Dam Passage and Fallback by Chinook Salmon and Steelhead as Determined by Passive Integrated Transponder Tags and Radio Tags

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Report of research by

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EXECUTIVE SUMMARY

Most estimates of adult passage behavior and survival have been determined by either visual fish counts or radiotelemetry for Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* listed under the U.S. Endangered Species Act. Radiotelemetry methods have also been the primary monitoring tool for evaluating adult salmonid fallback at dams, multiple ascents, behavior in fishways, and tributary turnoff in the Columbia and Snake River Basin. Increasingly, however, passive integrated transponder (PIT) tags are being used for adult salmonid research and monitoring because of their low cost (per tag) and extended life span, the availability of adults previously PIT tagged as juveniles, and the development and installation of PIT-tag interrogation systems in adult fishways at dams.

While both radiotelemetry and PIT-tag technology provide accurate and cost-effective data under certain circumstances, neither alone meets all needs. The strengths, weaknesses, and biases of these two methods must be evaluated and understood if fisheries managers are to better aid in successful recovery of Pacific salmonids. During 2002 and 2003, we double tagged over 3,200 adult Chinook salmon *O. tshawytscha* and steelhead with both a radio tag and a PIT tag as they migrated upstream past Bonneville Dam on the lower Columbia River. We used two behavioral measures of fish performance, dam passage and fallback, to compare radiotelemetry and PIT-tag systems at each of four dams: Bonneville and McNary Dams on the Columbia River and Ice Harbor and Lower Granite Dams on the Snake River.

We developed an interpretive model for measuring dam passage and fallback events and used 2002 PIT-tag data from the double-tagged fish to help define critical parameters for the model. We then applied the model to double-tagged fish in 2003 and compared results from the PIT-tag data to those from radiotelemetry data. The PIT-tag model was accurate at determining dam passage events (the largest percent difference between the two methods was 5.1%). However, no PIT-tag interrogation system was able to directly detect a fallback event. We therefore concluded post-fallback reascension rate was the best surrogate for fallback rate. Because of low fallback sample sizes relative to passage-event sample sizes and different definitions of fallback (fallback versus post-fallback reascension), comparisons between PIT-tag data and radiotelemetry data were less consistent for fallbacks than for passage events.

To understand why the comparison between the two tag technologies using fallback and post-fallback reascension rates did not match up as well as passage comparisons, we analyzed radiotelemetry data from 1998 through 2002 to determine the relationship between fallback and reascension rates. There were no consistent trends in this relationship among years or among dams. The only general trend was that spring/summer Chinook salmon had higher post-fallback reascension rates than either fall Chinook salmon or steelhead trout.

Finally, we applied the PIT-tag interpretive model to a broader group of non-radio-tagged fish to simulate the type of data analysis one could expect in years without radiotelemetry data. We used spring, summer, and fall Chinook populations from 2003 for this analysis. Passage and reascension rates were similar to those estimated from radiotelemetry data sets, although some differences, such as the exact timing of peak passage, were apparent.

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INTRODUCTION

Pacific salmon *Oncorhynchus* spp. populations in the Columbia and Snake Rivers have declined dramatically since the early part of the twentieth century, and recent estimates of population growth rate (λ) are still at or below 1.0 (McClure et al. 2003). Twelve Columbia basin stocks, or evolutionarily significant units (ESUs), are currently listed under the U.S. Endangered Species Act: nine as threatened and three as endangered (a thirteenth ESU has candidate status). Various factors are recognized as contributing to this decline, including hatcheries, overharvest, habitat loss and degradation, and the installation and operation of hydropower projects (Raymond 1988). Numerous efforts to recover these listed species have typically focused on one or more of these factors.

Along with developing recovery programs comes the need to monitor the recovery efforts to evaluate success. One approach for monitoring recovery efforts involves the use of counting windows located in fishways at each of the hydropower projects. These are used to quantify species composition and abundance of migrating anadromous fish. Fish managers use visual counts at individual dams to estimate production, escapement, and harvest limits for specific river segments. However, visual counts 1) typically underestimate fallback and reascension events, 2) are limited in evaluating stock-specific escapement rates, and 3) are not able to provide information regarding behavior and other passage indices, such as individual fallback and passage times at and between dams (Dauble and Mueller 1993, 2000; Boggs et al. 2004).

A variety of marking technologies, such as freeze-brand marks, fin clips, and coded-wire tags, have also been used in monitoring efforts over the past century (Trefethen and Collins 1975; Guy et al. 1996). During the past decade, two internal tags that permit individual identification, the passive integrated transponder (PIT) and radiotelemetry tags, have helped increase our knowledge of adult fish behavior and the impacts of hydropower projects on fish performance. This report compares the results of using PIT-tag technology to determine passage and fallback events to results obtained with radiotelemetry technology.

Over the past several years, radiotelemetry has improved our understanding of how hydropower operations directly affect juvenile and adult salmonid behavior and survival. For example, radiotelemetry studies yielded the first comprehensive estimates of adult salmonid fallback and reascension in the Columbia River Basin (Boggs et al. 2004) and documented the complex behavior of salmonids around migration obstacles in large river systems (Bjornn et al. 1998a; Hinch and Rand 1998; Keefer et al. in press).

Radiotelemetry tags and receivers essentially provide continuous information on migration routes of individual fish within certain sections of the river system (e.g., near receivers at dams). Consequently, data collected by some radiotelemetry projects are quite abundant and can require large amounts of time to interpret and analyze. Although the results have greatly expanded knowledge of fish passage behavior and survival, the protracted analyses can hinder the timely supply of information to fisheries researchers and managers.

Since the installation of PIT-tag interrogation systems in fish ladders at several major hydropower projects in the Columbia and Snake Rivers (Figure 1), some questions that historically could only be answered with radiotelemetry technology can now be addressed with PIT-tag technology. PIT-tag technology has been used extensively for research and management in the Columbia River basin for over a decade, primarily for studies of juvenile migrations. For example, numerous studies that rely exclusively on PIT-tag data have yielded stock- and location-specific estimates of juvenile migration survival (Smith et al. 2002; Muir et al. 2001a,b). However, until recently, detections of PIT-tagged adults have been limited, and analyses of adult fish migration through the hydrosystem using PIT-tag data exclusively are few.

Widespread PIT-tagging of juvenile fish has resulted in large numbers of adult fish detections by the interrogation systems recently developed and installed in fish ladders. When PIT-tagged samples are representative of overall runs, these interrogation data may be useful for adult passage estimates and could include larger sample sizes than are typically available for radiotelemetry studies. Fish managers need to know whether PIT-tagged fish can provide estimates of dam passage events and inter-dam losses with precision and accuracy comparable to radiotelemetry. In order to do that, a standard for interpreting PIT-tag data for adult salmonids needed to be established. In this report, we describe the development of a model to interpret PIT-tag data based on 2002 radiotelemetry data. We then use data from salmonids double-tagged in 2003 to compare results of interpretations using PIT and radiotelemetry technologies.

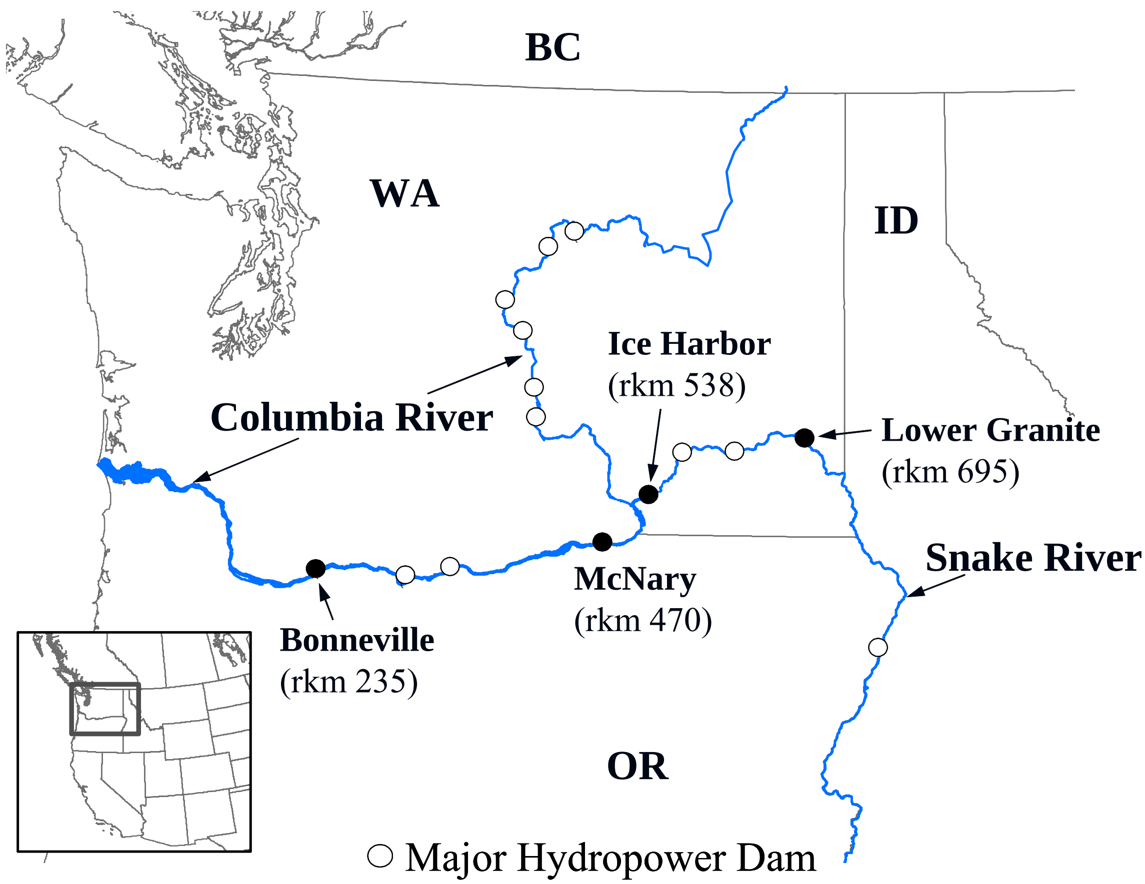

Figure 1. Columbia River Basin including location of mainstem hydropower dams (circles). Fish ladders at Bonneville and McNary Dams on the Columbia River and Ice Harbor and Lower Granite Dams on the Snake River (solid circles) are equipped with adult PIT-tag interrogation systems.

Radiotelemetry

Large-scale radiotelemetry research on adult salmonids has been ongoing in the Columbia River Basin since the early 1990s (Stuehrenberg et al. 1995; Bjornn et al. 2003; Keefer et al. in press). Accurately monitoring the movements of fish outfitted with radio transmitters was significantly enhanced with the development of digital spectrum processors (DSPs), which, when combined with SRX radio receivers (SRX/DSP units), allowed simultaneous monitoring of all transmitter frequencies.

Radio transmitters have much longer transmission ranges than PIT tags, and therefore radio receivers can monitor fish as they move over much larger areas (see Appendix A for locations of receivers within and around fishways). In this study, for example, radiotelemetry receivers have not just been placed throughout the fish ladders, but were also placed in forebays and tailraces of dams and in tributaries. This greater coverage allows radiotelemetry technology to efficiently detect behaviors such as fallback and tributary entry that are not as accurately ascertained with current PIT-tag technology. In addition, radiotelemetry antennas can be moved either within season or between seasons to improve their performance at a minimal cost. During 2002 and 2003, there were more than 80 antennas deployed at Bonneville Dam and more than 20 each at McNary, Ice Harbor, and Lower Granite Dams (although receivers exist in large numbers at other dams as well, this report is specific to these four dams). Further, the mouths of many tributaries were monitored for fish entering these systems.

PIT-Tag Interrogation Systems

PIT tags are inexpensive ($2-3/tag) compared to radio tags (>$100/tag) and are easy to quickly and safely insert into juvenile or adult salmonids (Prentice et al. 1990). Throughout the Columbia River Basin, researchers routinely PIT tag 500,000-1,000,000 juvenile salmonids annually, mostly at hatcheries. Data are collected as smolts migrate out to sea and as they return to freshwater locations as adults by a network of interrogation systems, installed primarily at hydroelectric dams located throughout the river system. Data collected by antennas from all interrogation systems are automatically sent to a central server managed by Pacific States Marine Fisheries Commission (PSMFC) and are available to the public in near real time.

When adult fish return to the Columbia River Basin, those with PIT tags can be identified and recorded by interrogation systems installed in fish ladders at several hydroelectric dams (see Figure 1). Most interrogation systems in fish ladders cover orifices in eight consecutive weirs (each ladder typically has 50-100 weirs) and therefore some fish can avoid detection if they use the weir overflows exclusively at these weirs rather than the weir orifices. Indeed, some Chinook populations, such as summer and fall Chinook salmon *O. tshawytscha*, use the weir overflows more than other populations (e.g., spring Chinook salmon), and thus they are not detected as well by the orifice-based interrogation systems (Downing and Prentice 2004; Downing et al. 2004). However, with most adult interrogation systems, all of the fish transit multiple PIT-tag antennas, and less than one percent of PIT-tagged fish go completely undetected (Downing et al. 1999).

PIT-tag interrogation systems for adult salmonids are currently installed at Bonneville, McNary, Ice Harbor, and Lower Granite Dams. Diagrams and antenna locations within fishways can be found at the PSMFC website (www.psmfc.org/pittag/). Unlike radiotelemetry antennas, PIT-tag antennas are costly permanent installations, and their placement into weir orifices is dependent on technology limits. The original placement of antennas within the fish ladders was based on input from the U.S. Army Corps of Engineers (COE) to yield information on how fish responded to changes in dam operation. The COE and Bonneville Power Administration (BPA) are currently planning modifications to the PIT-tag interrogation systems at Bonneville and McNary Dams to improve their overall detection performance.

DATA COLLECTION AND ANALYSIS

From spring 2002 through fall 2003, we collected adult fish at the Adult Fish Facility at Bonneville Dam on the Columbia River (river kilometer [rkm] 235.1; Figure 1). Radio tags were gastrically implanted and fish were scanned for PIT tags received as juveniles. Fish were PIT tagged if no PIT tag was detected. We tagged 3,165 Chinook salmon *O. tshawytscha* (mean fork length = 81.1 cm, range = 51.5 to 113.0 cm) and 1,172 steelhead *O. mykiss* (in 2002 only; mean fork length = 75.0 cm, range = 48.0 to 99.0 cm). For all analyses, Chinook salmon run designations were based on their tagging date at Bonneville Dam: spring (April 1 to May 31), summer (June 1 to July 31), and fall (August 1 to October 31) Chinook salmon. Fish kept their run designation from Bonneville Dam regardless of date of passage at upstream dams.

Fish were monitored during their upstream migration using radiotelemetry, with the greatest concentrations of radio receivers deployed in and around major hydropower projects on the Columbia and Snake Rivers (Appendix A). Keefer et al. (2004 in press) provide a detailed description of tagging and monitoring methods.

Because salmonid behavior around dams is complex, researchers have often defined behaviors in different ways. For this analysis, we defined dam passage as exiting a fishway or navigation lock into the forebay of a dam. We defined a fallback as traveling, by any route, from the forebay to the tailrace of a dam. Fallback routes can be over spillways or downstream through fishways, navigation locks, juvenile collection facilities, turbines, or ice/trash sluiceways. Finally, we defined a post-fallback reascension as a fallback followed by another ascension of the fish ladder, at least as far as the first PIT-tag antenna (i.e., fish do not necessarily have to pass the dam after falling back).

Radiotelemetry data sets often contain many false positives (detections of tags not present), primarily at sites with aerial antennas. In our studies, receivers with aerial antennas were used at tailraces of dams and in tributary streams where large detection ranges were required. Top-of-ladder antennas were underwater systems with minimal false positives. False records at any telemetry site can be caused by boat traffic, dam operations, or any source of radio waves that mimic transmitter signals. Data need to be filtered and often manually interpreted, with the amount of time required depending on the amount of data collected. Excluding malfunctioning equipment, PIT systems do not create false positives. For this study, there were relatively few PIT antennas installed to detect adult salmonids at dams, resulting in simplified data sets in comparison to the radiotelemetry data sets. The relative simplicity of the PIT-tag data allowed us to more easily interpret the data using a set of rules with minimal manual or visual inspection of the data.

Both methods suffer from another problem: tagged fish can pass radio- and/or PIT-tag antennas undetected. Detection probability depends on several factors, including environmental conditions, the proximity of the fish to a detector, the proximity of other tagged fish (signal interference), and fish behavior (e.g., fish using the overflow weirs will not be detected by the orifice-based PIT-tag system). Further, tag retention rates differ between radiotelemetry (96-97.8%, Keefer at al. 2004) and PIT tags (99-100%, Prentice et al. 1987). Both false positives and missing detections affected our ability to accurately detect passage and fallback events.

Radio-Tag Data

Data downloaded from radio receivers were electronically transferred to the NOAA Fisheries Northwest Fisheries Science Center in Seattle, WA for initial processing. Each file was loaded into a database and run through initial screening to remove obvious errors and false records produced from electronic background noise. The screened data were then transferred to the University of Idaho for coding.

Coding involved inspecting all records for each fish at a given dam and assigning a code to appropriate records that defined a specific behavior for that fish (e.g., first passage of the tailrace receiver, entrance or exit from a fishway). Prior to 2002, coding was facilitated with the use of a semi-automated program developed with ArcView, Version 2.0 for Windows (ESRI 1992). Starting in 2002, we used a fully automated program to interpret behaviors/records at dams that we developed using Visual Basic.NET, Version 7.0 (Microsoft Corp. 2002). We reviewed records that were assigned a code by the automated program for appropriateness and accuracy. We assembled a final processed database by inserting records from tributary receivers, those found while mobile tracking by boat and truck, and those of fish recaptured at spawning grounds, weirs, hatcheries, or in fisheries. We used this data set to identify and summarize complete migration histories of radio-tagged fish.

PIT-Tag Data

As PIT-tagged fish migrated through the hydrosystem, they were detected on a network of PIT-tag interrogation systems installed inside juvenile and adult fishways at the major hydropower dams in the Columbia and Snake Rivers (Figure 1). Collection, processing, and dissemination of the large amount of data collected by the interrogation systems are managed by a cooperative regional steering committee. PSMFC established the PIT Tag Operations Center with funding from BPA to house and manage the database generated from these efforts. The result, Columbia Basin PIT Tag Information System (PTAGIS), is operated by PSMFC and allows users to connect remotely and load, download, or query the database. All PIT-tag data in this report were downloaded from PTAGIS (PSMFC 1996) with approval of the PIT Tag Steering Committee and the researchers who tagged the salmon and steelhead not originally tagged for this project.

PIT-tag detections for individual fish were sorted by date in ascending order, and the resulting detection histories run through an interpretive model to reconstruct and quantify passage and post-fallback reascension behaviors or events. In particular, we were interested in detecting fish passing and falling back over dams. During 2002 and 2003, PIT-tag interrogation systems were deployed at several hydropower projects on the Columbia and Snake Rivers. The number and placement of antennas at each dam varied, and only four dams were included in this analysis: Bonneville, McNary, Ice Harbor, and Lower Granite Dams (Figure 1). Other dams that had PIT-tag interrogation systems either contained too few antennas to make accurate interpretations or had them only in juvenile passage routes.

MODEL DEVELOPMENT

Reascension Rates

Methods

Because multiple ascensions were necessary to detect a fallback in the PIT-tag model, the relationship between fallbacks and reascensions needed to be evaluated to put our results into context. Using radiotelemetry data only, we counted fallback events in 1998, 2000, 2001, 2002, and 2003 and compared them to counts of reascension events during corresponding years. Fish used in the reascension analysis were not necessarily the same individuals used in other analyses reported here (no PIT-tag data were needed for this analysis). For statistical procedures, we assumed reascension data were binomially distributed. Spring and summer Chinook salmon runs were combined for this analysis.

This analysis differed from the calculation of reascension proportion by Boggs et al. (2004) in that we included all fallback and reascension events rather than events for unique fish. For example, if a fish fell back, reascended, and fell back again, we counted two fallback events and one reascension for a post-fallback reascension rate of 0.5 for that fish. Reascension proportion as defined by Boggs et al. (2004) would have counted one unique fish falling back and no reascension (because the fish was last detected downstream from the dam) for a post-fallback reascension proportion of zero.

Results

Small sample sizes for fallback and reascension events by fish radio-tagged in 2002 prevented analyses of temporal trends in reascension rates, so only annual rates were considered. A wide range of fallback events occurred per year at each of the four dams (Table 1). Annual post-fallback reascension rates ranged from 0 to 0.935 and varied considerably across years, dams, and species (Figure 2). In general, spring-summer Chinook salmon had the highest post-fallback reascension rates, followed by fall Chinook salmon and steelhead. Fish at Bonneville Dam tended to reascend at higher rates than at other dams. No consistent trends existed in post-fallback reascension rates across years except for steelhead, for which there was a decrease from 2000 to 2003 at multiple dams. However, it was unclear whether this trend was related to dam operations or environmental conditions or was simply random. Error around each estimate was calculated assuming binomially distributed data (Steel et al. 1997).

Table 1. Count of fallback events by radio-tagged fish at each dam used for calculations of post-fallback reascension rates. No steelhead were radio tagged at Bonneville Dam in 1998.

		Bonneville Dam	McNary Dam	Ice Harbor Dam	Lower Granite Dam
Sp/Su Chinook	1998	151	64	19	11
	2000	177	35	34	7
	2001	103	16	8	4
	2002	99	45	21	11
	2003	67	20	21	7
Fall Chinook	1998	41	9	2	3
	2000	67	9	1	3
	2001	111	19	11	4
	2002	83	17	8	3
	2003	28	12	6	2
Steelhead	2000	84	71	24	13
	2001	87	97	50	63
	2002	98	81	62	77
	2003	71	42	29	44

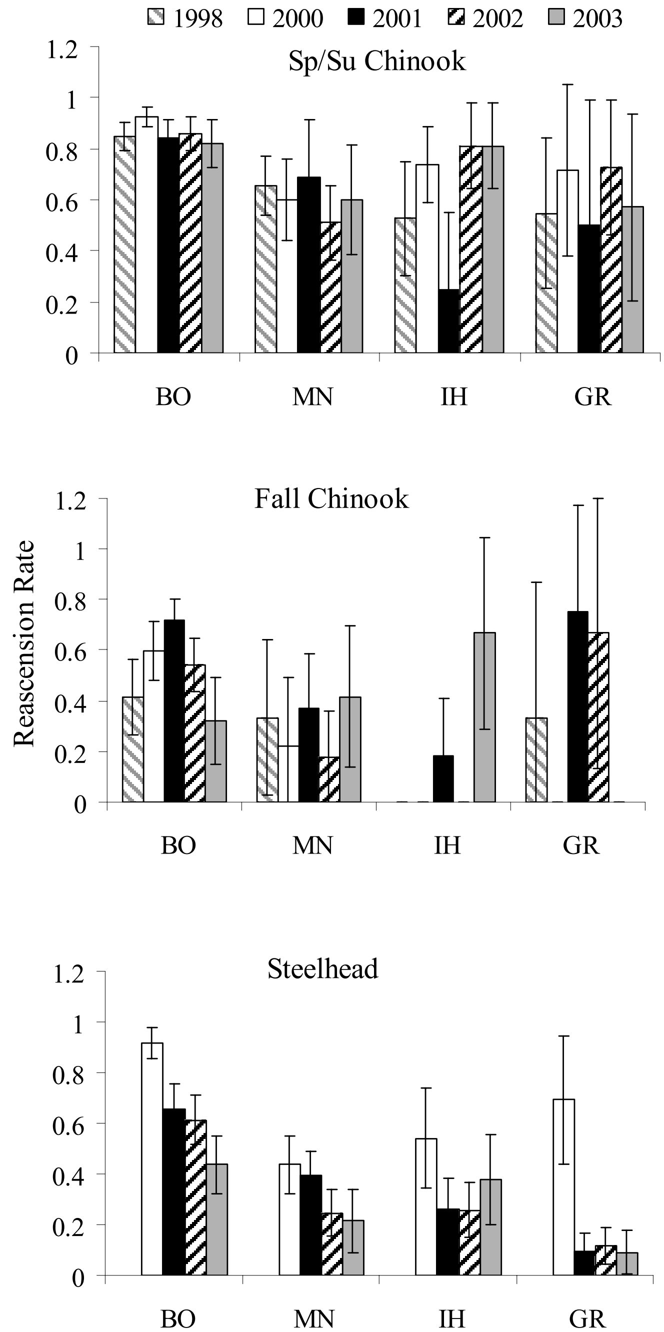

Figure 2. Post-fallback reascension rate (number of reascension events divided by number of fallback events; error bars indicate SE) for radio-tagged spring and summer Chinook, fall Chinook, and steelhead. BO = Bonneville Dam, MN = McNary Dam, IH = Ice Harbor Dam, GR = Lower Granite Dam.

Fitting the PIT-Tag Interpretive Model

Automated interpretation of behaviors by PIT-tagged fish in the Columbia River Basin required a set of rules to evaluate PIT-tag detections. These rules were used to infer passage or fallback events.

We used data from adults double tagged in 2002 and detected at Bonneville and McNary Dams to determine the best set of rules for interpretation (i.e., to parameterize the model). For 1,541 double-tagged fish, we summarized the radiotelemetry data for each fish and quantified their passage and fallback events. We then ran the PIT-tag data for those same fish through our interpretative PIT-tag model and compared the results to those from radiotelemetry. Through an iterative process, we determined both the best set of rules and the optimal parameter values.

Directionality

The main function in the PIT-tag interpretive model concerned directionality (Figure 3). The last evidence we had of the direction of movement of a fish must have been upstream in order for the model to infer that a passage occurred. This criterion had several consequences. First, any fish with a single PIT-tag detection at a dam could not be directly interpreted as having passed that dam. Directionality could only be determined by at least two detections, the second of which must be upstream from the first. Second, even if a fish appeared to be swimming upstream, if the last detection of that fish was one or more weirs downstream from the previous detection, that fish was not listed as passing the dam. We know from both PIT-tag and radiotelemetry data that fish swim downstream in fishways. If our last evidence of movement was not in the upstream direction, a passage event was not assigned based on those detections. It should be noted, however, that fish that did not meet the criteria for passage but were later detected upstream from the dam were listed as passing the dam.

For simplicity, we will temporarily assume that each fish ascends a ladder once; detection and interpretation of fish that pass through ladders multiple times will be addressed below. The PIT-tag interpretive model identifies the last detection of each fish at a dam, while tracking directionality at all times. If the last detection at a dam was upstream from the previous detection, a passage code was assigned to the last record. In cases where two or more consecutive detections were recorded at the same weir, directionality was not considered to change. In other words, if a fish was heading

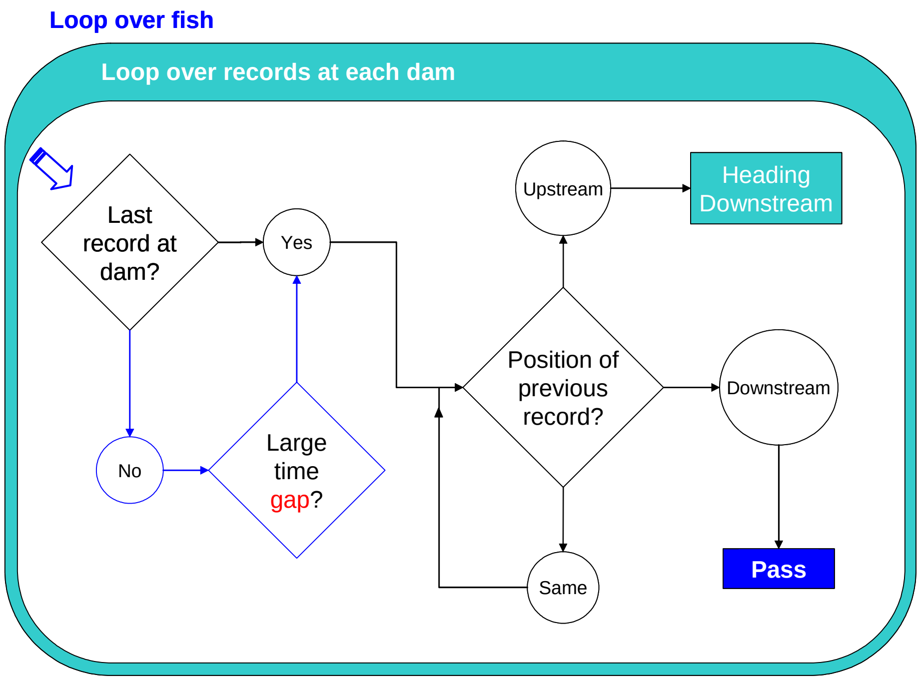

Figure 3. Flow diagram of directionality as evaluated by the PIT-tag interpretive model. Open arrow indicates the "start" of the model for each fish at each dam.

upstream and was detected twice in a row at the same weir, we assumed it was still heading upstream. Directionality only changed when we had evidence that the fish changed direction. As a consequence, regardless of the number of detections at a dam, if all detections occurred at the same weir, a passage event was not assigned (directionality was never established).

Fallback and Reascension

We know from previous studies that some salmonids fall back over dams (Bjornn et al. 2000; Boggs et al. 2004). With current technology, PIT-tag antennas need to have fish either swim through them or closely by them (current detection range for a 28-inch antenna is about 15 to 20 inches) and they cannot be used in all fish pathways (e.g., the navigation channels and spillways are too large); consequently, some behaviors, such as fallback over the spillways, cannot currently be detected directly using PIT systems. We therefore required multiple ladder ascensions to infer a fallback. However, because some fish that fall back do not reascend a dam (Boggs et al. 2004) it was expected that the number of fallback events determined by radio tags would not match exactly the number of post-fallback reascensions determined by PIT tags.

Time Gap Parameters

Following a fallback, many fish reascended the dam. If the interpretive model only assigned a passage code to the last record at a dam, it would be unable to detect multiple ascensions by an individual fish. To identify when a fish reascended a dam, the model needed to identify multiple passage events. We therefore designed the model to divide PIT-tag data into segments and to treat each segment as a potential passage event. The model identified segment boundaries as time gaps in a detection history (a certain amount of time with no detections). For example, if a fish passed a dam, fell back over the spillway, and passed again the next day, we wanted the model to recognize that there were two passage events, separated by a gap in time. We optimized the performance of the PIT-tag model by adjusting this time gap parameter and comparing the resulting model estimates to radiotelemetry data. If values of the time gap were too large, many reascensions would be missed by the model; however, if values were too small, one passage event might be interpreted as multiple passes.

We used three types of analyses to determine the best value for this time gap. First, we ran the model using different values of the time gap to see whether different values resulted in different levels of agreement between the PIT model and radiotelemetry data. Next, we evaluated discrepancies in passage and fallback rates between the model and radiotelemetry. Finally, we assessed the minimum reascension time for fallbacks.

Assessing agreement between methods--We tested the model using a variety of reasonable values for the time gap, determining the best model fit using three criteria: the total number detected by both methods (matches), the number detected by radiotelemetry only (radio only), and the number detected by PIT only (PIT only). Maximizing the number of passage events detected by both radiotelemetry and the PIT system (matches) was the primary criterion.

The other two criteria, however, were more complex. Passage events detected by radiotelemetry but not by the PIT-tag system (radio only) occurred when either the PIT tag was not detected at that dam or the set of detections did not meet the interpretive PIT-tag model criteria. Alternatively, passage events detected by the PIT-tag system but not radiotelemetry (PIT only) occurred for multiple reasons: 1) a fish may have indeed passed the dam but the radiotelemetry antenna array missed it; 2) a fish did not pass a dam, but its detections were incorrectly interpreted as a passage event by the PIT-tag model, or 3) a fish regurgitated its radio transmitter prior to passing a dam (and so was not detected by radiotelemetry) but was correctly interpreted as passing by the PIT-tag model.

At each value of the time gap tested, we determined the number of passage events in each of the three categories (matches, PIT only, and radio only). Values of the time gap that produced the most matches and the fewest radio only and PIT only events were considered optimal.

We checked the model fit to both passage events and fallback events using radiotelemetry data. On average, as the time gap increased, the frequency of "matches" and "PIT only" passage events decreased (Figures 4 and 5). This was primarily because as the time gap increased, fewer groups of PIT-tag data met the criteria for a passage event. Some of these "lost" passage events were detected by radiotelemetry (decreasing the "matches") and some were not (decreasing the "PIT only"). The response of "radio only" events to increases in the time gap was variable, but usually small. These results were consistent for the comparisons of both passage and fallback events.

The most dramatic changes in the "PIT only" group occurred using a time gap from 1 to 12 h, whereas large changes in "matches" still occurred using time gaps up to 24 h or more. Since we wanted to minimize the "PIT only" group with the least impact on "matches," we selected the 12-h time gap as the optimal fit for the model.

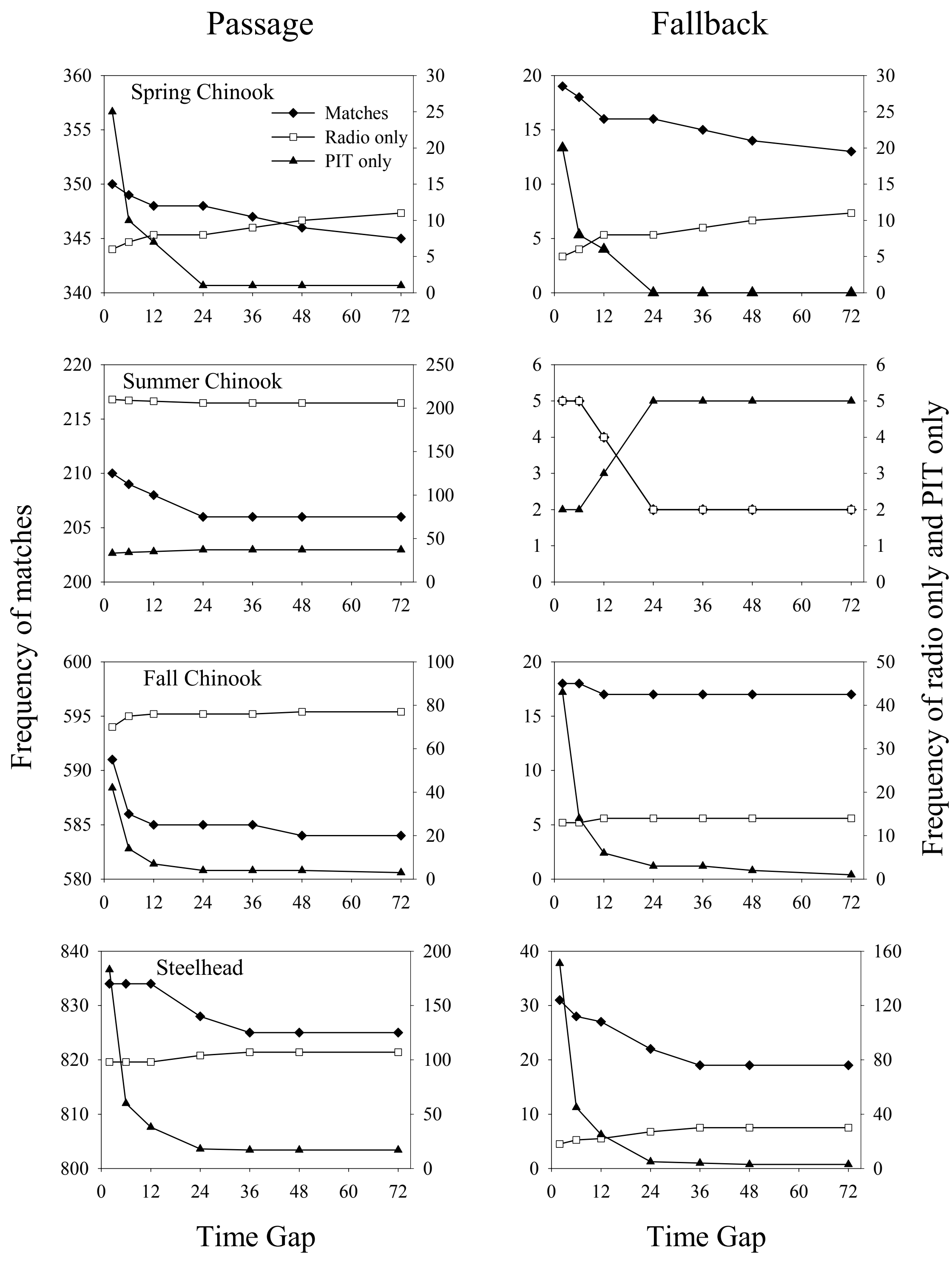

Figure 4. Frequency of "matches," "radio only," and "PIT only" detections of passage and fallback at Bonneville Dam in 2002 as a function of the time gap (h).

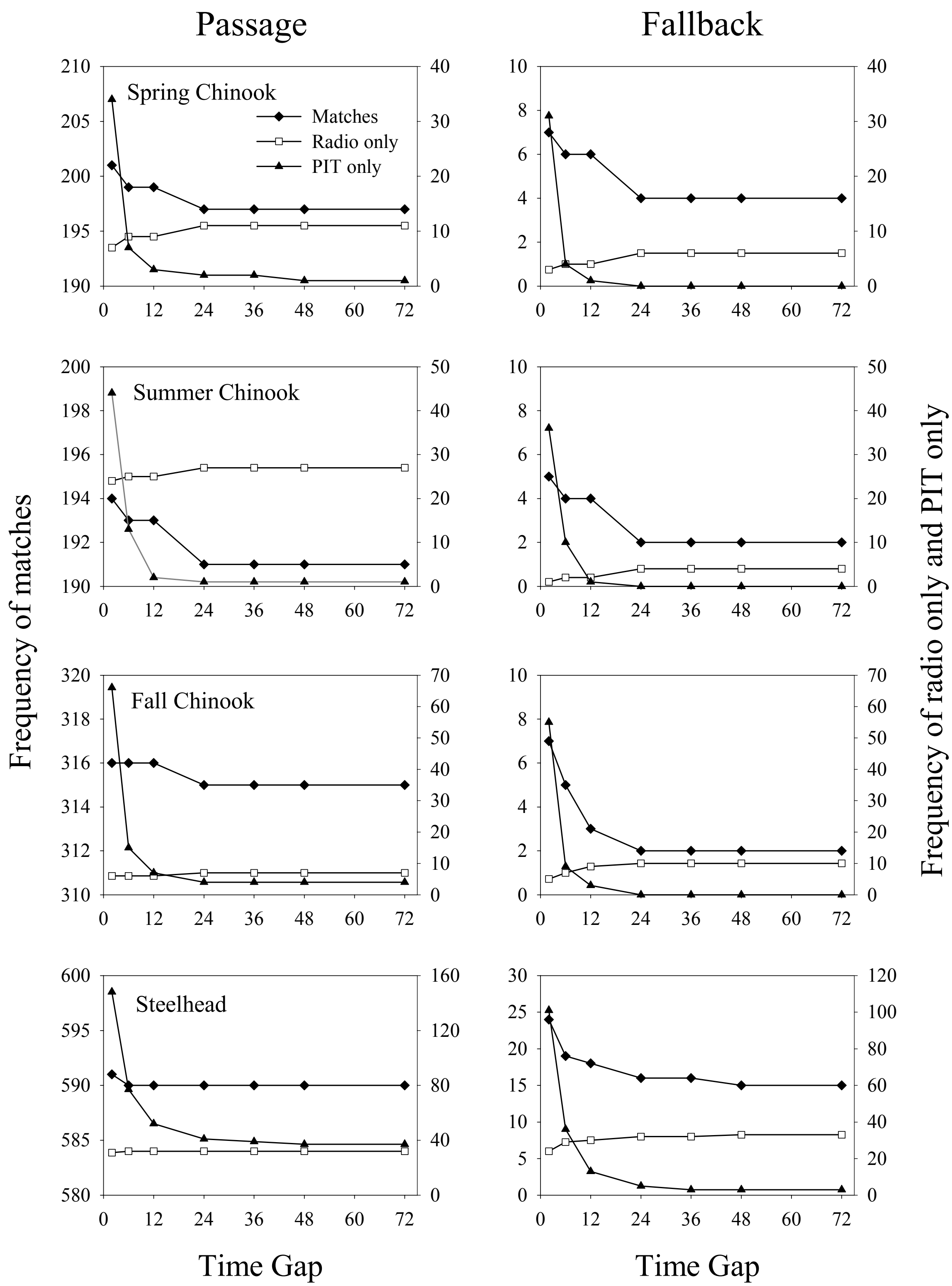

Figure 5. Frequency of "matches," "radio only," and "PIT only" detections of passage and fallback at McNary Dam in 2002 as a function of the time gap (h).

Assessing timing discrepancies between methods--Because the furthest upstream PIT-tag interrogators were not at the tops of the ladders and radiotelemetry receivers were, a discrepancy in time existed between the two detections of a passage event. It was possible that a fish detected by one method during a failed passage attempt would later be detected by the other method on a successful attempt. In this situation, both methods detected a passage, so a "match" would be assigned; however, they were detecting separate events. Similarly, one passage event could be labeled as both a "radio only" and a "PIT only," depending on the order and timing of data records. These discrepancies were inherent to the definitions and assignment of "matches," "radio only," and "PIT only." We therefore evaluated the extent of agreement in the total number of passage and fallback events determined by radiotelemetry (matches + radio only) and the PIT system (matches + PIT only) over a range of time gap values.

For the bulk of species/population comparisons, the total number of passage and fallback events was approximately equal between radiotelemetry and PIT data when the time gap was between 6 and 12 h (Figures 6 and 7). This corroborated with the previous analysis and strengthened our confidence in using a value near 12 h as the time gap for future analyses. For determination of steelhead passage at Bonneville and McNary Dams, no value of the time-gap parameter resulted in comparable counts between model estimates and the radiotelemetry data.

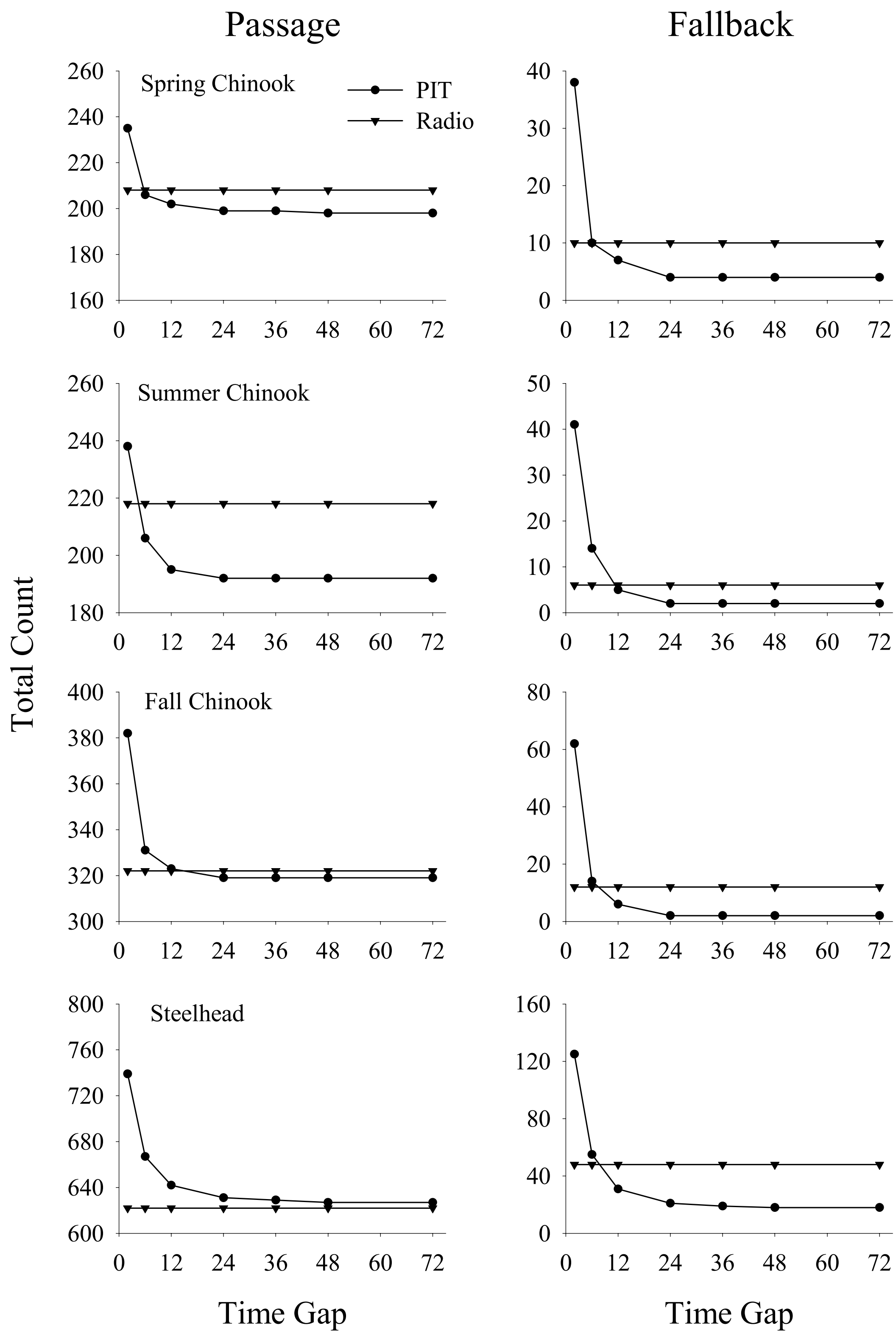

Figure 6. Total count of passage and fallback events from the PIT-tag model and radiotelemetry data at Bonneville Dam in 2002 as a function of the time gap.

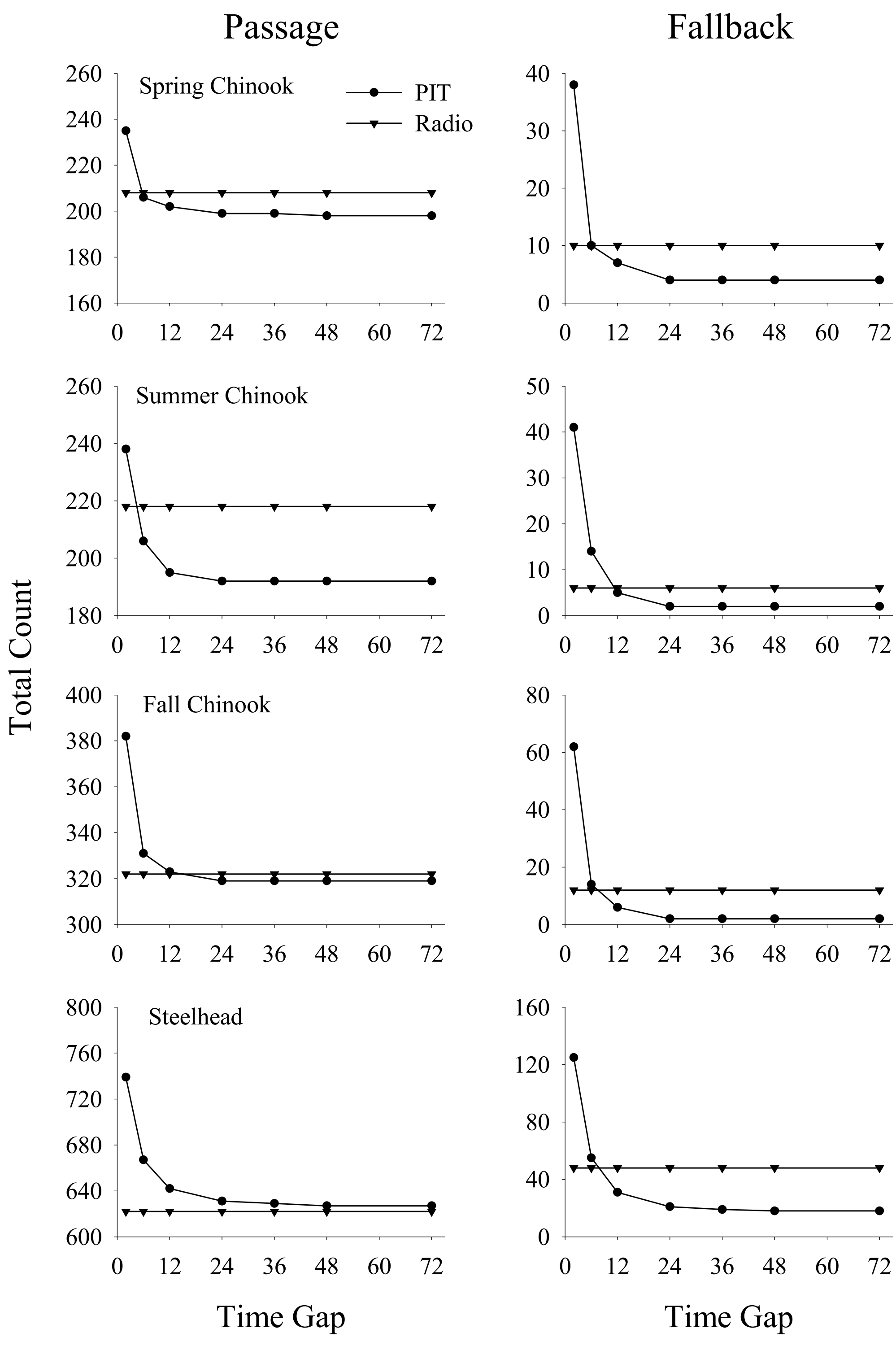

Figure 7. Total count of passage and fallback events from the PIT-tag model and radiotelemetry data at McNary Dam in 2002 as a function of the time gap.

Assessing reascension timing--Finally, we determined the minimum amount of time necessary for fish to reascend a ladder after passing and falling back at a dam. This minimum was determined using only radiotelemetry data (and only for fish that fell back at a dam), and was calculated from the time a fish passed a dam until it first reentered the fishway on its second ascension.

Over 90% of fish that fell back at Bonneville, McNary, Ice Harbor, or Lower Granite Dam took more than 12 h to reenter a fishway after initially passing the dam (Figures 8 and 9). This was a conservative estimate of the time required for a reascension based on PIT-tag data, since no PIT-tag interrogators were available at either the fishway entrances or at the tops of ladders, while radiotelemetry antennas were available at both these locations.

On median, double-tagged fish required between 1.0 and 2.7 h from their last entry into a fishway (radiotelemetry detection at a fishway entrance) until their first PIT-tag detection at each dam and between 0.4 and 2.4 h from the last PIT-tag detection until passing the dam (radiotelemetry detection at the top of a fish ladder).

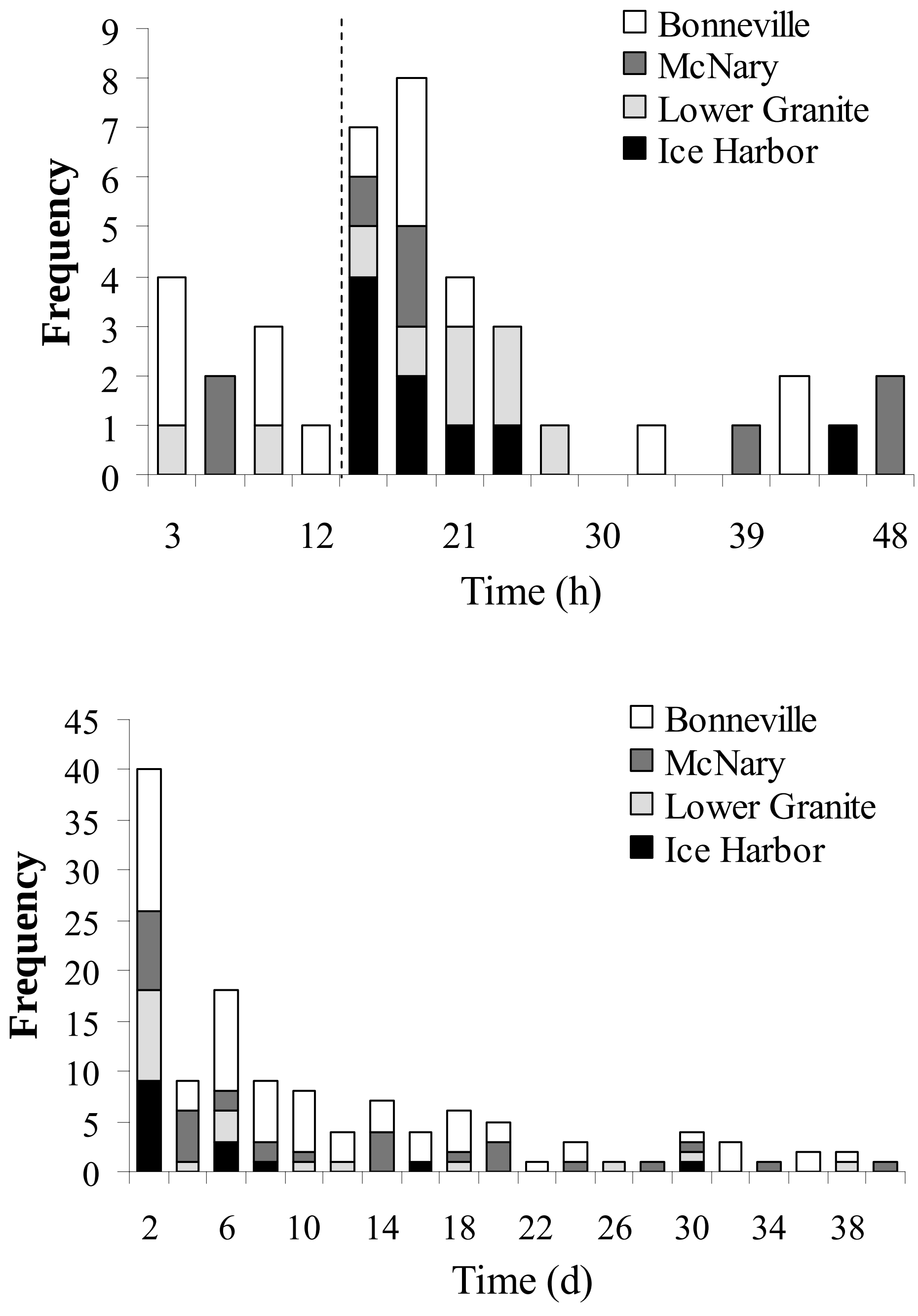

Figure 8. Time in hours (data up to 48 h in top panel) and days (all data in bottom panel) required for fish to reenter a fishway after passing and falling back at each dam (all species combined). Data are from radiotelemetry in 2002 only. Dotted line represents a 12-h time gap.

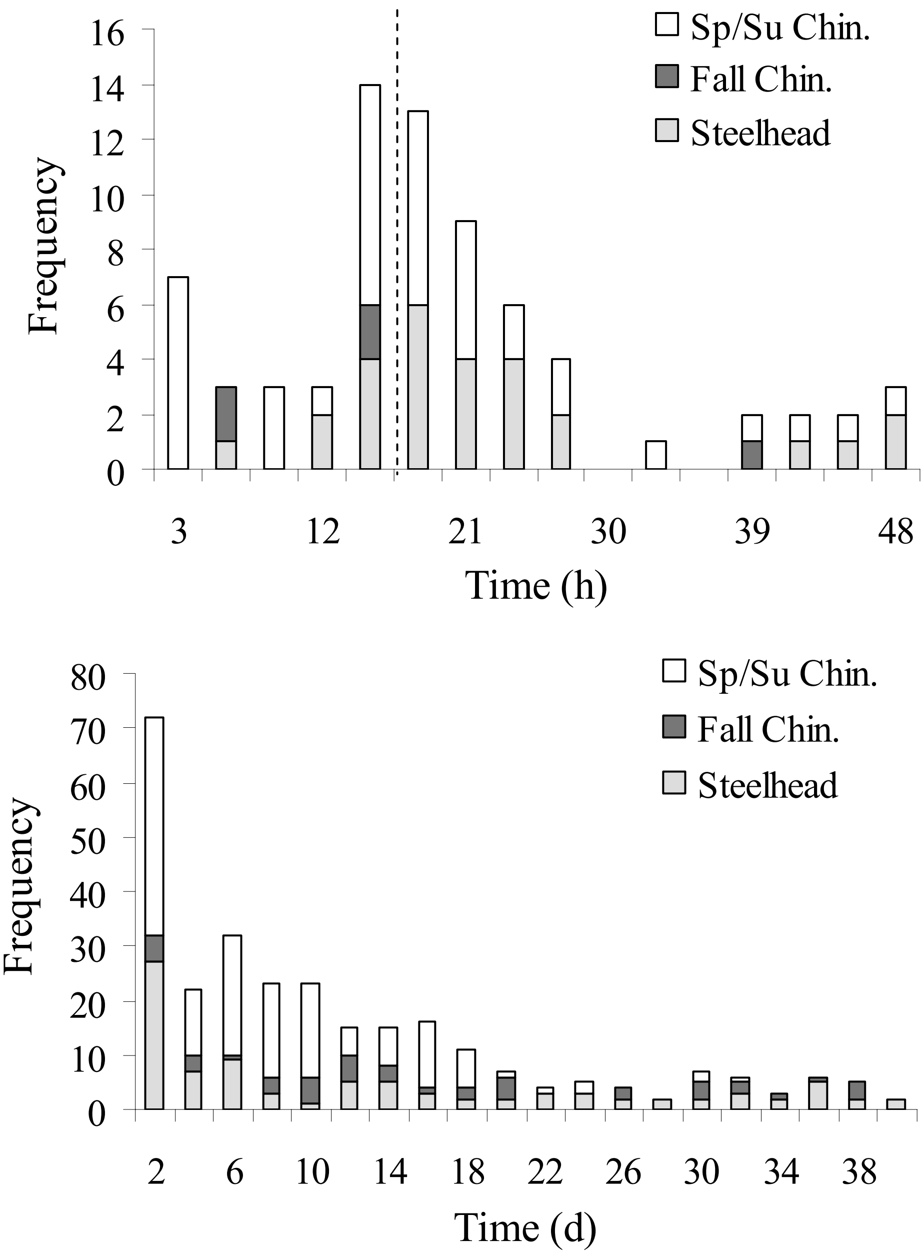

Figure 9. Time in hours (data up to 48 h in top panel) and days (all data in bottom panel) required for fish to reenter a fishway after passing and falling back at a dam, plotted by species. Data are from radiotelemetry in 2002 only (all four dams combined). Dotted line represents a 12-h time gap.

Rank Analysis

Methods--In addition to directionality and the time-gap parameter, location within the ladder of the last detection was evaluated as model criteria. Since detection efficiency was quite high for individual PIT-tag detectors (Downing and Prentice 2004), we required that all passage events end with a detection near the furthest upstream PIT-tag antenna. We determined the rank of the last detection before a potential passage event (highest detector in a ladder being defined as rank = 1, the range of ranks depended on the number of detectors in the system). Only potential passage events with a rank of 3 or higher (detection in one of the top three weirs) were initially interpreted as a passage event. We then ran the model using various values of the rank parameter (up to 20) to determine the optimal value (best model fit).

Results--Optimizing passage events by rank within fishways for the three criteria of "matches," "radio only," and "PIT only" was problematic. Decreasing the value of the rank necessary for a passage event (i.e., requiring the last detection be closer to the ladder top) often decreased the number of "PIT only" detections but increased the number of "radio only" detections. However, it was clear that decreasing the rank almost never increased the number of "matches" (Figure 10). We therefore removed the criterion of rank from the model.

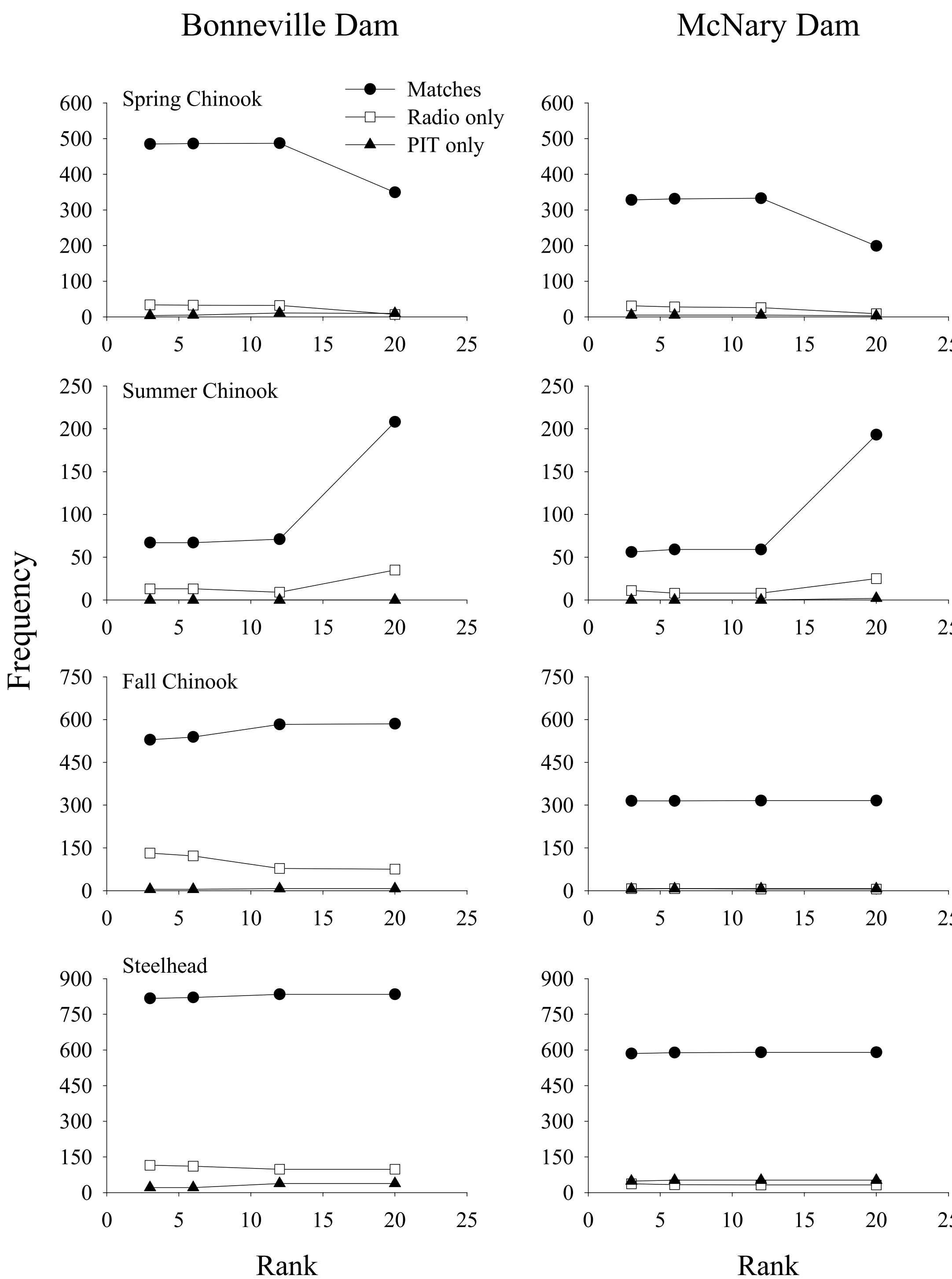

Figure 10. Frequency of "matches," "radio only," and "PIT only" as a function of the minimum rank necessary for a passage determination at Bonneville and McNary Dams for 2002 double-tagged fish.

MODEL VALIDATION

Methods

We used data from adults detected in 2003 as an independent test of the ability of the PIT-tag interpretive model to correctly assign passage and fallback events. We downloaded and analyzed PTAGIS data from 1,620 Chinook salmon, excluding from the data set any fish that did not have an ISO-based PIT tag and any fish that never passed a dam. We then compared results from the model to those from radiotelemetry data coding. At the time of this report, radiotelemetry data for steelhead were not completely coded (interpreted), so comparisons for steelhead in 2003 were not included. Weekly counts of passage and fallback events were calculated both for 2002 (the test year) and 2003 (the validation year). For 2003 tests, we were able to use data from the newer PIT-tag interrogation systems at Ice Harbor and Lower Granite Dams (deployed in 2003) as well as those at Bonneville and McNary Dams (deployed in 2002). We tested the null hypothesis, that there was no difference between the two detection systems, by subtracting the weekly count produced by PIT tags from the weekly count produced by radiotelemetry and tested for deviations from zero. Because results were not normally distributed, we used a signed rank test to determine significant differences (Steel et al. 1997).

Results

We divided all PTAGIS data into segments; each segment contained data for one fish and was separated by other segments for that fish by a time gap of at least 12 h. We summarized model results by determining model output for each data segment (Table 2). The majority of PIT-tag data segments were interpreted as fish passing a dam (Passage), particularly at Ice Harbor Dam where over 92% of all segments resulted in passage. Across all dams and populations, between 0 and 24% of PIT-tag data segments showed fish last detected swimming downstream in the ladder (Downstream). We implied passage at dams for fish that were not directly detected passing that dam, but were detected upstream at a later time (Unkn Passage). Post-fallback reascensions accounted for 0 to 7% of data segments. When directionality was not established (No Direction), which happened at Bonneville more than at other dams, fish were not listed as passing.

Table 2. Proportion of PIT-tag data resulting in each of five categories for spring and summer Chinook (SS), fall Chinook (FC) and steelhead (SH).

		Bonneville Dam			McNary Dam			Ice Harbor Dam			Lower Granite Dam		
		SS	FC	SH	SS	FC	SH	SS	FC	SH	SS	FC	SH
2002	Passage	0.72	0.70	0.68	0.86	0.91	0.91						
	Downstream	0.04	0.07	0.10	0.07	0.06	0.02						
	Unkn Passage	0.18	0.19	0.17	0.04	0.00	0.02						
	Reascension	0.05	0.03	0.04	0.02	0.02	0.04						
	No Direction	0.01	0.01	0.01	0.01	0.01	0.00						
2003	Passage	0.88	0.75	0.74	0.82	0.87	0.83	0.94	0.95	0.92	0.84	0.76	0.77
	Downstream	0.02	0.08	0.09	0.05	0.05	0.07	0.00	0.00	0.02	0.15	0.24	0.20
	Unkn Passage	0.04	0.11	0.08	0.08	0.03	0.04	0.01	0.00	0.03	0.00	0.00	0.00
	Reascension	0.05	0.02	0.07	0.03	0.05	0.05	0.05	0.05	0.03	0.02	0.00	0.03
	No Direction	0.01	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00

Both to test the model and show the degree to which the PIT-tag interpretive model results match with radiotelemetry results, we calculated weekly counts of both passage events and fallback events for the double-tagged fish. We provide results for 2002 to demonstrate the fit we were able to obtain with these data (Figures 11 and 12). We then used the model on an independent PIT-tag data set (2003) and compared results to those obtained from radiotelemetry (Figures 13 and 14).

After fitting the model to 2002 data, only one significant difference (at the $P < 0.05$ level) was found between the PIT and radio counts of passage or fallback: the interpretive PIT-tag model estimated significantly more passage events at McNary Dam in 2002 than were found using radiotelemetry data (Table 3). In comparisons between PIT and radiotelemetry data from adult detections in 2003, the radiotelemetry data determined significantly more passage and fallback events by fall Chinook salmon at Bonneville Dam ($P = 0.031$ for passage, $P = 0.008$ for fallback) than did PIT-tag data and significantly fewer passage events by spring Chinook salmon at McNary Dam ($P = 0.032$; Table 3). Although statistically significant, these differences were minor when compared to the magnitude of the absolute number of fish that passed or fell back.

All other dam/run combinations showed no significant differences. The largest percent difference in passage counts between radiotelemetry and PIT-tag data occurred with fall Chinook at Ice Harbor Dam in 2003 (5.1% difference), though this was not statistically significant. Percent differences in fallback counts were generally much higher. However, small sample sizes provided little statistical power for these results (e.g., the only statistically significant difference was for fall Chinook at Bonneville Dam in 2003; Table 3).

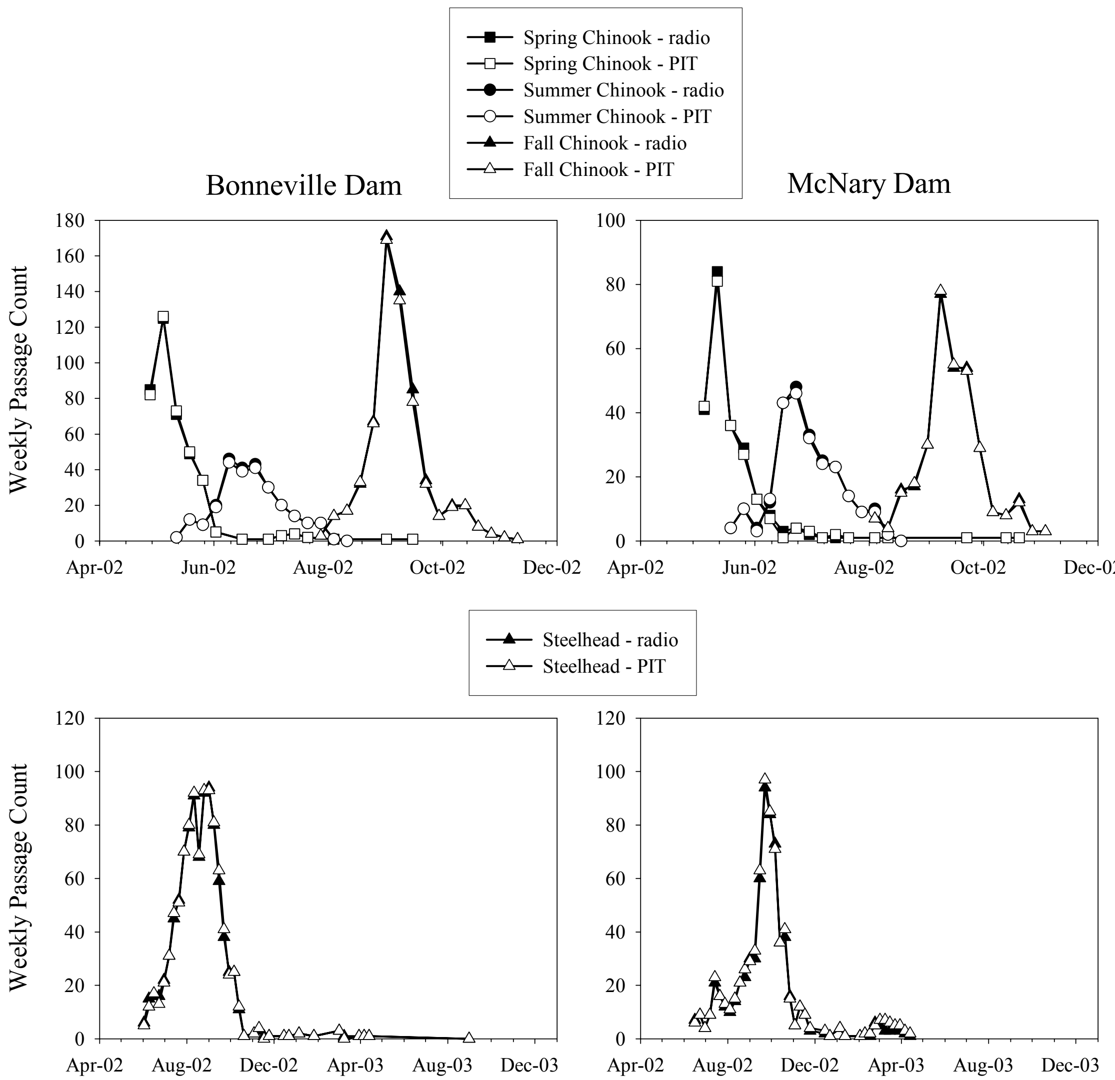

Figure 11. Weekly dam passage counts for Chinook (top two panels) and steelhead (bottom two panels) as determined by the PIT-tag interpretive model vs. radiotelemetry data from Bonneville and McNary Dams, 2002.

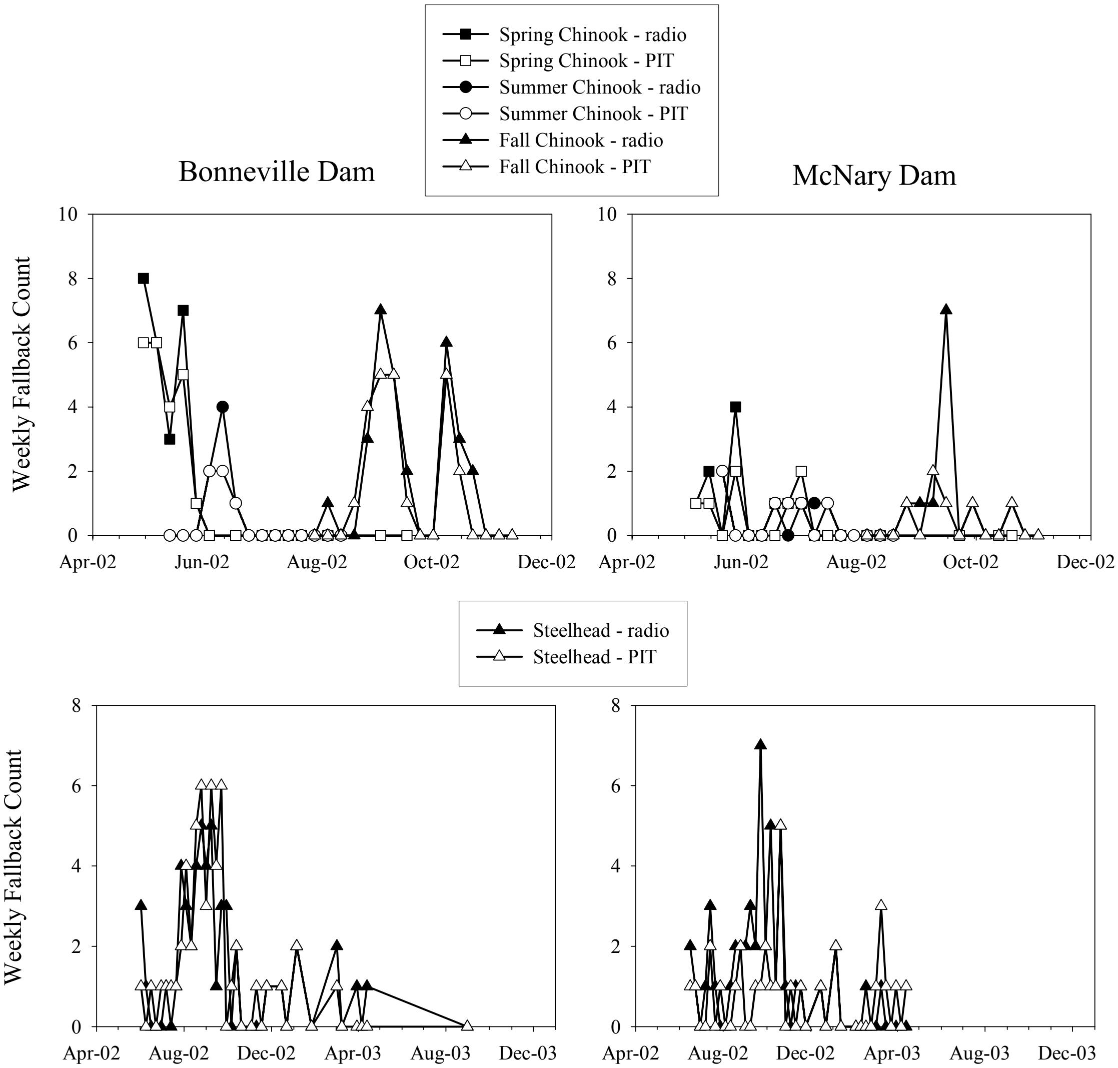

Figure 12. Weekly dam fallback/reascension counts for Chinook (top two panels) and steelhead (bottom two panels) as determined by the PIT-tag interpretive model vs. radiotelemetry data from Bonneville and McNary Dams, 2002.

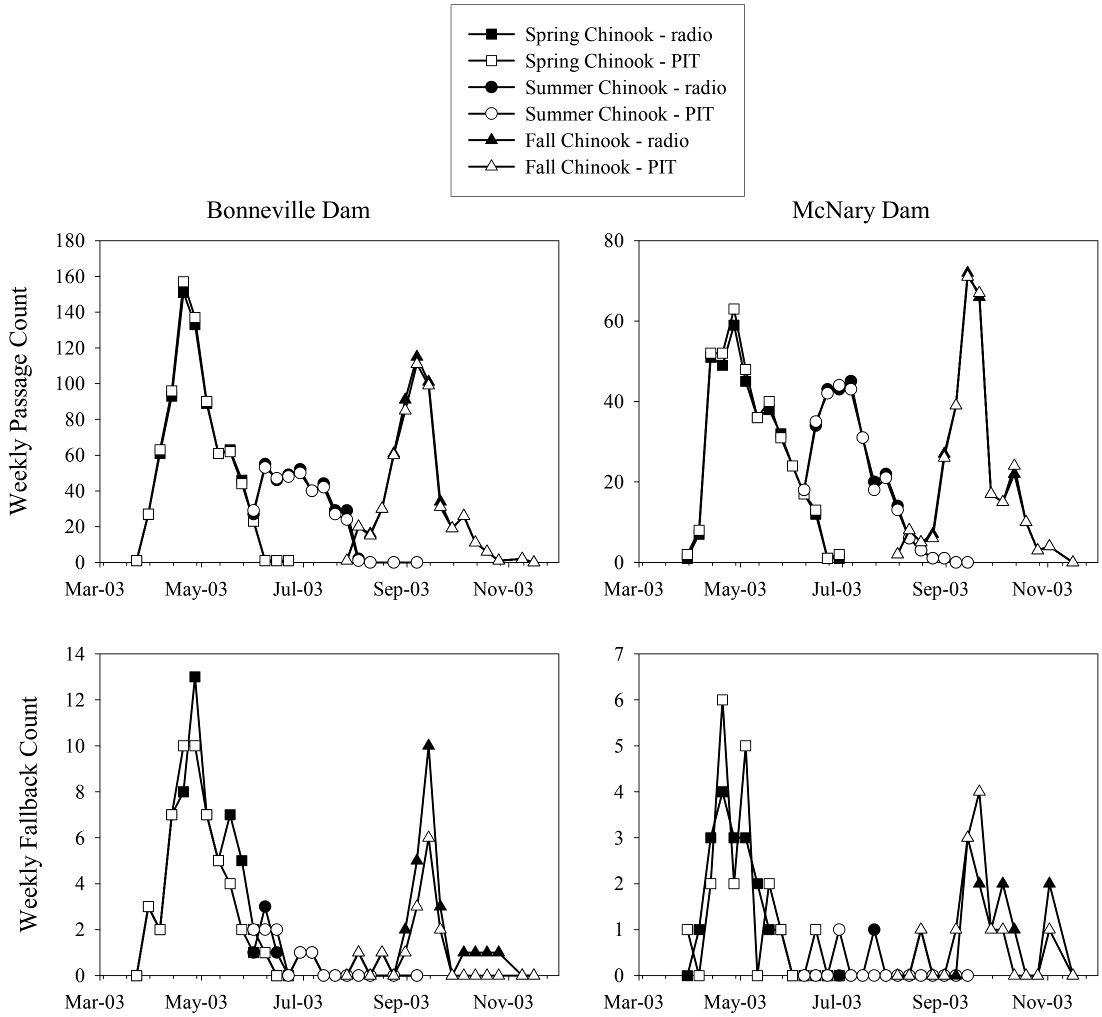

Figure 13. Weekly dam passage and fallback/reascension counts as determined by the PIT-tag interpretive model vs. radiotelemetry data from Bonneville and McNary Dams, 2003.

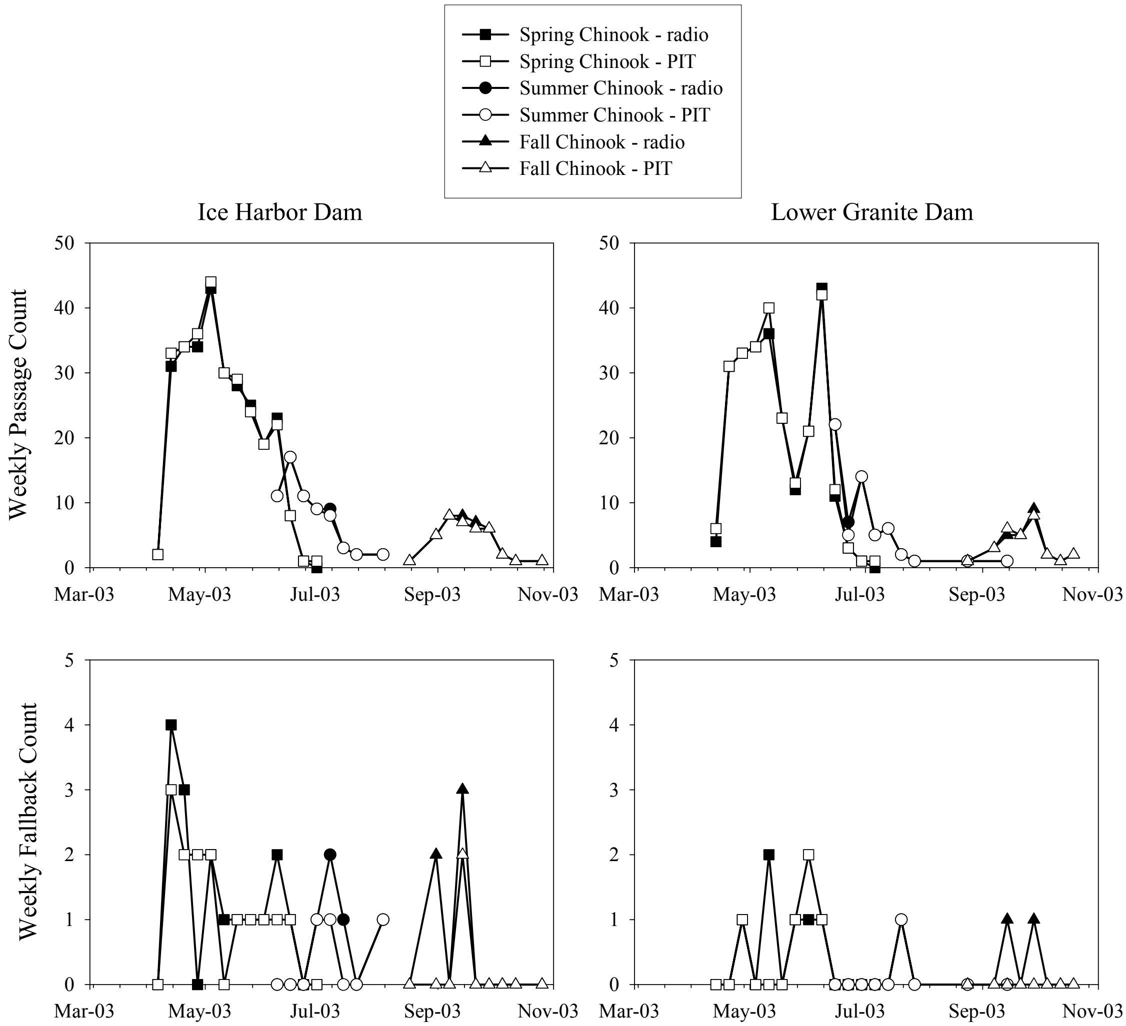

Figure 14. Weekly dam passage and fallback/reascension counts as determined by the PIT-tag interpretive model vs. radiotelemetry data from Ice Harbor and Lower Granite Dams, 2003.

Table 3. Passage and fallback counts determined by radiotelemetry (RT) and PIT-tag (PIT) data from adult spring (SP), summer (SU), and fall (FA) Chinook salmon and steelhead (SH).

		Bonneville Dam			McNary Dam			Ice Harbor Dam			Lower Granite Dam		
Passage		RT	PIT	Diff (%)	RT	PIT	Diff (%)	RT	PIT	Diff (%)	RT	PIT	Diff (%)
2002	SP	383	384	2.6	228	223	-2.2						
	SU	258	251	-2.7	237	232	-2.1						
	FA	632	615	-2.7	324	324	0						
	SH	955	959	0.4	675	707	4.7[b]						
2003	SP	751	764	1.7	373	389	4.3[b]	278	283	1.8	252	260	3.2
	SU	373	361	-3.2	281	276	-1.8	64	63	-1.6	59	57	-3.4
	FA	534	517	-3.2[b]	297	297	0	39	37	-5.1	28	28	0
Fallback[a]													
2002	SP	25	22	-12.0	10	7	-30.0						
	SU	7	5	-28.6	6	6	0						
	FA	29	23	-20.7	12	6	-50.0						
	SH	50	53	-6.0	48	31	-35.4						
2003	SP	60	52	-13.3	18	20	11.1	16	14	-12.5	6	5	-16.7
	SU	7	8	14.3	1	1	0	5	3	-40.0	1	1	0
	FA	26	14	-46.2[b]	12	12	0	5	2	-60.0	2	0	N/A

a For PIT data, post-fallback reascensions were used as a surrogate for fallbacks.

b Significant difference (*P* <0.05) using a signed rank test on weekly counts

MODEL APPLICATION

Methods

To apply the model to a larger group of fish, we used all PIT-tagged fish in the PTAGIS database that were designated as Species 1 (Chinook) and Run 1, 2, or 3 (spring, summer, or fall run, respectively) and that had at least one adult PIT-tag detection at any of the four adult interrogation systems during calendar year 2003. We removed from the analysis all juveniles and any fish that we radio-tagged as an adult (to maintain independence from the data used to create and parameterize the model).

Although there was no direct independent test for the results of this analysis, we compared them to results from two other analyses. First, we quantified the proportion of unique fish that passed each dam out of the total number of fish in the data set and compared these values to the same values from radiotelemetry data collected during 2003 (i.e., the double-tagged fish). Similarly, we quantified the number of dam passage events that were followed by both a fallback and reascension (PIT-tag data can not directly detect a fallback) and compared this to the combined fallback and reascension rate estimated using radiotelemetry data. Post-fallback reascension rates estimated from radiotelemetry were averaged over 5 years (spring/summer Chinook) and 3 years (fall Chinook). Even though data were obtained from Boggs et al. 2004, we calculated reascension rates as previously described (see "Reascension Rates," p. 11) rather than reascension proportions.

Our second comparison for the results of this analysis was to the PIT-tag-only data from the double-tagged fish in 2003. The comparison was then between two sets of model output, each from a different group of fish. If both sets of fish were truly randomly drawn from the population at large, we would expect similar results for the two groups. Comparisons of this nature can determine how selection of fish and differences in sample size can affect results. Similar to the model validation, we quantified weekly passage and post-fallback reascension events at each of the four dams for spring, summer, and fall Chinook salmon.

Results

After removing juveniles and fish that were radio tagged from PTAGIS adult detections for 2003, a total of 2,845 spring Chinook, 2,649 summer Chinook, and 1,563 fall Chinook (Table 4) were available for an independent application of the interpretive model. Fish included for analysis had been detected on at least one adult PIT-tag interrogation system at any of the four dams.

Comparisons with radiotelemetry data from the double-tagged fish during that same year showed general agreement, though some significant differences existed. The proportion of all PIT-tagged fish passing the four dams declined precipitously between Bonneville Dam (range of 0.93 to 0.99) and Lower Granite Dam (range of 0.19 to 0.48; Figure 15). It should be noted that not all tagged fish were expected to travel up the Snake River (i.e., we expected a decline in the proportion detected). Proportions of radio-tagged Chinook salmon passing the four dams showed similar results, although the values were slightly lower, particularly for fall Chinook salmon at McNary, Ice Harbor, and Lower Granite Dams.

Table 4. Total number of PIT-tagged fish detected as adults at dams during 2003 (N) and count of passage and post-fallback reascension events at Bonneville (BO), McNary (MN), Ice Harbor (IH), and Lower Granite (GR) Dams.

	Juvenile migration year	N	Passage				Post-fallback reascension			
			BO	MN	IH	GR	BO	MN	IH	GR
Spring Chinook	2000	1572	1741	1215	760	710	180	66	18	8
	2001	803	845	452	386	355	47	22	8	2
	2002	470	487	444	352	324	24	17	10	8
Summer Chinook	2000	1617	1637	1424	445	427	30	16	10	11
	2001	866	840	768	239	231	14	10	6	3
	2002	166	169	163	150	145	3	0	4	3
Fall Chinook	1999	75	7	7	7	0	0	0	0	0
	2000	881	844	630	56	37	12	8	0	1
	2001	202	202	188	133	132	2	3	0	3
	2002	405	405	380	140	131	7	15	1	5

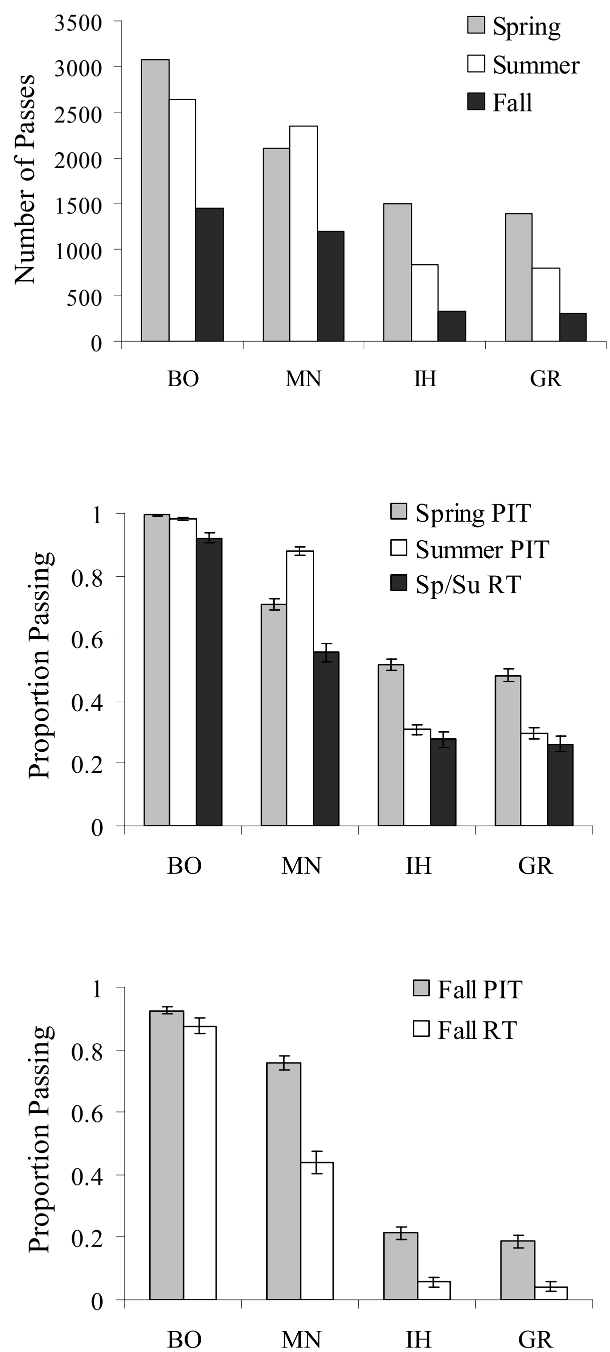

Figure 15. Number of passage events estimated by the interpretive model for spring, summer, and fall Chinook salmon in 2003 (top panel) and the proportion and SE of all fish passing each dam (middle and bottom panels) as determined by the PIT model (PIT) vs. radiotelemetry data (RT). Spring and summer runs were computed together from RT data. BO = Bonneville Dam, MN = McNary Dam, IH = Ice Harbor Dam, GR = Lower Granite Dam.

Spring Chinook salmon fallback and reascension rates also declined between Bonneville Dam and Lower Granite Dam in 2003 (Figure 16). However, neither summer nor fall Chinook salmon showed a trend among dams in reascension rate. Estimates of combined fallback and reascension rate from radiotelemetry data were comparable to estimates from PIT-tag data in all cases except spring Chinook salmon at Bonneville Dam and fall Chinook salmon at Lower Granite Dam. At Lower Granite Dam, radiotelemetry data for fall Chinook salmon showed an exceptionally high fallback and reascension rate compared to any other data source/dam combination, although this was also the group with the lowest sample size.

PIT-tag interpretive model results for double-tagged fish from 2003 were similar to those of the larger group of PIT-tagged (non-radio tagged) fish from PTAGIS in the same year (Figures 17 and 18). However, the timing of estimated peak passage or fallback did not always match up precisely (e.g., fall Chinook salmon passage at Ice Harbor Dam). These discrepancies could result from multiple sources: 1) observation error (e.g., inaccurate interpretation of PIT-tag data), 2) random error, possibly related to differences in sample size or run timing of the two samples, or 3) process error, (e.g., behavioral differences between the two populations of fish).

It should also be noted that separating runs by their date of passage at Bonneville Dam, which was necessarily done for radiotelemetry tagging because not all fish were of known origin, produced some inaccuracies. For example, the spring and summer Chinook salmon runs overlapped at Bonneville from early April through July (Figure 17), yet most fish radio-tagged during that time were labeled spring Chinook in the radiotelemetry database. At Lower Granite Dam, fish labeled as spring Chinook salmon in the radiotelemetry database passed the dam in high numbers almost until the peak summer Chinook salmon passage date. However, these discrepancies represented a small fraction of the data; most model output matched well with results from radiotelemetry. General trends were less clear in fallback event distributions due to the low sample size and, therefore, higher variability.

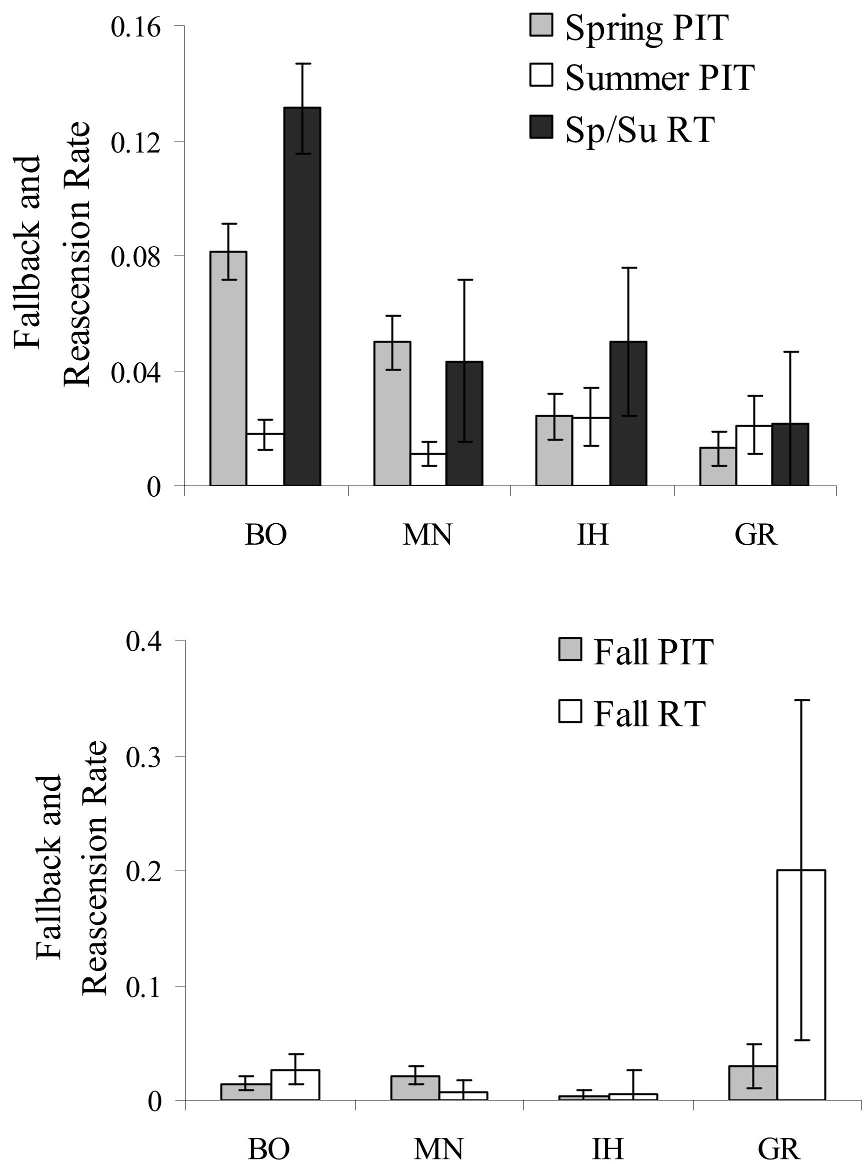

Figure 16. Combined fallback and reascension rate (proportion of passage events that were followed by both a fallback and reascension) for spring/summer (top) and fall (bottom) Chinook salmon in 2003. Spring and summer runs were computed together from RT data. Error bars represent one standard error. BO = Bonneville Dam, MN = McNary Dam, IH = Ice Harbor Dam, GR = Lower Granite Dam.

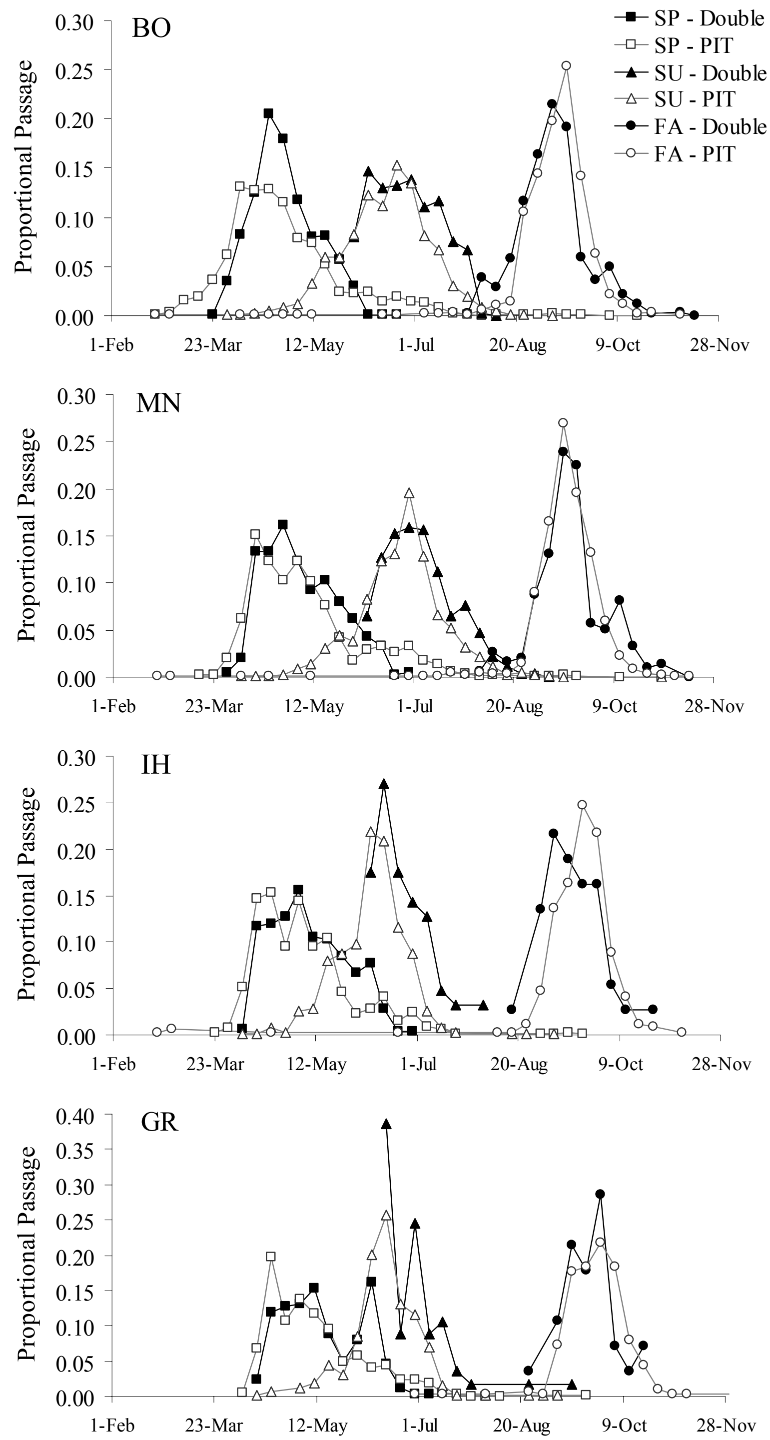

Figure 17. Weekly passage distribution estimated by the PIT tag interpretive model for double-tagged fish (filled symbols) and fish with only a PIT tag (PTAGIS open symbols) detected as adults in 2003. Runs include spring (SP, squares), summer (SU, triangles), and fall (FA, circles) Chinook salmon. BO = Bonneville Dam, MN = McNary Dam, IH = Ice Harbor Dam, GR = Lower Granite Dam.

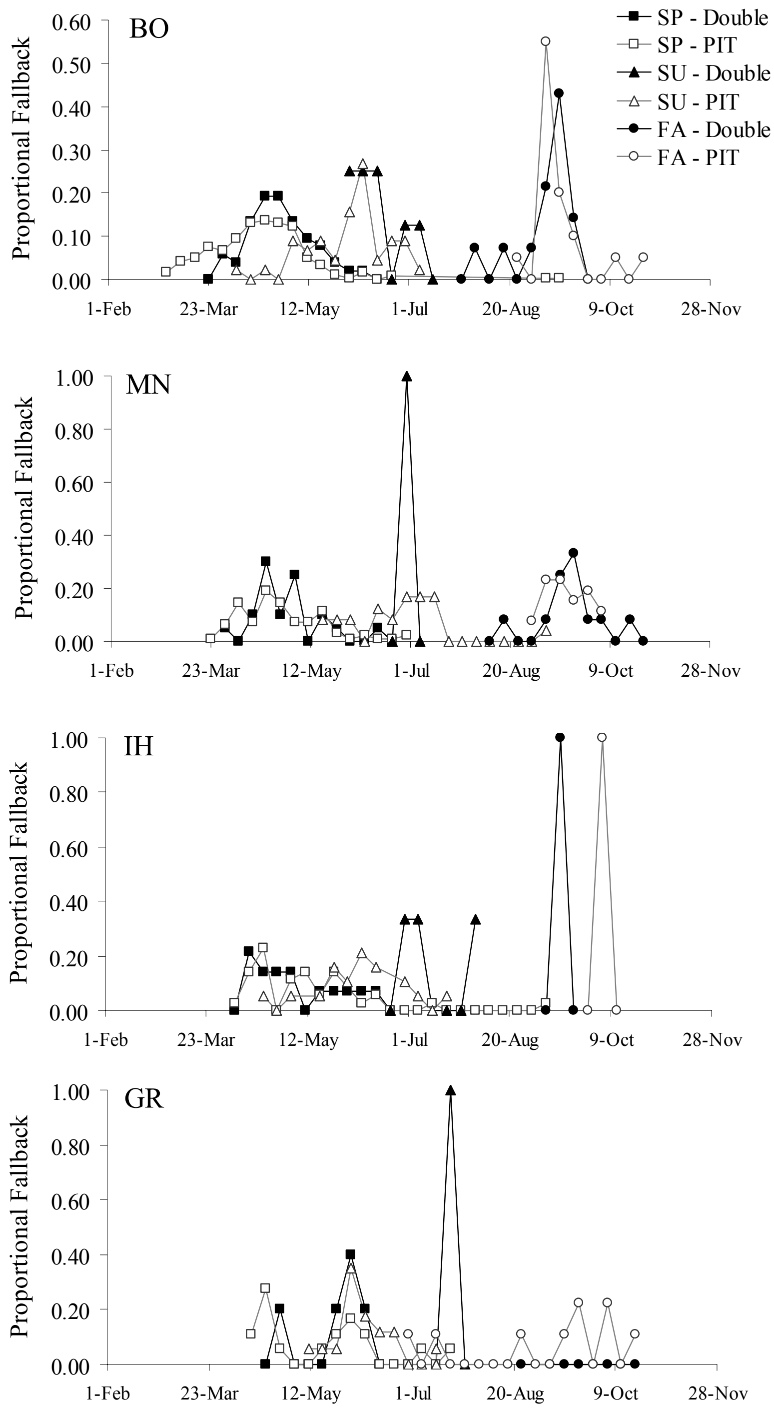

Figure 18. Weekly fallback distribution estimated by the PIT tag interpretive model for double-tagged fish (filled symbols) and fish with only a PIT tag (PTAGIS; open symbols) detected as adults in 2003. Includes spring (SP, squares), summer (SU, triangles), and fall (FA, circles) Chinook salmon. BO = Bonneville Dam, MN = McNary Dam, IH = Ice Harbor Dam, GR = Lower Granite Dam.

SUMMARY AND CONCLUSIONS

There has been increased interest by fisheries managers and researchers in developing means to best interpret data collected by PIT-tag interrogation systems within adult fishways at Columbia and Snake River dams. Several of the major hydropower dams in the Columbia and Snake Rivers currently contain PIT-tag interrogation systems for adult fish, which permit easy and relatively accurate interpretation of passage metrics. Two simple rules were necessary to interpret the PIT-tag data, namely directionality and a time-gap function to detect multiple ascensions.

The interpretive PIT-tag model performed well when determining the magnitude and timing of dam passage events. Model output matched radiotelemetry data for both species and all runs of salmonids tested at all four dams. This level of performance was achieved with the same set of rules and parameters for all comparisons, indicating that the model will interpret large data sets efficiently. Moreover, if PIT-tag detectors are installed at other dams, the model may not need much adjusting to accurately interpret the additional data.

In contrast to its accuracy in interpreting dam passage events, the PIT-tag model had varying degrees of success with determining post-fallback reascensions. With reascension events forming much smaller sample sizes than those used for passage metrics, we had less power to determine model parameters for fallback behavior. Moreover, some fish do not reascend after falling back (or are not detected reascending).

Many fish enter fishways at dams but do not pass directly through the ladders (Bjornn et al. 1998b). Assuming that every set of PIT-tag detections indicated a passage event would overestimate both the number of passage and fallback events. If a fish was detected at downstream antennas shortly after being detected at upstream antennas, it was likely the fish was heading downstream in the ladder. Similarly, if a fish was only detected at one antenna, it was difficult to determine if that fish passed the dam. Milling behavior can be quite common in and around dam fishways, and determining the direction of movement was necessary for accurate interpretation of PIT-tag data.

With radiotelemetry, detecting a fallback event is relatively easy because of the range and placement of radio receivers and antennas. PIT-tag antennas are not capable of directly detecting a fallback unless the fish swims back down through the ladder. Therefore, fallback events could only be inferred from PIT-tag data indicating a fish made multiple ascensions of the ladder. Allowing for a specific amount of time between ladder ascensions was the only other rule that improved model fit. From a variety of methods, we determined that a time gap of 12 h provided the best fit for most fish we analyzed from 2002 and 2003 data.

One drawback in evaluating post-fallback reascensions rather than fallbacks was that some fish did not reascend a dam following a fallback event (Boggs et al. 2004; Figure 3). Fish that did not reascend a fishway after a fallback may have migrated past their tributary of origin and turned back to locate that tributary (Boggs et al. 2004). However, it was also possible that a fish did not reascend because it was injured during the fallback, expended too much energy and could not reascend, or was captured by predators or in a fishery downstream from the dam before getting a chance to reascend. When determining the effect of dam operations or environmental conditions on salmonid migration, the inability to detect a fallback may be problematic, particularly when fish do not reascend.

The fact that some proportion of fallback fish did not reascend could be accounted for if that proportion was consistent through time. However, the relationship between fallback and reascension rates has varied considerably over the years. While reascension counts have provided some indication of actual fallback rates, there has been no consistent conversion factor. Further, the variance among species and runs (within a year) argues against using any single value to manage all salmonid populations.

One objective of the past several years of radiotelemetry research in the basin was to estimate fallback rates. These rates were sought mainly to understand the behavior of adult salmonids and how dam operation practices and environmental factors might affect their behavior and survival, but also to estimate bias in visual counts at counting windows. Fish that fall back at dams and reascend may artificially inflate the estimated escapement (Boggs et al. 2004). An adjustment factor (AF) to visual counts for fallback has been calculated from radiotelemetry data as:

$$AF = (P - FB + R) / TP \qquad \text{Eq. 1}$$

where P is the number of fish with transmitters known to have passed the dam via the fishways or the navigation lock (only locks at Bonneville and McNary were monitored), FB is the number of fish that fell back at the dam one or more times, R is the number of fish that reascended the dam and stayed upstream from the dam regardless of the number of fallbacks, and TP is the total number of times fish with transmitters were known to have passed the dam via fishways (Bjornn et al. 2000; Boggs et al. 2004). This adjustment factor was then used as a proportional change to adjust visual counts at dams.

Calculation of an adjustment factor determined from PIT-tag data (AF_{PIT}) would necessarily differ from Eq. 1. Since FB would be unknown, the adjustment factor would have to be calculated as:

$$AF_{PIT} = P / (P + R) \qquad \text{Eq. 2}$$

where P is the number of fish passing by any route and R is the total number of post-fallback reascensions.

The difference between the two metrics is particularly important for those using visual count data for survival analyses. Eq. 1 states that fish that passed, fell back, and did not reascend should not be counted as having passed. Eq. 2 states that any fish that passes should be counted, even if it falls back and does not reascend. For survival analyses, this translates to the difference between assigning loss to the stretch of river downstream from the dam (Eq. 1) or upstream from the dam (Eq. 2). Telemetry data can be used in both equations, while PIT-tag data can currently be applied only using Eq. 2. Although the appropriate equation depends on the question and type of data available, anyone using data from adjusted visual counts should be aware of how the adjustment was determined.

The independent model application using PTAGIS data from 2003 showed that data from large numbers of PIT-tagged fish can be rapidly analyzed with results comparable, with varying levels of accuracy, to other methods. Although exact agreement was not produced between radiotelemetry data or data from other groups of PIT-tagged fish, the differences were either small (passage metrics) or had low power (reascension metrics).

Inclusion into either the PIT-tag or the radiotelemetry data set was somewhat selective (e.g., only fish passing the Washington Shore ladder at Bonneville Dam were captured and radio tagged, and only fish with a PIT tag were used in the interpretive model application). However, these data sets were created with completely different fish, and likely comprised different proportions of fish from each ESU. Furthermore, a small proportion of fish in the radiotelemetry data set was inaccurately assigned to a run (spring, summer, or fall Chinook salmon). Therefore, variability between the two data sets may, in fact, be attributable to systematic genetic and behavioral differences among these groups of fish rather than model error or random variability. Management decisions based on results of either radiotelemetry or PIT-tag data should take into account the populations of fish being studied, as the population composition can affect the results obtained.

For future research and management, the increased sample size, long duration of operation, and lower cost of PIT tags (per tag) should be weighed against the longer range of radio transmitters and portability of radio receivers when comparing the usefulness of each method. Decisions about which method is best for a given purpose will ultimately depend on the questions being asked. For example, radiotelemetry is currently a more appropriate method for fish distribution and short-term survival studies, as the long transmission range allows for detection in large sections of the mainstem rivers, in tributaries, and with remote and mobile monitoring techniques. Telemetry is also well suited for monitoring fine-scale movements (e.g., entry and exit rates) and passage times in fishways, though PIT-tag antennas may eventually be able to duplicate some monitoring of this type.

On the other hand, studies aimed at determining variance among individuals in run timing or smolt-to-adult return rate would be better off with the larger sample sizes, longer tag life, and more accurate species/run assignments available with PIT tags. As more PIT-tag interrogation systems or additional antennas are installed, the interpretive PIT-tag model will require revalidation. Interpretive modeling of PIT-tag data will likely become more accurate and precise, but models will need to be verified using independent data such as provided by radiotelemetry.

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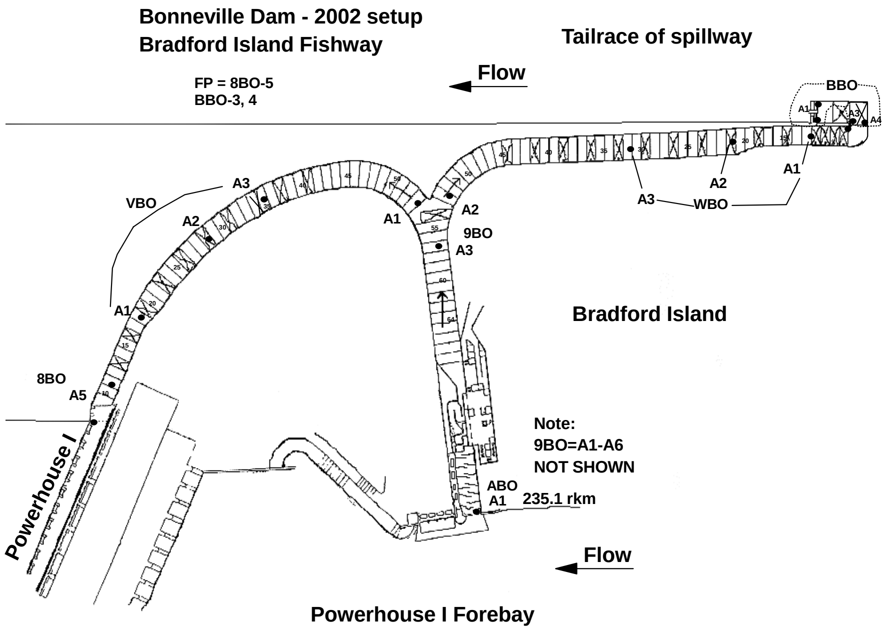
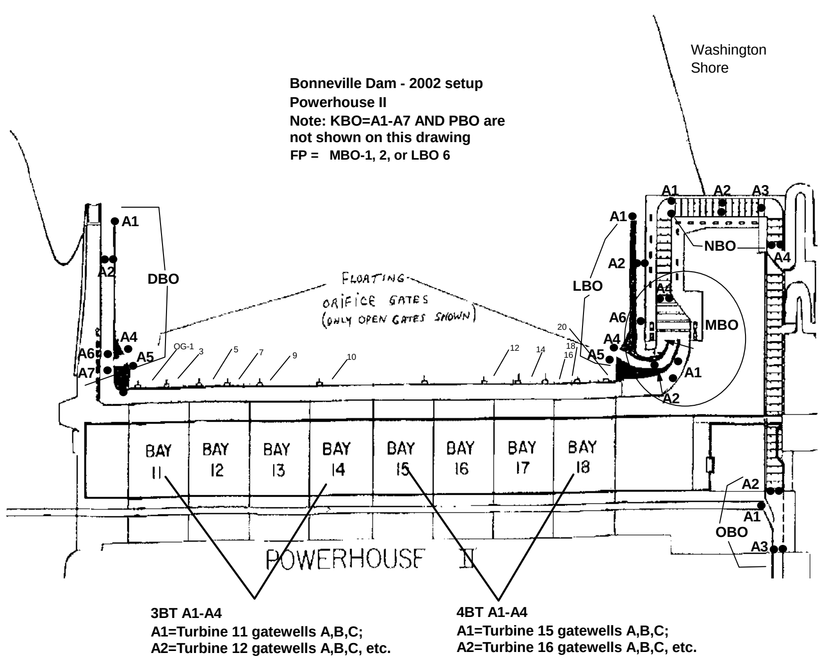
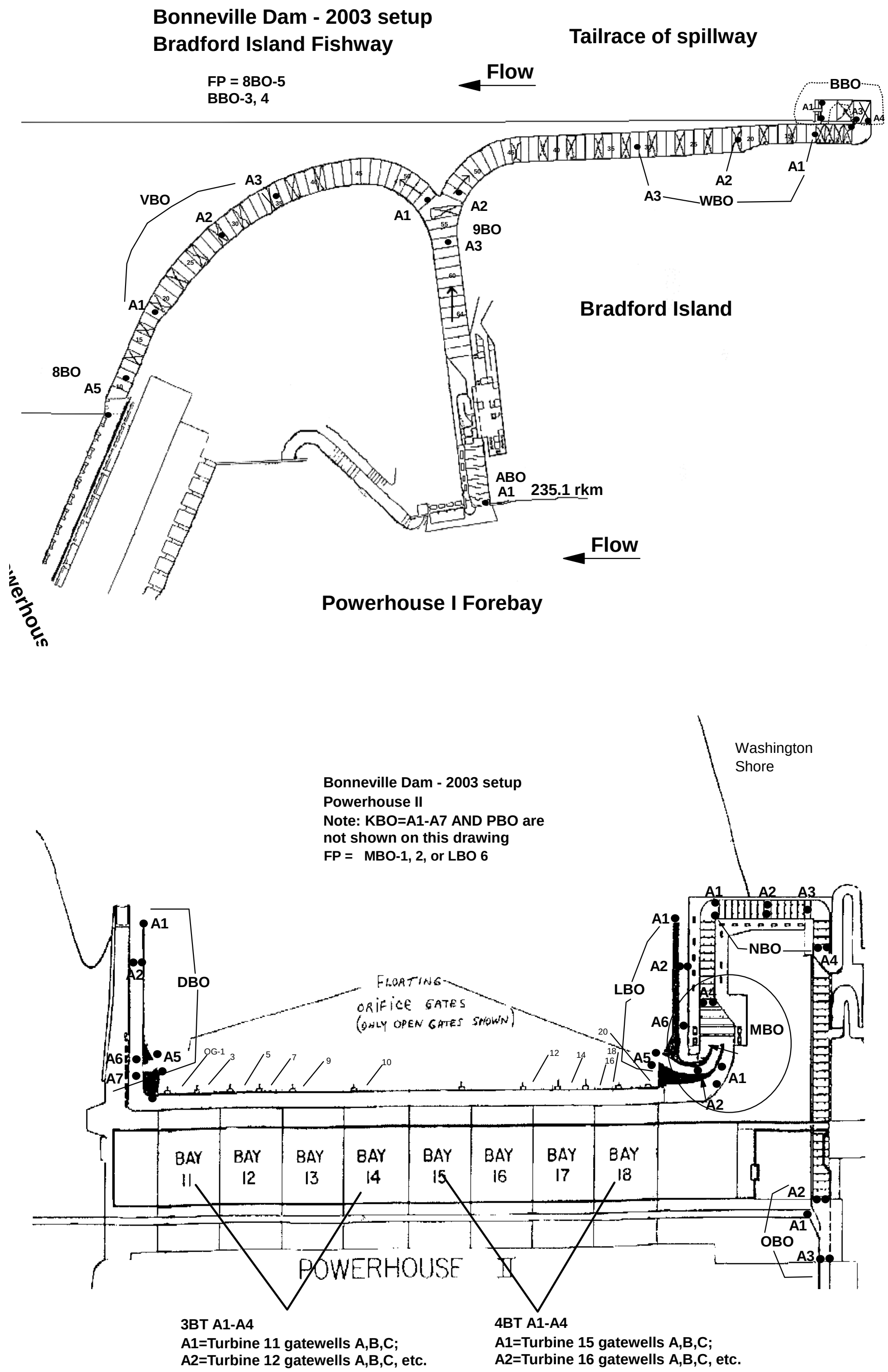
APPENDIX: Radiotelemetry Receiver Locations

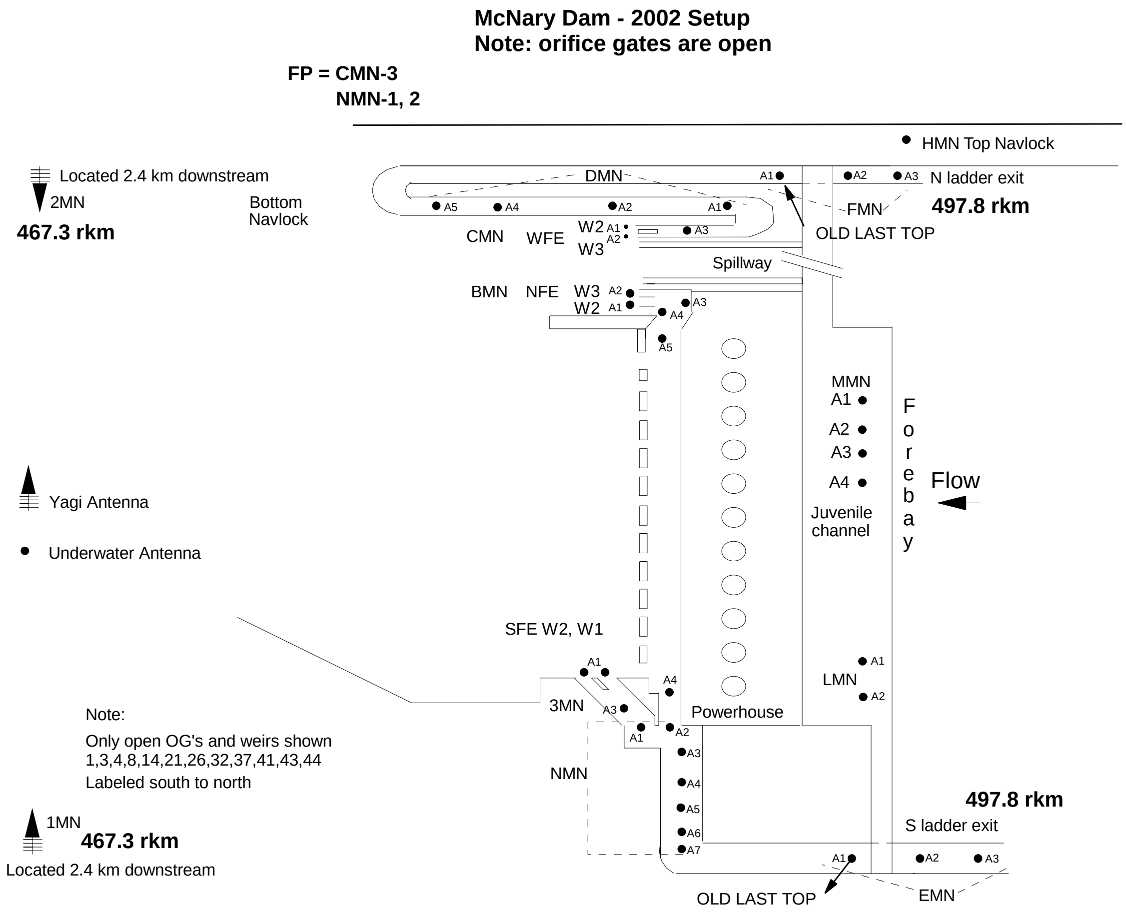




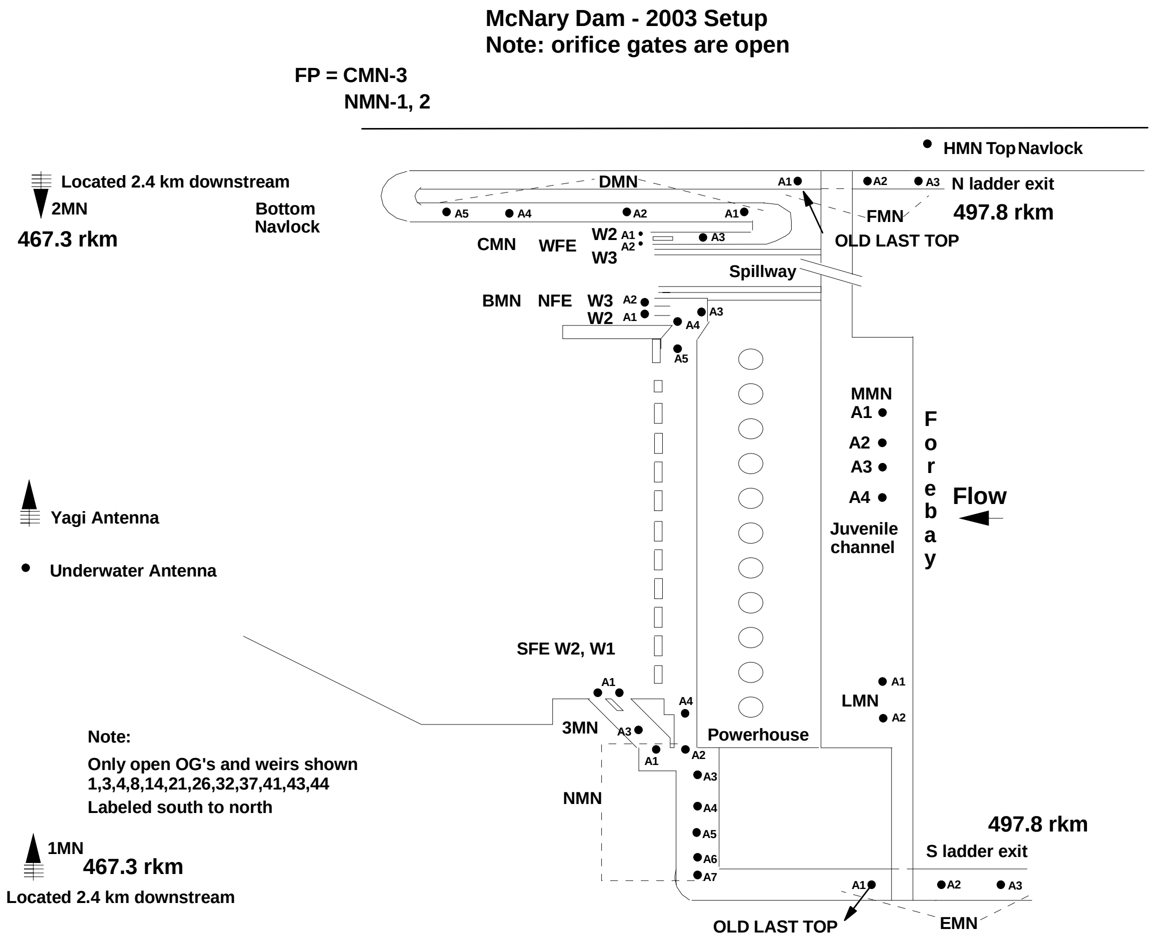
Appendix Figure 1. Radiotelemetry receiver locations in 2002 at Bonneville Dam.



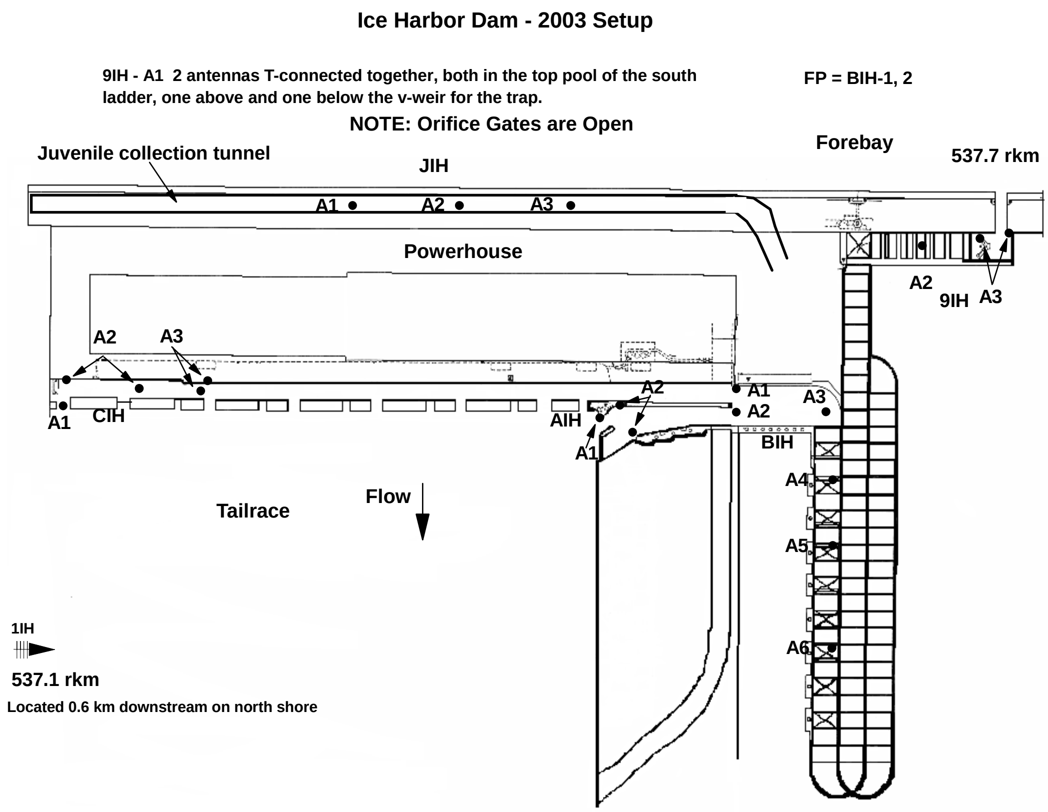
Appendix Figure 2. Radiotelemetry receiver locations in 2003 at Bonneville Dam.

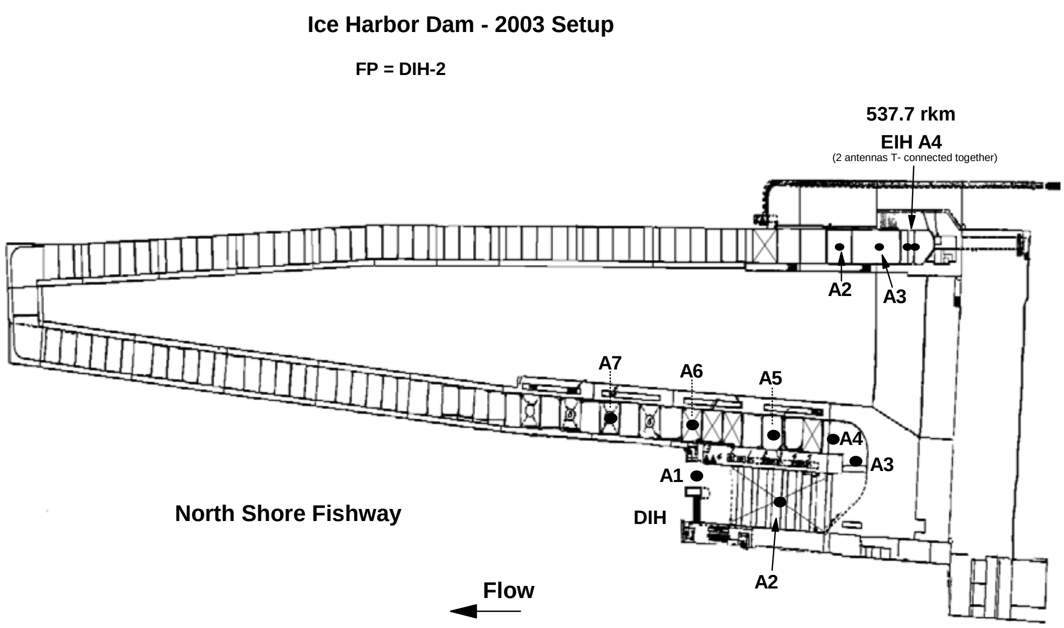


Appendix Figure 3. Radiotelemetry receiver locations in 2003 at McNary Dam.

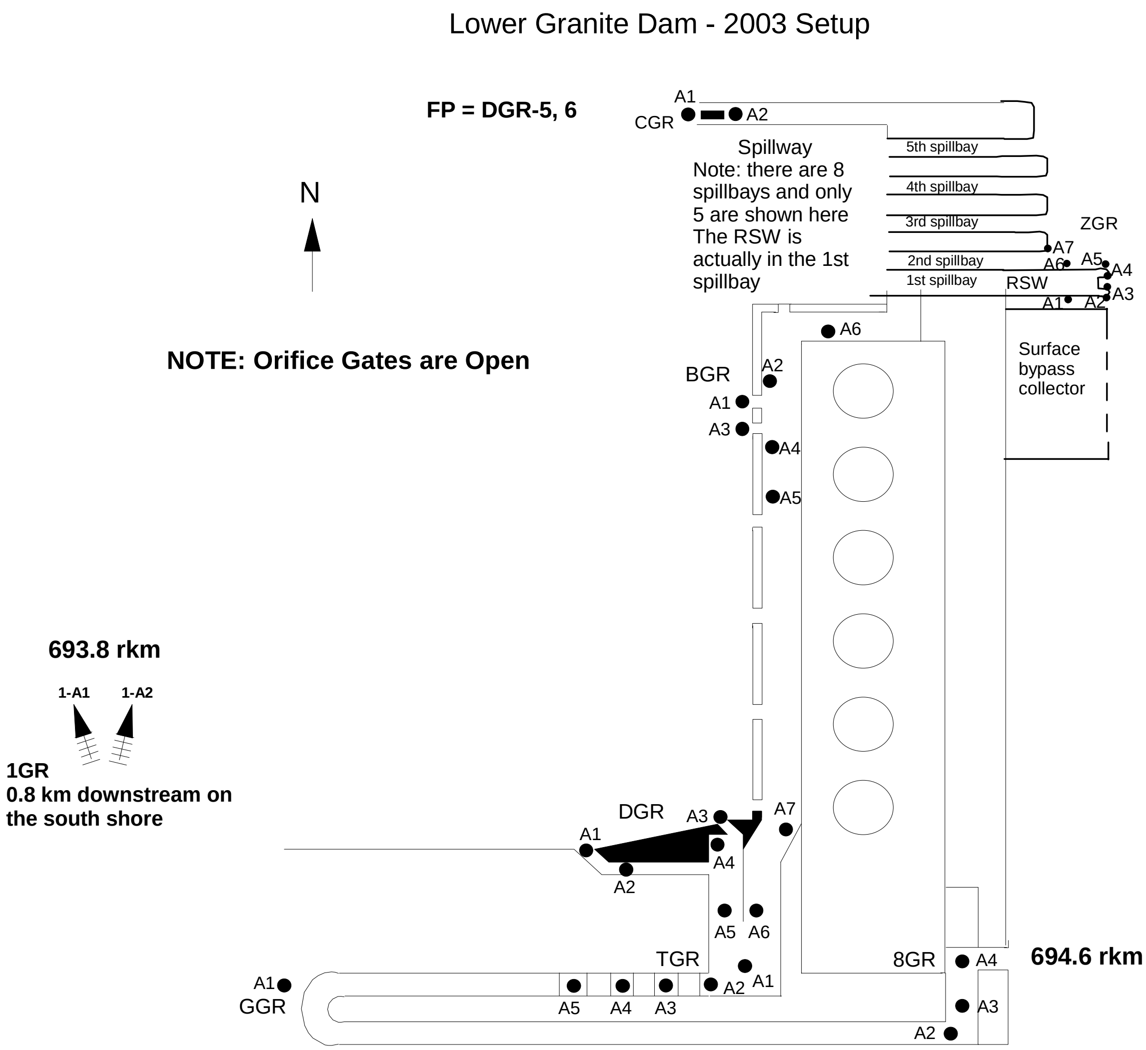


Appendix Figure 4. Radiotelemetry receiver locations in 2002 at McNary Dam.





Appendix Figure 5. Radiotelemetry receiver locations in 2003 at Ice Harbor Dam.



Appendix Figure 6. Radiotelemetry receiver locations in 2003 at Lower Granite Dam.