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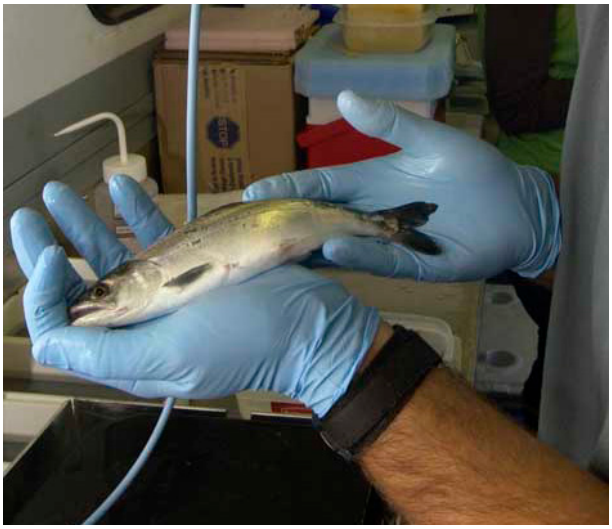
Lower Monumental Reservoir Juvenile Fall Chinook Salmon Behavior Studies, 2007



FINAL REPORT

Battelle
Pacific Northwest Division
Richland, Washington 99352

Prepared for the
U.S. Army Corps of Engineers
Walla Walla District, Walla Walla, Washington
under Contract W912EF-07-C-0022

September 2008

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Abstract

Juvenile Snake River fall Chinook salmon (*Oncorhyncus tshawytscha*) typically emigrate as age-0 fish from the Snake River to the Pacific Ocean between early June and September, with the majority of the fish swimming seaward between mid-June and mid-July. The fish emigrating later in the season have a higher likelihood of remaining in freshwater for an extended period, eventually emigrating seaward as age-1 fish after rearing in reservoirs over the winter. The migratory behavior and survival of these extended freshwater-rearing fall Chinook salmon may be influenced by reservoir hydrodynamics, which may, in turn, be influenced by the operations of the dams in the federal hydropower system. In this study, we examined the relationships between juvenile fall Chinook salmon migratory behavior and physical characteristics of Lower Monumental Reservoir on the lower Snake River. In addition, we developed new statistical models to estimate the fate of acoustic-tagged subyearling fall Chinook salmon in the reservoir. The study area was focused on the lower 19 km of the reservoir, based on findings from a pilot study in 2006 that found that juvenile fall Chinook salmon emigrating in late June and July tended to cease migration in the lower 19 km of this reservoir in an area with pronounced vertical temperature gradients and periodic upstream-directed water motions.

A total of 1,771 subyearling fall Chinook salmon were captured and implanted with both a JSATS acoustic transmitter and a PIT tag as they passed Little Goose Dam at the upstream end of Lower Monumental Reservoir. Following recovery overnight, 24 groups of fish were released 5 km downstream of Little Goose Dam between 31 July and 13 October 2007. Autonomous receivers placed every kilometer in the lower 19 km of the reservoir recorded over 26 million detections of acoustic-tagged salmon in this study. The reservoir showed a strong vertical temperature gradient in late July, which gave way to isothermal conditions by 14 September. Lower Monumental Dam was in a spill operation to aid fish passage through 31 August. Most release groups of fish migrated the 22 km from the release location to the first line of acoustic receivers where they were regrouped into seven 'virtual' releases. The proportions of each release group that migrated and survived, delayed and survived, or died was estimated based on detection histories from the acoustic receivers over multiple time periods and spatial scales. Within each release group, most of the fish that emigrated from the reservoir did so within the first 2 weeks of entering the study area. For fish that remained after the initial two weeks, mortality was estimated to be relatively high early in the study period (August to early September) and substantially lower after mid-September. Over all spatial scales and time periods, an estimated 36% of the fish survived and emigrated from the reservoir, 11% remained in the reservoir beyond the 8-week life of the acoustic transmitter, and the remaining 53% died. Of the fish that remained in the reservoir and were alive, 72 (37% of the number estimated to have been delayed and alive) were detected in the PIT-tag system in spring 2008 as they migrated seaward after surviving the winter in freshwater. Passage and travel time of tagged juvenile fall Chinook salmon past Lower Monumental Dam were correlated with variables related to dam operations (e.g., spill), hydraulic characteristics in the reservoir and immediate forebay, ATPase activity levels, and other environmental variables. The study design implemented in 2007 resulted in the most comprehensive understanding to date regarding the migratory behavior and survival of juvenile fall Chinook salmon that cease migration in Snake River reservoirs during their first year of life. Remaining uncertainties would be addressed by monitoring the migratory behavior and estimating survival over the full emigration period as well as examining other covariates, such as the operation of the new removable spillway weir at Lower Monumental Dam and biological variables related to trophic interactions.

Executive Summary

This report documents the second year (2007) of a study to assess relationships between migratory behavior of juvenile fall Chinook salmon (*Oncorhyncus tshawytscha*) and water circulation patterns that developed in Lower Monumental Reservoir in the summer and fall. Data collected in 2007 were intended to provide a 'baseline' understanding of late migrating juvenile fall Chinook salmon behavior and survival prior to the installation of a new removable spillway weir (RSW) at Lower Monumental Dam, which became operational in spring 2008. The study was conducted for the U.S. Army Corps of Engineers, Walla Walla District, by Battelle–Pacific Northwest Division, the National Oceanic and Atmospheric Administration, and Columbia Basin Research.

Results from a pilot effort in 2006 indicated that 44% (N = 852) of the tagged subyearling fall Chinook salmon did not pass downstream of Lower Monumental Reservoir. The spatial distribution of the fish that did not pass the reservoir was weighted toward the lower half of the reservoir, but their detailed distribution and fate through time was not determined. Based on the 2006 results, the 2007 study employed a higher density of autonomous acoustic receivers and sensors monitoring hydraulic conditions in the lower portion of the reservoir during the period extending from late summer to early winter. Autonomous receivers, temperature sensors, and acoustic Doppler current profilers (ADCPs) were deployed before 31 July and maintained through 12 December 2007. Actively migrating subyearling Chinook salmon (N = 1,771) were surgically implanted with both acoustic and passive integrated transponder (PIT) tags at Little Goose Dam at the upstream end of Lower Monumental Reservoir. Twenty-four groups of study fish were collected, tagged, held overnight, and then released by boat 5 km downstream of Little Goose Dam. Releases occurred between 31 July and 13 October 2007.

The following list presents each research objective, followed by our key results and observations relevant to those objectives:

1. **Characterize fish movements and hydraulic conditions from August through mid-December.**
   - Most subyearling fall Chinook salmon migrating downstream in the last 18% of the emigration period ceased active migration in the lower 19 km of Lower Monumental Reservoir.
   - Between late July and 14 September vertical temperature gradients were present in the lower 19 km of the reservoir. Differences in water temperature between the surface (top 5 to 10 m) and subsurface layers ranged between 1 and 5°C.
   - After mid-September, Lower Monumental Reservoir became predominantly isothermal and cooled from a mean temperature of 19°C in mid September to a mean of around 8°C by 12 December.
   - Tagged subyearling fall Chinook salmon tended to be distributed more in the portion of the reservoir between 10 and 19 km upstream of the dam through late September, and then more in the lower 10 km of the reservoir between early October and mid-December.
   - Most tagged subyearling fall Chinook salmon that emigrated from the reservoir tended to do so within a week after detection in the study area or in the following spring.
   - Mortality rates were highest in the groups of subyearling fall Chinook tagged and released in August and tended to decrease as the season progressed.

- Few tagged subyearling fall Chinook salmon were delayed in the immediate forebay of Lower Monumental Dam in August when summer spill was occurring at the dam. Larger portions of the fish reaching that area later, after the end of the spill operation, remained in the vicinity of the dam for longer periods.
- Spill proportion, vertical thermal gradients, and water particle travel time explained a significant (although small) amount of the variability in the probability of juvenile fall Chinook salmon migration and survival through the 10 km immediately upstream of Lower Monumental Dam.
- Covariate effects analysis found that river regime (representing dates of stratification and spill) explained the greatest amount of variation in migration and survival of tagged juvenile fall Chinook salmon in the immediate forebay (within 500 m) of Lower Monumental Dam. Nevertheless, river regime accounted for only approximately 5% of the variability in migration and survival through the forebay for these fish.
- Spill proportion and various water velocity and direction variables (from ADCP deployments) explained a significant, albeit small (~3 to 4% each) portion of the variability in the probability of juvenile fall Chinook salmon migration and survival past Lower Monumental Dam.
- Multiple regression relating the joint probability of migrating and surviving through the Lower Monumental Dam forebay to the tailrace to environmental and biological covariates resulted in a final model that included spill proportion at Lower Monumental Dam, time of day of arrival at the forebay (day versus night), and ATPase levels.
- Travel time of juvenile fall Chinook salmon through the immediate forebay of Lower Monumental Dam was correlated most closely with the river regime (representing dates of stratification and spill).

2. **Determine fate of subyearling fall Chinook salmon that ceased migration in Lower Monumental Reservoir.**
   - Most of the fish that emigrated from the reservoir did so within 2 weeks of release throughout the study period.
   - Mortality generally declined over the course of the study (i.e., releases 1–6), with the change in fate going to more residualization or delayed migration. Release 7 showed an abrupt jump in mortality after successive declines in mortality earlier in the season.
   - Fish remaining within specific study reaches had relatively high mortality earlier in the study period (August through early September) than later (mid-September through late November).
   - Overall, about 53% of the fish in the study area were estimated to have died during the 8-week-long interrogation period. An additional 36% were estimated to have survived and emigrated from Lower Monumental Reservoir. The final 11% were estimated to have been present and alive within the study area but delayed in their migration seaward.
   - Predator fish, primarily smallmouth bass, appeared to be relatively sedentary in comparison to the juvenile fall Chinook salmon in Lower Monumental Reservoir during the late summer through early winter period. The predator fish did not appear to alter their distribution in response to the distribution of the overwintering juvenile fall Chinook salmon.

3. **Examine ATPase level as a biological factor that may be related to loss of migratory urge by subyearling Chinook salmon.**
   - ATPase levels, measured at the time of tagging, in run-of-river subyearling fall Chinook salmon did not explain a significant amount of the variability in emigration success out of Lower Monumental Reservoir, with very similar ATPase levels among those salmon detected downstream of the reservoir and those salmon not detected downstream.
   - However, ATPase levels explained a relatively large proportion of the variability in emigration success through the middle of Lower Monumental Reservoir (Rkm 600 to 589), although this effect did not extend downstream to the dam itself.
4. **Document if fish residualize or continue movement downstream through the study period.**
   - As stated above, about 36% of the fish that entered the study area emigrated from the reservoir during the 8-week period during which each of the seven release groups was monitored.
   - An estimated 11% of the tagged juvenile salmon remained alive in the reservoir following the 8-week period during which each of the seven release groups was monitored.
   - Roughly half of the fish were estimated to have died or to have moved upstream out of the study area.
   - Seventy-one fish remained within freshwater for extended periods (through the winter) and were subsequently detected emigrating during the spring of 2008. Most of the fish emigrating after overwintering were tagged and released between mid-September and mid-October 2007.

In summary, the juvenile Chinook salmon migrating, whether passively or actively, during the late summer through fall period in the lower Snake River reservoirs appear to emigrate relatively rapidly (within 2 weeks) or remain behind in the reservoir. The juvenile Chinook salmon that cease migration appear to do so in a portion of the reservoir where the water is thermally stratified, with 1–5°C temperature differences between the warmer surface layer (5 to 10 m thick) and the cooler subsurface water. The subsurface water in the lower reservoir areas where there was a vertical thermal gradient was similar in temperature to the isothermal areas in the Little Goose Dam tailrace and upper Lower Monumental Reservoir. Those fish that remained in this area tended to experience a relatively high mortality rate during the late summer while the water remained stratified. By early fall, the water in the reservoir was no longer stratified and was cooling. During this later period, fairly large proportions of the study groups continued to emigrate from the reservoir during the first 2 weeks. The fish that remained within the reservoir for extended periods later in the season (~ after mid-September) survived at a higher rate and subsequently contributed more to the groups of fish detected emigrating seaward the following spring.

The summer spill operations at Lower Monumental Dam appeared to be a significant factor in both travel times and the probability of migrating and surviving for juvenile fall Chinook salmon in the immediate forebay of the dam. Other variables that influenced the movement and survival of these fish were thermal stratification, water particle travel time, ATPase levels at the time of tagging, and other environmental and biological variables.

Based on the results from 2006, we were able to design and implement a study in 2007 that produced very detailed information on the fate of the fish that elected the extended freshwater-rearing life history strategy in Lower Monumental Reservoir. The results from 2007 should provide a solid foundation for evaluating the influence of the newly installed RSW at Lower Monumental Dam in the future. A similar

acoustic receiver deployment approach as well as some additional hydraulic and biological variable data collection should allow for an effective evaluation of the effects of the RSW on the migratory behavior and survival of these late season subyearling fall Chinook salmon that reside within the lower Snake River reservoirs.

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Acronyms and Abbreviations

ADCP	acoustic Doppler current profiler
ATPase	enzyme that catalyzes a process involving the hydrolysis of ATP; used as an indicator of a juvenile salmonid's readiness to adapt from freshwater to seawater
BRZ	boat restricted zone
CF	CompactFlash memory media
CTD	conductivity-temperature-depth (measurements)
EFR	extended freshwater-rearing
FL	fork length (mm)
GPS	Global Positioning System
JSATS	Juvenile Salmon Acoustic Telemetry System
LGS	Little Goose Dam
LMN	Lower Monumental Dam
LMT	Lower Monumental Dam tailrace
MASS1	Modular Aquatic Simulation System–1D hydraulic model
MS-222	tricaine methanesulphonate (fish anesthetic)
node	autonomous acoustic receiver
PDT	Pacific Daylight Time
PIT tag	passive integrated transponder tag
Rkm	river kilometer
RM	river mile
RSW	removable spillway weir
SE	standard error
SD	standard deviation
SMP	Smolt Monitoring Program
USACE	U.S. Army Corps of Engineers
WPTT	water particle travel time

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1.0 Introduction

This report documents the second year of a study to assess interactions between migrating juvenile fall Chinook salmon (*Oncorhyncus tshawytscha*) and water circulation patterns that develop in Lower Monumental Reservoir during the summer months. The research discussed in this report was conducted for the U.S. Army Corps of Engineers (USACE), Walla Walla District, by Battelle–Pacific Northwest Division, the National Oceanic and Atmospheric Administration, and Columbia Basin Research.

1.1 Objectives and Purpose

The scope of the project was to address four research objectives:

1. Characterize fish movements and hydraulic conditions from August through mid-December.
2. Determine fate of subyearling fall Chinook salmon that ceased migration in Lower Monumental Reservoir.
3. Examine ATPase level as a biological factor that may be related to loss of migratory urge by subyearling Chinook salmon.
4. Document if fish residualize or continue movement downstream through the study period.

The overall purpose of the project is to provide information on how subyearling fall Chinook salmon behavioral decisions are related to forebay hydrodynamic conditions and the potential effect on long-term survival probability. This information can then be used for future management decisions related to Lower Monumental Dam project operations during summer months that promote the safest, most effective fish passage.

1.2 Rationale

Water circulation patterns in large rivers and reservoirs can be affected by temperature (density) gradients resulting from inflows and meteorological conditions. These circulation patterns and variable thermal gradients have been shown to affect fish movement (Khangaonkar et al. 2005). On the Deschutes River, warmer surface water moving downstream from the Crooked River was demonstrated to move upstream into the Metolius River after approaching Round Butte Dam. This surface layer was where fish were residing, and passage behavior was affected due to dam operations that withdrew cold water from the hypolimnion layer. Previous circulation studies undertaken in the lower Snake River have noted that some stratification exists at times during summer months in Lower Granite, Little Goose, and Lower Monumental reservoirs. During periods of stratification, meteorological conditions can result in winds of sufficient magnitude to affect the reservoir circulation patterns within the top 5 m of the reservoir, causing the warmer water to move upstream.

The need for further research on effective migration through Lower Monumental Reservoir during summer months is critical to managing water efficiently and promoting safe fish passage effectively. Radio tag survival and passage studies during summer 2005 and 2006 with juvenile fall Chinook salmon documented the lack of passage through the dam after their release 6 km upstream of the dam (Absolon et al. 2007; Absolon et al. in review). These data were collected during early summer and were limited by tag life and the ongoing research plan to discern any fish behavior other than project passage. During

2006, the USACE funded a pilot study to further investigate the relationship between the physical environment and fish movement. The study took place from June through September with fish released into the upstream end of the reservoir above Lower Monumental Dam. The study results confirmed that a significant portion of the tagged subyearling Chinook salmon never left the reservoir during the study period (Cook et al. 2007). A significant correlation was noted between the presence of thermal stratification and the time and location at which downstream migration ceased. A more complete understanding of the aquatic environment that smolts experience in this region of the reservoir could increase the understanding regarding why migration cessation is more common in this localized area. In addition, a removable spillway weir (RSW) was installed at Lower Monumental Dam during fall 2007 and began operating during spring 2008. The information collected in this study could serve as a 'pre-RSW' assessment of relationships between migratory behavior of juvenile fall Chinook salmon and reservoir hydrodynamics in Lower Monumental Reservoir.

1.3 Report Organization

In this report, Chapter 2 presents some background information on the extended freshwater-rearing life history type of Snake River fall Chinook salmon. Chapter 3 details the methods used to tag the juvenile salmon and predator fishes with acoustic tags, and to deploy, maintain, and retrieve the acoustic receivers and water temperature and water velocity sensors. This chapter also discusses application of a hydrodynamic model and development of new statistical tools to determine fate of fish that remained within the reservoir. Chapter 4 documents the results of the study. Results include estimates of fate of the juvenile salmon through space and time in the lower half of Lower Monumental Reservoir, characterization of the water temperature and water velocity patterns over the study period, and the relationships between migration variables and physical and biological covariates. Chapter 5 presents the discussion and conclusions, followed by the recommendations in Chapter 6 and cited references in Chapter 7. Appendices A through E provide additional detail on methods and results.

2.0 Background

When Snake River fall Chinook salmon were reviewed for listing under the Endangered Species Act in 1992 (Waples et al. 1991), it was believed that most juvenile fall Chinook salmon within this evolutionarily significant unit followed a single life history. During the spring and summer after hatching, juvenile fall Chinook salmon would begin migration toward the ocean at age-0 (Connor et al. 2005; NMFS 1995). However, not all juvenile fall Chinook salmon spend their first winter in the ocean, as many have been documented migrating the following year at age-1 (Durkin et al. 1971; Williams et al. 2005).

While the typical fall Chinook salmon life history involves seaward migration at age-0, referred to as ocean-type, fish that winter in fresh water and migrate to sea the following year are referred to as reservoir-type (Connor et al. 2005). Additionally, recent evidence indicates that individuals that leave the Snake River Basin at age-0 may not spend their first winter in the ocean but instead spend their first winter in the tidal freshwater of the Columbia River Estuary (Hinrichsen and Van Holmes 2006).

Growth rates, which are related to water temperatures during incubation and rearing as well as primary productivity of natal waters, have been linked to life history in Snake River fall Chinook salmon. Salmon that spawn in warmer and more productive waters are thought to be more likely to produce ocean-type juveniles, while fry hatched and reared in colder and less productive areas are likely to delay seaward migration until age-1 (Connor et al. 2005). Durkin et al. (1971) reported that juvenile fall Chinook salmon were more likely to adopt this extended freshwater-rearing strategy in Brownlee Reservoir on the Snake River during years with higher water levels and low (and "disoriented") reservoir velocities.

In 2006, Cook et al. (2007) initiated a study for the USACE to assess interactions between migratory behavior of juvenile fall Chinook salmon and water circulation patterns that developed in Lower Monumental Reservoir on the lower Snake River during the summer period. The 2006 study (Cook et al. 2007) was a pilot effort to determine whether juvenile fall Chinook salmon captured as they migrated into Lower Monumental Reservoir (captured as run-of-river "migrants" in the bypass system at Little Goose Dam) would cease migration in the reservoir, and further, whether there was a relationship between the cessation of migration and vertical temperature gradients in the reservoir.

Using a combination of acoustic telemetry and empirical and model-derived hydraulic information, they found that 44% of the acoustic-tagged juvenile fall Chinook salmon did not pass out of Lower Monumental Reservoir during the summer and early fall. Further, they found that the timing and location where most fish (76% of those that ceased migration in the reservoir) ceased migration was related to the onset of vertical thermal gradients in the reservoir. Thermal stratification and underflow conditions in the lower half of the reservoir were observed from early July through September 2006. High proportions of study fish that ceased migration did so at times when the reservoir was stratified and in locations where underflow conditions also were present. However, this relationship did not imply causation because confounding factors (e.g., possible changes in the origin/release location of study fish and decrease in fish size through time) also were present. The results from the 2006 study indicated that a large portion of the late migrant juvenile fall Chinook salmon ceased migration in Lower Monumental Reservoir. However, the study results did not provide much detailed information on the fate of those fish that elected to remain within the reservoir for extended periods in the fall and early winter. Further, there was a need for more

detailed information regarding the relationship between operations at Lower Monumental Dam and the migratory behavior of these fish. These additional information needs provided the impetus for the 2007 study that is the subject of this report.

3.0 Methods

3.1 Juvenile Salmon Collection and Microtransmitter Implantation

Juvenile fall Chinook salmon were obtained from the juvenile fish bypass facility at Little Goose Dam on the Snake River between 30 July and 12 October 2007. Fish were sorted to ensure that only juvenile fall Chinook salmon without previously implanted passive integrated transponder (PIT) tags were collected. The maximum number of available fish was collected during each collection day and held without food for 24 to 48 hr prior to surgery in two 84-L tanks with freshly circulating ambient-temperature river water. Holding tanks were located in a covered trailer (2.7 m wide and 6.1 m long) designed specifically as a mobile fish surgery unit.

Surgeries to implant microtransmitters were performed on 24 dates from 31 July through 13 October. Sample sizes of implanted fish ranged from 12 to 172 fish per tagging day, depending on fish availability (Table 3.1). Length data of subyearling Chinook salmon measured by the Smolt Monitoring Program (SMP) every Sunday from 28 July through 13 October were assumed to be representative of the population and coincided with the dates of our study (Figure 3.1). Juvenile salmon tagged for our study (mean fork length [FL] = 158 mm, SE = 0.51) were longer than fish collected by the SMP (mean FL = 149 mm, SE = 0.99) ($t_{2264} = 8.39$, $P < 0.0001$). However, FL data provided by the SMP were in 5-mm length bins, while FL for tagged fish was measured to the nearest millimeter, which could bias the comparison. The lower limit in FL for tagging (95 mm long) did not contribute to the difference because there were no fish under 100 mm in the SMP sample.

Fish were anesthetized in 80–100 mg of tricaine methanesulfonate (MS-222)/L of water prior to surgery for about 3–4 minutes until equilibrium was lost (i.e., fish could no longer hold themselves upright). Each sedated fish was then transported in a 1-L pitcher containing anesthetizing water to a technician who measured fork length (millimeters) and weight (grams). Prior to implantation of the transmitters, gill tissue was snipped from a gill arch and placed in a buffered solution of sucrose, EDTA, and imidazole according to McCormick (1993), frozen on dry ice at the tagging location for the day, and then transported to a −80°C freezer until assayed for gill Na^+-K^+ATPase activity. Gill Na^+-K^+ATPase activity was assessed using the method of McCormick (1993). All Gill Na^+-K^+ATPase activities are reported in units of μmole PO_4 mg protein^{-1} hr^{-1}.

One PIT tag (Destron-Fearing, Model TX1411ST; 12.5 mm × 2 mm) and one Juvenile Salmon Acoustic Telemetry System (JSATS) acoustic tag (Sonic Concepts, Model E101; 16 mm (SD = 0.2, N = 100) weighing 0.585 g in air (SD = 0.08, N = 100); Figure 3.2) were placed in the pitcher containing the corresponding fish and delivered to one of three surgeons. Acoustic microtransmitters were programmed to emit an individually encoded signal every 10 seconds, and expected battery life was 60 days. Tag life was evaluated in a separate study (Figure 3.3).

Each fish was placed on the surgery table ventral side up, a silicon tube was inserted into the mouth, and freshly oxygenated water was supplied continuously from two gravity-fed buckets positioned above the surgeon. One bucket contained a maintenance dose of 40 mg/L MS-222, and the other bucket contained water. Surgeons ensured the proper sedation level by controlling the valves on each bucket. An incision approximately 8 mm long was made about 3 mm from and parallel to the mid-ventral line between the pectoral and pelvic girdles. The PIT tag was inserted into the incision, followed by the

acoustic transmitter, which was placed with the battery toward the anterior portion of the fish. The acoustic transmitter was inserted following the PIT tag to reduce the possibility of the PIT tag passing out through the incision. Both tags were positioned parallel to the long axis of the fish. The incision was closed with two simple, interrupted sutures using 5-0 Monocryl (monofilament manufactured by Ethicon). Fish were placed in a 75-L recovery bucket with flow-through river water and supplemental oxygen following surgery and were monitored to ensure that they recovered equilibrium before being transferred to the holding and release tank.

Table 3.1. Descriptive statistics by release date of juvenile fall Chinook salmon tagged at Little Goose Dam and released in the Lower Monumental Reservoir of the Snake River, 2007. Little Goose Dam tailrace temperature and fish condition (Fulton condition factor) on the day of release also are presented.

			Length (mm)				Weight (g)				Condition	
Release Date	Temp (°C)	*N*	Mean	SE	Min	Max	Mean	SE	Min	Max	Mean	SE
31-Jul	20.9	111	138	0.8	109	157	29.1	0.5	14.7	44.4	1.1	0.01
2-Aug	20.8	172	140	0.7	121	174	30.3	0.5	18.4	59.4	1.1	0.01
4-Aug	20.4	153	141	0.7	112	166	31.5	0.5	13.2	49.2	1.1	0.01
7-Aug	20.4	151	145	0.5	125	160	35.4	0.5	22.7	85.6	1.2	0.01
9-Aug	20.6	151	147	0.7	116	173	36.9	0.7	17.6	86.2	1.2	0.02
11-Aug	20.6	153	149	0.7	120	183	38.2	0.7	17.5	72.1	1.1	0.01
14-Aug	19.9	101	150	0.9	129	172	38	0.7	22.5	62	1.1	0.01
16-Aug	19.5	94	153	0.9	118	177	40.9	0.7	17.3	56.4	1.1	0.01
20-Aug	19.4	41	174	1.5	155	191	47.6	1.2	32.5	60.9	0.9	0.01
23-Aug	19.2	99	173	1.1	130	194	46.3	0.9	19.1	68.3	0.9	0.01
25-Aug	19.2	71	177	1.5	145	205	49.7	1.3	25.7	81.4	0.9	0.00
28-Aug	19.5	123	170	1	145	199	62.4	3.6	35.4	98.4	1.2	0.01
30-Aug	19.3	78	170	1.1	148	193	57.5	1.2	37.4	83.2	1.2	0.01
6-Sep	18.8	55	176	1.5	140	204	64.5	1.6	31.8	97.8	1.2	0.01
8-Sep	18.9	50	175	1.7	145	208	63.2	1.8	31.1	90.6	1.2	0.01
11-Sep	18.9	17	182	2.6	161	200	71.3	3.5	44.8	98.9	1.2	0.03
13-Sep	18.8	12	178	3.7	157	202	68.4	4.9	40.4	92.1	1.2	0.03
20-Sep	18.8	14	188	4.4	164	225	84.2	5.9	47.3	133.5	1.2	0.02
27-Sep	17.6	16	199	2.7	185	218	96.2	4.3	69.4	128.2	1.2	0.02
4-Oct	16.4	15	205	1.4	195	216	107.6	2.5	90.4	127.7	1.2	0.02
6-Oct	16	22	207	2.2	178	229	109.9	3.4	68	141.7	1.5	0.28
9-Oct	15.8	22	208	1.2	199	218	108.6	2.5	88.5	130.8	1.2	0.01
11-Oct	15.8	26	211	1.9	195	230	112.4	3	86.5	137.3	1.5	0.26
13-Oct	15.7	24	210	2.3	168	227	111.5	4.1	54	155.5	1.2	0.03

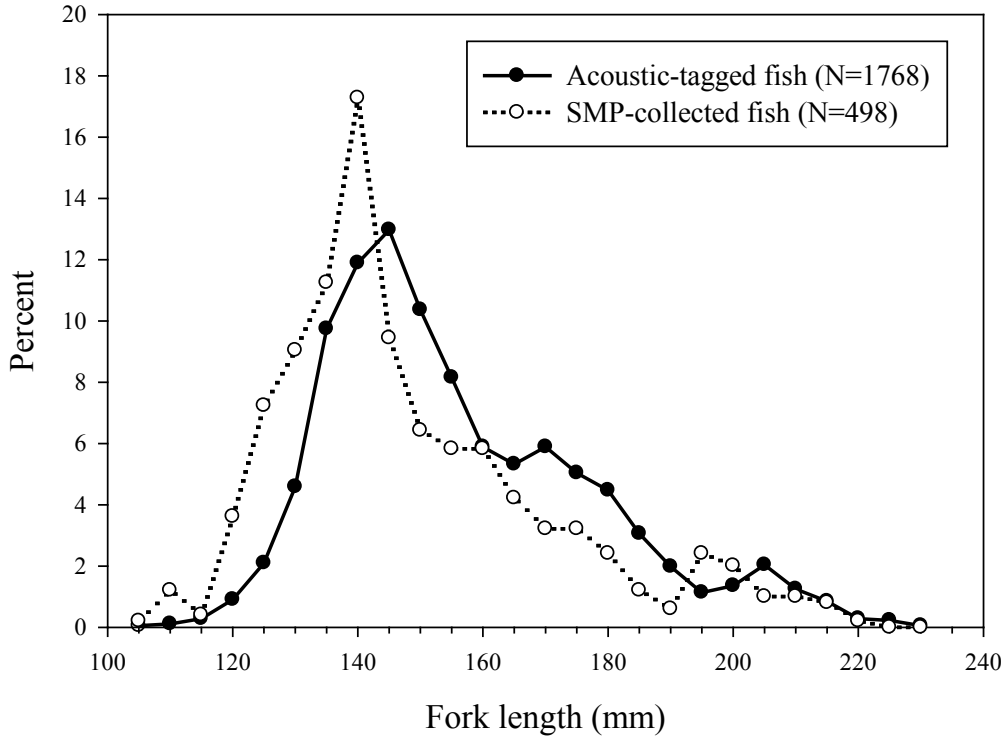

Figure 3.1. Length-frequency distribution of acoustic-tagged subyearling Chinook salmon (black line) compared to subyearling Chinook salmon collected by the Smolt Monitoring Program (SMP; dotted line) at Little Goose Dam, 2007. Data collected by the Smolt Monitoring Program are from Saturdays only. Length data are grouped into 5-mm-length bins. Acoustic-tagged fish were obtained during the final 18% of the subyearling Chinook salmon run according to the SMP sample.

Figure 3.2. JSATS microacoustic transmitter used in subyearling Chinook salmon released downstream of Little Goose Dam in 2007

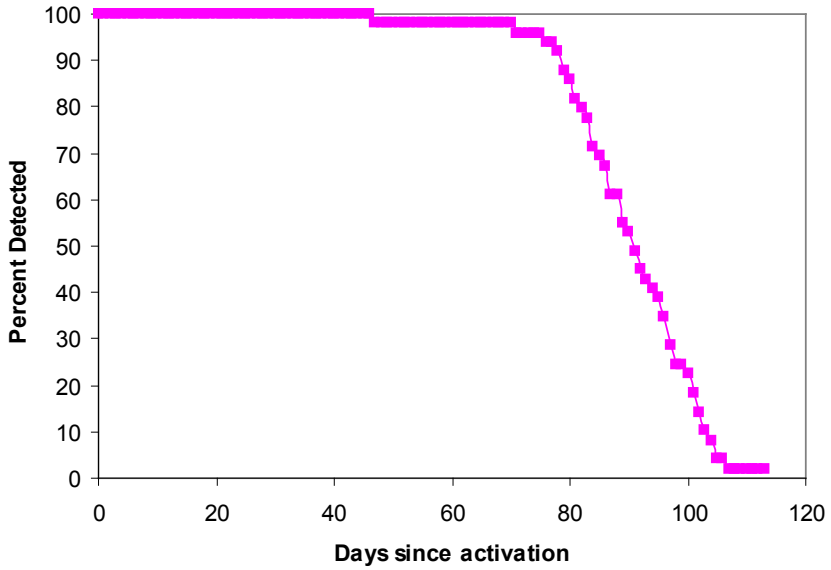

Figure 3.3. Cumulative tag life of 2007 JSATS microacoustic transmitters (10-second tags, N = 50). The percentage of tags detected is plotted versus days since the tags were activated.

After surgery, the juvenile Chinook salmon were held until the following evening in 120-L recovery buckets with flow-through river water to assess tagging mortality and to allow fish to recuperate from surgery before being released into Lower Monumental Reservoir. Sixty fish died (3.2%) post-surgery (overnight) during the study. The majority of the post-surgery mortalities occurred during late July and August (47/60 = 78%) when water temperatures were warmest. Salmon were transferred water-to-water from the recovery buckets to a 600-L release tank on a boat. During transportation to the release site, the fish were maintained with supplemental oxygen and flow-through river water. Salmon were released from the boat in the thalweg 5 km downstream of the Little Goose Dam (river kilometer [Rkm] 630), at the upstream end of Lower Monumental Reservoir. The water source used during post-surgical recovery and transportation to the release location was ambient river water; therefore, acclimation to mitigate for water temperature differences was not required. All releases prior to 4 October occurred at 2000 hours PDT; releases between 4 and 13 October took place at 1900 hours PDT.

3.2 Predator Collection and Tagging

Approximately 100 predators (smallmouth bass *Micropterus dolomieu*, channel catfish *Ictalurus punctatus*, and northern pikeminnow *Ptychocheilus oregonensis*) were collected using hook-and-line on two occasions from 26–27 July and 19–20 September, for a total of 197 predators tagged (Table 3.2). Sampling and tagging occurred in specific areas of the Lower Monumental Reservoir to correspond with the spatial distribution of juvenile fall Chinook salmon that had ceased migration in 2006. Predator tagging methods were similar to salmon tagging methods; however, a few modifications were necessary due to field conditions. All predators were anesthetized in a manner similar to that for Chinook salmon, and total length was measured. Predator fish were placed ventral side up in a surgery bath with anesthetic-free water, and gills were irrigated continuously. Predators received only an acoustic transmitter; PIT tags were not implanted in predator fish. Incisions were closed with two 2-0 silk sutures and an FS needle (26-mm reverse cutting needle with a 3/8 circle). All predators were monitored for at least 1 hr following surgery to ensure that they maintained equilibrium. Predators were then released at their point of capture.

Table 3.2. Descriptive statistics of predator fishes tagged in Lower Monumental Reservoir of the Snake River, 2007

			Length (mm)			
Month	Species	*N*	Mean	SE	Min	Max
July	Smallmouth bass	100	277	4.6	200	425
September	Smallmouth bass	93	257	4.2	205	390
September	Channel catfish	3	511	39.8	442	580
September	Northern pikeminnow	1	340	--	340	340

3.3 Autonomous Receiving System Deployment and Servicing

Acoustic receivers (Model N201, Sonic Concepts Inc., Bothell, WA) were placed at 41 locations in the Snake River from Little Goose Dam to just upstream of the confluence with the Columbia River (Figure 3.4 and Table 3.3). Twenty-one of these locations were part of survival gates; each gate had two to three acoustic receivers spaced equidistant on cross-sectional lines with spatial redundancy to maximize detection probabilities. There were three main survival gates in Lower Monumental Reservoir (Lake Herbert G. West), two gates inside the Lower Monumental Dam boat restricted zone (BRZ), and one in each of the Lower Monumental Dam tailrace, and Ice Harbor Dam forebay and tailrace. The remaining 20 acoustic receivers were placed at 1-km intervals, centered in the middle of the river beginning 1 km downstream of the first survival gate in Lower Monumental Reservoir and ending just upstream of the BRZ in the Lower Monumental forebay (Figure 3.4). Throughout the report we present information in terms of the number of kilometers from the mouth of the Columbia River. To adjust these river kilometers to Snake River kilometers, 521 kilometers must be subtracted.

Each autonomous node consisted of a hydrophone, battery compartment, 15-second beacon, buoy line, acoustic release (Model 111, InterOcean Systems Inc. San Diego, CA), anchor line, and anchor (Figure 3.5). The beacons emit a signal every 15 seconds, which was used as a confirmation that the hydrophone was working properly. Prior to deployment, each acoustic receiver was attached to an acoustic release by a 0.9-m-long bridle made of 12.7-mm-diameter braided nylon rope. Each bridle end was terminated by a braided splice around a professionally braided 9.5-mm SeaDog nylon thimble. Three yellow buoys (Baolong BL-6, 16.5 × 12.4 cm, 1.45-kg buoyancy each) were threaded on the bridle between the acoustic receiver and release (Figure 3.5). Depending on the water depth, each acoustic release was shackled to a 35-kg anchor with either a 1.5- or 3.6-m-long shock-corded mooring made from 12.7-mm braided nylon rope terminated by a 10-cm galvanized steel ring held by the acoustic release mechanism. The configuration of the various components of the autonomous node system as it was deployed in the water column is represented in Figure 3.6.

The majority of the acoustic receivers in Lower Monumental Reservoir were deployed 26 through 27 July 2007, although acoustic receivers immediately upstream (forebay) and downstream (tailrace) of Lower Monumental and Ice Harbor dams had been deployed to support another study and were in place beginning in mid-April, and the acoustic receivers inside the Lower Monumental Dam BRZ were deployed 14 August 2007.

Receivers were recovered and serviced approximately every two weeks through the study period. To recover each node, the boat was situated close to the waypoint of the node, displayed on a laptop using

Fugawi Marine ENC map software (Northport Systems Inc, Toronto, ON). A command unit and transducer (Model 1100E, InterOcean Systems Inc. San Diego, CA) were used to activate the acoustic release. Upon receiving the signal from the command unit, the acoustic release opened and released the ring on the anchor line (Figure 3.6), which allowed the node and release to float to the surface. During servicing, CompactFlash (CF) cards (SanDisk Extreme III 1.0 GB) containing data were replaced. The node batteries were replaced approximately every 28 days on alternating servicing trips. In addition, prior to redeployment, receiver function was tested. The acoustic release was re-armed using two hand-held magnets to activate the motor to close the link to a new anchor line attached to a new anchor. We used Global Positioning System (GPS) receivers and Fugawi to position the boat as close to the previous deployment point as possible, then lower the reactivated node to the bottom using a rope fed through the anchor handle to control its descent and create a new waypoint.

All receivers were recovered by 12 December 2007. Appendix A provides details regarding the time and location at which data were not available due to battery failure or equipment damage. On average, the receivers used for this study recorded data for 94% of the time they were deployed. Based on individual receivers, the period during which they worked effectively ranged from 78.6 to 100% of the time they were deployed.

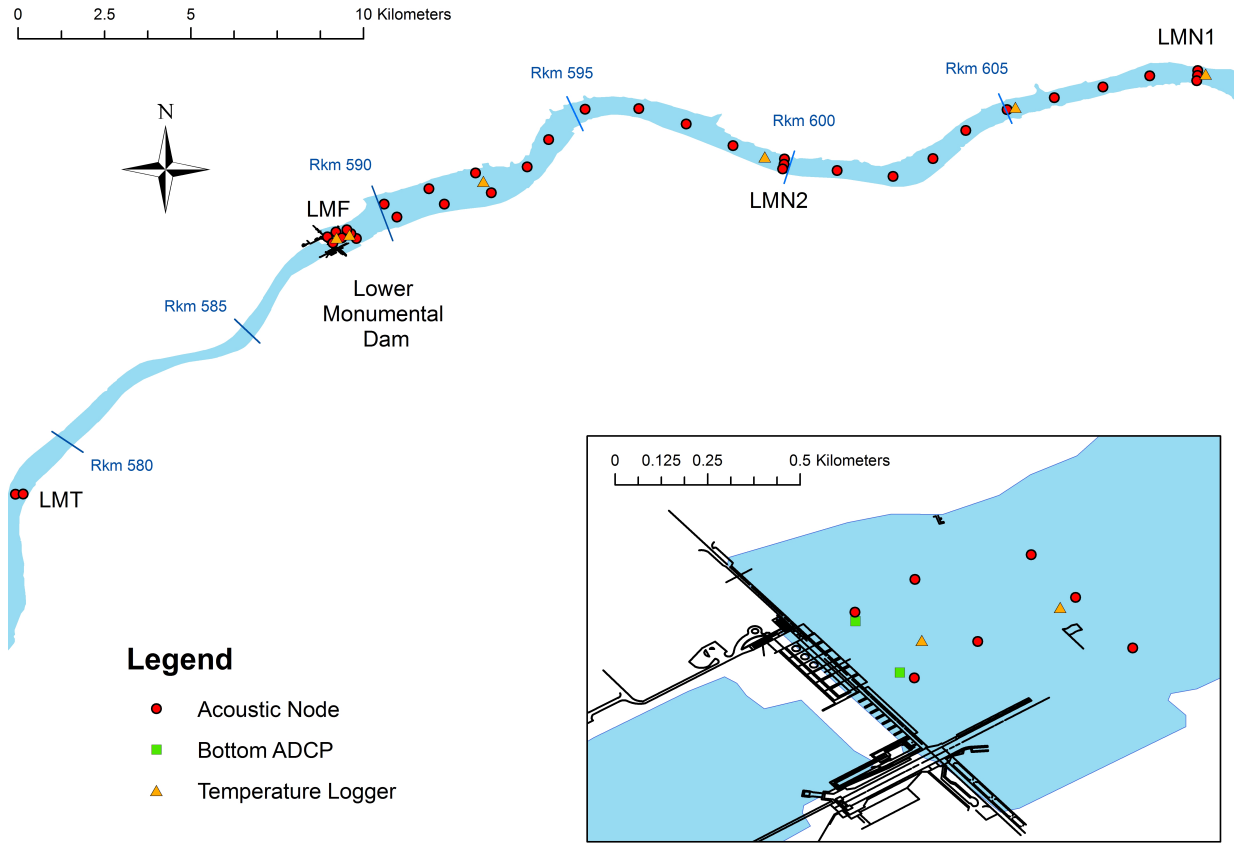

Figure 3.4. Autonomous acoustic receiver deployment locations on the lower Snake River between Little Goose Dam and the Columbia River confluence during spring and summer 2007

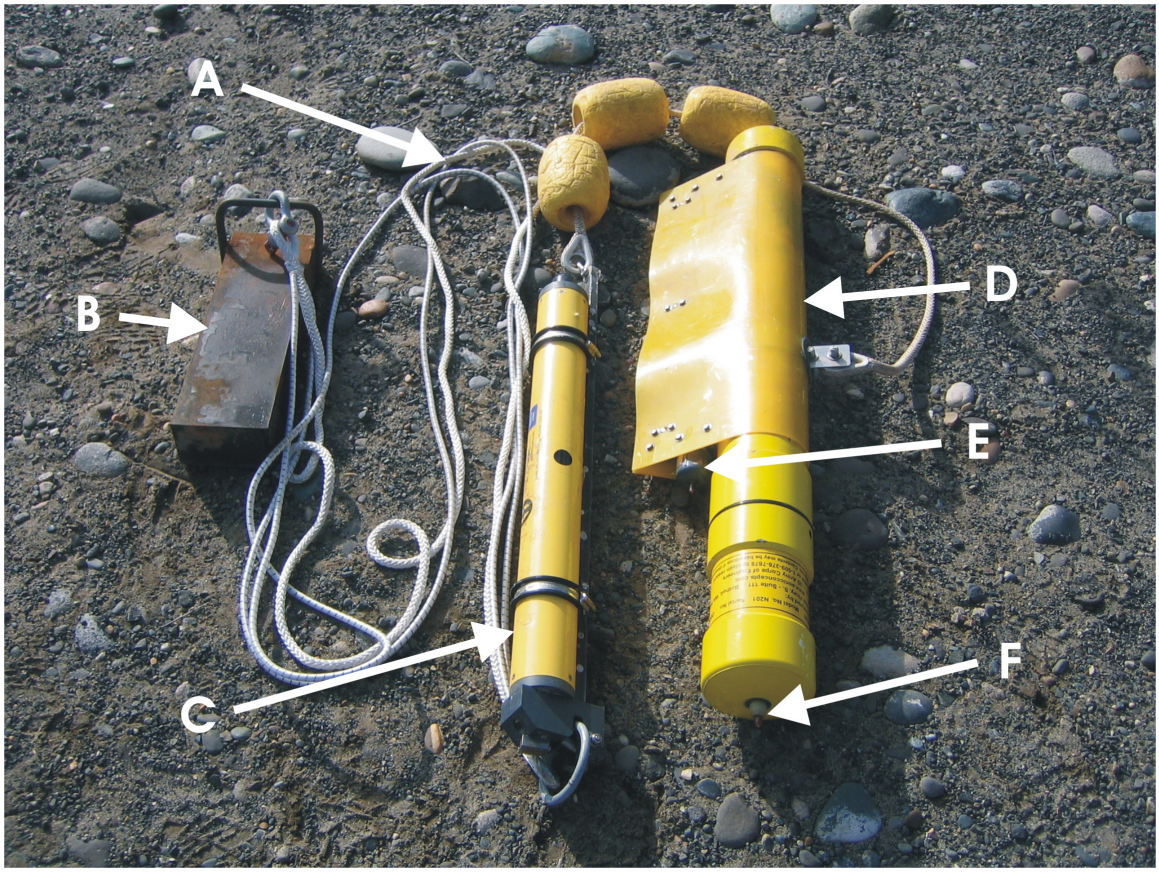

Figure 3.5. Autonomous acoustic telemetry receiver and associated rigging. A = anchor line; B = 35-kg steel anchor; C = acoustic release (InterOceans, Inc., Model 111); D = battery compartment; E = 15-second beacon; F = hydrophone.

Table 3.3. Name, location, and deployment and recovery dates of acoustic telemetry arrays in Snake River used to detect acoustic-tagged juvenile Chinook salmon released in 2007

Array Code	Snake Rkm	Rkm from Pacific Ocean	Physical Description	Project
LMN1	86	608	LMN array 1, ~mid reservoir	LoMo
LM01-LM20	68-86	590-608	Inter-array nodes in the LMN reservoir	LoMo
LMN2	78	600	LMN array 2, near Skookum Canyon	LoMo
LMF1	68	589	LMN forebay, (~0.5 km from dam)	LoMo
LMF2	67	589	LMN forebay, (~300 m from dam)	LoMo
LMF3	67	589	LMN forebay, (~100 m from dam)	LoMo
LMT1	57	579	LMN tailrace, ds of Windust	LoMo
IHF1	16	538	IHR forebay BRZ (~0.5 km from dam)	Tag Effects
IHT1	4	525	IHR tailrace primary, at Hwy 12 Br	Tag Effects

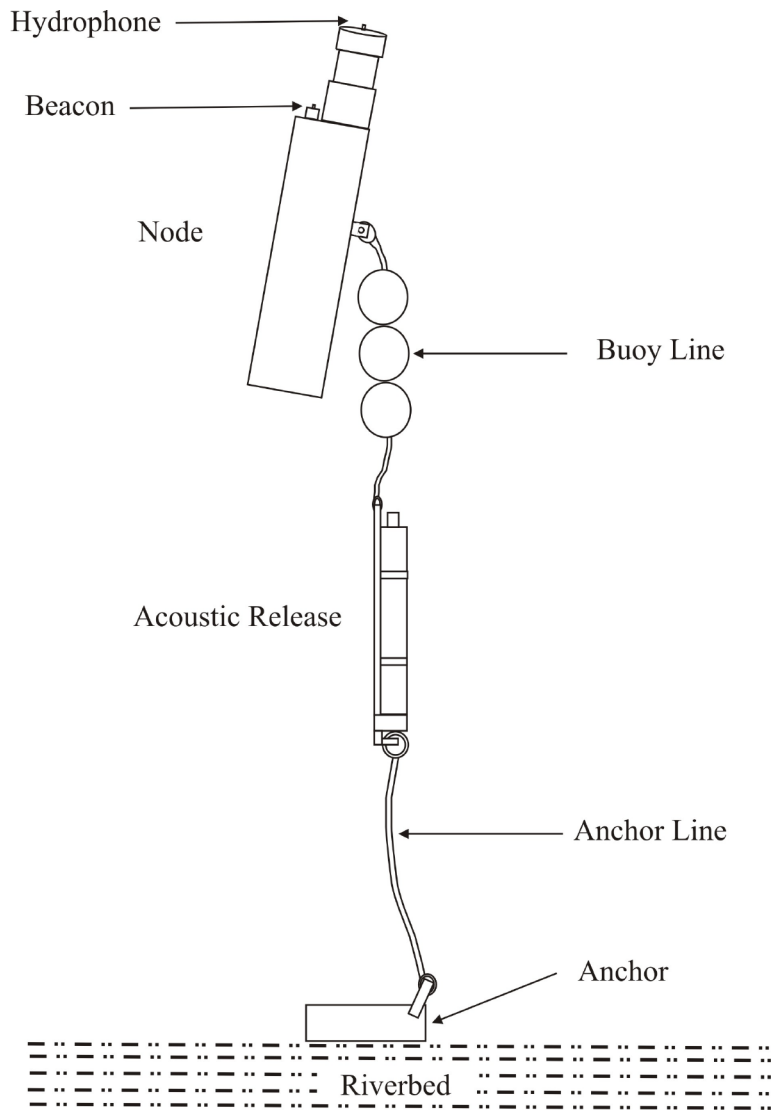

Figure 3.6. Orientation of autonomous acoustic receiver and rigging as deployed in river

3.4 Autonomous Acoustic Receiver Data Processing Methods

Data collected by the autonomous acoustic receivers were recorded as text files on CF cards. These text files were transferred to a laptop computer when the acoustic receivers were serviced during the season or when recovered at the end of the season. Physical data were written to file every 15 seconds. Physical data recorded included date, time, pressure, water temperature, tilt, and battery voltage. Detections of transmitters were recorded in real time as they were received. They were written to media with TagID (individual code of transmitter), time stamp, receive signal strength indicator, and RxThreshold (a calculated measure of noise). Data files from all acoustic receivers were coded with the acoustic receiver location and stored in a database developed specifically for storing and processing acoustic telemetry data (TagViz). To filter out false positives (detections of TagIDs that did not meet criteria to be considered a valid detection), a post-processing program was implemented. This program comprised a sequence of steps that included comparing each detection to a list of tags that were released (only tags that were released were kept), then comparing the detection date to the release date (only tags

detected after they were released were kept). A minimum of four detections in 120 seconds was required, and the time spacing between these detections had to match the ping rate interval (PRI) of the tag or be a multiple of the PRI for the detections to be kept in the valid detection file.

3.5 Hydraulic Characterization

All river kilometers in the hydraulics sections are referenced to the mouth of the Columbia River to be consistent with other regional databases (e.g., PTAGIS).

3.5.1 Water Temperature Measurements

Continuous water temperature measurements were made for this study using strings of autonomous temperature loggers. Three kinds were used. Most of the temperature loggers were Onset Computer Corporation HOBO Water Temp Pro v2 loggers. These loggers have a stated accuracy of ±0.2°C within the temperature range of −20° to 70°C. The other loggers used measured pressure in addition to temperature. The Onset Computer Corporation HOBO U20 Water Level Logger had accuracy similar to the Temp Pro v2 loggers when measuring temperature. High-accuracy SeaBird SBE39 temperature and pressure loggers also were used in the study. SBE39 temperature loggers were calibrated by the manufacturer to be accurate within ±0.002°C between −5°C to 35°C. The pressure sensors on both of these were accurate to within 0.1 m. The accuracy of all loggers was confirmed to be within the manufacturer's specification using a constant temperature water bath both before and after deployment.

At each of five sites, loggers were suspended vertically in the water column as depicted in Figure 3.7. Loggers were spaced variably from 1.5 m near the surface to 5.0 m near the bottom. The scheme shown in Figure 3.7 was used at all sites except the Lower Monumental Dam forebay, where a single-weight string was used. The two-weight system was required to avoid shipping barge traffic, which has a draft of 4.3 m (14 ft). The thalweg weight, with a subsurface buoy attached, was deployed at the deepest point in the cross section. Pressure-sensing loggers were mounted near the weight and the subsurface buoy. The pressure-sensor logger on the subsurface buoy monitored vertical movement of the buoy throughout the deployment, which can occur if drag forces on the buoy or logger line are large enough to counteract the positively buoyant force of the buoy. Negligible vertical movement occurred throughout the study, and at no time were subsurface buoys submerged by drag forces by more than 1 m. A connecting line was attached from the thalweg weight to a second weight positioned out of the navigation channel. This weight was attached also to a line that went up to a surface buoy. In previous work (Cook et al. 2007), multiple transects measured by conductivity-temperature-depth (CTD) probes across each open-water site confirmed that lateral temperature differences between the subsurface and surface buoy were negligible. To simplify reporting, data collected by the surface temperature loggers are reported at the horizontal location of the subsurface buoy.

Figure 3.8 shows the locations of the measurement sites relative to the acoustic receiver locations. In addition to the temperature-logger strings deployed for this study, data were obtained also from a continuously operated logger string located just outside the Lower Monumental Dam forebay BRZ (USACE-WMD 2008a). Table 3.4 lists the site locations, river kilometers, start and end dates, and the total number of loggers.

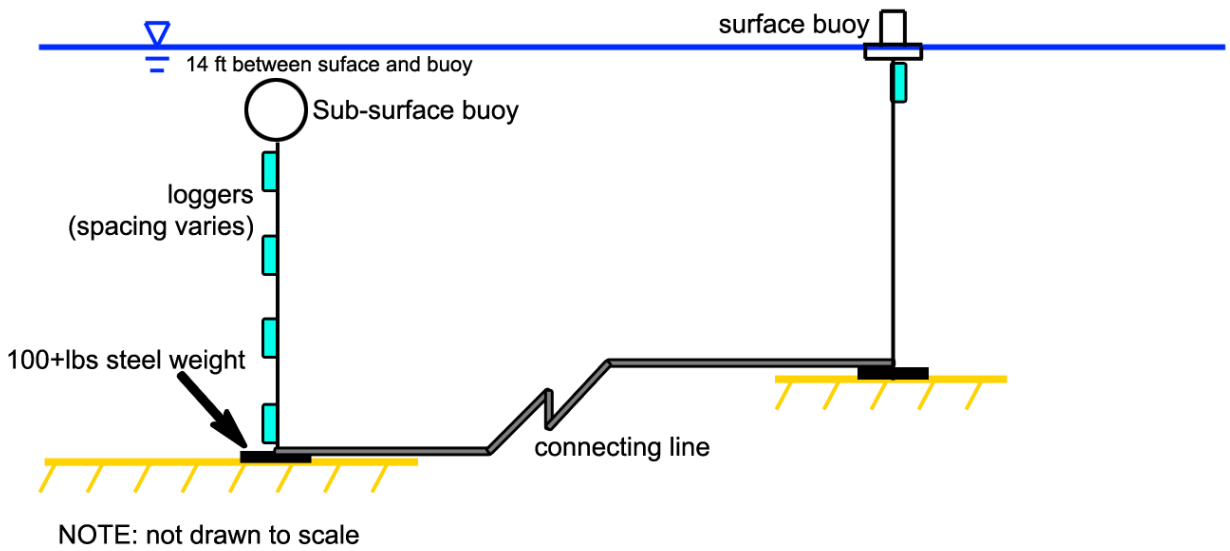

Figure 3.7. Open-water temperature logger deployment used in Lower Monumental Reservoir

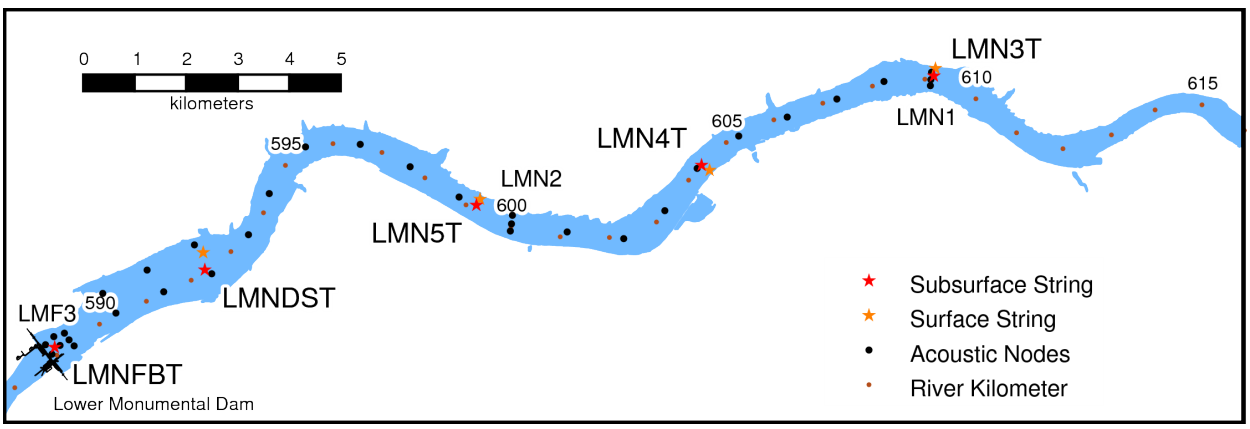

Figure 3.8. Temperature-logger string deployment locations relative to acoustic receiver locations in Lower Monumental Reservoir

Table 3.4. Temperature logger string deployment locations and dates in Lower Monumental Reservoir in 2007. River Kilometer is kilometers to the mouth of the Columbia River.

Site Name	River Kilometer	Start Date	End Date	Number of Loggers
LMN3T	609.4	25 Jul	14 Dec	15
LMN4T	604.6	25 Jul	14 Dec	15
LMN5T	599.4	25 Jul	14 Dec	16
LMNDST	592.5	26 Jul	14 Dec	17
LMNFBT (Bay 8)	589.3	13 Aug	03 Oct	13
LMNFBT (Unit 2)	589.3	03 Oct	11 Dec	13
LMNCorps	589.7	year-round		

Individual loggers measured temperature at 10-minute intervals and were averaged hourly. Hourly statistics were computed from the vertical profile at each temperature string: the minimum, maximum, and depth-averaged temperature over the profile. Depth-weighted average temperature was computed by assigning each logger a portion of the water column.

Depth-weighted average temperature was computed using

$$\overline{T} = \frac{\sum_i T_i d_i}{\sum_i d_i}$$

where T_i is the temperature from logger i and d_i is the portion of the water column assigned to logger i, which extended half way from the logger above (or water surface) to half way to the logger below (or bottom).

The vertical temperature profile data were analyzed to quantify and/or classify the strength of a thermal layer, if present. For this work, it was assumed that the thermal layer was that portion of the water column in which the temperature was above the depth-weighted average temperature of the entire profile. The thermal layer depth was the depth at which the water column temperature was equal to the depth-weighted average. The temperature in the thermal layer ranged from the profile depth-weighted average to the maximum. This range was termed the *thermal layer temperature delta*. These values were computed at hourly intervals for each logger string. These hourly thermal layer statistics were used to assign a class value as follows:

- If the temperature range over the entire profile was less than 1°C, that hour was automatically assigned a layer class of 0 (and its layer depth was plotted as 0 m).
- A layer class of 0 was assigned also if the thermal layer temperature delta was less than 1°C(a layer depth was still computed and plotted).
- A layer class of 1 was assigned if the thermal layer temperature delta was more than 1°C, regardless of the layer depth.
- A layer class of 2 was assigned *only* if the thermal layer temperature delta was more than 2°C *and* the layer depth was greater than 5 m.

3.5.2 Water Velocity Measurements

Vertical profiles of three-dimensional water velocity vectors (i.e., both magnitude and direction) were collected using both bottom-mounted (i.e., fixed position) and boat-mounted mobile ADCPs. Before the ADCPs were used, internal system diagnostic tests were performed to confirm the unit was functioning properly. The tests included checks of the central processing unit (CPU), internal memory, and the receiving and transmitting boards and sensors. Additionally, the flux-gate compass was calibrated for any local magnetic fields, including any influence from the internal battery pack when the ADCP was bottom-mounted. All ADCP data were corrected to true north by applying a local magnetic declination factor to the compass output. The magnetic variation used for this study was 16.3°E (NGDC 2008).

3.5.2.1 Bottom-Mounted Acoustic Doppler Current Profilers

Two bottom-mounted 600-kHz RD Instruments Workhorse ADCPs were deployed at three sites (Table 3.5) in the reservoir, one just upstream of the LMNDST temperature string (Figure 3.9) and the other in the Lower Monumental Dam forebay approximately 100 m and 250 m from the dam (Figure 3.10). Initially, the two forebay ADCPs were placed directly along a line upstream of spillbay 8. Due to the installation of the RSW, it was necessary to move the ADCPs over in front of turbine unit 2.

Table 3.5. Bottom-moored acoustic Doppler current profiler deployment locations. River Kilometer is kilometers to the mouth of the Columbia River.

Site Name	Start Date	End Date	River Kilometer	Downstream Azimuth (degrees)
LMNDS	26 Jul	13 Aug	594.6	198
LMNFB1 (Bay 8)	13 Aug	03 Oct	589.3	232
LMNFB1 (Unit 2)	03 Oct	11 Dec	589.3	232
LMNFB2 (Bay 8)	13 Aug	03 Oct	589.5	232
LMNFB2 (Unit 2)	03 Oct	11 Dec	589.5	232

The ADCPs were attached to a noncorrosive fiberglass mount via dual-axis gimbals that could compensate for small bathymetric irregularities (Figure 3.11). The ADCP bottom-mount was deployed in a manner similar to that for the temperature logger string deployment. The mount was retrieved via a surface buoy connected to a weight placed a short distance away and outside the beam swath of the ADCP.

In general, the bottom-mounted ADCPs collected an ensemble-averaged profile of three-dimensional water velocity every 2 minutes with a 0.5-m vertical resolution. Each velocity ensemble consisted of 40 pings with a resulting Doppler uncertainty of 1.26 cm/second. LMNFB1 ADCP, during the period 2–31 October was inadvertently programmed to collect water velocity every 20 minutes with a 2.0-m vertical resolution, averaging 50 pings. Also, LMNFB1, for unknown reasons, failed to collect usable data from 11 September through 2 October.

The resulting velocity profile data were edited to remove the spurious data near the water surface and above. Because of beam reflections off the water surface, at least 6% of the water column near the surface was ignored (RDI 1996). Slightly more of the upper water column was ignored at the LMNFB2 site because spurious data seemed to extend deeper into the water column, possibly due to wind-generated disturbance on the surface.

At each ADCP deployment location, the direction of downstream flow was estimated from the general orientation of the river direction. This river flow orientation was used to compute the horizontal downstream and cross-stream velocity magnitude. These velocity magnitudes were depth-averaged over time.

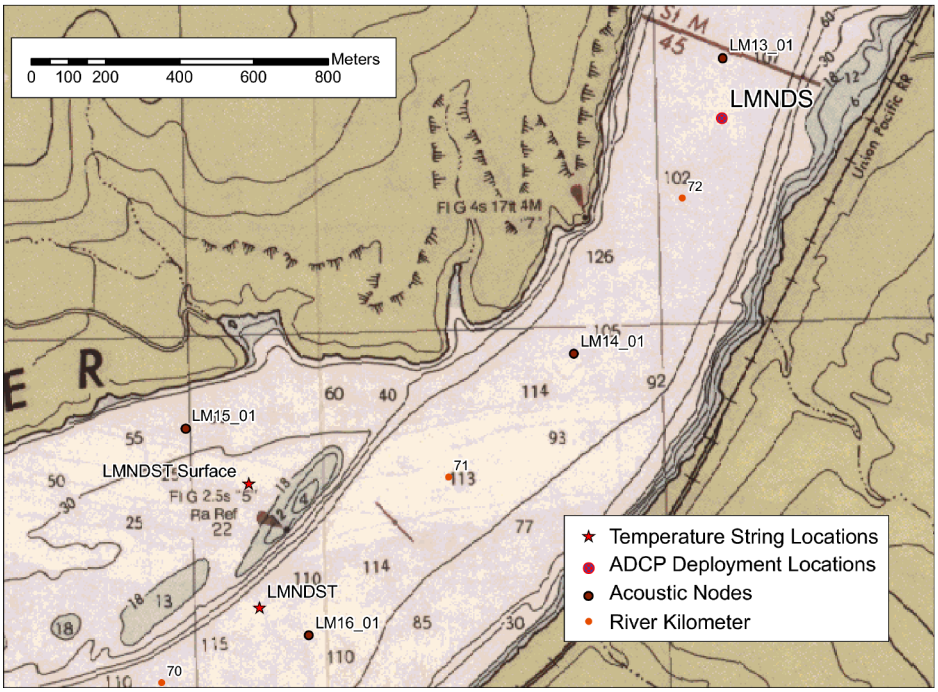

Figure 3.9. Initial bottom-mounted acoustic Doppler current profiler deployment location

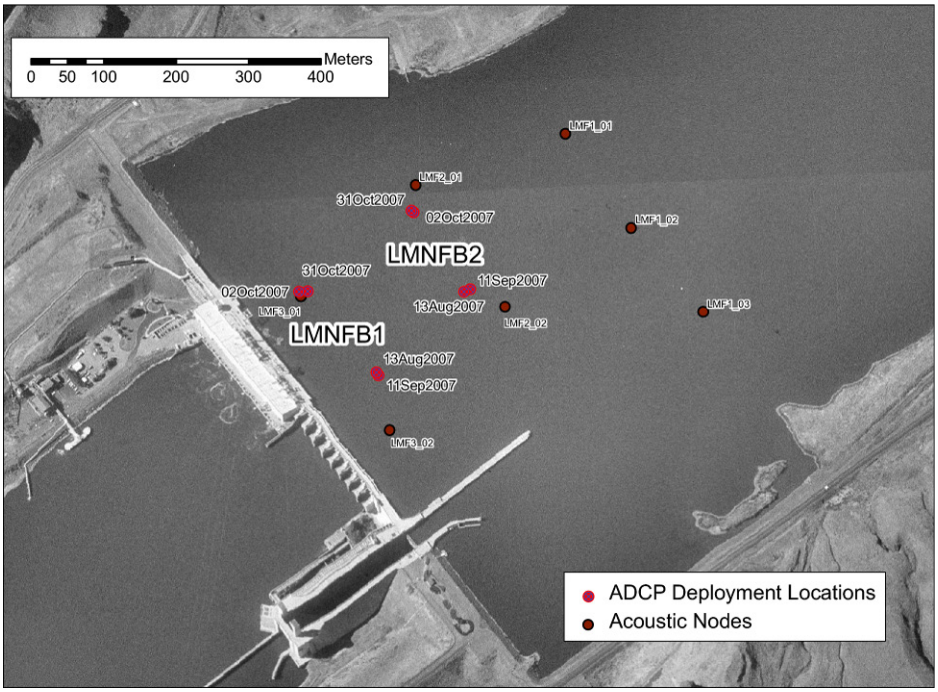

Figure 3.10. Bottom-mounted acoustic Doppler current profiler deployment locations in the Lower Monumental Dam forebay

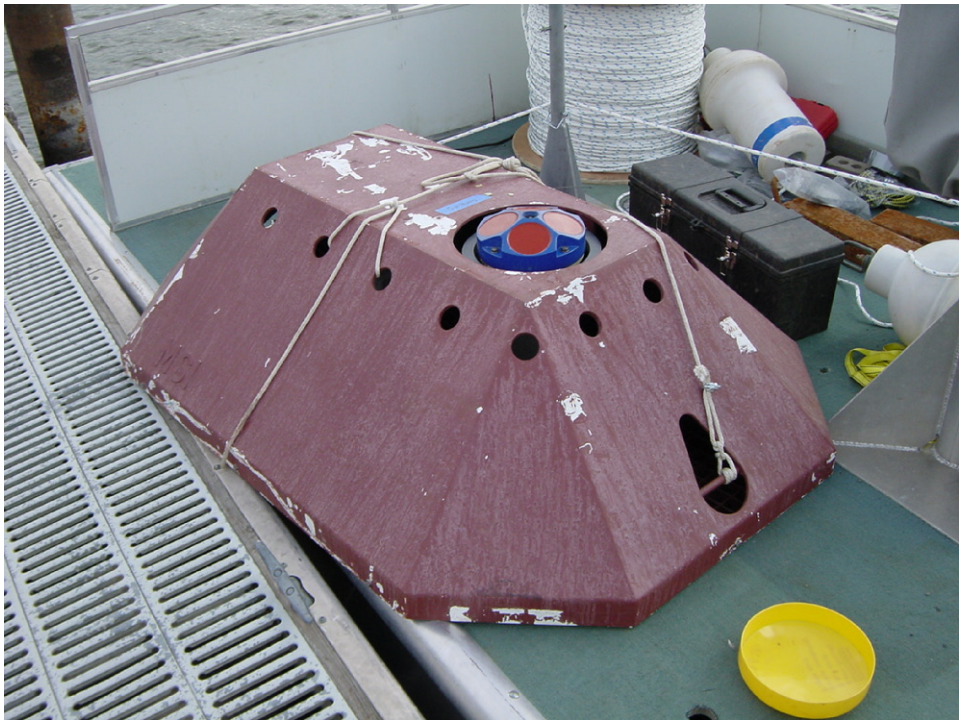

Figure 3.11. Acoustic Doppler current profiler installed in a bottom mount (from Cook et al. 2007)

3.5.2.2 Mobile Surveys

A 1200-kHz RD Instruments Workhorse ADCP was used to collect all mobile ADCP measurements. The ADCP was programmed to collect information at depth increments of 1 m throughout the water column. Each velocity measurement collected by the ADCP was composed of several individual acoustic pings, which were combined to form an ensemble average. Averaging the pings together over time can decrease the ensemble error standard deviation due to random Doppler error. Twenty-two pings collected over 5 seconds were used to produce an ensemble velocity measurement with an associated Doppler uncertainty of 1.5 cm/second.

Between 31 July and 31 October, data from 80 ADCP transects were collected. Initially, surveys were to be performed every two weeks in July through September, then once per month for the remainder of the field study. However, the ADCP used for mobile surveys failed, and repairs took considerable time. Consequently, only five mobile surveys were performed during the study. Figure 3.12 shows the location of all transects from which data were collected during the study.

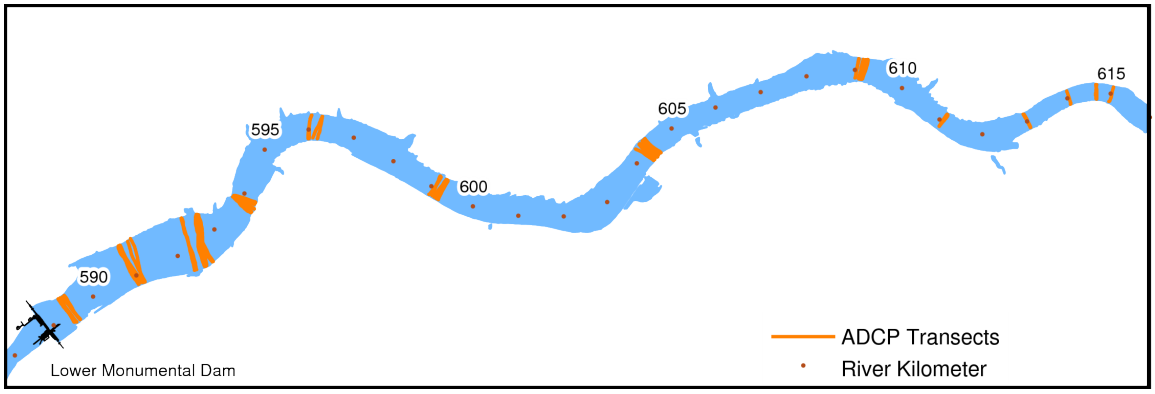

Figure 3.12. Mobile acoustic Doppler current profiler measurements in Lower Monumental Reservoir

The ADCP transect data were analyzed primarily to identify and summarize river flow circulation patterns similar to those observed in previous work (Cook et al. 2007), including upstream-oriented flow. A downstream direction was determined for each transect based on the general course of the river at its location. The horizontal velocity component in the downstream direction was computed for each measured point. Figure 3.13 shows an example. To summarize flow direction, the transect downstream velocity component was averaged laterally across the channel and vertically over the channel depth.

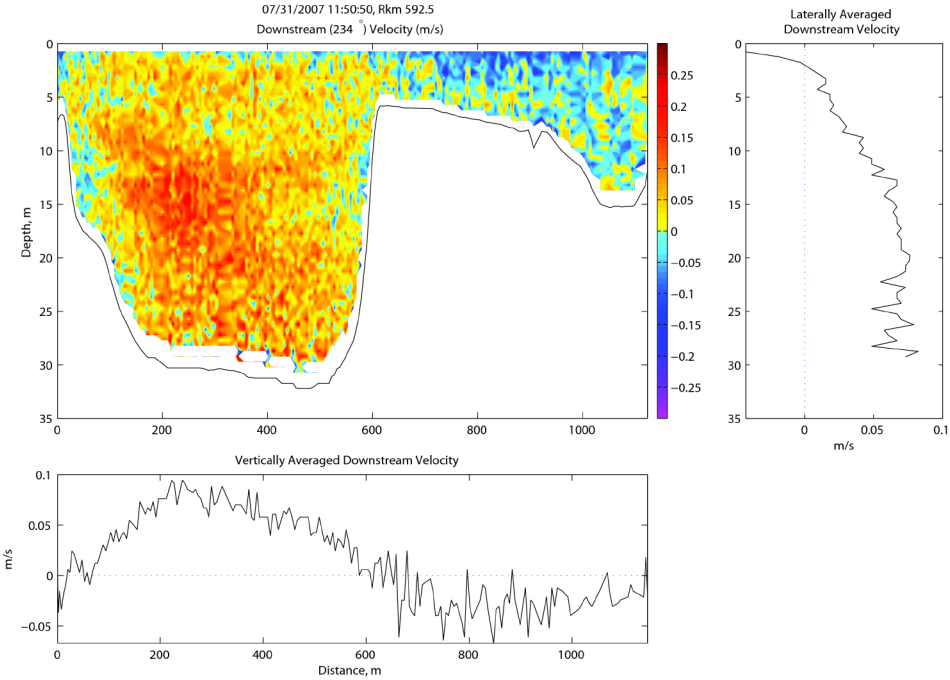

Figure 3.13. Sample mobile acoustic Doppler current profiler transect showing the velocity magnitude in the downstream direction. Downstream (positive) flow is colored yellow and red; upstream (negative) flow is colored blue and violet. The downstream velocity was averaged laterally and vertically.

3.5.3 Conductivity-Temperature-Depth Casts

During this study, periodic measurements were made with a portable conductivity-temperature-depth (CTD) probe. The Hydrolab-Hach MiniSonde MS5 CTD probe had a temperature accuracy of ±0.10°C within the range of −5°C to 50°C. The pressure sensor on the probe had a maximum depth range of 100 m water depth and was accurate to ±0.3 m. The specific conductance sensor was accurate to within ±1% of reading ±0.001 mS/cm. Calibration of the specific conductance sensor was checked and/or calibrated each day we were in the field. Cast locations are shown in Figure 3.14.

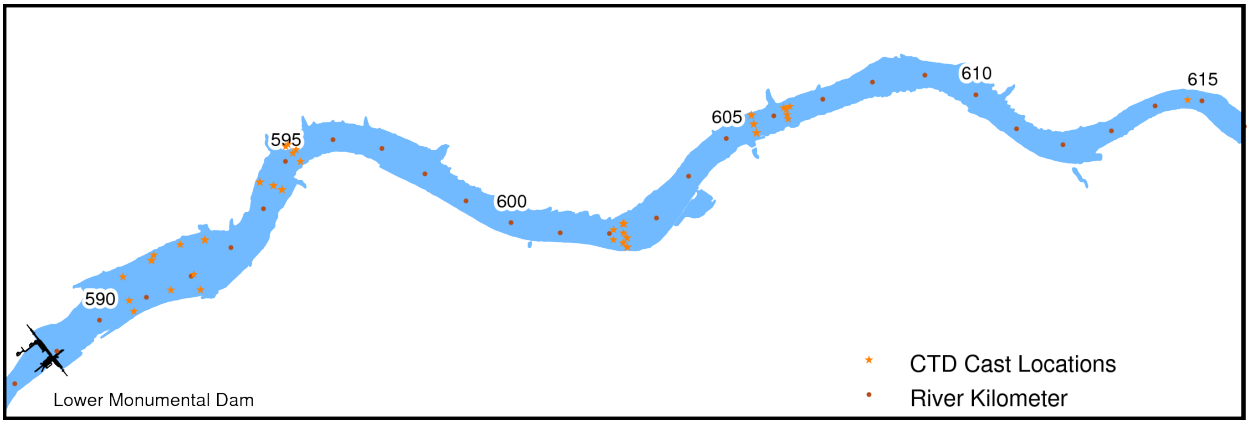

Figure 3.14. Locations of conductivity-temperature-depth casts during the study period

3.5.4 Dam Operations

Dam operations data for the study period were obtained in two forms. First, hourly forebay stage, total discharge, and spillway discharge were extracted from the USACE Water Management Division water quality reports (USACE-WMD 2008b). Second, 5-minute bay-by-bay and unit-by-unit operations data were obtained directly from the USACE, Walla Walla District (Tim Wik, USACE, personal communication).

3.6 Numerical Modeling of Reservoir

Discharge and water velocity vary dramatically within the Lower Monumental Reservoir, both temporally and spatially. This variation is a complex function of dam operations at either end of the reservoir. Often, the reported discharge at either the Little Goose or Lower Monumental dam is not representative of the discharge, and the corresponding velocity, within Lower Monumental Reservoir.

To provide better, more localized estimates of time-varying discharge and velocity, the Modular Aquatic Simulation System–1D (MASS1) model was applied to the study area. MASS1 is described in detail by Richmond et al. (2000) and Perkins et al. (2002), and so, for brevity, is not described here. MASS1 is a one-dimensional, cross-section–averaged hydrodynamic model. It uses the physics of fluid flow, simplified to one dimension, to compute an average value across the river for discharge, velocity, and stage over time. MASS1 has been applied successfully to a variety of problems over the last 10 years (Richmond et al. 2000; Perkins and Richmond 2001; Perkins et al. 2002; Rakowski et al. 2003; McMichael et al. 2003; Waichler et al. 2005).

An existing configuration of MASS1, from Rakowski et al. (2003), was used for this work. This configuration included the Snake River downstream from the U.S. Geological Survey Anatone gage (13334300) and the Columbia River downstream from Priest Rapids dam. A schematic of the simulated river network is shown in Figure 3.15. In general, the spatial resolution everywhere was 0.8 km (0.5 mile) 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-minute computational step was used, and results were saved at 1-hour intervals.

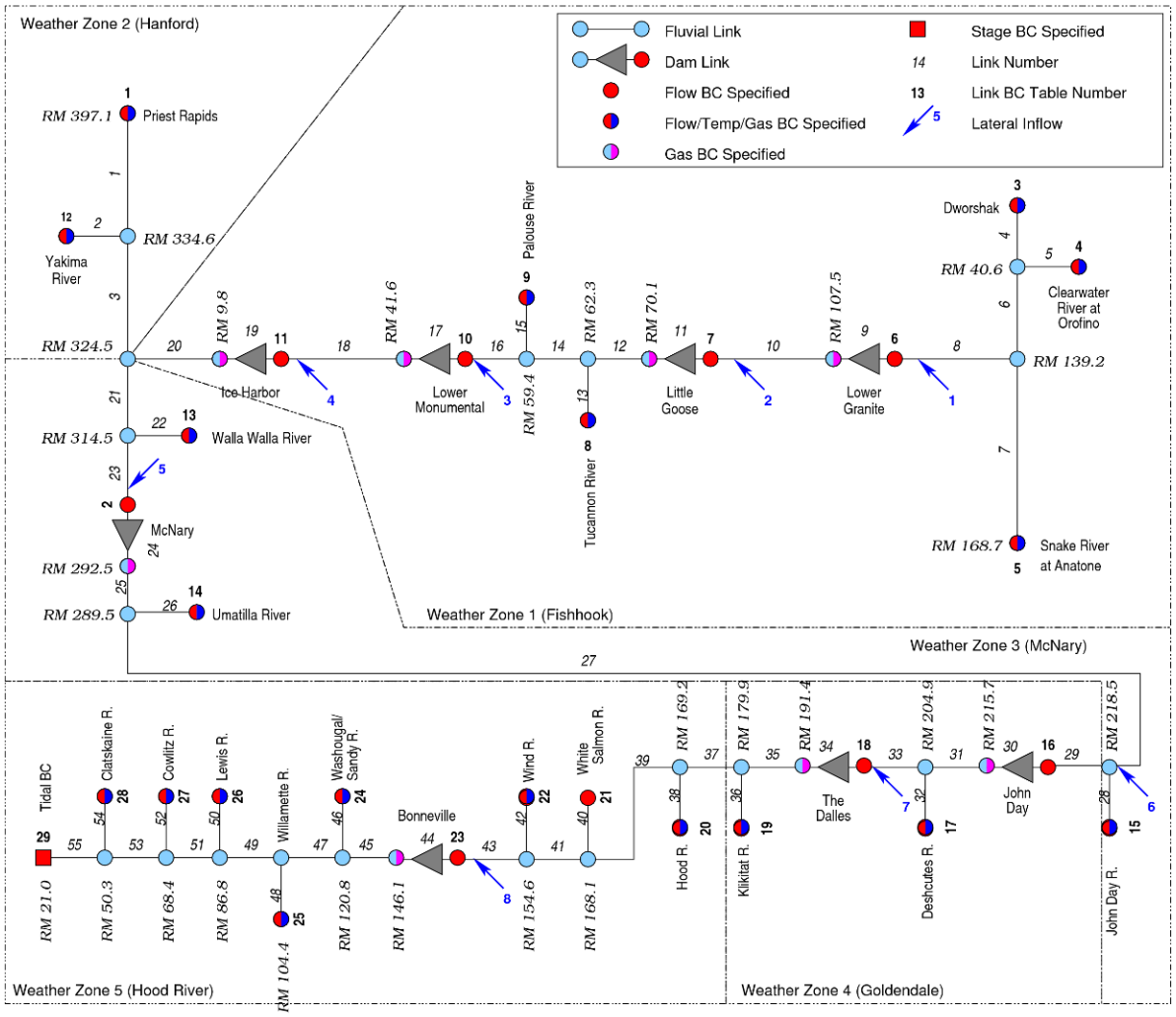

Figure 3.15. MASS1 configuration used to estimate discharge and velocity within the study area (from Rakowski et al. 2003). While the model was configured to simulate the Columbia River, only the results from the Snake River were used in this study.

A minor update was made to this configuration for this work. In previous use (e.g., Richmond et al. 2000; Rakowski et al. 2003), Snake River dams were represented using a stage boundary condition and artificial lateral inflows were computed to ensure accurate discharge. The configuration for this work was the proportional, integral, derivative (PID) feedback boundary condition described by Perkins et al. (2002) to represent dam operations.

MASS1 was used to predict time-varying discharge and cross-section average velocity at important points within the study area: temperature and velocity measurement sites, all acoustic receiver locations, and fish release sites. When necessary, discharge and velocity were interpolated linearly between MASS1 computational points to the nearest 0.16 km (0.10 mi).

3.6.1 Water Particle Travel Time

Water particle travel times were used to integrate estimated local velocity (Section 3.6) over space and time. This information answers questions such as "How long did it take a particle of water to travel to the LMN2 acoustic receivers after it passed the LMN1 acoustic receivers at 8:30 pm on 30 July?" The river velocity in the study area varies considerably in time due to variation in discharge, and in space due to the variation of cross-sectional area. Particle travel times provide an aggregate velocity from one point to another while accounting for the temporal and spatial variation of river velocity.

Particle travel times were computed for four reaches:

- from the fish release location (Rkm 631.5) to the LMN1 acoustic receiver gate (Rkm 609.3)
- from LMN1 to the LMN2 gate (Rkm 600.2)
- from LMN2 to the LMF3 gate in the Lower Monumental Dam forebay (Rkm 589.2)
- from LMF3 to the LMT gate downstream of Lower Monumental Dam (Rkm 578.9).

For each reach, a particle was released at the upstream location every hour from 1 July through 15 December 2007. Its progress downstream was computed at 5-minute intervals using a velocity linearly interpolated in both space and time from the MASS1 simulation results. The particle position was saved at 15-minute intervals.

It addition, one particle was released at the place and time of each fish release. Travel times to each acoustic receiver gate (LMN1, LMN2, LMF3, and LMT) were computed for each particle.

3.7 Statistical Methods

Statistical analysis of the tagging data was divided into two categories: fate determination and effects analysis. Fate determination focused on estimation of the probabilities of migration, delay (i.e., residualization), and mortality within the study area, either at the end of the study (i.e., after 8 weeks of detection) or biweekly throughout the study. The study area ranged from the LMN1 array in the Lower Monumental Reservoir downstream to the dam tailrace and was subdivided into smaller reaches (Figure 3.16). Fate probabilities were estimated on both the reach scale and the larger "reservoir" scale using acoustic-tag detection data. Estimates of fate probabilities on the biweekly reach scale and estimates of travel time through each reach were related to covariates describing environmental and fish conditions using effects analyses. Methods for the fate determination are described first, followed by methods for the effects analyses.

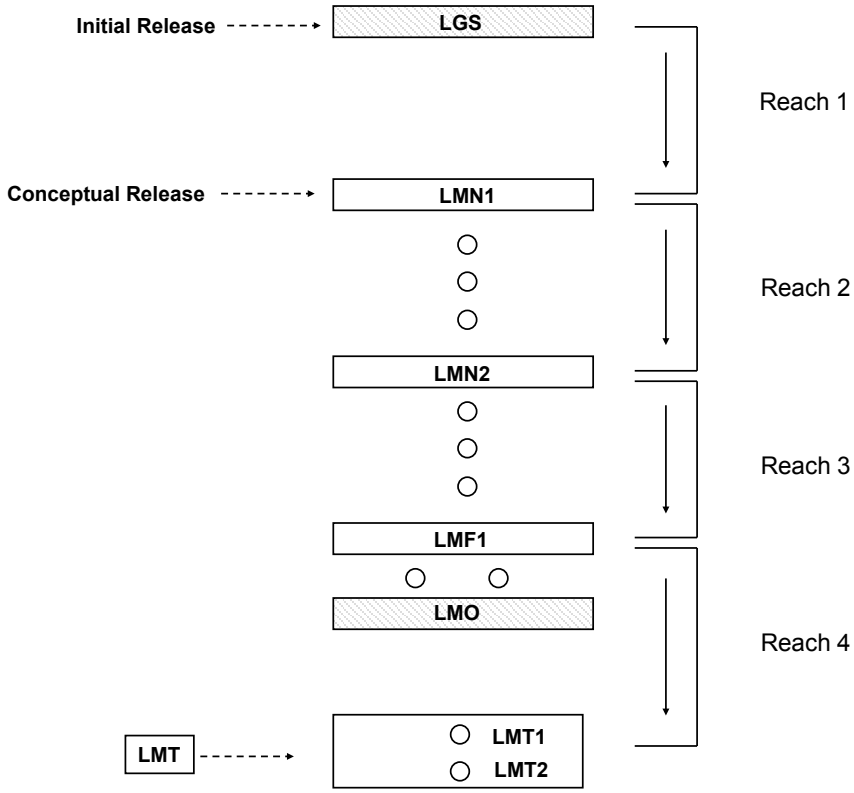

Figure 3.16. Initial release location at Little Goose (LGS), conceptual release location (LMN1), acoustic line arrays (LMN1, LMN2, LMF1), intrareach nodes (sets of circles in reaches 2, 3, and 4), tailrace nodes (LMT), and reaches for the far-field analysis. Lower Monumental Dam (LMO) is not used as a detection site for the far-field analysis.

3.7.1 Sampling and Detection Design

Acoustic-tagged Chinook salmon smolts were detected at fixed hydrophone arrays, each consisting of three nodes positioned across the river perpendicular to the river banks (Figure 3.4). Three arrays were located in the Lower Monumental Reservoir (LMN1, LMN2, and LMF1). In addition to these three arrays, single nodes were placed at approximately 1-km intervals between the line arrays from LMN1 to LMF1 (Figure 3.16). These single nodes are referred to as *intrareach nodes*. The LMF1 array at the BRZ for LMO denoted the upstream boundary of the LMO forebay. In addition to the LMF1 array, four single nodes were placed in the Lower Monumental Dam forebay. Collectively, these four single nodes and the three nodes comprising the LMF1 line made up the forebay nodes, labeled "LMF." Two additional nodes were placed in the Lower Monumental Dam tailrace. These two nodes are collectively referred to as "LMT." Each node collected acoustic detection data continually, except when being serviced and when data were downloaded.

A *reach* was defined as the stretch of river between two adjacent acoustic arrays or between LMF1 and the tailrace nodes at LMT (Figure 3.16). Thus, there were four reaches: Reach 1 = Little Goose Dam (LGS) to LMN1, Reach 2 = LMN1 to LMN2, Reach 3 = LMN2 to LMF1, and Reach 4 = LMF1 to LMT. The estimation of delay and mortality probabilities was dependent on the presence of intrareach nodes

within a river reach. Thus, it was not possible to include the first reach (LGS – LMN1) in the study area for this portion of the analysis. Instead, the study area was restricted to reaches 2, 3, and 4. Acoustic-tagged fish used in the analysis were those known to have arrived at the first array (LMN1).

Conceptual release groups at LMN1 were assigned based on arrival date at LMN1 (Table 3.6). In the early part of the study when many subyearling Chinook salmon were being tagged and released at LGS, weekly release groups were assigned, with approximately 100 to 200 fish in each release group. In the latter part of the study when fewer subyearling Chinook salmon were being tagged and released at LGS, it was necessary to extend the temporal definition of the release groups in order to increase sample size. In particular, release group 6 consisted of all tagged subyearling Chinook salmon that first arrived at LMN1 in the 2-week period from 5 September through 19 September 2007, and release group 7 consisted of all tagged subyearling Chinook salmon that first arrived at LMN1 in the 5-week period from 19 September through 24 October 2007 (Table 3.6). An eighth release group consisted of the tagged subyearlings that first arrived at LMN1 from 24 October through 28 November 2007; this group had only 8 fish and was not included in fate determination analysis. Detection data from release groups 1–7 were used from the beginning of the period defining the release group through a period of 8 weeks. For the biweekly analysis, the overall 8-week detection period was subdivided into four 2-week detection periods (Table 3.7), and estimation was performed on each of the four periods separately.

Each acoustic-tagged subyearling Chinook salmon was also PIT-tagged. PIT-tag detection was available at LMO and downstream dams until the PIT-tag detection system was shut off in mid-winter. The shut-off date for the detection system varied by dam, with detections at LMO available through 2 January 2008. The detection system was turned on again in March at the Snake River dams in 2008.

Table 3.6. Virtual release groups of acoustic-tagged subyearling Chinook salmon. Release groups were defined based on arrival date (2007) at the LMN1 acoustic line. * = Release group 8 was not used in fate determination analysis.

Release Group	LMN1 Arrival: Start Date	LMN1 Arrival: End Date	Duration	Number of Fish
1	01 Aug	08 Aug	1 week	241
2	08 Aug	15 Aug	1 week	282
3	15 Aug	22 Aug	1 week	131
4	22 Aug	29 Aug	1 week	135
5	29 Aug	05 Sep	1 week	155
6	05 Sep	19 Sep	2 weeks	109
7	19 Sep	24 Oct	5 weeks	101
8*	24 Oct	28 Nov	5 weeks	8

Table 3.7. Detection periods (2007) for release groups used in fate determination analysis

Release Group	8-Week Detection Period	2-Week Detection Periods 1	2	3	4
1	01 Aug to 26 Sep	01 Aug to 15 Aug	15 Aug to 29 Aug	29 Aug to 12 Sep	12 Sep to 26 Sep
2	08 Aug to 03 Oct	08 Aug to 22 Aug	22 Aug to 05 Sep	05 Sep to 19 Sep	19 Sep to 03 Oct
3	15 Aug to 10 Oct	15 Aug to 29 Aug	29 Aug to 12 Sep	12 Sep to 26 Sep	26 Sep to 10 Oct
4	22 Aug to 17 Oct	22 Aug to 05 Sep	05 Sep to 19 Sep	19 Sep to 03 Oct	03 Oct to 17 Oct
5	29 Aug to 24 Oct	29 Aug to 12 Sep	12 Sep to 26 Sep	26 Sep to 10 Oct	10 Oct to 24 Oct
6	05 Sep to 31 Oct	05 Sep to 19 Sep	19 Sep to 03 Oct	03 Oct to 17 Oct	17 Oct to 31 Oct
7	19 Sep to 14 Nov	19 Sep to 03 Oct	03 Oct to 17 Oct	17 Oct to 31 Oct	31 Oct to 14 Nov

3.7.2 Fate Determination

Fate determination consisted of characterizing the fate of the subyearling Chinook salmon in the release groups on two temporal scales and two spatial scales. Final fate at the end of the study characterized the state of the tagged fish at the end of the expected life of the acoustic tag, approximately 60 days. The final fate analysis used a single detection period of 8 weeks and characterized fate on both the reach scale and the reservoir scale. The intermediate fate analysis characterized fate on the reach scale for biweekly detection periods throughout the study. On each temporal and spatial scale, the questions to be answered were as follows:

- What proportion of the fish migrated out of the study area (i.e., reach or LMN reservoir) during the detection period?
- What proportion delayed in the study area and survived there until the end of the detection period?
- What proportion died within the study area before the end of the detection period?

These questions were answered by estimating the following parameters:

- ϕ = joint probability of surviving and migrating out of the study area during the detection period
- ψ = joint probability of delaying and surviving in the study area through the end of the detection period
- μ = probability of dying in the study area before the end of the detection period.

These parameters were estimated at the end of the study (i.e., with an 8-week detection period) on both the reach scale and the reservoir scale and using biweekly intervals on the reach scale throughout the study. At each scale, 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 3.17).

Fate determination was performed using detections of acoustic tags at arrays and nodes throughout the study area, analyzed on the various temporal and spatial scales. Statistical methods for the biweekly analysis build upon the methods used for the study-wide (i.e., 8-week) analysis, so the study-wide methods are presented first. Both the biweekly and the study-wide methods use the same initial release groups and detection sites (Section 3.7.1). The analytic approach is described here for a single release group. Details on the form of the statistical models used are available in Appendix B.

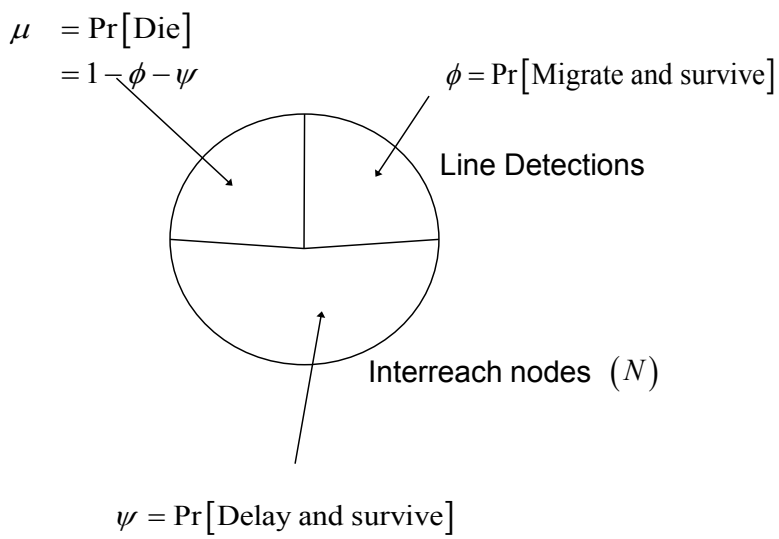

Figure 3.17. Relationship between ϕ (joint probability of migrating and surviving), ψ (joint probability of delaying and surviving), and μ (probability of death) in a single reach and detection period for a single release group

3.7.2.1 Data Format for Single Detection Period

For a single tagged release group R, defined by arrival date at LMN1, the line detections at the two downstream acoustic arrays (LMN2 and LMF1) and the tailrace node detections (LMT) were organized into detection histories for each detection period (either 8 weeks or 2 weeks). The eight possible detection histories were analyzed using the single release-recapture model (Skalski et al. 1998). The analysis estimated the joint probability of migration and survival (ϕ) on the reach spatial scale.

For the biweekly analysis, forming the detection histories for the second and later detection periods was complicated by the fact that at the beginning of those detection periods, live tagged fish may be distributed throughout the entire study area. Assuming 100% detection at the arrays, it was possible to track all fish from reach to reach and so determine where each fish ended each detection period or, equivalently, where they began the next detection period. The fish assigned to reach $j\,(j = 2,3,4)$ at the beginning of detection period $t\,(t = 2,3,4)$ comprised the "virtual release group" for that reach and detection period, with size $R_{(jt)}$. To restrict these virtual release groups to live fish, a decision rule was devised to distinguish between live and dead fish (Section 3.7.2.2).

To estimate the joint probability of delay and survival through the detection period (ψ), two temporal subsamples of the intrareach node detections in each reach were taken from 0600 to 1200 hours on the last two days of the detection period (Table 3.8). Assuming closure, a two-sample mark-recapture model (Seber 2002, pp. 59-62) was used to estimate the number of live smolts within the reach at the end of the detection period. To avoid confounding survival with upstream movement, subsamples of intrareach node detections in a given reach were restricted to fish known to have begun the detection period in the reach in question or upstream. Subsamples also were restricted to live fish, based on the decision rule described in Section 3.7.2.2.

Table 3.8. Sampling design of the temporal subsamples of intrareach nodes in each detection period

Subsample	Day	Time
1	Next to last day of detection period	0600 to 1200 hours
2	Final day of detection period	0600 to 1200 hours

3.7.2.2 Decision Rule: Dead or Alive

Estimation of the abundance of live fish present in each reach at the end of each period depended on the ability to distinguish between detections of live fish and detections of dead fish. The determination of whether a detection comes from a live or dead fish was based on a series of decision rules (Figure 3.18). 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. In other words, movement implies life. This decision allowed us to focus attention on detections at the final node where a fish was detected; only at this last detection event or *final node* could the fish be assumed dead. The classification of a fish as live or dead at its final node was based on two measures: 1) the delay or gap in time between the first detection at the fish's final node and the last detection at its penultimate node (the *ultimate gap*) and 2) the length of time the fish's tag was detected at its final node (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 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 as the duration threshold for dead fish. These methods resulted in a gap of 6.4 h and a duration of 9.4 h used to classify fish as either living or dead. Fish classified as dead at their final node were assumed dead upon arrival.

The decision rule to determine dead or alive is summarized by the decision tree in Figure 3.18:

Step 1. Was the tag subsequently detected at a different node? If yes, then the tag comes 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 6.4 h or less? If yes, then the tag comes from a live fish. If no, then go to Step 3.

Step 3. Was the tag detected for a duration of 9.4 h or more at the last detection location? If no, then the tag comes from a live fish. If yes, then the tag comes from a dead fish.

Assessment of the decision rule was performed via visual inspection of fish tracks of fish classified as "dead" within the study area.

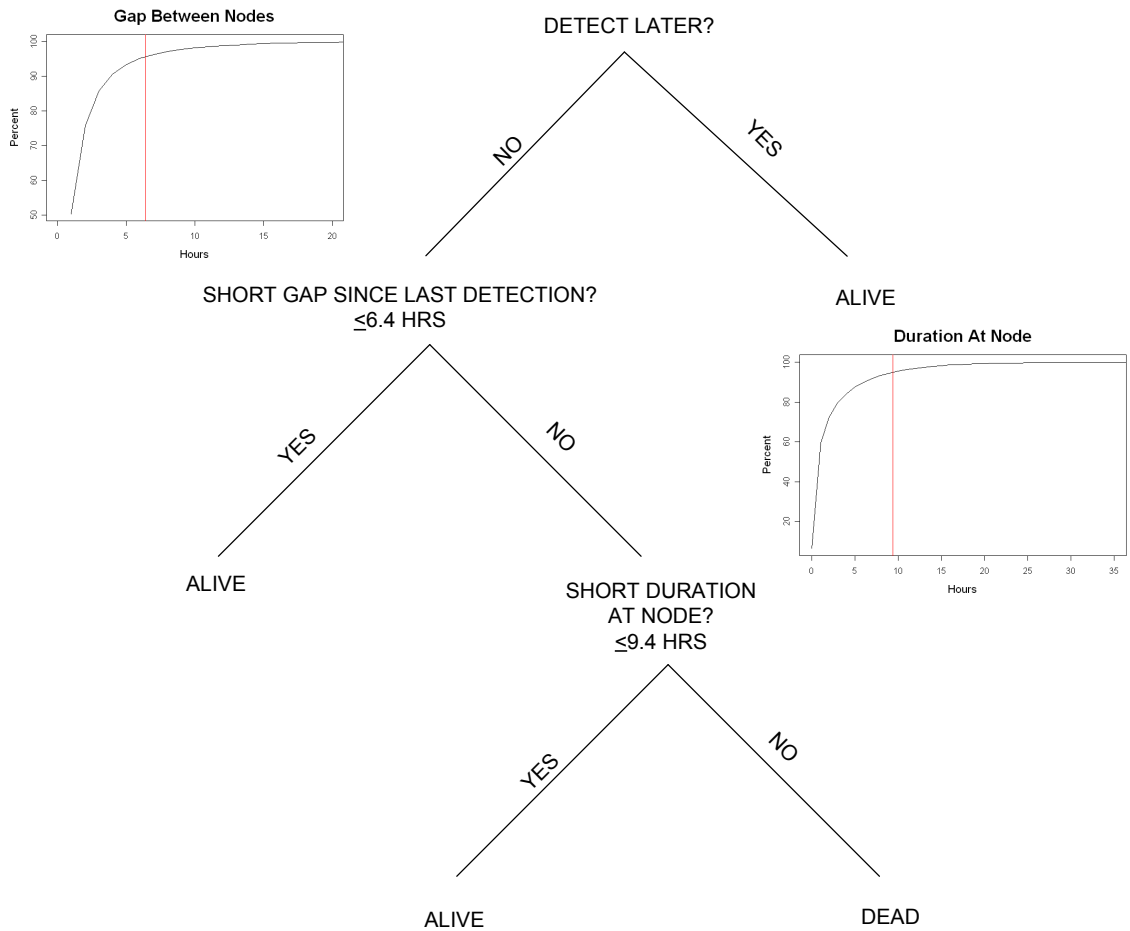

Figure 3.18. Decision rule for determining if an acoustic detection came from a dead fish or from a live fish

3.7.2.3 Fate at End of Study: Reach Scale

For a single release group (R), three parameters were estimated for each reach $i\,(i = 2,3,4)$ for the single 8-week detection period (Figure 3.19; a second subscript indicating the detection period has been dropped here for ease of presentation):

1. ϕ_i, the joint probability of migrating and surviving through reach i within the detection period, conditional on getting to that reach within the detection period; the "migration" parameter.
2. ψ_i, the joint probability of delaying and surviving in reach i to the end of the detection period, conditional on getting to that reach within the detection period; the "delay" or "residualization" parameter.

3. μ_i, the probability of dying in reach i within the detection period, conditional on getting to that reach within the detection period; the "mortality" parameter, $\mu_i = 1 - \phi_i - \psi_i$.

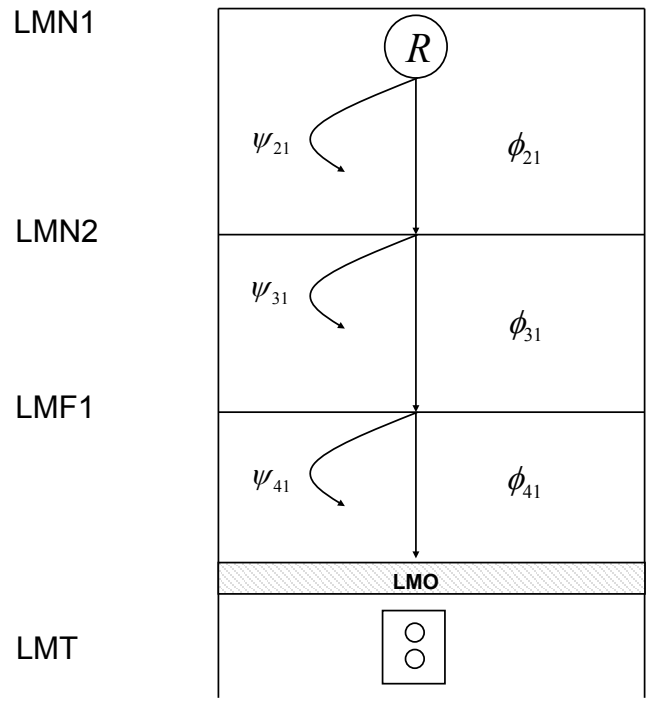

Figure 3.19. Migration and residualization parameters estimated from a single release (R) for the first detection period. LMN1, LMN2, and LMF1 are the acoustic arrays (line detection sites), and LMT is the pair of tailrace nodes. The parameter ϕ_{i1} is the joint probability of migrating and surviving through reach i and detection period 1, for $i = 2,3,4$. The parameter ψ_{i1} is the probability of delaying ("residualizing") and surviving in reach i $(i = 2,3,4)$ to the end of detection period 1.

The Cormack-Jolly-Seber (CJS) model (Cormack 1964; Jolly 1965; Seber 1965) was used to analyze detection histories (Section 3.7.2.1) and estimate the reach-specific migration parameters ϕ_i. It was assumed that detection probabilities at the acoustic line arrays (LMN2 and LMF1) were 100%. Analysis confirmed the reasonableness of this assumption. The two tailrace acoustic receivers were used to estimate the detection probability at LMT (Figure 3.4 and Figure 3.19).

Detection histories from the intrareach node subsampling (Section 3.7.2.1) were used with a two-sample mark-recapture model (Seber 2002, pp. 59–62) to estimate N_i, the abundance of live tagged smolts in reach i $(i = 2,3,4)$ at the end of the detection period. The conditional probability of delaying in reach i and surviving to the end of the detection period (ψ_i) was estimated as the ratio of the estimated

number of live fish in reach i at the end of the detection period to the estimated number of fish that were determined to have entered the reach during the detection period:

$$\hat{\psi}_2 = \frac{\hat{N}_2}{R},$$

$$\hat{\psi}_3 = \frac{\hat{N}_3}{R\hat{\phi}_2},$$

and

$$\hat{\psi}_4 = \frac{\hat{N}_4}{R\hat{\phi}_2\hat{\phi}_3}.$$

The variance of $\hat{\psi}_i$ was estimated using the Delta Method (Seber 2002, pp. 7–9).

The conditional probability of death within the detection period in reach $i\,(i = 2,3,4)$, conditional on getting to reach i in the detection period (μ_i), was estimated as

$$\hat{\mu}_i = 1 - \hat{\phi}_i - \hat{\psi}_i.$$

The variance of $\hat{\mu}_i$ was estimated using the Delta Method.

3.7.2.4 Fate at End of Study: Reservoir Scale

The conditional reach-scale parameter estimates were integrated over reaches to yield estimates of the reservoir-scale migration, delay, and mortality probabilities. The probability of migrating out of the reservoir (i.e., past Lower Monumental Dam) during the study period, ϕ, is simply the product of the conditional reach-scale migration parameters:

$$\phi = \phi_2\phi_3\phi_4.$$

The probability of residualizing or delaying migration within the study area through the end of the study period (ψ) was estimated as

$$\hat{\psi} = \hat{\psi}_2 + \hat{\phi}_2\hat{\psi}_3 + \hat{\phi}_2\hat{\phi}_3\hat{\psi}_4,$$

or equivalently, as

$$\hat{\psi} = \frac{\hat{N}_2 + \hat{N}_3 + \hat{N}_4}{R}.$$

The probability of dying within the study area before the end of the study period (μ) was estimated as

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

Variances were estimated using the Delta Method.

3.7.2.5 Biweekly Fate: Reach Scale

Migration, delay, and mortality parameters were estimated on the reach spatial scale for the biweekly temporal scale. Parameters were estimated for each reach for each 2-week detection period. This resulted in estimates of the form ϕ_{it}, ψ_{it}, and μ_{it}, where i represents the reach $(i = 2,3,4)$ and t represents the detection period $(t = 1,2,3,4)$.

The same release groups were used for the biweekly scale as for the studywide temporal scale (Section 3.7.1). For analysis on the biweekly scale, the 8-week detection period was subdivided into four 2-week detection periods. The first 2-week detection period for a given release group began at the beginning of the release period and ended 2 weeks later.

Estimation methods used for the first detection period were identical to the methods used for the reach-scale parameters for the studywide analysis (Section 3.7.2.4), with the exception that the detection period lasted only 2 weeks, rather than 8 weeks. Analysis for the second detection period was dependent on virtual release groups in reaches 2, 3, and 4, as described in Section 3.7.2.1. For each reach $j\,(j = 2,3,4)$, the virtual release group $R_{(j2)}$ was identified for that reach and for the second detection period. Detection histories were compiled for the virtual release group $R_{(j2)}$ as described previously. The migration parameters were labeled with the reach of the virtual release in the form ϕ_{i2j}, for migration through reach i, detection period 2, from the virtual release in reach j, with $i \geq j$ (i.e., only downstream movement was parameterized). From the virtual release from reach 2, the migration parameters ϕ_{222}, ϕ_{322}, and ϕ_{422} were estimated. The virtual release from reach 3 resulted in estimates of the migration parameters ϕ_{323} and ϕ_{423}. The virtual release from reach 4 resulted in estimation of the migration parameter ϕ_{424}.

The reach-scale migration probabilities for detection period 2 $(\phi_{22}, \phi_{32}, \phi_{42})$ were estimated by combining the ϕ_{i2j} parameters in a weighted average across virtual release groups. The weights used were the proportions of all fish present in the given reach during the second detection period that came from the various virtual releases, as detailed below. Only one virtual release group yielded estimates of ϕ for reach 2, so for reach $i = 2$, the estimator of ϕ_{i2} was simply

$$\hat{\phi}_{22} = \hat{\phi}_{222}.$$

The virtual releases $R_{(22)}$ and $R_{(32)}$ both yielded estimates of ϕ for reach 3: $\hat{\phi}_{322}$ and $\hat{\phi}_{323}$, respectively. For fish from the virtual release group in reach 2 $\left(R_{(22)}\right)$ to get to reach 3, they must have migrated through reach 2 in the second detection period, so the estimated number of fish from $R_{(22)}$ that were present in reach 3 in the second period was $R_{(22)}\hat{\phi}_{222}$. Fish from the virtual release group from reach 3 $\left(R_{(32)}\right)$ began the second period in reach 3, so the total number of fish estimated to have been in

(or entered) the third reach in the second period was $R_{(22)}\hat{\phi}_{222} + R_{(32)}$. The weight for the virtual release from reach 2 was $R_{(22)}\hat{\phi}_{222} \Big/ \left(R_{(22)}\hat{\phi}_{222} + R_{(32)}\right)$, and the weight for reach 3 was $R_{(32)} \Big/ \left(R_{(22)}\hat{\phi}_{222} + R_{(32)}\right)$. This resulted in the conditional probability of migration and survival through reach 3 in detection period 2, ϕ_{32}, estimated by

$$\hat{\phi}_{32} = \frac{R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323}}{R_{(22)}\hat{\phi}_{222} + R_{(32)}}.$$

The virtual releases in reaches 2, 3, and 4 each yielded estimates of ϕ for reach 4: $\hat{\phi}_{422}$, $\hat{\phi}_{423}$, and $\hat{\phi}_{424}$, respectively. The expected number of fish from these three virtual releases that arrived in reach 4 during the second detection period was $R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}$. Fish from the virtual release in reach 2 that contributed to estimation of ϕ in reach 4 must have migrated through reaches 2 and 3 in the second period, so the weight for the $R_{(22)}$ fish was $R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} \Big/ \left(R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}\right)$. Fish from the virtual release in reach 3 that contributed to estimation of ϕ in reach 4 must have migrated through reach 3 in the second period, so the weight for the $R_{(32)}$ fish was $R_{(32)}\hat{\phi}_{323} \Big/ \left(R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}\right)$. The weight for the virtual release group from reach 4 was simply $R_{(42)} \Big/ \left(R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}\right)$. This resulted in the following estimator of the conditional probability of migration through reach 4 in detection period 2 $\left(\phi_{42}\right)$:

$$\hat{\phi}_{42} = \frac{R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322}\hat{\phi}_{422} + R_{(32)}\hat{\phi}_{323}\hat{\phi}_{423} + R_{(42)}\hat{\phi}_{424}}{R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}}.$$

Variance estimators were devised using the Delta Method.

The residualization parameter for reach $i\left(i = 2,3,4\right)$ in detection period 2, ψ_{i2} is the conditional probability of remaining in reach i and surviving there until the end the second period, for fish that began the second period in reach i or arrived there during that period from upstream. The estimator of ψ_{i2} is the ratio of the estimated number of live smolts present in reach i at the end of the second detection period $\left(\widehat{N}_{i2}\right)$ to the estimated number of smolts that were present in reach i during that detection period. The number of live smolts present in reach i at the end of the second period, N_{i2}, was estimated using the subsamples of the intrareach node detections at the end of the second period and a multinomial likelihood model (details in Appendix B). Because only downstream movement was considered in estimating ψ_{i2}, the estimation of N_{i2} excluded fish known to have begun period 2 downstream of reach i. The number of smolts that entered reach i or were present in that reach during the second period was estimated as described above for the weights used in estimating ϕ_{i2}. For the second reach, the estimator of ψ_{i2} was

$$\widehat{\psi}_{22} = \frac{\widehat{N}_{22}}{R_{(22)}}.$$

For the third reach, the estimator of ψ_{i2} was

$$\widehat{\psi}_{32} = \frac{\widehat{N}_{32}}{R_{(22)}\hat{\phi}_{222} + R_{(32)}}.$$

The denominator of $\widehat{\psi}_{32}$ is the same as the denominator of $\hat{\phi}_{32}$. For the fourth reach, the estimator of ψ_{i2} was

$$\widehat{\psi}_{42} = \frac{\widehat{N}_{42}}{R_{(22)}\hat{\phi}_{222}\hat{\phi}_{322} + R_{(32)}\hat{\phi}_{323} + R_{(42)}}.$$

The denominator of $\widehat{\psi}_{42}$ is identical to the denominator of $\hat{\phi}_{42}$. Variance estimators for $\widehat{\psi}_{22}$, $\widehat{\psi}_{32}$ and $\widehat{\psi}_{42}$ were developed using the Delta Method.

The mortality parameter μ_{i2} is the conditional probability of dying in reach $i\left(i = 2,3,4\right)$ in the second detection period, for fish that were present in that reach during that detection period. As Figure 3.17 demonstrates, mortality is the complement of migration and residualization, so for all reaches we have

$$\widehat{\mu}_{i2} = 1 - \hat{\phi}_{i2} - \widehat{\psi}_{i2},$$

with variances estimated using the Delta Method.

Estimating the conditional reach-scale migration, delay, and mortality parameters for detection periods after the second used the methods from the second period, together with virtual release groups and detections from the appropriate detection period.

3.7.3 Effects Analysis

Estimates of the joint probability of migration and survival and of travel time through each reach were related to measures of environmental condition, fish condition, and migration timing (Table 3.9, Table 3.10). The estimated joint migration and survival probability, $\hat{\phi}_{it}$, for reach $i\left(i = 2,3\right)$ and detection period $t\left(t = 1,2,3,4\right)$ was related to group-based covariates that described the release group and 2-week detection period associated with the estimate of ϕ_{it}, as appropriate. The estimated joint probability of migration and survival through the forebay (LMF1–LMT) was related to individual-based covariates. Travel time through reach $i\left(i = 1,2,3,4\right)$ was also related to individual-based covariates.

The effects analysis was performed on two regions of the study area: far field and near field. The far field consisted of reaches 1 (LGS–LMN1), 2 (LMN1–LMN2), and 3 (LMN2–LMF1). Only travel time was available for reach 1. The near field consisted of reach 4 (LMF1–LMT), which included the LMO forebay and dam. The near-field and far-field analyses used somewhat different sets of covariates (Section 3.7.3.1).

3.7.3.1 Covariates

The covariates considered included measures of environmental condition, fish condition, and migration timing. Fish condition variables included length, weight, condition factor (K), and ATPase at tagging (Table 3.9). Additionally, each fish that reached the array at LMF1 was classified as either "directed" or "undirected" based on detections from release at LMN1 until reaching LMF1. Environmental (hydrological) variables included measures of vertical temperature stratification, water velocity, and discharge and spill at LMO. Timing variables included measures of entry date into the study area (i.e., arrival at LMN1), and arrival time at each reach measured by day of year and time of day (noted as day or night). River regime was another timing variable, defined by dates when the river temperature was vertically stratified and there was spill at LMO. Additionally, the group-based analysis of the joint probability of migration and survival was related to detection period as a measure of time since release. Timing variables were explored in single-variable regression models, along with fish and hydrological variables. Fish and hydrological variables, along with the single timing variable that was unrelated to season (i.e., time of day of fish arrival in reach), were used to develop multiple-variable regression models attempting to account for observed variation in migration and survival and travel time. Table 3.9 lists definitions of covariates, and Table 3.10 identifies which covariates were used in each effects analysis.

Table 3.9. Covariates used in effects analyses and their definition within scope of this report

Covariate Code	Covariate	Definition
x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}	Temperature stratification	The vertical distribution of water temperature was measured on an hourly basis at multiple locations throughout the study area. The temperature distribution at each location was simplified to a 3-level categorical variable indicating the degree of temperature stratification. The group-based effect analyses used the level of temperature stratification in a given reach, averaged over each 2-week detection period. The individual-based effect analyses used an indicator variable ("yes" or "no") for stratification in a given reach, measured both at the time of fish arrival in the reach and 24 hours after fish arrival.

Table 3.9. (contd)

Covariate Code	Covariate	Definition
x_{16}, x_{17}	River regime	River regime is a categorical variable that combines temperature stratification and spill at LMO, both of which may affect migration and travel time. This covariate reflects hydrological conditions, but is defined based on time (below), and is considered a timing covariate. It was used in both individual-based and group-based effect analyses. River regime is defined as follows: • Regime 1 = 31 July 2007 – 31 August 2007. Temperature stratification and LMO spill both present. • Regime 2 = 1 September 2007 – 16 September 2007. Temperature stratification present; no LMO spill. • Regime 3 = 17 September 2007 – end of study. Neither temperature stratification nor LMO spill present.
x_{18}, x_{19}, x_{20}	Water particle travel time through reach	Water particle travel time (WPTT) is a measure of water velocity. Water particle travel time through reaches upstream of the LMO forebay was used as both an individual-based and a group-based covariate. The individual-based analyses for travel time used the log of WPTT, measured at the time of fish arrival in the reach. The group-based analyses used both the average WPTT and the CV of water velocity through the reach, calculated from WPTT, measured over each 2-week detection period.
x_{21}, x_{22}, x_{23}, x_{24}	Total discharge at LMO	Total discharge (kcfs) at LMO is a measure of the stability of the river environment. This hydrological variable was used in both individual-based and group-based effect analyses. It was characterized by both its average and its coefficient of variation (CV) over the 24-hour period from the time of fish arrival in the forebay for individual-based analyses, and over each 2-week detection period for group-based analyses.
x_{25}, x_{26}	Spill discharge at LMO	Discharge (kcfs) over the spillway at LMO is a measure of dam operations and the river environment. This hydrological variable was used in both individual-based and group-based effect analyses. It was characterized by its average over the 24-hour period from the time of fish arrival in the forebay for the individual-based analyses, and over each 2-week detection period for the group-based analyses.
x_{27}, x_{28}	Spill proportion at LMO	Spill proportion at LMO was defined as the ratio of spill discharge to total discharge. This hydrological variable was used in both individual-based and group-based effect analyses. It was characterized by its average over the 24-hour period from the time of fish arrival in the forebay for the individual-based analyses, and over each 2-week detection period for the group-based analyses.
x_{29}, x_{30}, x_{31}, x_{32}, x_{16}, x_{34}, x_{35}, x_{36}, x_{37}, x_{38}, x_{39}, x_{40}	Water velocity in forebay	Water velocity is a measure of the river environment in the forebay. This hydrological variable was measured at two locations in the forebay ("proximal" and "distal" to the dam). At each location, the overall magnitude of water velocity, as well as the downstream and cross-stream components, were measured. Both observed values at the time of fish arrival in the forebay and the CV of values over the 24-hour period starting at fish arrival were used in the individual-based near field effect analyses.

Table 3.9. (contd)

Covariate Code	Covariate	Definition
x_{41}	Release group	Release group is a categorical variable (1 – 7) indicating the conceptual release group formed at LMN1. This timing variable is a measure of fish entry date into the study area, and was used as both an individual-based and a group-based covariate in the single-variable effect analyses.
x_{42} , x_{43}	Arrival time	Arrival time at the upstream boundary of a given reach was represented both as the day of the year and as the time of day, simplified to a categorical variable indicating "day" or "night." The day of the year may reflect seasonal effects on migration, whereas the time of day may reflect diel effects. This timing factor was used in the individual-based analyses.
x_{44}	Detection period	Detection period is a categorical variable used in the group-based effect analyses, indicating the 2-week detection period used to estimate the migration parameters. This variable is a measure of time since release at LMN1.
x_{45} , x_{46} , x_{47} , x_{48}	Fish condition at tagging	Fish condition at tagging was represented by length (L), weight (W), condition factor (K), and ATPase. Condition factor is computed as $K = 100,000W/L^3$, and may be related to survival. Size and ATPase are indicative of smolting, and may be related to migration. These fish covariates were included in both the individual-based analyses and the group-based analyses.
x_{49}	Fish classification as "directed "or "undirected"	Fish were classified as "directed" or "undirected" by calculating the Spearman correlation (ρ) between location (river kilometer) and date from the time of arrival at LMN1 to the time of arrival at the forebay. Fish with $\rho \le -0.5$ were classified as "directed," and fish with $\rho > -0.5$ were classified as "undirected." The directedness classification was used in the individual-based effect analysis for survival through the forebay.

Table 3.10. Covariates considered in effect analyses of travel time, migration and survival, and their associated reference code. Covariates are categorized as hydrological, timing, or fish covariates. Entries in the Analysis columns indicate consideration of the covariate in the specific effect analysis. Inclusion in analysis limited to a single reach is indicated. * = used only in single-variable regression models.

Covariate			Analysis			
Code	Definition	Category	Far-Field Travel Time	Near-Field Travel Time	Far-Field Survival	Near-Field Survival
	Temperature stratification at LMN3T	Hydrological				
x_1	At time of arrival in reach		LGS-LMN1			
x_2	24 hours after arrival in reach		LGS-LMN1			
	Temperature stratification at LMN4T	Hydrological				
x_3	At time of arrival in reach		LMN1-LMN2			
x_4	24 hours after arrival in reach		LMN1-LMN2			
x_5	Average over 2-week detection period				LMN1-LMN2	
	Temperature stratification at LMN5T	Hydrological				
x_6	At time of arrival in reach		LMN2-LMF1			
x_7	24 hours after arrival in reach		LMN2-LMF1			
x_8	Average over 2-week detection period				LMN2-LMF1	
	Temperature stratification at LMNDST	Hydrological				
x_9	At time of arrival in reach		LMN2-LMF1			
x_{10}	24 hours after arrival in reach		LMN2-LMF1			
x_{11}	Average over 2-week detection period				LMN2-LMF1	
	Temperature stratification at LMNCorps	Hydrological				
x_{12}	At time of arrival in reach			X		X
x_{13}	24 hours after arrival in reach			X		X

Table 3.10. (contd)

Covariate			Analysis			
Code	Definition	Category	Far-Field Travel Time	Near-Field Travel Time	Far-Field Survival	Near-Field Survival
	Temperature stratification at LMNFBT	Hydrological				
x_{14}	At time of arrival in reach			X		X
x_{15}	24 hours after arrival in reach			X		X
	River regime*	Timing				
x_{16}	At time of arrival in reach		X	X		X
x_{17}	At beginning of 2-week detection period				X	
	Water particle travel time (WPTT)	Hydrological				
x_{18}	At time of arrival in reach		X			
x_{19}	Average over 2-week detection period				X	
x_{20}	Water velocity calculated from WPTT (CV over 2-week detection period)				X	
	Total discharge at LMO	Hydrological				
x_{21}	Average over 24 hours from arrival in forebay			X		X
x_{22}	CV over 24 hours from arrival in forebay			X		X
x_{23}	Average over 2-week detection period				X	
x_{24}	CV over 2-week detection period				X	
	Spill at LMO	Hydrological				
x_{25}	Average over 24 hours from arrival in forebay			X		X
x_{26}	Average over 2-week detection period				X	
	Spill proportion at LMO	Hydrological				
x_{27}	Average over 24 hours from arrival in forebay			X		X
x_{28}	Average over 2-week detection period				X	

Table 3.10. (contd)

Covariate			Analysis			
Code	Definition	Category	Far-Field Travel Time	Near-Field Travel Time	Far-Field Survival	Near-Field Survival
	Water velocity in forebay, proximal to dam	Hydrological				
x_{29}	Overall magnitude			X		X
x_{30}	Downstream component			X		X
x_{31}	Cross-stream component			X		X
x_{32}	Overall magnitude (CV over 24 hours from arrival in forebay)			X		X
x_{33}	Downstream component (CV over 24 hours from arrival in forebay)			X		X
x_{34}	Cross-stream component (CV over 24-hours from arrival in forebay)			X		X
	Water velocity in forebay, distal to dam	Hydrological				
x_{35}	Overall magnitude			X		X
x_{36}	Downstream component			X		X
x_{37}	Cross-stream component			X		X
x_{38}	Overall magnitude (CV over 24-hours from arrival in forebay)			X		X
x_{39}	Downstream component (CV over 24 hours from arrival in forebay)			X		X
x_{40}	Cross-stream component (CV over 24 hours from arrival in forebay)			X		X
x_{41}	Release group at LMN1*	Timing	X	X	X	X
	Arrival at top of reach	Timing				
x_{42}	Date*		X	X		X
x_{43}	Day or night		X	X		X

Table 3.10. (contd)

Covariate			Analysis			
Code	Definition	Category	Far-Field Travel Time	Near-Field Travel Time	Far-Field Survival	Near-Field Survival
x_{44}	Detection period*				X	
x_{45}	Length at tagging	Fish	X	X	X	X
x_{46}	Weight at tagging	Fish	X	X	X	X
x_{47}	Condition factor (K) at tagging	Fish	X	X	X	X
x_{48}	ATPase at tagging	Fish	X	X	X	X
x_{49}	Directed from release to LMF	Fish				X

3.7.3.2 Far-Field Effects Analysis: Survival and Migration

Estimates of the joint survival and migration probability (ϕ) were related to covariates for reaches 2 (LMN1–LMN2) and 3 (LMN2–LMF1). Scatter plots and single-variable regressions were performed first to identify important covariates in explaining variation in survival and migration. Weighted linear regression models were used with a proportional hazards transformation and with weights equal to the inverse squared CV of the ϕ_{it} estimates, based on the observed relationship between $\hat{\phi}_{it}$ and $\widehat{\mathrm{Var}}\left(\hat{\phi}_{it}\right)$. Linear regression was used to identify important single factors, followed by multiple linear regression to identify important sets of factors. Significance testing was based on analysis of variance (ANOVA) using *F*-tests, and model selection used forward selection. The migration and survival probability estimates were transformed using the proportional hazards log-log transformation to generate normally distributed errors:

$$\ln\left(-\ln\left(\hat{\phi}_{it}\right)\right) = \beta_{0i} + \beta_{1i}x + \varepsilon_{it},$$

where β_{1i} is the effect of covariate x on the joint probability of migration and survival of release group i, and ε_{it} is the error term for release group i and detection period t.

3.7.3.3 Far-Field Effects Analysis: Travel Time

Travel time through reaches 1, 2, and 3 was calculated for all tagged smolts detected at both the upstream and downstream boundaries of the given reach. Travel time through each reach was regressed on individual covariates describing fish condition and environmental conditions; see Table 3.9 and Table 3.10 for details. The reaches were analyzed independently.

Linear regression was used to identify important single factors, followed by multiple linear regression to identify important sets of factors. Model selection was performed using ANOVA and forward

selection to account for the presence of both continuous and categorical variables. Travel times were transformed using the log transformation to generate normally distributed errors:

$$\ln\left(T_i\right) = \beta_{0i} + \beta_{1i}x + \varepsilon_i,$$

where T_i is travel time through the reach in question for individual i, β_{1i} is the effect of covariate x on travel time of individual i, and ε_i is the error term for individual i.

3.7.3.4 Near-Field Effects Analysis: Survival and Migration

The near-field analysis focused on survival and migration timing through the Lower Monumental forebay to the tailrace nodes (acoustic array LMT). Analysis was restricted to tagged subyearlings that were detected on any of the forebay nodes. Joint survival and migration through the forebay were analyzed using a known-fate proportional hazards model with individual-based covariates. Because a known-fate analysis cannot be corrected for tag failure, this analysis was restricted to tagged subyearlings that were detected on any of the forebay nodes with sufficient time to reach the tailrace nodes before tag failure, based on observed travel times from LMF to LMT and an expected 60-day tag life. Detections from all downstream acoustic arrays (including LMT) and all PIT-tag detectors downstream of LMO were pooled to indicate whether the fish successfully reached the LMO tailrace. The individual-based covariates used in effects analysis for survival through the forebay are listed in Table 3.9 and Table 3.10.

The binary survival data were analyzed using a binomial error structure and parameterized with a proportional hazards link to analyze forebay and dam passage survival: that is,

$$E\left(\phi_i\right) = 1 - S_0^{\exp\left(\beta_{0i}+\beta_{1i}x+\varepsilon_i\right)},$$

where $E\left(\phi_i\right)$ is the expected joint probability of migration and survival from the forebay to the tailrace for individual i, S_0 is the average complement of the survival and migration probability across all individuals (i.e., the average probability of either mortality or residualization), and β_{1i} is the effect of covariate x on survival of individual i. Both single-variate and multivariate response models were considered. Model selection was performed using analysis of deviance and *F*-tests using forward selection.

3.7.3.5 Near-Field Effects Analysis: Travel Time

Travel time through LMO forebay and dam was estimated for each tagged subyearling Chinook salmon that was detected both in the forebay and in the tailrace as the time between entering the forebay and reaching the tailrace nodes. Travel time was related to hydrological, fish, and timing covariates; see Table 3.9 and Table 3.10 for details.

Both simple and multiple regressions were used to relate near field travel time to the covariates, using the log transformation. The following general mean response model was used, with normally distributed errors:

$$\ln\left(T_i\right) = \beta_{0i} + \beta_{1i}x + \varepsilon_i,$$

where T_i is travel time from the forebay to the tailrace nodes for individual i, β_{1i} is the effect of covariate x on travel time of individual i, and ε_i is the error term for individual i. Both single-variable and multivariate response models were considered. Model selection was performed using ANOVA and forward selection.

4.0 Results

4.1 General Juvenile Fall Chinook Salmon Distribution

The deployment pattern of acoustic receivers allowed for production of very detailed detection histories of acoustic-tagged juvenile fall Chinook salmon in the lower 19 km of the Lower Monumental Reservoir. Nearly 26 million individual valid detections were analyzed to determine the migratory behavior and fate of the tagged fish detected in the study area. An additional 481,316 individual detections were recorded on receivers downstream of LMN in 2007. Many fish migrated from the release location to the immediate forebay of the dam and subsequently moved many kilometers back upstream in the reservoir prior to finally emigrating from the reservoir in the late fall through following spring. Appendix C provides some sample fish tracks and information on subsequent PIT-tag detections of these fish.

A total 1,162 of the 1,771 acoustic-tagged subyearling Chinook salmon were detected on the receiver arrays in the lower 19 km of Lower Monumental Reservoir between 1 August and 12 December 2008. Acoustic-tagged subyearling Chinook salmon were found throughout the lower reservoir during the study period, with a general trend of more fish in the upper portion of the study area (Rkm 596–608; 7 to 19 km from Lower Monumental Dam) during the period between 1 August and early October and transitioning to more fish in the lower 10 km of the reservoir after early October (Figure 4.1).

Additional treatment of the migratory and survival information is presented in Sections 4.4 and 4.5. Section 4.6 presents information on relationships between fish fate and movement and hydraulic/ operations parameters. In addition fish fate and movement is presented in the context of biological and physiological variables in Section 4.6. Examples of fish tracks are presented in Appendix C.

4.2 Predator Fish Distribution and Movement

A total 167 of the 197 predators tagged were detected on the acoustic receivers in the lower half of Lower Monumental Reservoir. The mean number of days these fish were detected was 41.3 (median = 35.9).

Smallmouth bass were relatively sedentary and did not typically migrate to any extent during the study period. On average, acoustic-tagged smallmouth bass used an average of 2.6 km of the reservoir. For predator fish detected for more than 1 day (n = 152), 57 (37.5%) used 1 Rkm or less, while 37 (24.5%) used between 1 and 2 Rkm. In general, the movement of predator fish decreased as the season progressed (Figure 4.2).

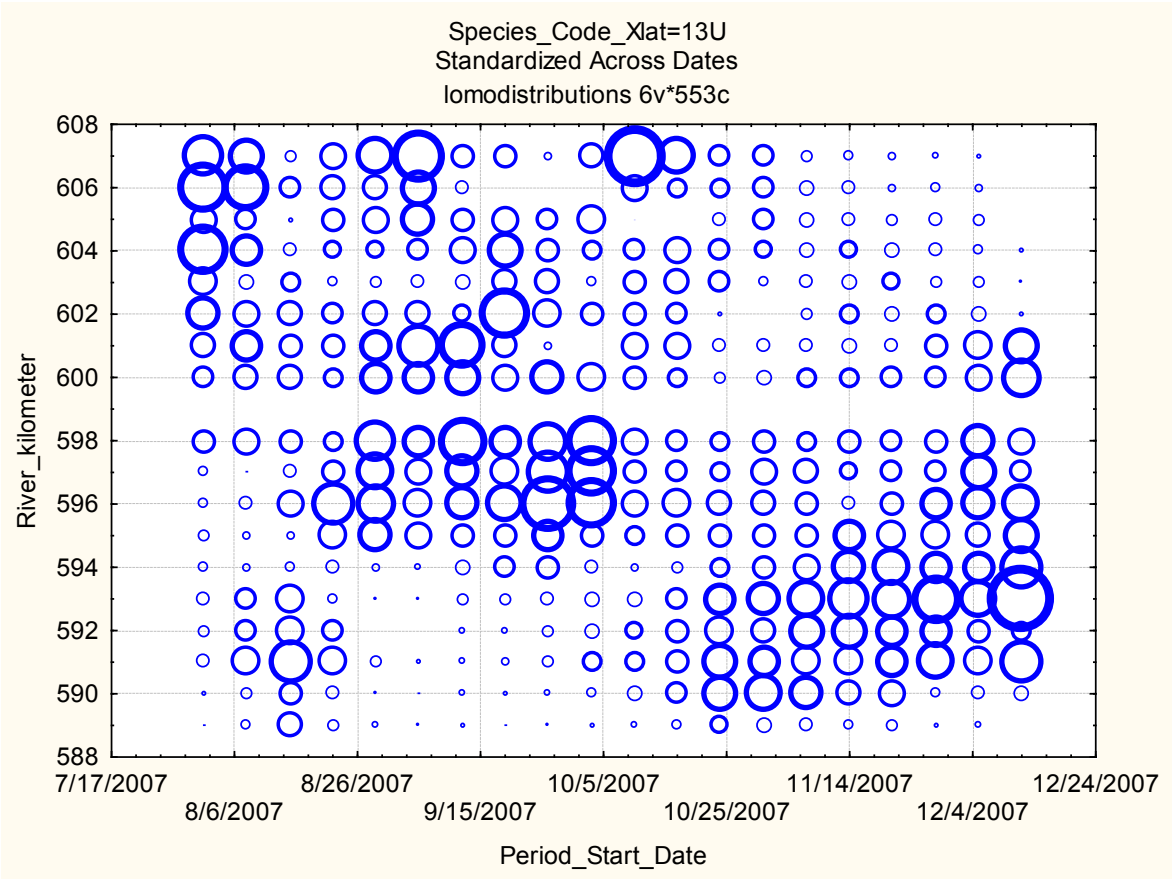

Figure 4.1. Distribution of acoustic-tagged juvenile fall Chinook salmon in the lower 19 km of Lower Monumental Reservoir 1 August to 12 December 2007. Distributions are standardized within each 1-week period, with larger circles corresponding to a greater number of fish present at that river kilometer.

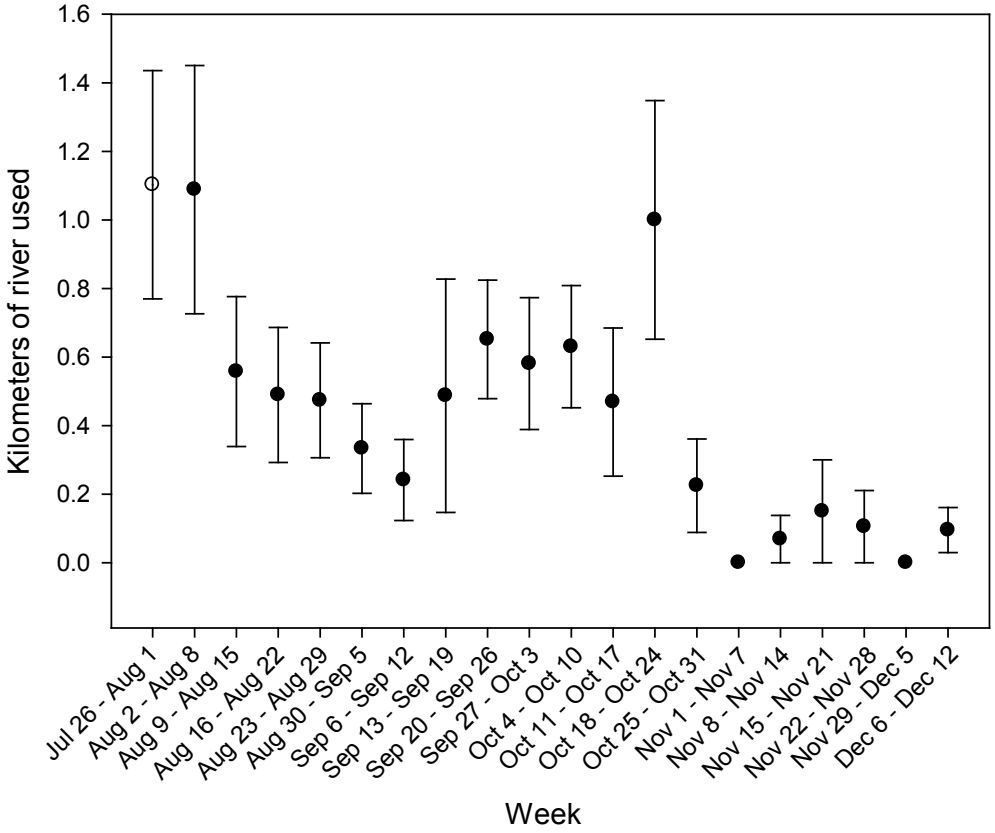

Figure 4.2. Mean (±SE) kilometers of Lower Monumental Reservoir used by acoustic-tagged predator fishes between 26 July and 12 December 2007

Acoustic-tagged smallmouth bass tended to stay relatively close to where they were captured, tagged, and released. The majority of the predators were captured between the Lower Monumental Dam forebay (Rkm 589) and the Skookum Habitat Management Unit (Rkm 598). Figure 4.3 shows that these fish were most often detected near these locations.

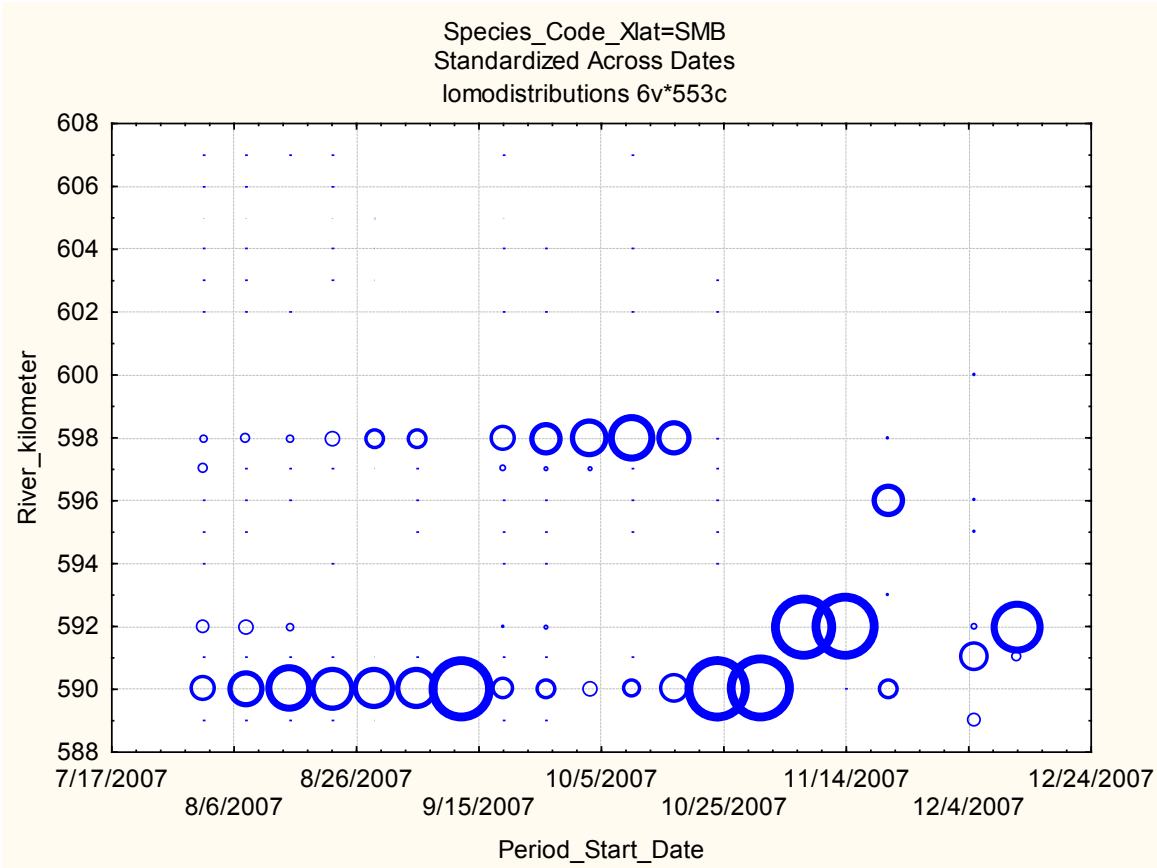

Figure 4.3. Distribution of detections of acoustic-tagged smallmouth bass through time in Lower Monumental Reservoir between 26 July and 12 December 2007

4.3 Hydraulic Studies Results

4.3.1 Project Operations

Hourly operations for Lower Monumental and Little Goose dams are summarized in Appendix D. In addition, 5-minute operations that include individual spillbay and turbine unit discharges are presented in Appendix D. Lower Monumental Dam operated near minimum operating pool (MOP) near 163.8 m and with spillway discharge (primarily through spillbays 8 and 6) according to the fish passage plan until 1 September. After 1 September, mandatory spill ceased and most water passed the project through the powerhouse as shown in Figure D.3. Forebay elevation was also raised back to normal pool near 164.4 m. In general, discharge tended to decrease from the start of the study until 1 September, and thereafter it fluctuated frequently (on a daily basis).

4.3.2 Water Temperature

Vertical water temperature profiles were measured at six sites during the study (see Figure 3.6 and Table 3.4). A typical time history of hourly water temperature at station LMN4T is shown in Figure 4.4. The top part of Figure 4.4 shows the water temperature as a function of depth. The middle plot in Figure 4.4 subtracts the profile minimum temperature to better show thermal layer in the upper part of the water column. Finally, maximum, minimum, and depth-averaged temperatures are shown in the bottom

part of Figure 4.4. Prior to about 14 September, temperatures were very transient and were above 18°C over the entire water column. A distinct thermal layer existed that ranged in depth from 10 to 15 m and was 1–5°C warmer than the profile minimum. After 14 September, vertical temperature gradients disappeared and the water column temperature was nearly constant. A complete set of similar figures is provided in Appendix E for each measurement station.

Figure 4.5 shows depth distribution of water temperature above the profile minimum along the reservoir at two points in time on 31 August and 17 September. Figure 4.5 was created by contouring the data from each measurement station. On 31 August, a distinct thermal layer existed over the entire study reach and then was not present on 17 September following the onset of isothermal conditions after 14 September.

For use as a covariate in the effects analysis, the characteristics of the thermal layer at each measurement station were quantified and classified according to the scheme presented in Section 3.7.1. Typical thermal layer characteristics at station LMN4T are shown in Figure 4.6. At this location, the thermal layer (defined as the portion of the water column above the depth-averaged temperature) was generally 10 to 15 m deep and 1–5°C warmer than the depth-average value. Again, these values were very transient prior to the onset of isothermal conditions on about 14 September.

4.3.3 Water Velocity

Figure 4.7 shows the measured water velocity at station LMNDS resolved into the upstream/downstream direction together with nearby vertical temperatures at station LMNDST during late July and early August. Periods existed when flow in the upper part of the water column was directed upstream, but these were episodic events and did not appear to be highly correlated with the presence of a "strong" thermal layer (2 degrees or more above the profile minimum). The results from mobile surveys showed similar behavior, with episodic occurrences of upstream-directed water velocity. Figure 4.8 shows the spatial distribution of downstream water velocity as well as its lateral and vertical averaged value with occasional occurrences of upstream moving water. Laterally-averaged downstream velocity from several mobile survey dates are shown in Figure 4.9. Again, upstream-directed water was not consistently observed during the time when thermal gradients were prevalent prior to 14 September. Occurrences of upstream-directed flow in the surface layer were not correlated to wind velocities measured near Fishhook Park, but local measurements of wind speed and direction were not available for this study. However, after the onset of nearly isothermal conditions on 14 September, laterally averaged velocities were consistently in the downstream direction.

In an effort to further understand whether upstream-directed surface velocities were related to wind conditions, river velocity data collected in the Cook et al. (2007) study were reexamined at ADCP meaurement location LMN5 for two time periods: 26 July 2006, 1400 hours, to 13 August 2006, 1200 hours, and 31 August 2006, 1200 hours, to 20 September 2006, 1400 hours, approximately 18 and 20 days long, respectively. During these periods, there was upstream flow in the upper 20 meters of the water column 81% and 63% of the time, respectively. A strong correlation between wind direction and speed and the presence of upstream flow was not found even when using the locally measured wind conditions reported by Cook et al. (2007). The analysis showed that upstream flow of various magnitudes was scattered among various wind directions and wind speeds with no consistent pattern.

In the immediate forebay of Lower Monumental Dam, velocities measured from the fixed position ADCP tended to closely follow the timing of changing dam operations and were generally oriented

toward the area of highest discharge (as expected). An example of the time history of velocity at station LMNFB1 (located about 100 m upstream of spillbay 8) is shown in Figure 4.10. Prior to shutoff on spill on 1 September, velocities moved toward the spillbay (negative cross-stream direction). Thereafter, the cross-stream direction became variable but tended more toward the powerhouse. A complete set of results is presented in Appendix E.

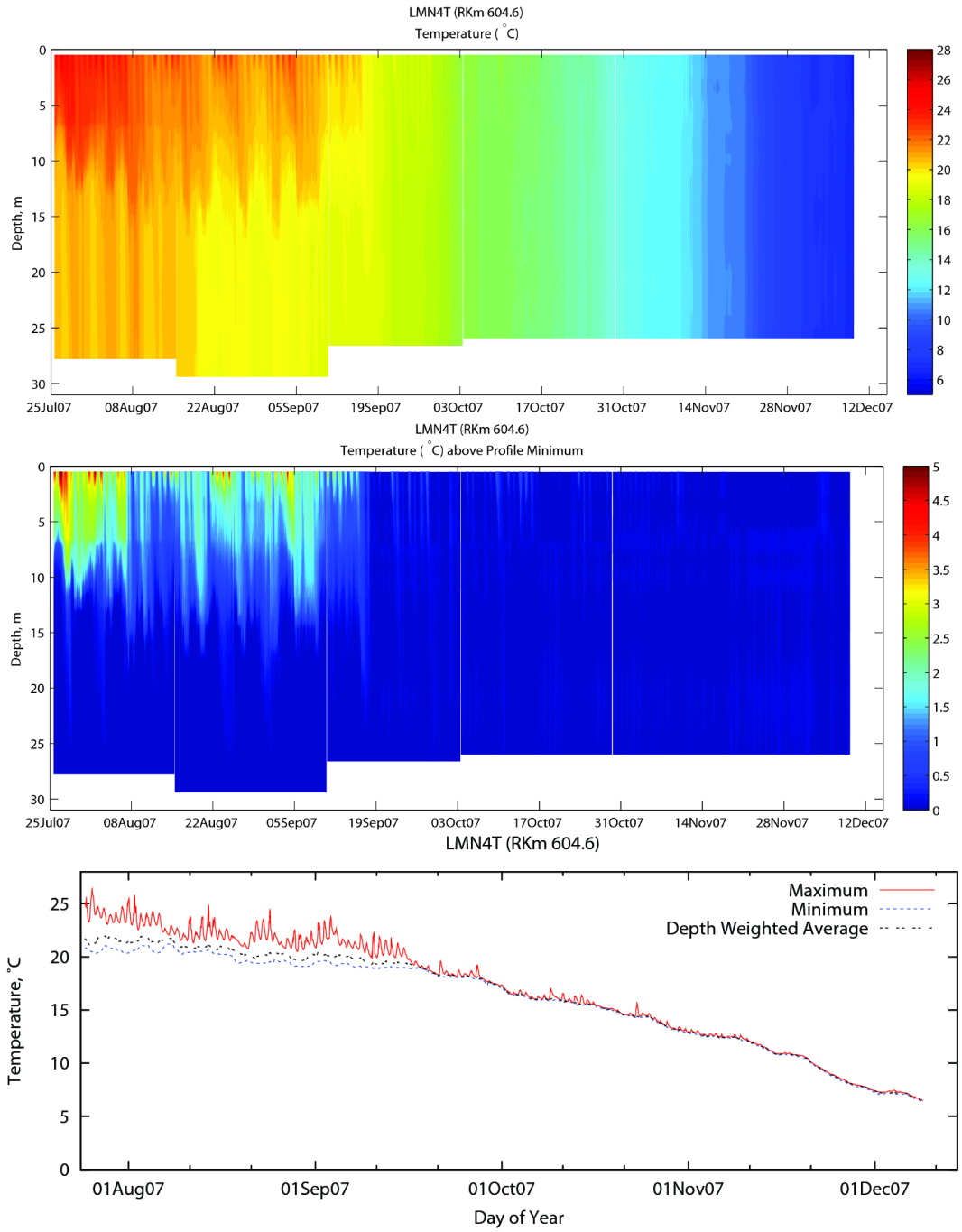

Figure 4.4. Hourly temperature record from LMN4T site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

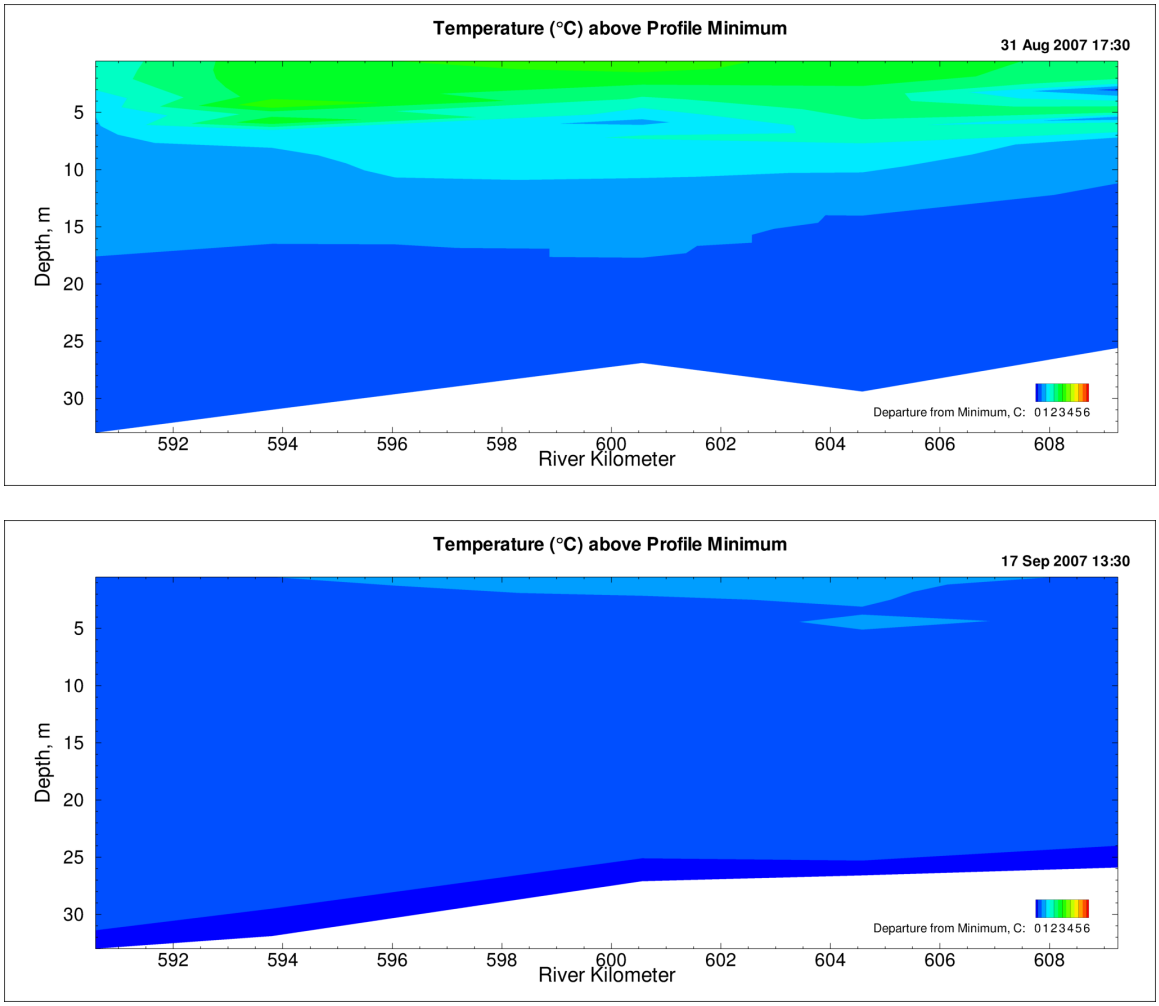

Figure 4.5. Snapshots of vertical temperature variation along Lower Monumental Reservoir showing typical conditions when vertical temperature gradients were present (31 August 2007) and afterreservoir became nearly isothermal (17 September 2007)

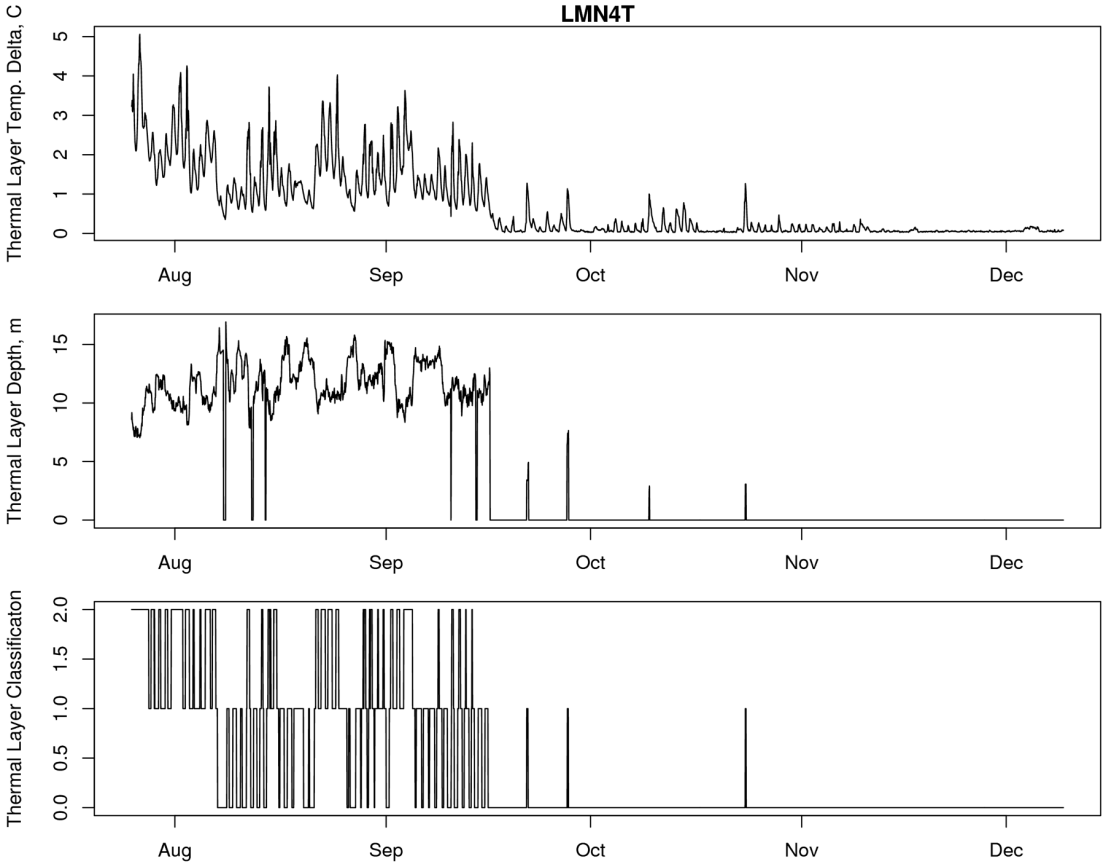

Figure 4.6. Calculated thermal layer characteristics at LMN4T

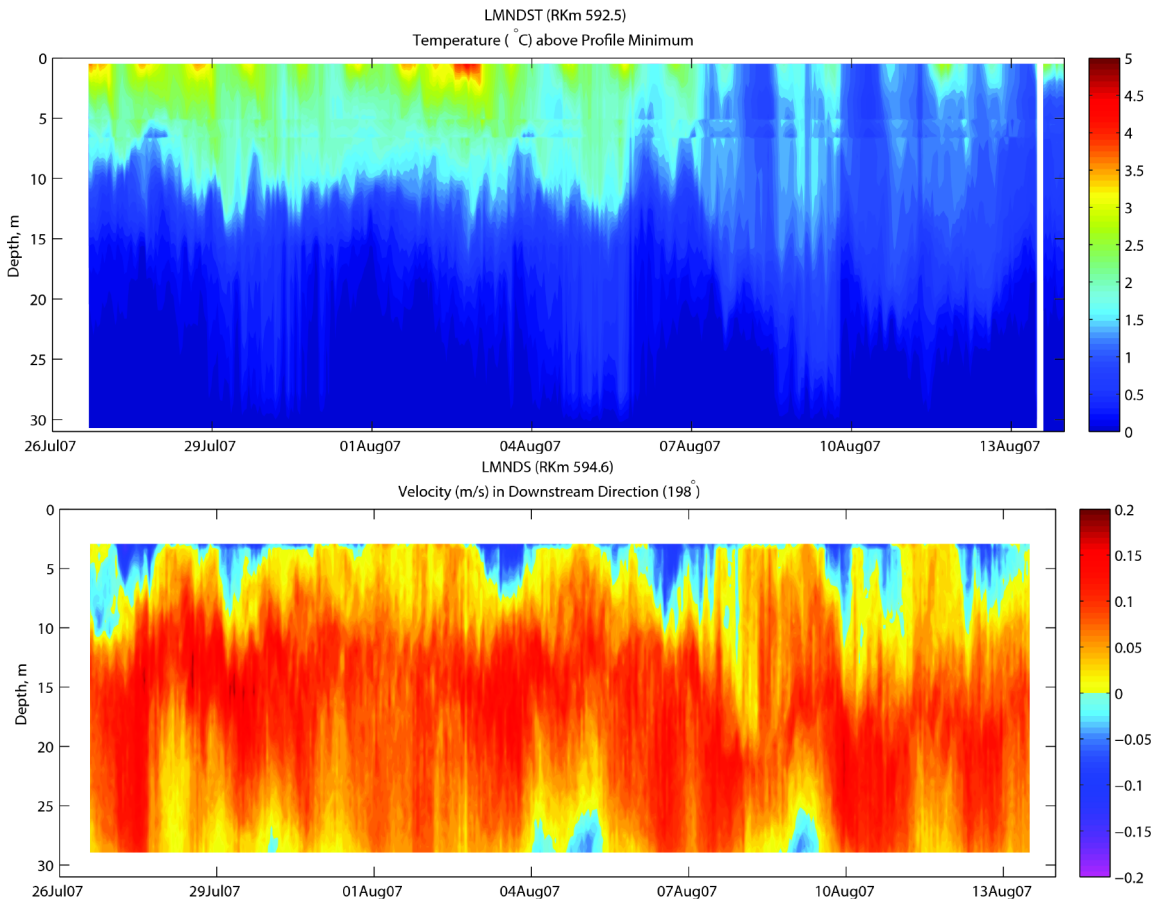

Figure 4.7. Comparison of temperature at LMNDST (top) and velocity just upstream at LMNDS (bottom)

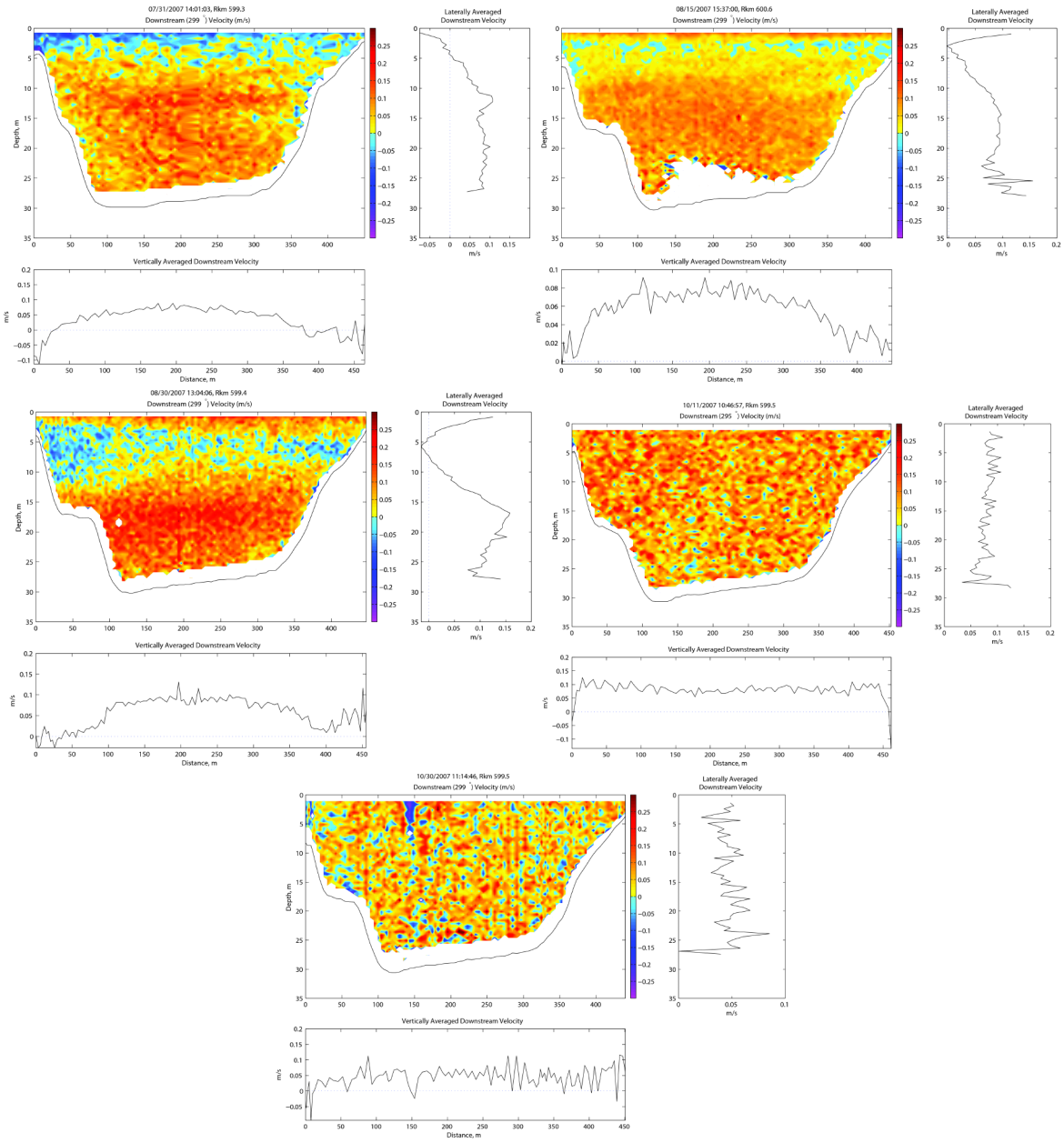

Figure 4.8. Acoustic Doppler current profiler transects measured near LMN5T temperature string (and LMN2 acoustic gate). Blue indicates upstream-directed flow.

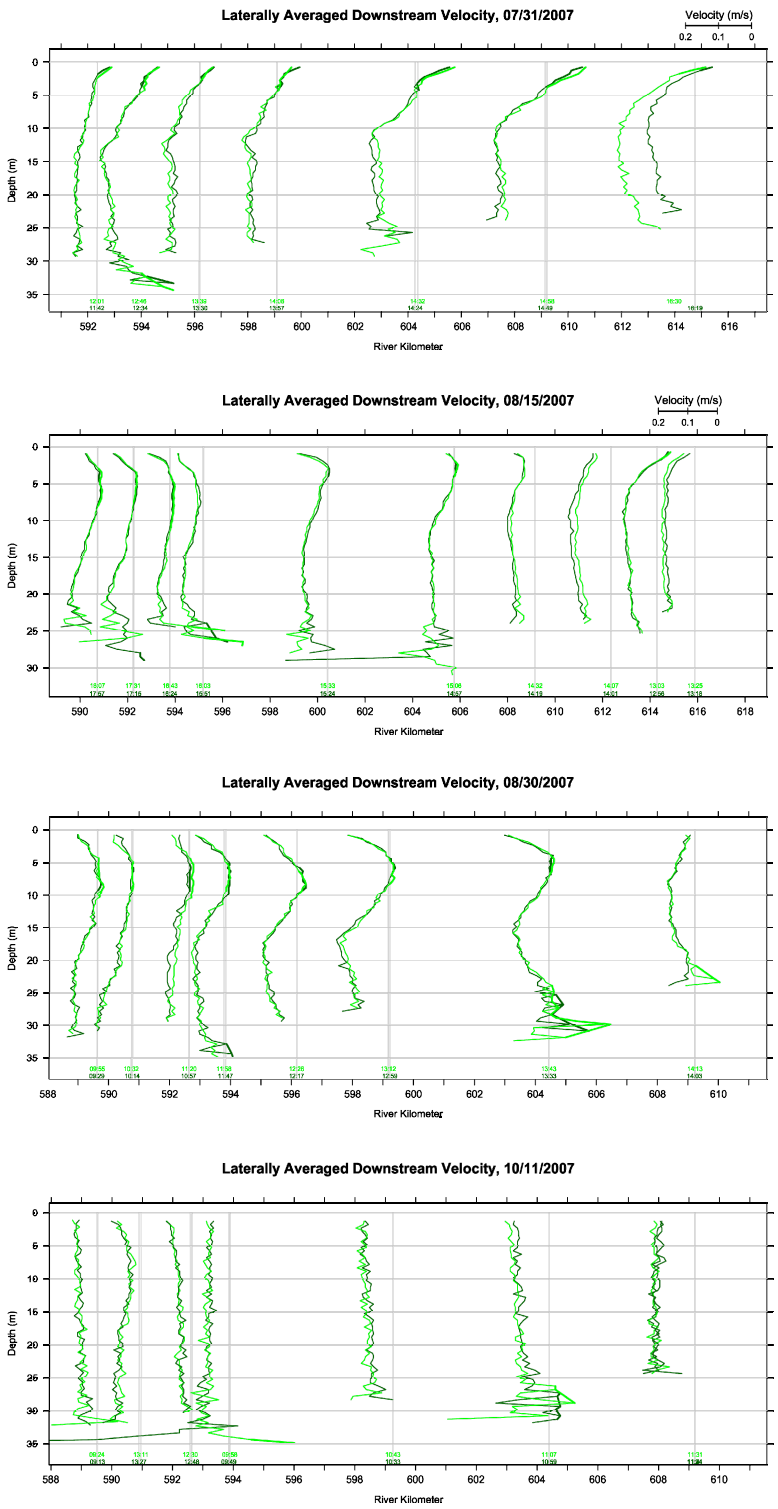

Figure 4.9. Laterally averaged downstream velocity from ADCP mobile surveys. Upstream-directed flow is indicated when the velocity profile crosses to the right of the light gray axis. For example, all profiles on 31 July 2007 show upstream flow occurring in the upper part of the water column, and profiles on 10 October 2007 show relatively uniform velocity with no upstream flow in the upper part of the water column.

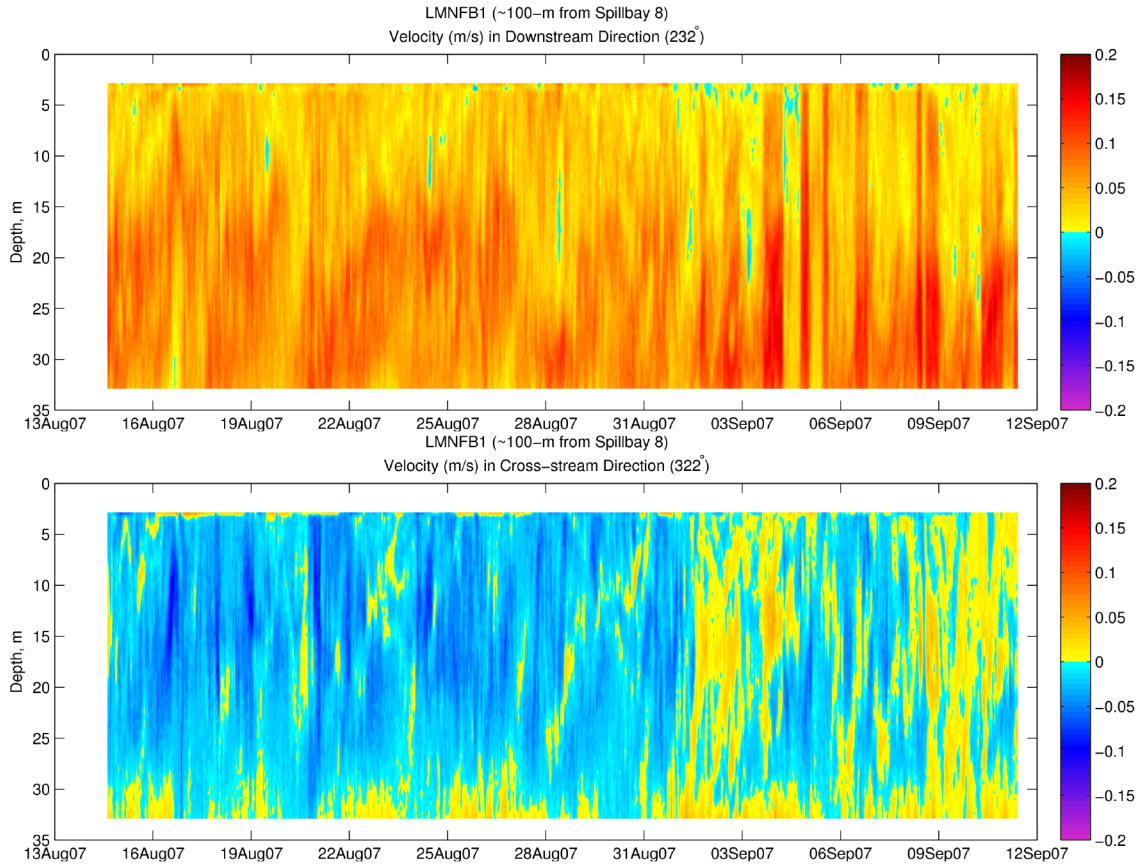

Figure 4.10. Downstream and cross-stream velocity magnitude measured at LMNFB1 site while upstream of spillbay 8. Positive values (red colors) indicate flow in the downstream and north shore directions.

4.3.4 One-Dimensional Unsteady Flow Modeling

Typical results from the one-dimensional unsteady flow model presented in Figures 4.11 and 4.12 show that both discharge and velocity are variable in the reservoir. Depending on specific operating conditions, discharge can vary considerably along the reservoir (Figure 4.11) or undergo periods in which variations are relatively small (Figure 4.12). Velocities tend to decrease in the downstream direction as depth and the cross-sectional area increase. The effect of operations changes after 1 September is reflected by the increase of the weekly averaged velocity coefficient of variation shown in Figure 4.13.

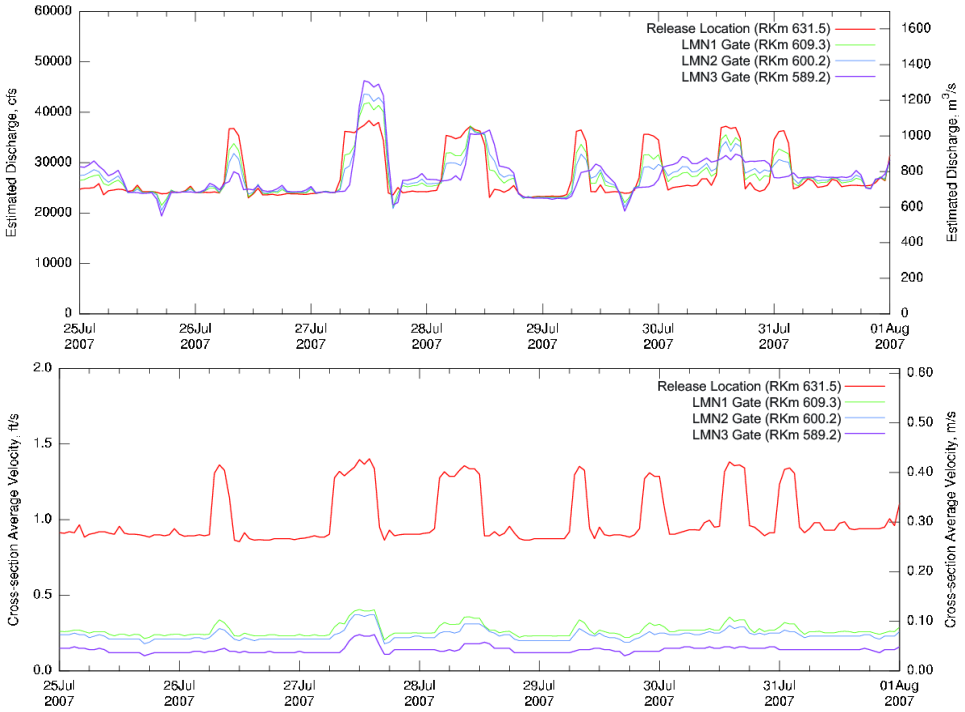

Figure 4.11. Examples of estimated river discharge and velocity for late July 2007

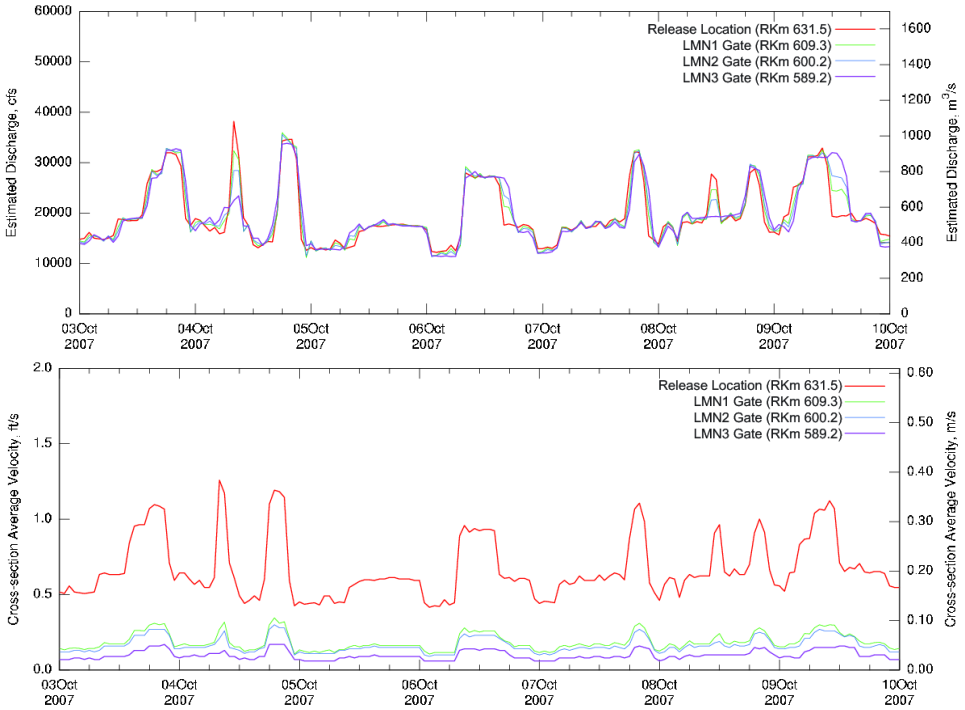

Figure 4.12. Examples of estimated river discharge and velocity for early October 2007

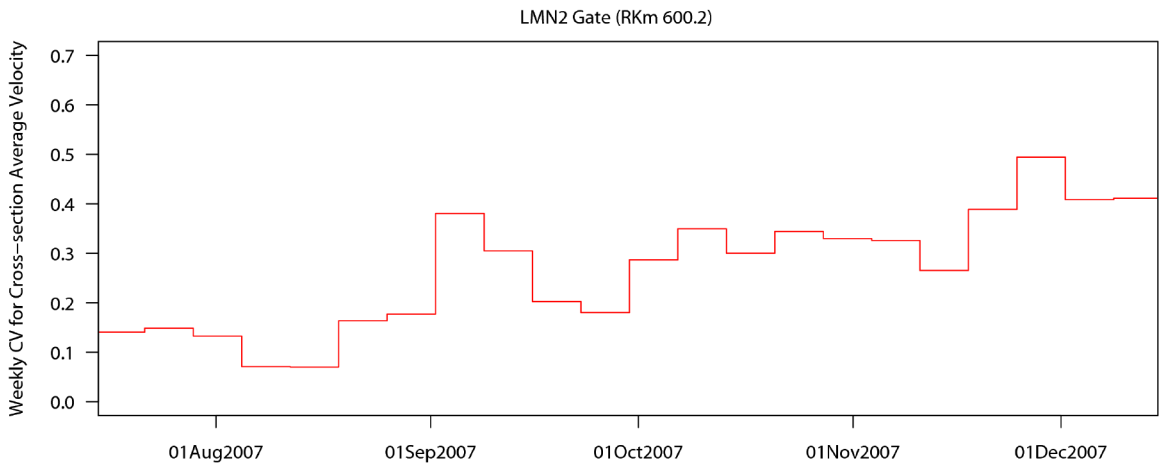

Figure 4.13. Coefficient of variation calculated from simulated cross-sectional average velocity over weekly intervals at LMN2 gate

4.3.5 Water Particle Travel Time

Water particle travel times (WPTTs) from the tagged fish release location to downstream gates tended to increase over the study as river discharge decreased (Figure 4.14). The apparent speed of water particles tended to decrease over the study and became more temporally variable after cessation of spill on 1 September (Figure 4.15) and turbine operations began more frequent changes.

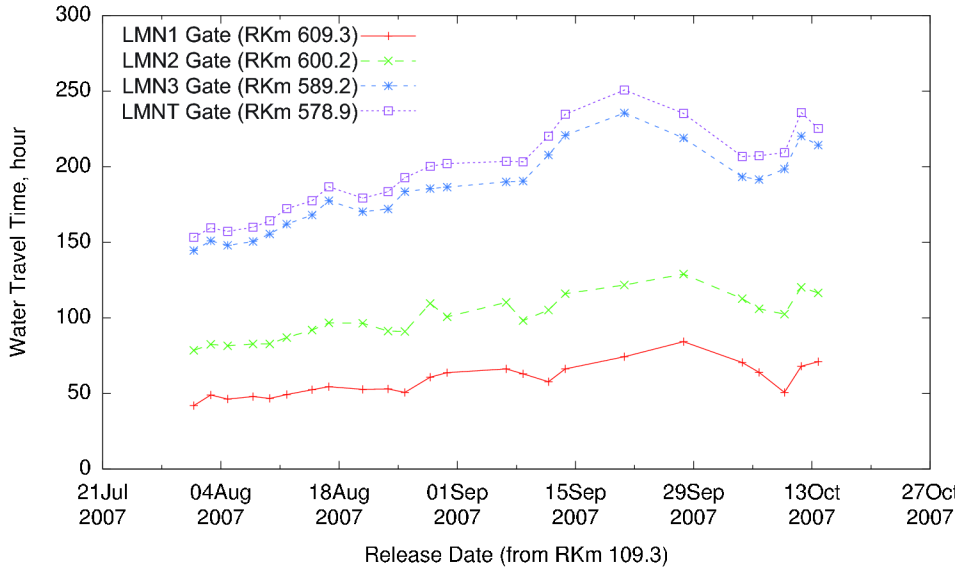

Figure 4.14. Computed travel times of water particles released at same time and location as tagged fish to downstream gate locations

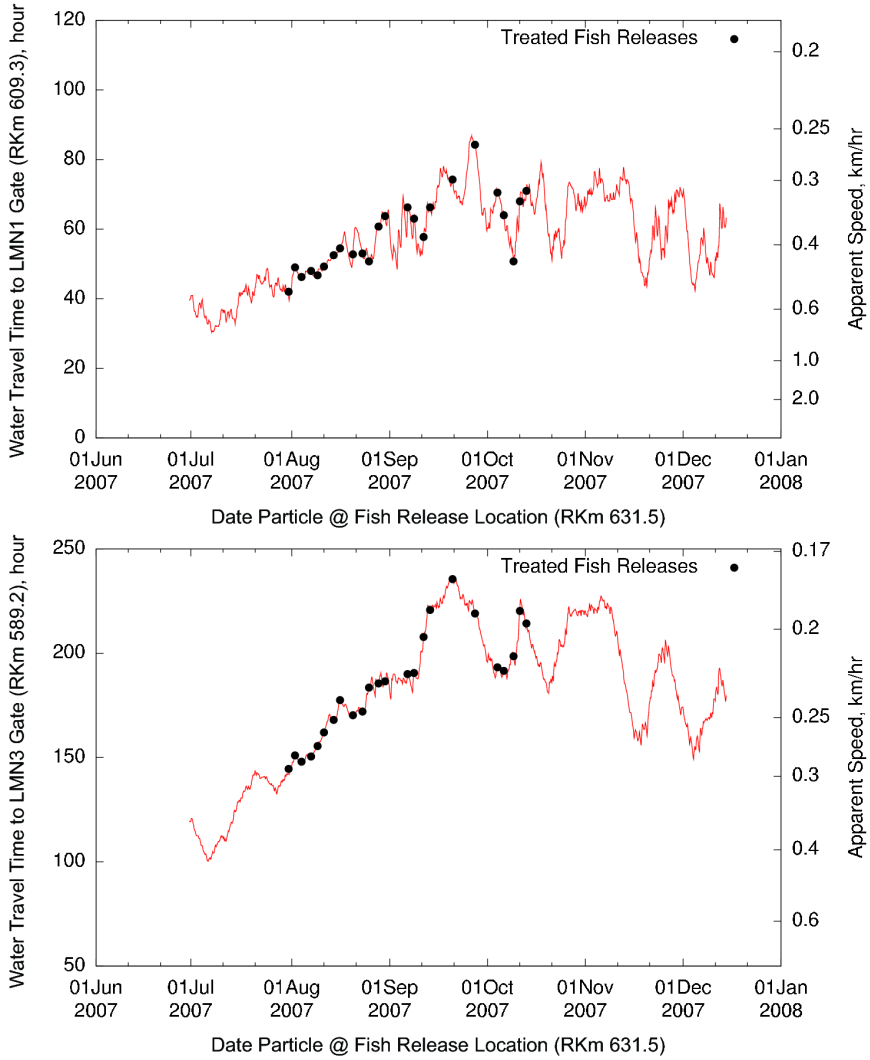

Figure 4.15. Computed water particle travel times and apparent speed from fish release location (RKm 109.3) to LMN1 gate (top) and LMF3 gate (bottom). Acoustic-tagged fish releases are noted by black dots.

4.4 Fate Determination

A total of 1,771 acoustic-tagged subyearling Chinook salmon were released at Little Goose Dam from 31 July 2007 through 13 October 2007. Of these 1,771 fish, 1,154 were detected at the acoustic array at LMN1 before 24 October 2007. These 1,154 fish formed the seven release groups used in the fate determination. An additional 8 fish were detected at LMN1 between 24 October and 26 November 2007 but were not used for fate determination. Of the total 1,162 fish detected at LMN1, 511 were subsequently detected on the Lower Monumental tailrace array or on other acoustic arrays or PIT-tag detectors downstream of Lower Monumental Dam.

The fate determination was based on the 1,154 acoustic-tagged fish that survived to the detection array LMN1, arriving at LMN1 before 24 October 2007. Fate determination was performed only where intrareach acoustic receivers were located, between LMN1 and the tailrace of Lower Monumental Dam.

Smolts that residualized between Little Goose Dam and LMN1 were not part of this analysis. Smolts that crossed the LMN1 array and later migrated back above the LMN1 array were indistinguishable from mortalities in this analysis. Without intrareach nodes between the release location and LMN 1, fish within that reach (24 km) were "invisible" to the fate analysis. Dates of release and periods of acoustic tracking for the seven release groups in the study are illustrated in Figure 4.16. Inference from the tag analysis pertains to the 8-week period following each release.

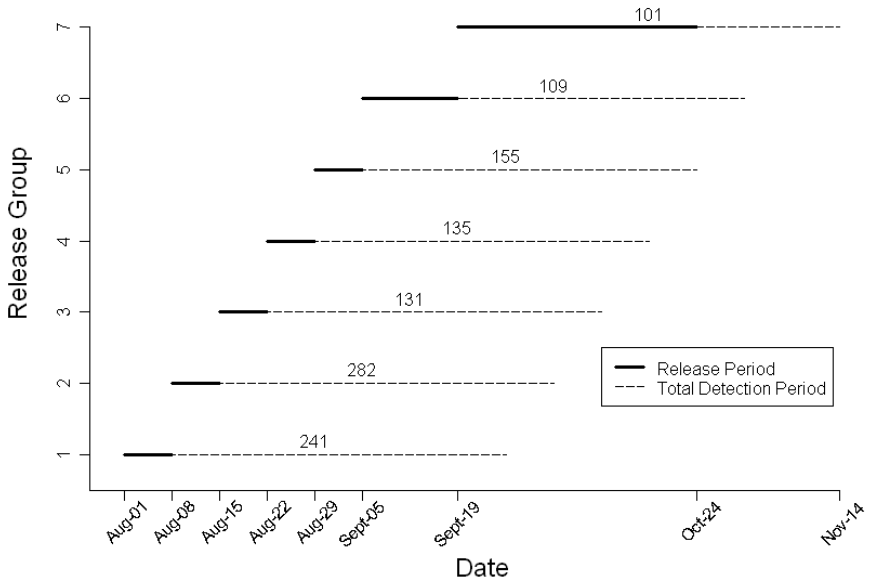

Figure 4.16. Time line of release and acoustic tracking periods for each of seven release groups used in fall Chinook salmon fate study at Lower Monumental Dam. Sample sizes are shown above each release.

The fate analysis is presented at different scales to illustrate and summarize the migration dynamics of fall Chinook salmon within the Lower Monumental reservoir. The first scale of analysis presented is the biweekly fate of each of the seven release groups through the three different reaches examined. These results illustrate the change in fate of the release groups over time as they migrate through the reaches. The second analysis summarizes the fate of each release group within the various reaches by collapsing the information over time of migration (i.e., 8 weeks). The third summary characterizes the fate of each release group over time in the study area. This analysis produces a single summary for each of the seven release groups. Finally, the overall fate of the fish over the study is presented as a weighted average of the release-specific results, weighted proportionally to migrant abundance at the time of the study.

4.4.1 Biweekly Fate Results by Release Group and by Reach

The duration of the migration of the acoustic-tagged subyearling fall Chinook salmon allowed us to examine the fate of the fish over time as they entered and migrated through the three separate reaches of the study (i.e., LMN1 to LMN2, LMN2 to LMF, and LMF to LMT; Figure 3.4). The fate was examined over four biweekly periods (4 × 14 = 56 days) corresponding to the approximately 60-day tag life of the acoustic tags. Within each of these 2-week periods, the fate of the fish from a release group within a study reach was characterized as the conditional probability of migrating downriver and out of the reach

(ϕ), residualizing and/or delaying migration within the reach (ψ), or mortality (μ) (Figure 3.16). These biweekly fates are conditional on the fish entering (from upstream) or being alive in the reach during the 2-week period. While the numbers of fish present from a release group decline over time within a study reach, the conditional probabilities of migrating, delaying migration, or mortality still sum to 1 for that biweekly period.

For example, release group 1 in reach LMN1–LMN2 during the first biweekly period experienced about 20% mortality, about 75% of the fish migrated downriver, and the remaining 5% delayed migration and were alive at the end of the 2-week period (Figure 4.1). In the second biweekly period for the same release group, of those fish present (i.e., just arrived or carried over from the previous period), approximately 90% died, with about 7% migrating and 3% alive but delaying migration. Similar fates were seen for the fish in the third and fourth biweekly periods for release 1 in reach LMN1–LMN2. Hence, early arrivals fared well in this reach, but smolts that delayed migration until later experienced substantially higher risks of mortality.

Across the seven release groups in the first reach (i.e., LMN1–LMN2), there was a trend of decreased mortality and more successful residualization or delayed migration for smolts that arrived later or stayed longer in the reach (Figure 4.17). By the time of the sixth release group, most of the smolts either migrated or successfully delayed migration (Figure 4.17) within this reach. The last release group showed a reversal to this overall studywide trend.

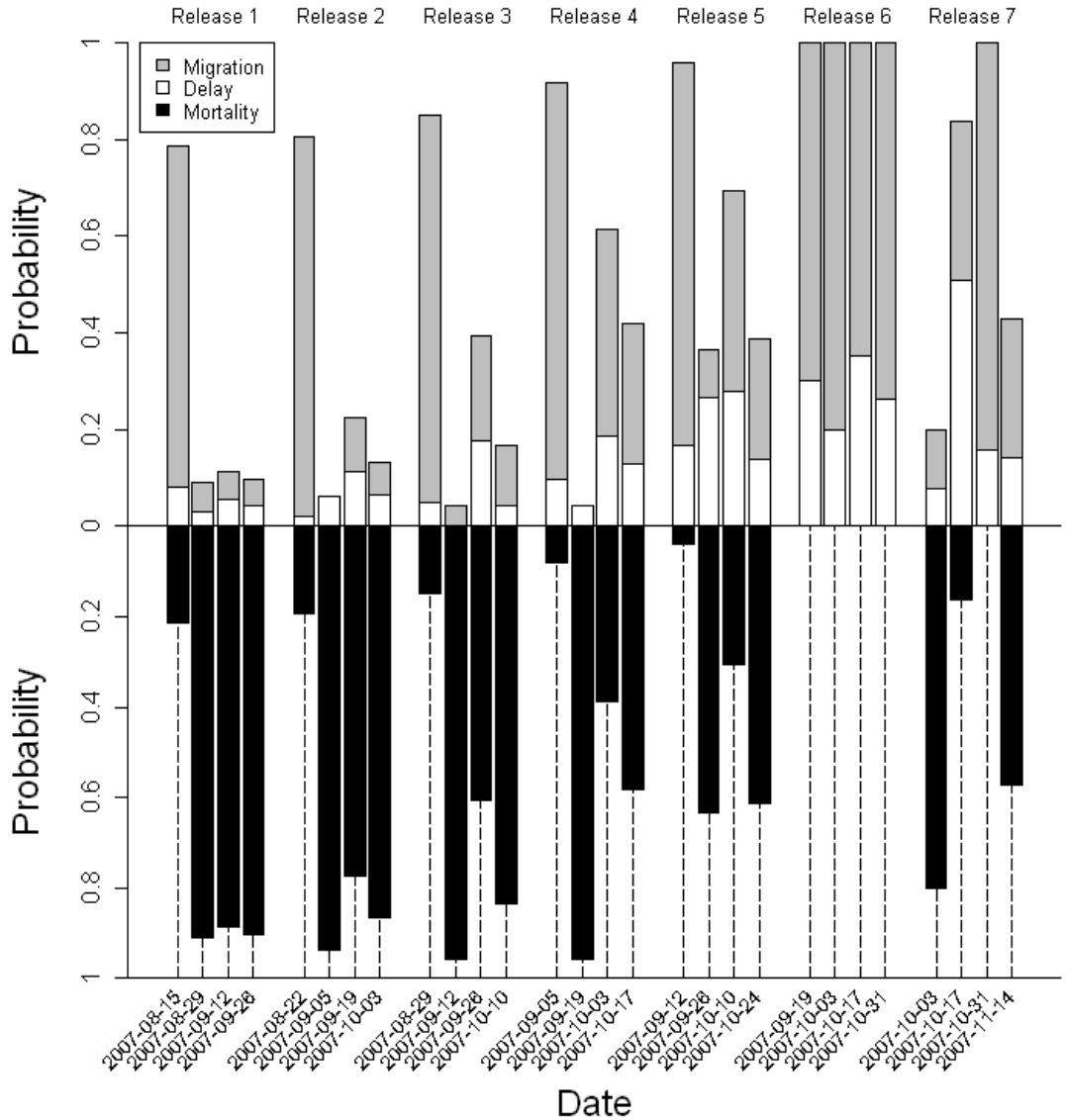

Figure 4.17. Biweekly conditional probabilities of migrating (ϕ), delaying migration and surviving (ψ), or mortality (μ) for each of the seven release groups in the reach LMN1 to LMN2

In the reach LMN2–LMF, a very similar pattern in fate was observed as previously observed in reach LMN1–LMN2. For the earlier release groups (e.g., 1–3), late arrival or delayed migration in biweekly periods 2–4 usually resulted in mortality (Figure 4.18). As the study progressed, smolts arriving or delaying migration to later biweekly periods had greater probabilities of surviving and migrating (ϕ) or surviving and delaying migration (ψ). By releases 6 and 7, most smolts either successfully migrated through this reach or were still alive at the end of the tracking periods.

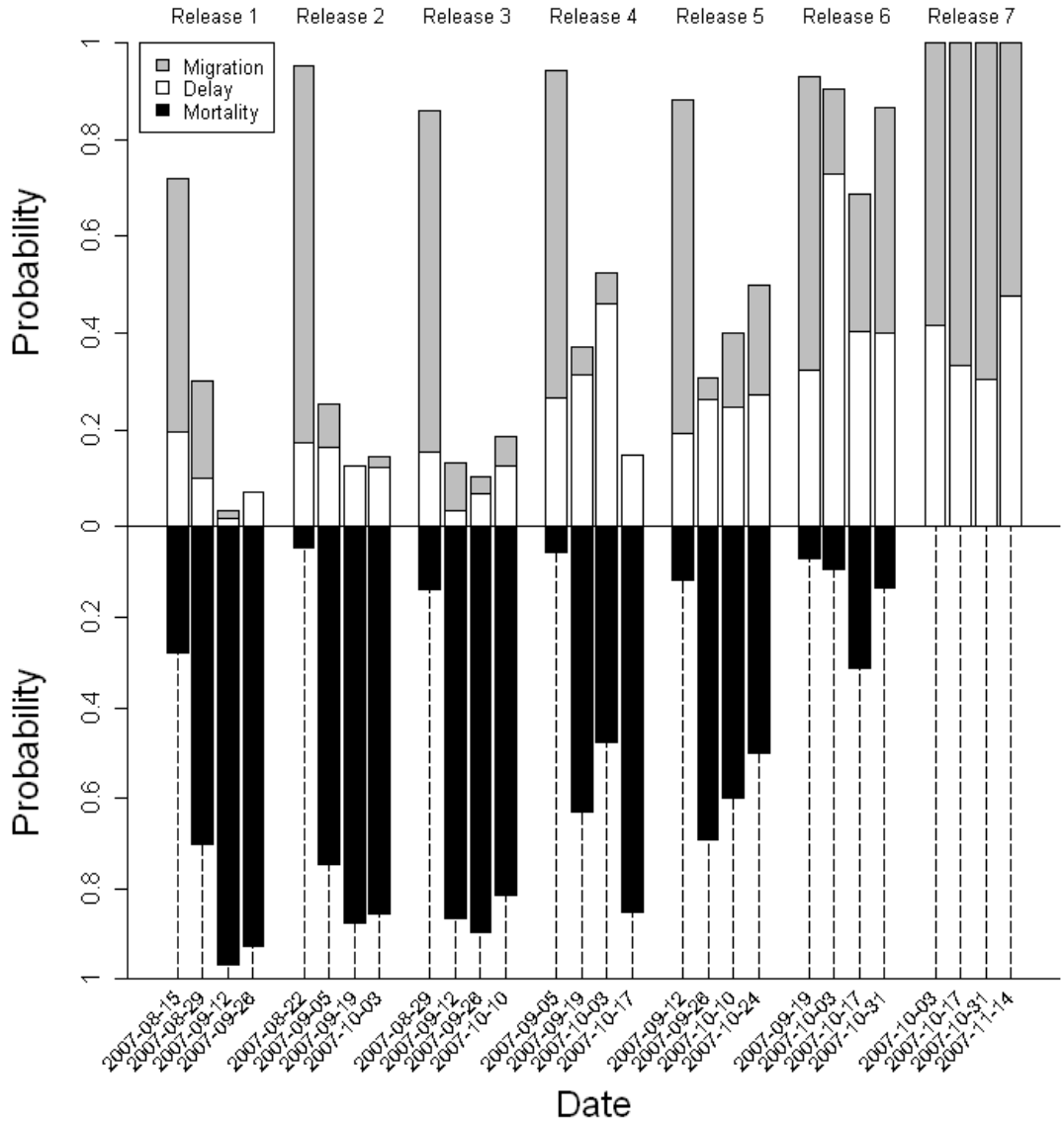

Figure 4.18. Biweekly conditional probabilities of migrating (ϕ), delaying migration and surviving (ψ), or mortality (μ) for each of the seven release groups in the reach LMN2 to LMF

In the last reach monitored (LMF–LMT), very little residualization was detected over the study for releases 1–5 (Figure 4.19). Again, early arrivals to the reach had a high probability of successful migration to the tailrace. Smolts that arrived in the later biweekly periods or delayed migration had high probabilities of mortality. Not until releases 6 and 7 was there any sign of appreciable migration delay. Those smolts that arrived later or delayed migration until later biweekly periods had greater chances of residualizing, delaying migration, or eventually migrating (Figure 4.19).

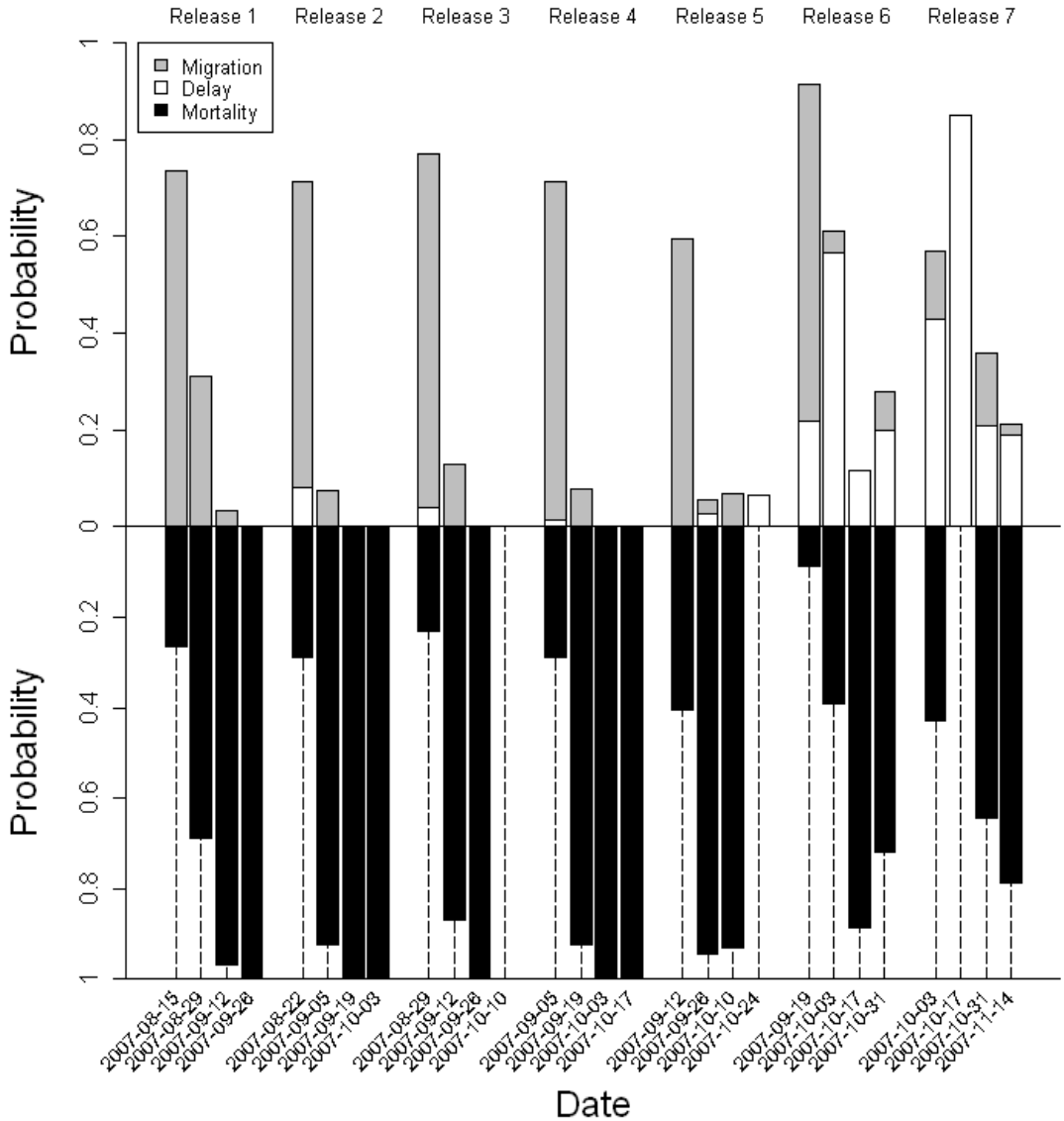

Figure 4.19. Biweekly conditional probabilities of migrating (ϕ), delaying migration and surviving (ψ), or mortality (μ) for each of the seven release groups in the reach LMF to LMT

4.4.2 Fate Summarized Over Time within a Release Group by Reach

The four biweekly estimates of conditional fate within a reach (Figures 4.17–4.19) can be collapsed over time to provide estimates of fate by release group within each study reach (Table 4.1). Interpretation of the results is enhanced by graphs of the data (Figures 4.20 through 4.22).

In the first study reach (LMN1–LMN2), early release groups experienced mortality that gradually decreased from approximately 23% at the beginning of the study to virtually no detectable mortality by the end of the study (i.e., releases 6 and 7) (Figure 4.20). Residualization or delayed migration gradually increased over the study, from 2–4% for the initial releases to 7–8% by the final releases.

Table 4.1. Estimates and standard errors of ϕ (joint probability of migration and survival), ψ (joint probability of delay and survival), and μ (probability of mortality) in reaches 2 (LMN1 to LMN2), 3 (LMN2 to LMF1), and 4 (LMF1 to LMT) during the 8 weeks of detection for each release group

Release Group	Reach	$\hat{\phi}$	$\widehat{\mathrm{SE}}(\hat{\phi})$	$\hat{\psi}$	$\widehat{\mathrm{SE}}(\hat{\psi})$	$\hat{\mu}$	$\widehat{\mathrm{SE}}(\hat{\mu})$
1	LMN1 – LMN2	0.7262	0.0287	0.0415	0	0.2323	0.0287
2	LMN1 – LMN2	0.7908	0.0242	0.0284	0	0.1808	0.0242
3	LMN1 – LMN2	0.8321	0.0327	0.0305	0	0.1374	0.0327
4	LMN1 – LMN2	0.8518	0.0306	0.0593	0	0.0889	0.0306
5	LMN1 – LMN2	0.8452	0.0291	0.0903	0.0134	0.0645	0.0320
6	LMN1 – LMN2	0.9266	0.0250	0.0734	0.0250	0	NA
7	LMN1 – LMN2	0.9208	0.0269	0.0792	0.0269	0	NA
1	LMN2 – LMF	0.6286	0.0365	0.0343	0.0014	0.3371	0.0365
2	LMN2 – LMF	0.7982	0.0269	0.0460	0.0029	0.1559	0.0270
3	LMN2 – LMF	0.7248	0.0428	0.0367	0.0014	0.2385	0.0428
4	LMN2 – LMF	0.6870	0.0432	0.0435	0.0016	0.2696	0.0433
5	LMN2 – LMF	0.7633	0.0371	0.1090	0.0059	0.1277	0.0376
6	LMN2 – LMF	0.7822	0.0411	0.2178	0.0411	0	NA
7	LMN2 – LMF	0.8817	0.0335	0.1183	0.0335	0	NA
1	LMF – LMT	0.7481	0.0480	0	NA	0.2519	NA
2	LMF – LMT	0.6530	0.0358	0.0056	0.0003	0.3413	0.0358
3	LMF – LMT	0.7216	0.0504	0	NA	0.2784	NA
4	LMF – LMT	0.6872	0.0551	0	NA	0.3128	NA
5	LMF – LMT	0.5646	0.0519	0.0900	0.0450	0.3454	0.0687
6	LMF – LMT	0.4874	0.0602	0.1392	0.0764	0.3733	0.0973
7	LMF – LMT	0.2684	0.0901	0.1402	0.0532	0.5914	0.1047

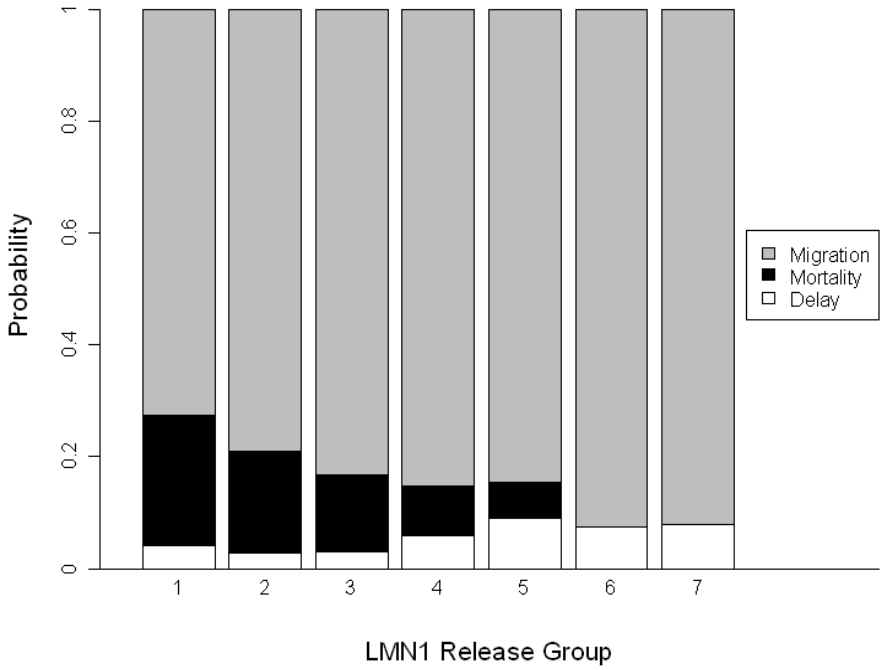

Figure 4.20. Overall estimates of migration and survival (ϕ), delay and survival (ψ), and mortality (μ) between LMN1 and LMN2 for each of the seven release groups. See Figure 4.16 for release periods and detection periods for each release group.

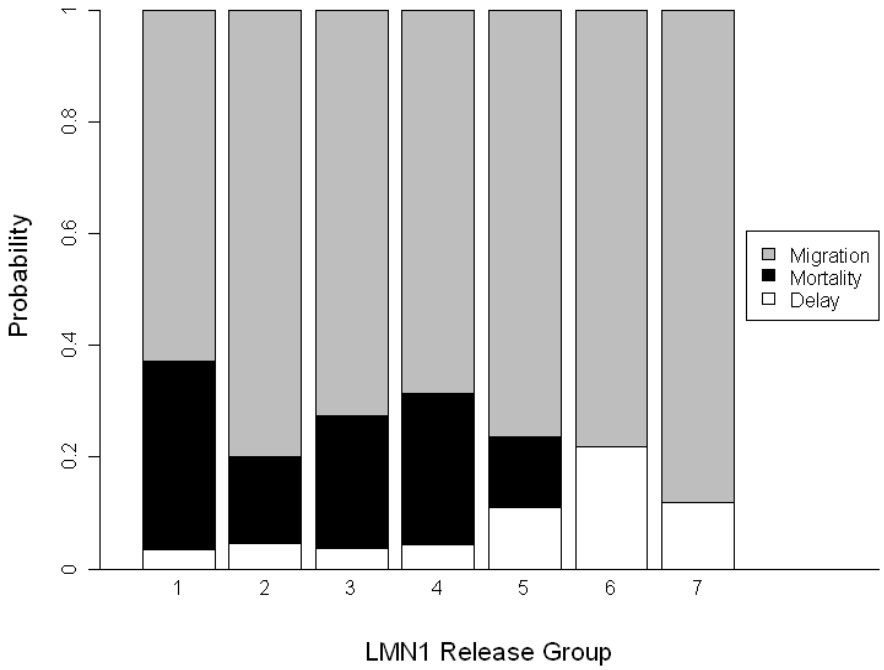

Figure 4.21. Overall estimates of migration and survival (ϕ), delay and survival (ψ), and mortality (μ) between LMN2 and LMF1 for each of the seven release groups. See Figure 4.16 for release periods and detection periods for each release group.

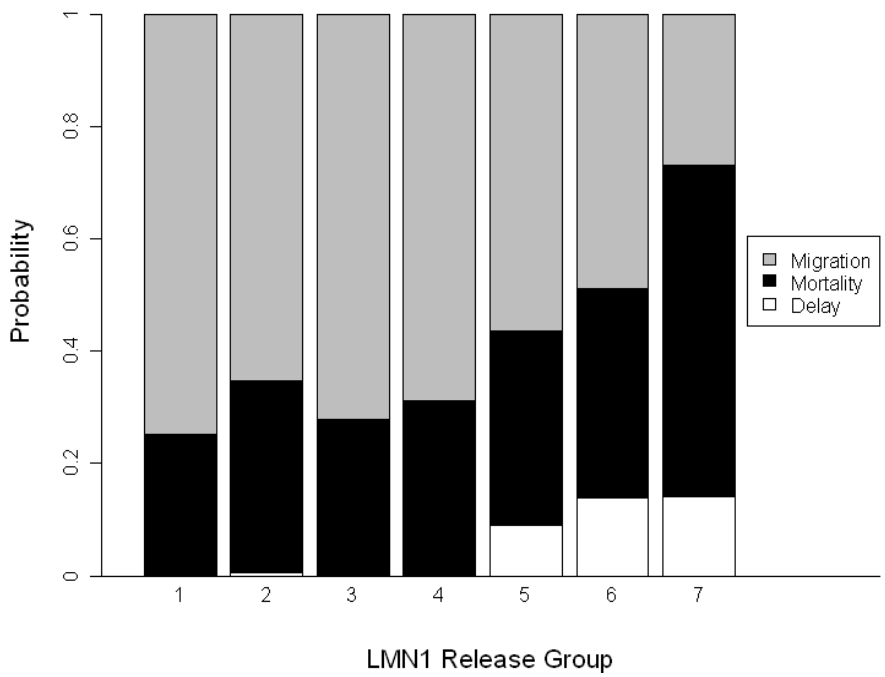

Figure 4.22. Overall estimates of migration and survival (ϕ), delay and survival (ψ), and mortality (μ) between LMF1 and LMT for each of the seven release groups. See Figure 4.16 for release periods and detection periods for each release group.

In the Lower Monumental forebay (reach LMF to LMT), the first four releases exhibited virtually no residualization or delayed migration (Figure 4.22). By the end of the study, releases 6 and 7 were experiencing rates of delayed migration of 13–14%. Mortality in the forebay ranged from 25–30% at the beginning of the study to as much as 59% by the time of the last release group (Figure 4.22). This increased trend in mortality in the forebay is in contrast with the decline in mortality observed in the upper reaches over time.

4.4.3 Fate Summaries by Release Group

By combining the fate results over reaches for a release group (Section 4.4.2), the overall fate of a release group from LMN1 to LMT can be summarized (Table 4.2, Figure 4.23). These summaries depict the change in fate within the reservoir (i.e., LMN1 to LMT) over time. Overall, there was a trend of increasing residualization or delayed migration from release 1 to release 7. Overall residualization was as small as 6 7% for the first three release groups, increasing to as much as 24–37% for releases 5–7. The probabilities of migration over the study were relatively stable, ranging from 21% to 43%.

Table 4.2. Estimates and standard errors of ϕ (joint probability of migration and survival), ψ (joint probability of delay and survival), and μ (probability of mortality) within the study area (i.e., between the arrays at LMN1 and LMT) during the 8 weeks of detection after release for release groups 1–7. See Figure 4.16 for release periods and detection periods for each release group.

Release Group	Release Size	$\hat{\phi}$	$\widehat{\mathrm{SE}}(\hat{\phi})$	$\hat{\psi}$	$\widehat{\mathrm{SE}}(\hat{\phi})$	$\hat{\mu}$	$\widehat{\mathrm{SE}}(\hat{\mu})$
1	241	0.3415	0.0325	0.0664	0	0.5921	0.0325
2	282	0.4122	0.0294	0.0683	0.0020	0.5195	0.0294
3	131	0.4352	0.0433	0.0611	0	0.5038	0.0433
4	135	0.4021	0.0435	0.0963	0	0.5016	0.0435
5	155	0.3642	0.0399	0.2405	0.0320	0.3953	0.0512
6	109	0.3533	0.0484	0.3761	0.0697	0.2706	0.0736
7	105	0.2179	0.0739	0.3020	0.0579	0.4801	0.0895

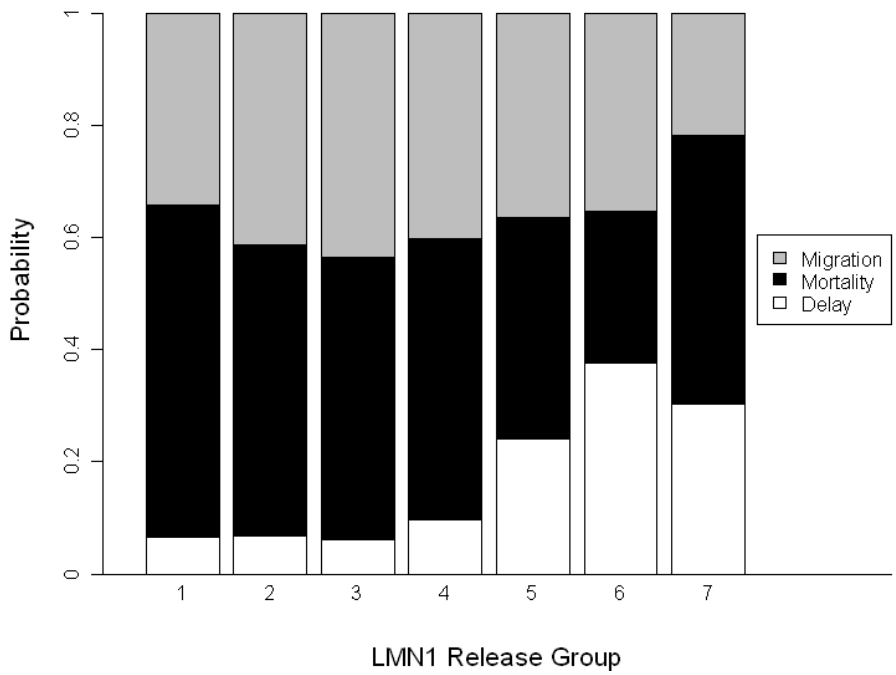

Figure 4.23. Overall estimates of the probability of migration and survival (ϕ), delay and survival (ψ), and mortality (μ) in the study area (i.e., between the arrays at LMN1 and LMT) for each of the seven release groups. See Figure 4.16 for release periods and detection periods for each release group.

Mortality generally declined over the study (i.e., releases 1–6) with the change in fate going to more residualization or delayed migration. Release 7 showed an abrupt jump in mortality after successive declines in mortality earlier in the season (Figure 4.23).

4.4.4 Studywide Fate Results

The final characterization of the 2007 fall Chinook salmon acoustic-tag study is an estimate of studywide fate. Using the results from the separate releases (Figure 4.23), overall study results were calculated as a weighted average of the individual release results. The individual release results were weighted by the Fish Passage Center (FPC) fall Chinook salmon passage index at Little Goose Dam (Figure 4.24). The average passage index at time of release was used as a weighting factor. Consequently, results from the earlier releases (Table 4.2) contributed more than did later releases to the overall fate across the study.

Based on the weighted average of individual release results (Table 4.2), the tagging data estimated 36.1% ($\widehat{\text{SE}}$ = 1.8%) of the smolts migrated successfully through the study area. Another 10.6% ($\widehat{\text{SE}}$ = 0.5%) residualized or delayed migration and were still alive at the end of the 8-week tracking period. The balance, 53.3% ($\widehat{\text{SE}}$ = 1.9%), were estimated to have died during migration or extended rearing (Figure 4.25).

Based on the detection design, it is reasonable to conclude that at least 46.9% (i.e., 36.1% + 10.6%) of the fall Chinook salmon smolts successfully migrated or were still alive in the reach (i.e., LMN1–LMT) by the end of the acoustic-tracking periods. It is possible, however, that some of the estimated 53.3% mortality may include undiagnosed residualization. Because the reach from Little Goose to LMN1 was not monitored for residualization, it is possible that some of the smolts that entered the study (i.e., those that were detected at LMN1) may have moved back upstream above LMN1 undetected and were presumed to be mortalities based on the nature of the calculations.

Of the 1,162 smolts in the study that arrived at LMN1, 25 were detected only at that array, and another 79 moved downstream but eventually were last detected at LMN1. These fish constituted 8.95% (i.e., $(25+79)/1162$) of the study fish, some of which might have moved into the unmonitored upper reach and unwittingly contributed to the mortality estimate. Based on roughly a 50% mortality for smolts in the lower study reaches, perhaps as much as 4.5% (i.e., 8.95% × 0.50) of the mortality in the study may have been misidentified, but not likely much more. For this reason, it is reasonable to conclude that the actual smolt mortality may be between 48.8 and 53.3%.

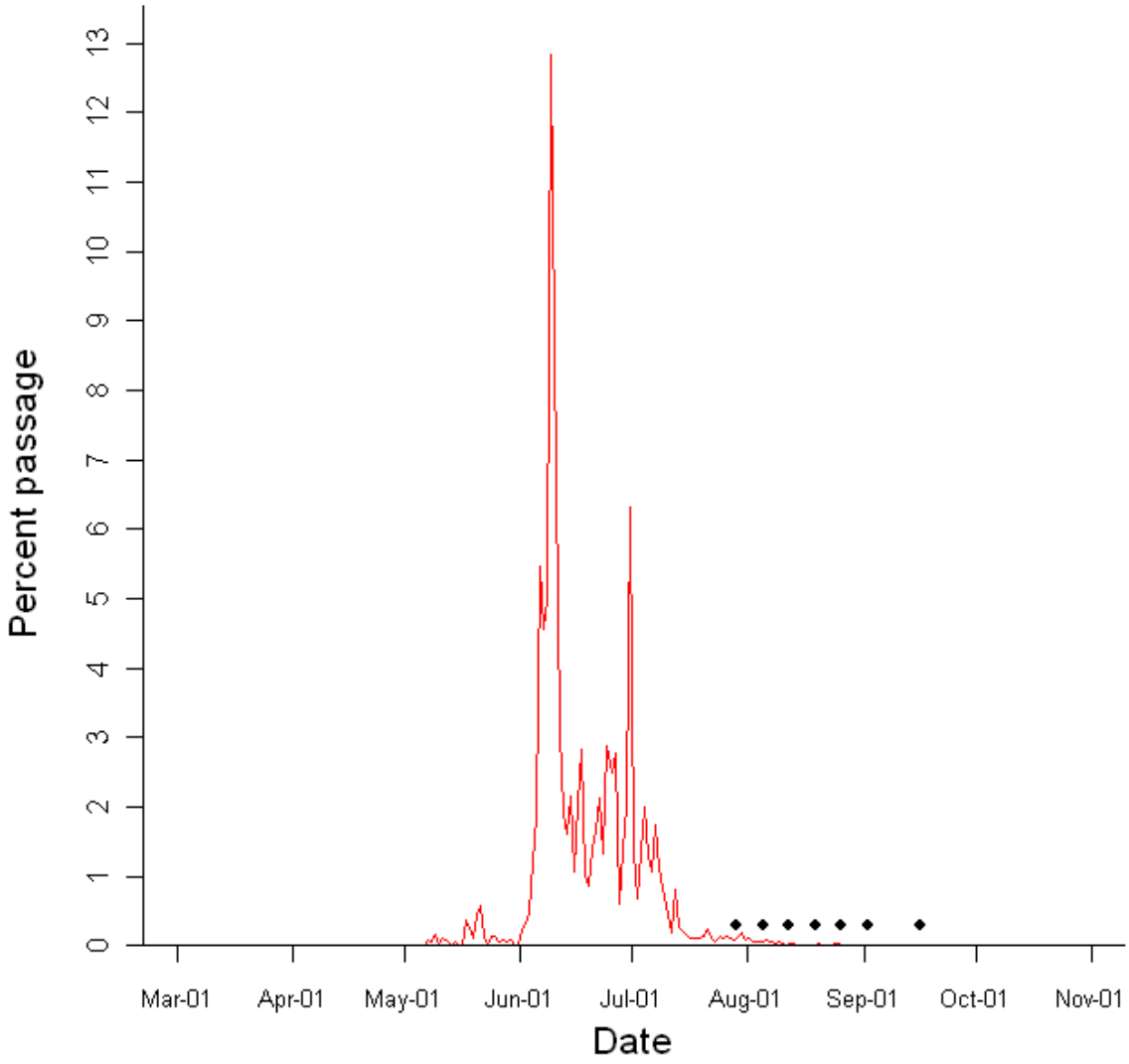

Figure 4.24. Daily smolt passage index for fall Chinook salmon smolts as reported by Fish Passage Center over time in 2007, and indications (♦) of the release dates for the seven release groups used in fate determination in the 2007 Lower Monumental study

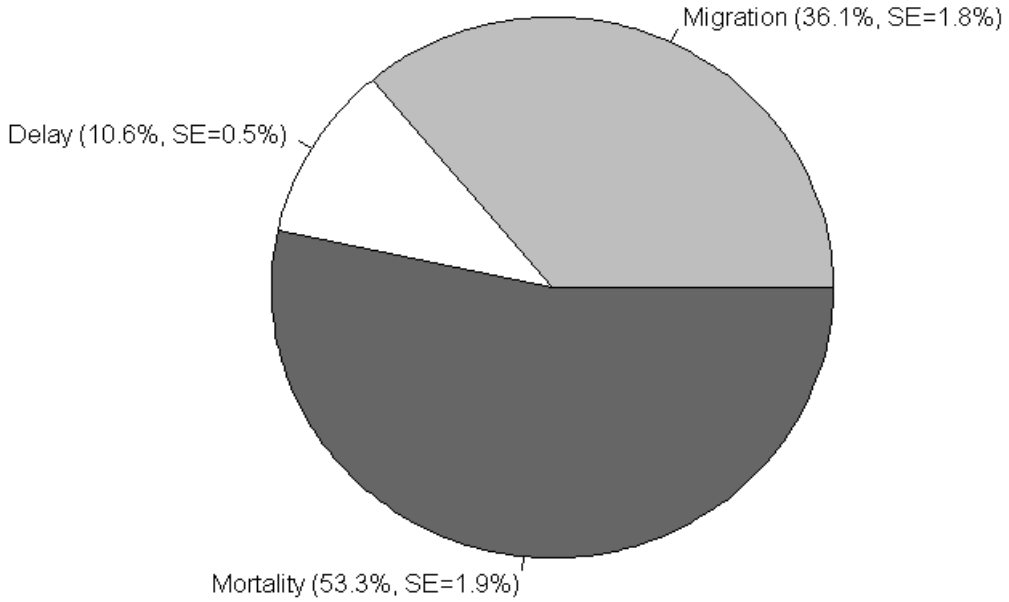

Figure 4.25. Summary of studywide fate analysis based on a weighted average of release-specific results, using weighting proportional to FPC smolt passage index for fall Chinook salmon at Little Goose Dam

4.5 PIT-Tag Data: Data Summary

Each of the 1,771 subyearling Chinook salmon that were acoustic-tagged at Little Goose was also PIT-tagged. Of these 1,771 PIT-tagged fish, 253 (14.3% of those released) unique fish were detected on PIT-tag detectors at Lower Monumental Dam or downstream before the PIT-tag detection system was turned off in December, 7 of which were also detected after the detection system resumed operation in March 2008. An additional 64 unique fish (3.6% of those released) were detected on PIT-tag detectors before 23 May 2008 (when PIT-tag data were downloaded from the PTAGIS database), but not in 2007. The proportion of fish detected in the PIT-tag system during spring 2008 was higher for the later release groups than it was for the groups released earlier (e.g., prior to September; Figure 4.26).

Use of PIT-tag detections to compute estimated joint probabilities of survival and migration for comparison to estimates based on detections of acoustic transmitters is presented in Chapter 5 of this report.

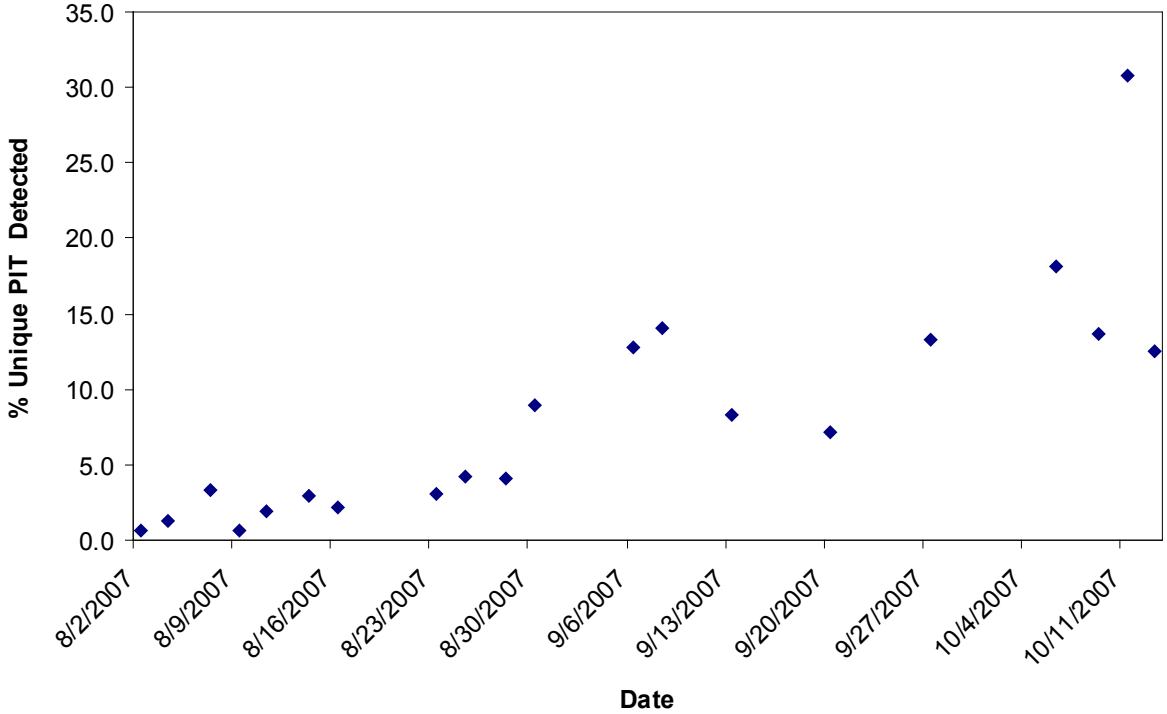

Figure 4.26. Proportion of PIT-tagged fall Chinook salmon (fish also were double tagged; a PIT tag and an acoustic tag) released downstream of Little Goose Dam in summer/fall 2007 subsequently detected by PIT-tag detection systems at Lower Monumental Dam or downstream during spring 2008 (17 March through 22 May 2008)

4.6 Covariate Analyses

Numerous covariates describing the river environment and fish condition at time of tagging were measured throughout the study. Relationships between these covariates and the joint probability of migrating and surviving through each reach were explored, as well as relationships between covariates and travel time through each reach. Descriptions of the distributions of fish condition covariates (i.e., ATPase, length, and weight at time of tagging) are presented first, followed by results of the covariate effects analyses for migration and survival (ϕ) and travel time.

4.6.1 Fish Condition at Tagging and Studywide Migration and Survival

The distribution of ATPase, length, and weight among acoustic-tagged fall Chinook salmon that were detected downstream of Lower Monumental Dam either by acoustic tag or PIT tag in 2007, or by PIT tag by 29 April 2008, was compared to the analogous distribution among those tagged fish that were not detected downstream of Lower Monumental. There was little discernable difference between the ATPase distributions for the two groups of fish (Figure 4.27) and no difference between groups of fish by release (Figure 4.28). Among fish detected downstream of Lower Monumental, ATPase at tagging ranged from 1.72 to 9.78, with an average of 4.45 (Figure 4.27). Among fish that were not detected downstream of Lower Monumental, ATPase ranged from 1.09 to 9.04, with an average value of 4.37. ATPase was not correlated with release date at Little Goose Dam (−0.021; Figure 4.29).

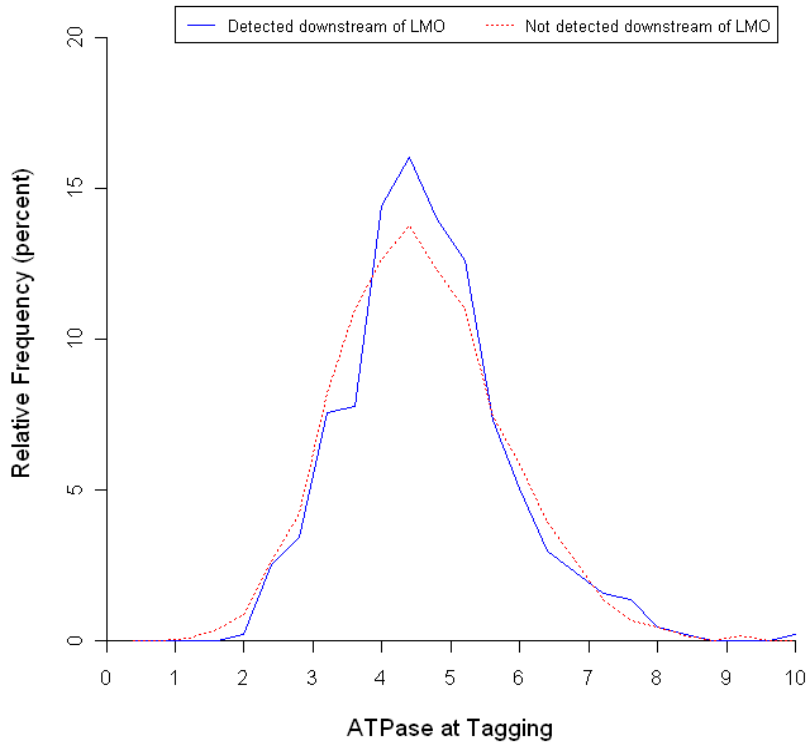

Figure 4.27. Distribution of ATPase at time of tagging for fish detected downstream of Lower Monumental Dam in 2007 or by 29 April 2008, and for fish not detected downstream of Lower Monumental Dam

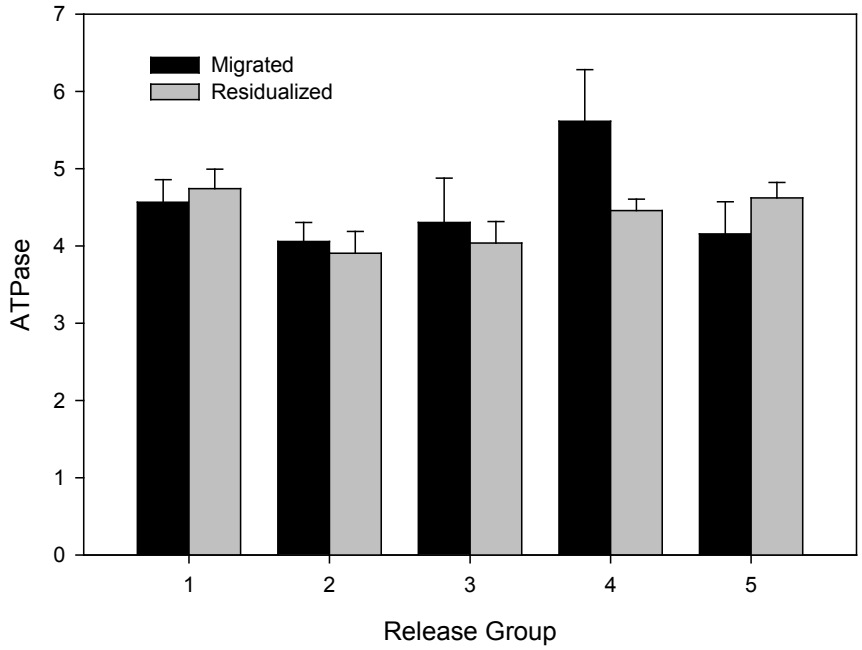

Figure 4.28. Mean ATPase of acoustic-tagged juvenile Chinook salmon that migrated out of Lower Monumental Reservoir or residualized within the reservoir. Error bars are one standard error.

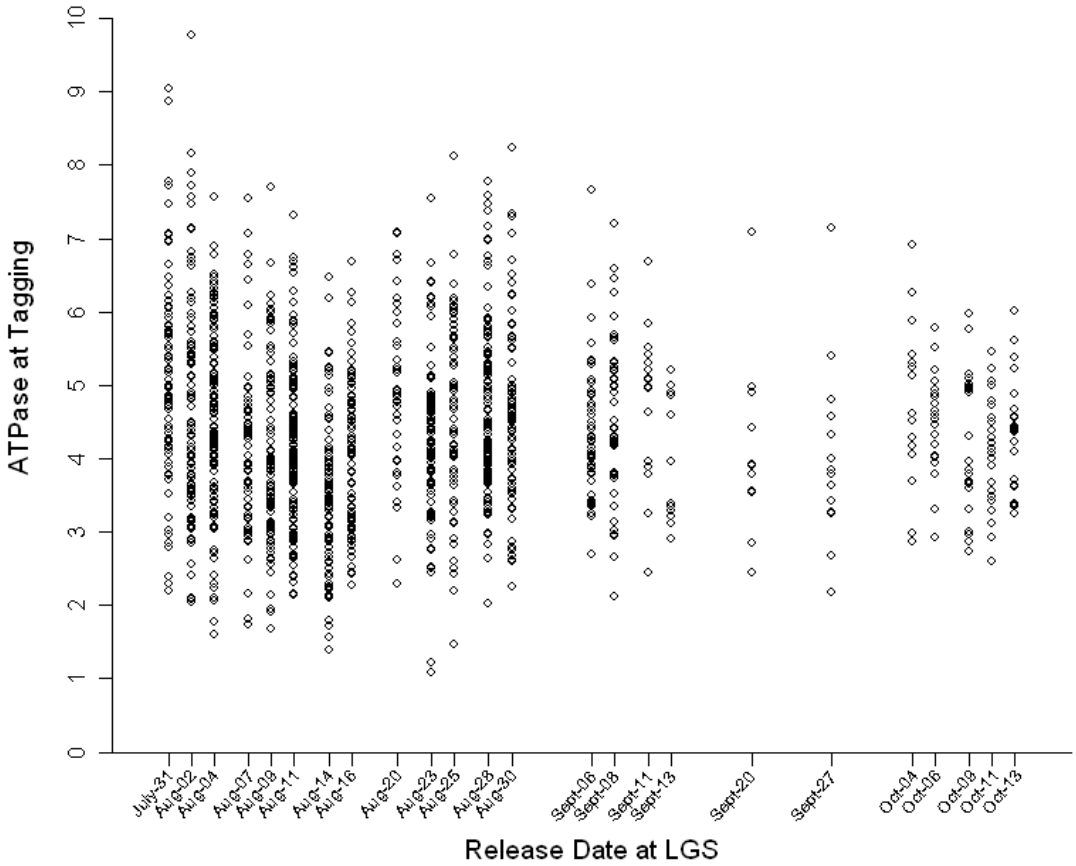

Figure 4.29. ATPase at time of tagging versus date of release at Little Goose Dam for acoustic-tagged subyearling fall Chinook salmon in 2007 acoustic-tag study

On average, the group of acoustic-tagged fall Chinook salmon detected downstream of Lower Monumental Dam in 2007 or by 29 April 2008 was slightly larger in length than the group of tagged fish not detected downstream of Lower Monumental (Figure 4.30). However, the length distributions of these two groups overlapped considerably. Fish detected downstream of Lower Monumental had length at tagging ranging from 124 to 230 mm, with an average length of 163 mm (Figure 4.30), while fish last detected upstream of Lower Monumental or never detected had length at tagging ranging from 109 to 229 mm, with an average length of 156 mm. Length at tagging was highly correlated with release date at Little Goose ($\hat{\rho}$ = 0.8357; Figure 4.31).

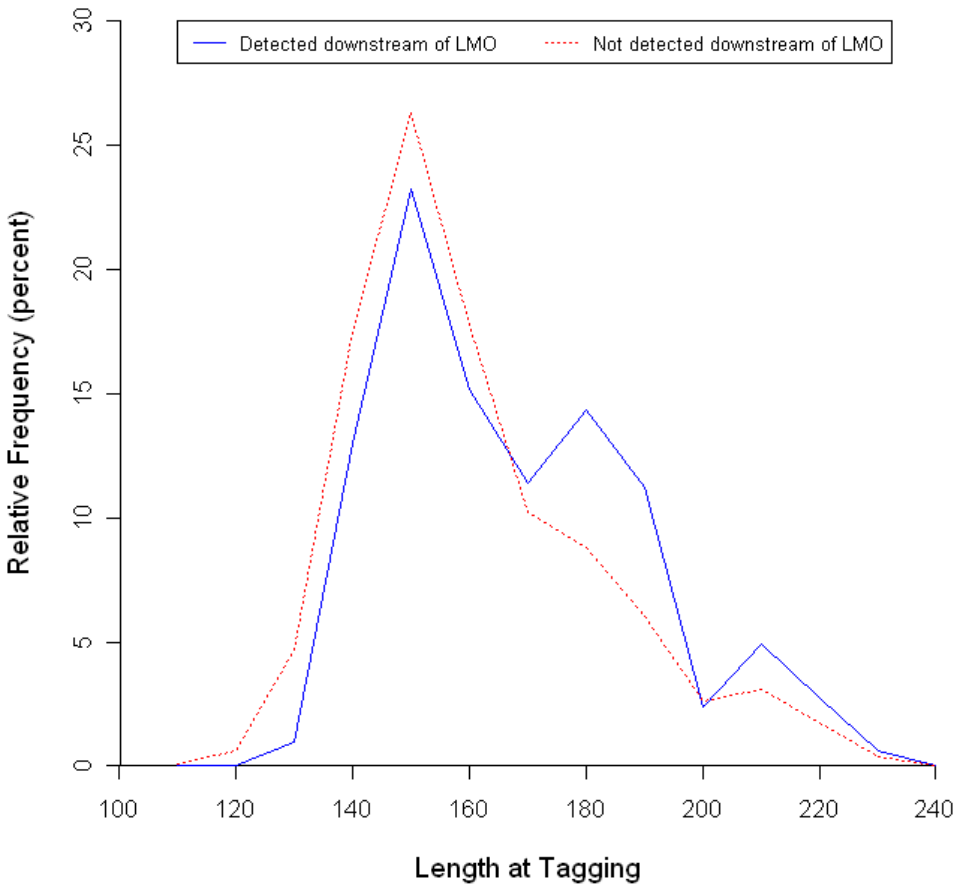

Figure 4.30. Distribution of length at tagging (mm) for fish detected downstream of Lower Monumental Dam in 2007 or by 29 April 2008, and for fish not detected downstream of Lower Monumental Dam

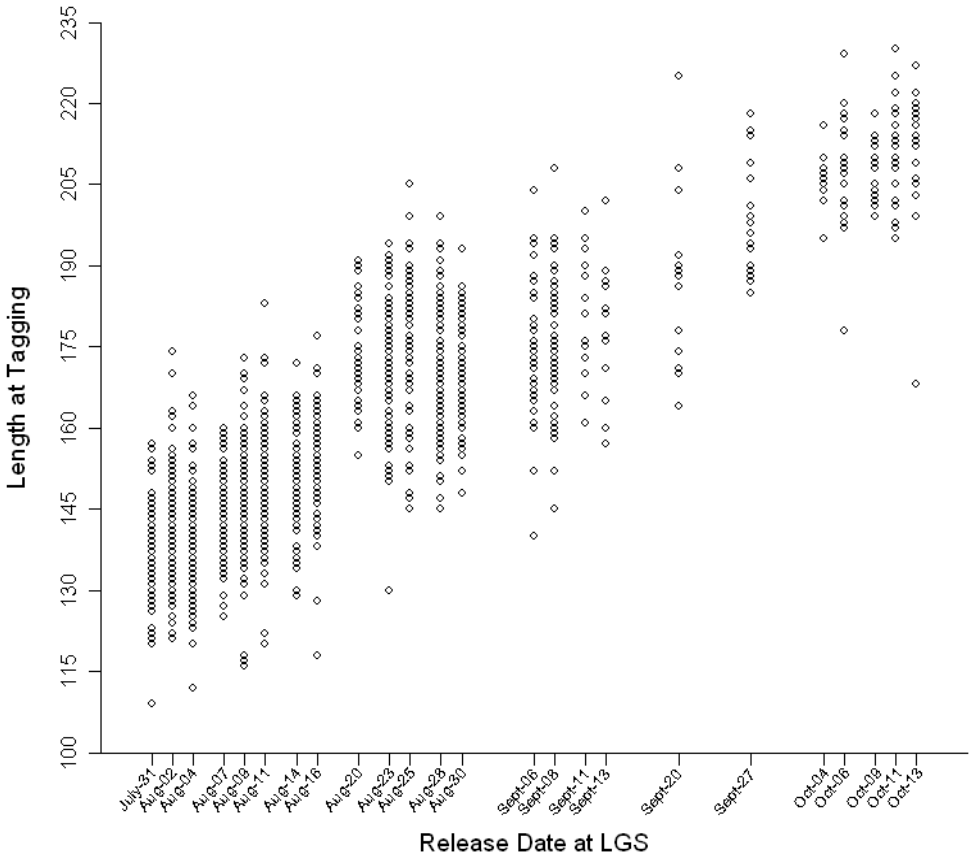

Figure 4.31. Length at tagging (mm) versus date (2007) of release at Little Goose Dam for acoustic-tagged subyearling fall Chinook salmon

On average, weight at tagging was slightly greater for acoustic-tagged fall Chinook salmon subsequently detected downstream of Lower Monumental Dam in 2007 or by 29 April 2008, compared to fish last detected upstream of Lower Monumental or never detected (Figure 4.32). However, the weight distributions of these two groups overlapped considerably. Among the tagged fish detected downstream of Lower Monumental, weight at tagging ranged from 20.9 to 155.5 g, with an average of 51.7 g. Among those tagged fish last detected upstream of Lower Monumental or never detected, weight at tagging ranged from 13.2 to 141.7 g, with an average of 44.9 g. Weight at tagging was highly correlated with release date at Little Goose ($\hat{\rho} = 0.8204$; Figure 4.33).

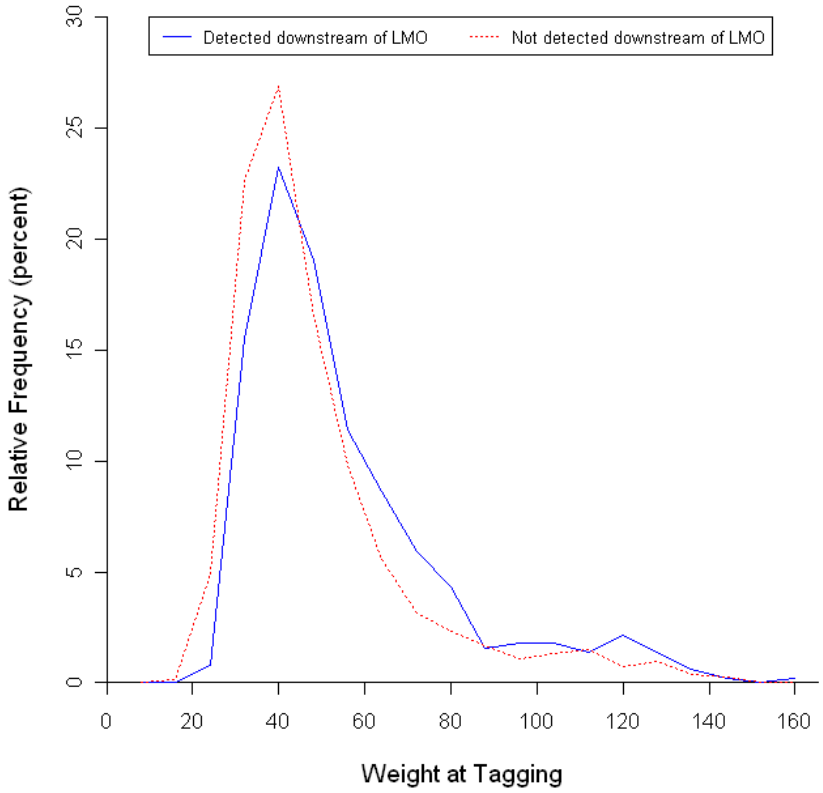

Figure 4.32. Distribution of weight (g) at tagging for fish detected downstream of Lower Monumental Dam in 2007 or by 29 April 2008, and for fish not detected downstream of Lower Monumental Dam

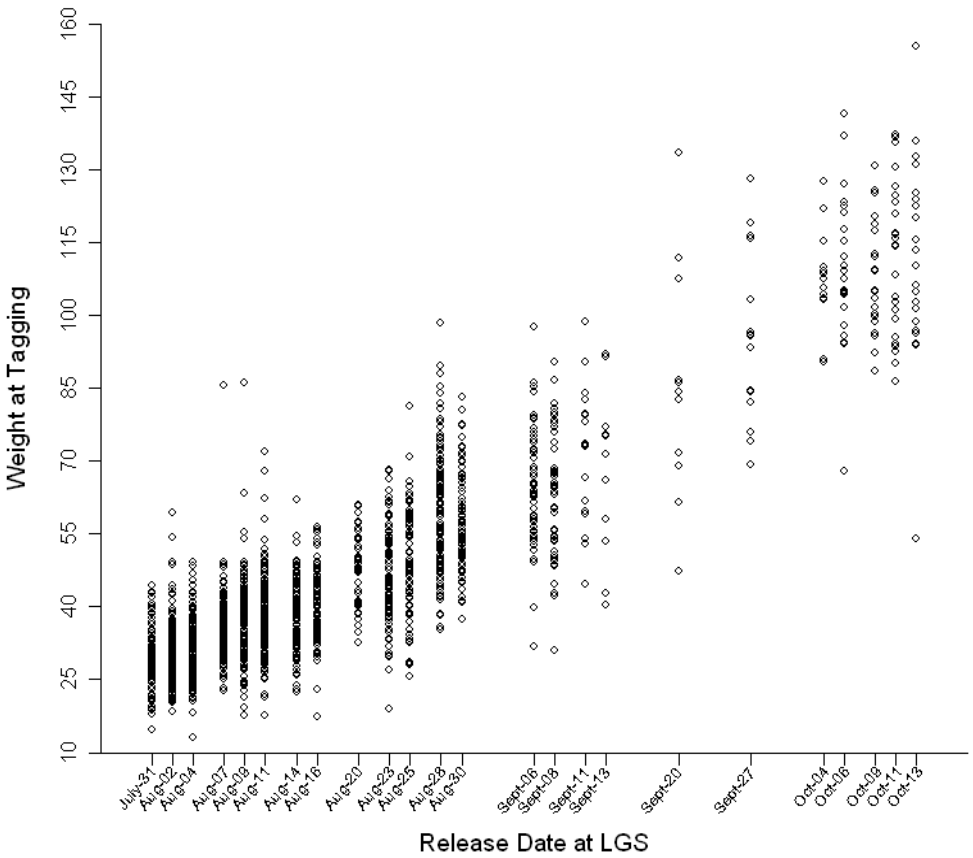

Figure 4.33. Weight at tagging (g) versus date of release (2007) at Little Goose Dam for acoustic-tagged subyearling fall Chinook salmon

4.6.2 Far-Field Migration and Survival

Relationships were explored between the joint probability of migration and survival (ϕ) estimated on the biweekly reach scale, and group-based covariates describing the river environment and fish condition at time of tagging for the individual far field reaches LMN1–LMN2 and LMN2–LMF. Covariates representing temporal processes (e.g., release group, detection period) were also explored in single-variate analyses. For each reach, there were 28 observations (7 release groups by 4 biweekly detection periods). Results for each reach are reported separately.

Results from single-variate effects analyses relating the probability of migrating and surviving through the reach from LMN1 to LMN2 showed no significant effect of either environmental, fish condition, or temporal measures (Table 4.3). No further analysis was performed for migration and survival through this reach.

Table 4.3. Results of single-variable covariate analyses for survival and migration through the reach from LMN1 to LMN2. The response variable was $y = \ln\left(-\ln\left(\hat{\phi}\right)\right)$, based on a proportional hazards model. Group-based covariates were used. Covariates are ordered by *P*-value.

Covariate Code	Covariate	*P*-value	R^2
x_{17}	River regime	0.1802	0.1281
x_5	Stratification at LMN4T	0.1986	0.0627
x_{44}	Detection period	0. 2792	0.1452
x_{48}	ATPase	0.4224	0.0249
x_{45}	Fish length	0.4875	0.0187
x_{47}	Fish condition factor (K)	0.4953	0.0181
x_{19}	Water particle travel time	0.5425	0.0144
x_{28}	Spill proportion at LMO	0.5727	0.0124
x_{41}	Release group at LMN1	0.6659	0.1631
x_{46}	Fish weight	0.7206	0.0050
x_{26}	Spill at LMO	0.7240	0.0049
x_{24}	Discharge at LMO (CV)	0.8838	0.0008
x_{20}	Water velocity through reach (CV)	0.9023	0.0006
x_{23}	Discharge at LMO	0.9347	0.0003

The joint probability of migrating and surviving (ϕ) through the reach from LMN2 to LMF1 was correlated with several covariates (Table 4.4). The categorical covariate representing release group was the most significant factor, accounting for approximately 57% of the variability in the migration probability ($P = 0.0036$; Table 4.4). Other significant covariates included ATPase at tagging, water particle travel time through the reach, and spill, spill proportion, discharge, and the variability in discharge at Lower Monumental. The categorical variables representing the biweekly detection period and the presence of both spill and temperature stratification (i.e., river regime) also had significant effects (Table 4.4). Except for release group, each significant covariate explained relatively little of the variability in migration probability in the reach from LMN2 to LMF1, with R^2 values ranging from 0.1065 for the CV of discharge at LMO to 0.2112 for ATPase at tagging (Table 4.4).

Table 4.4. Results of single-variable covariate analyses for survival and migration through the reach from LMN2 to LMF1. The response variable was $y = \ln\left(-\ln\left(\hat{\phi}\right)\right)$, based on a proportional hazards model. Group-based covariates were used. Covariates are ordered by *P*-value.

Covariate Code	Covariate	*P*-value	R^2
x_{41}	Release group at LMN1	0.0036	0.5727
x_{48}	ATPase	0.0139	0.2112
x_{28}	Spill proportion at LMO	0.0286	0.1712
x_{19}	Water particle travel time	0.0306	0.1675
x_{44}	Detection period	0.0356	0.2953
x_{26}	Spill at LMO	0.0382	0.1550
x_{23}	Discharge at LMO	0.0448	0.1461
x_{17}	River regime	0.0728	0.1891
x_{24}	Discharge at LMO (CV)	0.0902	0.1065
x_{8}	Stratification at LMN5T	0.2205	0.0571
x_{45}	Fish length	0.2410	0.0525
x_{46}	Fish weight	0.3193	0.0381
x_{20}	Water velocity through reach (CV)	0.4312	0.0240
x_{47}	Fish condition factor (K)	0.7798	0.0031
x_{11}	Stratification at LMNDST	0.8037	0.0024

Further analysis exploring the combined effect of the river environment and fish condition covariates on the migration and survival probability (ϕ) from LMN2 to LMF1 identified several that were jointly significant. ATPase at tagging, temperature stratification at two sites within the reach, and fish weight at tagging together explained approximately 81% of the observed variability in the migration probability (Table 4.5).

Table 4.5. Estimates of coefficients in the final linear model for survival and migration in the reach from LMN2 to LMF, with standard error, observed t-statistic, and P-value. The response variable was $y = \ln\left(-\ln\left(\hat{\phi}\right)\right)$, based on a proportional hazards model. Multiple R^2=0.8117.

Covariate Code	Coefficient	Estimate	SE	t	P-value
	Intercept	-2.0568	0.6336		
x_{48}	ATPase	0.9350	0.1533	6.0992	<0.0001
x_8	Stratification at LMN5T	-5.2982	0.6468	-8.1910	<0.0001
x_{11}	Stratification at LMNDST	3.9122	0.5596	6.9917	<0.0001
x_{46}	Fish weight	-0.0270	0.0040	-6.6748	<0.0001

4.6.3 Near-Field Migration and Survival

The joint probability of migrating and surviving (ϕ) through the Lower Monumental forebay (i.e., from LMF1 to LMT) was regressed against numerous individual-based covariates describing environmental conditions in the forebay at the time of fish arrival there or soon thereafter, fish conditions at the time of tagging, and several measures representing temporal processes. The near-field analysis included various measures of water velocity in the forebay, both near (proximal) and away (distal) from the dam, as well as measures of operations at the dam (e.g., spill, discharge).

Single-variate analyses found many significant covariates, with the temporal covariate that measured arrival date at the forebay the most significant ($P < 0.0001$; Table 4.6). The other temporal measures, river regime (representing dates of stratification and spill) and a categorical variable representing release group at LMN1, were also significant ($P = 0.0002$ and $P = 0.0498$, respectively; Table 4.6). The most significant of the environmental covariates was spill proportion at Lower Monumental ($P = 0.0004$; Table 4.6). Other significant environmental covariates included multiple measures of the variation of water velocity in the forebay, primarily distal to the dam; spill and discharge (magnitude and variation) at Lower Monumental; and temperature stratification in the forebay 24 hours after fish arrival there (Table 4.6). Covariates describing fish condition and history that were significant included fish weight and length at time of tagging, a measure of the fish's history of directed migration, and the time of day of arrival at the dam (Table 4.6). None of the individual covariates accounted for an appreciable amount of the observed variation in the probability of migrating and surviving from the forebay to the tailrace, with R^2 for each significant covariate ranging from $R^2 = 0.0084$ for the CV of the downstream component of water velocity proximal to the dam, to $R^2 = 0.0535$ for river regime (Table 4.6).

Table 4.6. Results of single-variable covariate analyses for survival and migration (ϕ) through the Lower Monumental forebay (LMF1 to LMT). The response variable was $y = \ln\left(-\ln\left(1-\hat{\phi}\right)\right)$, assuming a proportional hazards model. Individual-based covariates were used. Covariates are ordered by *P*-value.

Covariate Code	Covariate	*P*-value	R^2
x_{42}	Arrival date at LMF	<0.0001	0.0520
x_{16}	River regime	0.0002	0.0535
x_{27}	Spill proportion at LMO	0.0004	0.0384
x_{25}	Spill at LMO	0.0005	0.0365
x_{39}	Water velocity in forebay distal to dam (CV of downstream component)	0.0035	0.0255
x_{38}	Water velocity in forebay distal to dam (CV of overall magnitude)	0.0049	0.0234
x_{40}	Water velocity in forebay distal to dam (CV of cross-stream component)	0.0069	0.0221
x_{46}	Fish weight	0.0080	0.0217
x_{22}	Discharge at LMO (CV)	0.0145	0.0179
x_{45}	Fish length	0.0154	0.0182
x_{43}	Day or night at arrival at LMF	0.0248	0.0153
x_{21}	Discharge at LMO	0.0403	0.0139
x_{15}	Stratification at LMNFBT 24 hours after arrival at LMF	0.0450	0.0119
x_{41}	Release group at LMN1	0.0498	0.0378
x_{49}	Directed from release to LMF	0.0612	0.0112
x_{33}	Water velocity in forebay proximal to dam (CV of downstream component)	0.0941	0.0084
x_{36}	Water velocity in forebay distal to dam (downstream component)	0.1013	0.0088
x_{35}	Water velocity in forebay distal to dam (overall magnitude)	0.1112	0.0081
x_{32}	Water velocity in forebay proximal to dam (CV of overall magnitude)	0.1189	0.0074
x_{48}	ATPase	0.1574	0.0058
x_{13}	Stratification at LMNCorps 24 hours after arrival at LMF	0.1722	0.0056

Table 4.6. (contd)

Covariate Code	Covariate	*P*-value	R^2
x_{47}	Fish condition factor (K)	0.1782	0.0058
x_{37}	Water velocity in forebay distal to dam (cross-stream component)	0.2599	0.0039
x_{14}	Stratification at LMNFBT at time of arrival at LMF	0.4471	0.0017
x_{34}	Water velocity in forebay proximal to dam (CV of cross-stream component)	0.5270	0.0015
x_{31}	Water velocity in forebay proximal to dam (cross-stream component)	0.5782	0.0010
x_{30}	Water velocity in forebay proximal to dam (downstream component)	0.5982	0.0009
x_{12}	Stratification at LMNCorps at time of arrival at LMF	0.6830	0.0005
x_{29}	Water velocity in forebay proximal to dam (overall magnitude)	0.7200	0.0004

Multiple regression relating the joint probability of migrating and surviving through the Lower Monumental forebay to the tailrace (ϕ) to environmental and fish covariates resulted in a final model that included spill proportion at Lower Monumental, time of day of arrival at the forebay (day versus night), and ATPase at tagging (Table 4.7). Together, these three variables accounted for 5.37% of the variation in migration and survival probability estimates through the forebay. While this value is low, no other measured covariate accounted for a significant amount of the remaining variation in forebay survival, once these three variables were included.

Table 4.7. Estimates of coefficients in the final generalized linear model for survival and migration in the Lower Monumental forebay (LMF1 to LMT), with standard error, observed F-statistic, degrees of freedom (df_1, df_2), and *P*-value. The response variable was $y = \ln\left(-\ln\left(1-\hat{\phi}\right)\right)$, assuming a proportional hazards model. Multiple $R^2 = 0.0537$.

Covariate Code	Coefficient	Estimate	SE	F	(df_1, df_2)	*P*-value
	Intercept	-0.4660	0.2710			
x_{27}	Spill proportion at LMO	1.1014	0.2922	13.1120	(1, 412)	0.0003
x_{43}	Day or night at arrival at LMF	-0.2562	0.1305	3.2159	(1, 412)	0.0737
x_{48}	ATPase	0.1024	0.0539	2.9584	(1, 412)	0.0862

4.6.4 Far-Field Travel Time

Travel time through each reach was related to covariates describing the river environment and fish condition at tagging. Single-variate analyses were also performed using variables representing temporal processes, such as release date at Little Goose or the release group at LMN1. Analyses were performed on each reach separately, including the reach from Little Goose to LMN1. Individual-based covariates were also considered in this analysis.

Numerous covariates were associated with highly significant effects for travel time through the reach from Little Goose to LMN1. All covariates considered had *P*-values <0.01, and all but ATPase had *P*-values <0.0001 (Table 4.8). However, most single covariates explained little of the variation in travel time through this reach. The categorical covariate representing the release group at LMN1 explained the most variation ($R^2 = 0.2352$), while the other variables had R^2 values ranging from 0.0101 (ATPase) to 0.1728 (release date at LGS) (Table 4.8).

Table 4.8. Results of single-variable covariate analyses for travel time through the reach from Little Goose to LMN1. The response variable was $y = \ln(\text{travel time})$. Covariates are ordered by *P*-value and R^2.

Covariate Code	Covariate	*P*-value	R^2
x_{41}	Release group at LMN1	<0.0001	0.2352
x_{42}	Release date at Little Goose	<0.0001	0.1728
x_{16}	River regime	<0.0001	0.1709
x_{46}	Fish weight	<0.0001	0.1461
x_{18}	Water particle travel time (log)	<0.0001	0.1202
x_{45}	Fish length	<0.0001	0.1157
x_1	Stratification at LMN3T at time of arrival at LMN1	<0.0001	0.0493
x_2	Stratification at LMN3T 24 hours after arrival at LMN1	<0.0001	0.0267
x_{47}	Fish condition factor (K)	<0.0001	0.0190
x_{48}	ATPase	0.0016	0.0101

The combined effects on travel time of river environment and fish condition were further explored using multiple regression. Fish weight and ATPase at time of tagging, water particle travel time through the reach, and temperature stratification near LMN1 at the time of fish arrival at LMN1 were all significant (Table 4.9). Significant interactions were found between the effects of fish weight and ATPase, water particle travel time, and stratification (Table 4.9). Despite the fact that these covariates had significant effects, together these four covariates explained only about 20% of the observed variability in travel time from Little Goose to LMN1.

Table 4.9. Estimates of coefficients in the final linear model for travel time in the reach from Little Goose to LMN1, with standard error, observed *t*-statistic, and *P*-value. The response variable was y = 1n (travel time). Multiple R^2 = 0.2015.

Covariate Code	Coefficient	Estimate	SE	*t*	*P*-value
	Intercept	-6.6524	1.5188		
x_{46}	Fish weight	0.0782	0.0235	3.3211	0.0009
x_{48}	ATPase	0.0147	0.0373	0.3949	0.6930
x_{18}	Water particle travel time (log)	1.7144	0.3758	4.5624	<0.0001
x_1	Stratification at LMN3T at time of arrival at LMN1	0.3430	0.1129	3.0366	0.0025
x_{46} x x_1	Weight x stratification at LMN3T	-0.0090	0.0021	-4.2969	<0.0001
x_{46} x x_{18}	Weight x WPTT (log)	-0.0158	0.0057	-2.7891	0.0054
x_{46} x x_{48}	Weight x ATPase	-0.0013	0.0007	-1.8059	0.0712

Single-variate analyses for travel time from LMN1 to LMN2 indicated that all covariates except ATPase were significant, with *P*-values ranging from 0.0386 (fish condition factor at tagging) to <0.0001 for multiple covariates (Table 4.10). However, none of these covariates explained an appreciable amount of the variability in travel time through this reach, with R^2 values ranging from 0.0476 for river regime (representing the presence of stratification and spill at Lower Monumental) to 0.0045 for fish condition factor.

Table 4.10. Results of single-variable covariate analyses for travel time through the reach from LMN1 to LMN2. The response variable was y = 1n (travel time). Covariates are ordered by P-value and R^2.

Covariate Code	Covariate	P-value	R^2
x_{16}	River regime	<0.0001	0.0476
x_{42}	Arrival date at LMN1	<0.0001	0.0447
x_{41}	Release group at LMN1	<0.0001	0.0427
x_{18}	Water particle travel time (log)	<0.0001	0.0267
x_{46}	Fish weight	<0.0001	0.0229
x_{45}	Fish length	0.0001	0.0168
x_4	Stratification at LMN4T 24 hours after arrival at LMN1	0.0008	0.0118
x_3	Stratification at LMN4T at time of arrival at LMN1	0.0009	0.0116
x_{47}	Fish condition factor (K)	0.0386	0.0045
x_{48}	ATPase	0.5730	0.0004

Results from multiple regressions relating the river environment and fish covariates to travel time from LMN1 to LMN2 indicated that water particle travel time and stratification in the reach 24 hours after arrival at LMN1 together had significant effects, with none of the other covariates significant once these factors were accounted for (Table 4.11). However, together these two covariates explained only about 3.3% of the variation in travel time from LMN1 to LMN2.

Table 4.11. Estimates of coefficients in the final linear model for travel time in the reach from LMN1 to LMN2, with standard error, observed t-statistic, and P-value. The response variable was y = 1n (travel time). Multiple R^2 = 0.0334.

Covariate Code	Coefficient	Estimate	SE	t	P-value
	Intercept	-2.8250	0.7372		
x_{18}	Water particle travel time (log)	0.9126	0.1990	4.5950	<0.0000
x_4	Stratification at LMN4T 24 hours after arrival at LMN1	-0.1514	0.0592	-2.5600	0.0106

Several single covariates had significant effects for travel time from LMN2 to LMF1, including water particle travel time, fish length and weight, a measure of temperature stratification, and two temporal measures (release group at LMN1, and river regime). *P*-values for these covariates ranged from 0.0793 for temperature stratification to 0.0019 for both water particle travel time and fish length (Table 4.12). However, the R^2 value was very small for each of these factors, ranging from 0.0045 (stratification) to 0.0285 (release group), indicating that although the perceived effects were significant, they did not actually explain much of the variation in travel time between LMN2 and LMF1.

Table 4.12. Results of single-variable covariate analyses for travel time through the reach from LMN2 to LMF1. The response variable was y = 1n (travel time). Covariates are ordered by *P*-value and R^2.

Covariate Code	Covariate	*P*-value	R^2
x_{18}	Water particle travel time (log)	0.0019	0.0138
x_{45}	Fish length	0.0019	0.0139
x_{41}	Release group at LMN1	0.0027	0.0285
x_{46}	Fish weight	0.0115	0.0092
x_{16}	River regime	0.0169	0.0117
x_{10}	Stratification at LMNDST 24 hours after arrival at LMN2	0.0793	0.0045
x_{9}	Stratification at LMNDST at time of arrival at LMN2	0.1101	0.0037
x_{48}	ATPase	0.2557	0.0022
x_{6}	Stratification at LMN5T at time of arrival at LMN2	0.2966	0.0016
x_{47}	Fish condition factor (K)	0.3784	0.0011
x_{42}	Arrival date at LMN2	0.3831	0.0010
x_{7}	Stratification at LMN5T 24 hours after arrival at LMN2	0.5251	0.0006

Multiple regression relating travel time from LMN2 to LMF1 to the environmental and fish covariates (Table 4.13) produced results similar to those for the LMN1–LMN2 reach (Table 4.11). As in the previous reach, the final model for LMN2–LMF1 included both water particle travel time and temperature stratification in the reach 24 hours after arrival in the reach. Unlike the previous reach, the final model for LMN2–LMF1 also included fish length. No other covariates had significant effects once these three covariates were accounted for. Despite the very significant *P*-values for water particle travel time and fish length ($P < 0.0001$ for both covariates; Table 4.13), the final model accounted for only 9% of the variability in travel time through the reach from LMN2 to LMF1 (Table 4.13).

Table 4.13. Estimates of coefficients in the final linear model for travel time in the reach from LMN2 to LMF1, with standard error, observed t-statistic, and P-value. The response variable was y = 1n (travel time). Multiple R^2 = 0.0900.

Covariate Code	Coefficient	Estimate	SE	t	P-value
	Intercept	-9.9054	1.7261		
x_{18}	Water particle travel time (log)	3.2173	0.4514	7.1275	<0.0001
x_{45}	Fish length	-0.0192	0.0026	-7.4660	<0.0001
x_{10}	Stratification at LMNDST 24 hours after arrival at LMN2	-0.1529	0.0858	-1.7814	0.0753

4.6.5 Near-Field Travel Time

Travel time through the near field (i.e., from LMF1 to LMT) was regressed against additional environmental covariates not available in the upstream reaches. These covariates were associated with water movement and velocity in the forebay (Tables 3.9 and 3.10 in the statistical methods section). Numerous covariates were seen to have significant correlation with travel time in the forebay, with the temporal measure river regime having the most significant effect ($P < 0.0001$, $R^2 = 0.1030$; Table 4.14). Two other temporal measures were also significant: release group at LMN1 and arrival date at the forebay. Spill and spill proportion at Lower Monumental, water particle travel time through the forebay, discharge (magnitude and variation) at Lower Monumental, and several measures of the variability in water velocity in the forebay were also significant, as well as fish weight and length (Table 4.14). However, the R^2 values were low (<0.1500) for all covariates, indicating that although many covariates were significantly correlated with travel time, they explained very little of the actual variation in travel time through the forebay.

Table 4.14. Results of single-variable covariate analyses for travel time through the Lower Monumental forebay (LMF1 to LMT). The response variable was y = 1n (travel time). Covariates are ordered by P-value and R^2.

Covariate Code	Covariate	P-value	R^2
x_{16}	River regime	<0.0001	0.1030
x_{41}	Release group at LMN1	<0.0001	0.0928
x_{42}	Arrival date at LMF	<0.0001	0.0727
x_{25}	Spill at LMO	<0.0001	0.0718
x_{27}	Spill proportion at LMO	<0.0001	0.0701
x_{18}	Water particle travel time (log)	<0.0001	0.0673
x_{21}	Discharge at LMO	<0.0001	0.0646
x_{38}	Water velocity in forebay distal to dam (CV of overall magnitude)	0.0005	0.0377
x_{39}	Water velocity in forebay distal to dam (CV of downstream component)	0.0007	0.0357
x_{32}	Water velocity in forebay proximal to dam (CV of overall magnitude)	0.0008	0.0380
x_{22}	Discharge at LMO (CV)	0.0010	0.0274
x_{33}	Water velocity in forebay proximal to dam (CV of downstream component)	0.0025	0.0308
x_{40}	Water velocity in forebay distal to dam (CV of cross-stream component)	0.0030	0.0275
x_{46}	Fish weight	0.0065	0.0189
x_{45}	Fish length	0.0860	0.0076
x_{47}	Fish condition factor (K)	0.1719	0.0048
x_{34}	Water velocity in forebay proximal to dam (CV of cross-stream component)	0.1737	0.0063
x_{14}	Stratification at LMNFBT at time of arrival at LMF	0.1890	0.0056
x_{37}	Water velocity in forebay distal to dam (cross-stream component)	0.2886	0.0037
x_{29}	Water velocity in forebay proximal to dam (overall magnitude)	0.3529	0.0031

Table 4.14. (contd)

Covariate Code	Covariate	*P*-value	R^2
x_{15}	Stratification at LMNFBT 24 hours after arrival at LMF	0.3653	0.0026
x_{31}	Water velocity in forebay proximal to dam (cross-stream component)	0.4558	0.0020
x_{30}	Water velocity in forebay proximal to dam (downstream component)	0.4885	0.0017
x_{35}	Water velocity in forebay distal to dam (overall magnitude)	0.5591	0.0011
x_{36}	Water velocity in forebay distal to dam (downstream component)	0.6143	0.0008
x_{12}	Stratification at LMNCorps at time of arrival at LMF	0.6313	0.0006
x_{13}	Stratification at LMNCorps 24 hours after arrival at LMF	0.6627	0.0005
x_{48}	ATPase	0.6777	0.0005
x_{43}	Day or Night at arrival at LMF	0.7971	0.0002

Multiple regression relating travel time through the Lower Monumental forebay to environmental and fish covariates resulted in a final model that included spill and spill proportion at Lower Monumental Dam and fish length, as well as significant interaction effects among cross-stream water velocity proximal to the dam (magnitude and variation), water particle travel time, and both spill and spill proportion (Table 4.15). These six covariates account for approximately 31% of the variation in travel time through the forebay. This is considerably more than the multiple regression models derived for the upstream reaches but is still small enough to suggest that other, unmonitored factors contribute to travel time through this reach.

Table 4.15. Estimates of coefficients in the final linear model for travel time in the Lower Monumental forebay (LMF1 to LMT), with standard error, observed t-statistic, and P-value. The response variable was y = 1n (travel time). Multiple R^2 = 0.3061.

Covariate Code	Coefficient	Estimate	SE	t	P-value
	Intercept	1.2135	1.0920		
x_{25}	Spill at LMO	3.6950	1.0960	3.3713	0.0009
x_{31}	Water velocity proximal to dam (cross-stream component)	174.0200	43.2747	4.0213	0.0001
x_{45}	Fish length	-0.0129	0.0033	-3.9099	0.0001
x_{34}	Water velocity proximal to dam (CV of cross-stream component)	-0.0438	0.0210	-2.0905	0.0375
x_{18}	Water particle travel time (log)	0.5967	0.3760	1.5869	0.1137
x_{27}	Spill proportion at LMO	-74.5189	25.6530	-2.9049	0.0040
x_{31} x x_{18}	Water velocity (proximal, cross-stream) x WPTT(log)	-79.2622	18.1322	-4.3714	0.0000
x_{25} x x_{18}	Spill x WPTT (log)	-1.6051	0.4679	-3.4307	0.0007
x_{18} x x_{27}	WPTT (log) x Spill proportion	31.4783	10.8272	2.9073	0.0039
x_{34} x x_{31}	CV of water velocity (proximal, cross-stream) x water velocity (proximal, cross-stream)	3.4181	1.6071	2.1269	0.0343

5.0 Discussion and Conclusions

5.1 Subyearling Chinook Salmon Movement and Behavior

The deployment approach used in this study was modified from a simpler version that was used in the pilot year of this work (2006). We used information gained through research in 2006 to modify the study design for 2007 to allow for better estimation of the fate of juvenile fall Chinook salmon that elect to remain in freshwater over their first winter. This modified deployment approach resulted in a very rich dataset that allowed us to develop new statistical models to estimate the proportion of groups of fish, through time and space, that migrated and survived, remained in a specific reach and were alive (moving), and appeared to have become stationary or died. This information has provided a new understanding of how these fish behave in the reservoir environment and how changes in hydraulic conditions, whether natural or influenced by dam operations, may relate to life history trajectories selected by these fish.

Juvenile Chinook salmon passing through the lower Snake River reservoirs in late summer through fall show a high propensity for remaining in these reservoirs through the winter. Survival of these fish was higher in early fall (after early to mid-September) than it was in late summer (late July through August). Nevertheless, many of the juvenile Chinook salmon collected and tagged as they passed Little Goose Dam survived and resided within the reservoir behind Lower Monumental Dam for extended periods. These fish tended to reside predominantly in the lower 19 km of the reservoir where the water was stratified with 1 to 5°C temperature differences between the surface and subsurface layers of the water column.

Many of the fish tagged for this study exhibited movement behaviors that indicated they were not directed in their seaward migration. These fish often moved fairly rapidly (within a few days) from the release site (Rkm 631) to the immediate forebay of Lower Monumental Dam (Rkm 589), then turned around and swam back upstream, and then changed direction again and swam all or part of the way back toward the dam. Many of the fish subsequently detected by the PIT-tag system exhibited this type of behavior in Lower Monumental Reservoir until the time when their acoustic tags lost power.

Acoustic tag failure during the period used for the fate analyses would result in increased estimates of mortality, and decreased estimates of migration and residualization. The observed tag failure data (Figure 3.3) indicated that 98% (49/50) of the tags in the tag-life study lasted at least 60 days, and 92% (46/50) of the tags lasted 78 days. Thus, 8 weeks (56 days) was considered a suitable detection period for which tag-life corrections to the fate analyses were unnecessary, and we truncated the data for each release group at 8 weeks. However, many of the acoustic tags continued to be detected for 80 to 90 days, providing additional behavioral and travel time information.

5.2 Hydraulic Characterization

Thermal stratification, evidenced by vertical gradients of water temperature, was consistently observed from late-July to about 14 September. The reservoir was nearly isothermal from mid-September to December. There was no consistent occurrence of upstream-directed flow during this period in the upper 10 m of the water column. Near-surface flow reversals were observed, but these events were transient. Consistent with the change in dam operations after 1 September, the coefficient of variation of velocity increased and water particle travel times showed higher levels of fluctuation.

Although vertical temperature gradients were present in the reservoir until about 14 September, underflow conditions, as discussed in Cook et al. (2007), were not observed during this study. Fixed-location and mobile ADCP measurements documented the intermittent (both in time and space) occurrence of upstream-directed velocity in the upper 10 m of the water column prior to the disappearance of vertical temperature gradients after 14 September. After that date, laterally averaged vertical velocity profiles were fairly uniform and directed downstream. The measurements indicate that the presence of vertical temperature gradients provides the opportunity for the occurrence of near-surface flow reversals but is not the sole factor determining whether they exist. Flow reversals are a complex function of river discharge, vertical temperature gradients, surface heat exchange, and local wind conditions (speed, direction, fetch and duration) at the water surface. Detailed wind measurements along the reservoir were not available but are spatially variable, given the large topographic relief (Cook et al. 2007). The local wind-sheltering effect is a key factor that affects the detailed structure of near-surface flow, as shown by Ruppert and Kongeter (2005).

In the immediate forebay of Lower Monumental Dam, velocities measured from the fixed position ADCP nearest to the dam (about 100 m upstream) tended to closely follow the timing of changing dam operations and generally were oriented toward the area of highest discharge (as expected). Measurements from the ADCP approximately 200 m upstream did not show nearly as strong a relationship to project operations. The nearest ADCP showed that prior to shutoff of spill on 1 September, velocities generally were oriented toward the spillbay. After 1 September, the forebay elevation returned to normal operating pool (near elevation 164.4 m) and mandatory spill ceased. Turbine discharges fluctuated frequently (on an hourly timescale), which caused the cross-stream (north-south) velocity direction and magnitude to also vary. Velocity during this period was variable but tended more toward the powerhouse, with directions fluctuating as different turbines were operated and discharges varied.

5.3 Covariate Analyses

Both the joint probability of migrating and surviving (ϕ) through a given reach, and travel time through the reach, were related to covariates that described fish condition at tagging and hydraulic conditions in the reach in question. When interpreting the results of these covariate analyses, it is important to note the difference between correlation and causation. The covariate analyses identify factors that were highly correlated with either the migration and survival probability (ϕ) or travel time, but not necessarily causation. For example, the high correlation between water particle travel time through the Lower Monumental Dam forebay and fish travel time through the forebay ($P < 0.0001$, Table 4.14) may be explained by an unknown third factor that independently influenced the travel time of both water and fish. Thus, the results of the covariate analyses should be interpreted with caution.

Although no measure of fish condition or environmental conditions was correlated with the estimated probability of migration and survival (ϕ) in the reach LMN1–LMN2, many covariates were correlated with the estimate of ϕ in the reach from LMN2–LMF1. Temperature stratification in the reach, ATPase at tagging, and fish weight at tagging together explained approximately 81% of the variation in the estimate of ϕ in this reach (Table 4.5). Migration and survival through the forebay was seen to be correlated with many individual measures of hydraulic conditions in the forebay, fish condition at tagging, and whether fish were "directed" during their migration to the forebay (Table 4.6). However,

many covariates were correlated, and when multiple covariates were considered, only spill proportion at Lower Monumental Dam, time of day of arrival at the forebay, and ATPase at tagging had significant effects (Table 4.7). Together, these three measures accounted for only 5.37% of the variation in migration and survival through the Lower Monumental Dam forebay. ATPase values were generally highly variable and did not appear to be significantly different in fish that emigrated from Lower Monumental Reservoir in 2007 versus fish that did not leave the reservoir.

Many covariates describing environmental and fish conditions were seen to be highly correlated with travel time through each reach, with most of the significant P-values < 0.0001 (Tables 4.8, 4.10, 4.12, and 4.14). However, these very small P-values were often accompanied by small R^2 values, implying that although the correlation between the covariate and travel time was estimated to be significant, the amount of variation in travel time actually accounted for by the covariate was nevertheless very low. In particular, water particle travel time was seen to be significantly correlated with fish travel time in each reach, with P-values < 0.0001 for the reaches LGS–LMN1, LMN1–LMN2, and LMF–LMT, and $P = 0.0019$ for the reach LMN2–LMF. However, the accompanying R^2 values for these P-values ranged from 1.4% for the reach LMN2–LMF (Table 4.12) to 12.0% for the reach LGS–LMN1 (Table 4.8). Water particle travel time was highly correlated with fish travel time, but there was a large amount of variation in fish travel time that was unexplained by water particle travel time, as demonstrated also in Figure 5.1. The same was true for most significant factors in the travel time analyses. The exception was the categorical variable representing release group, which accounted for 24.5% of the variation in travel time from the release 5 km downstream of Little Goose Dam tailrace to LMN1 (Table 4.8). Release group is a temporal variable that is confounded with numerous other time-varying factors, such as water temperature and fish length at tagging. Its effect on travel time does not reveal which underlying biological factors influence travel time through this reach.

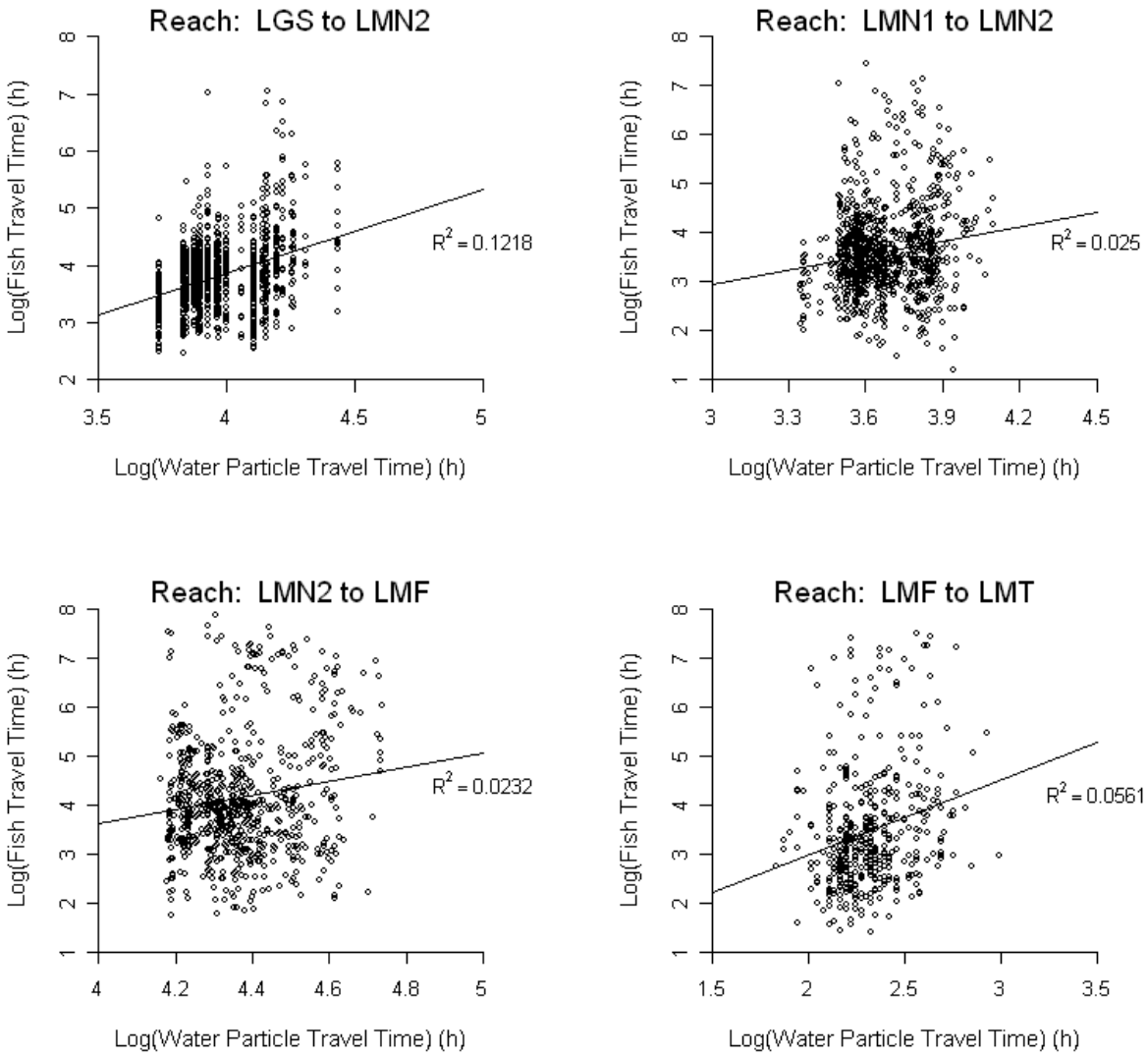

Figure 5.1. Fish travel time (h) versus water particle travel time (h) on logarithmic scale through each reach, with fitted linear regression line and R^2

5.4 PIT Tags Versus Acoustic Tags

The subyearling Chinook salmon used in this study were tagged with both acoustic and PIT tags. The PIT-tag data were used primarily to account for nondetection on the acoustic array in the Lower Monumental Dam tailrace and to assign mortality status to individual fish. It is tempting to also use the PIT-tag data to estimate the joint probability of migration and survival from release in the Little Goose Dam tailrace to the Lower Monumental Dam tailrace. This would provide alternative migration and survival estimates that could be compared to the acoustic-tag survival estimates. Although tempting, such an exercise may be misleading in several ways, as described below.

Migration and survival estimates from the acoustic-tag data were based on conceptual release groups formed at the acoustic array at LMN1, approximately 23 km downstream of the release site 5 km

downstream of Little Goose Dam. In theory, the same release groups may be used with the PIT-tag data to estimate migration and survival from LMN1 to the acoustic array in the Lower Monumental tailrace (LMT). However, the conceptual release groups were small, ranging in size from 101 to 282 fish. Such release sizes are reasonable for an acoustic-tag study where detection probabilities are 90–100% but are very small for a PIT-tag study where detection probabilities are 10–20%. Most PIT-tag studies use release groups of 1000–2000 fish, even for survival from one dam to the next. Small release groups result in high uncertainty in survival estimates, represented by large standard errors and wide confidence intervals. The low PIT-tag detection probabilities at Lower Monumental Dam encountered by most release groups during this study (5% to 15% during spill) also contribute to increased uncertainty in survival estimates. Thus, migration and survival estimates based on PIT-tag data from the virtual release groups that were based on the acoustic-tag data would be essentially meaningless.

Instead of using many small conceptual release groups at LMN1, it is possible to pool all fish released downstream of Little Goose Dam into a single large release group. With 1771 fish, this release group is of reasonable size for estimation of the migration and survival probability to Lower Monumental using PIT-tag data. However, pooling across several months like this would violate assumptions that underlie the survival analysis of the PIT-tag data, as we observed that migration probabilities and residualization probabilities varied throughout the study (Figures 4.5–4.8). Additionally, while it would be attractive to compare the resulting migration and survival estimate to the overall estimate of migration and survival based on the acoustic-tag data (Figure 4.10), this is unwarranted because the PIT-tag estimate and the acoustic-tag estimate refer to different stretches of river. The PIT-tag estimate would refer to migration and survival from the Little Goose Dam tailrace to the Lower Monumental Dam tailrace, while the acoustic-tag estimate refers to movement from the acoustic array at LMN1 to the Lower Monumental Dam tailrace. Thus, the PIT-tag estimate would refer to a stretch of river that is 23 km longer than that referred to by the acoustic-tag estimate. Because the two estimates differ on the stretch of river to which they refer, it is not reasonable to compare them. Furthermore, our acoustic-tag estimates were weighted by the FPC passage index at Lower Monumental Dam, and a PIT-tag estimate from a single release group over this period would effectively use a different weighting scheme.

Double-tagging with both acoustic tags and PIT tags provided a wealth of information about the fish in this study. Acoustic tags provided excellent information about fish movement and on a finer spatial and temporal scale than available from PIT-tag data. PIT tags are useful for studying long-term processes over larger spatial scales that are not addressed by acoustic tags because of limitations in tag life of active tags (batteries). Carefully designed analysis that incorporates data from both types of tag may provide more information than using either type of tag alone. However, it is important to recognize the restrictions from each tag type and to limit the expected inference from the data accordingly.

5.5 Assessment of Dead-or-Alive Decision Rule

The decision rule used to classify fish as dead or alive at the last node where they were detected was based on the assumption that movement of the acoustic tag implies the fish was alive. There are two alternative explanations for tag movement that do not imply live salmon. First, an acoustic-tagged salmon might be classified as alive if it were eaten by a predator that then moved within the study area before the tag was evacuated. Second, an acoustic-tagged dead salmon may drift with the current and so be mistakenly classified as alive. We considered the possible effects and likelihood of these two situations as discussed below.

In most cases, misclassifying a dead fish as "alive" will result in no bias in fate estimation for the detection period for which the decision rule was applied. This is because the release-recapture model used to estimate the migration parameter for that period does not depend on the mortality rule outcome. Additionally, in order for a dead fish to bias estimates of residualization, the tag from the dead fish must be detected (and classified as alive) during a short period during the final two days of the detection period. Later detection periods may see a small bias in fate estimates. The size and direction of the bias will depend on the relative proportion of misclassified dead fish relative to live fish present in the reach during the detection period. It is important to note that the season-wide fate estimates for the 8-week detection period are more robust to mortality misclassification than are the biweekly detection periods.

The main piscine predator encountered by subyearling fall Chinook salmon in this reservoir is smallmouth bass. Daily consumption rates (prey/predator/day) of smallmouth bass on subyearling Chinook salmon were estimated from 15 June to 1 August. Digestion rate (time to evacuate 90% of prey) of smallmouth bass was first calculated using the equation

$$ET90 = 24.542S^{0.29}e^{0.15T}W^{0.23}$$

where *ET90* = the time in hours for a prey item to be 90% evacuated, *S* = prey weight (g), *T* = temperature (°C), and *W* = predator weight (g) (Rogers and Burley 1991; Fritts and Pearsons 2004). Using this equation, we estimated that a 50-g tagged juvenile Chinook salmon (and the acoustic tag within its body) would be passed out of a 300-g smallmouth bass within 28.5 hr at a water temperature of 19°C. Therefore, it is possible that a tagged fish that was in fact dead may have been classified for a short time (~1 day) as alive if it were inside a predator that was moving around within the reservoir. However, based on the limited movement we observed in tagged smallmouth bass and the short gut evacuation time, we assume the influence of this phenomenon on our fate assignments is minor.

Avian predation results in removal of the acoustic tag from the study area and thus has a smaller effect on fate estimates than does piscine predation, in which the tag remains in the study area. However, avian predation rates on our study fish were not available.

It is possible that tags from dead salmon that drifted with the current may have been classified as alive according to the decision rule. This error would be problematic only for such tags that were last detected upstream of the Lower Monumental forebay, because the decision rule was not applied to tags whose last detections were in the forebay or tailrace. Under the assumption that drifting tags moved at the speed of the current, we compared the current speed based on water travel time measurements to the travel rate of the tags from their penultimate node to their last node, for tags that were classified as coming from live fish at their last node. For the 490 fish classified as alive at their last node (upstream of the forebay), tag travel speed ranged from 0.001 km/hr to 10.39 km/hr, while current speed ranged from 0.09 km/hr to 0.29 km/hr over the same times and reaches. A total of 27 (5.5%) of these 490 tags were moving downstream slower than the current when they reached their last node and may have been erroneously classified as alive due to tag drift. This error rate corresponds well to the desired 5% error rate used in designing the decision rule. Further, 264 fish (53.9% of 490) were observed moving upstream to their last node and were unlikely to have been drifting with the current.

Misclassifying live fish as "dead" may occur in the case of a tag loss or if live acoustic-tagged salmon remain stationary for long periods as they residualize within the study area. Misclassifying fish as dead results in a negative bias in the delay estimate and a positive bias in the mortality estimate for the

detection period for which the decision rule was applied. However, such misclassification should result in no bias in the migration estimate or in fate estimates for later detection periods. We assessed the mortality decision rule for misclassification of live fish by visually examining fish tracks for acoustic tags belonging to fish classified as "dead" within the study area. Out of 1162 acoustic-tagged salmon detected after release 5 km downstream of Little Goose Dam, there was only a single fish with a discrepancy between visual inspection of the fish tracks and the mortality classification algorithm described in Section 3.7.2. A sensitivity analysis assessing the effect on results of either treating this fish as alive at the end of the study or classifying it as a mortality showed no effect on fate determination results. We are confident that our decision rule correctly assigned mortality to fish within the study area, based on all available acoustic-tag and PIT-tag detection data as they pertained to fate determination and the covariate effects analysis.

5.6 Intrareach Node Data

The intrareach node detections were used primarily at the end of each detection period to estimate the number of live, tagged smolts in each reach at the end of the period, whether for a biweekly period or for the full 8-week period. In addition, the complete set of detections from the intrareach nodes throughout the entire study were used in order to classify fish as living or dead. The continuous detections from these single acoustic nodes made it possible to estimate the proportion of fish residualizing or delaying migration during the study. Because separating residualization from mortality depended on the intrareach nodes, analysis was necessarily limited to the river reaches with full coverage by the intrareach acoustic nodes.

5.7 Upstream Movement

The conditional biweekly fate determination characterized downstream movement. For this reason, the estimated residualization probability for a given reach and time period refers to the population of fish that began the time period either in the reach or upstream. Fish that moved back upstream and remained within the study area (i.e., downstream of LMN1) were included in the release group for the appropriate upstream reach for the next time period, and thus contributed to fate determination in later time periods. On the other hand, fish that moved upstream of LMN1 were removed from the study until they returned to the study area. In general, upstream movement may be confounded with mortality in the biweekly fate estimates. In the studywide fate estimates based on the 8-week detection period, however, such confounding is limited to those fish that moved upstream of LMN1 and did not return to the study area during the study. In the absence of such confounding, we estimated overall mortality to be 53.3% ($\widehat{SE}$ =1.9%). Based on the number of fish determined to have ended their 8-week detection period upstream of LMN1, we may have misidentified mortality by as much as 4.5%, but likely not much more. This results in an adjusted estimate of smolt mortality as low as 48.8% over the study.

5.8 Re-Initiation of Migration

Most of the surviving Chinook salmon tagged as subyearlings in late summer and fall 2007 tended to remain within the reservoirs (both Lower Monumental and Ice Harbor) through the late fall and early winter. Acoustic tags and receivers provided detailed quantitative information on the migration and survival of these fish for the first 60 to 90 days after tagging. PIT tags allowed for a qualitative assessment of the re-initiation of migration following the over-winter period of extended freshwater rearing. Because the PIT tag system is not operated throughout the winter, and because the detection

probabilities are generally low and variable (see Section 5.4), the data from PIT-tag detections of these fish can provide only a qualitative representation of the relationships between the time period when fish are tagged and their subsequent survival through the winter and then re-initiation of migration toward the sea the following spring.

A total of 72 of the 1,771 juvenile fall Chinook salmon tagged in summer/fall 2007 were detected at mainstem Snake or Columbia River dams in spring 2008 (data through 23 May 2008). This amounts to 37% of the fish estimated to have remained alive in the reservoir at the end of their 8-week acoustic-tag life. A trend in these PIT-tag detections supports the conclusions of the fate analyses within this report. That is, a larger proportion of the fish tagged later in the summer and early fall were detected migrating seaward the following spring than those fish tagged earlier in the summer. Up to 30% of the individual release groups were detected migrating seaward in spring 2008. If PIT-tag detection probabilities were 30% during the spring emigration period, that would indicate that most of that particular release group survived through the winter to emigrate the following spring.

5.9 Smolt Physiology

There was not much seasonal variation in mean ATPase level of subyearling fall Chinook salmon entering the reservoir (Figure 4.28). However, these ATPase levels were generally greater than 2, suggesting that many of the fish had initiated the smolting process. In an effort to assess relations between ATPase level and overall performance, we partitioned smolt movements into two categories: *Stayers* were defined to be acoustic-tagged Chinook salmon that were detected in the Lower Monumental Reservoir during the fourth week after tagging, excluding those fish that were either classified as dead during the first 28 days after tagging according to the decision rule, or were detected downstream of Lower Monumental Dam during the first 28 days. *Movers* were defined to be acoustic-tagged Chinook salmon that were detected on acoustic arrays at Bonneville Dam or downstream of Bonneville Dam during the first 28 days after tagging.

We then compared ATPase levels between these two groups of fish (Figure 4.28). We found no significant difference between the groups, and average ATPase levels were generally 4 or above. Several caveats are associated with this finding: sample size was low (34 movers) and divided across several release groups. In addition, only the latter part of the migration of subyearling fall Chinook salmon through the reservoir was assessed. Different relationships may have been found earlier in the season. Nonetheless, it is clear that the ATPase levels in both groups of fish were indicative of the smolting process—the fish were not parr. This suggests that a large overall difference in behavior found in subyearling Chinook salmon smolts (stay in the reservoir or migrate downstream past Bonneville) is not due to a difference in physiological condition at reservoir entry. Instead, these data suggest that differences in smolting originate within the reservoir (or the migratory behavior that is an essential part of the smolting process).

Thus, these data suggest that the migratory urge may be suppressed within the reservoir. To fully explore and confirm this hypothesis, one would have to capture and assess the physiological status of subyearling Chinook salmon remaining in the reservoir after their cohorts had migrated downstream.

6.0 Recommendations

To better understand the fate of juvenile fall Chinook salmon that enter Lower Monumental Reservoir in the latter part of the emigration season, two approaches could be used. The first approach would use long-life acoustic tags and a receiver deployment approach similar to that used in the 2007 study. Tags designed to last approximately 270 days would be implanted in fish as they passed through Little Goose Dam in September–November. A study with similar objectives in the Snake and Clearwater rivers upstream of Lower Granite Dam (Tiffan et al. in preparation) used JSATS acoustic tags in 2007 that weighed an average of 0.88 g in air and lasted 175 days or more. Improvements in transmitter technology should allow for the production of transmitters that would be small enough to use in these relatively large juvenile fall Chinook salmon (100 g and larger) to facilitate monitoring of their behavior and survival through the following spring. This would allow for precise estimation of survival of the EFR phase of these fish. The second approach would involve PIT-tagging large numbers of fish and maintaining the PIT detection system through the winter period. The problems with this approach are, first, that large numbers of run-of-the-river fish are not generally available late in the migration, and, second, ice causes logistical problems with operating the PIT-tag detection system through the winter period. Increasing the sample sizes of the release groups would provide greater precision in the estimates of fate. It is possible that hatchery fish might be used as a surrogate for run-of-the-river fish to increase sample sizes for this purpose; Tiffan et al. (in preparation) used hatchery fish for their study, and the behavior of those fish appears to be relatively similar (e.g., delayed migration) to that of the fish tagged in the Lower Monumental Reservoir study.

Research on bioeffects (the effects of the surgery and the transmitter on the host animal) planned for 2008 would provide some useful information on the long-term tag retention and effects on the host fish. These data should be reviewed prior to the decision to use larger transmitters for extended periods so that the limitations of the technology and its application may be understood when studies are planned.

It has been postulated that subyearling Chinook salmon migrating seaward very late in the emigration season may encounter prey resources that prompt them to remain in freshwater, 'thinking they have made it to the sea.' This hypothesis could be tested by examining prey resource availability and distribution (e.g., zooplankton and larval introduced American shad *Alosa sapidissima*) in Lower Monumental Reservoir during the full subyearling Chinook salmon emigration period. By assessing the distribution and abundance of prey organisms and fish migratory behavior throughout the full emigration period and the overwinter rearing period, it would be possible to determine whether the prey base and related fish behavior changes appreciably through the emigration season. In addition, subyearling Snake River fall Chinook salmon gut contents could be periodically examined to provide new insight into the trophic relationships between these fish and their prey base as well as the interactions between reservoir/dam operations (e.g., RSW) and prey resources.

The effects of project operations on the passage and survival of subyearling Chinook salmon would benefit from more detailed behavior information on tagged subyearling Chinook salmon in the immediate vicinity of Lower Monumental Dam. Data from acoustic tagging studies in 2006 and 2007, prior to the installation and operation of the RSW, have provided an indication of behavior and delay of late migrating juvenile fall Chinook salmon that would be useful as a reference to the behavior of these fish when the RSW is operating. The combination of detailed fish behavior and flow information near the RSW would provide necessary information regarding the efficacy of the RSW in the passage of these

late-season fish that are not 'highly motivated' migrants. However, before-and-after comparisons should be made with caution, as a large amount of the variability in the survival and behavior of these fish is not yet well understood or explained in existing statistical models.

Characterization of forebay flow in the near-field region (closer than 50 m) of the RSW would best be accomplished using side-looking, narrow-beam angle ADCP(s) mounted on the dam structure. These measurements should be done in combination with bottom-mounted ADCPs. Resolving the presence and absence of flow reversals in the far-field would be enhanced by using long-term deployment of bottom-mounted ADCPs that can document the transient nature of these events.

To better estimate the portion of tagged fish that may have entered our study area (starting 19 km upstream of Lower Monumental Dam) and then subsequently moved back upstream out of the area where we operated acoustic receivers, it would be helpful to have additional intrareach receivers upstream of the LMN1 detection array. This would reduce the uncertainty regarding the fate of fish that moved out of the area where we operate receivers. This may ultimately reduce the estimate of mortality in these EFR fish. In addition, a second array downstream of Lower Monumental Dam would increase the precision of the fate estimates for fish leaving the reservoir by increasing the detection probabilities in this swift water area.

Finally, obtaining depth distribution information and general habitat use information on the extended freshwater-rearing juvenile fall Chinook salmon in Lower Monumental Reservoir would enable us to better understand the relationships between hydrodynamics and project operations and the behavior of these fish. It would be possible to collect this information with the current transmitters (2008 model is now 0.43 g in air versus the tags used in the 2007 study, which were 0.59 g in air) by employing a three-dimensional mobile tracking system similar to the one developed for use on the lower Columbia River by NOAA Fisheries.

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Appendix A

Acoustic Receiver Data Gaps

Appendix A – Acoustic Receiver Data Gaps

Acoustic receivers used for this study sometimes were not functional. Figures A.1 through A.3 display the data gaps for arrays/receiver locations used in this study.

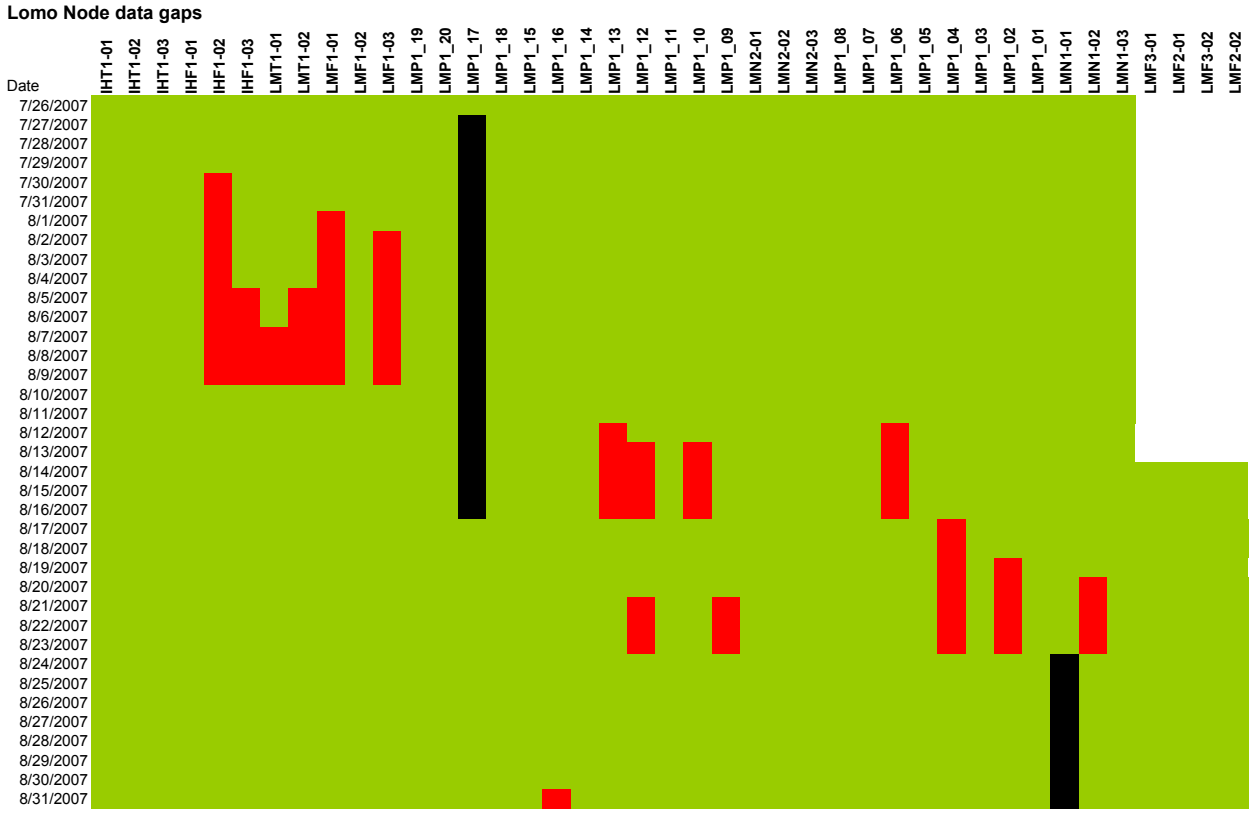

Figure A.1. Acoustic receiver data gaps for Lower Monumental Reservoir migratory behavior study, 26 July through 31 August 2007. Green areas indicate periods/locations where data were collected. Red indicates no data due to battery failure. Black indicates no data due to hydrophone damage. Areas indicated by white represent locations where receivers were not deployed during that time.

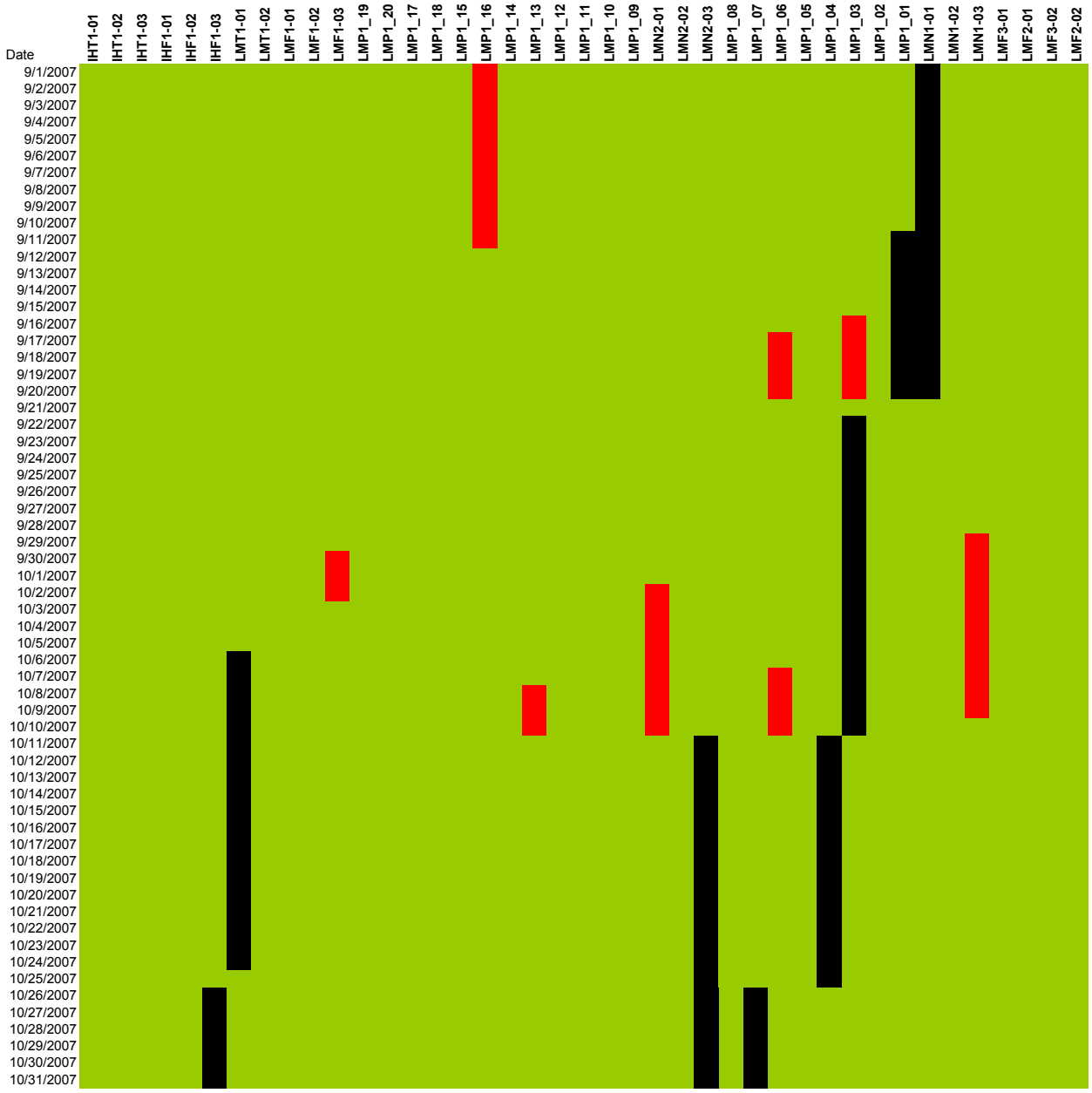

Figure A.2. Acoustic receiver data gaps for Lower Monumental Reservoir migratory behavior study, 1 September through 31 October 2007. Green areas indicate periods/locations where data were collected. Red indicates no data due to battery failure. Black indicates no data due to hydrophone damage.

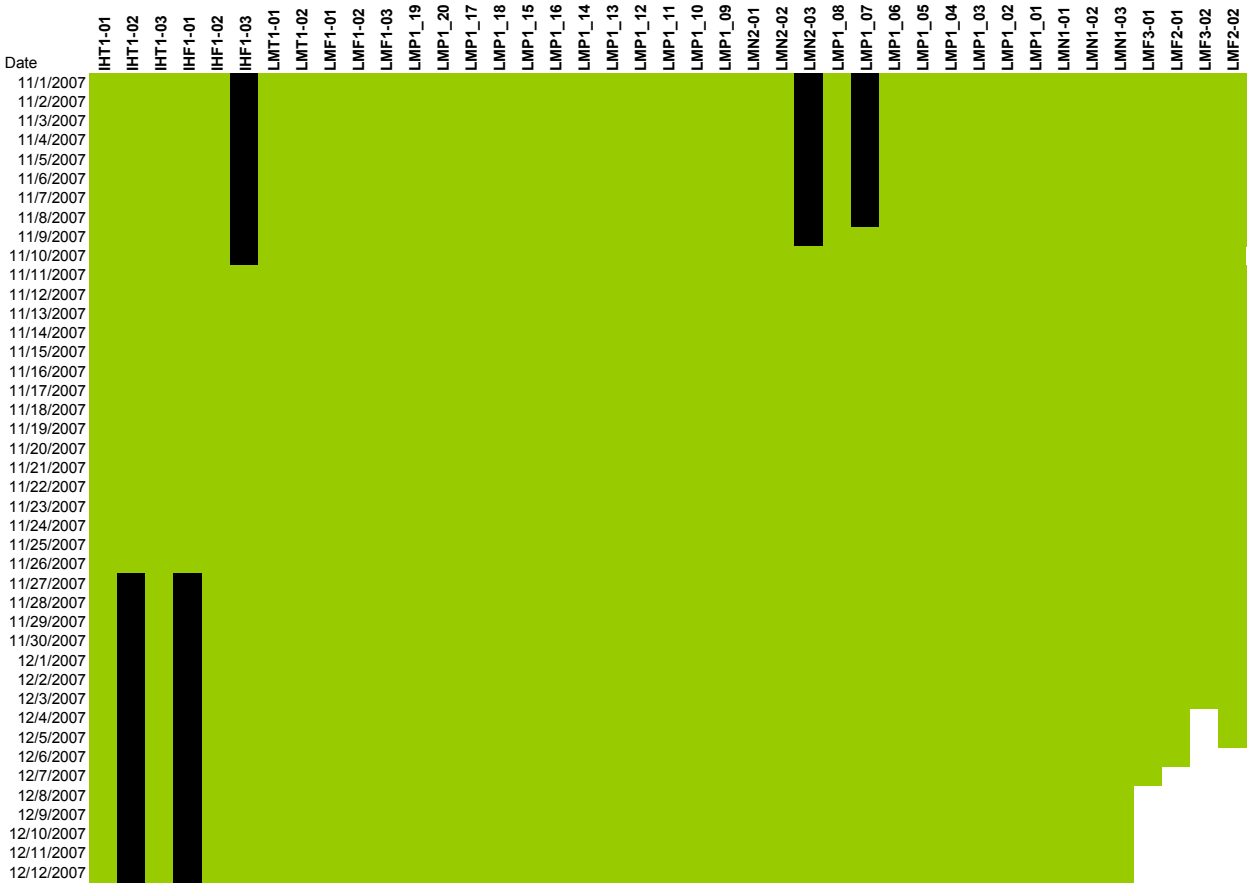

Figure A.3. Acoustic receiver data gaps for the Lower Monumental Reservoir migratory behavior study, 1 November through 12 December 2007. Green areas indicate periods/locations where data were collected. Red indicates no data due to battery failure. Black indicates no data due to hydrophone damage. Areas indicated by white represent locations where receivers were not deployed during that time.

Appendix B

Statistical Model Used To Estimate Fate

Appendix B – Statistical Model Used To Estimate Fate

B.1 Release Groups

Two types of release groups of tagged smolts were considered in the fate determination analysis: LMN1 release groups and "virtual" release groups. The LMN1 release groups, referred to in Section 3.7, consisted of tagged subyearling Chinook salmon that arrived at the LMN1 acoustic array during a specific period (e.g., a particular week). Subgroups of these LMN1 release groups formed the virtual release groups, defined for each downstream reach and detection period by the number of live fish determined to be present in the reach at the beginning of the detection period. The virtual release group, size in reach j $(j = 2,3,4)$, and detection period $t\,(t = 1,2,3,4)$ are denoted $R_{(jt)}$.

B.2 Estimating Migration Parameters for a Single LMN1 Release Group

B.2.1 Overview

Salmonid migration parameters based on acoustic detection data from a single LMN1 release group were estimated using a statistical release-recapture likelihood that is the product of multiple components. The likelihood (L_t) for a given LMN1 release group and detection period (t) can be decomposed into three auxiliary likelihoods:

$$L_t = L_{t-LD} \cdot L_{t-TR} \cdot L_{t-IRN},$$

where L_{t-LD} is the likelihood of reach migration and survival probabilities conditional on the line detections (LD) and tailrace detections, L_{t-TR} is the likelihood of detection probabilities at the tailrace nodes (LMT), and L_{t-IRN} is the likelihood of the reach abundance parameters based on detections from the intrareach nodes (IRN). Two temporal subsamples of the intrareach node detections were used in each reach and detection period to estimate the number of live, tagged smolts delaying ("residualizing") in that reach during that detection period. Reach transition probabilities and abundance estimates were combined to estimate the probability of delaying in a particular reach within a given detection period.

B.2.2 Notation and Assumptions Used in L_{t-TR} Underlying Migration Model

The parameters used in the smolt migration model for a single release group (Table B.1) include downstream migration probabilities (d_{itj}), survival probabilities for both migrating and residualizing smolts (S_{ditj}, S_{rit}), "transition" (i.e., joint migration and survival) probabilities (ϕ_{itj}), and residualization probabilities (ψ_{it}), as well as abundance parameters (N_{it}) and detection parameters (p_{it}). The individual movement (d_{itj}) and survival probabilities (S_{ditj}, S_{rit}) are not separately estimable, but the transition (ϕ_{itj}) and delay (ψ_{it}) parameters are estimable. The data necessary to estimate the transition

and delay parameters for a single release group are detailed in Table B.2. Figure B.1 presents a schematic of the movement and survival parameters for the three reaches of the study area for the virtual release group $R_{(2t)}$ in reach 2 in detection period t.

Table B.1. Parameters and interpretation for smolt migration model for a single release group and detection period t

Parameter	Definition
d_{itj}	Probability of downstream migration through reach i in detection period t, conditional on being in reach j at the beginning of detection period t; not separately estimable.
S_{ditj}	Probability of survival through reach i in detection period t, conditional on downstream migration through reach i in detection period t and being in reach j at the beginning of detection period t; not separately estimable.
S_{rit}	Probability of survival in reach i to the end of detection period t, conditional on being in reach i in detection period t and not migrating through the reach during that detection period; not separately estimable.
ϕ_{itj}	Joint probability of migrating and surviving through reach i in detection period t, conditional on being in reach j at the beginning of detection period t; "migration transition probability." $\phi_{itj} = d_{itj} S_{ditj}$; estimable for $i = 2, 3, 4$.
ψ_{it}	Joint probability of delaying migration (residualizing) in reach i and surviving to the end of detection period t, conditional on being in reach i in detection period t (either begin period t in reach i or arrive there in period t from upstream); "delay probability." $\psi_{it} = \left(1 - d_{itj}\right) S_{rit}$ for all reaches j, $j \le i$; estimable for $i = 2, 3, 4$.
p_{it}	Conditional probability of detection on intrareach nodes in reach i during detection period t, given presence in reach i in that detection period, for $i = 2, 3, 4$.
p_{4t1}	Conditional probability of detection on first tailrace node (LMT1) during detection period t, given reaching tailrace nodes during that detection period.
p_{4t2}	Conditional probability of detection on second tailrace node (LMT2) during detection period t, given reaching tailrace nodes during that detection period.
p_{4t}	Conditional probability of detection on tailrace nodes (LMT) during detection period t, given reaching tailrace nodes during that detection period; $p_{4t} = 1 - \left(1 - p_{4t1}\right)\left(1 - p_{4t2}\right)$.
N_{it}	Number of live tagged smolts present in reach i at end of detection period t; estimable for $i = 2, 3, 4$.

Table B.2. Statistics used in smolt migration model for a single release group and detection period t

Statistic	Definition
R	Size of the initial LMN1 release group.
$R_{(jt)}$	Number of live tagged smolts known to be present in reach j at the beginning of detection period t; "virtual release." $R_{(21)} = R$, the size of the initial LMN1 release group.
m_{itj}	Number of smolts from virtual release group $R_{(jt)}$ whose last line detections during detection period t were on the line at the downstream border of reach i, for $i \geq j$.
r_{jt}	Number of smolts from virtual release group $R_{(jt)}$ that are detected on lines or at tailrace nodes downstream of reach j during detection period t; $r_{jt} = \sum_{i=j}^{4} m_{itj}$.
$T_{t(11)}, T_{t(10)}, T_{t(01)}$	Number of tagged smolts detected at the tailrace nodes (site LMT) during detection period t that were detected at: both LMT1 and LMT2; LMT1 but not LMT2; and LMT2 but not LMT1, respectively.
$m_{4t\cdot}$	Total number of tagged smolts detected at the tailrace nodes (site LMT) during detection period t; $m_{4t\cdot} = T_{t(11)} + T_{t(10)} + T_{t(01)}$; also $m_{4t\cdot} = m_{4t1} + m_{4t2} + m_{4t3} + m_{4t4}$.
$n_{it(11)}, n_{it(10)}, n_{it(01)}$	Number of tagged smolts detected on intrareach nodes in reach i at end of detection period t in: both (temporal) subsamples; the first but not the second subsample; and the second but not the first subsample, respectively.
n_{it}	Total number of tagged smolts detected on intrareach nodes in reach i at end of detection period t; $n_{it} = n_{it(11)} + n_{it(10)} + n_{it(01)}$.

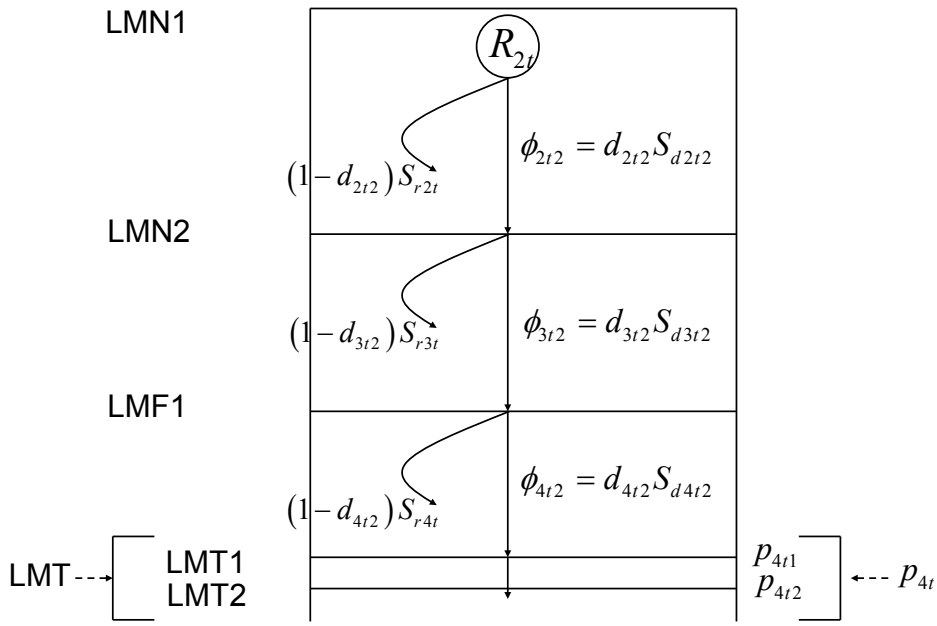

Figure B.1. Line detection and tailrace models, using virtual release group $R_{(2t)}$ in reach 2, detection period t, with underlying migration and survival parameters and tailrace detection parameters. Parameter d_{it2} is the probability of downstream movement (i.e., migration) in reach i in detection period t, and parameter S_{dit2} is the probability of survival for migrating fish in reach i in detection period t, both for fish that began detection period t in reach 2. Parameter S_{rit} is the probability of surviving through detection period t in reach i, conditional on delaying (or residualizing) in that reach during period t. Parameter ϕ_{it2} is the joint probability of migration and survival through reach i in detection period t, for fish that began detection period t in reach 2. Analysis of the virtual release $R_{(2t)}$ with the CJS model provides estimation of the conditional migration and survival probabilities ϕ_{it2}. An auxiliary likelihood estimates the conditional detection probabilities at the two tailrace nodes for detection period t, p_{4t1} and p_{4t2}, as well as the overall conditional detection probability at LMT, $p_{4t} = 1-(1-p_{4t1})(1-p_{4t2})$.

The size of the virtual release group $R_{(jt)}$ was determined by tracking the movements of the tagged subyearling Chinook salmon on the acoustic line arrays and the intrareach nodes. Under the assumption of 100% detection at lines LMN1, LMN2, and LMF, it was possible to identify the location of each fish at the end of each detection period. The decision rule described in Section 3.7.2.2 was used to classify each fish within the study area (i.e., between LMN1 and LMT) as either "alive" or "dead" at the end of the detection period and, equivalently, at the beginning of the next detection period. Only fish classified as alive at the beginning of detection period t in reach j were included in the virtual release group $R_{(jt)}$. Fish that were detected at the tailrace array (LMT) were designated as having left the study area. Fish that were determined to have begun a given detection period in reach 1 (i.e., between LGS and LMN1) were omitted from analysis in that detection period because it was not possible to determine their live/dead status.

The following assumptions are used in the salmon migration model:

- **A1**. The fate of each tagged salmon is independent of the fate of every other tagged salmon.
- **A2**. All tagged salmon in a single virtual release group in reach j (or LMN1-release group in reach $j = 2$) have a common probability of migrating and surviving through a given reach and detection period, conditional on entering that reach during the detection period, regardless of previous residence time in reach j.
- **A3**. The conditional detection probability at a line array (i.e., LMN1, LMN2, or LMF) is 100%, given reaching the line.
- **A4**. Detection at a line array or intrareach node does not affect future survival or detection probabilities.
- **A5**. All tagged fish in a single release group have a common probability of being detected at either of the tailrace nodes within a given detection period, conditional on reaching that site in that detection period.
- **A6**. Survival between the two tailrace nodes (within detection site LMT) is 100%, so that any fish that passes the first node (LMT1) will pass the second node (LMT2).
- **A7**. All live tagged fish present in a given reach at the end of a given detection period have a common probability of being detected on the intrareach nodes in that reach during either of the two temporal subsamples of intrareach node detections.
- **A8**. The number of live, residualizing tagged smolts present in a given reach is constant throughout the two temporal subsamples of intrareach node detections.
- **A9**. Live fish are correctly distinguished from dead fish on the intrareach node detections, and when determining virtual release groups.
- **A10**. All tags are active, attached to the fish, and read properly throughout the detection period.

Assumption A2 addresses the probability of future migration and survival for all fish in a given virtual release group, and depends on the addition assumption A9 that live and dead fish are classified properly at the end of each detection period. Assumptions A2 through A5 state that all fish in a given release group have a common probability of achieving any given detection history of line detections and

tailrace detections. Together with assumptions A1 and A6, this means that the likelihoods for the line detections and tailrace detections are multinomial. Assumption A3 is likely to be met, based on past studies. Assumptions A1, A7, A8, and A9 indicate that the intrareach node detections can be analyzed with a multinomial likelihood to estimate the abundance of live tagged fish present in a reach at the end of a given detection period. Assumption A10 includes the assumption that tag battery life lasts throughout the study for each tag. Because the tag-life study indicated an expected tag life longer than needed for this analysis, it was unnecessary to adjust the multinomial likelihoods to account for the possibility of a dead battery.

We further assumed that the survival probability through a detection period of non-migrating (delaying) fish does not depend on where the fish began that detection period; that is, S_{rit} is the same for all virtual releases $R_{(jt)}$ $(j \le i)$. This means that the delay parameter $\psi_{it} = (1 - d_{itj}) S_{rit}$ is also equal for all virtual releases $R_{(jt)}$ $(j \le i)$.

B.2.3 Estimating Migration Transition Probabilities (Acoustic Line Array and Tailrace Detections)

The migration transition probability for a fish in a given reach is the joint probability of migrating and surviving through the reach, conditional on being alive in that reach. For reach i in detection period t, let ϕ_{itj} be the joint probability of migrating (d_{itj}) and surviving (S_{ditj}) through reach i to the line at the downstream boundary of the reach during period t, conditional on starting period t in reach j: $\phi_{itj} = d_{itj} S_{ditj}$. The parameter ϕ_{itj} was estimated using the CJS model with the release group $R_{(jt)}$ (Table B.3). The joint CJS analysis of all available virtual release groups for detection period t comprised the likelihood L_{t-LD}, using the assumption that detection at line arrays LMN2 and LMF was effectively 100%:

$$L_{t-LD} = \prod_{j=2}^{4} L_{t-LD,j} ,$$

where

$$L_{t-LD,2} = \binom{R_{(2t)}}{m_{2t2} \quad m_{3t2} \quad m_{4t2} \quad R_{(2t)} - r_{2t}} \left[\phi_{2t2}\left(1-\phi_{3t2}\right)\right]^{m_{2t2}} \left[\phi_{2t2}\phi_{3t2}\left(1-\phi_{4t2}p_{4t}\right)\right]^{m_{3t2}}$$
$$\times \left[\phi_{2t2}\phi_{3t2}\phi_{4t2}p_{4t}\right]^{m_{4t2}} \left(1-\phi_{2t2}\right)^{R_{(2t)}-r_{2t}} ,$$

$$L_{t-LD,3} = \binom{R_{(3t)}}{m_{3t3} \quad m_{4t3} \quad R_{(3t)} - r_{3t}} \left[\phi_{3t3}\left(1-\phi_{4t3}p_{4t}\right)\right]^{m_{3t3}} \left[\phi_{3t3}\phi_{4t3}p_{4t}\right]^{m_{4t3}} \left(1-\phi_{3t3}\right)^{R_{(3t)}-r_{3t}} ,$$

and

$$L_{t-LD,4} = \binom{R_{(4t)}}{m_{4t4} \quad R_{(4t)} - r_{4t}} \left[\phi_{4t4} p_{4t}\right]^{m_{4t4}} \left(1 - \phi_{4t4} p_{4t}\right)^{R_{(4t)} - r_{4t}} .$$

The two single nodes comprising the tailrace detection site (LMT) were not certain to have 100% detection, so an auxiliary multinomial likelihood $\left(L_{t-TR}\right)$ was used to estimate the overall conditional probability of detection at LMT for detection period t $\left(p_{4t}\right)$, given presence there:

$$L_{t-TR} = \binom{m_{4t\cdot}}{T_{t(11)} \quad T_{t(10)} \quad T_{t(01)}} \left(\frac{p_{4t1} p_{4t2}}{p_{4t}}\right)^{T_{t(11)}} \left(\frac{p_{4t1}\left[1 - p_{4t2}\right]}{p_{4t}}\right)^{T_{t(10)}} \left(\frac{\left[1 - p_{4t1}\right] p_{4t2}}{p_{4t}}\right)^{T_{t(01)}} .$$

The estimate of p_{4t} allowed separate estimation of ϕ_{4tj} from likelihood L_{t-LD} for detection period t and virtual release $R_{(jt)}$.

B.2.4 Estimating Live Tagged Reach Population Sizes (Intrareach Node Detections)

Detections from the intrareach nodes for a given detection period and reach were used to estimate the size of the live, tagged population in the reach at the end of the detection period (i.e., the tagged delaying population). Detections were available on a continual temporal basis. Two temporal subsamples of the intrareach node detections were taken during the last two days of each detection period. These two subsamples were analyzed in a multinomial likelihood $\left(L_{t-IRN}\right)$ to estimate the size of the live, tagged population in each reach at the end of detection period t. The number of tagged salmonids from a given release alive in reach i at the end of detection period t is denoted N_{it}, for $i = 2,3,4$.

The intrareach node detection data for the two subsamples in reach i ($i = 2,3,4$) and detection period t were organized in detection histories, indicating whether the fish was detected in each subsample. The possible detection histories, accompanying statistics, and probabilities are listed in Table B.3, where "1" indicates the fish was detected and "0" indicates the fish was not detected in a given subsample. The probability of detection on any of the intrareach nodes in reach i and detection period t during the first subsample is p_{it1}; the analogous probability for the second subsample is p_{it2}. For ease of presentation, define $q_{it1} = 1 - p_{it1}$ and $q_{it2} = 1 - p_{it2}$ to be the conditional probabilities of *not* being detected in each subsample, given present in reach i at the end of detection period t.

The likelihood used with the intrareach node detections to estimate N_{it} is L_{t-IRN}:

$$L_{t-IRN} = \binom{N_{it}}{n_{it(11)} \quad n_{it(10)} \quad n_{it(01)} \quad N_{it} - n_{it}} \left(p_{it1} p_{it2}\right)^{n_{it(11)}} \left(p_{it1} q_{it2}\right)^{n_{it(10)}} \left(q_{it1} p_{it2}\right)^{n_{it(01)}} \left(q_{it1} q_{it2}\right)^{N_{it} - n_{it}} .$$

Table B.3. Detection histories from intrareach nodes for a single release group, reach i, and detection period t

Detection History	Number of Fish with Detection History for reach i and detection period t	Probability of Detection History
1 1	$n_{it(11)}$	$p_{it1}p_{it2}$
1 0	$n_{it(10)}$	$p_{it1}q_{it2}$
0 1	$n_{it(01)}$	$q_{it1}p_{it2}$
0 0	$n_{it(00)}$ (not observed)	$q_{it1}q_{it2}$
Total Observed	$n_{it} = n_{it(11)} + n_{it(01)} + n_{it(01)}$	
Total	N_{it}	

Appendix C

Fish Track Examples

Appendix C – Fish Track Examples

Examples of detection histories of individual acoustic-tagged juvenile fall Chinook salmon are presented in this appendix to provide some insight into how many of these fish move through space and time—as well as additional fate information as determined by subsequent detection in the PIT tag system. Figures C.1 through C.3 are examples of "undirected" movement within Lower Monumental Reservoir during the period when acoustic receivers were deployed. The fish depicted in Figures C.4 and C.5 represent fish that were "directed" with respect to their migration through Lower Monumental Reservoir but then apparently overwintered somewhere between Ice Harbor Dam and Bonneville Reservoir (Figure C.4) and somewhere upstream of McNary Dam (Figure C.5).

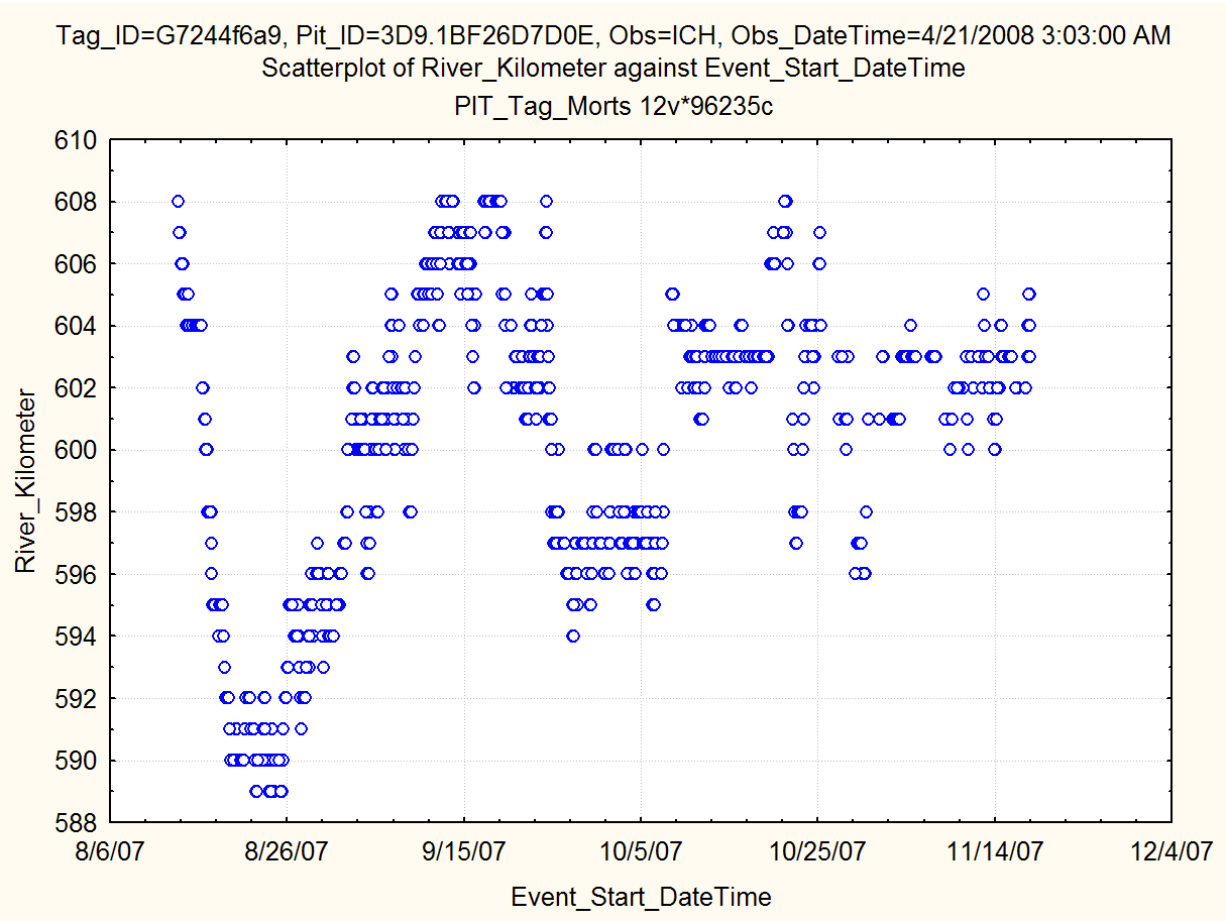

Figure C.1. Acoustic receiver detection history for a 149-mm, 39.8-g juvenile fall Chinook salmon released at Rkm 631 on 11 August 2007. LMN is at Rkm 589. This fish was detected on the PIT tag system while passing through the full flow bypass at Ice Harbor Dam on 21 April 2008.

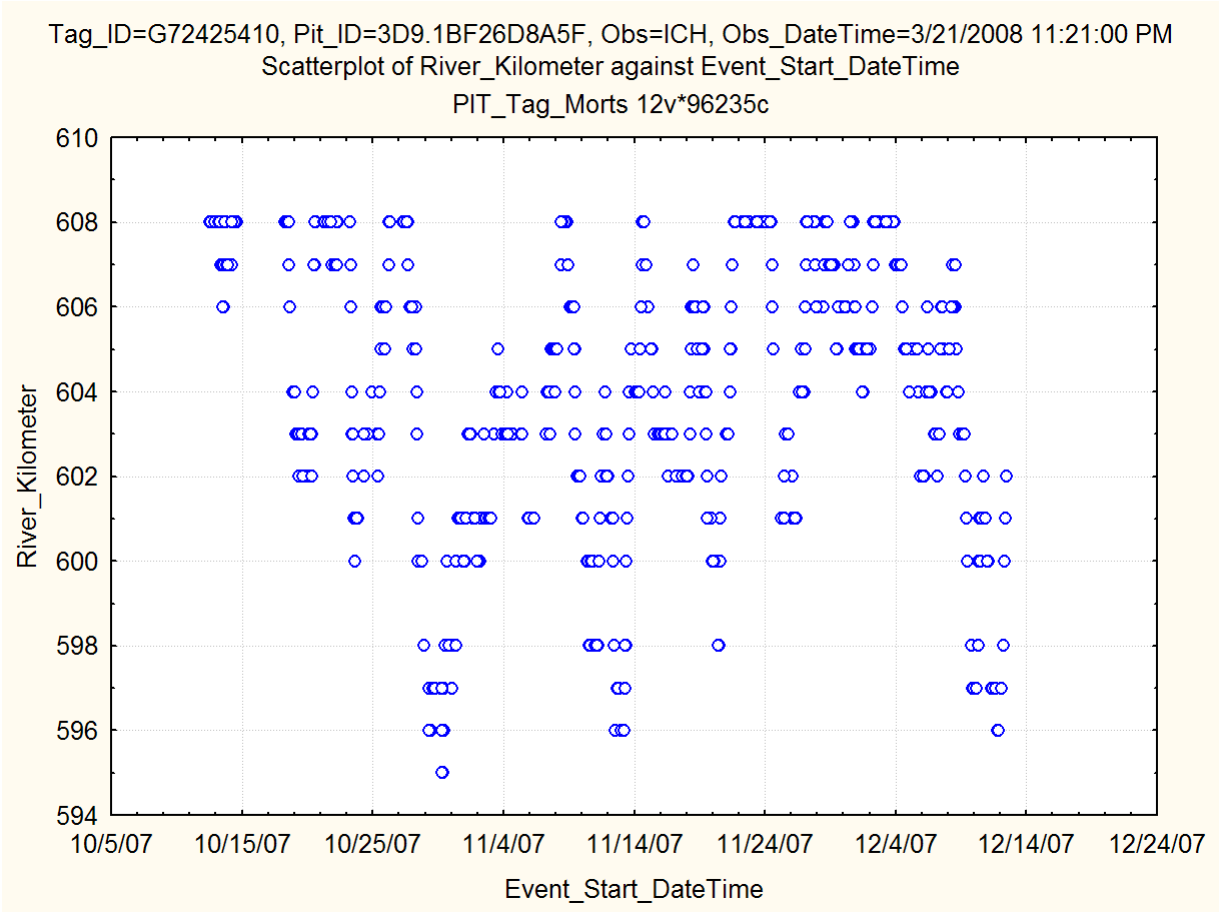

Figure C.2. Acoustic receiver detection history for a 201-mm, 98.1-g juvenile fall Chinook salmon released at Rkm 631 on 6 October 2007. LMN is at Rkm 589. This fish was detected on the PIT tag system while passing through the full flow bypass at Ice Harbor Dam on 21 March 2008.

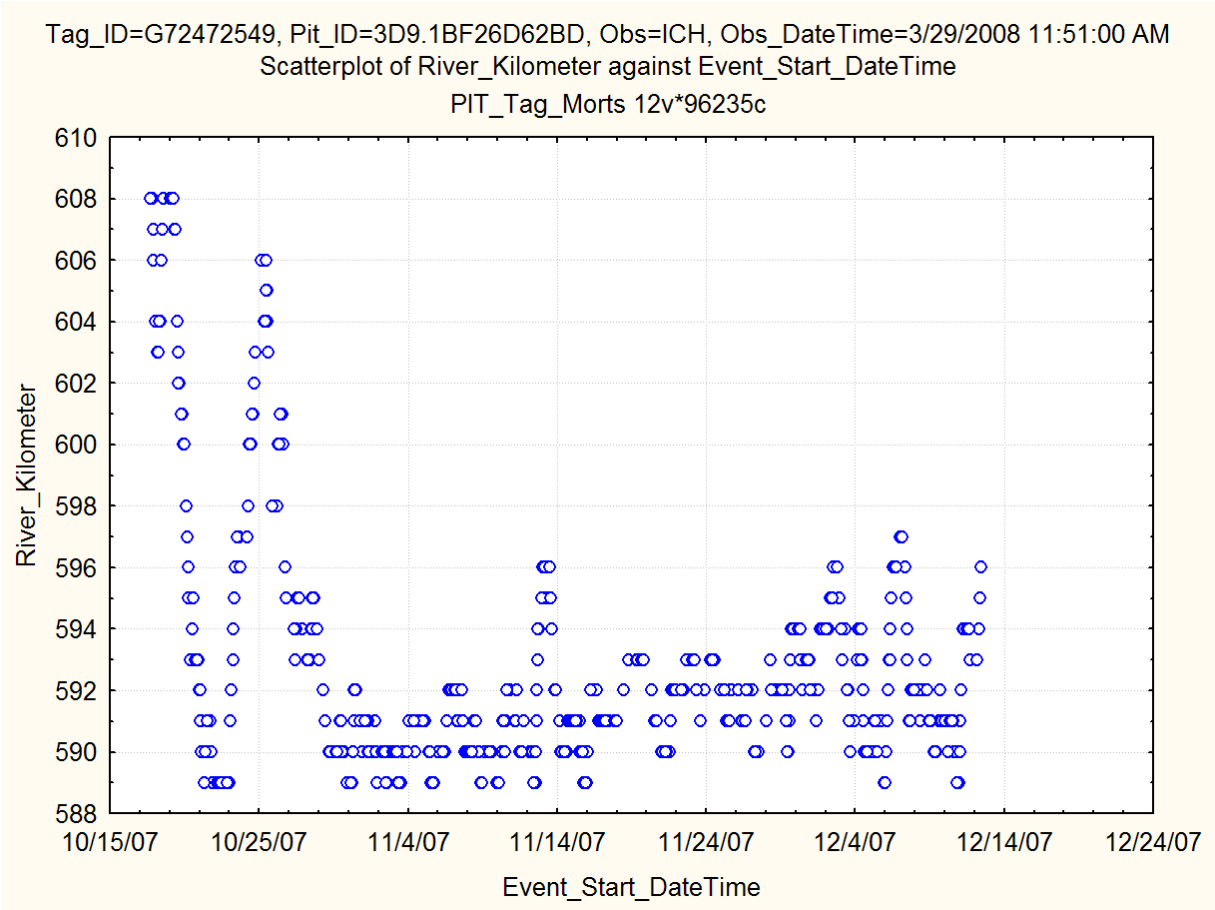

Figure C.3. Acoustic receiver detection history for a 202-mm, 94.3-g juvenile fall Chinook salmon released at Rkm 631 on 11 October 2007. LMN is at Rkm 589. This fish was detected on the PIT tag system while passing through the full flow bypass at Lower Monumental Dam on 19 March 2008 and again in the full flow bypass at Ice Harbor Dam on 29 March 2008.

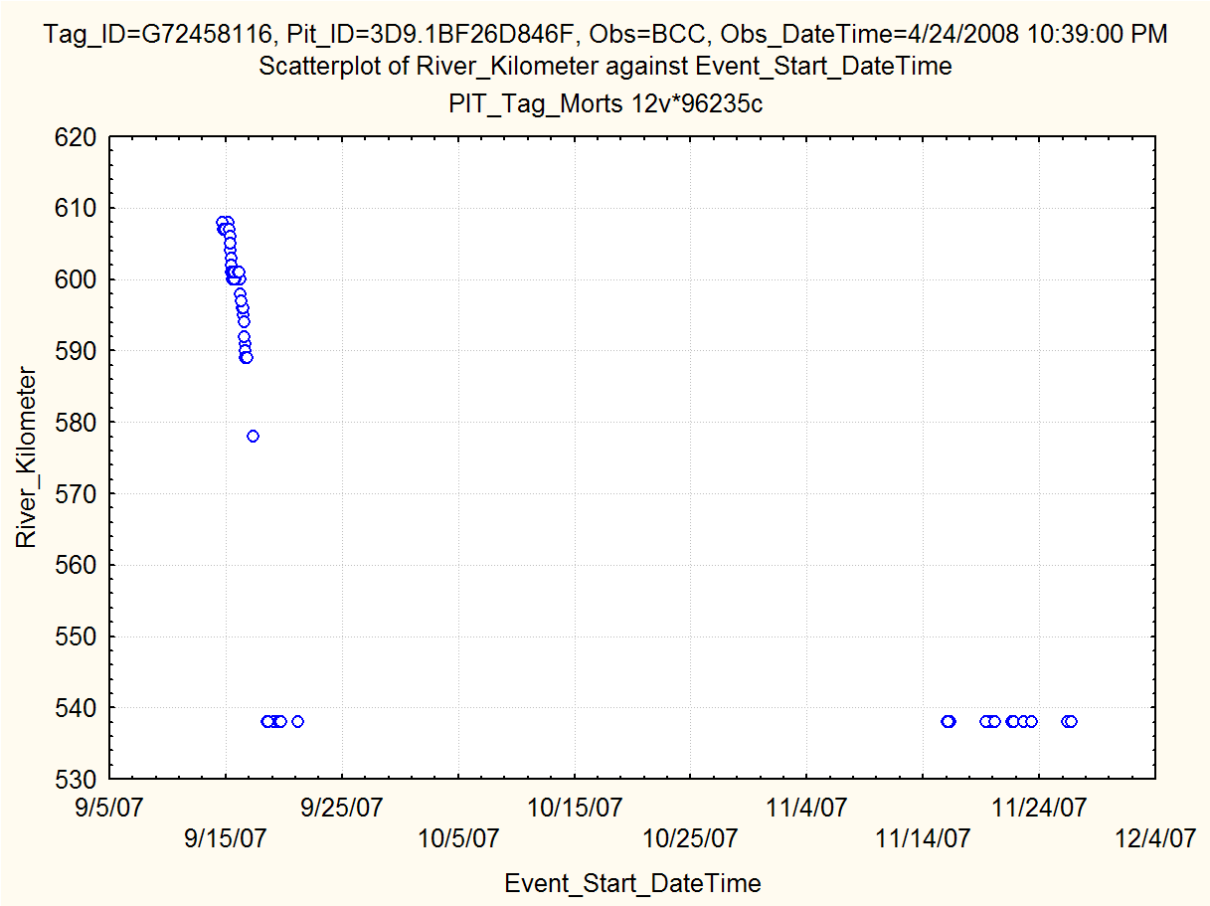

Figure C.4. Acoustic receiver detection history for a 202-mm, 92.1-g juvenile fall Chinook salmon released at Rkm 631 on 13 September 2007. LMN is at Rkm 589, the LMN tailrace array is at Rkm 578.5, and the Ice Harbor Dam forebay array is at Rkm 538.1. This fish was detected on the PIT tag system while passing through the full flow bypass at Ice Harbor Dam on 26 November 2007 and then on the large antenna in the Bonneville Corner Collector on 24 April 2008.

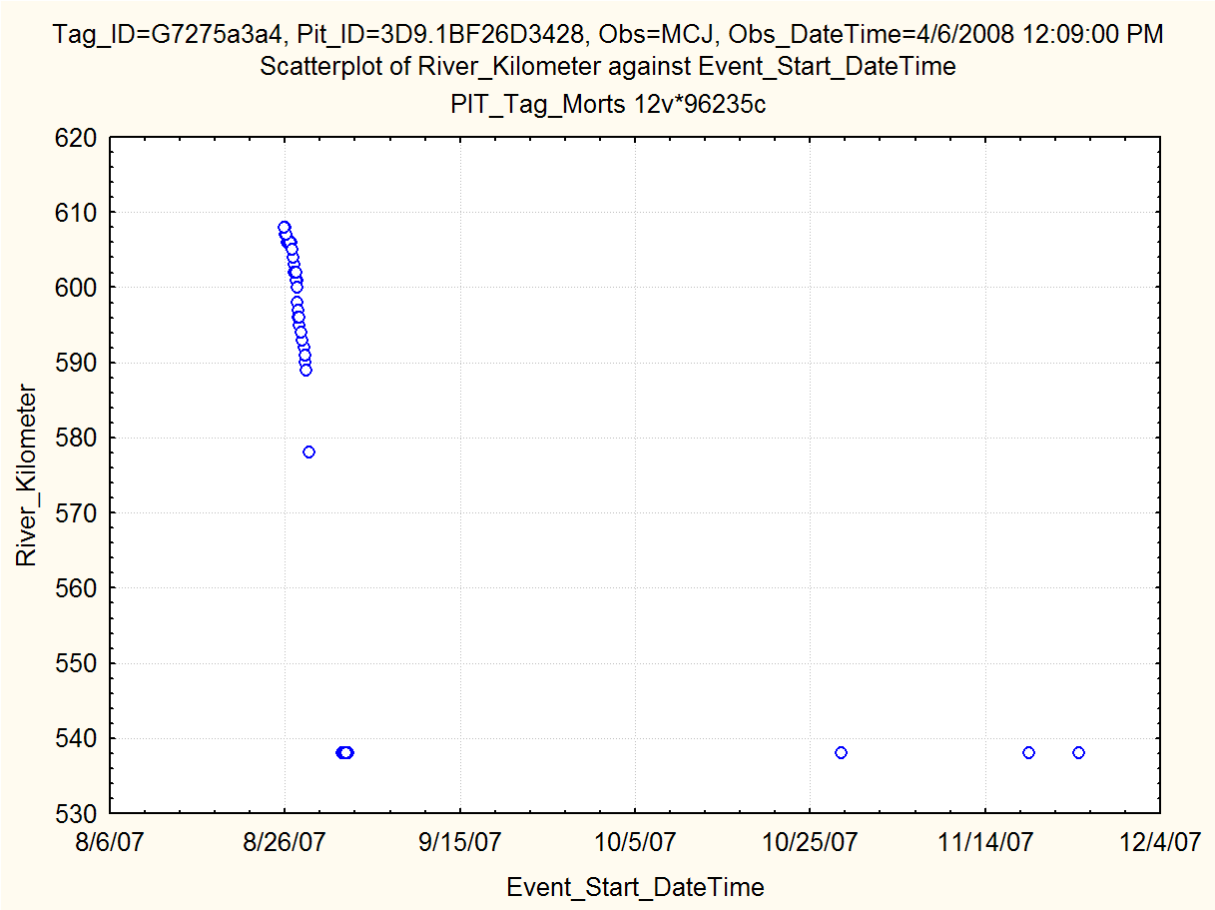

Figure C.5. Acoustic receiver detection history for a 169-mm, 42.1-g juvenile fall Chinook salmon released at Rkm 631 on 23 August 2007. LMN is at Rkm 589, the LMN tailrace array is at Rkm 578.5, and the Ice Harbor Dam forebay array is at Rkm 538.1. This fish was detected on the PIT tag system while passing through the full flow bypass at McNary Dam on 6 April 2008 and then in the full flow bypass at John Day Dam on 13 April 2008.

Appendix D

Project Operations

Appendix D – Project Operations

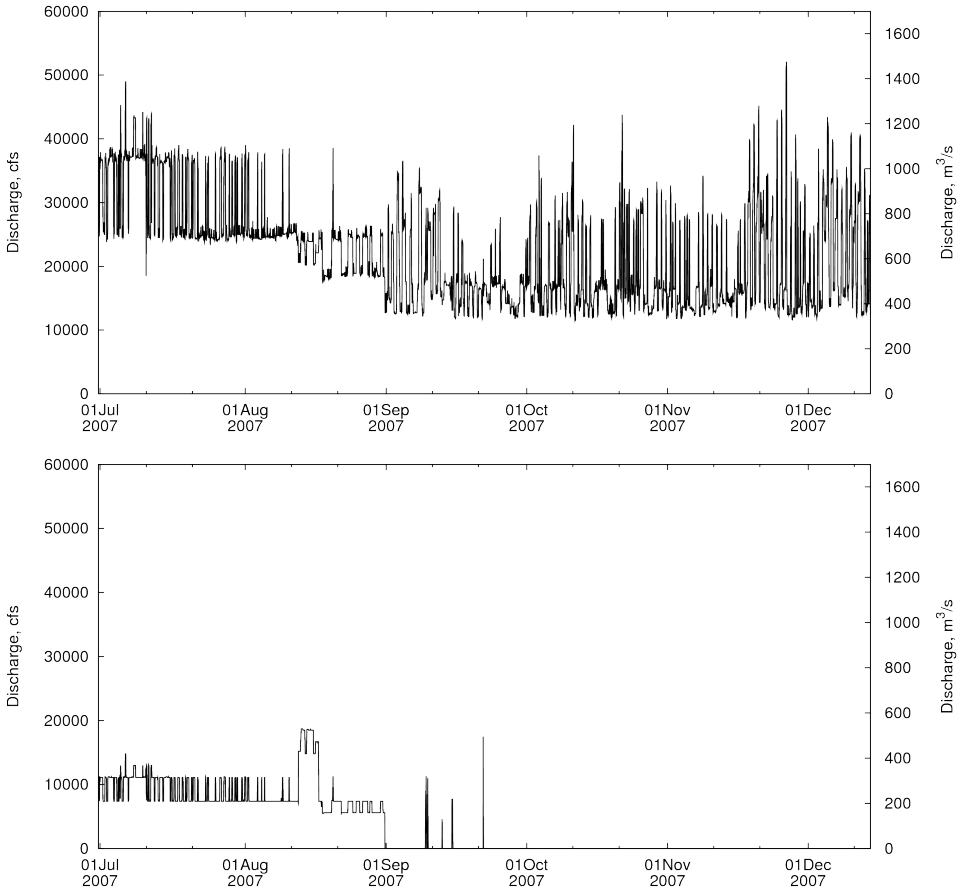

Figure D.1. Recorded hourly discharge (above) and spill (below) at Little Goose Dam during study period

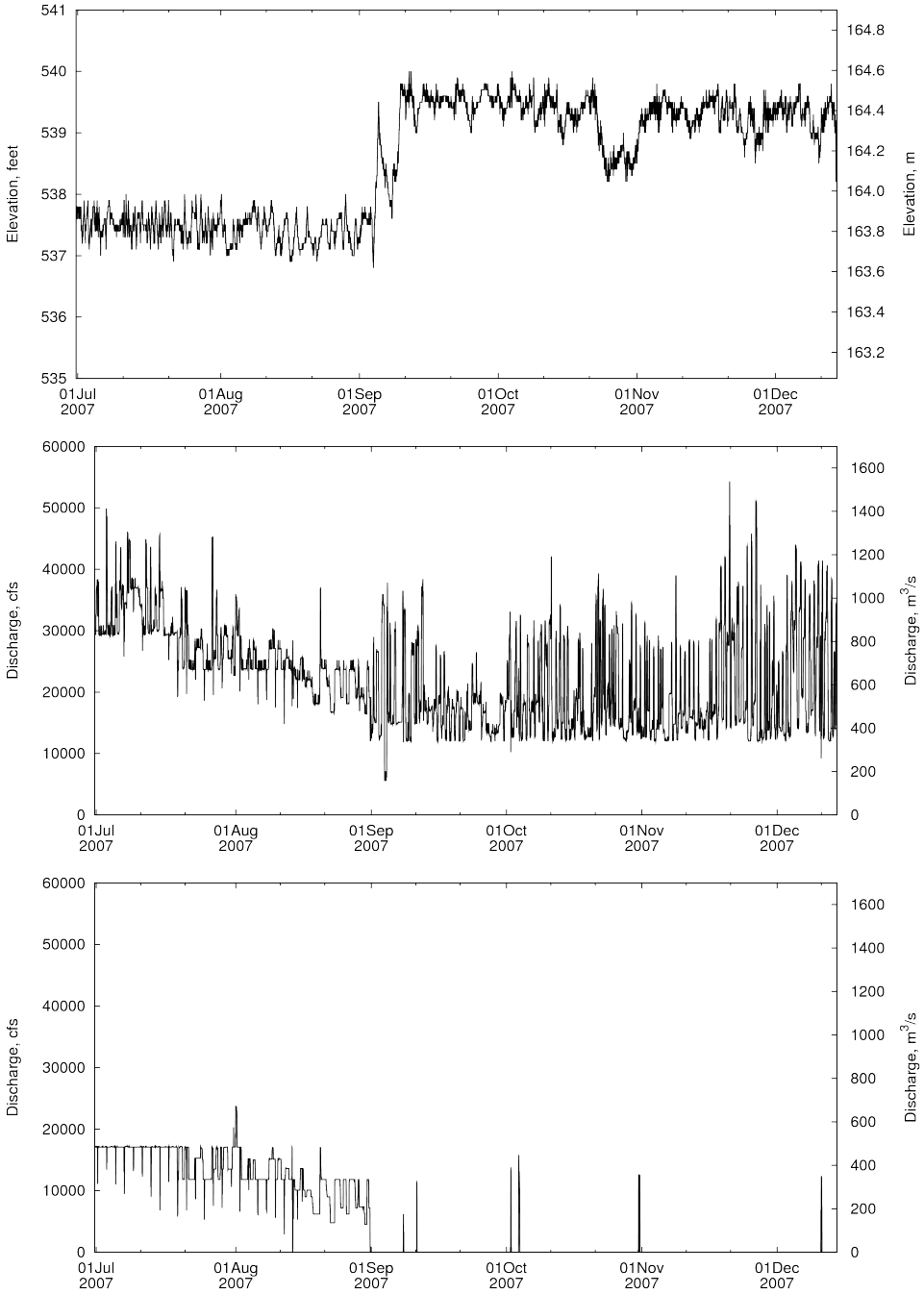

Figure D.2. Recorded hourly forebay stage (top), total river discharge (middle), and spill (bottom) at Lower Monumental Dam during study period

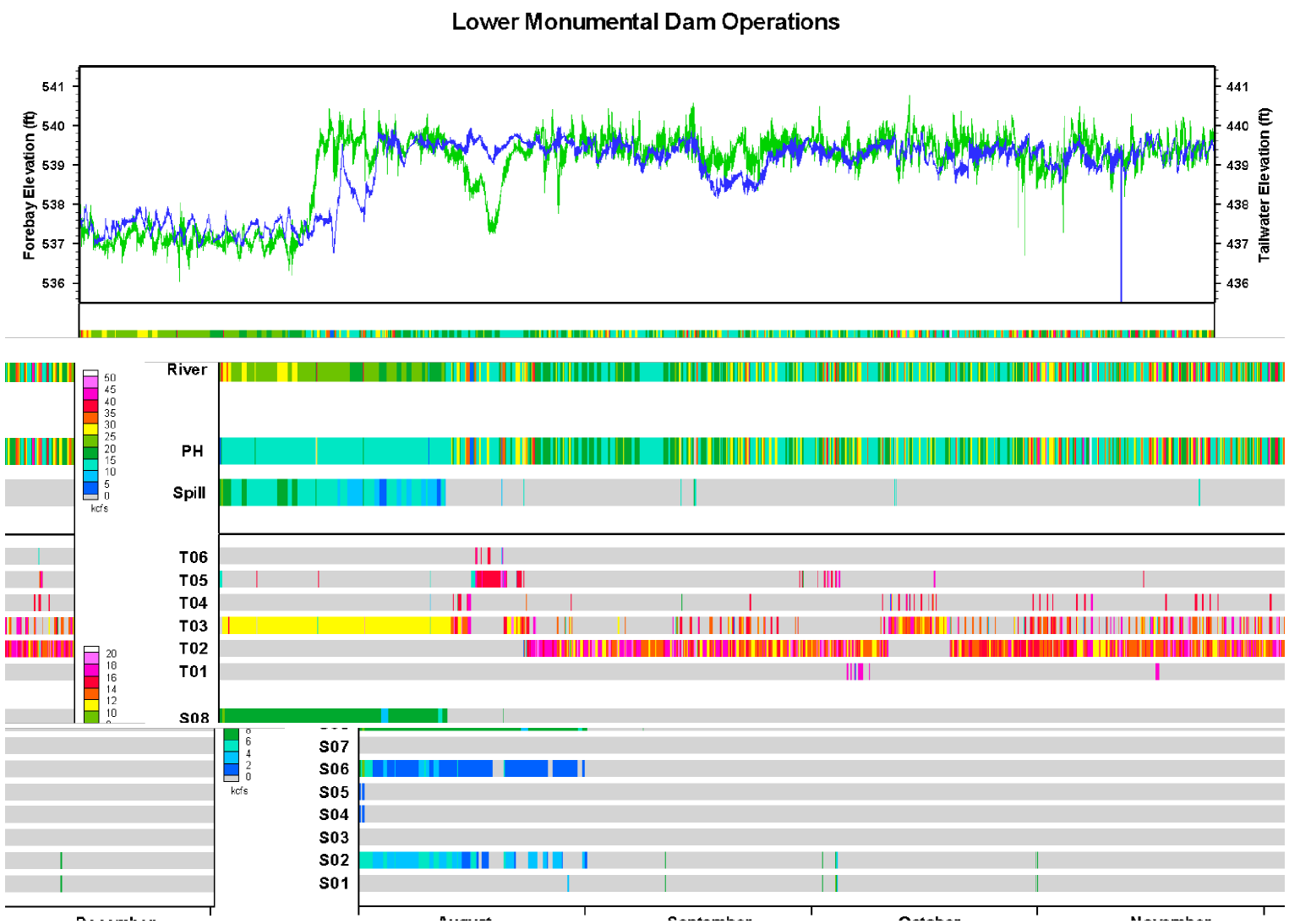

Figure D.3. Summary of 5-minute dam operations data at Lower Monumental Dam during study period

Appendix E

Hydraulic Data Summary

Appendix E – Hydraulic Data Summary

This appendix summarizes the hydraulic data collected or computed for this study, mostly in graphical form. Temperature data are summarized in Section E.1. Water velocity data from bottom-moored acoustic Doppler current profiler (ADCP) deployments are summarized in Section E.2. Water velocity measurements made during mobile ADCP surveys are presented in Section E.3. Estimated discharge and velocity at key locations and computed water travel times between key locations are presented in Sections E.4 and E.5, respectively.

River kilometers noted in the graphics are the distance from the mouth of the Columbia River.

E.1 Temperature

E.1.1 Vertical Profile Data

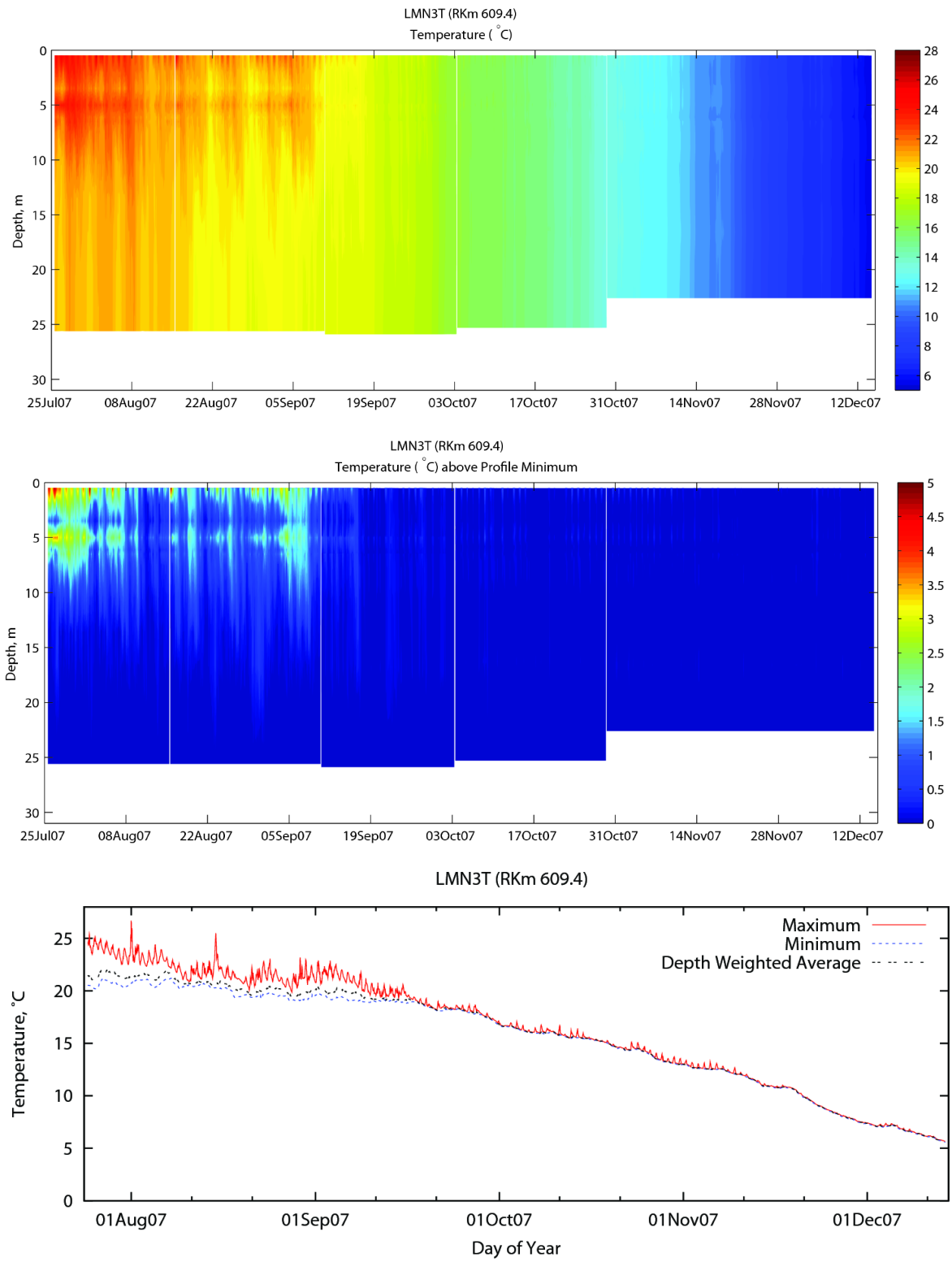

Figure E.1. Hourly temperature record from LMN3T site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

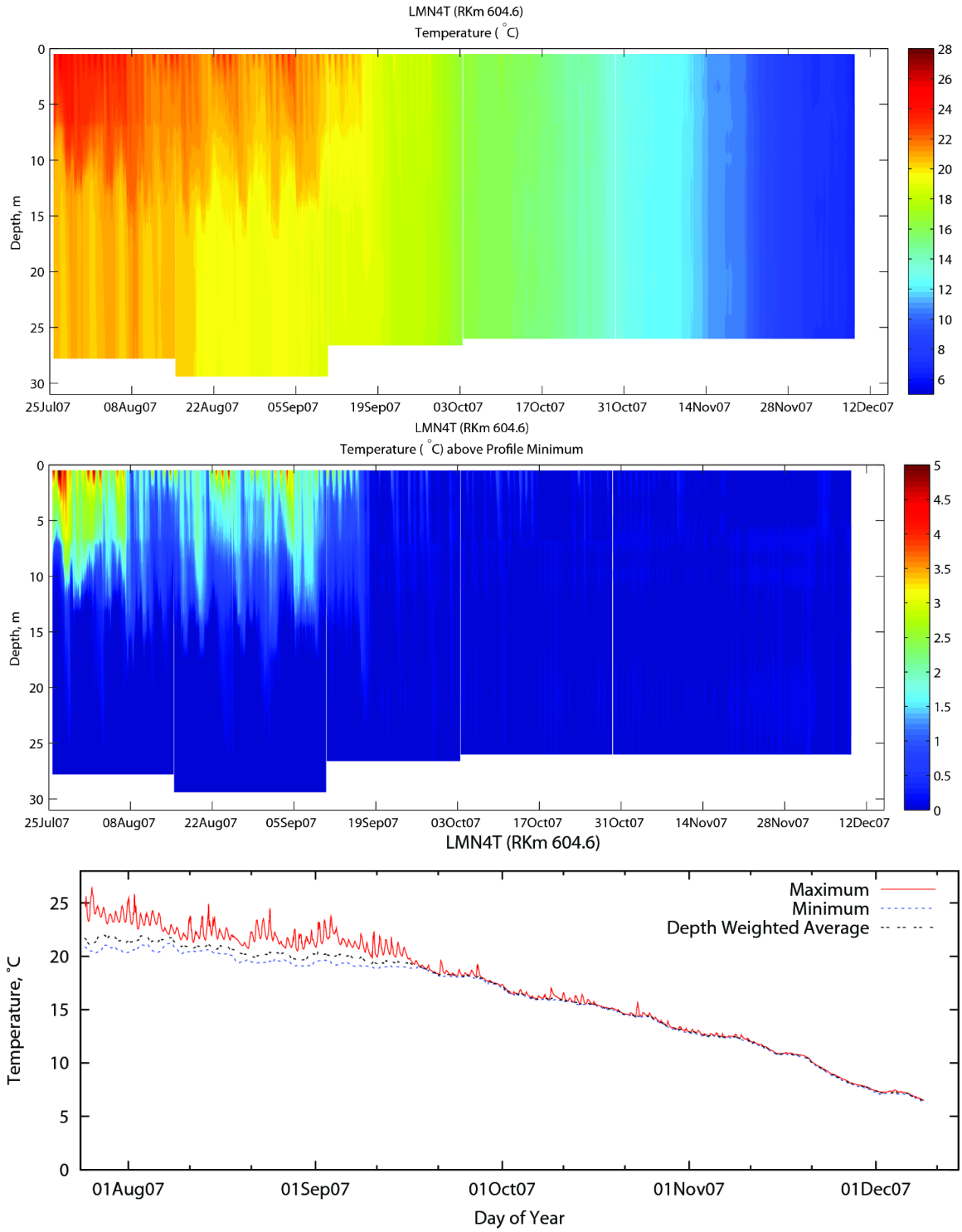

Figure E.2. Hourly temperature record from LMN4T site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

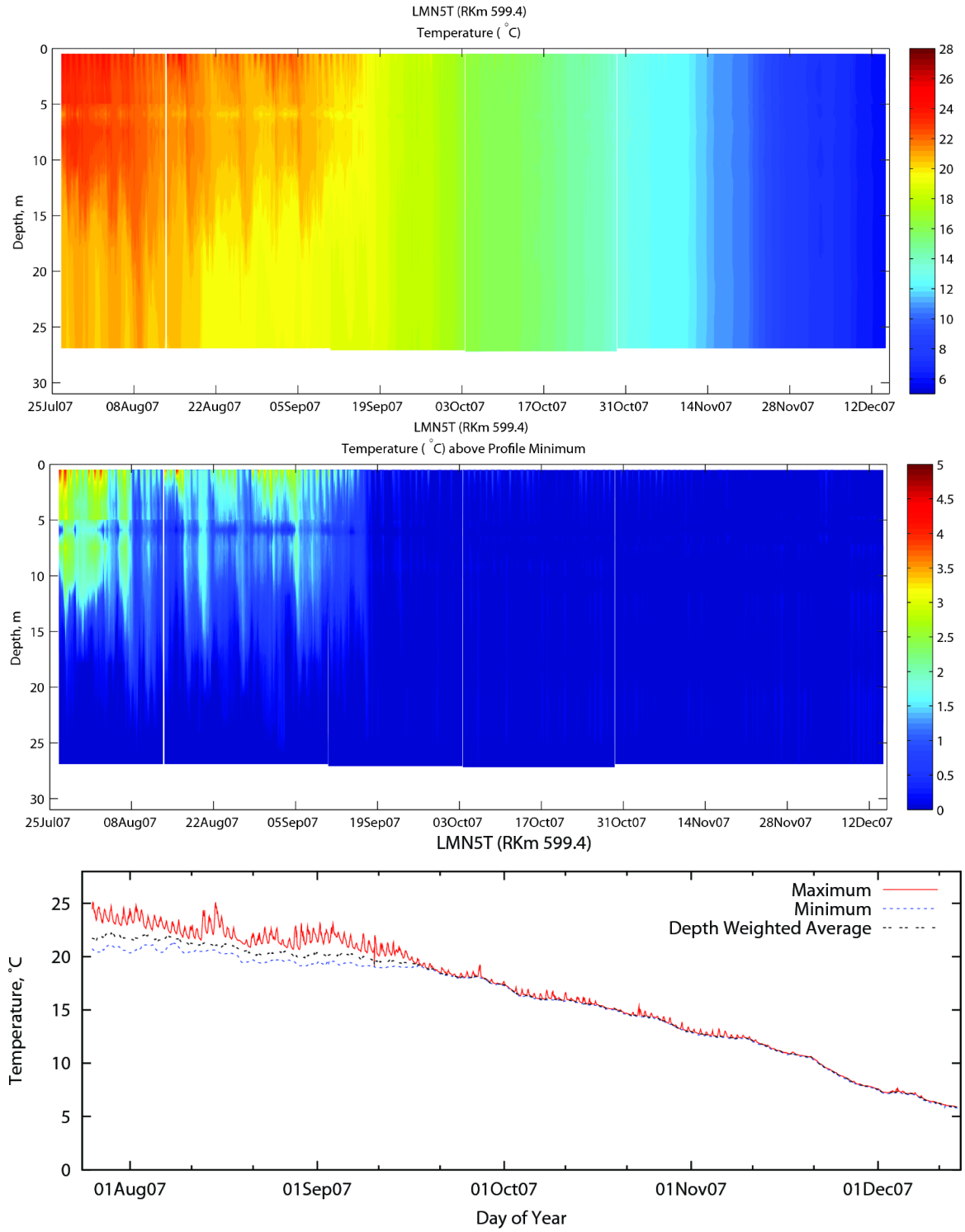

Figure E.3. Hourly temperature record from LMN5T site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

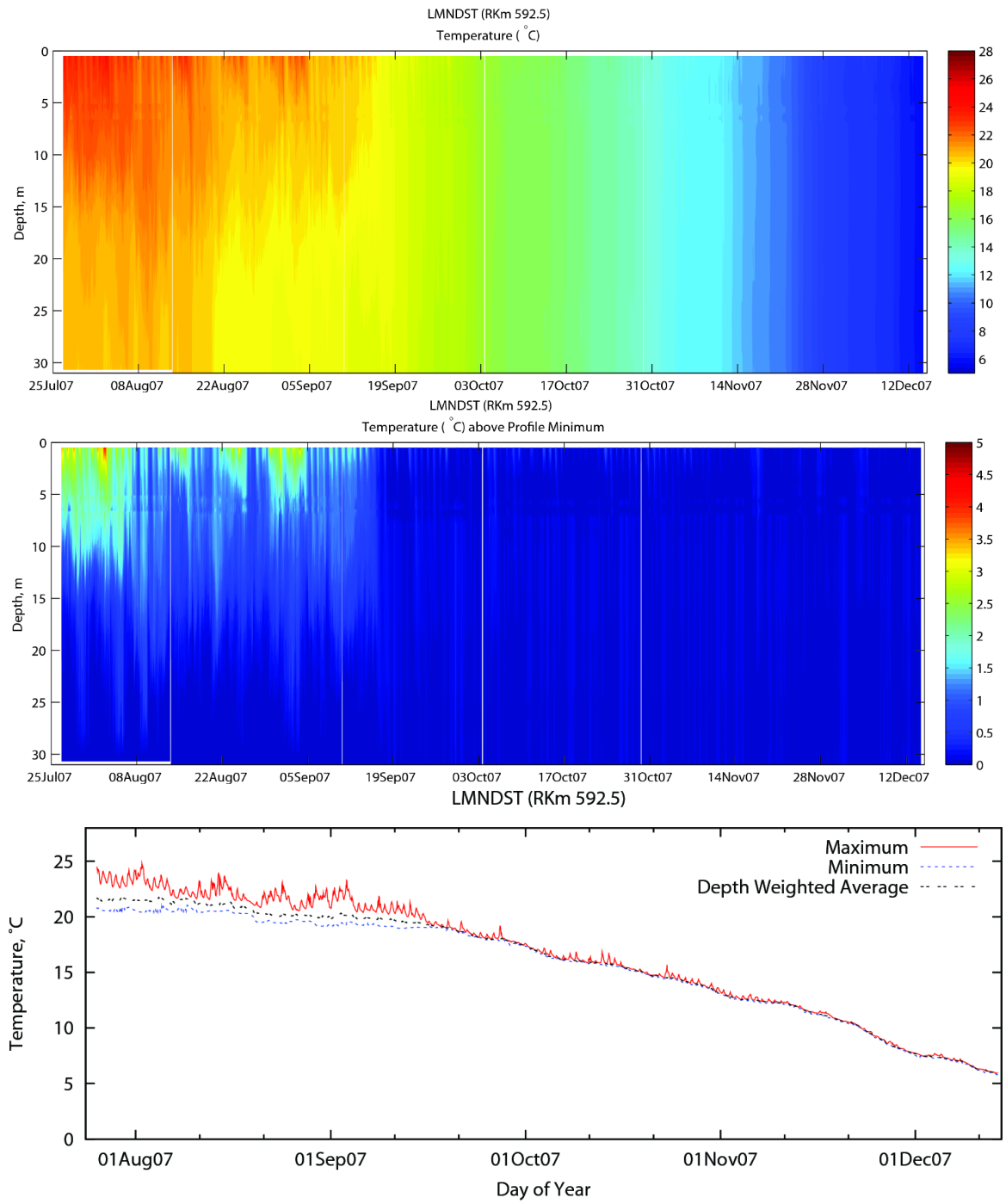

Figure E.4. Hourly temperature record from LMNDST site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

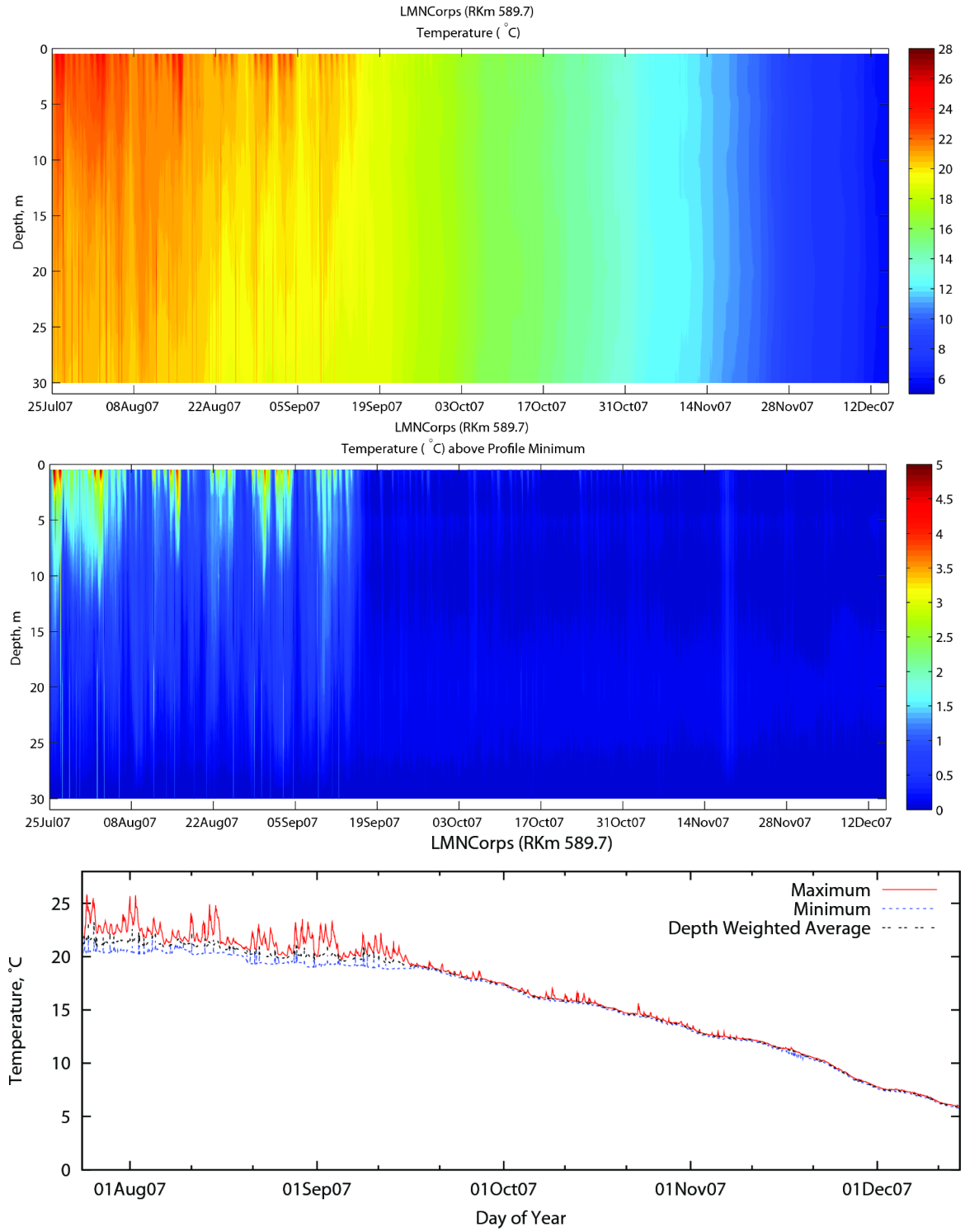

Figure E.5. Hourly temperature record from LMNCorps site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

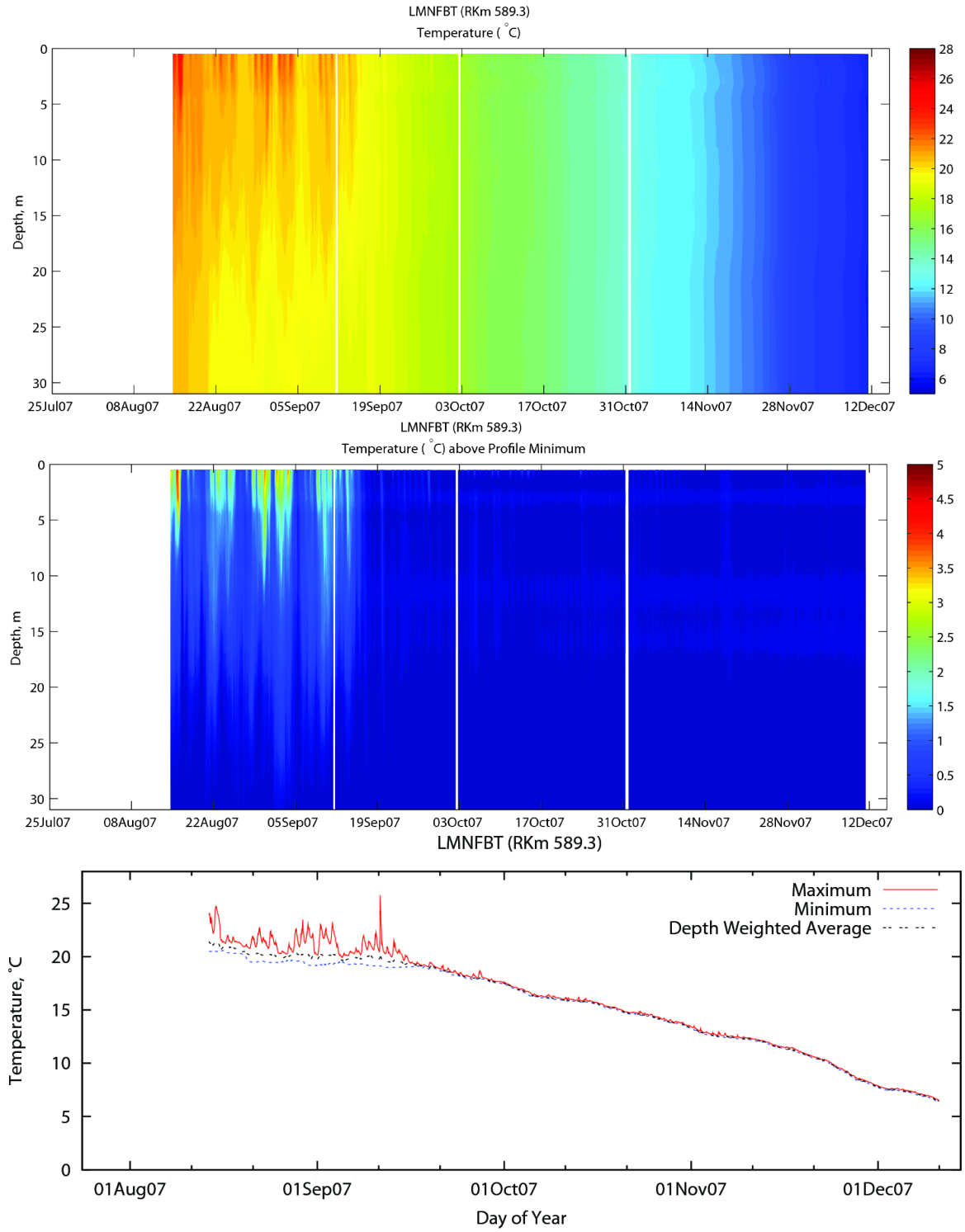

Figure E.6. Hourly temperature record from LMNFBT site, including complete vertical temperature profile record over time (top), temperature above profile minimum (middle), and profile statistics

E.1.2 Thermal Layer Properties

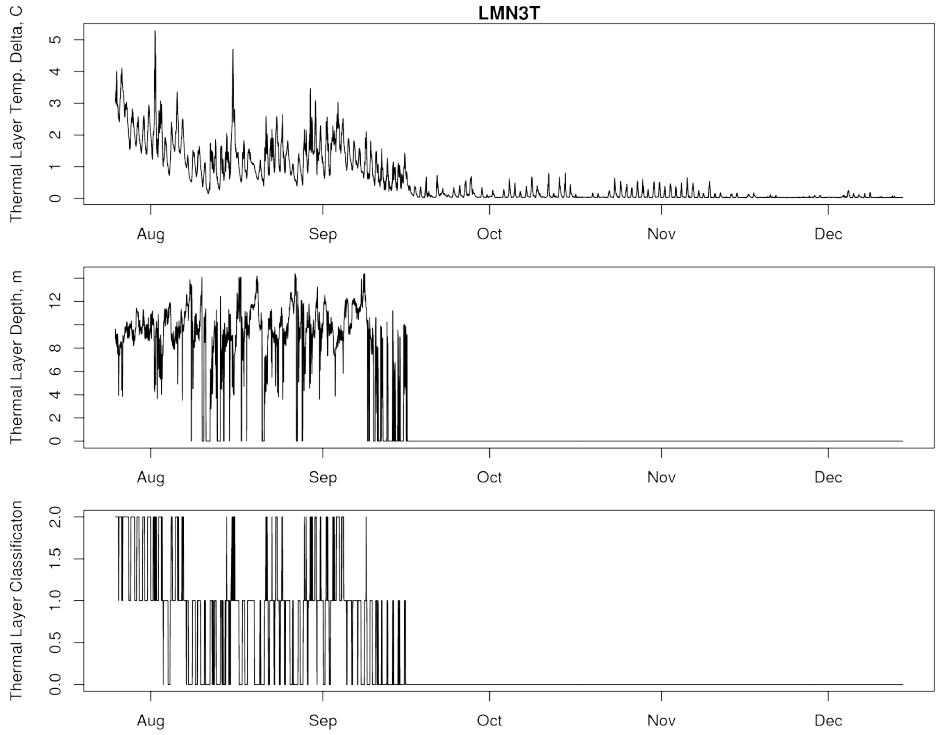

Figure E.7. Computed thermal layer statistics for LMN3T

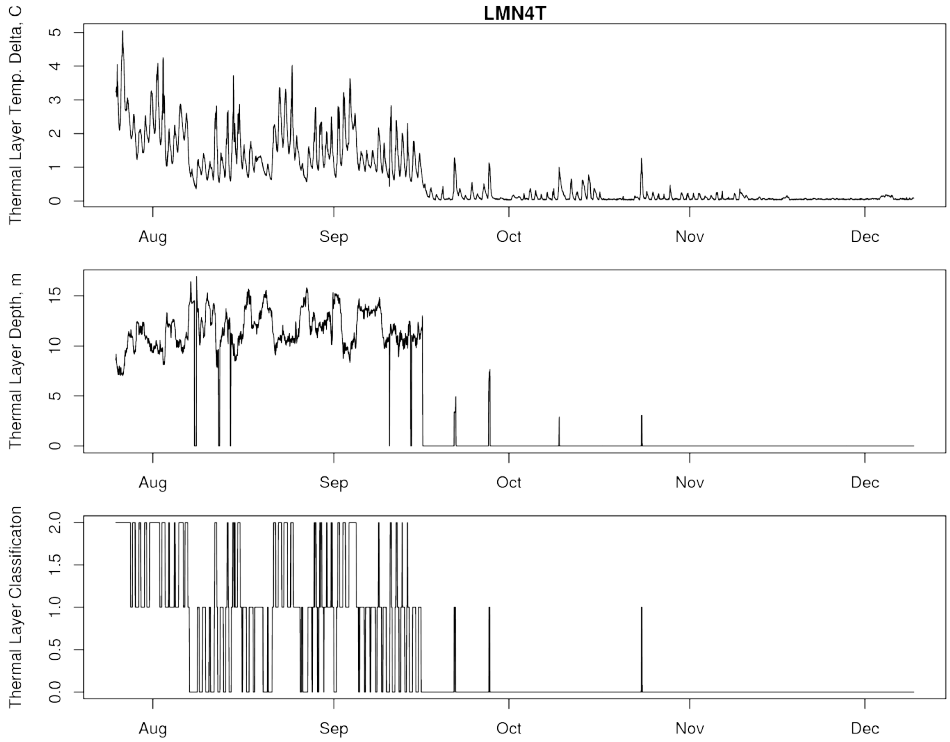

Figure E.8. Computed thermal layer statistics for LMN4T

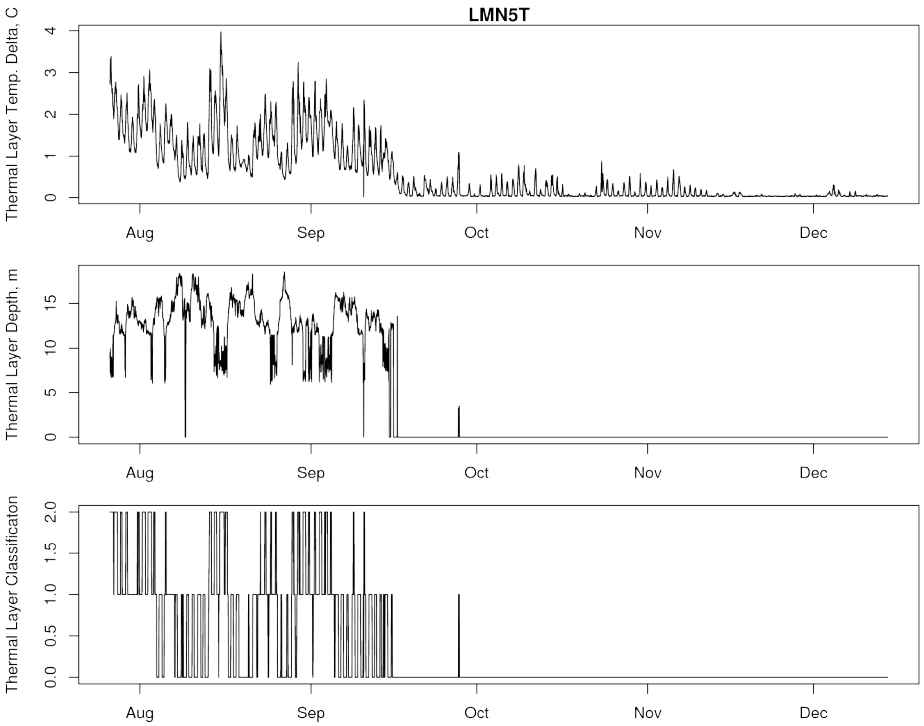

Figure E.9. Computed thermal layer statistics for LMN5T

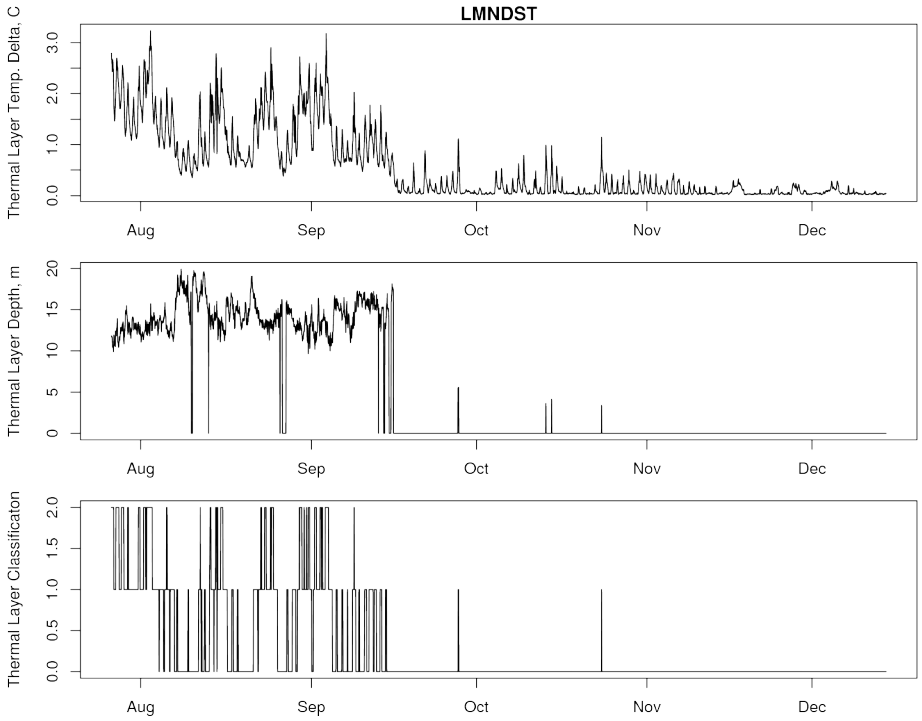

Figure E.10. Computed thermal layer statistics for LMNDST

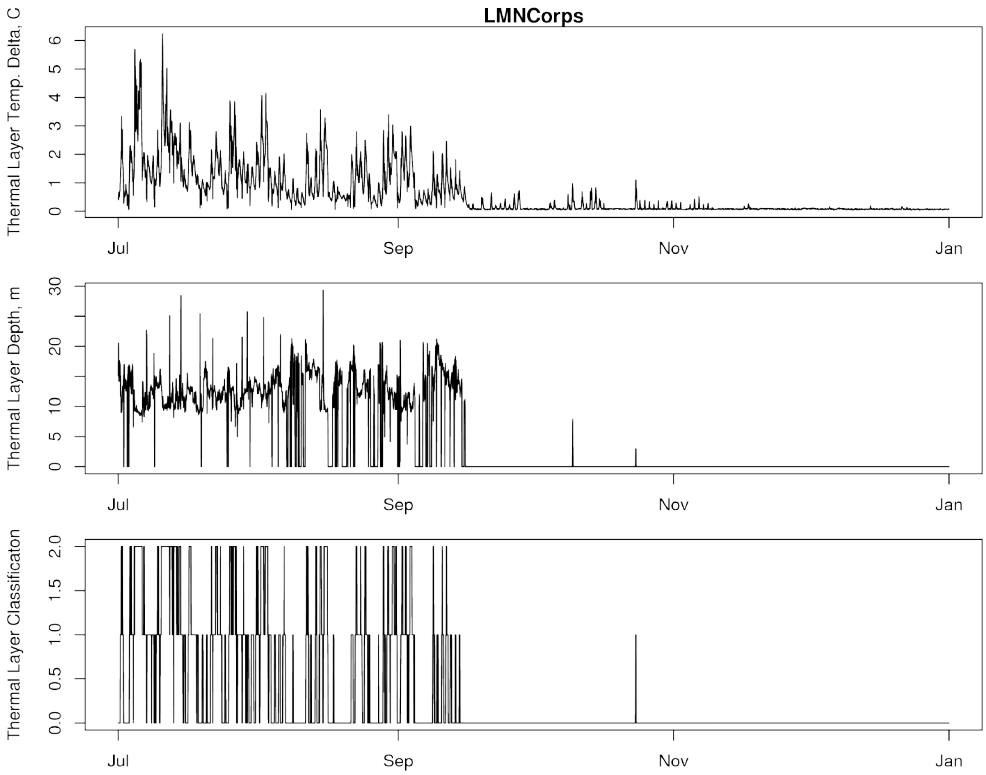

Figure E.11. Computed thermal layer statistics for LMNCorps

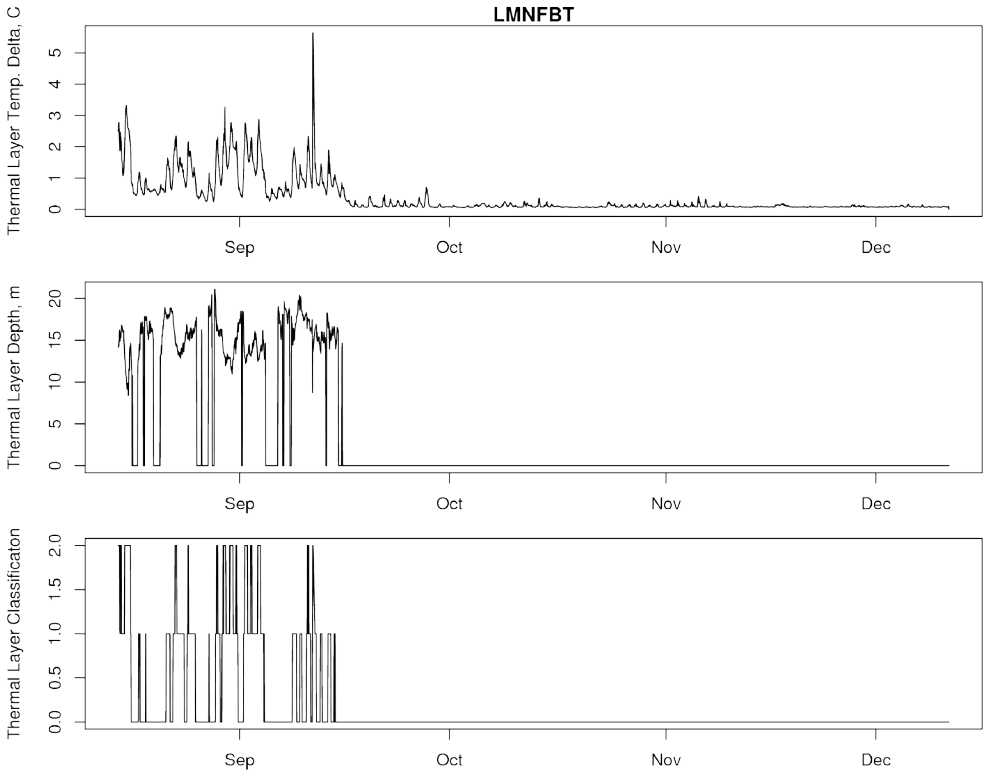

Figure E.12. Computed thermal layer statistics for LMNFBT

E.2 Water Velocity at Fixed Locations

Bottom-moored velocity measurements were reduced to downstream and cross-stream horizontal components. Summaries are presented in Figure E.13 through Figure E.17. Downstream and cross-stream velocity components averaged over depth at sites LMNFB1 and LMNFB2 are shown in Figure E.18.

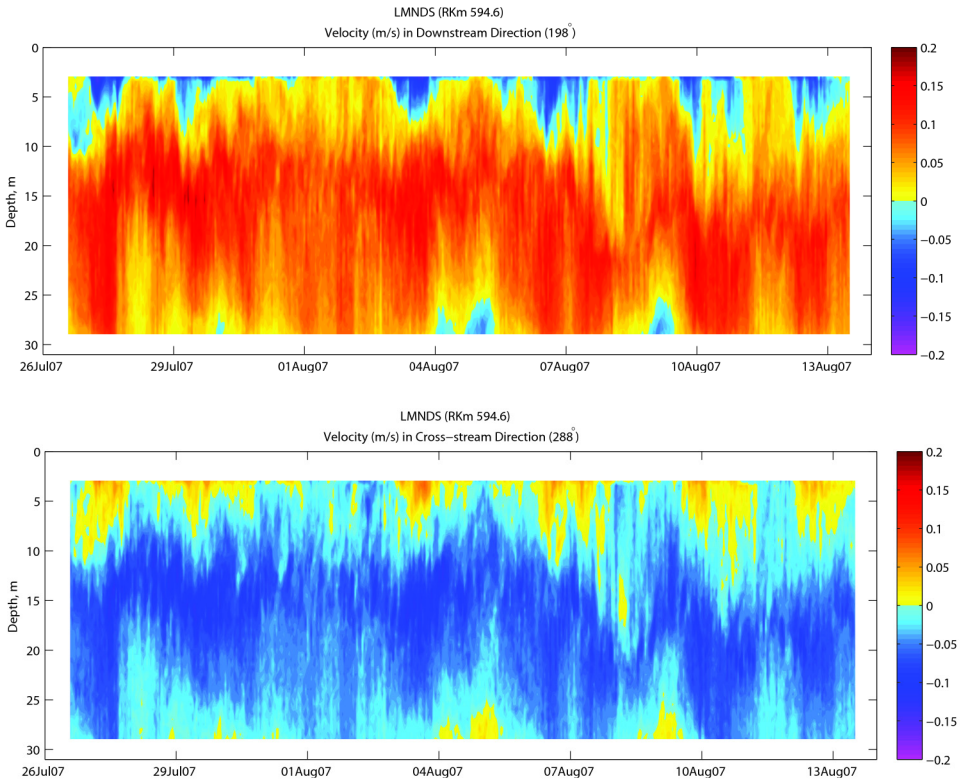

Figure E.13. Downstream and cross-stream velocity magnitude measured at LMNDS site

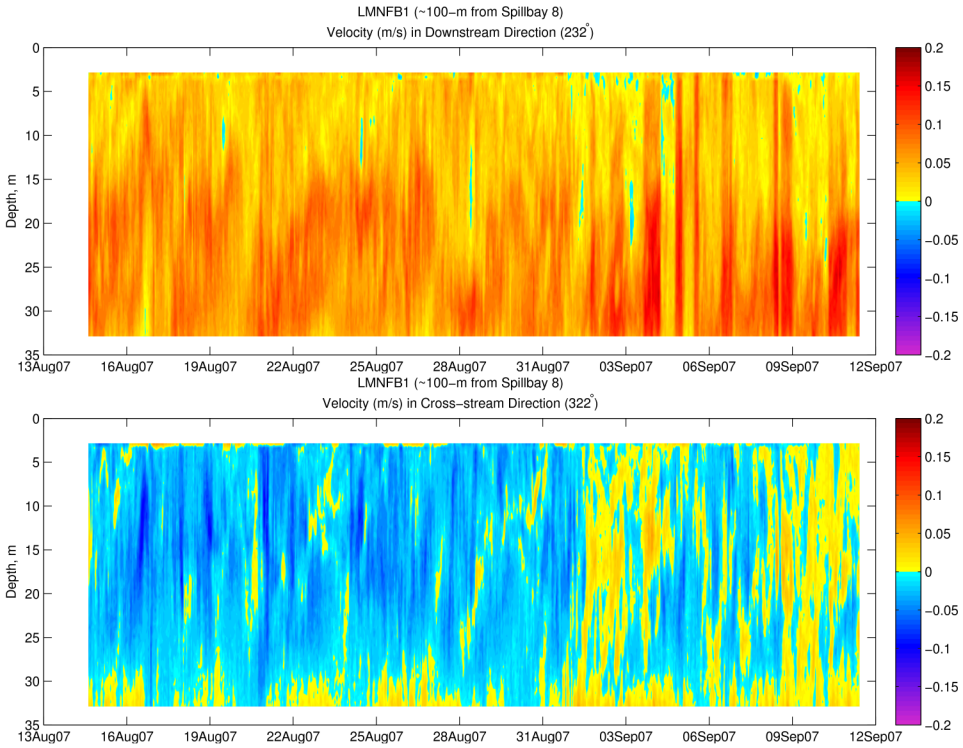

Figure E.14. Downstream and cross-stream velocity magnitude measured at LMNFB1 site while upstream of spillbay 8

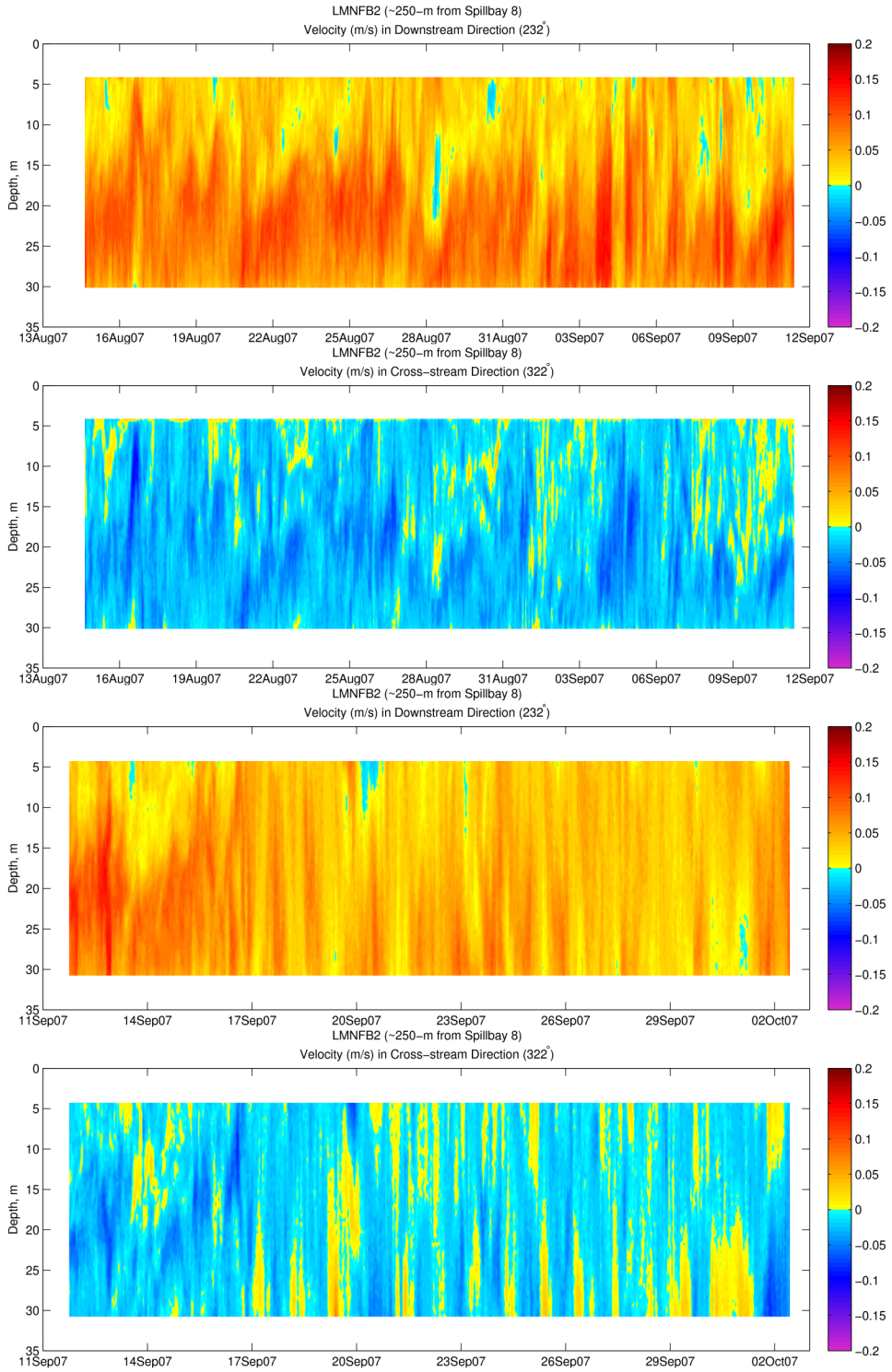

Figure E.15. Downstream and cross-stream velocity magnitude measured at LMNFB2 site while upstream of spillbay 8

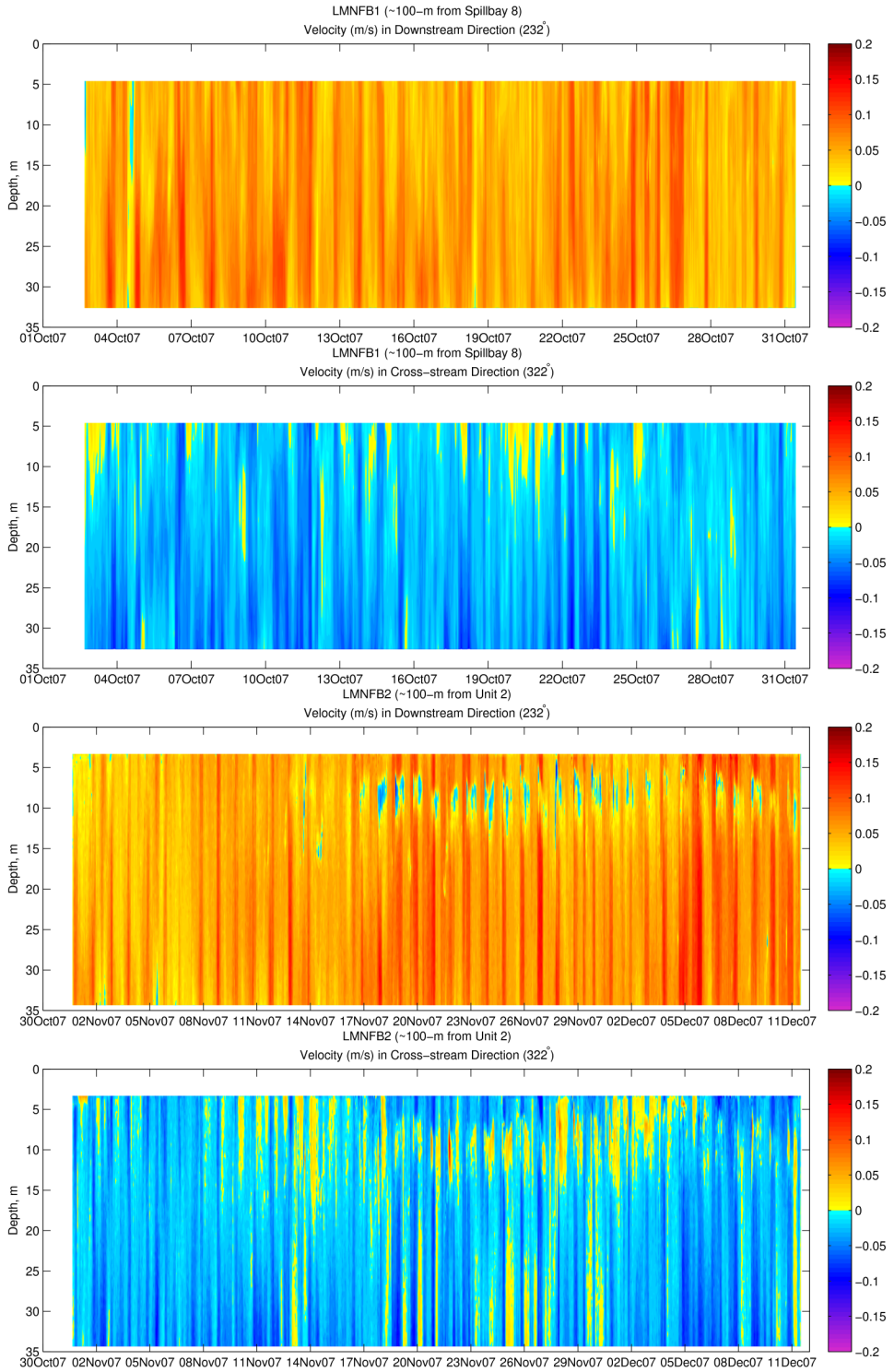

Figure E.16. Downstream and cross-stream velocity magnitude measured at LMNFB1 site while upstream of unit 2

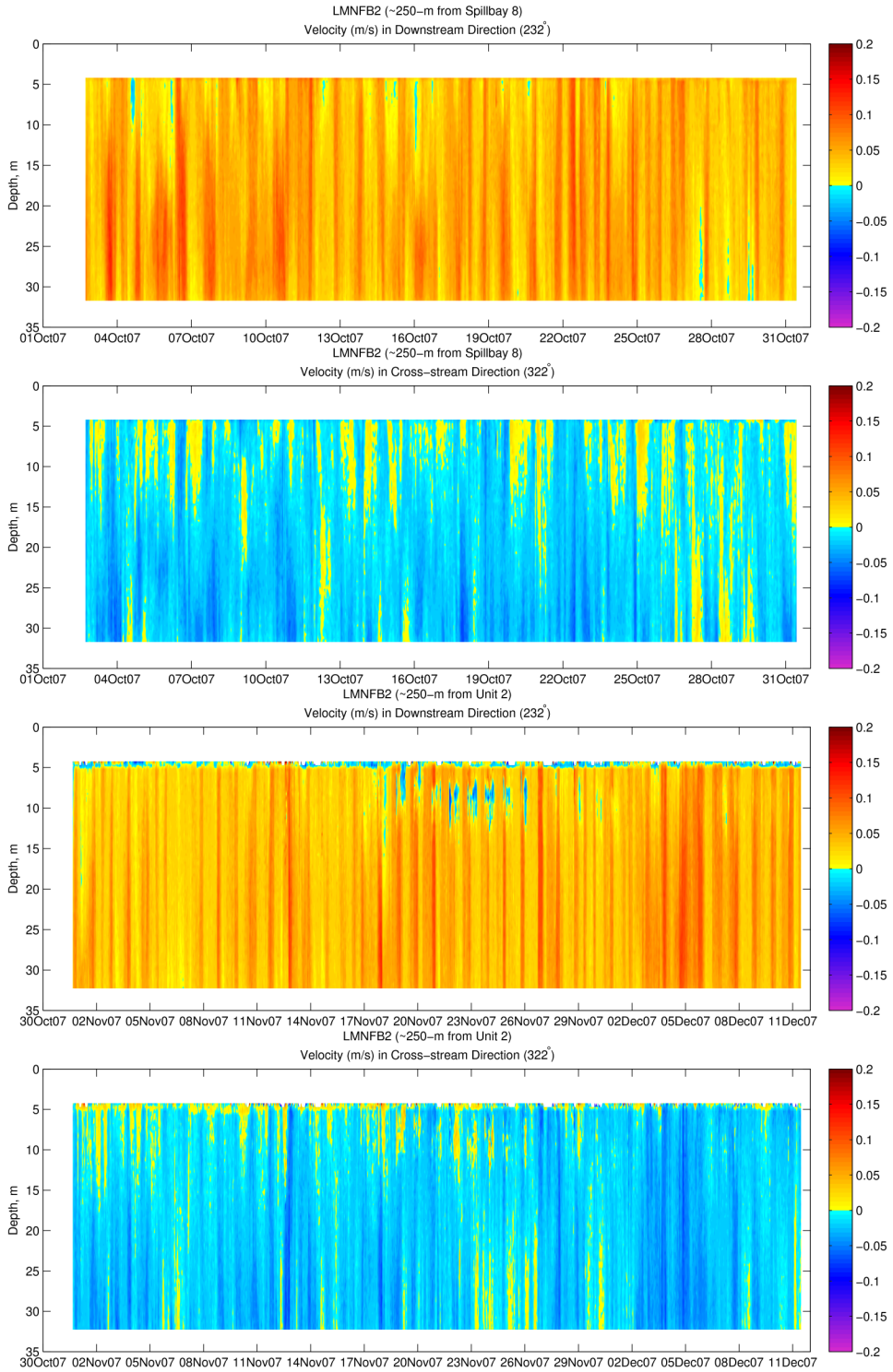

Figure E.17. Downstream and cross-stream velocity magnitude measured at LMNFB2 site while upstream of unit 2

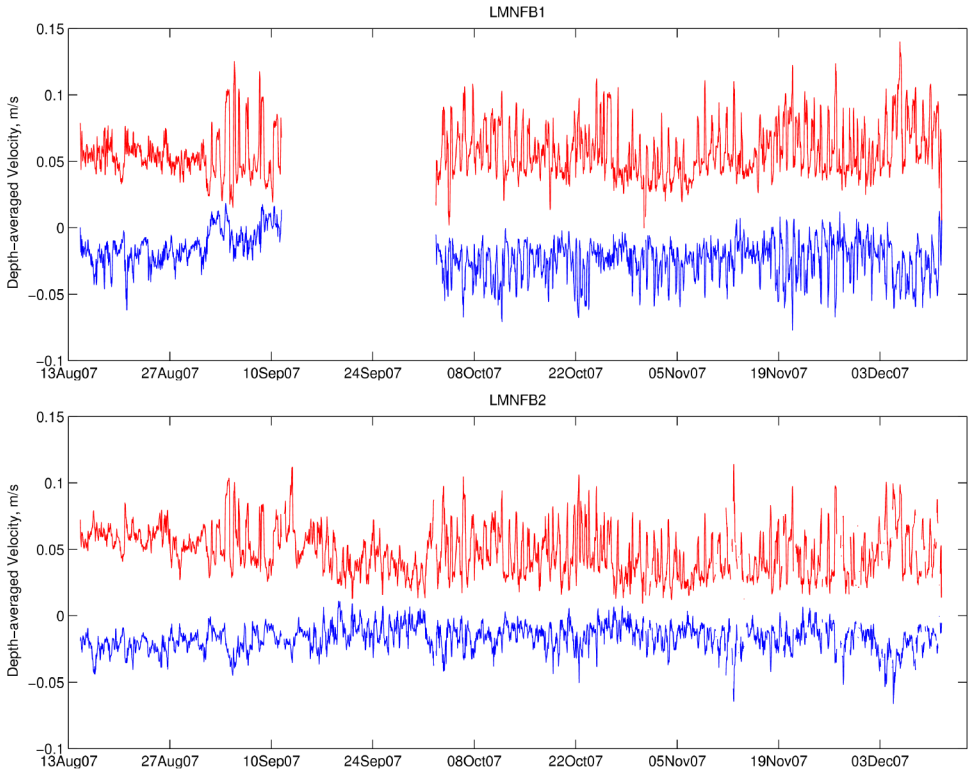

Figure E.18. Computed depth-averaged downstream and cross-stream velocity components at LMNFB1 and LMNFB2 (red is downstream, blue is cross-stream, negative blue is to the south, toward spillway)

E.3 Mobile Acoustic Doppler Current Profiler Surveys

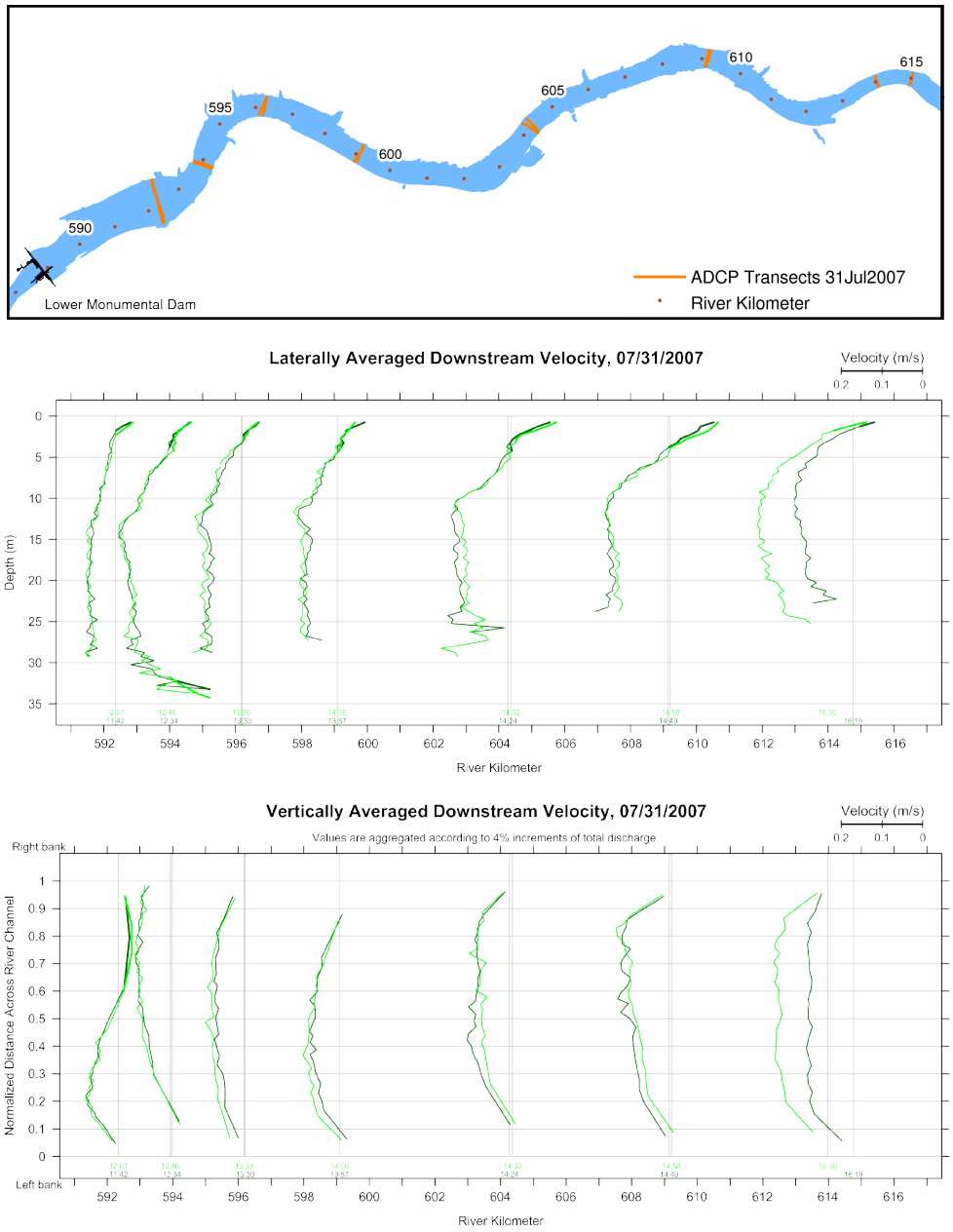

Figure E.19. Summary of velocity data collected during 31 July mobile ADCP survey

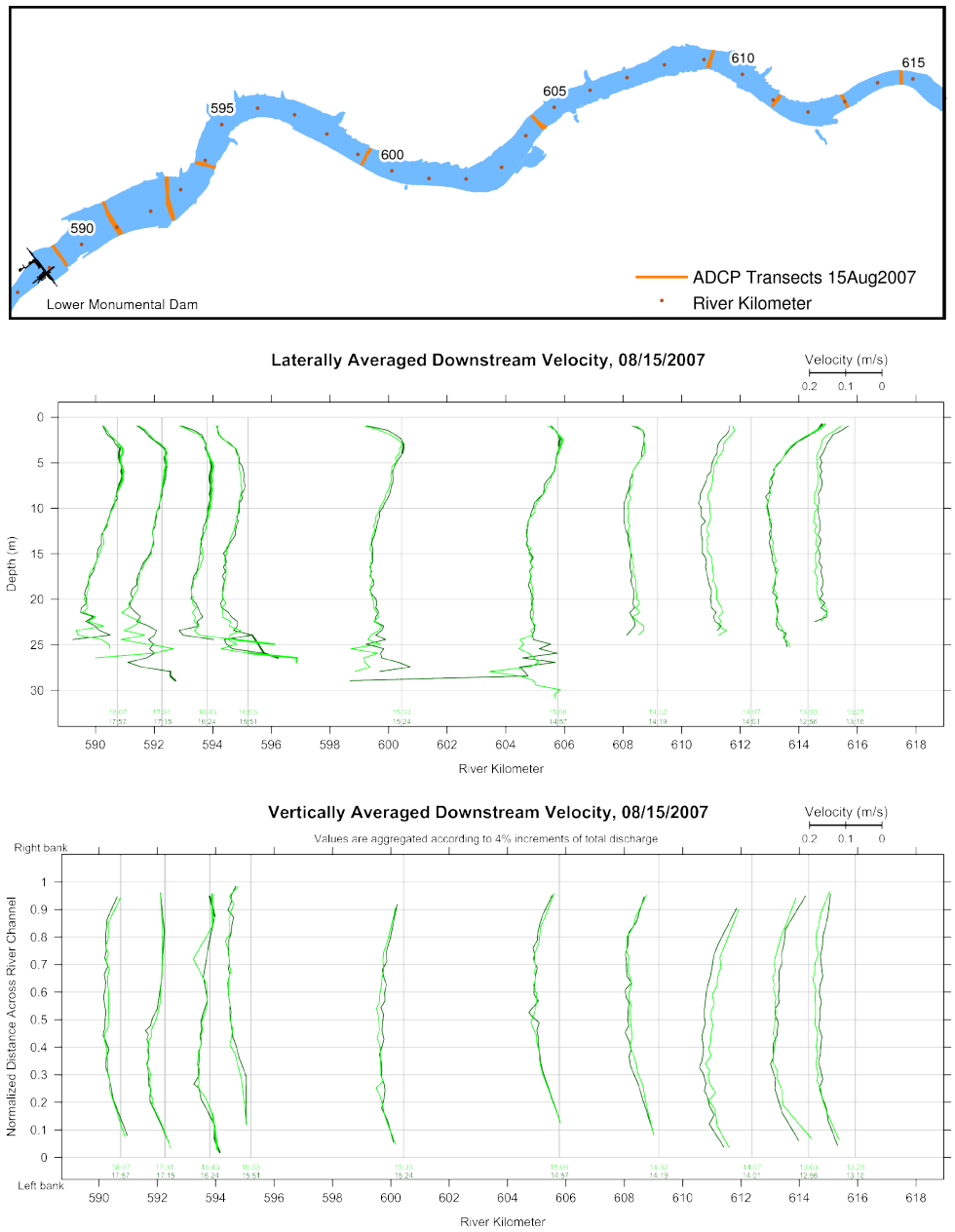

Figure E.20. Summary of velocity data collected during 15 August mobile ADCP survey

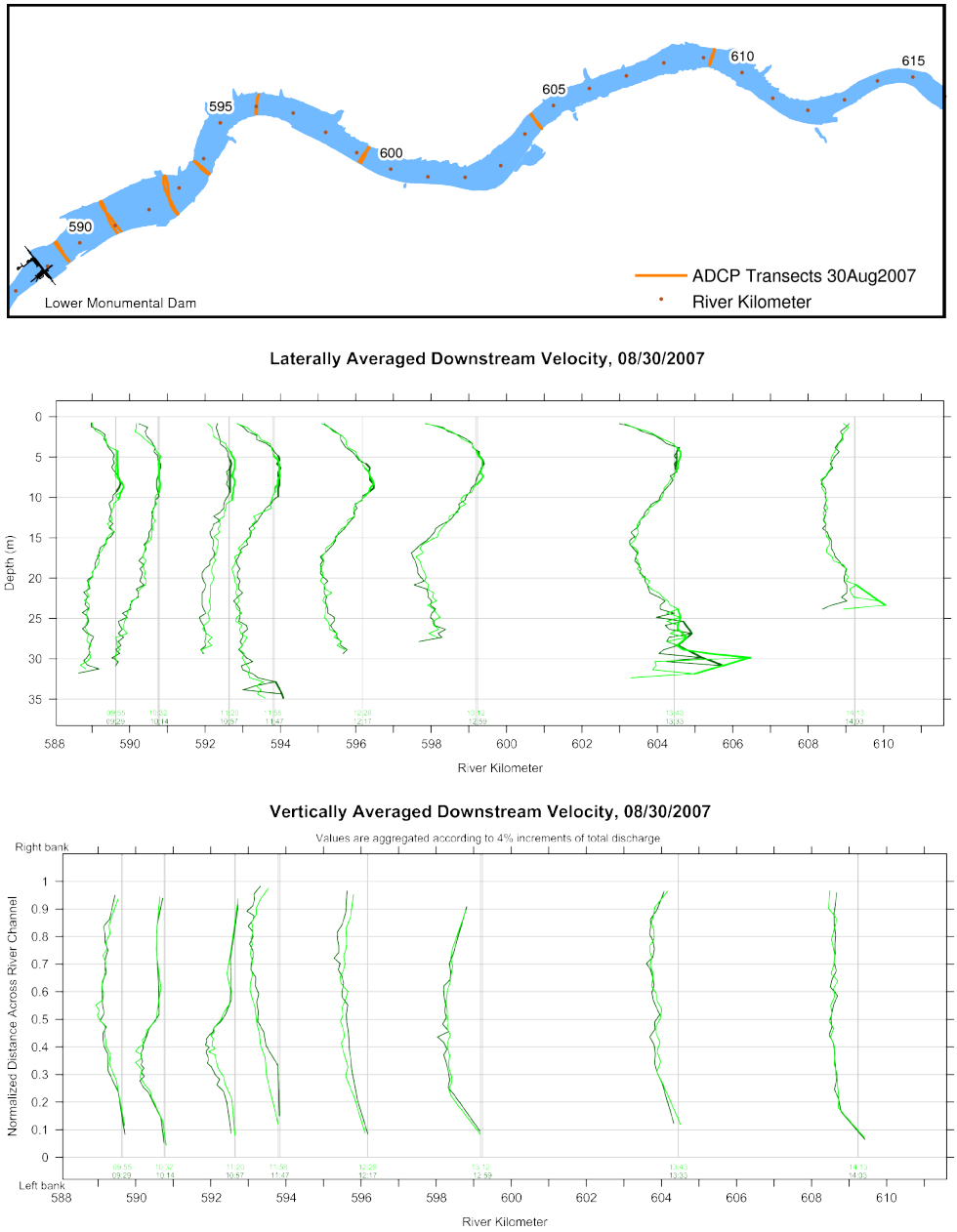

Figure E.21. Summary of velocity data collected during 30 August mobile ADCP survey

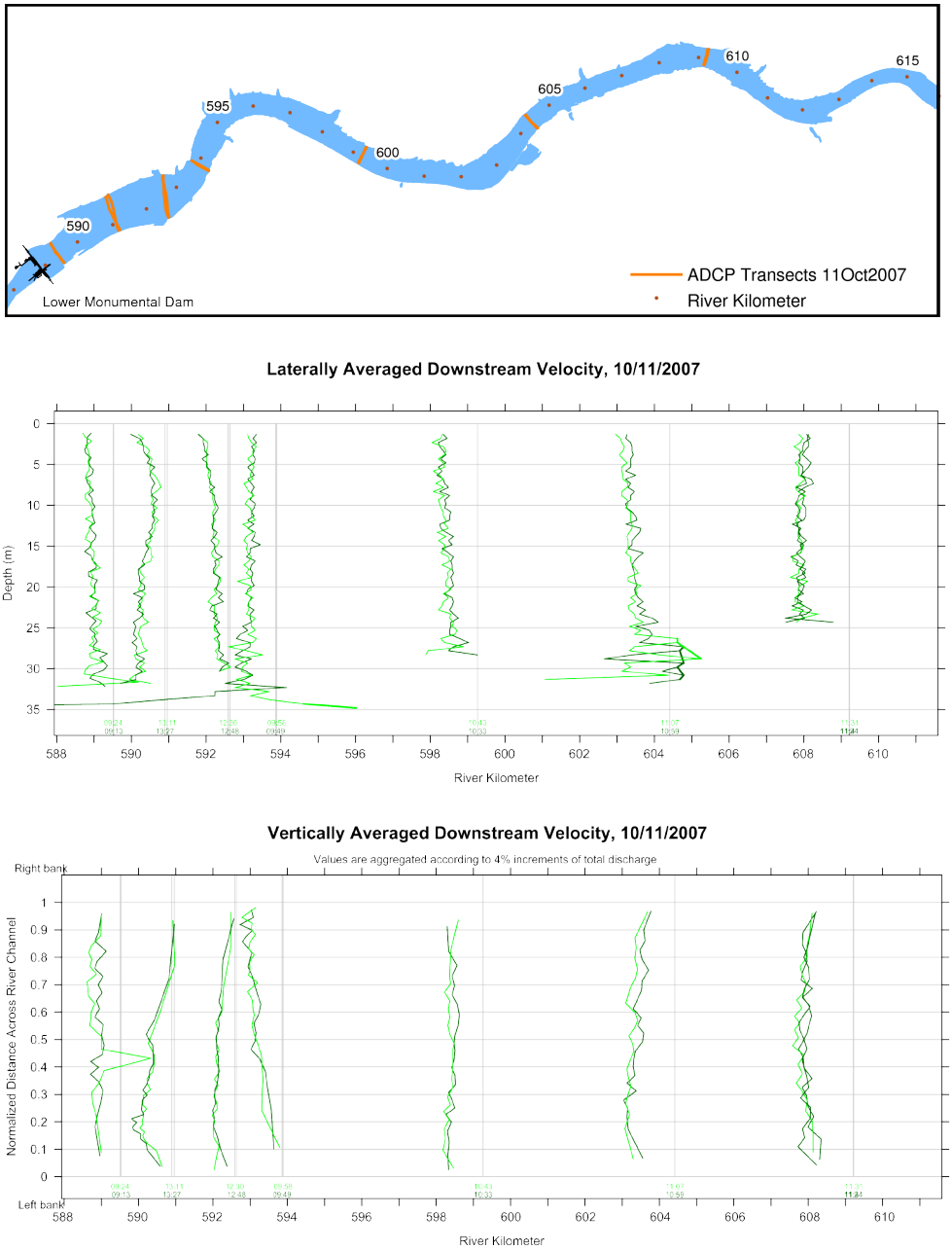

Figure E.22. Summary of velocity data collected during 11 October mobile ADCP survey

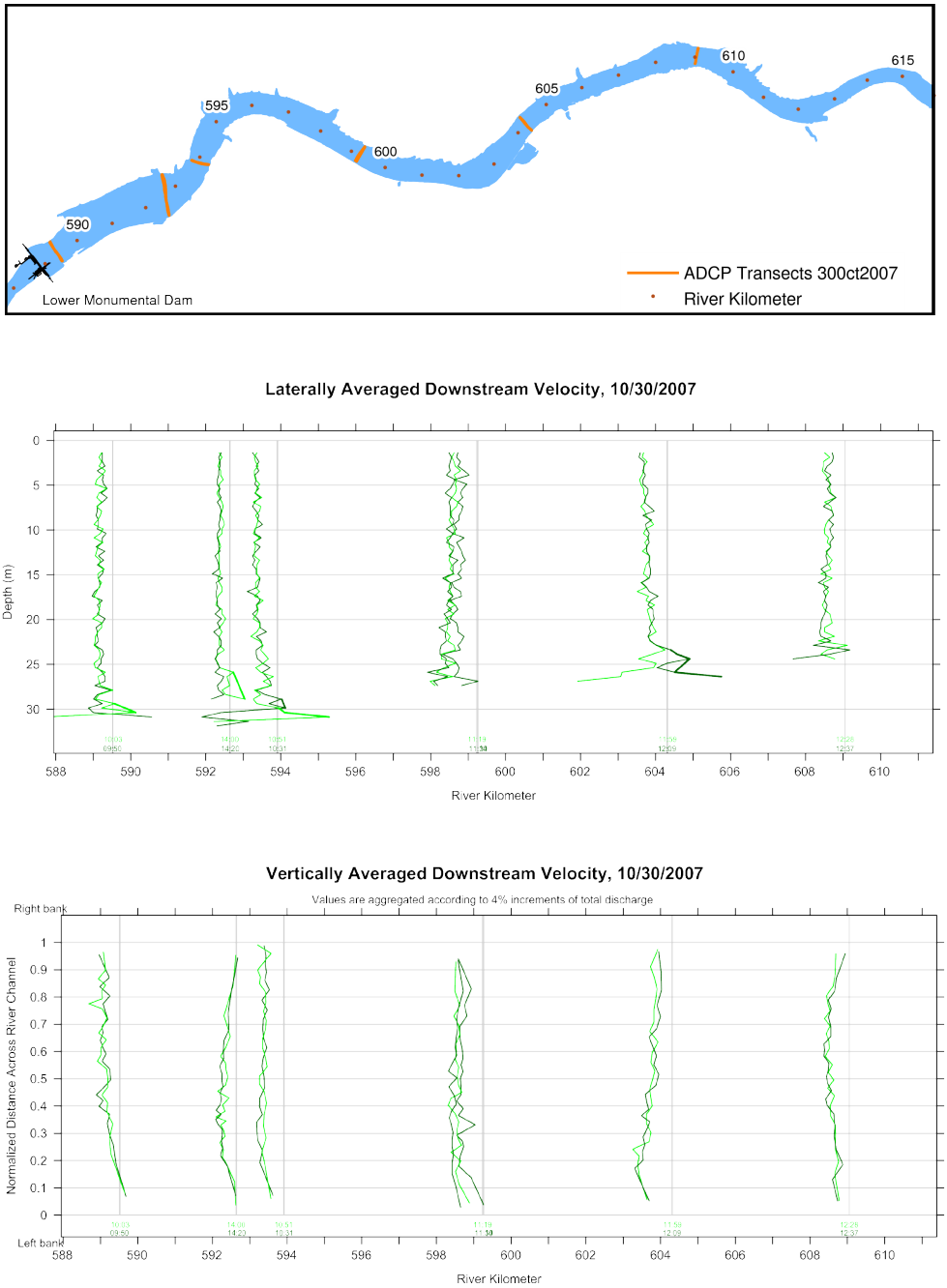

Figure E.23. Summary of velocity data collected during 30 October mobile ADCP survey

E.4 Estimated Discharge and Velocity

Figure E.24 and Figure E.25show estimated discharge and velocity, respectively, at the release and acoustic gate locations. Figure E.26 shows the coefficient of variation, computed over weekly periods, of the velocities in Figure E.25.

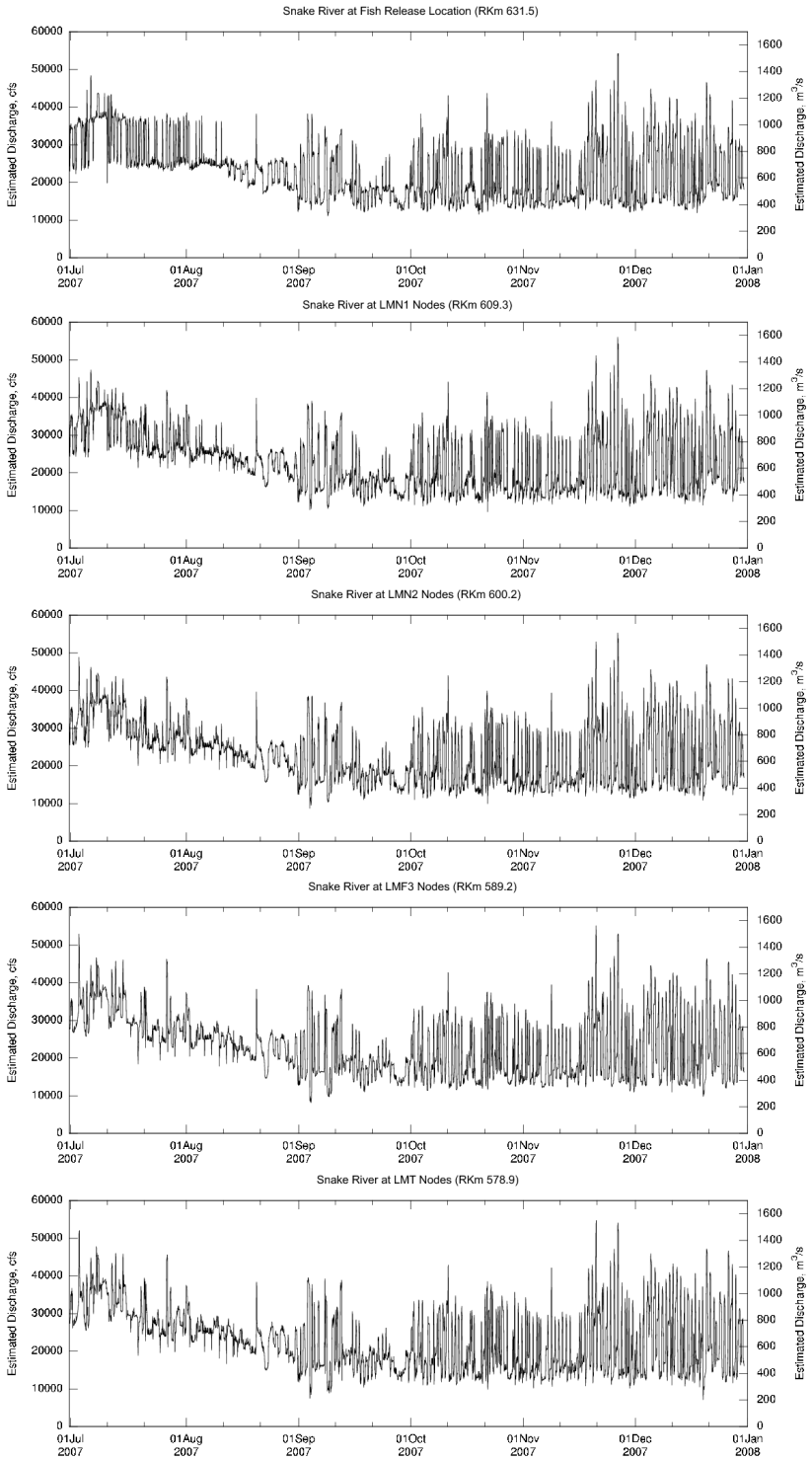

Figure E.24. Estimated discharge at each acoustic node gate within Lower Monumental Pool during study period

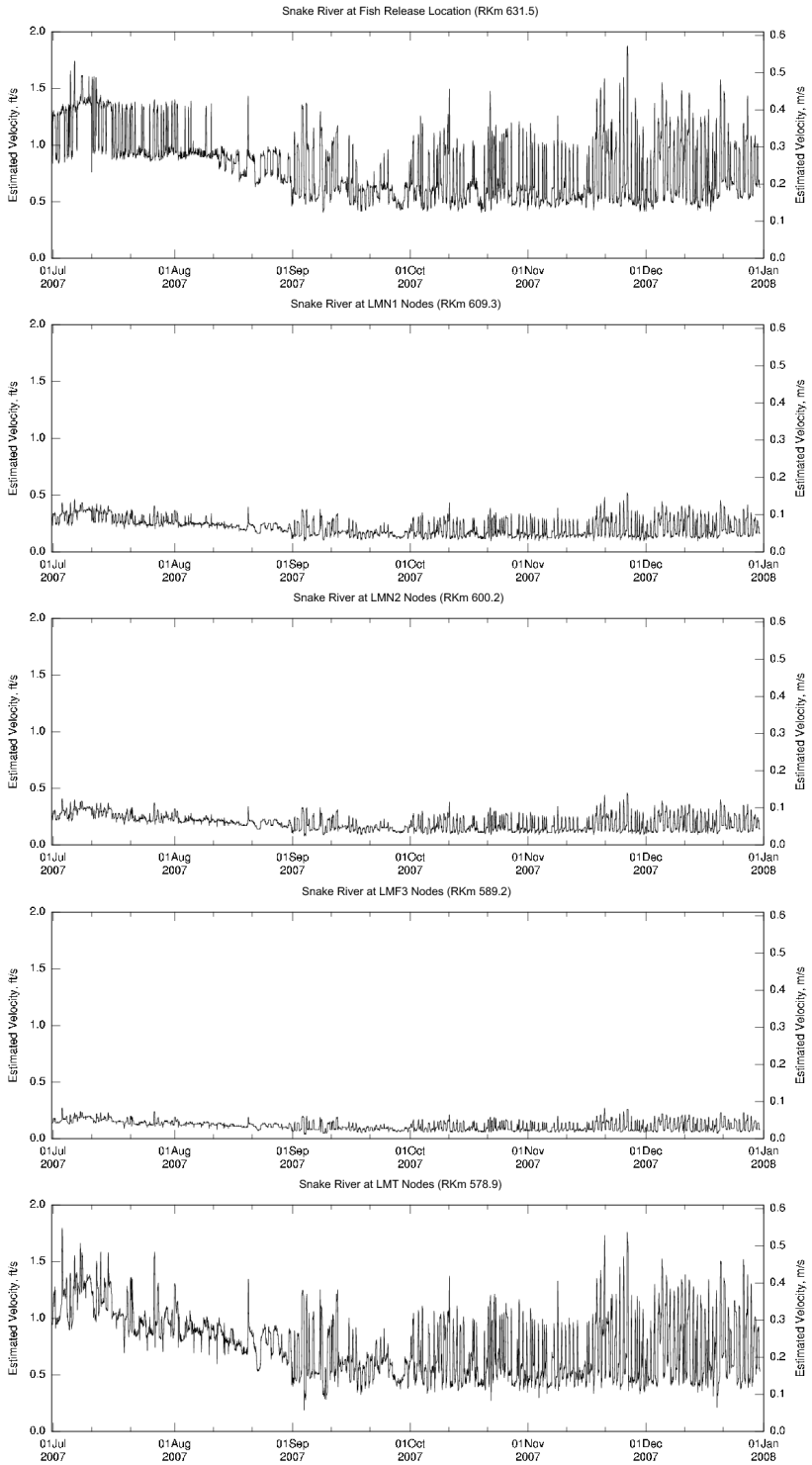

Figure E.25. Estimated cross-section average velocity at fish release location and each acoustic node gate in study area

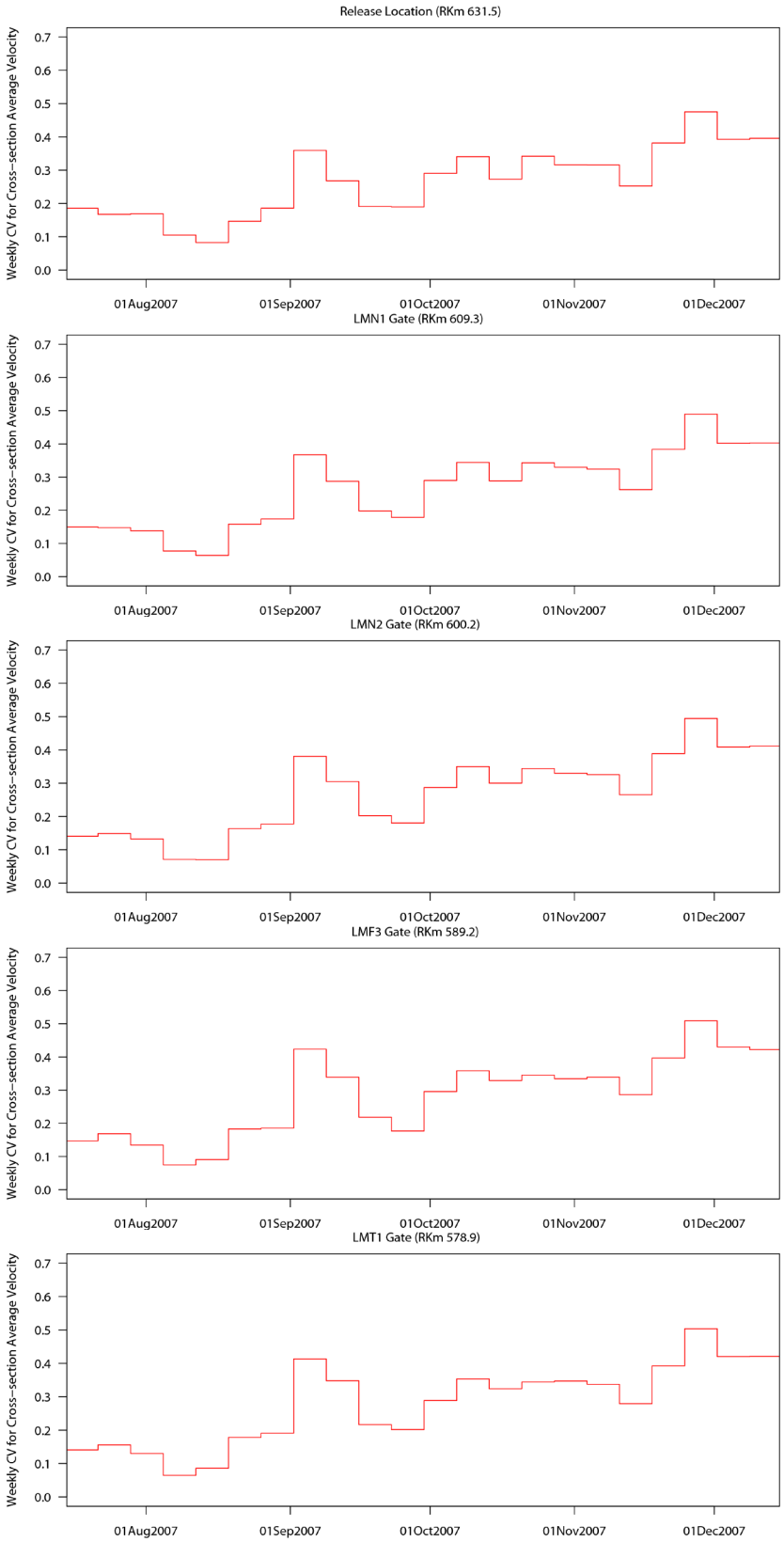

Figure E.26. Coefficient of variation computed for estimated cross-section average velocity over weekly intervals

E.5 Water Particle Travel Time

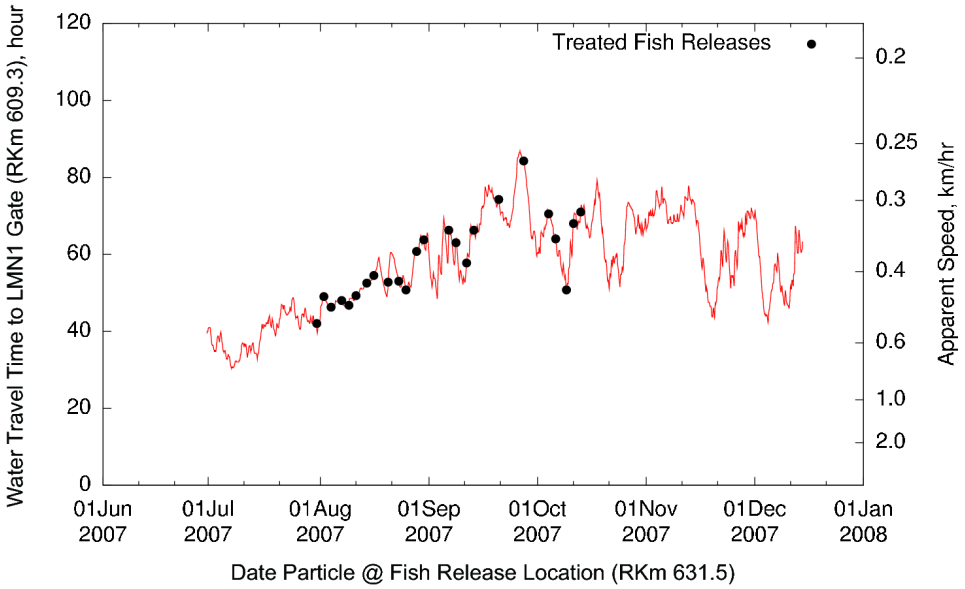

Figure E.27. Water particle travel time from fish release location to LMN1 acoustic node gate. Fish release dates are denoted by black dots.

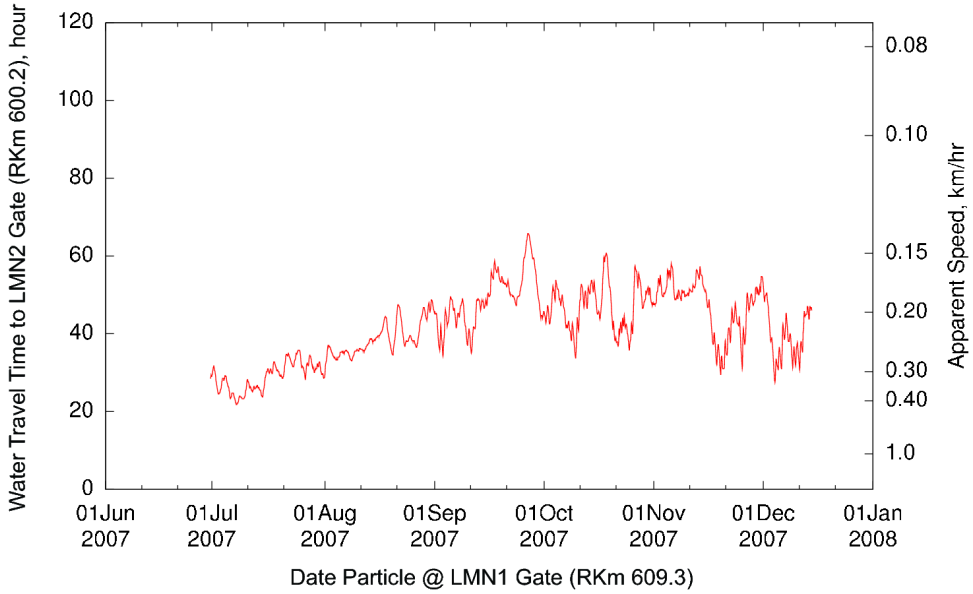

Figure E.28. Water particle travel time from LMN1 acoustic node gate to LMN2 acoustic node gate

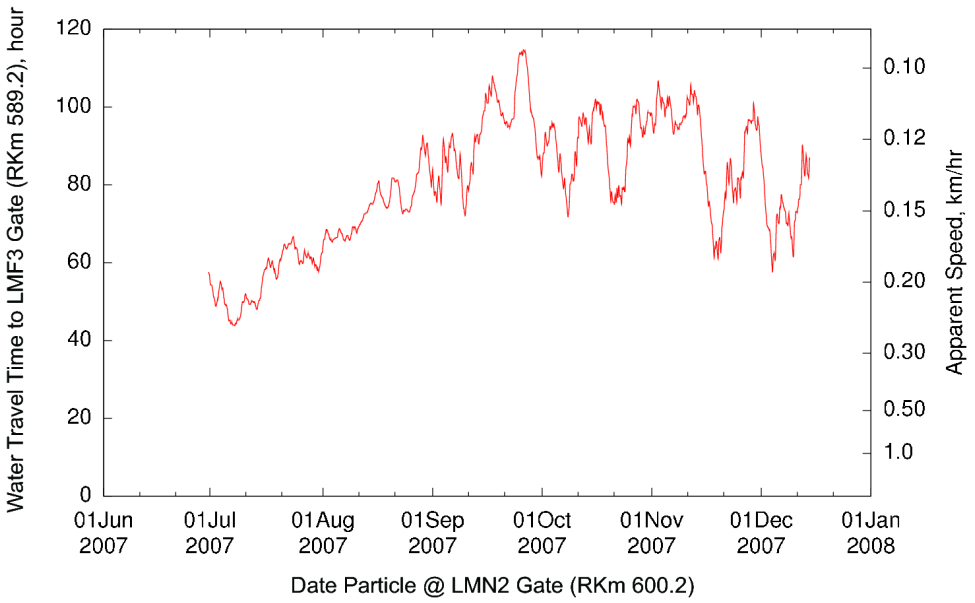

Figure E.29. Water particle travel time fromLMN2 acoustic node gate to LMF3 acoustic node gate

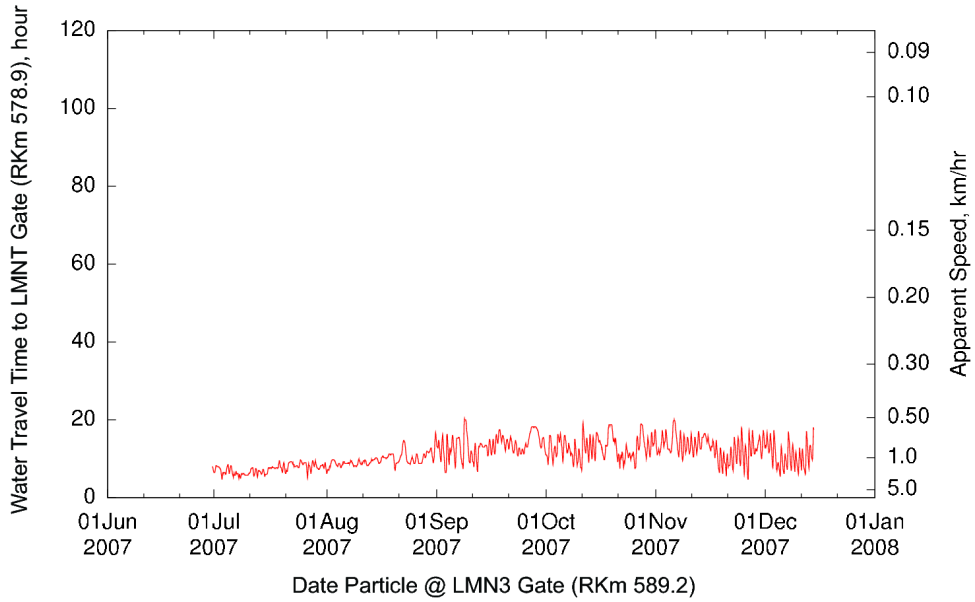

Figure E.30. Water particle travel time from LMF3 acoustic node gate to LMT acoustic node gate