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Comparison of acoustic and PIT tagged juvenile Chinook, Steelhead and Sockeye Salmon (*Oncorhynchus*, spp.) passing dams on the Columbia River, USA

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Key words: acoustic tags, PIT tags, fish behaviour, fish movement, salmon smolt survival.

Abstract

The purpose of the study was to compare migration behaviour and survival of acoustic and passive integrated transponder (PIT) tagged juvenile salmonids passing dams on the Columbia River, Washington State, USA. Downstream migrating yearling chinook (*Oncorhynchus tshawytscha* Walbaum 1792), steelhead (*Oncorhynchus mykiss* Walbaum 1792), sockeye (*Oncorhynchus nerka* Walbaum 1792), and sub-yearling chinook smolts were individually implanted with either acoustic or PIT tags and monitored at Rocky Reach and Rock Island dams during spring and summer 2002. Travel times and detection rates were compared for acoustic ("A" tag weight 1.0 g and "E" tag weight 1.5 g) and PIT (tag weight 0.06 g) tagged fish released upstream of Rocky Reach Dam and detected at a Surface Collector Bypass Channel and further downstream at the Rock Island Dam project. Surface Collector Bypass Channel efficiencies were very similar for acoustic and PIT tagged fish. Surface Collector Bypass Channel efficiency and harmonic mean travel times for acoustic and PIT tagged smolts, for three different species and two year classes of chinook smolts, were not significantly different (p>0.05) for 13 of 16 comparisons. There were no significant differences between the four comparisons of 1.0 g and 1.5 g acoustic tagged steelhead smolts. Rock Island Dam project survival for PIT tagged ($\hat{S}_{RI} = 0.9555$, $\hat{S}E = 0.0249$) and acoustic tagged ($\hat{S}_{RI} = 0.9520$, $\hat{S}E = 0.0263$) yearling chinook smolts was not significantly different (p>0.05). The acoustic tag survival study required far fewer fish (798) than the PIT tagged survival study (90,000).

Introduction

Migrating juvenile salmon and steelhead (*Oncorhynchus* spp.) runs on the Columbia River (Washington State, USA) and its tributaries have been evaluated using passive integrated transponder (PIT) telemetry techniques over the past 20 years (Prentice *et al*., 1990). PIT tags have been used to study survival, passage route determination, travel time, and smolt behaviour (Muir *et al*., 2001). The results from these PIT telemetry studies are widely accepted and utilized by fisheries agencies and project managers for making smolt passage decisions. One limitation of PIT tag technology is that detection range of PIT tagged fish is approximately 0.30-0.61 m, and for this reason, PIT tag detectors are primarily installed in relatively small bypass pipes and fish ladders.

Acoustic tags have been used recently to study the behaviour and passage routes of migrating juvenile salmon and steelhead (Steig, 2000; Steig and Timko, 2000). Acoustic tags have the advantage that they can be detected over long ranges (up to 900 m) and detection rates are much higher than for PIT tagged fish, thereby reducing the total number of fish required for tagging. In addition, the three-dimension position of acoustically tagged fish can be determined (Ehrenberg and Steig, 2002; 2003). One major difference is that acoustic smolt tags are heavier than PIT tags (0.75-1.5 g in air versus 0.06 g for PIT tags).

Acoustic tags have been used to monitor fish movement for over 50 years (Steig, 2000; Ehrenberg and Steig, 2002). PIT tags have been used extensively since 1996 to determine information about salmon smolts passing Rocky Reach Dam in the mid-Columbia River in central Washington, USA and have been used to estimate proportion of fish bypassed with in-turbine diversion screens and passed through the Surface Collector Bypass Channel. PIT tags have also been used since 1998 to estimate the survival of fish passing through the mid-Columbia River dams, including Rocky Reach and Rock Island dams.

In 2002, studies were conducted to compare behaviour and survival of smolts implanted with acoustic and PIT tags during their outmigration past Rock Reach and Rock Island dams (Fig. 1). Species studied were yearling chinook, steelhead, sockeye, and sub-yearling chinook smolts. Comparisons were made of the travel times and detection rates of acoustic and PIT tagged fish released 40 km upstream of Rocky Reach Dam and detected at the Surface Collector Bypass Channel at the dam (Skalski and Ngouenet, 2002; Steig *et al.*, 2003). In addition, comparisons of smolt survival from the tailrace of Rocky Reach Dam to the tailrace of Rock Island Dam (referred to as "Rock Island Dam project survival") were made for PIT tagged and acoustic tagged yearling chinook salmon smolts using a paired release-recapture study (Skalski *et al.*, 2003) (Fig. 1).

Reports concerning use of acoustic tags with juvenile Pacific salmon are rare, several studies have investigated use of acoustic tags with juvenile

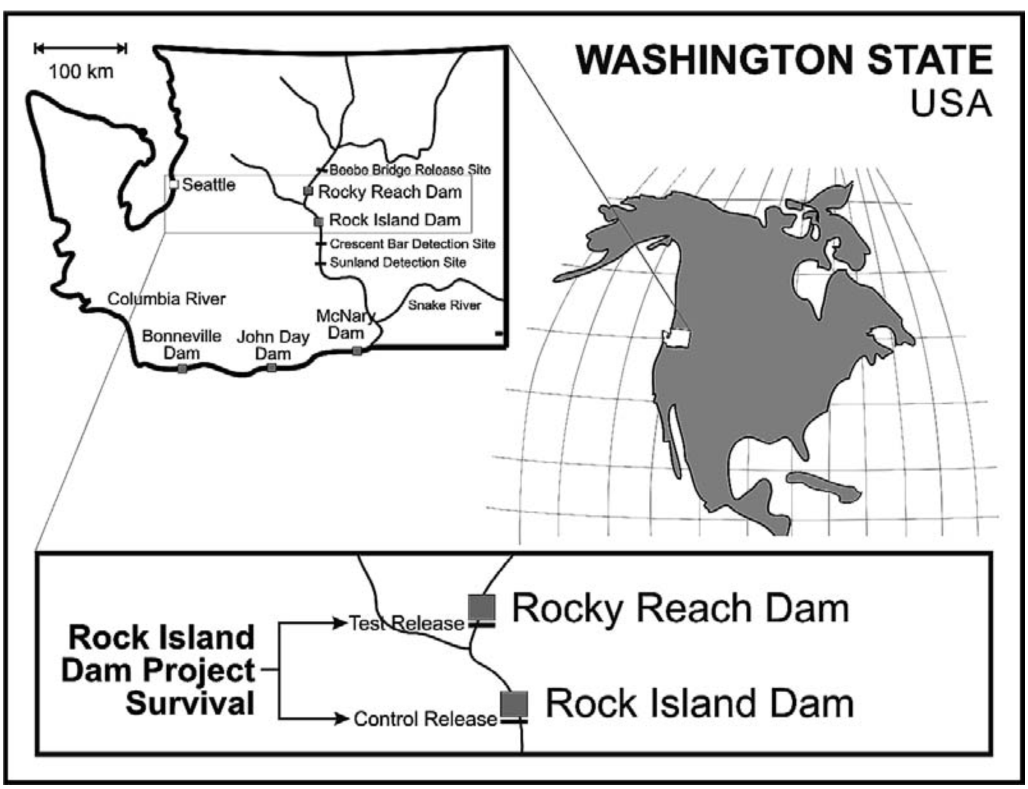


Fig. 1 – Location of release and detection sites on the Columbia River in Washington State, USA. Insert map of the mid-Columbia River basin shows the section of the river evaluated for yearling chinook smolt Rock Island Dam project survival study in 2002.

Atlantic salmon smolts (*S. salar*). Saddle tags significantly affected growth of fish <180 mm in length (Greenstreet and Morgan, 1989). McLeave and Stred (1975) found that both external tags and stomach-borne transmitters significantly reduced swimming speeds of Atlantic salmon smolts, but reduction was far less with internal tags. Surgically implanted tags showed no affect on smolts >120 mm and <190 mm in length (Moore *et al*., 1990). A recent assessment indicated it was feasible to use acoustic tags for three-dimensional positioning of Pacific salmon smolts at Lower Granite Dam (Steig and Timko, 2001). Anglea *et al*. (2004) conducted an investigation to compare the behavioural effects between fish implanted with 1.5 g "E" acoustic tags (up to 6.7% of the fish's body weight) and control fish. Implantation of acoustic tags in juvenile chinook salmon did not significantly affect swimming performance and did not result in greater predation susceptibility than to untagged fish.

Materials and methods

Study site

Rocky Reach Dam is located on the Columbia River, 11 km north of Wenatchee, Washington at river km 764 (Fig. 1). The dam's spillway is perpendicular and its powerhouse parallel to river flow (Fig. 2). During the 2002 Rocky Reach Dam behaviour study, PIT and acoustic tagged fish were released 40 river km upstream at Beebe Bridge (river km 803), in the center of the river. The Surface Collector Bypass Channel at Rocky Reach Dam was instrumented with four, 61 cm diameter circular coil PIT tag detectors spaced approximately 1.2 m apart. Similarly, the Surface Collector Bypass Channel was also instrumented with six acoustic tag hydrophones.

Rock Island Dam is located on the Columbia River at river km 729, 24 km southeast of Wenatchee, Washington and 35 km downstream of Rocky Reach Dam (Fig. 1). During the 2002 Rock Island Dam project survival study, PIT and acoustic tagged fish were released in the tailraces of Rocky Reach and Rock Island dams, in the center of the river. The PIT tagged fish were detected at juvenile collection facilities at McNary, John Day, and Bonneville dams, 262, 384, and 495 km downstream of Rock Island Dam, respectively that were instrumented with PIT tag detectors (Fig. 1). There were two downstream open river acoustic tag sampling sites located at Crescent Bar and Sunland Estates (Fig. 1). An array of evenly spaced hydrophones was placed in a straight line across the river at Crescent Bar and Sunland Estates used five and six hydrophones, respectively. A small trailer on the shore of the river at both detection sites housed the acoustic receivers.

Tagging

HTI *Model 795 Acoustic Tags* used during this study were 307 kHz encapsulated omni-directional pingers. The "E" tags were 20 mm long, 6.6 mm in diameter, and the weight in air was 1.5 g and 0.95 g in water. The in-water weight is important because that is the extra weight expressed by the tagged fish. The "A" tags were 17 mm long, 6.6 mm in diameter and the weight in air was 1.0 g and 0.55 gm in water. The only difference is that "A" tags are smaller and lighter than the "E" tags. Transmit power level for both the "A" and "E" tags were approximately 155 dB μPa @ 1 m. The acoustic tag pulse rates and pulse widths were programmable. The tags used in the 2002 study utilized standard CW pulses. Nominal pulse rate was 3.5-6.0 sec/pulse with a transmit pulse width of 0.5 msec. The useful life of the tag, once activated, averaged 28 days for the "E" tags and 14 days for the "A" tags.

PIT tags utilized in this study operated at a frequency of 134.2 kHz and were suitable for use with circular 30.5 cm and 61.0 cm diameter PIT tag detectors. PIT tags were 11.5 mm long, 2.1 mm in diameter and weighed approximately 0.06 g. The PIT tags had an operating temperature range of -40 to 70º C.

Fish handling procedures for the 2002 study were consistent with protocols used during the 1999, 2000, and 2001 juvenile survival evaluations. Fish selected for tagging were yearling and sub-yearling chinook (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), and sockeye smolts

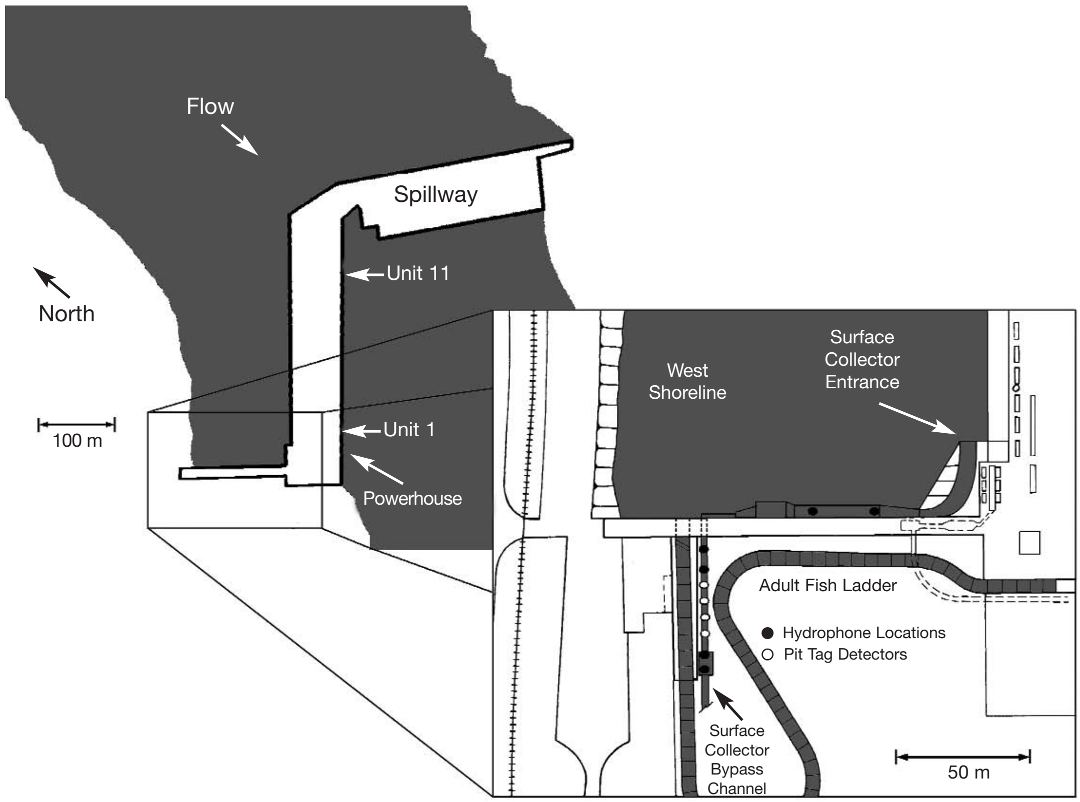


Fig. 2 – Plan view showing the orientation of Rocky Reach Dam on the Columbia River. The expanded plan view shows the hydrophone mounting locations and PIT tag detectors at the Surface Collector Bypass Channel at Rocky Reach Dam in 2002.

(*Oncorhynchus nerka*). Fish were collected from the Rocky Reach Dam Surface Collector Bypass Channel for the behavioural study and from the Turtle Rock Hatchery Facility for the survival study. Fish collected at the Surface Collector Bypass Channel were a combination of hatchery fish stocks (yearling chinook and steelhead) and natural fish stocks (yearling and sub-yearling chinook, steelhead, and sockeye). The fish were collected and transported to the tagging sites at both dams. Throughout the transport, dissolved oxygen levels were monitored and maintained between 7 and 12 ppm. Fish were held overnight after collection for recovery from handling stress prior to tagging. Fish were transferred from the holding tank to a tank containing a 100 mgl^{-1} solution of MS222. Fish were then placed into a V-shaped cradle and swabbed with iodine at the incision site. Acoustic tags were implanted through a 1 cm incision between the pectoral and pelvic fins, slightly off the mid-ventral line. The incision was closed with 2-3 internally knotted sutures followed by another application of iodine at the incision. Fish were placed into a recovery bucket prior to being returned to the holding tanks. PIT tags were implanted into the fish using standard methods as described by Prentice *et al*. (1990). All acoustic and PIT tagged fish were held together in 275-gallon tanks and supplied with fresh, de-nitrified river water throughout the holding period. All tagged fish were held up to 48 h prior to release to ensure fish survival, tag operation, and tag retention.

The acoustic receiver used for this study was the HTI *Model 290 Acoustic Tag Receiver;* designed to receive signals from up to 16 separate hydrophones. Signals received were synchronized in order to determine time of arrival for each detected pulse. Arrival time of the pulse at each hydrophone was used to determine the relative position of the tagged fish between hydrophones.

Rocky Reach Dam Behavioural Study

The Rocky Reach Dam behavioural study allowed for direct comparison between PIT-tagged fish and the two acoustic type tagged fish, since the Surface Collector Bypass Channel was equipped with both PIT tag detectors and acoustic tag hydrophones. Each tag type was tested for equal harmonic mean travel times. The mean travel time was computed using the harmonic mean ($\bar{t}_H$) calculated as follows:

$$\bar{t}_H = \frac{1}{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{t_i}} = \frac{n}{\sum_{i=1}^{n}\frac{1}{t_i}} \quad (1)$$

where

t_i=travel time from release to Rocky Reach Dam for the *i*th smolt recovered (i=1,...,n).

The variance for the harmonic mean travel time can be estimated by

$$\hat{Var}(\bar{t}_H) = \frac{\left(\frac{s^2_{1/t}}{n}\right)}{\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{t_i}\right)^4} \quad (2)$$

where

$$s^2_{1/t} = \frac{\sum_{i=1}^{n}\left(\frac{1}{t_i} - \hat{u}_{1/t}\right)}{(n-1)}, \quad (3)$$

$$\hat{u}_{1/t} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{t_i} \quad (4)$$

Asymptotic (1-α) 100% confidence interval for harmonic mean travel time was computed as:

$$\overline{t_H} \pm Z_{1-\frac{\alpha}{2}}\sqrt{\hat{Var}(\overline{t_H})} \quad (5)$$

for both PIT and acoustic tagged smolts.

The statistical test of equal mean travel times for both tag types was performed using the Z-test of the form:

$$Z = \frac{\bar{t}_{H-PIT} - \bar{t}_{H-AT}}{\sqrt{\hat{Var}(\bar{t}_{H-PIT}) + \hat{Var}(\bar{t}_{H-AT})}}. \quad (6)$$

Comparisons were also tested for independence of relative Surface Collector Bypass Channel efficiencies and arrival distributions using RxC contingency table tests (Skalski and Ngouenet, 2002; Zar, 1984).

Tagged fish releases occurred approximately 40 river km upstream of Rocky Reach Dam at Beebe Bridge (Fig. 1), in the center of the river. There were a total of 20 release groups, with 6 groups of yearling chinook, 10 groups of steelhead (5 each for the "A" and "E" tags), and 2 groups each of sockeye and sub-yearling chinook (Table 1).

A total of 472 acoustic tags were used during this study with 99 yearling chinook using "E" tags, 98 steelhead using "E" tags, 95 steelhead using "A" tags, 86 sockeye using "A" tags, and 94 sub-yearling chinook using "A" tags (Tables 1 and 2).

A total of 2,945 PIT tags were used during this study with 897 yearling chinook, 869 steelhead, 582 sockeye, and 597 sub-yearling chinook.

For statistical analyses, the yearling chinook and steelhead data were combined for time periods corresponding to the first half of the study (24 April through 5 May) and the last half of the study (17 through 26 May).

Acoustic "E" tagged fish lengths ranged between 145-200 mm (mean=165 mm) for yearling chinook and 150-220 mm (mean=193 mm) for steelhead smolts. Acoustic "A" tagged fish lengths ranged between 155-225 mm (mean=193 mm) for steelhead smolts, 116-150 mm (mean=136 mm) for sockeye smolts, and 120-152 mm (mean=127 mm) for sub-yearling chinook. PIT tagged fish lengths ranged between 105-210 mm (mean 141 mm) for yearling chinook, 125-235 mm (mean=193 mm) for steelhead smolts, 106-154 mm (mean=114 mm) for sockeye smolts, and 100-156 mm (mean=115 mm) for sub-yearling chinook.

The acoustic tag and PIT tag study designs compared six unique combinations of tag type (PIT tag, acoustic “E” tag, and acoustic “A” tag) and fish species (yearling chinook, steelhead, sockeye, and sub-yearling chinook), and study period, listed below and shown graphically in Table 2:

Table 1– Releases of tagged fish upstream of Rocky Reach Dam at Beebe Bridge in 2002 (release dates, locations, fish species, tag-types, and sample sizes).

	Yearling Chinook		Steelhead			Sockeye		Sub-Yearling Chinook	
Release Date	Acoustic "E"	PIT	Acoustic "A"	Acoustic "E"	PIT	Acoustic "A"	PIT	Acoustic "A"	PIT
24/04/02	17	150	16	16	82				
28/04/02	17	149	14	16	112				
03/05/02	17	149							
08/05/02						42	284		
12/05/02						44	298		
17/05/02	18	150	20	21	225				
22/05/02	15	149	25	22	225				
26/05/02	15	150	20	23	225				
12/07/02								45	300
19/07/02								49	297
Totals	99	897	95	98	869	86	582	94	597

a) comparison of PIT tagged versus acoustic “E” tagged yearling chinook (a_1, and a_2, Table 2);
b) comparison of PIT tagged versus acoustic “E” tagged steelhead (b_1, and b_2, Table 2);
c) comparison of PIT tagged versus acoustic “A” tagged steelhead (c_1, and c_2, Table 2);
d) comparison of acoustic “A” tagged versus acoustic “E” tagged steelhead (d_1, and d_2, Table 2);
e) comparison of PIT tagged versus acoustic “A” tagged sockeye (e_1, Table 2);
f) comparison of PIT tagged versus acoustic “A” tagged sub-yearling chinook (f_1, Table 2).

Rock Island Dam Project Survival

Project survival for the Rock Island Dam study was estimated by a paired release-recapture design. Rocky Reach tailrace releases were paired with Rock Island tailrace releases (Fig. 1). Releases occurred over 45 days, with 18 releases at each site, and included mixed groups of acoustic and PIT tagged smolts with approximately 22 acoustic tagged smolts (18x22; ≈400 per site) and approximately 2,500 PIT tagged smolts (18x2,500; ≈45,000 per site) in each release.

All releases occurred at approximately 08:00 each morning. Release-specific survival probabilities were computed for each paired-release. Study performance was measured by the average survival probability estimated across the 18 replicate releases. The project survival was estimated using the paired release-recapture models of Burnham *et al*. (1987).

The Rock Island Dam project results consisted of PIT tag and acoustic tag survival estimates. The analysis consisted of three elements: (a) tests of assumptions, (b) model fitting, and (c) estimation of project survival based on the paired-release design. Detailed methods and analysis are presented in Skalski *et al*. (2003).

The Rocky Reach Dam tailrace releases totaled 45,001 PIT and 399 acoustically tagged yearling chinook. The Rock Island Dam tailrace releases totaled 44,999 PIT and 399 acoustically tagged yearling chinook.

Table 2 – Statistically compared tag types and release groups of tagged fish upstream of Rocky Reach Dam in 2002.

Species	Beebe Bridge Releases (Rocky Reach Dam Detection Site)			
	Acoustic-E	Acoustic-A	PIT-Tag	
24 April - 3 May				
Chinook-1	51		448	a_1: Acoustic-E – PIT-Tag
17 May - 26 May				
Chinook-1	48		449	a_2: Acoustic-E – PIT-Tag
24 April - 28 April				
Steelhead	32	30	194	b_1: Acoustic-E – PIT-Tag; d_1: Acoustic-E – Acoustic-A; c_1: Acoustic-A – PIT-Tag
17 May - 26 May				
Steelhead	66	65	675	b_2: Acoustic-E – PIT-Tag; d_2: Acoustic-E – Acoustic-A; c_2: Acoustic-A – PIT-Tag
8 May - 12 May				
Sockeye		86	582	e_1: Acoustic-A – PIT-Tag
12 July - 19 July				
Chinook-0		94	597	f_1: Acoustic-A – PIT-Tag

Table 3 – Acoustic and PIT tagged detection results for the 2002 Rocky Reach Dam study. Note that the detection rates are based on Surface Collector Bypass Channel tag detectors.

Tagged Fish Species	Tag Type	Total Fish Last Detected at Surface Collector	Total Fish Released	Percent Fish Last Detected at Surface Collector (%)
Yearling Chinook	PIT	157	897	17.50
Yearling Chinook	Acoustic “E”	23	99	23.23
Steelhead	PIT	251	869	28.88
Steelhead	Acoustic “E”	29	98	29.59
Steelhead	Acoustic “A”	26	95	27.37
Sockeye	PIT	23	582	3.95
Sockeye	Acoustic “A”	3	86	3.49
Sub-Yearling Chinook	PIT	14	597	2.35
Sub-Yearling Chinook	Acoustic “A”	5	94	5.32

Results

Rocky Reach Dam Behavioural Study

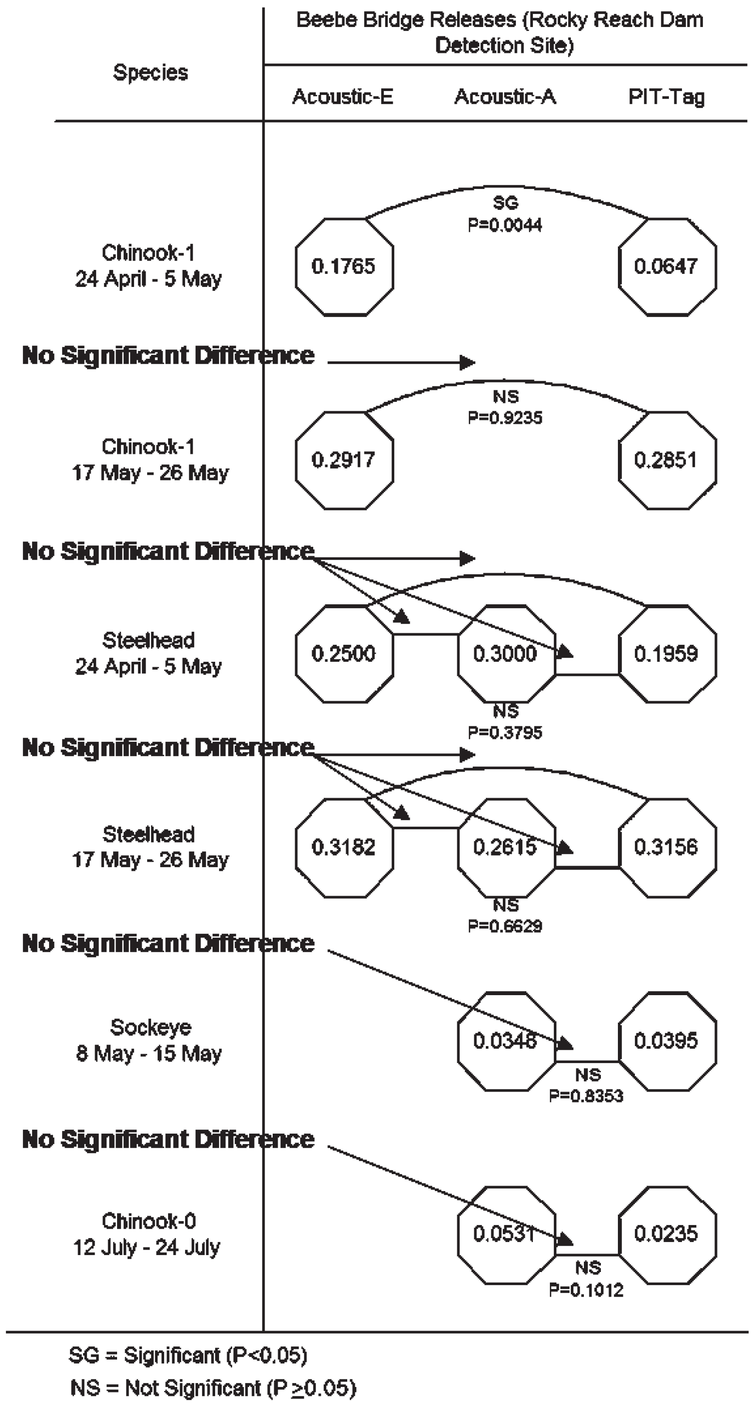
Percent of acoustic and PIT tagged fish detected at the Rocky Reach Dam Surface Collector Bypass Channel for each release is summarized in Table 3. Overall, Surface Collector Bypass Channel efficiencies were similar between acoustic and PIT tagged fish. Steelhead smolt collection efficiencies were 27%, 30%, and 29% for the acoustic “A”, acoustic “E”, and PIT tagged fish, respectively. Sockeye smolt collection efficiencies were similar for acoustic “A” tagged fish (3%) and PIT tagged fish (4%). Sub-yearling chinook smolt collection efficiencies were 5% and 2% for acoustic “A” and PIT tagged fish, respectively. Yearling chinook smolt collection efficiencies were slightly greater for the acoustic “E” tagged fish (23%) compared to the PIT tagged fish (17%).

Relative Surface Collector Bypass Channel collection efficiency for acoustic and PIT tagged fish indicated 9 of 10 tag type comparisons were not significantly different (P>0.05) (Table 4). Yearling chinook smolts released between 17 May and 26 May, steelhead, sockeye, and sub-yearling chinook collection efficiencies were not significantly different (P>0.05) between acoustic and PIT tagged fish. In addition, steelhead collection efficiencies were not different (P>0.05) between acoustic “A” and “E” acoustically tagged fish. Yearling chinook released between 24 April and 3 May were the only group found to have significantly different (P=0.0044) collection efficiencies (18% for acoustic tags, 6% for PIT tagged fish).

Mean harmonic travel times from release at Beebe Bridge to detection at Rocky Reach Dam indicated 8 of 10 tag type comparisons were not significantly different (P>0.05) (Table 5). Yearling chinook, sockeye, and sub-yearling chinook travel times were not significantly different (P>0.05) between acoustic and PIT tagged fish. Steelhead travel times were not significantly different (P>0.05) between acoustic “A” and “E” tagged fish. Steelhead released 24 April-28 April showed significantly different (P=0.0041) travel times between acoustic “A” and PIT tagged fish, but not between acoustic “E” and PIT tagged fish while steelhead released 17 May-26 May showed significantly different (P=0.0328) travel times between acoustic “E” and PIT tagged fish, but not between acoustic “A” and PIT tagged fish.

In summary, the statistical results showed that tagged fish were guided in similar proportions and with similar harmonic mean travel times, independent of tag type (PIT and acoustic) or tag size (acoustic “A” and “E”).

Table 4 – Summary of relative Surface Collector Bypass Channel efficiency comparing tag types (acoustic "E", "A", and PIT tagged fish). Dates, locations, fish species, and tag-types are presented for the various release groups. Comparisons denoted by lines are labeled with their level of statistical significance.



Rock Island Dam Project Survival

Survival estimates, obtained utilizing 90,000 PIT tagged yearling chinook smolts and 798 acoustic tagged yearling chinook smolts, indicated that Rock Island Dam project survival for PIT tagged and acoustic tagged fish were in close agreement (Table 6). An arithmetic average across the two methods provided an estimate of project survival of ($\hat{S}_{RI} = 0.9538$, $\hat{SE} = 0.0146$).

Table 5 – Summary of the harmonic mean travel times from release to detection (in days) comparing acoustic "E", "A", and PIT tagged fish. Dates, locations, fish species, and tag-types are presented for the various release groups. Comparisons denoted by lines are labeled with their level of statistical significance from tests of homogeneity.

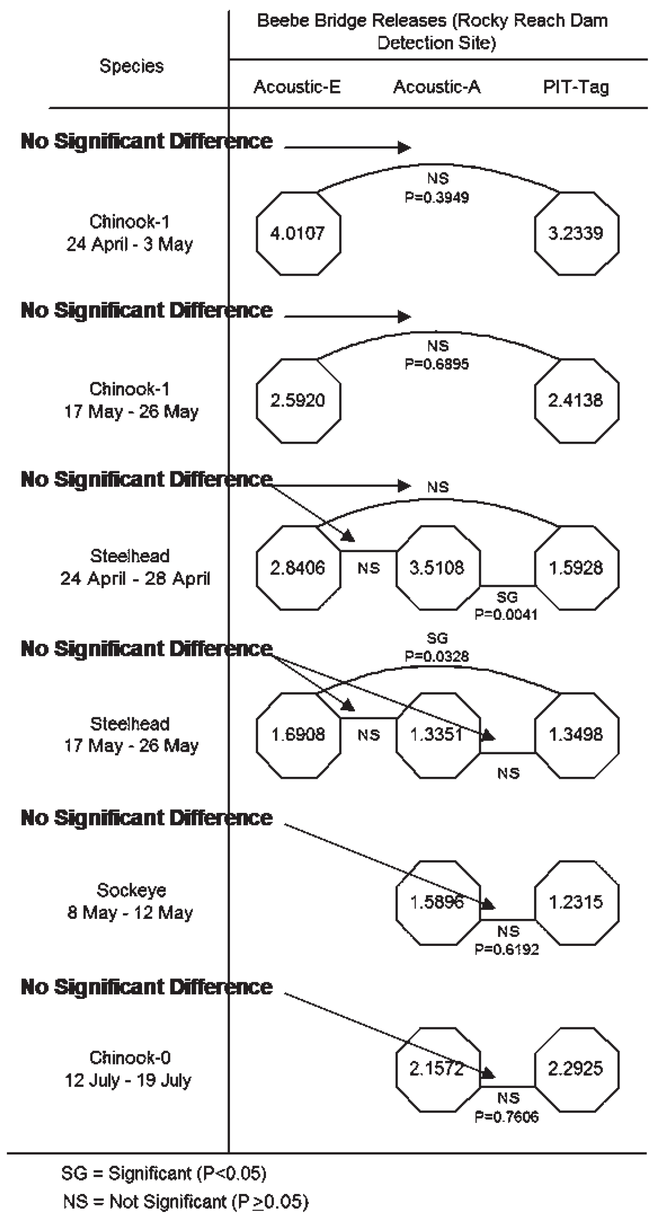


Table 6 – Results of yearling chinook smolts at Rock Island Dam in 2002 comparing PIT and acoustic tag results for project survival, standard error, and number of fish tagged.

PIT Tagged Fish Project Survival (Weighted Average)	PIT Tagged Fish Project Survival (Standard Error)	Number of PIT Tagged Fish
0.9555	0.0249	90,000
Acoustic Tagged Fish Project Survival (Weighted Average)	**Acoustic Tagged Fish Project Survival (Standard Error)**	**Number of Acoustic Tagged Fish**
0.9520	0.0263	798

Conclusion

Comparable study results were obtained between 1.0 g ("A") acoustic, 1.5 g ("E") acoustic, and PIT tagged fish. Acoustic tagged and PIT tagged yearling chinook salmon, steelhead, sockeye, and sub-yearling chinook smolts demonstrated similar migration dynamics as measured by survival, travel time and collection efficiencies at hydroelectric projects. In many applications, acoustic tags may utilize far fewer tags and fish to provide similar precision compared to PIT tags. Specific findings conclude the following.

1. The relative Surface Collector Bypass Channel efficiency and the harmonic mean travel times at Rocky Reach Dam comparing acoustic and PIT tagged fish for the 3 different species of salmon smolts and 2 year classes for chinook smolts were not significantly different ($P>0.05$) for 13 out of the 16 comparisons. In addition, there were no significant differences between the 1.0 g ("A") and the 1.5 g ("E") acoustic tags.
2. There was no significant difference between the survival estimates for acoustic or PIT tagged juvenile chinook smolts through the Rock Island Dam Project.
3. The acoustic tag survival study used 89,202 fewer chinook smolts to produce almost identical precision as the PIT tag survival study (798 versus 90,000, or <1%).

We conclude that acoustic tagged fish provide an effective alternative with comparable estimates to PIT tag survival studies. In addition, acoustic tags provide route specific fish passage results and three-dimensional fish paths. Acoustic tags also provide an effective alternative to PIT tag studies that may be advantageous when sample sizes are restricted as in the case of endangered or threatened species.

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