July 2000

THE DESIGN AND ANALYSIS OF SALMONID TAGGING STUDIES IN THE COLUMBIA BASIN

Volume XV: Appraisal of the Relationship between Tag Detection Efficiency at Bonneville Dam and the Precision of In-River Survival Estimates of Returning PIT-tagged Chinook Salmon

Technical Report 2000

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The Design and Analysis of Salmonid Tagging Studies in the Columbia Basin

Volume XV

Appraisal of the Relationship between Tag Detection Efficiency at Bonneville Dam and the Precision of In-River Survival Estimates of Returning PIT-tagged Chinook Salmon

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PREFACE

Project 8910700, Epidemiological Survival Methods, was developed to provide statistical guidance on design and analysis of PIT-tag (Passive Integrated Transponder) survival studies to the Northwest fisheries community. Studies under this project have determined the statistical feasibility of conducting PIT-tag smolt survival studies, assessed analytical capabilities for analyzing the tagging experiments, and made recommendations on study design. As PIT-tag capabilities developed and research interests increased, the project has been instrumental in maintaining the statistical capabilities for designing and analyzing tagging studies to meet these expanded objectives.

In the advent of the installation of a PIT-tag interrogation system in the Cascades Island fish ladder at Bonneville Dam, this report provides guidance on the anticipated precision of in-river survival estimates for returning adult salmonids, at various levels of system-wide adult detection probabilities at Bonneville Dam. This report evaluates the overall detection probability needed for a PIT-tag adult detection system at Bonneville Dam, powerhouses 1 and 2 to obtain precise estimates of in-river survival between Bonneville and Lower Granite dams for returning adult salmon. It calculates precision based on anticipated downstream survival and detection probabilities of chinook salmon smolts and their anticipated ocean and in-river survival back to Bonneville and Lower Granite Dam. The findings presented in this report complement those presented in volume XIV of this report series (Perez-Comas and Skalski, 2000*b*).

ABSTRACT

In the advent of the installation of a PIT-tag interrogation system in the Cascades Island fish ladder at Bonneville Dam, this report provides guidance on the anticipated precision of in-river survival estimates for returning adult salmonids, between Bonneville and Lower Granite dams, for various levels of system-wide adult detection probability at Bonneville Dam. Precision was characterized by the standard error of the survival estimates and the coefficient of variation of the survival estimates. The anticipated precision of in-river survival estimates for returning adult salmonids was directly proportional to the number of PIT-tagged smolts released and to the system-wide adult detection efficiency at Bonneville Dam, as well as to the in-river juvenile survival above Lower Granite Dam. Moreover, for a given release size and system-wide adult detection efficiency at Bonneville Dam, higher estuarine and marine survival rates also produced more precise survival estimates. With a system-wide detection probability of $P_{\mathrm{BA}} = 1$ at Bonneville Dam, the anticipated *CV*s for in-river survival estimate ranged between 9.4 and 20% with release sizes of 10,000 smolts. Moreover, if the system-wide adult detection efficiency at Bonneville Dam is less than maximum (i.e., $P_{\mathrm{BA}} < 1$), precision of $CV \leq 20\%$ could still be attained. For example, for releases of 10,000 PIT-tagged fish a *CV* of 20% in the estimates of in-river survival for returning adult salmon could be reach with system-wide detection probabilities of $0.2 \leq P_{\mathrm{BA}} \leq 0.6$, depending on the tagging scenario.

EXECUTIVE SUMMARY

Objectives

The overall detection probability needed for a PIT-tag adult detection system at Bonneville Dam, powerhouses 1 and 2, was evaluated in this report. The anticipated precision of salmonid survival estimates for the upstream passage of returning adults between the Bonneville adult ladders and Lower Granite Dam was calculated. Precision was characterized by the standard error of the survival estimates $\left(\text{i.e., } S\hat{E}\left(\hat{S}_{\text{BA-GRA}}\right)\right)$ and the coefficient of variation of the survival estimates $\left(\text{i.e., } CV\left(\hat{S}_{\text{BA-GRA}}\right) = S\hat{E}\left(\hat{S}_{\text{BA-GRA}}\right) / \hat{S}_{\text{BA-GRA}}\right)$. Precision was calculated based on anticipated downstream survival and detection probabilities of chinook salmon smolts and their anticipated ocean and inriver survival back to Bonneville and Lower Granite Dam.

Results

There was a direct proportionality between precision and release size, and between precision and system-wide detection efficiency of adult salmon at Bonneville Dam (Fig. 3-5). The anticipated precision (i.e., *CV*) of in-river survival estimates for adult salmon was directly proportional to the in-river juvenile survival $S_{\text{R-LGR}}$. Moreover, for a given release size and system-wide adult detection efficiency, higher estuarine and marine survivals did also produce more precise survival estimates.

With a system-wide detection probability of $P_{\text{BA}} = 1$ at Bonneville Dam, the anticipated *CV*s for in-river survival estimates of adult salmon ranged between 9.4 and 20% with release sizes of 10,000 smolts above Lower Granite Dam. With release sizes of 30,000 smolts, the *CV* for adult-salmon survival estimates decreased to 5.4-11.6% (Table 1). Moreover, with release sizes of 30,000 smolts, *CV*'s of 20% could still be obtained if the adult detection system at Bonneville Dam were to operate at less than full efficiency (e.g., $0.1 \le P_{\text{BA}} \le 0.3$; Table 2). Although the expected precision of in-river survival estimates for returning adult salmon was acceptably good, the precision of estuarine and marine survival estimates for the same returning fish would be much lower (41% < *CV* < 88% for releases of 10,000 smolts; Perez-Comas and Skalski, 2000*b*).

Recommendations

If the only purpose of a study on survival of Snake-Columbia chinook salmon is to obtain precise estimates of in-river survival between Bonneville and Lower Granite dams for returning adult salmon, then the system-wide detection rates Bonneville Dam could be $0.1 \leq P_{BA} \leq 0.6$ depending on release sizes and scenario characteristics. If, on the other hand, both ocean and in-river survivals for returning adults are to be estimated, then the detection system at Bonneville Dam must be designed to provide adequate precision (e.g., $CV \leq 20\%$) for both estimates. Because the requirements for studying ocean survival are more demanding, the detection system must be designed for this more sensitive objective of estimation. In which case, the PIT-tag detection system to be installed at the adult ladders of Bonneville Dam must be designed for maximum attainable detection efficiency (i.e., $P_{BA} = 1$), and releases kept at least at 55,000 PIT-tagged juveniles. Furthermore, the detection system at Bonneville Dam should be designed with both Powerhouses 1 and 2 in mind. A detection facility at only one powerhouse will produce overall detection probabilities at Bonneville Dam that are likely too low to provide precise studies of ocean survival of Snake-Columbia River salmonids.

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1. INTRODUCTION

Since 1993, the National Marine Fisheries Service (NMFS) and the University of Washington have applied a marked-recapture single-release model (Cormack 1964, Jolly 1965, Seber 1965) to produce reliable survival estimates for specific groups of PIT[1]-tagged yearling salmonids (Iwamoto et al. 1994). The majority of these estimates correspond to juvenile salmonids passing through Snake River dams and reservoirs during their downstream migration. Very little has been published in terms of juvenile survival through the reaches between McNary and Bonneville Dams (e.g., Smith et al., 2000; Perez-Comas and Skalski, 2000), and, to our knowledge, no estimation of estuarine and marine survival ($S_{\text{BON-B2A}}$) based on PIT-tagged salmonids has been attempted yet. Currently, adult salmon are only being interrogated in 31-cm pipes at the adult monitoring facilities of Lower Granite and Bonneville Dams.

BPA project 8331900 attempts to change the present situation by replacing the current network of 400-kHz PIT-tag interrogation systems with a 134.2-kHz ISO-based system. The longer read range of the 134.2-kHz tags, and the new data recovery scheme and silicon technology of the ISO-based system will enable the detection of returning adult salmon at several locations associated with fish ladders. By taking advantage of the enhanced performance of the ISO-based system, the NMFS is developing interrogation systems in a variety of locations in fish ladders. Its initial work has concentrated on the detection in fish ladder orifices, and the installation of a PIT-tag interrogation system that covers orifices in a maximum of four weirs in the Cascades Island fish ladder at Bonneville Dam is expected for 2001. Determining tag-reading efficiency using a suite of tools, including neutrally buoyant fish surrogates, PIT-tags, radio tags and video is among the tasks associated with the installation of this new adult detection system at Bonneville Dam.

In this report, we provide guidance on the expected precision of estimates of the in-river survival of returning adult PIT-tagged chinook salmon between Bonneville and Lower Granite dams as a function of various levels of adult detection efficiency at Bonneville Dam. This report complements our previous study (Perez-Comas and Skalski, 2000*b*) on the expected precision of estuarine and marine survival estimates of returning adult PIT-tagged chinook salmon. Hence, the present analysis was based on the same six simulated scenarios used in our previous study (Perez-Comas and Skalski, 2000*b*) to summarize our best knowledge on survival and detection probabilities for the Snake-

[1] Passive Integrated Transponder.

Columbia River Basin. We appraised the relationship between tag detection efficiency at Bonneville Dam and precision in in-river adult survival estimates in terms of:

1. number of PIT-tagged fish released,
2. juvenile survival to Lower Granite Dam, and
3. survival during the estuarine and marine period of chinook's life-cycle.

2. MATERIAL AND METHODS

The appraisal of the relationship between tag detection efficiency at Bonneville Dam (P_{B2A}) and the precision in in-river survival estimates of returning PIT-tagged chinook salmon requires the calculation of the standard errors expected in the estimation of estuarine and marine survival estimates ($S_{\text{BA-GRA}}$) for different values of P_{BA} and release sizes of PIT-tagged chinook smolts travelling in a particular river system. In our analysis, whenever we refer to tag detection efficiency at Bonneville Dam we mean the probability of adult PIT-tag detection across the entire Bonneville Dam powerhouses 1 and 2 complex. That is, although in 2001 the new Bonneville PIT-tag interrogation system will only cover orifices in a maximum of four weirs in the Cascades Island fish ladder at Bonneville Dam, our analysis assumed that the new Bonneville PIT-tag interrogation system was operational at both fish ladders (Fig. 1) with system-wide detection efficiency P_{BA}.

In our analysis, the precision in in-river adult survival estimates was measured as standard errors $\left(\text{i.e., } SE\left(\hat{\theta}\right)\right)$ and as coefficients of variation $\left(\text{i.e., } CV\text{, where } CV\left(\hat{\theta}\right) = SE\left(\hat{\theta}\right)/\hat{\theta}\right)$, the latter expressed as percentage. For example, a 95% confidence interval (*CI*) is calculated as approximately $\pm 2 \times SE\left(\hat{\theta}\right)$. With knowledge of the attempted size of the standard error in estimation, the reader can readily calculate the anticipated width of a 95%*CI*. On the other hand, the value of *CV* has a somewhat different interpretation on precision. Asymptotically, an estimate will be within $\pm 1 \times CV\left(\hat{\theta}\right)$ of the true value of the parameter 68% of the time, and an estimate will be within $\pm 2 \times CV\left(\hat{\theta}\right)$ of the true value of the parameter 95% of the time. For example, if the *CV* was 25%, then we can conclude that our estimate is within ± 50% of the true value 95% of the time. Thus, both *SE* and *CV* provide useful measures of precision.

The river system selected for the analysis consists of the Snake-Columbia system as sketched in Figure 2. This system has six PIT-tag detection dams: Lower Granite Dam (LGR), Little Goose Dam (LGS), Lower Monumental Dam (LMN), McNary Dam (McN), John Day Dam (JDA) and Bonneville

Figure 1: Map of Bonneville Dam, showing fish ladder locations on Cascades and Bradford Islands.

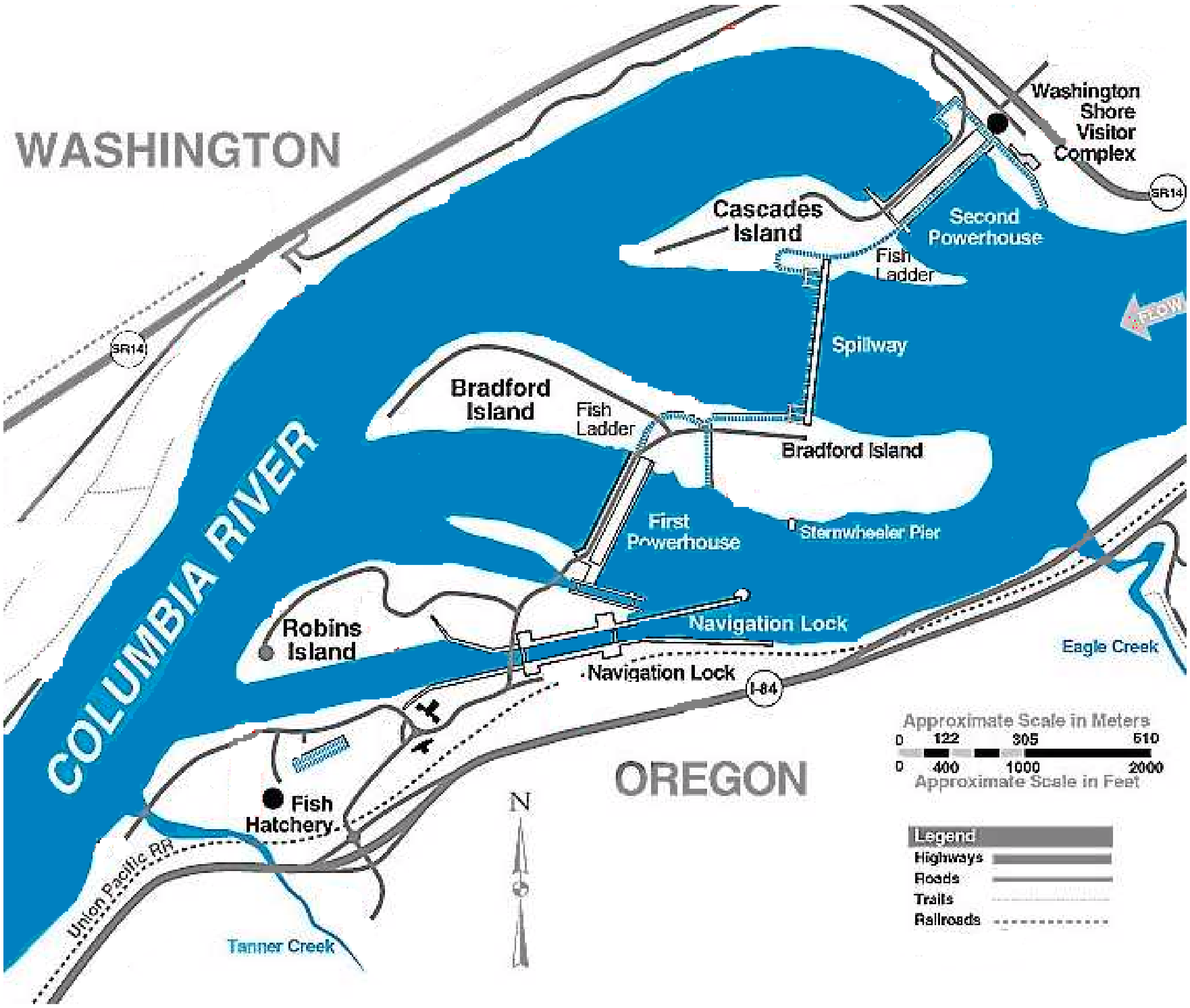
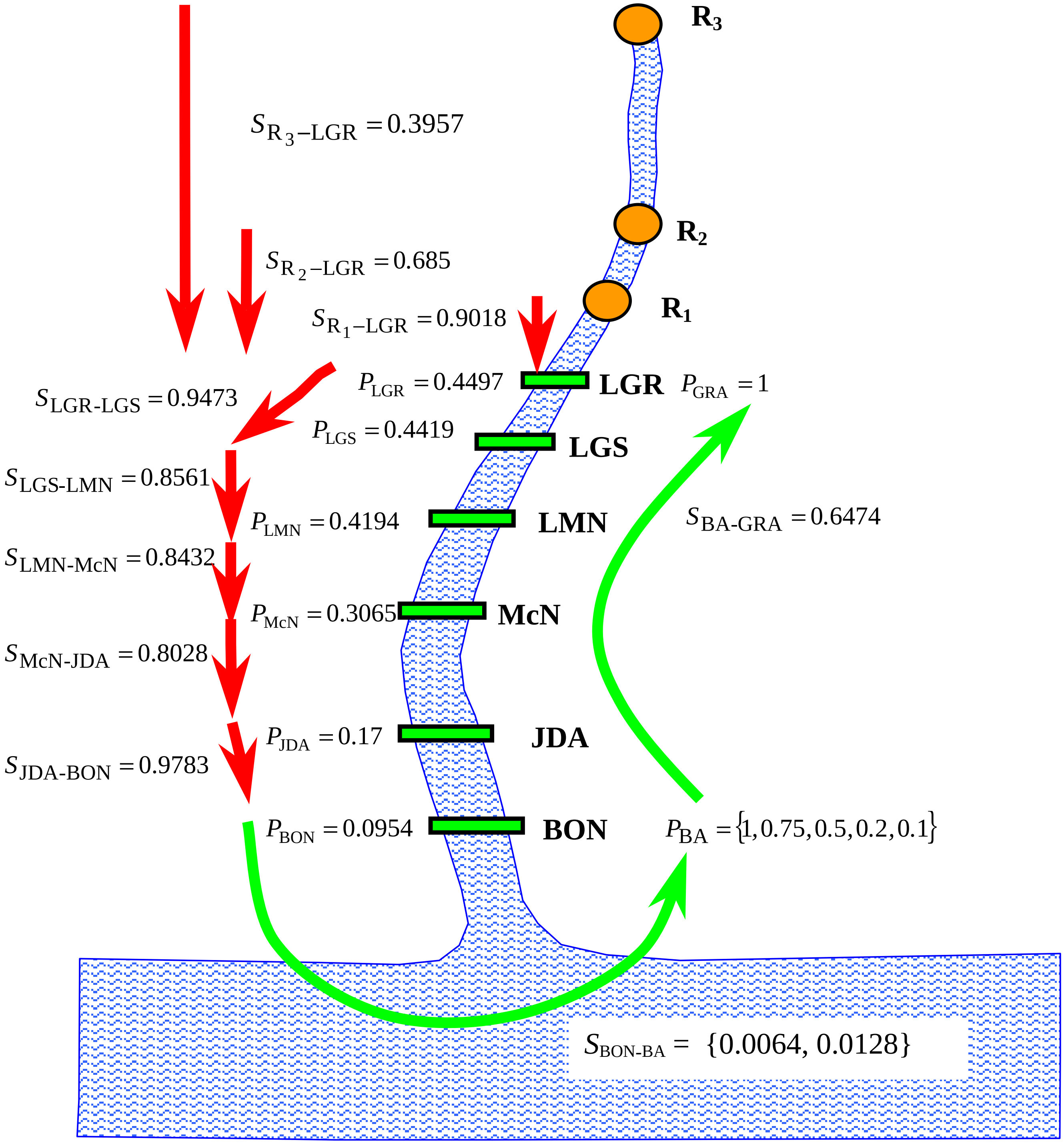


Figure 2: Reach survivals (*S*) and capture probabilities (*P*) utilized in the appraisal of the relationship between tag detection efficiency at Bonneville Dam and precision of in-river survival estimates of returning PIT-tagged chinook salmon.



Dam (BON). These six dams have PIT-tag detection systems for PIT-tagged juvenile fish operating with detection efficiencies denoted by: P_{LGR}, P_{LGS}, P_{LMN}, P_{McN}, P_{JDA} and P_{BON}. Only two dams, BON and LGR have PIT-tag detection systems for PIT-tagged adult fish that operate with detection efficiencies denoted by: P_{BA} and P_{GRA}. Thus, if a group of PIT-tagged chinook smolts of known sample size is released above LGR, the single-release model (Cormack 1964, Jolly 1965, Seber 1965) as implemented in *SURPH.1* (Smith et al., 1994) will produce estimates of seven reach survivals for the marked fish in the release group. Six out the seven reach survivals ($S_{\text{R}_i-\text{LGR}}$, $S_{\text{LGR}-\text{LGS}}$, $S_{\text{LGS}-\text{LMN}}$, $S_{\text{LMN}-\text{McN}}$, $S_{\text{McN}-\text{JDA}}$ and $S_{\text{JDA}-\text{BON}}$) are estimated on juvenile fish migrating down the river system. The survival $S_{\text{BON}-\text{BA}}$ is the survival of juvenile fish that left the tailrace of BON to enter the Columbia River estuary and spend one to four years feeding and growing at sea, to finally return as spawning adults to the tailrace of BON. Finally, $S_{\text{BA-GRA}}$, is the survival of adult fish between Bonneville and Lower Granite Dams that can only be estimated if $P_{\text{GRA}} = 1$. In other words, if the adult detection efficiency at Lower Granite Dam is 100%.

We calculated the standard errors for $\hat{S}_{\text{BA-GRA}}$ by first estimating the terminal detection probability λ. In river systems like the one depicted in Figure 2, Lower Granite Dam is the last PIT-tag detection facility in the system. For such systems, the single-release model cannot provide separate estimates for $S_{\text{BA-GRA}}$ and P_{GRA}. Only its product λ can be estimated. However, if we assume $P_{\text{GRA}} = 1$, then $\hat{S}_{\text{BA-GRA}} = \hat{\lambda}$ and $SE\left(\hat{S}_{\text{BA-GRA}}\right) = SE\left(\hat{\lambda}\right)$. Appendix I provides the equations used to estimate the variance of $\hat{\lambda}$, that is to estimate $SE\left(\hat{S}_{\text{BA-GRA}}\right)$.

We simulated PIT-tag releases from three release sites whose locations were various distances upstream of LGR. The number of PIT-tagged fish in each release group was varied from 1,000 to 100,000 fish, in increments of 1,000 fish. Finally, for the adult PIT-tag detection efficiency at BON (P_{BA}) we tried five values ranging from one to 0.1, such that $P_{\text{BA}} = \{1, 0.75, 0.5, 0.2, 0.1\}$. We assumed that $P_{\text{GRA}} = 1$ for all groups of PIT-tagged fish. All release scenarios were also investigated using two different values of estuarine and marine survival $S_{\text{BON}-\text{BA}}$.

The values for the six juvenile PIT-tag detection efficiencies and the eight reach survivals required by our calculations (Fig. 2) were obtained from published reports on survival and capture probability estimates for PIT-tagged chinook salmon releases (Eppard et al., 1999; Hockersmith et al., 1999; Iwamoto et al., 1994; Muir et al., 1995 and 1996; Perez-Comas and Skalski, 2000; Smith et al., 1998 and 2000) and results from radio-telemetry experiments on returning adult chinook salmon (Bjornn et al., 2000). Appendices I-V in Perez-Comas and Skalski (2000*b*) provide the estimates and calculation procedures used to generate the survival and capture probability values displayed in Figure 2. Since the values for survivals $S_{\text{LGR-LGS}}$, $S_{\text{LGS-LMN}}$, $S_{\text{LMN-McN}}$, $S_{\text{McN-JDA}}$, $S_{\text{JDA-BON}}$ and $S_{\text{BA-GRA}}$ were kept constant in all 3,000 standard error calculations, the six release scenarios were defined on the basis of the values assigned to the juvenile survival from release to LGR ($S_{\text{R}_i\text{-LGR}}$) and the estuarine and marine survival $S_{\text{BON-BA}}$ presented below:

Scenario	Release Site	$S_{\text{R-LGR}}$	$S_{\text{BON-BA}}$
1	Nisqually John Boat Landing	*0.9018*	*0.0064*
2	Nisqually John Boat Landing	*0.9018*	*0.0128*
3	Lookingglass Hatchery	*0.6850*	*0.0064*
4	Lookingglass Hatchery	*0.6850*	*0.0128*
5	Sawtooth Hatchery	*0.3957*	*0.0064*
6	Sawtooth Hatchery	*0.3957*	*0.0128*

3. RESULTS

3.1 Effects of Bonneville Dam detection efficiency and release size on precision

Figures 3-5 depict the effects of Bonneville Dam detection efficiency and release size on precision, expressed as standard errors and coefficient of variation of $S_{\text{BA-GRA}}$ estimates $\left(\text{i.e., } SE\left(\hat{S}_{\text{BA-GRA}}\right) \text{and } CV\left(\hat{S}_{\text{BA-GRA}}\right)\right)$, for a given PIT-tag release site. Each figure contrasts the influence of estuarine and marine survival $S_{\text{BON-BA}}$ on the relationship among Bonneville adult detection efficiency, release size and precision. In general, for releases from a particular site, an increase in estuarine and marine survival produces a general increase in the precision of the in-river adult survival estimates (i.e., a general shift upward of the standard error curves). For example, if 30,000 PIT-tagged fish were to be released from Nisqually John Boat Landing and $S_{\text{BON-BA}}$ is 0.0064, the $CV\left(\hat{S}_{\text{BA-GRA}}\right)$ would be between 7.65% and 10.82%, when the Bonneville adult detection efficiency ranges between 1 and 0.5 (Fig. 3*a*). However, *CV*s of 5.41 to 7.65% for $\hat{S}_{\text{BA-GRA}}$ would be

Figure 3: Standard error (SE) and coefficient of variation (CV) of adult in-river survival estimates ($\hat{S}_{\text{BA-GRA}}$) as functions of the number of fish released from Nisqually John Boat Landing $\left(S_{\text{Rel.-LGR}} = 0.9014\right)$ for various values of tag detection efficiency at Bonneville Dam $\left(P_{\text{BA}}\right)$, when estuarine and marine survival is: (***a***) $\hat{S}_{\text{BON-BA}} = 0.0064$ and (***b***) $\hat{S}_{\text{BON-BA}} = 0.0128$.

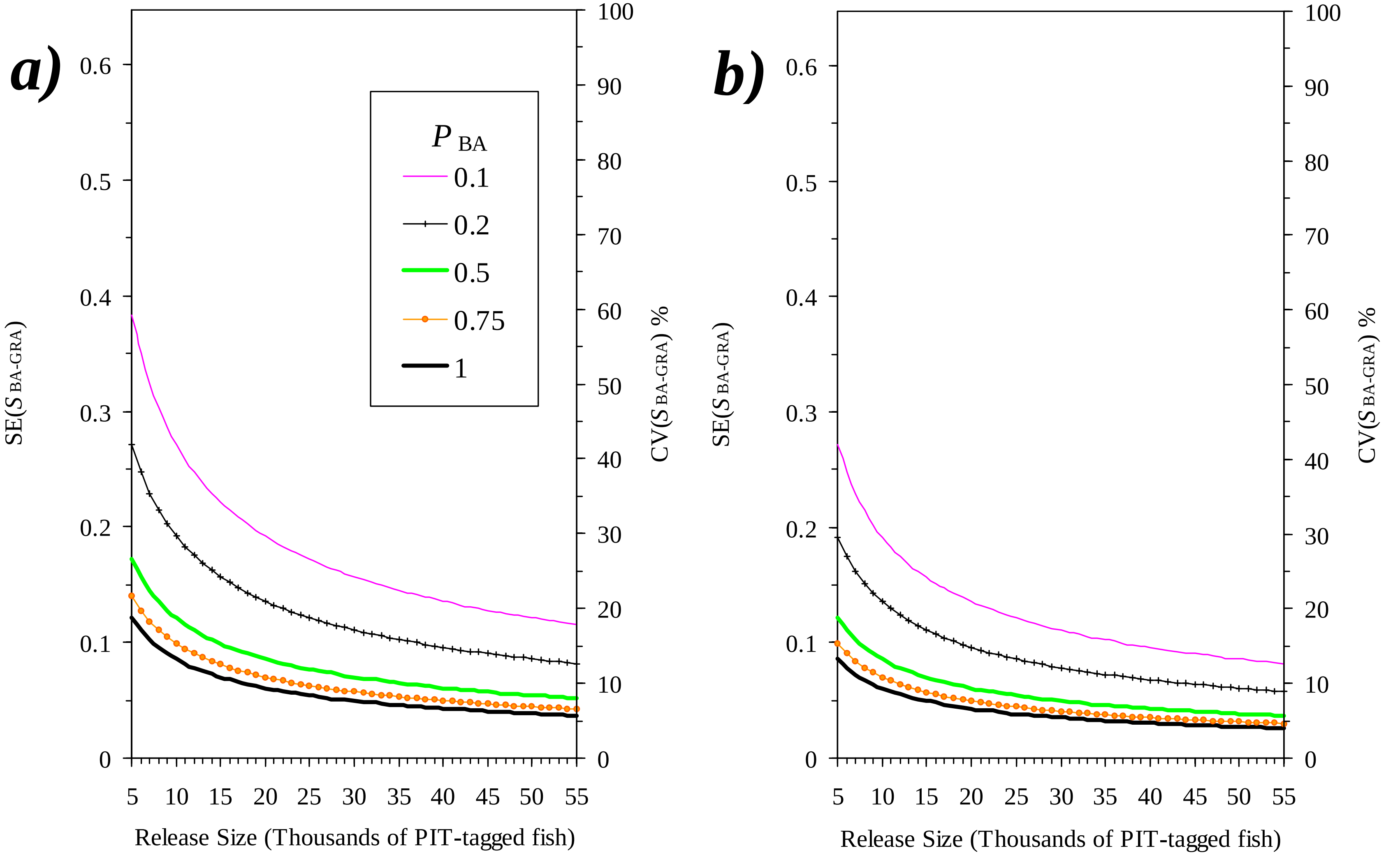


Figure 4: Standard error (SE) and coefficient of variation (CV) of adult in-river survival estimates ($\hat{S}_{\text{BA-GRA}}$) as functions of the number of fish released from Lookingglass Hatchery $\left(S_{\text{Rel.-LGR}} = 0.685\right)$ for various values of tag detection efficiency at Bonneville Dam $\left(P_{\text{BA}}\right)$, when estuarine and marine survival is: (***a***) $\hat{S}_{\text{BON-BA}} = 0.0064$ and (***b***) $\hat{S}_{\text{BON-BA}} = 0.0128$.

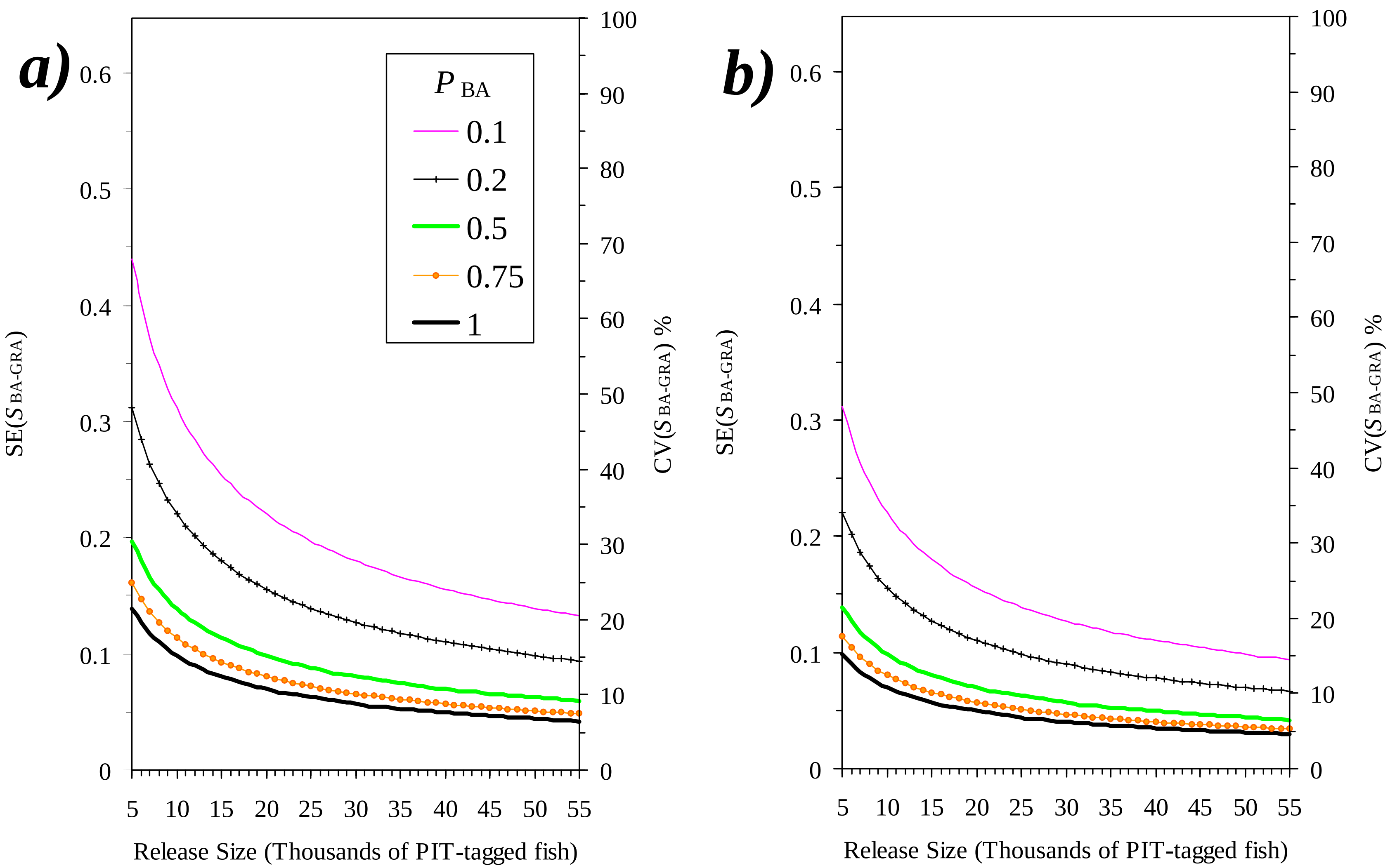
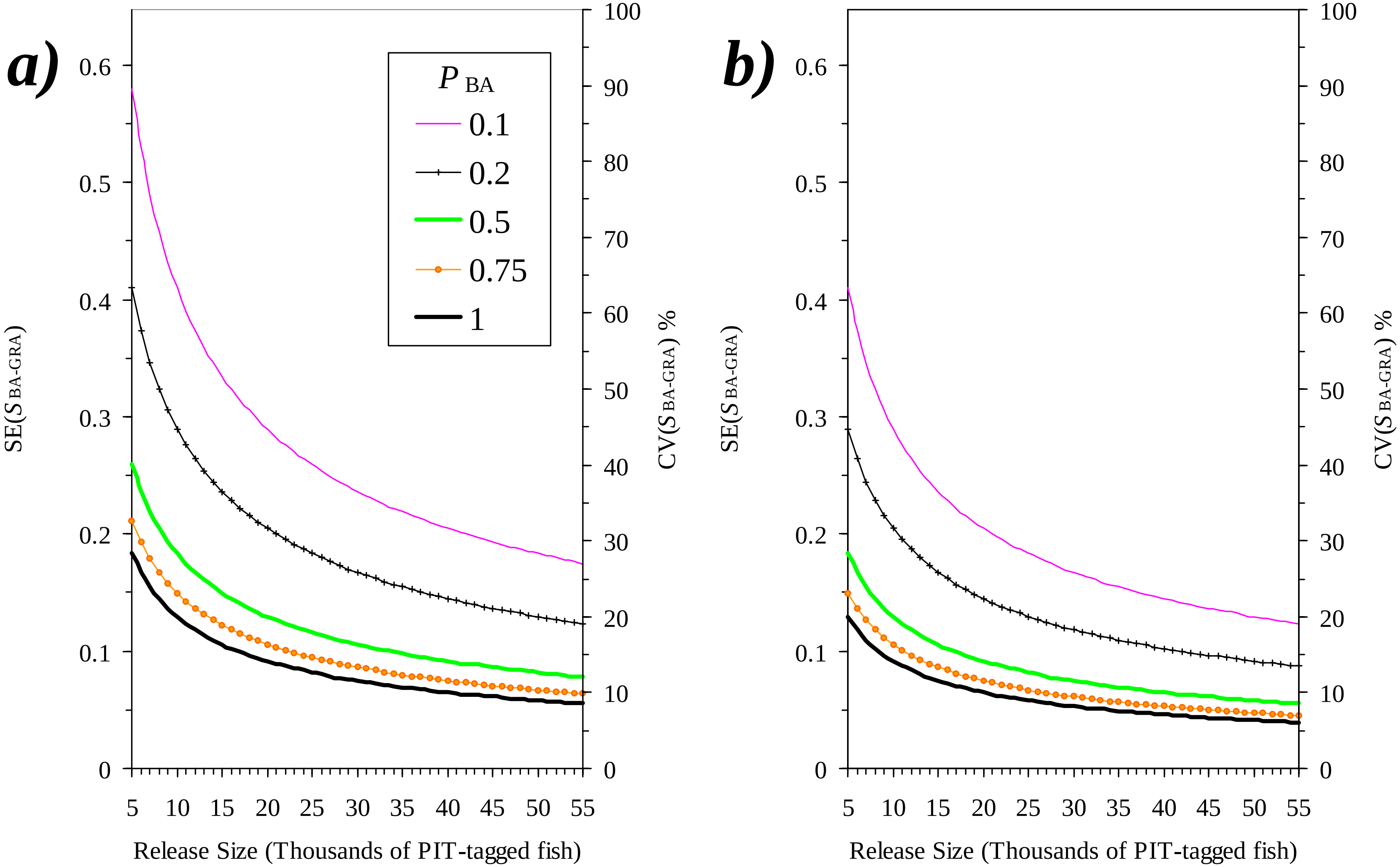


Figure 6: Standard error (SE) and coefficient of variation (CV) of adult in-river survival estimates ($\hat{S}_{\text{BA-GRA}}$) as functions of the number of fish released from Sawtooth Hatchery $\left(S_{\text{Rel.-LGR}} = 0.3957\right)$ for various values of tag detection efficiency at Bonneville Dam $\left(P_{\text{BA}}\right)$, when estuarine and marine survival is: (***a***) $\hat{S}_{\text{BON-BA}} = 0.0064$ and (***b***) $\hat{S}_{\text{BON-BA}} = 0.0128$.



obtained if $S_{\text{BON-BA}}$ was 0.0128 (Fig. 3*b*). Similarly, for 30,000 fish released from Lookingglass Hatchery, *CV*s would decrease from 8.78 - 12.42% ($S_{\text{BON-B2A}} = 0.0064$, Fig. 4*a*) to 6.21 - 8.78% ($S_{\text{BON-B2A}} = 0.0128$, Fig. 4*b*) when estuarine and marine survival changed from 0.0064 to 0.0128.

As detection efficiency decreased from $P_{\text{BA}} = 1$ to $P_{\text{BA}} = 0.1$, larger release sizes are required to achieve the same standard error. For example, in Figure 3*a* (scenario 1), to achieve a standard error of 0.12 that corresponds to a coefficient of variation (*CV*) of 18.5%, a release of 5,114 PIT-tagged fish would be required with Bonneville adult PIT-tag detection efficiencies of 1. However, if P_{BA} were between 0.5 and 0.1, the required release sizes would be in the range of 10,228 to 51,139 fish.

Figures 3-5 also illustrate the effects of release site, or more concretely of the related juvenile survival to LGR (i.e., $S_{\text{R-LGR}}$). In general, for a given release size and Bonneville adult detection efficiency, the higher $S_{\text{R-LGR}}$ is, the lower the standard error and coefficient of variation are (i.e., the higher the precision is). In addition, the further upstream of LGR the release site is, the higher the anticipated standard error and coefficient of variation in $S_{\text{BON-BA}}$ estimates are. For example, if we compare the expected precision of estuarine and marine survival estimates for 30,000 PIT-tagged chinook salmon released from Nisqually John Boat Landing, Lookingglass Hatchery and Sawtooth Hatchery, when $S_{\text{BON-BA}} = 0.0128$ and $P_{\text{BA}} = 1$, the anticipated *CV*s are 5.41, 6.21 and 8.17%, respectively (Fig. 3*b*, Fig. 4*b* and Fig. 5*b*).

3.2 Required Bonneville detection efficiency at the adult PIT-tag detection facility

Table 1 shows the maximum precision in the estimation of in-river survival for returning adult salmon, attainable under various release-recapture scenarios, if the adult detection efficiency at Bonneville adult PIT-tag detection facility were maximal (i.e., $P_{\text{BA}} = 1$). Release sizes of 55,000 or more PIT-tagged fish are required to produce *CV*s for $\hat{S}_{\text{BON-BA}}$ ranging from 4% to 8.53%, depending on the scenario specifications. If releases were as low as 10,000 fish, a common release size for the past nine years, we might expect lower precision (*CV*s of 9.37-20.01%), even with the Bonneville project operating at full detection efficiency (i.e., $P_{\text{BA}} = 1$).

Table 2 attempts to address the question of what detection efficiency is needed at the Bonneville project to achieve an adequate precision in $\hat{S}_{\text{BA-GRA}}$. We chose a precision of *CV* = 20%

Table 1: Maximum attainable precision in adult in-river survival estimates ($\hat{S}_{\text{BA-GRA}}$) for various release-recapture scenarios, when the adult detection efficiency at both Lower Granite and Bonneville adult PIT-tag detection facilities were maximal (i.e., $P_{\text{BA}} = 1$ and $P_{\text{GRA}} = 1$). Precision is expressed as coefficient of variation, in percent.

		Release Size (Thousands of fish)			
Release Site	$S_{\text{BON-BA}}$	*10*	*30*	*55*	*75*
Nisqually John ($S_{\text{R-LGR}}$ = *0.9018*)	*0.0064*	13.26	7.65	5.65	4.84
	0.0128	9.37	5.41	4.00	3.42
Lookingglass ($S_{\text{R-LGR}}$ = *0.685*)	*0.0064*	15.21	8.78	6.49	5.55
	0.0128	10.75	6.21	4.59	3.93
Sawtooth ($S_{\text{R-LGR}}$ = *0.3957*)	*0.0064*	20.01	11.55	8.53	7.31
	0.0128	14.15	8.17	6.03	5.17

Table 2: Required detection efficiencies at the Bonneville adult PIT-tag detection facility (i.e., P_{BA}) to attain a precision of CV = 20% for various release-recapture scenarios, when the adult detection efficiency at Lower Granite Dam is maximal (i.e., $P_{\text{GRA}} = 1$).

		Release Size (Thousands of fish)			
Release Site	$S_{\text{BON-BA}}$	*10*	*30*	*55*	*75*
Nisqually John ($S_{\text{R-LGR}}$ = *0.9018*)	*0.0064*	0.4	0.1	0.1	0.1
	0.0128	0.2	0.1	< 0.1	< 0.1
Lookingglass ($S_{\text{R-LGR}}$ = *0.685*)	*0.0064*	0.6	0.2	0.1	0.1
	0.0128	0.3	0.1	0.1	< 0.1
Sawtooth ($S_{\text{R-LGR}}$ = *0.3957*)	*0.0064*	1*	0.3	0.2	0.1
	0.0128	0.5	0.2	0.1	0.1

* The required precision of CV = 20% could not be obtained under the particular scenario and release size, even when the detection efficiency at Bonneville adult PIT-tag detection facility was 100%.

for the survival estimates. A *CV* = 20% implies that the survival estimate $\hat{S}_{\text{BA-GRA}}$ would be within ± 40% of the true in-river survival of returning adult salmon, 95% of the times. Table 2 shows that under most scenarios with release sizes of 10,000 or more fish, the required precision of *CV* = 20% could be obtained, even if the detection efficiency at entire Bonneville project was less than perfect (i.e., $P_{\text{BA}} < 1$). With release sizes of 10,000 tagged fish, a precision of *CV* = 20% in $\hat{S}_{\text{BA-GRA}}$ could still be attained with detection efficiencies at the entire Bonneville project ranging between 20% and 60%, depending on scenario conditions. Only with as few as10,000 tagged fish released from a site distant from LGR (e.g., Sawtooth hatchery) and with low estuarine and marine survival, could a *CV* of 20% not be achieved, even if the detection efficiency at the Bonneville project was 100%. For larger sample sizes (e.g., 30,000 - 75,000 PIT-tagged fish), a precision of *CV* = 20% in $\hat{S}_{\text{BA-GRA}}$ would still be achieved even with Bonneville detection efficiency as low as 10%. These results are in sharp contrast to those for the precision on estuarine and marine survival (Table 2 in Perez-Comas and Skalski, 2000*b*), where a precision of *CV* = 20% in $\hat{S}_{\text{BON-BA}}$ could not be attained, even with $P_{\text{BA}} = 1$.

4. DISCUSSION

The present appraisal provides guidance on the expected relationship between the detection efficiency at the Bonneville adult PIT-tag detection facility and the anticipated precision of in-river survival estimates of returning adult salmon between Bonneville and Lower Granite dams, for hypothetical releases of PIT-tagged yearlings from sites upstream of Lower Granite Dam. Together with our previous analysis on the precision of estuarine and marine survival estimates (Perez-Comas and Skalski, 2000*b*), this study addresses the issue of the expected precision of survival estimates for returning PIT-tagged adult salmon under various levels of adult detection efficiency at Bonneville Dam. As with our previous analysis, the precision calculations were based upon current estimates of survival and detection probabilities for the various reaches and dams of the Snake-Columbia River Basin, and consequently are constrained by the quality of available information. Moreover, our precision calculations for $\hat{S}_{\text{BA-GRA}}$ rely upon the assumption that $SE\left(\hat{S}_{\text{BON-BA}}\right) = SE\left(\hat{\lambda}\right)$ because $P_{\text{GRA}} = 1$.

Besides the rather obvious direct proportionality between precision and release size, and between precision and adult detection efficiency at Bonneville Dam (Fig. 3-5), the expected precision (i.e., *CV*) of in-river adult survival estimates appeared to be directly proportional to the inriver juvenile survival $S_{\text{R-LGR}}$. For a given release size and adult detection efficiency, the precision of $\hat{S}_{\text{BA-GRA}}$ will increase as $S_{\text{R-LGR}}$ increases (Fig. 3*a*-5*a*). Moreover, for a given release size and adult detection efficiency, higher estuarine and marine survivals will also produce more precise survival estimates (Fig. 3*b*-5*b*). The implication is obvious, if a precise adult PIT-tag study is desired, releases of PIT-tagged smolts should be as large and as down river as possible.

The expected standard errors for the in-river adult survival estimates in Figures 3-5 were large (e.g., $0.1 < SE < 0.55$) when compared to the expected standard errors for the ocean survival estimates (e.g., $0.002 < SE < 0.012$; Perez-Comas and Skalski, 2000*b*). Hence, the confidence interval widths for in-river adult survival (± 0.16 to ± 0.9) will be broader than the confidence interval widths for ocean survival (± 0.003 to ± 0.02). However, these confidence interval widths ignore the relative magnitude of the signal-to-noise ratio of the survival estimates. An ocean survival estimate $\hat{S}_{\text{BON-BA}}$ of 0.01, with a confidence interval width of ± 0.02, 95% of the time, will be precise on an absolute scale but not on a relative scale. In this latter situation, the coefficient of variation $\left(CV = SE\left(\hat{S}\right)/\hat{S} \right)$ would be 100%. Thus, the ocean survival estimate would be within ± 200% of the true value, 95% of the time. Alternatively, an in-river adult survival estimate $\hat{S}_{\text{BA-GRA}}$ of 0.65, with a confidence interval width of ± 0.2, 95% of the time, will also be imprecise on an absolute scale, but not on a relative scale. The coefficient of variation for $\hat{S}_{\text{BA-GRA}}$ would be 15%. Thus, the in-river adult survival estimate will be within ± 30% of the true value, 95% of the time. For this reason, the *CV* is a more useful measure of sampling precision and the focus of our discussion.

Based on our analyses, we conclude that currently common release sizes of 10,000 - 30,000 PIT-tagged fish will produce in-river adult survival estimates with a precision of $CV = 20\%$, even if the adult detection system at Bonneville is to operate at 10 - 50% efficiency (Table 2). A higher precision ($5\% < CV < 20\%$) will be attained with the system operating at 100% efficiency. However, a precision of $CV = 20\%$ in estuarine and marine survival cannot be achieved, even if the adult detection system at Bonneville is to operate at 100% efficiency (Table 2, Perez-Comas and Skalski, 2000*b*). Thus, for a PIT-tag study on chinook salmon in the Snake-Columbia rivers that attempts to obtain precise survival estimates for both ocean and in-river survival, the PIT-tag detection system to be installed at the adult ladders of Bonneville Dam should be designed for maximum detection efficiency.

Finally, we want to emphasize once more that our results are based on the detection efficiency P_{BA}, that is the detection efficiency for the entire Bonneville system, powerhouses 1 and 2. In 1999, 41.4% of the adult chinook detected at Bonneville were detected at Powerhouse 1, while 58.6% were detected at Powerhouse 2. Hence, if only the Powerhouse 2 had an adult PIT-tag detector operating at a 90% efficiency, the overall detection efficiency for the Bonneville project would be $0.586 \times 0.9 = 0.527$. This adjusted probability of detection (i.e., with adult detection occurring only at the Cascades Island fish ladder) could be used in conjunction with Figures 3-5 to determine anticipated precision in $\hat{S}_{\text{BA-GRA}}$ and in conjunction with Figures 4-6 (Perez-Comas and Skalski, 2000*b*) to determine anticipated precision in $\hat{S}_{\text{BON-BA}}$. For example, releases of 10,000 PIT-tagged chinook salmon with adjusted detection rates of 50% at the Bonneville project would attain somewhat moderate precision in $\hat{S}_{\text{BA-GRA}}$ (13.2% < CV < 28.4%), but the precision in $\hat{S}_{\text{BON-BA}}$ would be too low (45.5% < CV < 97.8%) to provide useful estimates of estuarine and marine survival. This further implies that the design of the Bonneville adult PIT-tag detection system must consider both powerhouses before an effective system can be established.

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APPENDIX I: Calculation of the variance of the estimated terminal detection and survival probability $\hat{\lambda}$

In a PIT-tag catch-recapture system consisting of K sampling events (i.e., that is K detection sites) there are (K-1) reach survivals (i.e., S_i with $i = 1, 2, ..., K-1$) and (K-1) capture probabilities (P_i with $i = 1, 2, ..., K-1$) that are normally estimated. For the K^{th} reach only a terminal probability $\lambda = S_K \times P_K$ can be estimated. Its estimator is defined: $\hat{\lambda} = \dfrac{n_{...11}}{n_{...11} + n_{...10}}$, where $n_{...11}$ is the number of fish of a given release of R tagged fish that were detected at both the (K-1) and K^{th} sampling events, and $n_{...10}$ is the number of tagged fish that were detected the (K-1)th sampling event, but not at the K^{th} sampling event.

The expected value of the estimator $\hat{\lambda}$ (i.e., $E(\hat{\lambda})$) is:

$$E(\hat{\lambda}) \doteq \frac{E(n_{...11})}{E(n_{...11}) + E(n_{...10})} \doteq \frac{R(S_1 S_2 ... S_{K-1} P_{K-1} \lambda)}{R(S_1 S_2 ... S_{K-1} P_{K-1} \lambda) + R(S_1 S_2 ... S_{K-1} P_{K-1}(1-\lambda))} \doteq \frac{R(S_1 S_2 ... S_{K-1} P_{K-1} \lambda)}{R(S_1 S_2 ... S_{K-1} P_{K-1})} = \lambda$$

The variance for $\hat{\lambda}$ can be estimated by applying the Delta method as:

$$Var(\hat{\lambda}) \doteq Var(n_{...11}) \left. \frac{n_{...10}}{(n_{...11} + n_{...10})^2} \right|_E^2 + Var(n_{...10}) \left. \frac{n_{...11}}{(n_{...11} + n_{...10})^2} \right|_E^2 - 2Cov(n_{...11}, n_{...10}) \left. \frac{n_{...10}}{(n_{...11} + n_{...10})^2} \right|_E \left. \frac{-n_{...11}}{(n_{...11} + n_{...10})^2} \right|_E$$

$$\doteq \left. \frac{n_{...10}}{(n_{...11} + n_{...10})^2} \right|_E^2 \left. \frac{n_{...11}}{(n_{...11} + n_{...10})^2} \right|_E^2 \left| \frac{Var(n_{...11})}{E(n_{...11})^2} + \frac{Var(n_{...10})}{E(n_{...10})^2} - \frac{2Cov(n_{...11}, n_{...10})}{E(n_{...11})E(n_{...10})} \right|$$

Thus:

$$Var(\hat{\lambda}) \doteq \lambda^2 (1-\lambda)^2 \left| \frac{Var(n_{...11})}{E(n_{...11})^2} + \frac{Var(n_{...10})}{E(n_{...10})^2} - \frac{2Cov(n_{...11}, n_{...10})}{E(n_{...11})E(n_{...10})} \right|$$, where

$E(n_{...11}) = R(S_1 S_2 ... S_{K-1} P_{K-1} \lambda)$ is the expectation value of $n_{...11}$,

$E(n_{...10}) = R(S_1 S_2 ... S_{K-1} P_{K-1}(1-\lambda))$ is the expectation value of $n_{...10}$,

$Var(n_{...11}) = R(S_1 S_2 ... S_{K-1} P_{K-1} \lambda)(1 - S_1 S_2 ... S_{K-1} P_{K-1} \lambda)$ is the variance of $n_{...11}$,

$Var(n_{...10}) = R(S_1 S_2 ... S_{K-1} P_{K-1}(1-\lambda))(1 - S_1 S_2 ... S_{K-1} P_{K-1}(1-\lambda))$ is the variance of $n_{...10}$ and

$Cov(n_{...11}, n_{...10}) = -R(S_1 S_2 ... S_{K-1} P_{K-1}\lambda)(S_1 S_2 ... S_{K-1} P_{K-1}(1-\lambda))$ is the covariance of $n_{...10}$ and $n_{...11}$