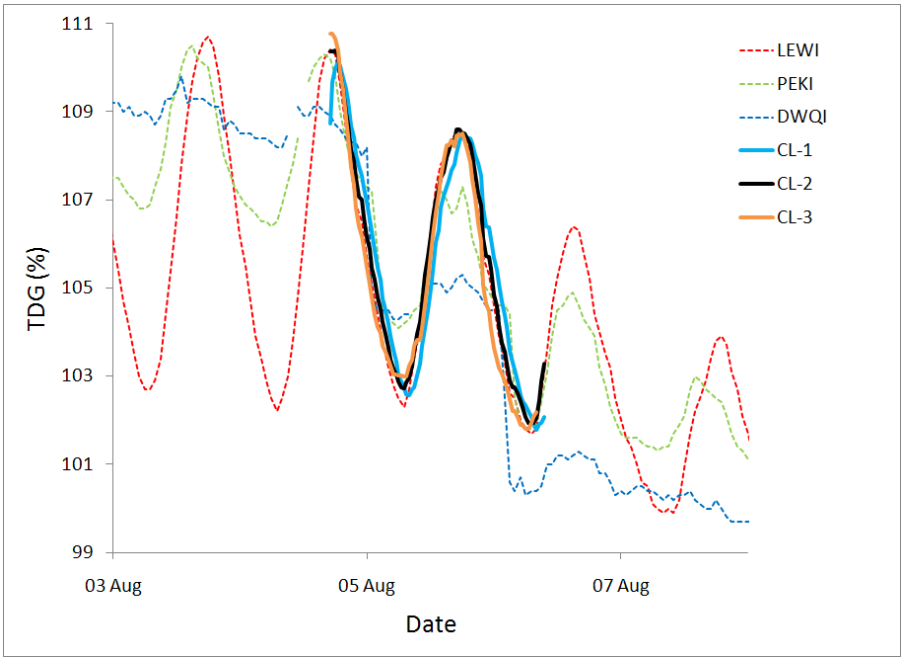

Figure 34.—TDG in the Clearwater River, 2009. Solid lines show Clearwater TDG during 4-6 August near Memorial Bridge, (CL-1), adjacent to the USGS Lewiston gauge across from the Potlatch Mill (CL-2), and approximately 1.6 km downstream of the confluence with the Potlatch river (CL-3). Dashed lines show TDG from USACE monitoring stations at Dworshak Dam (DWQI), Peck (PEKI), and Lewiston across from the Potlatch Mill (LEWI).

Supplemental Clearwater River temperature monitoring.—Temperature spot checks identified no meaningful vertical temperature gradients at any of the locations sampled during the study period. Similarly, the water was well mixed, with little lateral variation in temperatures across the channel at each study site (Figure 35). However, there was a trend of increasing temperature from spring to summer and increasing temperature from upstream to downstream. Temperatures increased seasonally, ranging from 6.2°C to 6.5°C during April to 12.1°C to 12.9°C during July (Figure 35). During August, following the initiation of flow augmentation at Dworshak Dam (shown later in Figure 39), temperatures decreased and ranged from 10.6°C to 10.9°C (Figure 35).

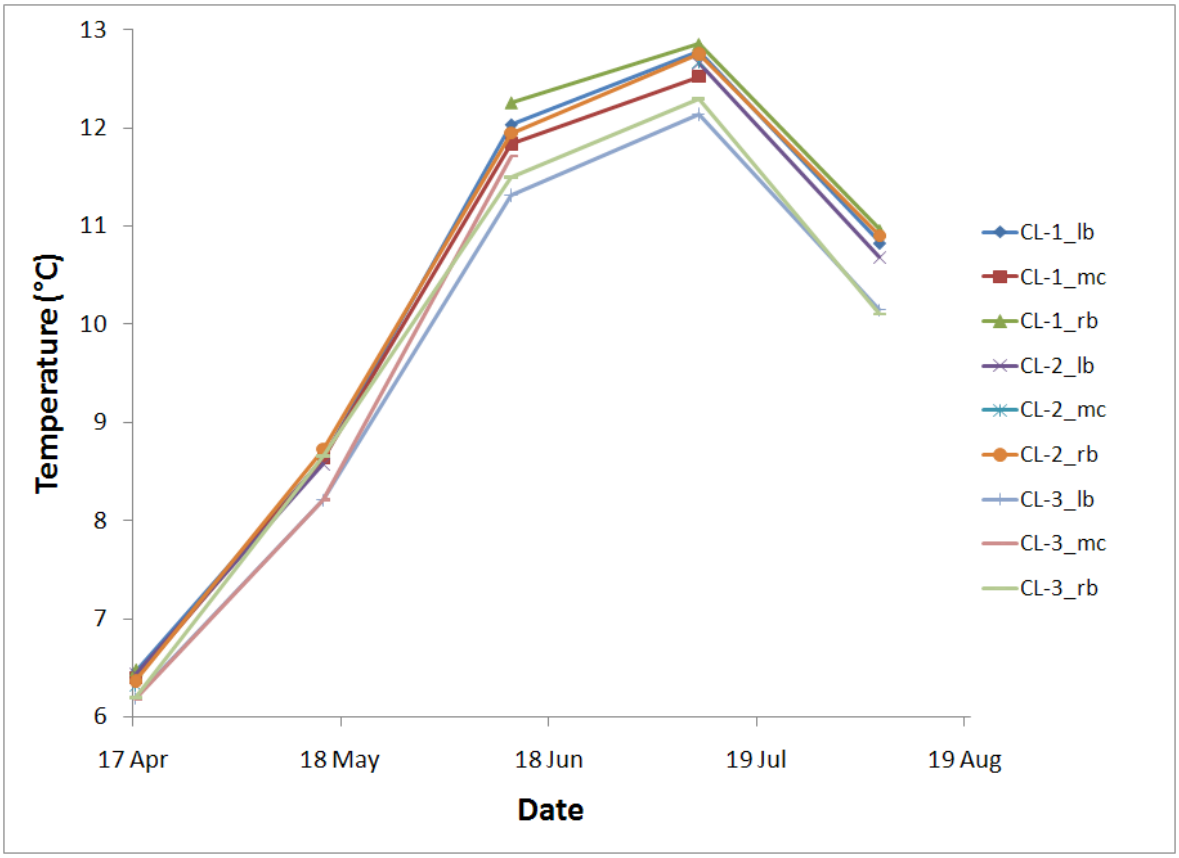

Figure 35.—Temperature spot check results showing data collected from the left bank (lb), mid-channel (mc), and right bank (rb) channel position at each sampling location (CL-1, CL-2, and CL-3). Each data point represents average temperature as measured vertically in the water column.

Data collected by the loggers every 30 min during the sampling period showed that at each location the temperature varied by about 2°C during a 24-h period (Figure 36). Temperatures were generally lowest in the morning and increased during the afternoon. This temperature increase potentially increased TDG by up to 5%. Temperature trends recorded by PNNL sensors were similar to those recorded by the USACE LEWI gauge (Figure 36). Temperatures at Dworshak Dam were substantially cooler due to flow augmentation used to lower the Clearwater River temperatures (Figure 36).

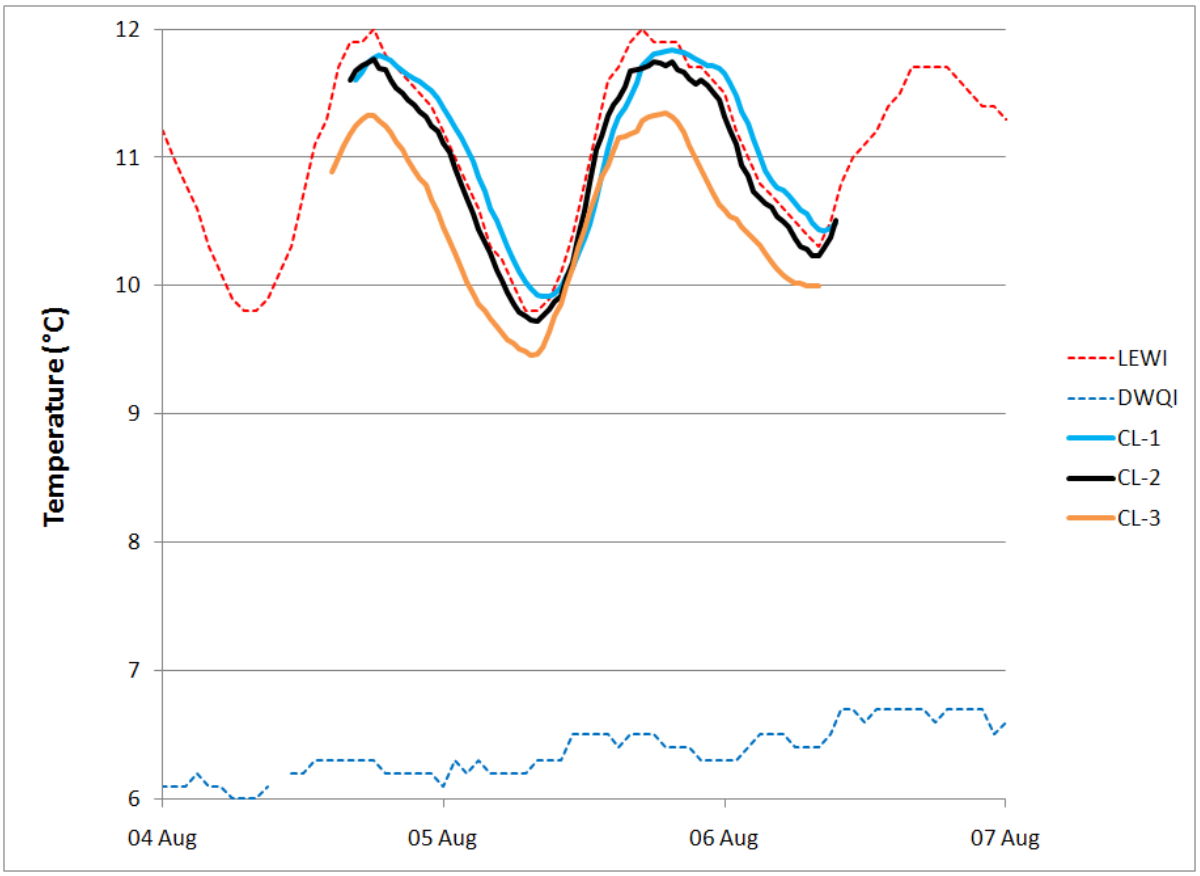

Figure 36.—Solid lines show Clearwater River temperature during 4-6 August 2009 near the Memorial Bridge in Lewiston (CL-1), adjacent to the USGS Lewiston Gauge across from the Potlatch Mill (CL-2), and approximately 1.6 km downstream of the confluence with the Potlatch river (CL-3). Dashed lines show temperature from USACE monitoring stations at Dworshak Dam (DWQI) and the USACE gauge in Lewiston (LEWI). Temperature was not available from the Peck (PEKI) gauge.

Total dissolved gas compensation depths.—TDG saturations peaked at about 110% on 4 August 2009 coincident with a barometric pressure of 736.9 mm Hg, which corresponded to a compensation depth of about 1.0 m. River discharge on 4 August 2009 was about 15.8 kcfs, so the percentage of the river equal to or shallower than the compensation depth was 11.7% (3.0 ha) of the study area from the mouth to Clearwater rkm 13 (Figure 37). Additionally, we estimated that during a low-water year (90th percentile exceedence flow; discharge = 10.8 kcfs), about 15.4% (3.9 ha) of the study area (mouth to Clearwater rkm 13) would be shallower than the 1.0-m compensation depth (Figure 37). The compensation depth is the depth below which fish will not experience TDG greater than 100% because of the increased water pressure.

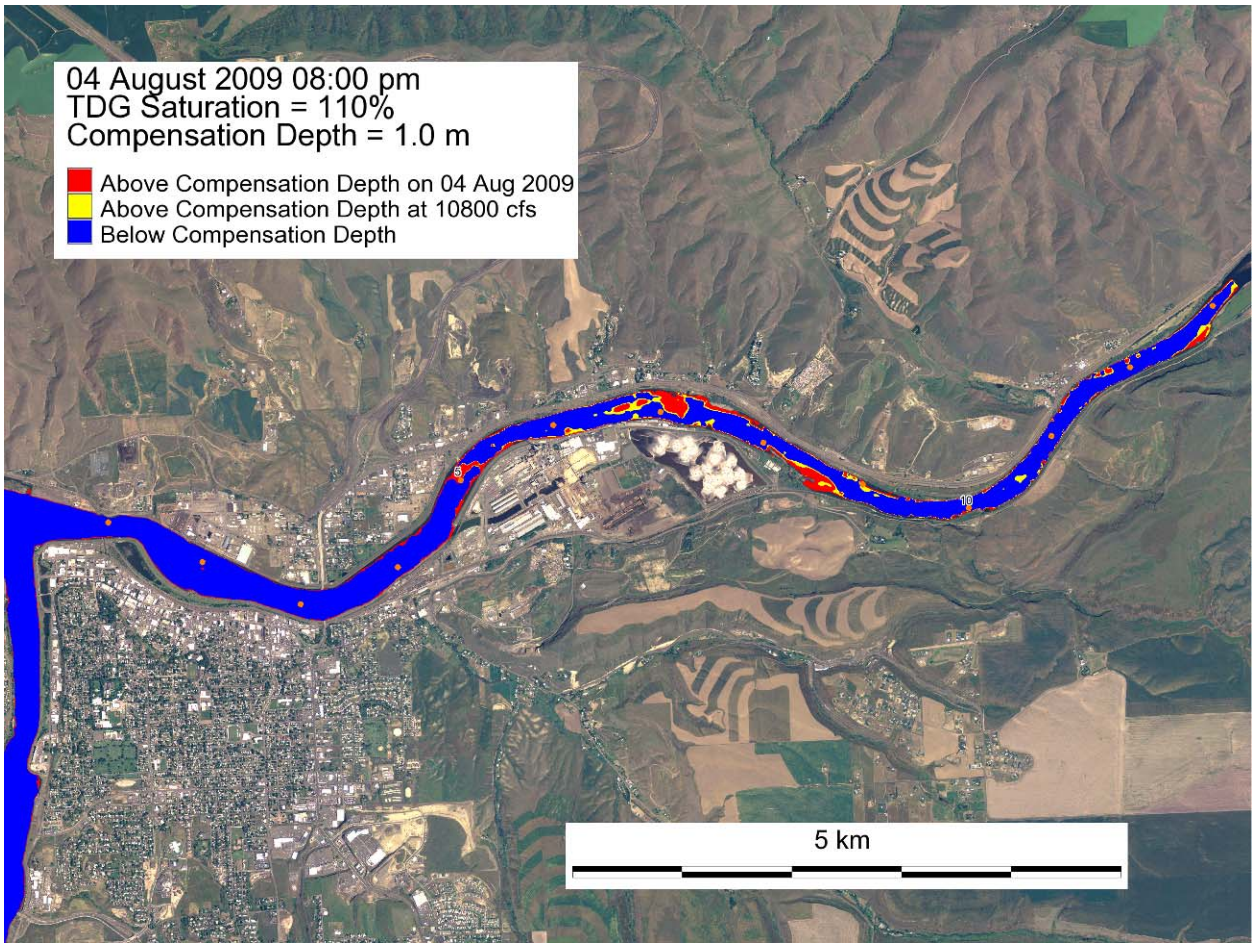

Figure 37.—The area of Clearwater River shallower than the compensation depth of 1.0 m on 4 August 2009 (red), shallower than 1.0 m during the 90th exceedence flow (yellow and red combined), and area deeper than the 1.0-m compensation depth (blue). The 1.0-m compensation depth assumes a total dissolved gas concentration of 110% and a barometric pressure of 736.9 mm Hg, which occurred on 4 August 2009.

Hydrodynamic Conditions

Water temperature.—Hydrodynamic conditions were generally similar to those of the previous seasons (2007–2008 and 2008–2009). Water temperatures were generally coolest in the Clearwater River arm and warmest in the Snake River arm (Figure 38). Temperatures in the Snake River arm exceeded 20°C throughout the water column from late June through late September, and only the top 5–7 m of the water column at the downstream boundary of the Confluence exceeded 20°C during this period. Measured temperatures in the Clearwater River arm exceeded 20°C only for a couple of weeks in late September (Figure 38). Thermal stratification of the Snake River at the downstream boundary of the Confluence began in early July and dissipated by mid-September. The 2009 spring freshet was more similar to 2008 than to 2007 in both the Snake and Clearwater rivers (Figure 39). Dworshak discharges in 2009 were about the same as 2007 during the summer, which was about 2000 kcfs lower than in 2008 (Figure 40). Snake River temperatures through early July 2009 were higher than the same period in 2008 but about the same as 2007 (Figure 41). Clearwater River temperatures in 2009 were similar to 2007 until about mid-September (Figure 41). Thereafter, 2009 Clearwater River temperatures were similar to those of 2008 (Figure 41).

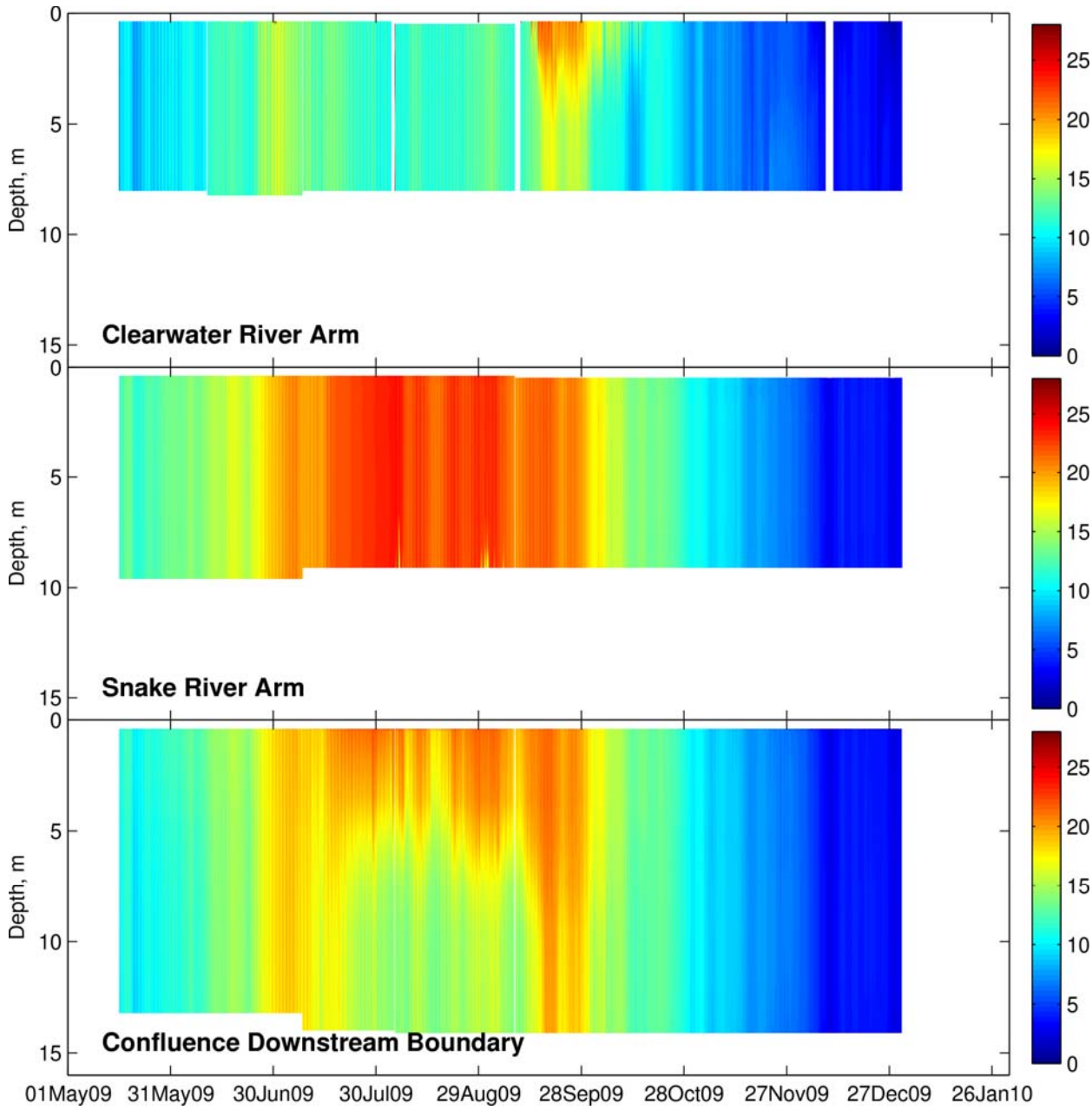

Figure 38.—Measured water temperatures in the Clearwater River arm of Lower Granite Reservoir (LGR1 temperature logger string, top panel), Snake River arm at the US Highway 12 bridge (LGR2 temperature logger string, middle panel), and the downstream boundary of the Snake and Clearwater rivers confluence at the Red Wolf Bridge (LGR3 temperature logger string, bottom panel) from May 2009 to January 2010.

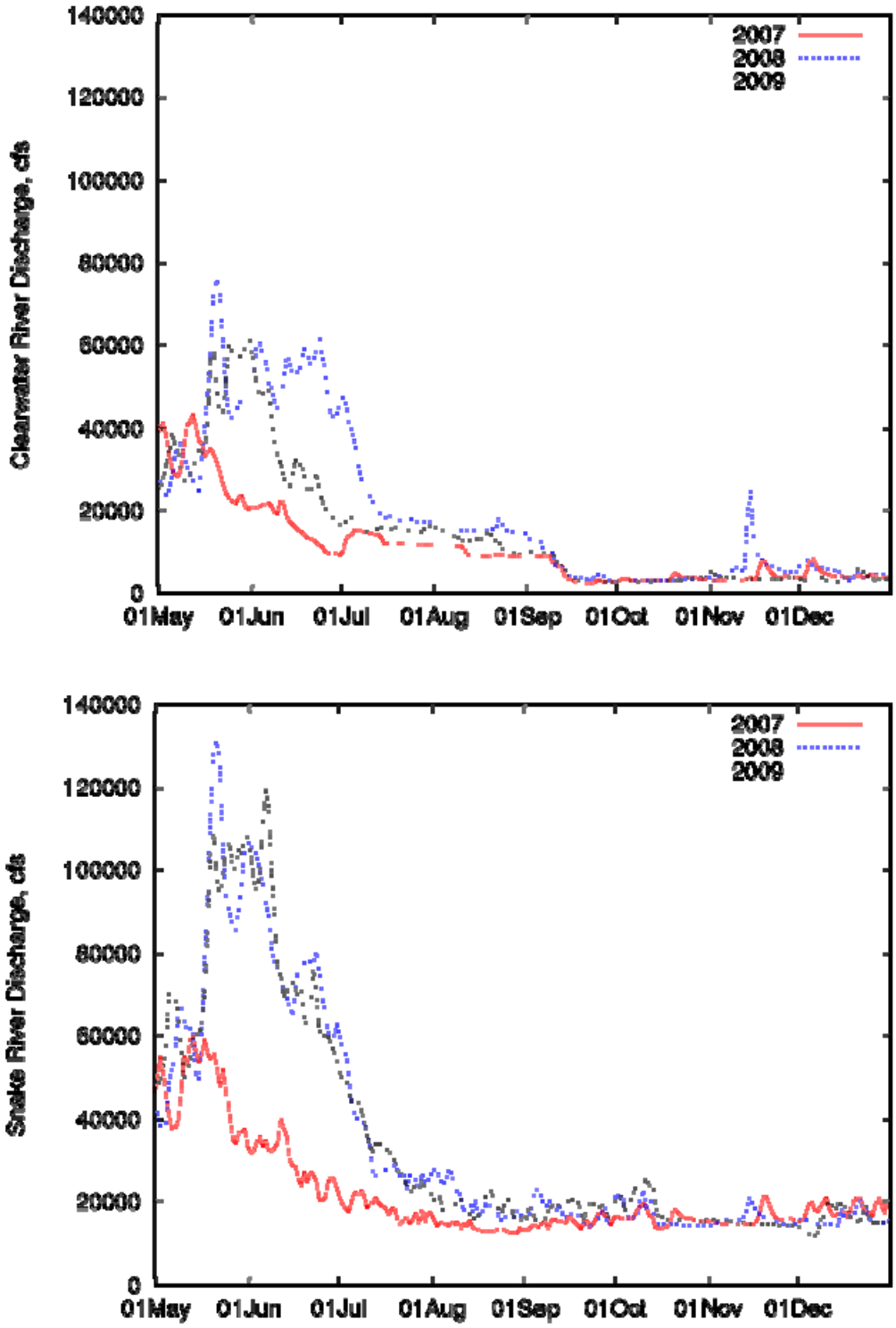

Figure 39.—Comparison of 2007, 2008, and 2009 discharges in the Clearwater River near Spalding, Idaho (USGS gauge no. 13342500, top panel) and the Snake River near Anatone, Washington (USGS gauge no. 13334300, bottom panel).

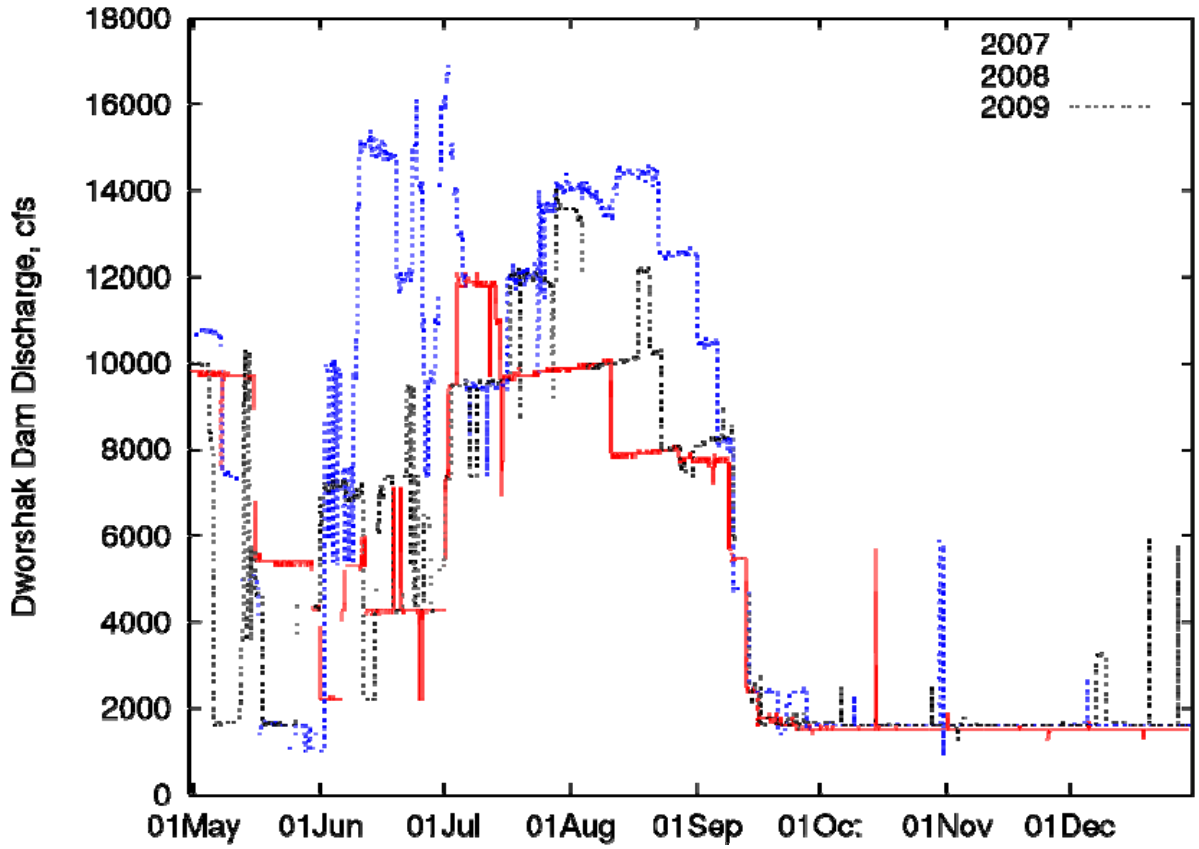

Figure 40.—Comparison of 2007, 2008, and 2009 discharges from Dworshak Dam (USGS gauge no. 13341000).

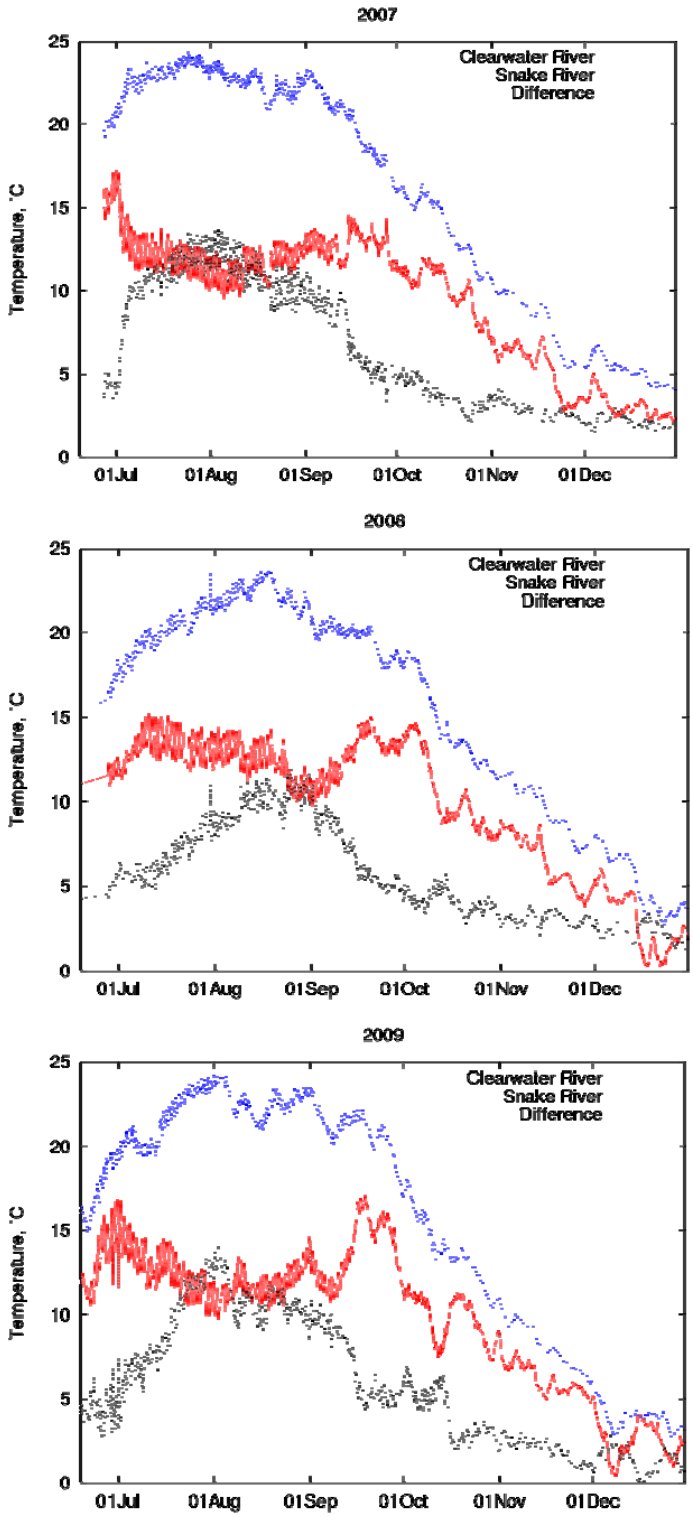

Figure 41.—Snake and Clearwater River temperatures measured in 2007 (upper left), 2008 (upper right), and 2009 (lower) collected from the LGR2 (Snake River) and LGR1 (Clearwater River) temperature logger strings. Temperature difference between the two rivers is also plotted for reference.

Water particle travel time.—The computed water particle travel time through the Clearwater/Snake Confluence reach for the 2009–2010 season was initially very similar to the 2008–2009 season, which gradually slowed from about 2 h on 1 June to about 10 h in early September and further slowed to about 35 h in mid-September through early November (Figure 42). From early December 2009 to mid-January 2010, travel times slowed to about 60 h, nearly twice the travel times for that period in 2007. This coincides with a decrease in Clearwater River and Snake River discharge at that time (Figure 42).

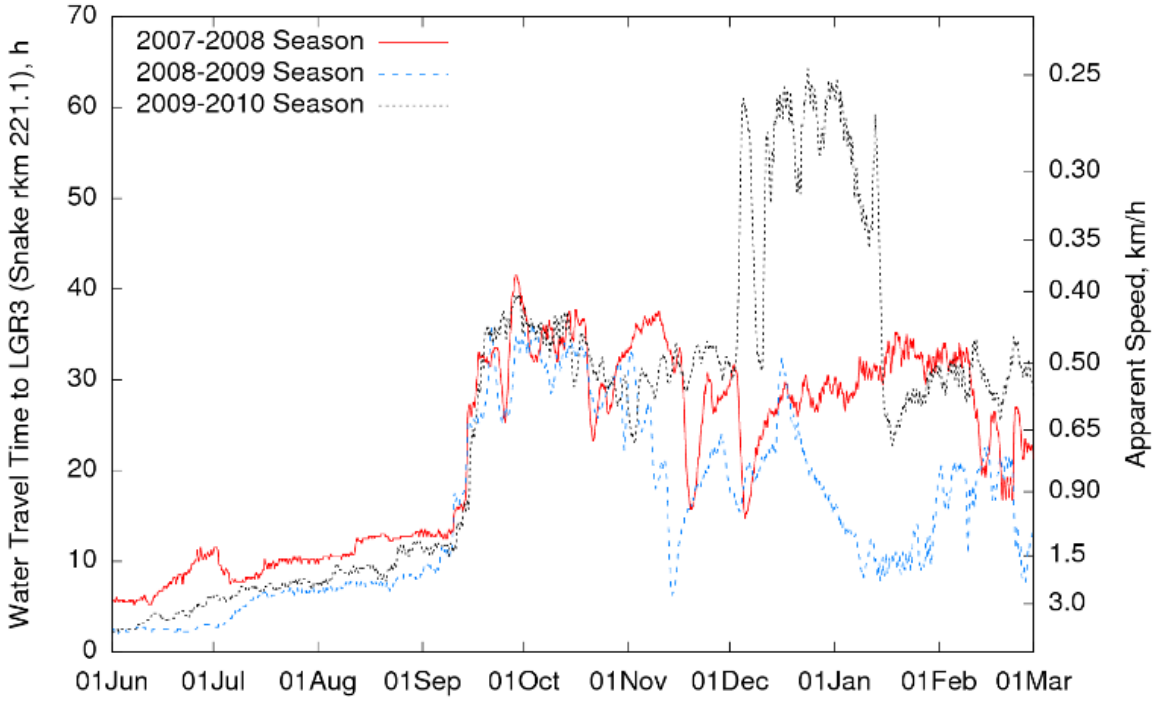

Figure 42.—Water particle travel time (h) and apparent speed (km/h) through the study area from Clearwater rkm 7.5 to the Red Wolf Bridge (LGR3 temperature loggers, Snake rkm 221.1) for the 2007–2008, 2008–2009, and 2009–2010 study seasons.

Simulated reach velocities.—Reach-length-weighted averages of cross-sectional velocity were higher in the Clearwater River reach that was not affected by Lower Granite Reservoir (rkm 10.3 to 12.6) than in the reach affected by the reservoir (rkm 0.0 to 1.8) from 2007 through 2009 (Figure 43). The velocity difference was generally about 1.2–1.5 m/s higher in the unaffected reach in early June, and the difference decreased gradually until mid-September. During a short period in mid-September, the velocity difference sharply decreased to about 0.6 m/s when flow augmentation ended (Figure 43, bottom panel). Velocity differences then gradually increased, with spikes up to 1.4 m/s and 1.3 m/s in mid-November 2009 and January 2010, respectively.

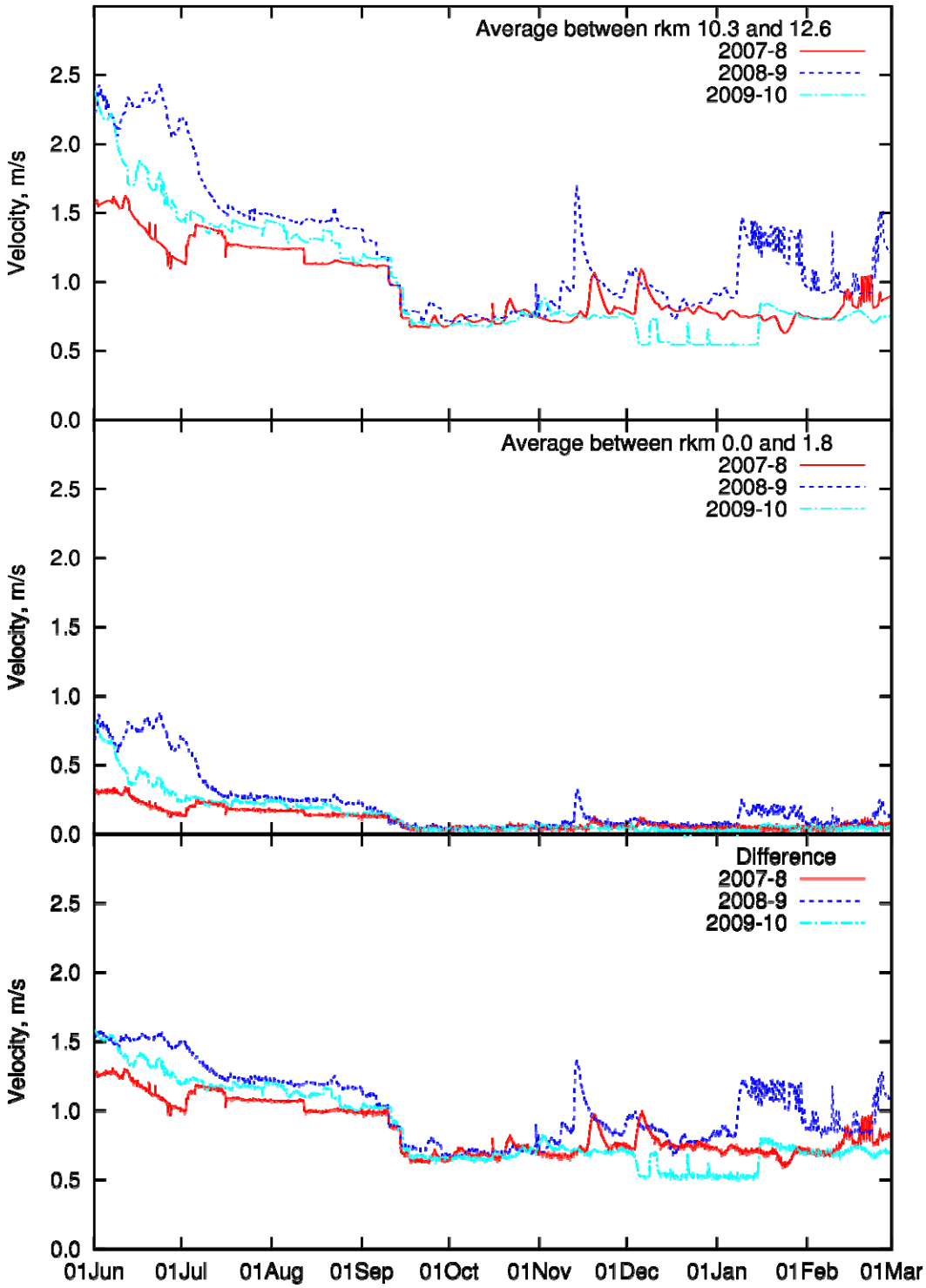

Figure 43.—Estimated hourly cross-section–averaged velocity for a Clearwater River reach unaffected by backwater effects of Lower Granite Dam (top panel), near the mouth (middle panel), and the difference between the two (bottom panel).

Discussion

Migration Delay and Survival

The goals of this project are to understand the mechanisms underlying Snake River juvenile fall Chinook salmon life history diversity and its consequences to management activities such as summer flow augmentation, transportation, and spill. It also seeks to quantify mortality risks that ultimately affect population productivity. In this report, we showed that the Transition Zone and Confluence are areas where hatchery subyearlings show a marked change in their migratory behavior that corresponds to an eventual decline in survival. Survival of both radio- and acoustic-tagged hatchery subyearlings was high (>85%) in the free-flowing Clearwater River, but then dropped substantially in the Transition Zone and Confluence. Fish that migrated through both of these combined reaches survived at rates between 30-40% that were fairly consistent through time. Fish that entered these reaches and delayed their migration had poor survival through time, and mortality increased when the duration of delay increased.

There are many possible factors that may contribute to migratory delay. The changes in water velocity from riverine to impounded habitats may partially explain the behavioral changes we observed. After release, tagged subyearlings moved relatively rapidly through the free-flowing Clearwater River, suggesting that given adequate water velocity, subyearlings can migrate rapidly downstream regardless of the time of year. However, fish then slowed substantially upon entering the Transition Zone. Water velocities in the free-flowing river during summer flow augmentation were about 1.4 m/s, but were only about 0.25 m/s in the Transition Zone during this time. The velocities in the Transition Zone were apparently not high enough to cue continued downstream movement. This is supported by our observations of both up and downstream movement by tagged fish within the Transition Zone. Velocity cues were further reduced after flow augmentation ended in mid September when water velocities in the Transition Zone dropped to about 0.1 m/s. Similarly, fish movement rates through the reservoir were slow and likely related to low water velocities. Tiffan et al. (2009c) showed that active early summer subyearling migrants traveled through Lower Granite Reservoir at rates of about 20 km/d, but fish in our study, moving downstream during late summer and fall, traveled through reservoir reaches at rates less than 6 km/d. Although radio-tagged fish moved rapidly (~29 km/d) through the Upper Reservoir, this reach was only a few kilometers long and these movement rates are probably not representative of those through the remainder of the reservoir. It is possible that downstream movement in the fall was triggered by the end of cool water releases that were used for summer flow augmentation, because most of our detections at Lower Granite Dam occurred after flow augmentation ended.

The physiological status of subyearlings in the Clearwater River during the summer may also contribute to their migratory behavior and delay. In contrast to subyearlings in the Snake River that outmigrate under an increasing photoperiod, the later emergence of Clearwater

subyearlings results in their outmigration occurring under a decreasing photoperiod. Increasing photoperiod and temperature have been shown to increase smoltification in salmonids (Wedemeyer et al. 1980; Muir et al. 1994). Thorpe (1981) discusses the influence that photoperiod has on specific hormones that may be related to downstream movement. It is possible that the combination of decreasing photoperiod (after June 21) and the large reduction in water temperature that accompanies summer flow augmentation may reduce growth (Arnsberg and Statler 1995), physiological development, and the urge to migrate in subyearlings.

In addition to affecting subyearling physiology, the cool water released from Dworshak Reservoir for flow augmentation might facilitate migratory delay by affecting growth of subyearlings in two ways. First, later emerging subyearlings may not reach migratory size before flow augmentation begins. For fish that delay in the Clearwater River, the cool temperature during flow augmentation probably slows growth that in turn requires fish to remain longer to reach migratory size. We have observed subyearlings feeding in the Transition Zone on numerous occasions, so it is plausible that some fish that disperse into this reach continue their rearing there. In contrast, fish that delay in the Confluence and Lower Granite Reservoir, can select optimal temperatures for growth through behavioral thermoregulation (Tiffan et al. 2009d). If temperatures and conditions for growth are good in the reservoir, then at least some fish may have less inclination to migrate. Subyearlings that do delay and survive in the reservoir can grow to large sizes (e.g., 200 mm) by late fall, lending support to this notion.

Although subyearlings that delay their migration can grow well and ultimately become yearling migrants with high survival, this life history strategy is accompanied by high mortality risk. We believe that many subyearlings that delay and die are eaten by predators because migratory delay should lead to increased exposure to predators. Predation is likely a significant source of mortality for subyearlings because of their relatively small size and because their main-stem rearing habitats often overlap or are in close proximity to habitats used by piscine predators such as smallmouth bass (Curet 1993; Tabor et al. 1993). The overlap of dead subyearling locations with that of tagged smallmouth bass locations that we observed provides partial support for this. We qualify this statement because we recognize that we could not detect radio-tagged fish in water deeper than about 10 m, so our conclusion may merely be an artifact of detection efficiency during mobile tracking. However, we reject this notion because of additional evidence that suggests predation may be a real threat to subyearlings. First, both Zimmerman (1999) and Naughton et al. (2004) showed that fish can comprise a large portion of smallmouth bass diets in Lower Granite Reservoir. Subyearlings probably now make up a larger portion of the forage fish population than they did 15 years ago when these studies were done, because of their increase in abundance following hatchery supplementation. Therefore, it is plausible that subyearlings should make up a larger portion of smallmouth diets. Second, we often found subyearling remains regurgitated when we were radio-tagging smallmouth bass during our study. Third, we have observed smallmouth bass attacking schools of subyearlings along the shorelines of the confluence area of Lower Granite Reservoir while collecting predators for tagging.

Fourth, most predatory fish hold in lower velocities near shore when not feeding and thereby have a greater chance of passing tags of depredated fish in those locations regardless of where they were consumed. Finally, mortality due to predation should be high during the summer because predators have higher consumption rates at warmer temperatures.

Exposure to elevated levels of TDG may contribute to the predation vulnerability of subyearlings, particularly when they move from the Transition Zone into the Confluence. We speculate that subyearlings could incur bodily TDG concentration of up to 145% as they move from the Clearwater River (~10 to 12°C and up to 110% TDG) into the much warmer Snake River (~20 to 24°C) as a result of the 14°C temperature change. This hypothesis is consistent with Nebeker et al. (1978) who showed that a 1°C temperature increase translated to a 2.5% increase in TDG. In a previous study, groups of juvenile spring Chinook salmon acclimated to 10°C or 15°C in supersaturated gas concentrations (125-130%) experienced significant mortality (time to 50% death range = 2 to 1080 min; Ebel et al. 1971) when exposed to higher water temperatures. The mechanism of mortality in these spring Chinook may have been the instant barotraumas caused by the quick change in bodily TDG. However, thermal tolerance differences between spring Chinook salmon, which were used in the study by Ebel et al. (1971), and fall Chinook salmon (Sauter et al. 2001) should be considered when applying these results to our study. Although we also showed that fish delaying in the Transition Zone could compensate for elevated TDG levels by seeking greater depths, very high bodily TDG concentrations incurred by swimming into the warmer Confluence reach could potentially cause quick and severe barotraumas and increase predation susceptibility. Sudden increases in temperature alone (not accounting for internal TDG concentrations) have been shown to increase swimming activity of subyearling fall Chinook salmon (Bellgraph et al. 2010), which may increase visibility to predators and increase predation risk. The physiological effects of the interaction between temperature and total dissolved gas, and its effect on predation susceptibility are future areas of research.

In addition to increased predation risk, another effect of migratory delay in subyearlings with presently unknown consequences is that they are not likely to experience summer spill and few pass Lower Granite Dam when the option of transporting them is limited. Only 1 radio-tagged subyearling reached Lower Granite Dam when summer spill was occurring and no acoustic-tagged fish reached the dam during this time. Only 6 radio- and 5 acoustic-tagged fish that reached the dam in September and October which means they did not have the opportunity to experience summer spill. Twelve acoustic-tagged fish passed Lower Granite Dam after the fish bypass facility was shut down at the end of October. Therefore, the potential for these fish to be transported was limited because the transport program is discontinued late in the run based on passage numbers.

Assumptions and Limitations

We intended to capture and tag run-at-large subyearlings from the Clearwater River for our study in 2009. Our goal was to tag and release all our fish in July, which our 2007 study results suggested was the time that fish began to delay in the Transition Zone. We then planned to monitor movement, survival, and delay from July through early September—the period of greatest delay and mortality observed in 2007. Our in-river collection efforts in 2009 were unsuccessful for two reasons. First, we were not able to collect enough fish to meet our tagging goal of 1,000 fish in July. Collection of subyearlings using a 107 m × 9 m lampara seine was spotty and we could not consistently collect requisite numbers of fish. Catches were composed of large, presumably hatchery fish and smaller presumably natural fish. The natural fish were never large enough nor present in sufficient numbers to meet our tagging needs. Second, we were unable to completely degas the water at the Nez Perce Tribal Hatchery in which we intended to hold fish for tagging. In July, we radio tagged 10 fish that we collected in the Transition Zone, brought to the hatchery, and held in water that had been passed through a stripping column. The following day, two fish had died and the rest did not appear to be in good condition, so we abandoned this collection, holding, and tagging approach. Our field measurements of TDG showed that levels in the Clearwater River ranged up to 110%, which supports the notion that elevated TDG during collection and handling may have contributed to poor fish condition. These reasons prompted us to tag the hatchery subyearlings that we held in reserve at the Dworshak National Fish Hatchery.

The hatchery subyearlings we tagged were larger (mean ≈ 103 mm) than many of the natural fish that were in the Transition Zone during July, but were probably representative of natural fish residing in the Transition Zone by the end of August. We recognize that the larger hatchery fish we tagged may have had different survival and displayed different migratory behavior than that of the natural population. Because of their larger size, our estimates of survival, mortality, delay, and travel rates for the fish we tagged may be different than that experienced by natural fish and should be viewed in this context. We also recognize that both radio and acoustic telemetry have limitations that should be considered when interpreting our results and conclusions. Although we did not examine specific tag effects during this study, we recognize that tagged fish may have had differential behavior and survival compared to untagged fish. In addition, there are differences in our ability to detect radio and acoustic tags. Acoustic tags could be detected throughout the water column whereas radio tags could only be detected in the top 10 m. The latter is an important limitation in detecting fish moving through deeper reservoir habitats. Radio-tagged fish could more easily be mobile tracked, whereas this approach is still under development for acoustic tagged fish. In spite of these limitations, our results provide insight into the extent of migratory delay in the Transition Zone and Confluence.

We have learned much about the migratory behavior, survival, and the environment in the Transition Zone and Confluence reaches by tagging hatchery subyearlings and collecting data in the field. However, current technological limitations and inter-annual variation in the size of natural subyearlings prevent us from fully representing the natural fish population and the different life history stages its member pass through. Both radio and acoustic tags are currently not small enough to implant in rearing parr that would be necessary to understand the early migratory and delay behaviors for these fish. These tags are also limited by their battery life and do not last long enough to obtain data over long time intervals. Detection of radio tags and mobile tracking acoustic tags remains a limitation as well. The collection of fish for telemetry tagging is also problematic for the TDG reasons previously discussed and the difficulty of consistently being able to collect fish from the river. An accurate determination of the abundance and fate of natural subyearlings that holdover in Lower Granite Reservoir (and other lower Snake River reservoirs) will only become possible when technology and methods advance. In the near future, we propose to (1) use the data we have to develop to assist during enhanced life cycle modeling efforts, (2) design and conduct a study to evaluate the influence of predation by smallmouth bass and channel catfish on survival, (3) explore the effects of temperature and total dissolved gas on physiology, survival, and susceptibility to predation, and (4) use otolith microchemistry to determine the first year wintering location of returning adults of natural origin.

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APPENDIX A

Total Dissolved Gas and Temperature Monitoring in the Clearwater River, April - August 2009

Table A.1. MiniSonde 5 water quality sensor specifications (Hach Environmental 2006).

Sensor	Range	Stated Accuracy	Resolution
Total dissolved gas	400 to 1400 mmHg	±1.5 mmHg	1.0 mmHg
Luminescent dissolved oxygen	0 to 60 mg/L	0.1 mg/L at < 8 mg/L and ±0.2 mg/L at > 8 mg/L	0.01 mg/L
Specific conductance	0 to 100 mS/cm	±2 µS/cm	0.001
Depth	0 to 25 m	±0.05 m	0.01 m
Temperature	−5 to 50ºC	±0.10ºC	0.01ºC

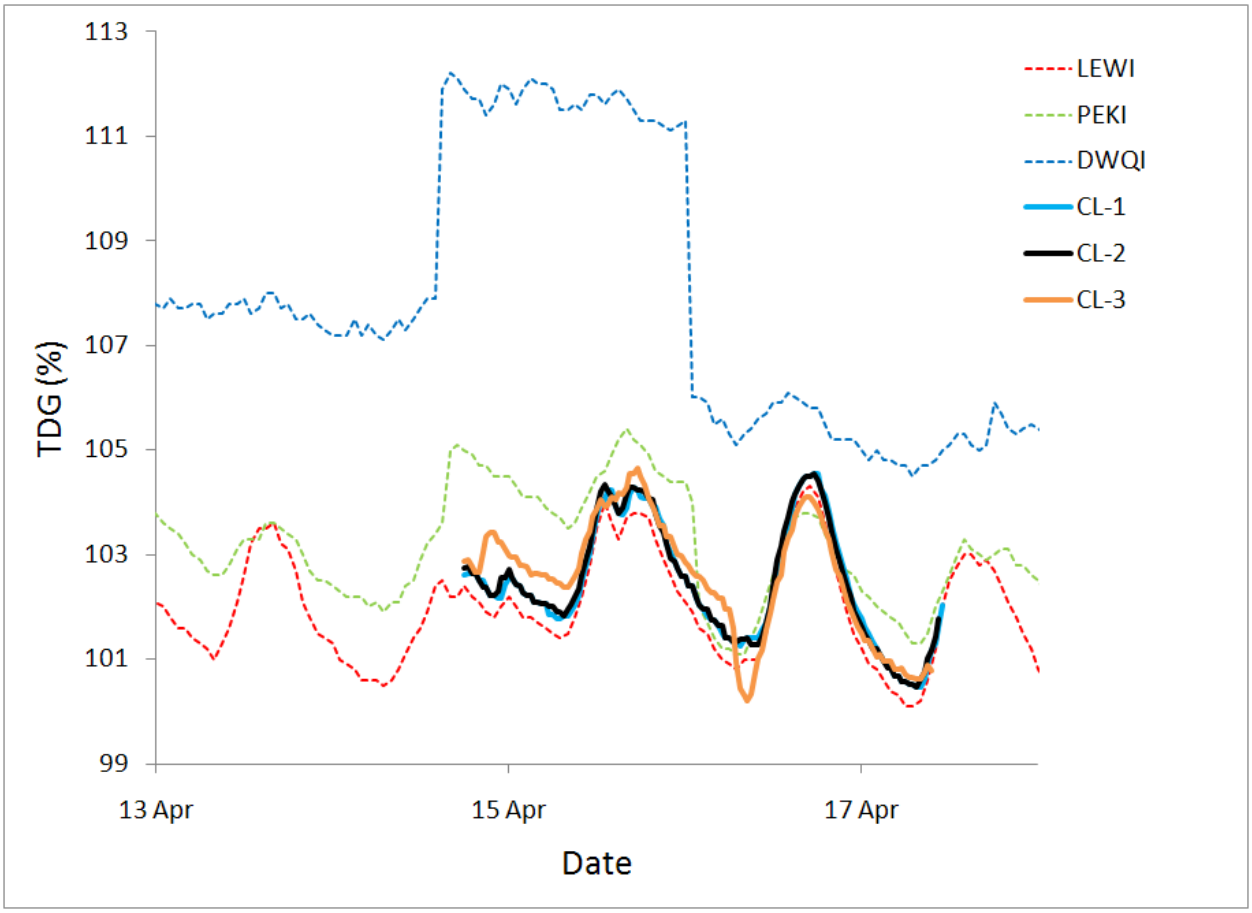

Figure A.1. April 2009 Clearwater TDG monitoring results. Solid lines show Clearwater TDG during April 15-17 near Memorial Bridge (CL-1), adjacent to the USGS Lewiston Gauge across from the Potlatch Mill (CL-2), and approximately 1 mi downstream of the confluence with the Potlatch River (CL-3). Dashed lines show TDG from USACE monitoring stations at Dworshak Dam (DWQI), Peck (PEKI), and Lewiston across from the Potlatch Mill (LEWI).

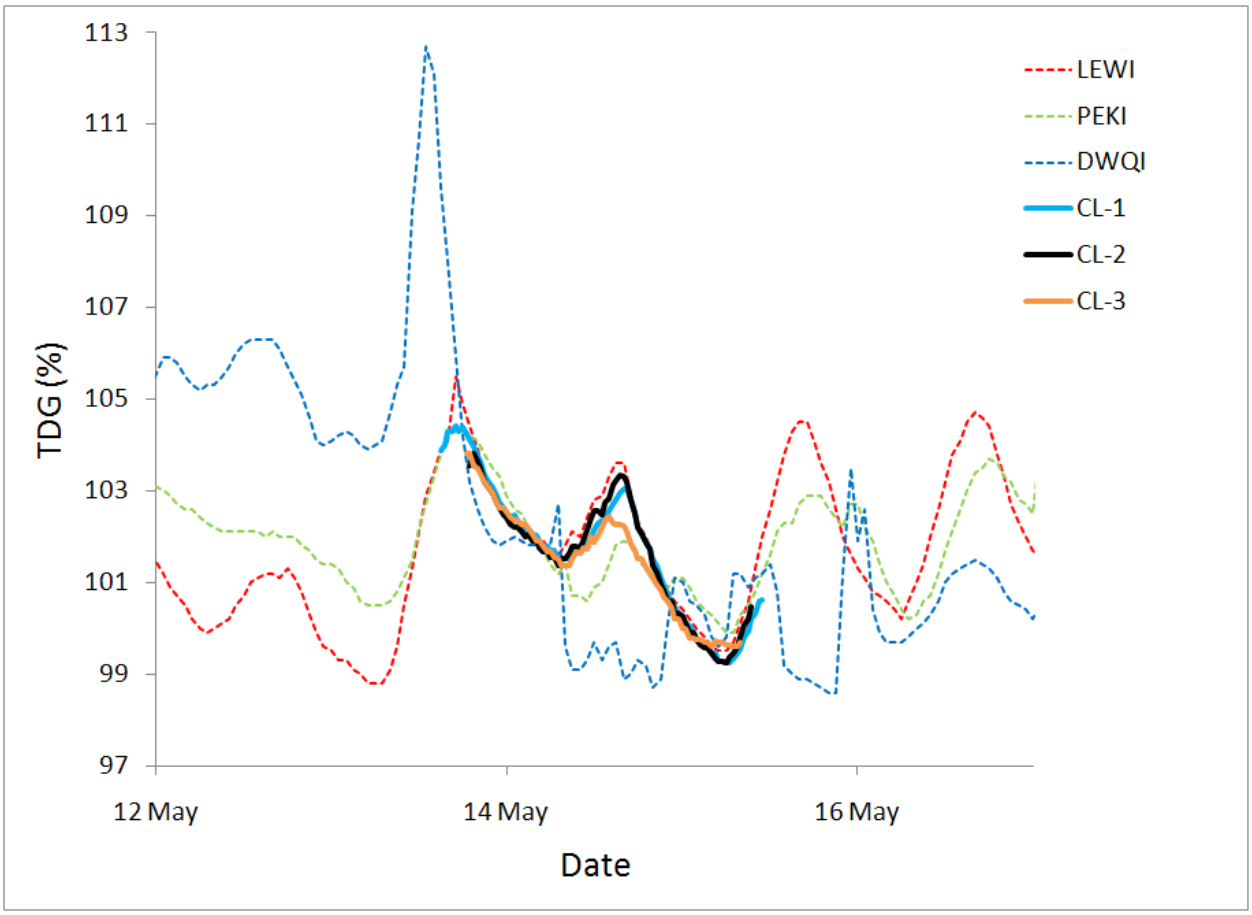

Figure A.2. May 2009 Clearwater TDG monitoring results. Solid lines show Clearwater TDG during May 13-15 near Memorial Bridge (CL-1), adjacent to the USGS Lewiston gauge across from the Potlatch Mill (CL-2), and approximately 1 mi downstream of the confluence with the Potlatch River (CL-3). Dashed lines show TDG from USACE monitoring stations at Dworshak Dam (DWQI), Peck (PEKI), and Lewiston across from the Potlatch Mill (LEWI).

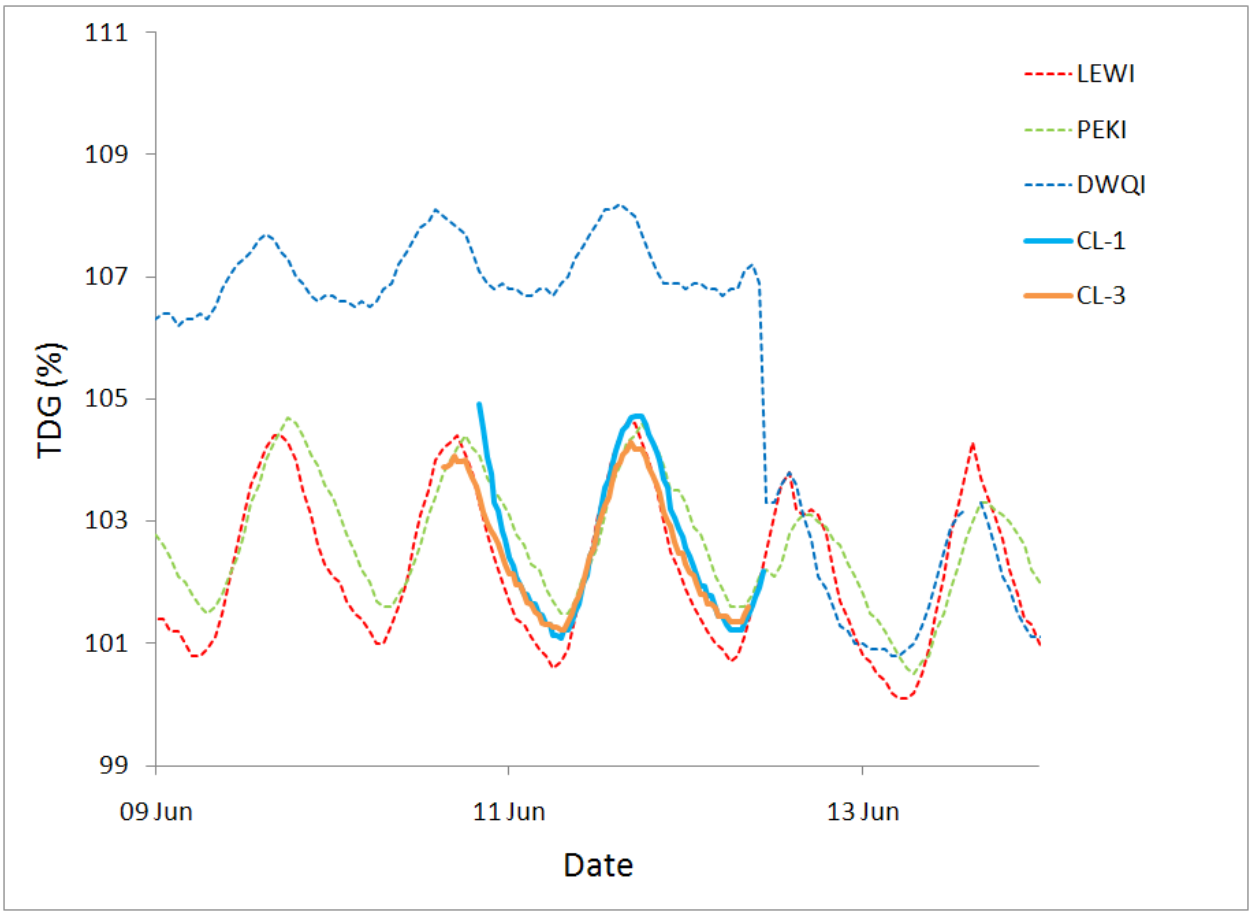

Figure A.3. June 2009 Clearwater TDG monitoring results. Solid lines show Clearwater TDG during June 11-12 near Memorial Bridge (CL-1) and approximately 1 mi downstream of the confluence with the Potlatch River (CL-3). TDG data were not available from CL-2 during June due to vandalism. Dashed lines show TDG from USACE monitoring stations at Dworshak Dam (DWQI), Peck (PEKI), and Lewiston across from the Potlatch Mill (LEWI).

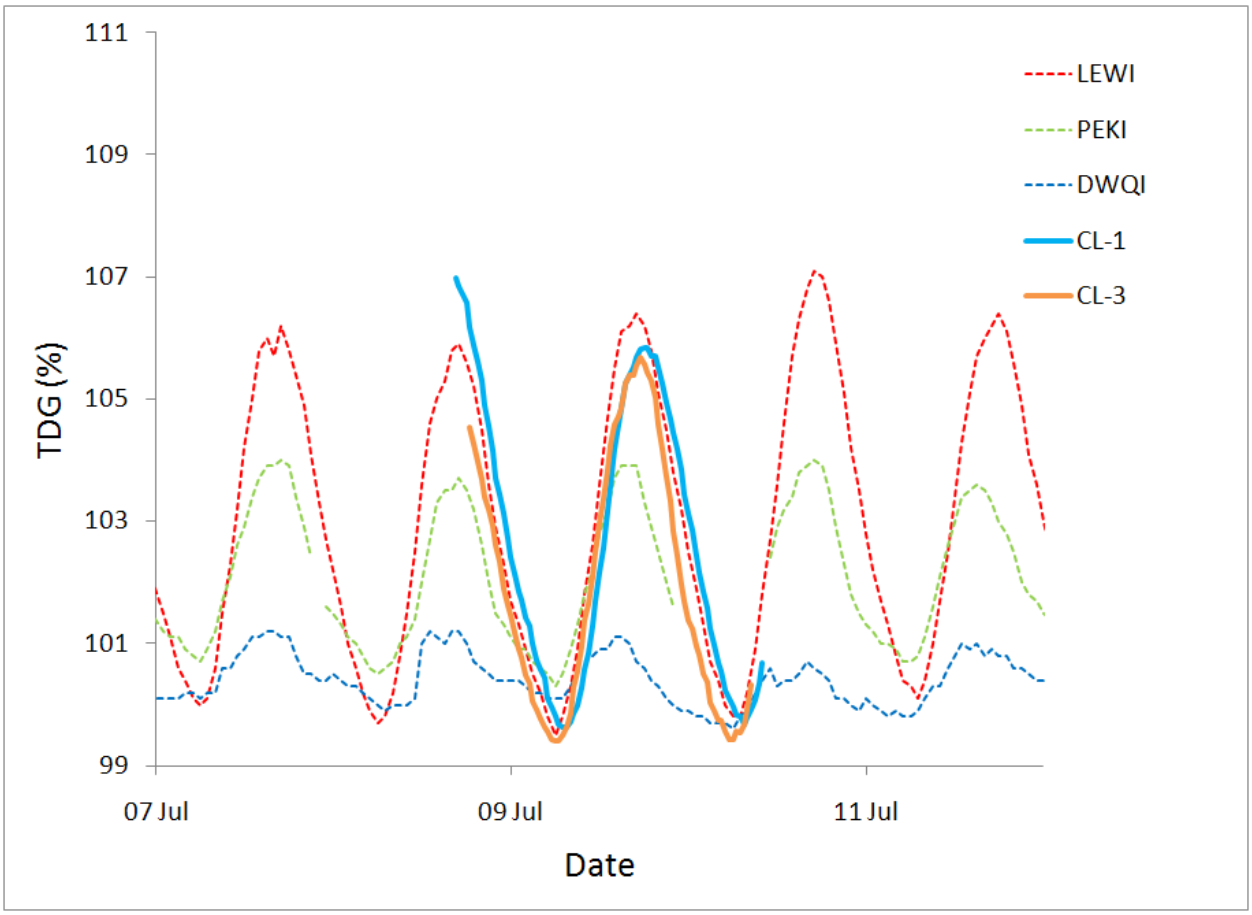

Figure A.4. July 2009 Clearwater TDG monitoring results. Solid lines show Clearwater TDG during July 9-10 near Memorial Bridge (CL-1) and approximately 1 mi downstream of the confluence with the Potlatch River (CL-3). Data from CL-2 were lost due to TDG membrane failure. Dashed lines show TDG from USACE monitoring stations at Dworshak Dam (DWQI), Peck (PEKI), and Lewiston across from the Potlatch Mill (LEWI).

APPENDIX B

Summary of Hydrodynamic Conditions and Water Quality in Lower Granite Reservoir and the lower Clearwater River

B.1 Temperature

B.1.1 Vertical Temperature Variation

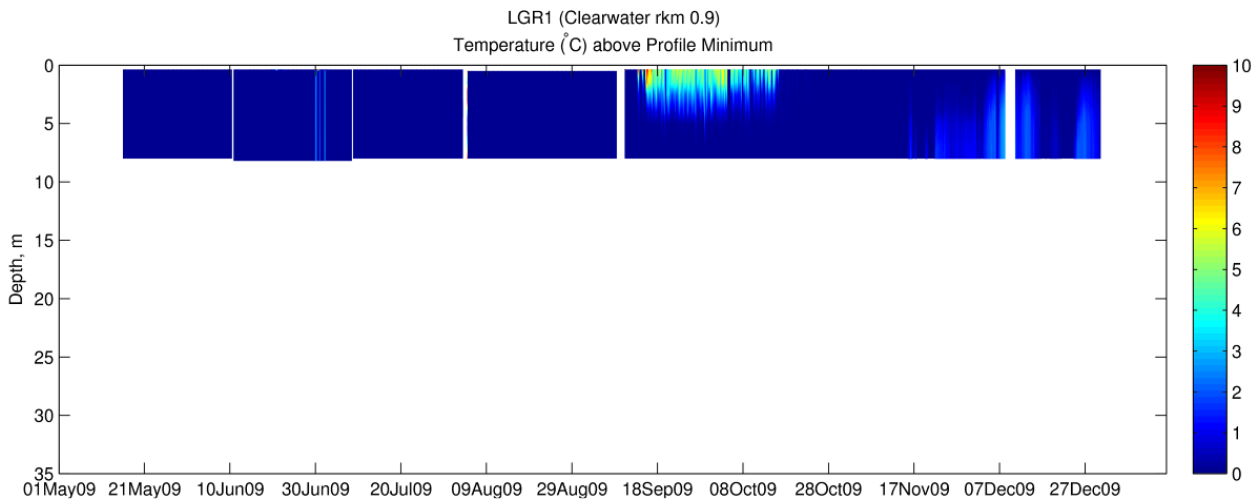

Figure B.1. Hourly temperature above the profile minimum at the LGR1 site.

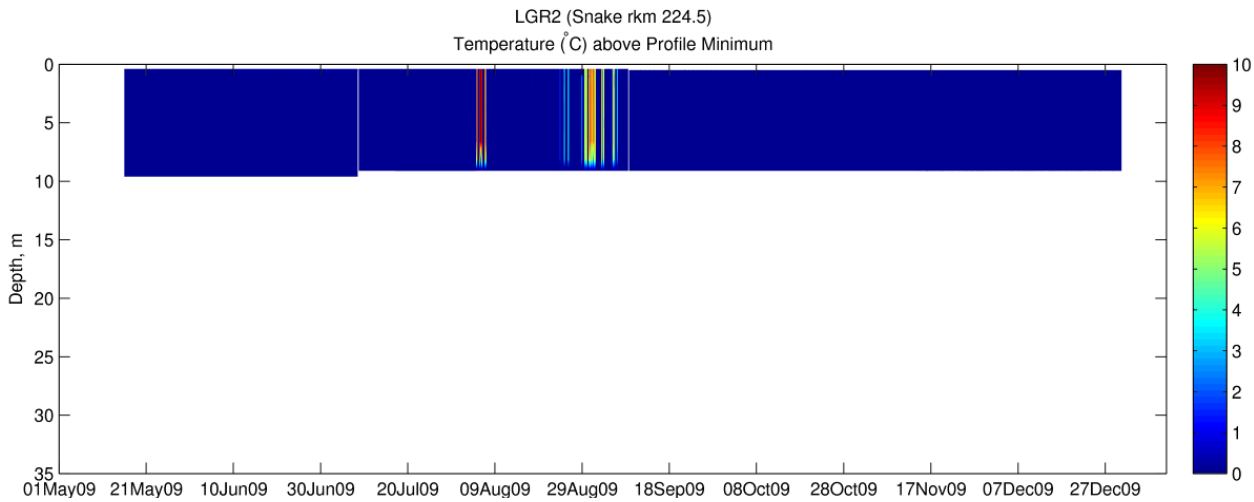

Figure B.2. Hourly temperature above the profile minimum at the LGR2 site.

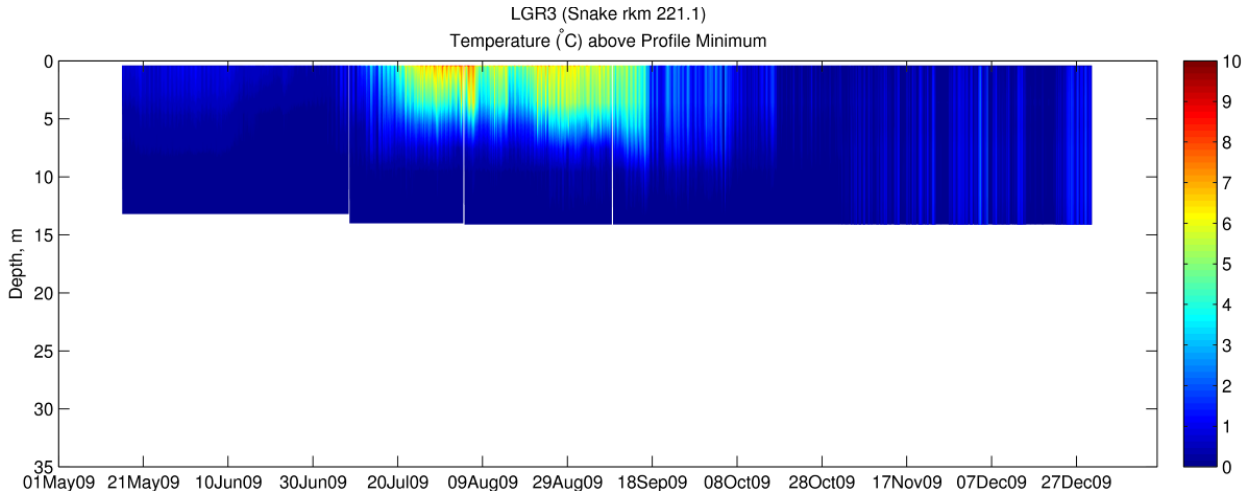

Figure B.3. Hourly temperature above the profile minimum at the LGR3 site.

B.1.2 Additional Vertical Profile Data

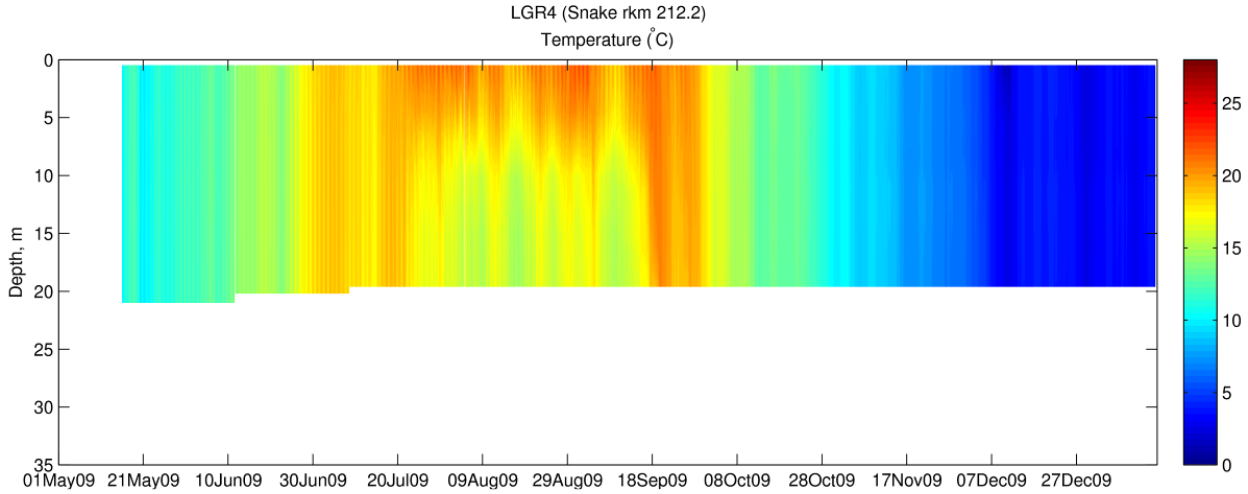

Figure B.4. Complete hourly vertical temperature record from the LGR4 site.

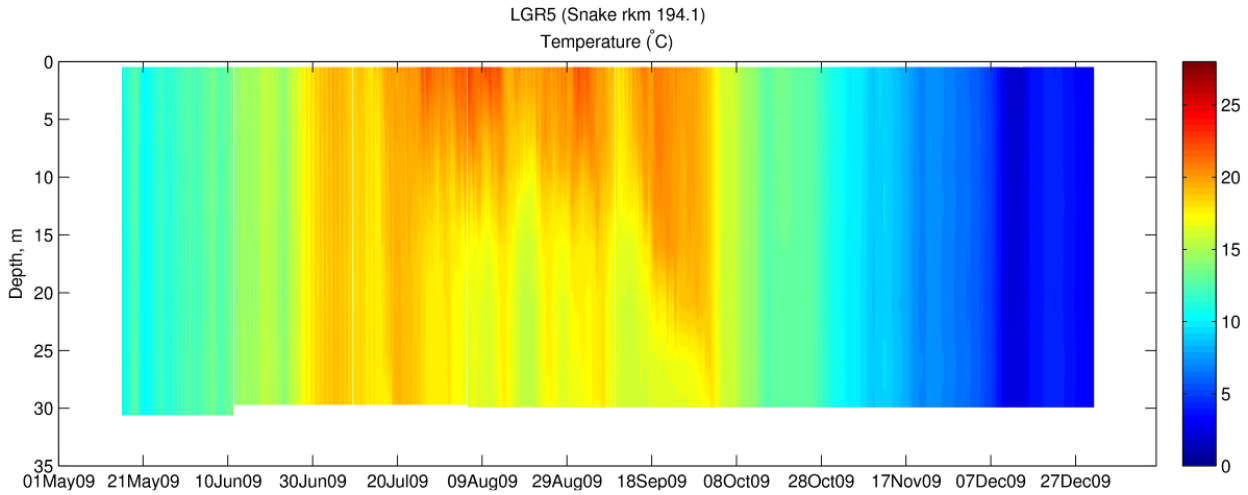

Figure B.5. Complete hourly vertical temperature record from the LGR5 site.

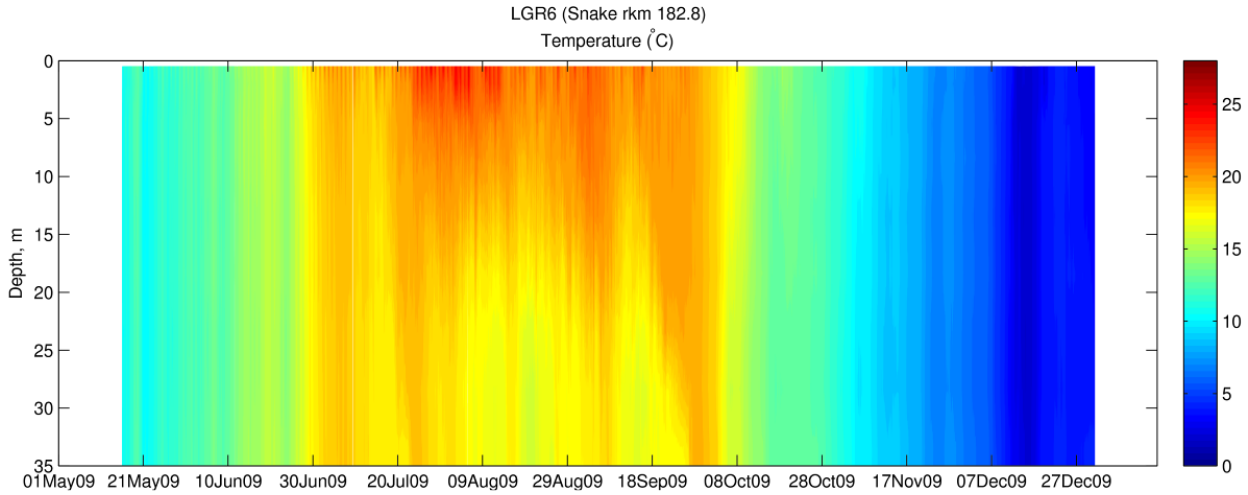

Figure B.6. Complete hourly vertical temperature record from the LGR6 site.

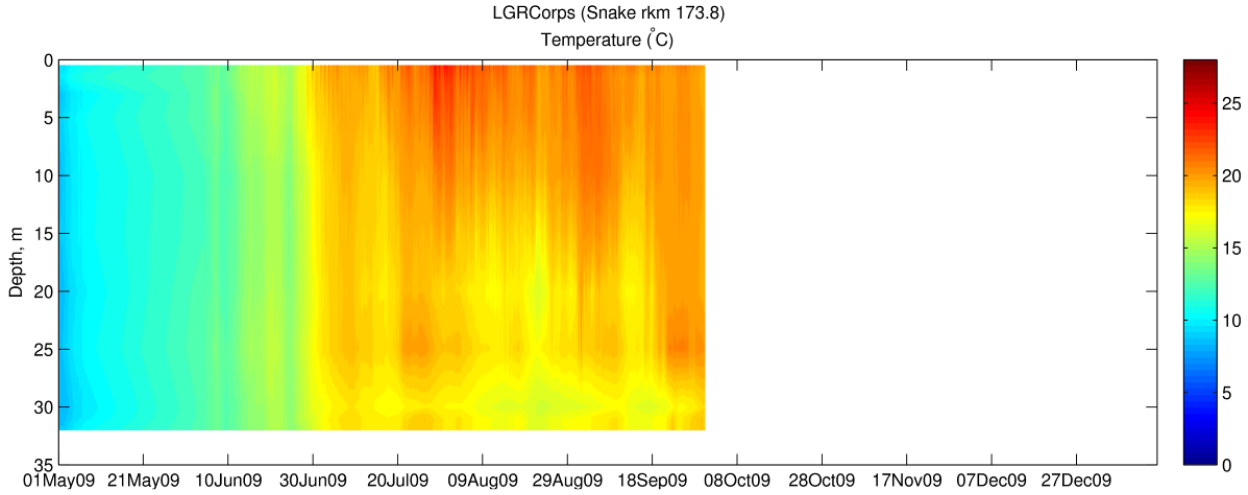

Figure B.7. Hourly temperature record from the USACE-operated temperature sensor string emplaced near Lower Granite Dam (LGRCorps). No data were posted for the string from September 30, 2009 to April 2010.

B.2 Estimated Discharge and Velocity

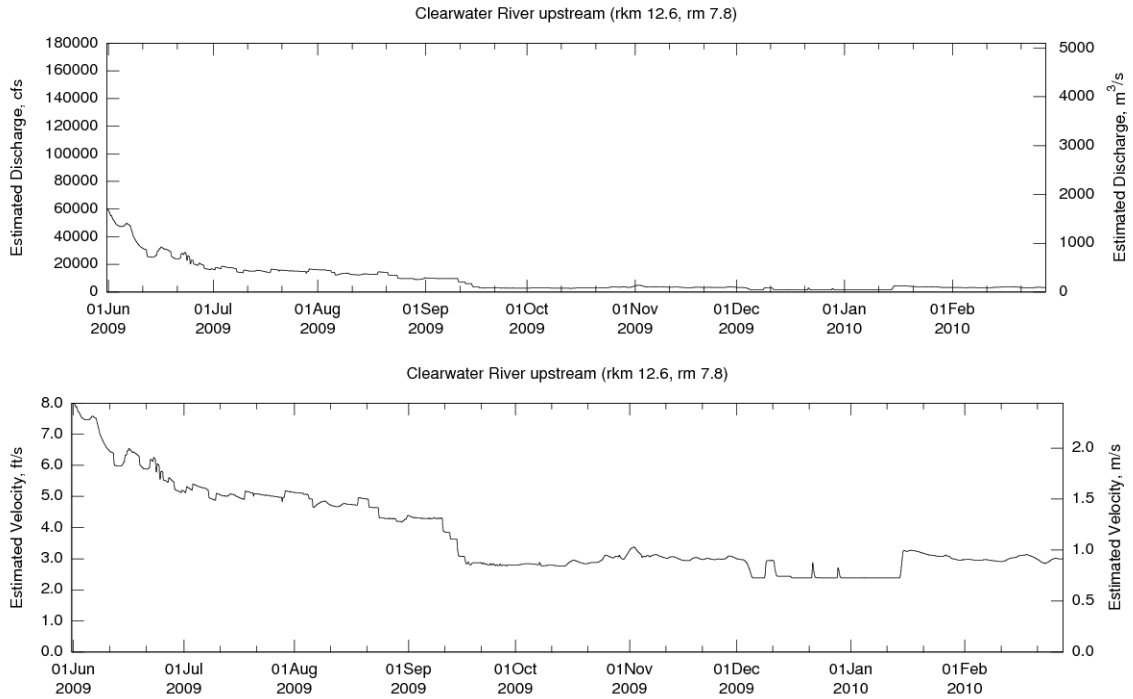

Figure B.8. Estimated discharge (top) and cross-section–averaged velocity (bottom) at Clearwater River rkm 12.6 during the study period.

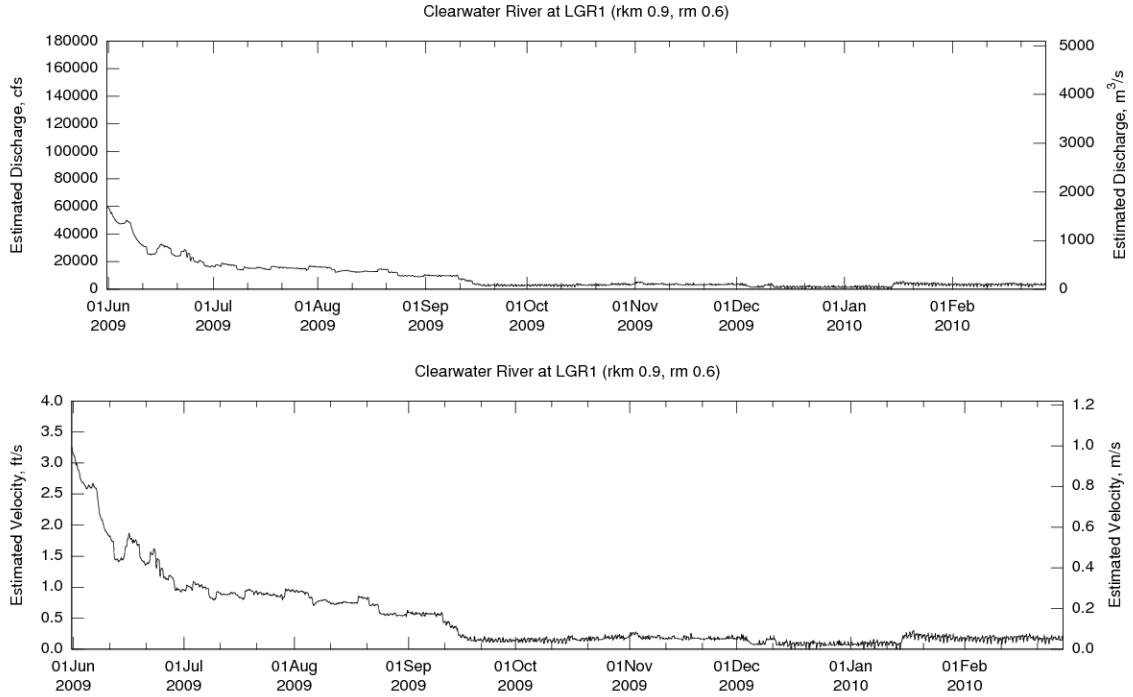

Figure B.9. Estimated discharge (top) and cross-section–averaged velocity (bottom) at LGR1 temperature string on Clearwater River during study period.

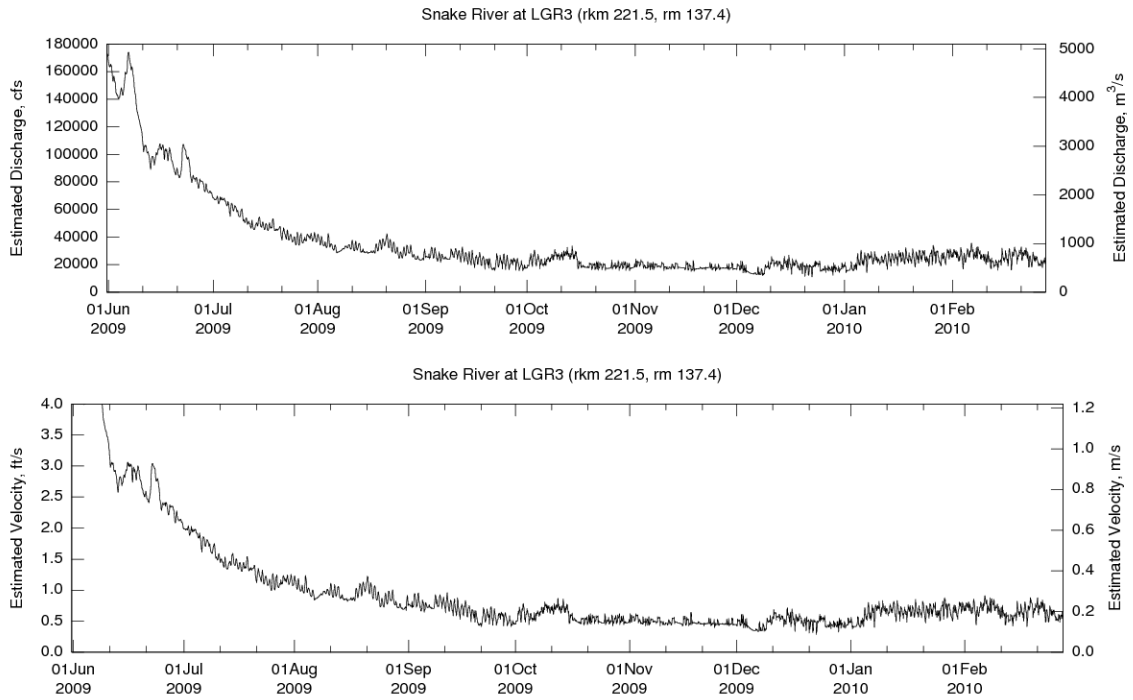

Figure B.10. Estimated discharge (top) and cross-section–averaged velocity (bottom) at LGR3 temperature string on Snake River during the study period.

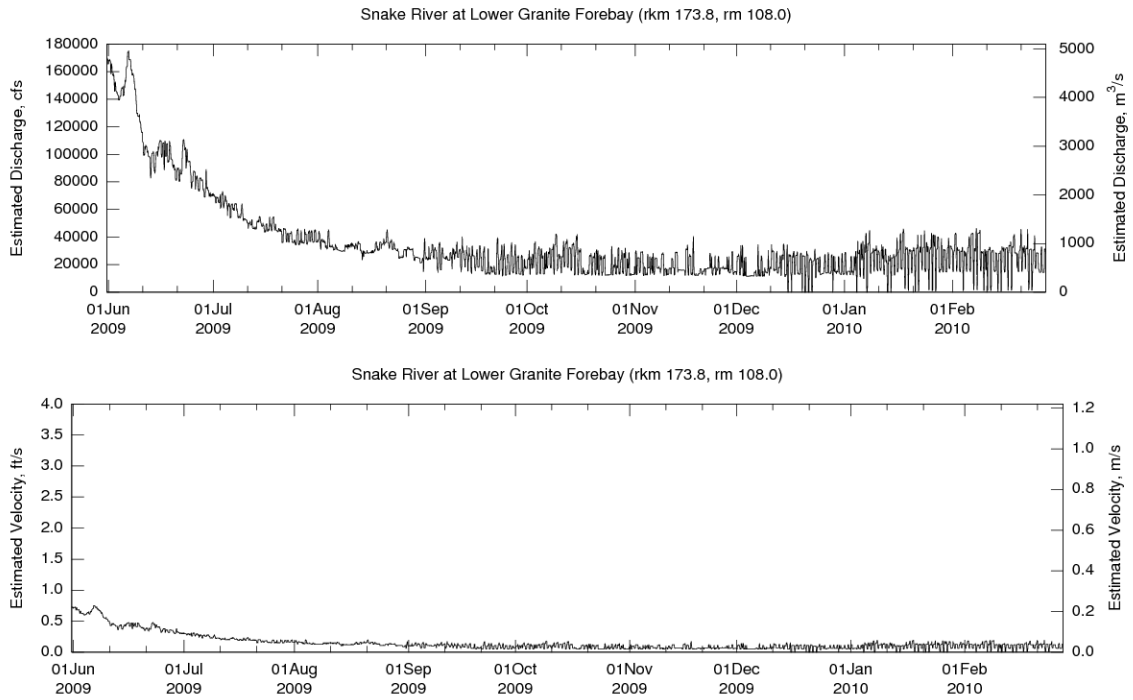

Figure B.11. Estimated discharge (top) and cross-section–averaged velocity (bottom) at Lower Granite Dam forebay temperature string on Snake River during the study period.