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Seattle, Washington

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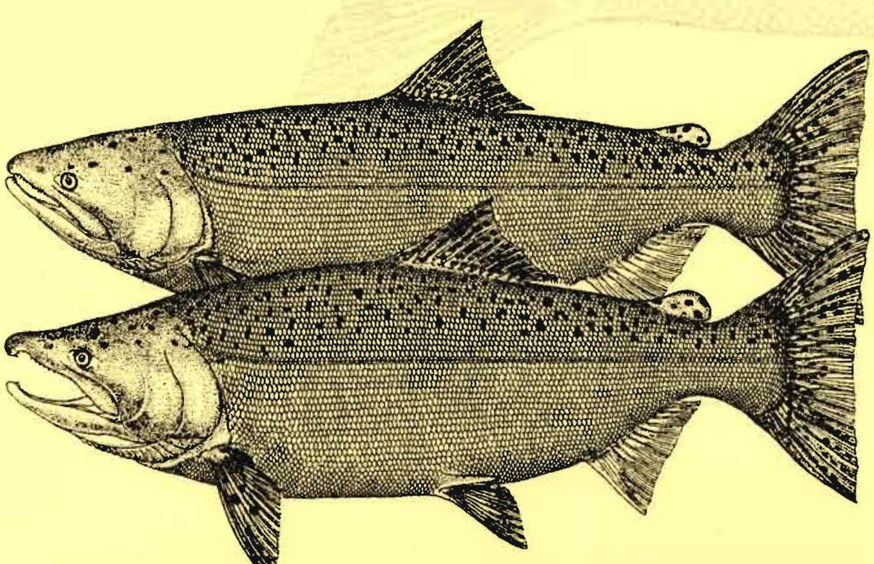

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INTRODUCTION

The mid-Columbia Habitat Conservation Plan (HCP) includes a goal of 95% survival for juvenile salmonids passing the projects operated by Public Utility District No. 1 of Chelan County (District). To meet the objectives of the HCP, estimates of migrating juvenile salmonids are needed. In the spring of 1998, we conducted a pilot study designed to evaluate methods of estimating survival of downstream migrating salmon at the District's Rocky Reach and Rock Island Hydroelectric projects.

Since 1993, the National Marine Fisheries Service (NMFS) has conducted survival studies on migrant juvenile salmonids in the Snake River (Iwamoto et. al., 1994: Muir et. al., 1995, 1996; Smith et. al., 1998). Survival estimation on the Snake River was made possible by the development of the passive integrated transponder tag (PIT tag), installation of detection and slide-gate systems at Snake River and Lower Columbia River dams, and adaptation of established statistical models for release-recapture data (Cormack, 1964; Jolly, 1965; Seber, 1965) to estimate survival for migrating fish.

Snake River survival studies have typically used a single release group of PIT-tagged juvenile salmonids. A detection history is constructed for each individual fish in the group, and the Single-Release (SR) Model (Skalski et al., 1998) is applied to the collection of detection histories to estimate survival probabilities through a series of river reaches (e.g., from Lower Granite Dam tailrace to Little Goose Dam tailrace, then from Little Goose Dam tailrace to Lower Monumental Dam tailrace). Using the SR Model, survival is estimated between sites that are capable of both detecting PIT-tagged fish and returning detected fish back to the river, down to the second-to-last site. Below the second-to-last site, it is impossible to separate the survival probability from the probability of detection.

The river reaches for which survival estimates were desired in the 1998 mid-Columbia River study were: (1) from Wells Dam tailrace to Rocky Reach Dam tailrace; (2) from Rocky Reach Dam forebay to Rocky Reach Dam tailrace; and (3) from Rocky Reach Dam tailrace to Rock Island Dam tailrace. It was not possible to use the SR Model to estimate these probabilities because PIT-tag detectors at Rocky Reach Dam did not consistently detect a large portion of passing fish, and because there is no PIT-tag detection at Rock Island Dam. Instead, the main statistical model we used was the Paired-Release (PR) Model (Burnham et al., 1987). For this model, groups of tagged fish are released at two sites, one upstream ("treatment") and one downstream ("reference"). Detection histories downstream from the reference release site are compiled for the two "paired" groups, survival and detection parameters are estimated for each group, and the survival probability in the section of river between the two release sites is estimated from differences in key parameters for the two groups.

METHODS

Study Area

PIT-tagged fish for the study were released or detected on the Columbia River from the tailrace of Wells Dam (Rkm 831) to the river estuary below Bonneville Dam (Rkm 235; Fig 1). The area included nine dams and eight reservoirs: Wells, Rocky Reach (Rkm 764), Rock Island (Rkm 730), Wanapum (Rkm 668), Priest Rapids (Rkm 639), McNary (Rkm 470), John Day (Rkm 347), The Dalles (Rkm 308), and Bonneville. PIT-tag detection facilities used in the study are located at Rocky Reach, McNary, John Day, and Bonneville Dams. PIT-tagged smolts were also detected by an experimental PIT-trawl detection system towed behind a boat in the river estuary below Bonneville Dam.

Test Fish

Fish used in this study were hatchery-reared yearling fall chinook salmon (*Onchorynchus tshawytscha*) from Turtle Rock Hatchery (Rkm 767). Prior to the study approximately 70,000 fish were transported to the Eastbank facility (Rkm 765) and held for tagging. Fish size was about 10 fish per pound. Fish were reared on river water (approximately 15.6° C) at the Turtle Rock Facility and moved into well water (approximately 12.8° C) at Eastbank for tagging.

Fish Marking and Handling

Fish were removed from raceways as needed and tagged with 400 kHz PIT tags using standard tagging methods (Prentice et. al., 1990). Laborers employed to mark fish had previous experience handling fish but they had not previously PIT tagged fish. Fish with obvious deformities, abnormalities or symptoms of disease were rejected for tagging. Following tagging, PIT-tagged fish were held in 738 liter tanks (about 750 fish per tank) provided with flow-through well water. Test fish were held for up to 24 hours to recover from anesthesia and to determine delayed tagging/handling mortality and tag loss. A siphon device was used to remove shed tags from the tanks prior to release of test fish. In preparation for transportation, tanks were disconnected from flow-through water and loaded onto flatbed trucks. Compressed air was used to aerate water in the tanks during transportation to the release sites. A group of about 1,500 PIT-tagged fish was transported to each release site and transferred to aluminum tanks (738 l) mounted on board a small barge where flow-through water was pumped to each tank. Immediately after transfer to the barge, groups of fish were transported to mid-channel, checked again for delayed handling mortality and tag loss, and released. Groups were released on each of 15 days in the tailraces of Rocky Reach and Rock Island Dams. Fish were released into the tailrace of Wells Dam on 10 days and into the forebay of Rocky Reach Dam on 5 days. Groups of tagged fish on a particular day were assigned to release locations based on a randomized schedule. Tailrace release sites were located approximately 300 m below the projects. The Rocky Reach Dam forebay release site was located at the head of Turtle Rock Island, approximately 3.2 km above the project. The distance from the Eastbank facility to the various release locations was not equal. We tried to avoid differential transport effects by equalizing the amount of time each group spent traveling from the tagging to the release location.

Statistical Analyses

Data Acquisition and Management

During the 1998 migration season, automatic PIT-tag detectors (Prentice et al. 1990) were operational in juvenile bypass systems at McNary and John Day Dams. A fraction of the smolts passing Bonneville Dam was interrogated for PIT tags, and still others were detected by an experimental PIT-trawl detection system towed behind a boat below Bonneville Dam. In addition, a small fraction of PIT-tagged smolts passing Rocky Reach Dam was detected. Tagging and detection data were retrieved from the PIT Tag Information System (PTAGIS) maintained by the Pacific States Marine Fisheries Commission (PSMFC)[1]. Data were examined for erroneous records, inconsistencies, and data anomalies. Records were eliminated where appropriate, and all eliminated PIT-tag codes were recorded with the reasons for their elimination. Fish for which length at tagging was not recorded were omitted from the analysis. For each remaining PIT-tag code, a record ("detection history") was constructed to indicate at which sites the tagged fish was detected and at which it was not detected. For most analyses, detection histories included the record for McNary, John Day, and Bonneville Dams (towed array detections were lumped with Bonneville Dam detections). For some analyses of releases in Wells Dam tailrace and Rocky Reach Dam forebay, we included a record of detection at Rocky Reach Dam. With one exception, the methods for data retrieval and database quality assurance/control were the same as those used in our Snake River studies (e.g., see Muir et al. 1995).

The exception was that for this study we treated "single-coil hits" at McNary Dam as legitimate observations. As a PIT-tagged fish passes through a juvenile bypass system, it passes multiple PIT-tag detectors. Each detector has several detecting "coils," and each coil generates a record in the database as it reads the PIT-tag code. Thus, in the vast majority of cases, each PIT-tagged fish passing through the bypass system generates multiple detection records ("hits"), one for each coil that reads the code. However, there exist in the PTAGIS database records that indicate that some PIT-tagged fish were read by only a single coil as they passed through a bypass system. These records are sometimes referred to as "single-coil hits."

[1] Pacific States Marine Fisheries Commission, PIT Tag Operations Center, 45 SE 82nd Drive, Suite 100, Gladstone, OR 97207.

In the Snake River studies single-coil hits were disproportionately involved in data anomalies, such as a fish being detected at a lower dam prior to an upper one, or detected before its release date. However, at McNary Dam in 1998 there was a relatively large number of single-coil hits that did not appear anomalous. All but one single-coil hit occurred on the "B-Separator Gate" detector. Including single-coil hits as legitimate detections increased the amount of available data, without introducing suspect data.

Model Selection and Survival Estimation

The "Paired-Release Model" (Burnham et al. 1987) is actually a family of models for release-recapture data gathered from paired release groups of tagged animals. In the most general case the PR Model consists of the Single-Release Model applied separately to each of the two release groups, with a full suite of detection and survival parameters estimated for each of the two groups (illustrated schematically in Fig. 2 for paired releases in Rocky Reach Dam tailrace and Rock Island Dam tailrace). The various models in the family are derived by setting equal one or more corresponding parameters in the two parallel SR Models.

For the most general model of paired releases in the mid-Columbia River in 1998 (Fig. 1), the SR Model was applied to each of the release groups, resulting in estimates of five parameters for each group: probability of survival from point of release to tailrace of McNary Dam (e.g., S_{T1} for upstream group); probability of detection of fish that survived to McNary Dam (P_{T1}); probability of survival from tailrace of McNary Dam to tailrace of John Day Dam (S_{T2}); probability of detection of fish that survived to John Day Dam (P_{T2}); and combined probability of survival and detection at Bonneville Dam or by the towed array (λ_T). Under this model, the estimated survival probability through the river section between release sites is the ratio of the SR-Model survival estimates to McNary Dam tailrace for the two groups:

$$\hat{S} = \frac{\hat{S}_{T1}}{\hat{S}_{R1}} \qquad (1)$$

with estimated variance:

$$\hat{Var}(\hat{S}) = \hat{S}^2 \left(\frac{\hat{Var}(\hat{S}_{T1})}{\hat{S}_{T1}^{\,2}} + \frac{\hat{Var}(\hat{S}_{R1})}{\hat{S}_{R1}^{\,2}} \right) \qquad (2)$$

The expression for the survival estimate (eq. 1) implies the assumption that the overall survival probability to McNary Dam tailrace for the upstream group is the product of the survival probability from the upstream release site to the downstream release site and the survival probability from the downstream release site to McNary Dam tailrace. Thus, a further implicit (and generally untestable) assumption of the ratio estimator is that the survival probability from the downstream release site to McNary Dam tailrace is the same for both of the paired groups. If this assumption is violated, the ratio of first-reach survival estimates is not a valid estimator; in fact, no valid estimator exists.

One potential benefit of the paired release protocol is that the two groups may have some parameters in common. That is, if fish from the two groups mix as they travel downstream, then the groups may have equal survival and detection probabilities downstream from the reach of interest. (Note, however, that mixing is not a sufficient condition for equality of parameters). If corresponding parameters are equal for each of the two groups (for example detection probability at McNary Dam), then it is not necessary to estimate a separate parameter for each group. Rather, within the framework of the family of PR Models, the probability can be set equal between the two groups, reducing the total number of parameters estimated from the data. Generally, reducing the number of estimated parameters increases the precision of the remaining parameter estimates that are calculated.

Burnham et al. (1987) suggested an approach to model selection for paired releases, beginning with the most general "parallel-SR" Model. A series of models is then estimated using maximum likelihood theory, each model with one more pair of parameters set equal than the previous model, beginning with the farthest-downstream parameter (combined probability of survival and detection at Bonneville Dam or by the towed array (λ)) and working upstream. Thus, six distinct models are possible (Table 1). A model is selected from the family of models by testing successively more restrictive models using either likelihood ratio tests, or a series of contingency tests (TEST 1 in Burnham et al. 1987) until a model with fewer parameters is rejected (significance level 0.10). The survival estimate for the section of river between the two release sites is then the ratio of the two groups' estimated survival probabilities to McNary Dam from the selected model (eq. 1).

In the next section we report survival estimates for each pair of release groups derived from both the model-selection approach and the more general parallel-SR Model. Each model was estimated using the SURPH computer program developed at the University of Washington (Skalski et al. 1993; Smith et al. 1994). In addition, we calculated a weighted geometric mean of the individual survival estimates for each series of paired releases, using the formula:

$$\hat{S}_{wt} = \left(\prod_{i}^{n} \hat{S}_i^{w_i}\right)^{\frac{1}{\sum_i^n w_i}} \tag{3}$$

where n was the number of paired releases and weights (w_i) were equal to the inverse of the corresponding relative variance (coefficient of variation squared):

$$w_i = \frac{1}{\dfrac{\hat{V}ar(S_{T1})}{S_{T1}^{2}} + \dfrac{\hat{V}ar(S_{R1})}{S_{R1}^{2}}} \tag{4}$$

Geometric mean is the appropriate measure of central tendency when the data are ratios, as are the PR-Model survival estimates (eq. 1). For example, consider a two-replicate paired study in which the treatment group has twice the survival of the control group in one replicate (treatment/control ratio 2.0) and the control group has twice the survival of the treatment group in the other replicate (ratio 0.5). Logically, there is no difference between the two treatment levels on average. However, the arithmetic mean of the two ratio estimates, assuming equal weights, is 1.25. The geometric mean gives the correct value of 1.0.

The geometric mean is weighted so that the influence of an individual estimate on the mean is commensurate with its precision. In previous survival studies we have sometimes weighted averages by inverse variance. In both the SR and PR Models, however, the variance of the estimate is partly a function of the square of the point estimate itself. Weighting by inverse variance tends to put inappropriately high weighting on lower survival estimates.

Because some PIT-tagged fish are interrogated passing Rocky Reach Dam, it was also possible to estimate survival to Rocky Reach Dam tailrace for releases above the dam (Wells Dam tailrace and Rocky Reach Dam forebay) using the Single-Release Model (i.e., no pairing with a Rocky Reach Dam tailrace release was necessary). For a series of SR-Model estimates the (weighted) arithmetic mean is the appropriate measure of central tendency, because the estimates are not derived from ratios.

Tests of Assumptions

Mixing of fish from upriver and downriver release groups in a paired release increases the chance (but does not guarantee) that the two groups will have equal survival and detection probabilities downstream from mixing. The model selection process (Burnham et al. 1987) for paired release data does not require a strict assumption of mixing of the groups. Nevertheless, mixing is desirable, and investigation of the degree of mixing may lead to improvements in release protocol in future years of this study. We used chi-squared tests on contingency tables to test for homogeneity of daily passage distributions of paired groups at downstream dams. Because of the sparseness of many of the contingency tables, especially in the later parts of the groups' passage distributions, we used Monte Carlo approximation of the exact method (Mehta and Patel 1992) to calculate P values for contingency tables. Because there were actually three release sites on each date, we began by comparing the three passage distributions in a single test. Results then suggested calculation of tests for Rocky Reach tailrace/Rock Island tailrace pairs separately.

Each release group of the pair is assumed to satisfy assumptions of the Single-Release Model. There are two critical assumptions of the SR Model:

A1) A fish's detection at a PIT-tag detection site does not affect its probability of subsequent detection at downstream sites.

A2) A fish's detection at a PIT-tag detection site does not affect its probability of subsequent survival through downstream river reaches.

Tests of Assumptions A1 and A2 are general tests of the "goodness of fit" of the SR Model to the data. Burnham et al. (1987) gave a series of goodness-of-fit tests for the SR Model (TESTs 2 and 3, Burnham et al. 1987, pp. 71-77; see also Muir et al. 1995). TESTs 2 and 3 test the assumptions that detection histories at one or more upstream dams are not related to detection histories (i.e., survival and/or detection histories) at subsequent detection sites. Factors that may lead to rejection in the assumption tests include heterogeneity of parameters across individuals, failure of the assumption of independent fish fates, and behavioral response to capture and subsequent release (i.e., behavioral changes after passage through a juvenile bypass facility). We computed the suite of goodness-of-fit tests for each release group.

RESULTS

Fish Marking and Releases

On 15 days between 15 April and 5 May, 66,626 PIT-tagged fish in groups of about 1,500 fish each were transported to and released from barges at each of three release sites. Groups were released on each of the 15 days in the tailraces of Rocky Reach and Rock Island Dams. Fish were released into the tailrace of Wells Dam on 10 days and into the forebay of Rocky Reach Dam on 5 days. Delayed tagging/handling mortality and tag loss averaged 0.4% and 0.8% for all tagging groups, respectively (Table 2). A considerable number of shed tags were found in the release containers on 21 April. Tag loss continued to be a problem through the releases conducted on 24 April. After April 24, tagging technique was modified, and the number of shed tags decreased.

Tests of Assumptions

Downstream Mixing

Generally, passage distributions for all three release groups on a given release date were not homogeneous (i.e., groups were not well mixed) at any downstream dam (Table 3), particularly for releases in Wells Dam tailrace. Of 30 tests involving a Wells Dam tailrace release group (passage distributions at 3 dams for each of 10 sets of releases), 28 showed significant lack of mixing (significance level 0.10), and most tests were highly significant ($P < 0.001$). Rocky Reach Dam forebay release groups were better mixed with Rocky Reach Dam tailrace and Rock Island Dam tailrace release groups; only 4 of 15 tests showed significant lack of mixing. Inspection of graphs of detection distributions (Appendix Figs.) show the cause of the highly significant tests: Wells Dam tailrace release groups almost always arrived at downstream dams later than the groups released downstream on the same day.

Considering only groups released into the tailraces of Rocky Reach and Rock Island Dams on the same day (i.e., the same contingency tables as above, without the column for Wells Dam tailrace groups), fish were much better mixed (Table 4). Only 8 of 45 tests showed significant lack of mixing, none at the extreme significance levels seen with the Wells Dam release groups, and only 1 of the 15 pairs had significant nonhomogeneity at more than one dam.

These chi-squared tests are extremely sensitive to small departures from perfect mixing. Results for Rocky Reach/Rock Island paired release groups show very good mixing. The results when including Wells Dam release groups suggest more caution is necessary when pairing with downstream groups.

Goodness-of-Fit Tests

Significant ($\alpha = 0.10$) lack of fit was indicated by Test 2 in 3 of 10 release groups (Table 5) from Wells Dam tailrace, but by Test 3 in only one of the 10 groups (Table 6). Overall goodness of fit was rejected only for the last two (1 and 2 May) Wells Dam tailrace release groups (Table 7). Of the five release groups into the forebay of Rocky Reach Dam, Test 2 was rejected only for the 5 May release (Table 5) and Test 3 was rejected only for the 30 April release (Table 6). The overall test was significant for both of these latest release groups (Table 7). Test 2 was rejected for 3 of 15 Rocky Reach Dam tailrace releases and 2 of 15 Rock Island tailrace releases (Table 8). Test 3 was not rejected for any Rocky Reach Dam tailrace releases and 2 of 15 Rock Island tailrace releases (Table 9). Overall goodness of fit was rejected for only 1 of 15

Rocky Reach Dam tailrace releases and 4 of 15 Rock Island Dam tailrace release groups (Table 7).

Counting all release groups, overall goodness of fit was rejected at the 0.10 significance level 9 of 45 times (Table 7). The probability of this many rejections by chance alone (9 "successes" in 45 independent Bernoulli trials each with probability of success 0.10) is only 0.013, suggesting possible problems with the releases. However, the effect of lack of fit is likely not great, as only 2 of 45 tests were rejected at the 0.05 significance level; approximately the expectation by chance alone. None of the goodness-of-fit tests were rejected at the extreme levels of significance seen for the mixing tests.

Model Selection and Survival Estimation

Wells Dam tailrace to Rocky Reach Dam tailrace

The weighted geometric mean of the survival probability estimates derived from the "parallel SR Model" (M_{3S}) version of the PR Model for paired releases into Wells Dam and Rocky Reach Dam tailraces was 0.867 (s.e. 0.065) (Table 10). In the model selection process, despite the general lack of mixing of the paired release groups (Tables 3 and 7), the Ricker model (M_{1S}) was selected for 4 of the 10 pairs. Overall, there was no apparent pattern to the models that were selected, and the use of the selected models had little effect on the average point estimate (0.859). The standard error for the estimated mean survival probability was reduced to 0.042 using the selected models.

Rocky Reach Dam forebay to Rocky Reach Dam tailrace

The weighted geometric mean of the survival probability estimates derived from Model M_{3S} for paired releases into Rocky Reach Dam forebay and tailrace was 0.922 (s.e. 0.138) (Table 11). By the model selection process, the total number of estimated parameters was greatly reduced (e.g., Model M_{1S} was chosen for 3 of the 5 pairs). The average estimate derived from the selected models was only slightly different (0.924), but the standard error (0.068) was cut in half.

Rocky Reach Dam tailrace to Rock Island Dam tailrace

The weighted geometric mean of the survival probability estimates derived from Model M_{3S} for paired releases into the tailraces of Rocky Reach and Rock Island Dams was 0.854 (s.e. 0.051) (Table 12). The geometric mean estimate derived from the selected models was 0.889 (s.e. 0.039).

Single-Release Model Survival Estimates

Estimates of survival and detection probabilities from the full Single-Release Model for all 45 release groups are given in Tables 13 through 15. For Wells Dam tailrace and Rocky Reach Dam forebay releases, survival estimates (SR Model) from release to Rocky Reach Dam tailrace and detection probability estimates at Rocky Reach Dam are given in Table 16. The weighted arithmetic mean of SR-Model estimates from Wells Dam tailrace to Rocky Reach Dam tailrace was 0.835 (s.e. 0.036). The weighted arithmetic mean of SR-Model estimates from the Rocky Reach forebay to Rocky Reach Dam tailrace was 0.974 (s.e. 0.100).

DISCUSSION

Sample sizes (number of replicates and number of fish per release group) were selected for 1998 research expecting detection probabilities at McNary and John Day Dams around 0.30 and 0.40, respectively. With those detection probabilities, we anticipated standard errors of about 0.025 (i.e., 95% confidence interval of plus/minus about 5%) for mean survival of 15 replicates of 1,500 fish per release under the "parallel-SR" Paired-Release Model. In reality, spill volumes at the dams were much higher than anticipated, resulting in observed detection probabilities in 1998 that averaged about 0.16 at McNary Dam and 0.19 at John Day Dam. Consequently, the precision of the estimated mean survival from Rocky Reach Dam tailrace to Rock Island Dam tailrace (15 replicates) was only about half (standard error 0.051) of what we anticipated. Estimates between Wells Dam tailrace and Rocky Reach Dam tailrace (10 replicates) and between Rocky Reach Dam forebay and Rocky Reach Dam tailrace (5 replicates) were even less precise. Reducing the number of estimated parameters through the model selection process increased the precision of the estimates, but the desired precision of plus/minus 5% was still not achieved. Under conditions observed in 1998 around 110,000 fish per site--rather than the 22,500 we actually released--would have been needed to achieve that level of precision under the parallel-SR Model. In the foreseeable future spill volumes at McNary and John Day Dams are likely to remain high. Thus, PIT-tag detection rates at those projects similar to those observed in 1998 are expected in the future.

When selecting from the family of Paired-Release Models, there is a tradeoff between improved precision and potential bias. Selecting a model that included more parameters than were actually necessary (i.e., the two release groups had parameters in common, but we estimated separate parameters), would not bias the survival estimate, but would decrease the precision. A more serious problem would occur if we selected a model that had too few parameters (i.e., we set equal two parameters that should have been estimated separately): a biased survival estimate could result. The most conservative approach to model selection would use the parallel-SR Model for all paired release groups. However, by using a rejection rule that was liberal in rejecting null hypotheses of equality of parameters (significance level $\alpha = 0.10$), we minimized the potential for bias. Survival estimates based on models selected from the PR family of models were reliable and had better precision.

Overall, more goodness-of-fit tests were rejected at the 0.10 significance levels than expected by chance alone. However, the degree of lack of fit was fairly mild (only 2 of 45 tests were rejected at the 0.05 significance level, 7 had P values between 0.05 and 0.10). If the lack of fit did in fact bias survival estimates, the effect was small. For the reach between Wells Dam tailrace and Rocky Reach Dam tailrace, excluding pairs where one or the other group had significant overall lack of fit (24 Apr, 1 May, 2 May; Table 7) resulted in average survival estimates of 0.848 (s.e. 0.075) based on Model M_{3S} and 0.869 (s.e. 0.053) from the model selection process. Excluding pairs where one or the other group had significant overall lack of fit for the Rocky Reach Dam forebay/tailrace releases (30 Apr, 5 May; Table 7), the average survival estimate based on Model M_{3S} was 0.993 (s.e. 0.069) and based on the selected model was 0.966 (s.e. 0.044). Finally, for the reach between Rocky Reach Dam tailrace and Rock Island Dam tailrace, excluding pairs where one or the other group had significant overall lack of fit (15 Apr, 22-24 Apr, 1 May; Table 7) resulted in average survival estimates of 0.888 (s.e. 0.072) based on Model M_{3S} and 0.919 (s.e. 0.053) based on the selected model.

For Rocky Reach Dam tailrace release groups, the reach between Rocky Reach Dam tailrace and McNary Dam tailrace was the first for which survival was estimated using the SR Model (Table 14). Using detections at Rocky Reach Dam, survival was estimated in the same way using the SR Model for releases above Rocky Reach Dam (Table 16). For these releases, the Rocky Reach Dam tailrace-to-McNary Dam tailrace was the second reach for which survival was estimated. The mean survival estimate for groups released in Rocky Reach Dam tailrace was lower than for groups released above Rocky Reach Dam. Independent analysis of the PIT-tag data conducted by the University of Washington's Columbia Basin Research group suggested that handling mortality or tag loss that occurred soon after release, in the first reach for which survival was estimated (Dr. J. Skalski, UW, pers. comm.), could explain the difference in survival estimates. Fish released in the Wells Dam tailrace release groups had been in the river for some time before entering the Rocky Reach-McNary reach while fish in the Rocky Reach Dam tailrace groups entered the Rocky Reach-McNary reach immediately when released.

For release groups paired by release date, the survival estimate from Rocky Reach Dam tailrace to McNary Dam tailrace for the Rocky Reach Dam tailrace groups averaged (weighted geometric mean) only 95.8% of the estimate for the Wells Dam tailrace release groups, suggesting about 4.2% tag loss/handling mortality. (However, the standard error on the estimated handling mortality was 6.6%, so that the point estimate of 4.2% was not significantly different from 0%.) The average survival estimate from the SR Model for Wells Dam tailrace to Rocky Reach Dam tailrace was 0.835. Adjusted for presumed 4.2% handling mortality results in a "true" mean survival estimate of 0.835/0.958 = 0.872, which is very similar to the estimate derived from the paired release group data (0.867). No adjustment for handling mortality is needed for the estimate from the PR Model, because handling effects--presuming they were equal for each of the paired groups--cancel out in the ratio estimator (eq. 1). It was unlikely that handling effects were expressed only in the Wells tailrace release groups, as considerable effort was made to equalize the effects of tagging, handling, and transportation on all release groups.

SUMMARY OF SURVIVAL ESTIMATES

Several distinct methods were used to estimate survival probabilities for some river reaches (e.g., Single-Release Model, Selected Paired-Release Model, Parallel-SR Model for paired release groups). The resulting weighted mean (arithmetic for SR Model, geometric for PR Model) survival estimates are summarized in Table 17.

RECOMMENDATIONS

The pilot survival study conducted in the spring of 1998 provided useful information regarding methods for estimating the survival of downstream migrating salmonids passing Rocky Reach and Rock Island dams. Furthermore, the pilot study identified logistical and procedural problems with the PIT-tag survival study protocol and methodology in the mid-Columbia River. Correction of these problems will allow the District, NMFS, and the mid-Columbia and Rock Island Coordinating Committees to develop survival study protocols for HCP confirmation studies scheduled to commence in 2003. Specific problems to be addressed and recommendations for future studies include:

1) Detection rates of PIT-tagged fish at downstream projects were much lower than anticipated. Under the current management plan for the Columbia River, spill levels at the downstream detection projects are anticipated to remain at levels similar to those observed in 1998 and, therefore, detection rates are not expected to increase. Installation of PIT-tag detection equipment at projects between Rock Island and McNary dams or by reducing spill programs at the downstream detection projects could alleviate the problem. Neither of these events is likely in the foreseeable future. Sample size requirements under these conditions may preclude the use of PIT tags. Alternative fish tagging technology, such as radio tags, should be investigated for potential use in future survival studies.

2) Moving fish from river water on Turtle Rock to well water at Eastbank could have affected the behavior and survivability of test fish. Future studies should not use this type of treatment.

3) Fish markers inexperienced with PIT-tagging procedures were employed to mark fish for the 1998 survival study, possibly leading to the high rate of tag loss observed in some release groups. Future studies should use experienced taggers to PIT tag fish.

4) Use of compressed air for aeration of tanks during fish transport may have resulted in supersaturation of total dissolved gas in the release tanks. Supersaturated water has been shown to lead to gas bubble trauma, a potentially lethal condition that occurs when gasses in an animal's bloodstream come out of solution. Future studies should use compressed oxygen to aerate tanks and measure the total dissolved gas levels in release tanks prior to release.

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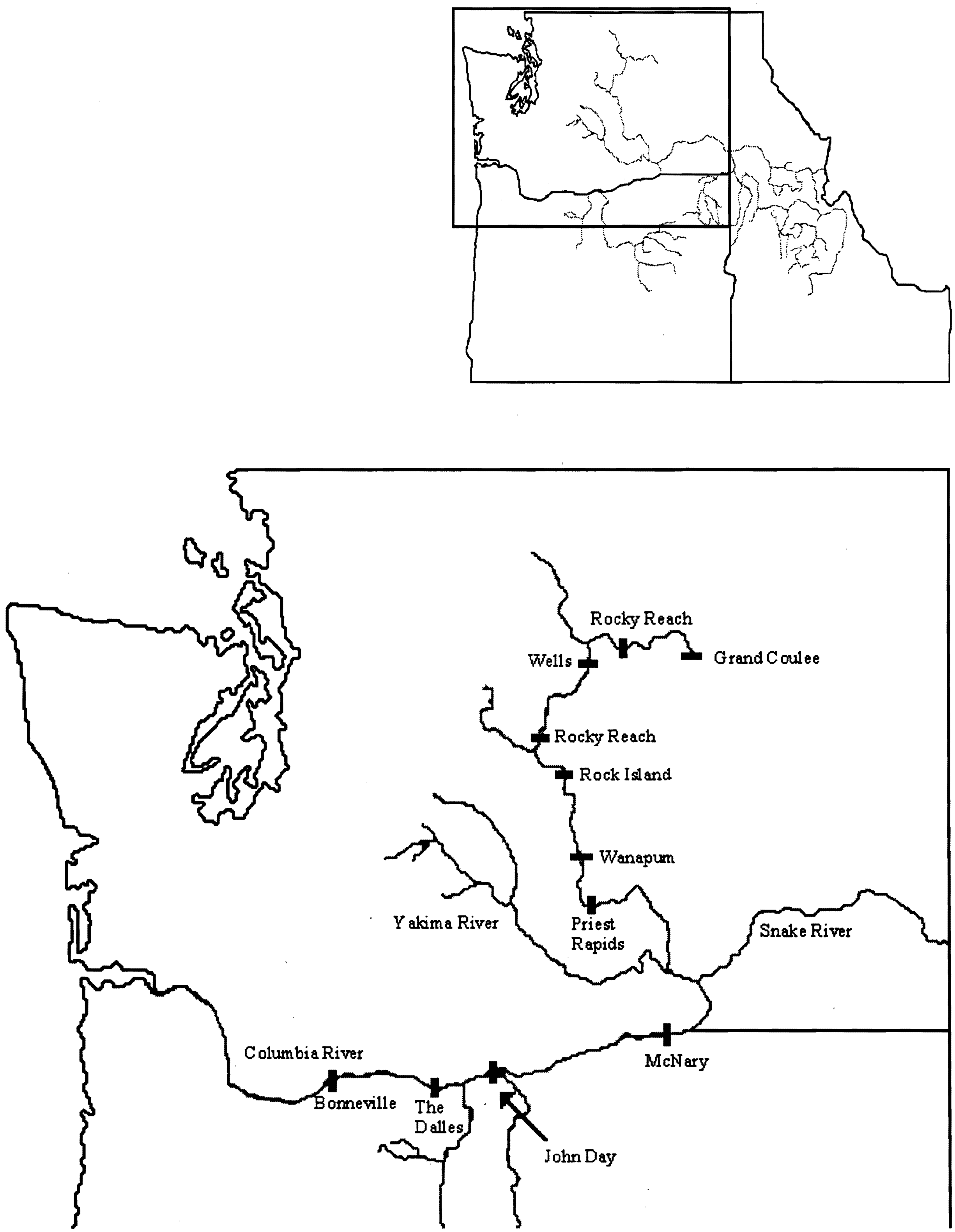


Figure 1. Study area showing release and detection sites.

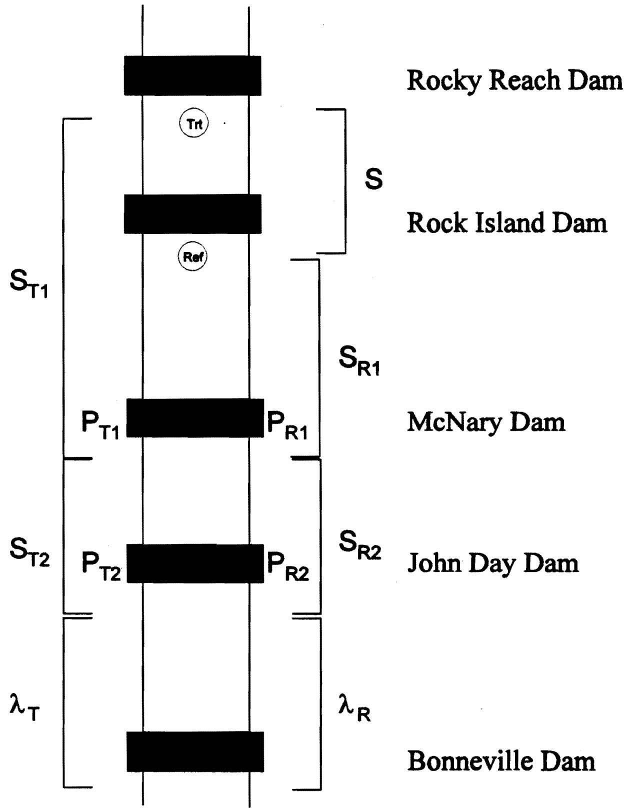


Figure 2. Schematic illustration of paired release groups into tailraces of Rocky Reach Dam and Rock Island Dam.

Table 1. Possible Paired-Release Models for paired release groups in the mid-Columbia River, 1998. Notation adapted from Burnham et al. 1987, Table 2.2.

Notation	Total number of parameters	Parameters estimated	Notes
M_{3S}	10	$S_{T1},P_{T1},S_{T2},P_{T2},\lambda_T$ $S_{R1},P_{R1},S_{R2},P_{R2},\lambda_R$	"Parallel SR Models"
M_{2P}	9	$S_{T1},P_{T1},S_{T2},P_{T2},\lambda$ $S_{R1},P_{R1},S_{R2},P_{R2}$	
M_{2S}	8	$S_{T1},P_{T1},S_{T2},P_2,\lambda$ S_{R1},P_{R1},S_{R2}	
M_{1P}	7	$S_{T1},P_{T1},S_2,P_2,\lambda$ S_{R1},P_{R1}	
M_{1S}	6	$S_{T1},P_1,S_2,P_2,\lambda$ S_{R1}	Only treatment effect is on survival to McNary Dam. "Ricker Model"
M_0	5	S_1,P_1,S_2,P_2,λ	No treatment effect; all probabilities equal.

Table 2. Date, release location, mortality, tag loss, transportation time, and flow at time of release for PIT-tagged hatchery yearling chinook salmon released during the mid-Columbia River survival study, 1998. Abbreviations: wel-Wells Dam tailrace; rrf-Rocky Reach forebay; rrt-Rocky Reach tailrace; rit-Rock Island tailrace.

Release date	Release site	Number tagged	Observed mortality		Observed tag loss		Transportation time (hr)[a]	Number released	Flow at release site (kcfs)	
			Number	Percent	Number	Percent			Flow	Spill
15 April	wel	1,500	1	0.1	0	0.0	1.5	1,499	68.2	0.9
	rrt	1,501	27	1.8	0	0.0	1.0	1,474	70.9	7.8
	rit	1,501	29	1.9	0	0.0	1.4	1,472	73.5	11.6
16 April	wel	1,500	2	0.1	0	0.0	1.6	1,498	54.9	4.6
	rrt	1,500	4	0.3	0	0.0	1.2	1,496	55.6	9.9
	rit	1,500	2	0.1	0	0.0	1.3	1,498	55.1	18.0
17 April	rrf	1,500	5	0.3	1	0.1	0.9	1,494	69.1	6.6
	rrt	1,500	5	0.3	2	0.1	1.2	1,493	69.1	6.6
	rit	1,501	2	0.1	0	0.0	1.3	1,499	69.5	20.4
18 April	wel	1,500	2	0.1	0	0.0	1.5	1,498	63.7	6.0
	rrt	1,500	3	0.2	0	0.0	1.2	1,497	72.3	10.7
	rit	1,500	1	0.1	0	0.0	1.3	1,499	72.1	20.0
21 April	wel	1,501	2	0.1	0	0.0	1.5	1,499	102.5	8.4
	rrt	1,501	0	0.0	0	0.0	1.2	1,501	102.1	9.3
	rit	1,500	4	0.3	13	0.9	1.6	1,483	102.4	20.3

Table 2. Continued.

Release date	Release site	Number tagged	Observed mortality		Observed tag loss		Transportation time (hr)[a]	Number released	Flow at release site (kcfs)	
			Number	Percent	Number	Percent			Flow	Spill
22 April	rrf	1,500	1	0.1	1	0.1	1.4	1,498	108.5	14.2
	rrt	1,500	1	0.1	48	3.2	1.2	1,451	108.5	14.2
	rit	1,502	0	0.0	46	3.1	1.6	1,456	108.5	26.9
23 April	wel	1,500	4	0.3	72	4.8	1.8	1,424	86.0	7.6
	rrt	1,501	5	0.3	83	5.5	1.4	1,413	98.4	16.8
	rit	1,500	3	0.2	76	5.1	1.6	1,421	99.5	30.1
24 April	wel	1,500	6	0.4	13	0.9	2.0	1,481	86.5	7.6
	rrt	1,500	2	0.1	77	5.1	2.0	1,421	82.8	20.9
	rit	1,503	10	0.8	16	1.1	0.7	1,477	85.6	29.7
25 April	rrf	1,400	0	0.0	1	0.1	2.0	1,399	89.0	14.4
	rrt	1,501	2	0.1	1	0.1	1.8	1,498	89.0	14.4
	rit	1,501	1	0.1	2	0.1	1.6	1,498	93.7	23.5
28 April	wel	1,500	3	0.2	2	0.1	1.8	1,495	114.9	9.7
	rrt	1,502	13	0.9	4	0.3	2.0	1,485	118.5	13.0
	rit	1,500	6	0.4	7	0.5	2.2	1,487	120.6	30.3
29 April	wel	1,500	10	0.7	3	0.2	2.4	1,487	123.7	10.3
	rrt	1,502	5	0.3	5	0.3	2.2	1,492	126.6	17.5
	rit	1,500	1	0.1	0	0.0	2.0	1,499	129.9	30.3

Table 2. Continued.

Release date	Release site	Number tagged	Observed mortality		Observed tag loss		Transportation time (hr)[a]	Number released	Flow at release site (kcfs)	
			Number	Percent	Number	Percent			Flow	Spill
30 April	rrf	1,503	4	0.3	5	0.3	2.0	1,494	115.1	20.0
	rrt	1,502	5	0.3	7	0.5	2.0	1,490	115.1	20.0
	rit	1,500	5	0.3	9	0.6	1.9	1,486	120.2	30.4
01 May	wel	1,500	7	0.5	6	0.4	1.9	1,487	126.3	10.6
	rrt	1,500	12	0.8	11	0.7	1.1	1,477	129.7	20.4
	rit	1,500	3	0.2	4	0.3	2.3	1,493	138.8	38.4
02 May	wel	1,500	7	0.5	6	0.4	2.2	1,487	123.2	9.9
	rrt	1,500	14	0.9	0	0.0	2.2	1,486	126.7	18.9
	rit	1,501	8	0.5	6	0.4	2.0	1,487	138.3	41.2
05 May	rrf	1,502	6	0.4	1	0.1	2.0	1,495	171.1	23.0
	rrt	1,500	26	1.7	0	0.0	1.9	1,474	171.1	23.0
	rit	1,501	12	0.8	1	0.1	2.0	1,488	181.1	41.0
Totals		67,426	271	0.4	529	0.8		66,626		

a. Transportation times from 15 April through 23 April represent the elapsed time from departure from the hatchery to release into the river. Times from 24 April through 05 May represent time tanks were removed from flow-through water at the hatchery to release into the river.

Table 3. Tests of homogeneity of passage distributions for sets of three release groups on each release date. P values calculated using Monte Carlo approximation of the exact method. Shaded cells indicate significant tests (significance level $\alpha = 0.10$). Abbreviations: wel-Wells Dam tailrace; rrt-Rocky Reach Dam tailrace; rit-Rock Island Dam tailrace; rrf-Rocky Reach Dam forebay; d.f.-degrees of freedom.

		McNary Dam			John Day Dam			Bonneville Dam		
Date	Sites	χ^2	d.f.	P value	χ^2	d.f.	P value	χ^2	d.f.	P value
15 Apr	wel,rrt,rit	161.0	118	0.001	138.8	98	0.001	116.5	84	0.001
16 Apr	wel,rrt,rit	153.6	106	<0.001	146.4	92	<0.001	114.0	86	0.006
17 Apr	rrf,rrt,rit	105.7	104	0.429	109.2	96	0.128	57.8	68	0.887
18 Apr	wel,rrt,rit	162.7	104	<0.001	170.9	96	<0.001	109.0	76	0.001
21 Apr	wel,rrt,rit	167.2	106	<0.001	187.1	104	<0.001	122.5	80	<0.001
22 Apr	rrf,rrt,rit	134.1	104	0.009	107.5	92	0.083	85.7	82	0.351
23 Apr	wel,rrt,rit	200.6	106	<0.001	218.7	92	<0.001	95.0	78	0.050
24 Apr	wel,rrt,rit	191.9	122	<0.001	167.8	116	<0.001	101.5	82	0.037
25 Apr	rrf,rrt,rit	154.7	114	0.001	104.0	94	0.189	85.3	84	0.442
28 Apr	wel,rrt,rit	161.3	120	0.002	166.1	112	<0.001	91.0	82	0.187
29 Apr	wel,rrt,rit	159.3	116	0.001	153.8	106	<0.001	105.9	88	0.054
30 Apr	rrf,rrt,rit	135.8	124	0.158	132.7	102	0.010	94.7	96	0.557
1 May	wel,rrt,rit	125.9	116	0.228	140.6	106	<0.001	95.5	82	0.099
2 May	wel,rrt,rit	137.7	118	0.067	135.2	108	0.018	113.1	96	0.056
5 May	rrf,rrt,rit	137.1	126	0.199	123.4	100	0.035	80.6	82	0.560

Table 4. Tests of homogeneity of passage distributions for paired Rocky Reach Dam tailrace/Rock Island Dam tailrace release groups on each release date. P values calculated using Monte Carlo approximation of the exact method. Shaded cells indicate significant tests (significance level $\alpha = 0.10$). Abbreviations: rrt-Rocky Reach Dam tailrace; rit-Rock Island Dam tailrace; d.f.-degrees of freedom.

		McNary Dam			John Day Dam			Bonneville Dam		
Date	Sites	χ^2	d.f.	P value	χ^2	d.f.	P value	χ^2	d.f.	P value
15 Apr	rrt, rit	56.3	52	0.276	41.6	41	0.439	40.0	32	0.088
16 Apr	rrt, rit	49.8	45	0.248	56.6	41	0.022	30.7	32	0.584
17 Apr	rrt, rit	55.3	50	0.237	38.3	39	0.530	24.3	32	0.916
18 Apr	rrt, rit	46.8	45	0.392	46.8	42	0.247	34.6	28	0.128
21 Apr	rrt, rit	52.1	45	0.170	47.1	45	0.374	34.6	35	0.519
22 Apr	rrt, rit	52.7	47	0.219	54.6	43	0.066	38.5	35	0.279
23 Apr	rrt, rit	55.2	38	0.013	60.6	43	0.016	34.9	31	0.262
24 Apr	rrt, rit	79.5	54	0.002	47.6	47	0.454	38.7	36	0.336
25 Apr	rrt, rit	56.4	49	0.171	52.6	45	0.158	36.3	40	0.719
28 Apr	rrt, rit	75.2	54	0.009	53.2	50	0.330	26.5	35	0.939
29 Apr	rrt, rit	54.0	49	0.255	53.5	47	0.200	38.7	37	0.392
30 Apr	rrt, rit	68.2	54	0.039	51.1	43	0.145	45.9	39	0.136
1 May	rrt, rit	48.0	54	0.775	55.0	49	0.228	39.6	36	0.283
2 May	rrt, rit	57.5	53	0.291	50.5	48	0.367	45.0	41	0.258
5 May	rrt, rit	58.1	58	0.490	51.9	46	0.220	34.2	37	0.688

Table 5. Test statistics and P values for Burnham et al. (1987) TEST 2 for Wells Dam tailrace and Rocky Reach Dam forebay release groups. Shaded cells indicate significant tests (significance level $\alpha = 0.10$). Abbreviations: wel-Wells Dam tailrace; rrf-Rocky Reach Dam forebay; d.f.-degrees of freedom.

		TEST 2.C2 (Rocky Reach Dam and Below--2 d.f.)		TEST 2.C3 (McNary Dam and Below--1 d.f.)		Total TEST 2 (3 d.f.)	
Date	Site	χ^2	P value	χ^2	P value	χ^2	P value
15 Apr	wel	1.146	0.564	0.089	0.765	1.235	0.745
16 Apr	wel	1.958	0.376	0.302	0.583	2.260	0.520
17 Apr	rrf	3.740	0.154	0.426	0.514	4.166	0.244
18 Apr	wel	0.485	0.785	1.262	0.261	1.747	0.627
21 Apr	wel	0.635	0.728	0.195	0.659	0.830	0.842
22 Apr	rrf	2.893	0.235	0.238	0.626	3.131	0.372
23 Apr	wel	6.442	0.040	0.362	0.547	6.804	0.078
24 Apr	wel	0.264	0.876	0.423	0.515	0.687	0.876
25 Apr	rrf	0.387	0.824	0.816	0.366	1.203	0.752
28 Apr	wel	1.641	0.440	0.022	0.882	1.663	0.645
29 Apr	wel	3.861	0.145	2.055	0.152	5.916	0.116
30 Apr	rrf	5.989	0.050	0.178	0.673	6.167	0.104
1 May	wel	6.030	0.049	1.207	0.272	7.237	0.065
2 May	wel	0.264	0.876	9.302	0.002	9.566	0.023
5 May	rrf	6.044	0.049	0.572	0.449	6.616	0.085

Table 6. Test statistics and P values for Burnham et al. (1987) TEST 3 for Wells Dam tailrace and Rocky Reach Dam forebay release groups. Individual tests had one degree of freedom. Test 3 total has degrees of freedom equal to sum for individual tests. Shaded cells indicate significant tests (significance level $\alpha = 0.10$). Abbreviations: wel-Wells Dam tailrace; rrf-Rocky Reach Dam forebay; NA-test cannot be calculated with available data.

		TEST 3.SR3		TEST 3.Sm3		TEST 3.SR4		Total TEST 3	
Date	Site	χ^2	P value	χ^2	P value	χ^2	P value	χ^2	P value
15 Apr	wel	0.045	0.832	0.039	0.843	6.481	0.011	6.565	0.087
16 Apr	wel	1.520	0.218	0.201	0.654	0.319	0.572	2.040	0.564
17 Apr	rrf	0.060	0.806	1.548	0.213	0.564	0.453	2.172	0.537
18 Apr	wel	0.204	0.652	3.402	0.065	0.694	0.405	4.300	0.231
21 Apr	wel	0.933	0.334	NA	NA	NA	NA	0.933	0.334
22 Apr	rrf	0.884	0.347	0.516	0.473	0.046	0.830	1.446	0.695
23 Apr	wel	0.106	0.745	0.551	0.458	0.224	0.636	0.881	0.830
24 Apr	wel	0.260	0.610	0.281	0.596	1.447	0.229	1.988	0.575
25 Apr	rrf	0.963	0.326	0.520	0.471	0.004	0.950	1.487	0.685
28 Apr	wel	0.734	0.392	1.800	0.180	1.519	0.218	4.053	0.256
29 Apr	wel	1.069	0.301	NA	NA	NA	NA	1.069	0.301
30 Apr	rrf	6.784	0.009	0.113	0.737	1.167	0.280	8.064	0.045
1 May	wel	2.083	0.149	NA	NA	NA	NA	2.083	0.149
2 May	wel	1.015	0.314	1.397	0.237	0.441	0.507	2.853	0.415
5 May	rrf	1.245	0.265	0.263	0.608	3.264	0.071	4.772	0.189

Table 7. Overall test statistics (sum of TESTs 2 and 3) and P values for Burnham et al. (1987) goodness-of-fit tests. Shaded cells indicate significant tests (significance level α = 0.10).

	Wells Dam tailrace release		Rocky Reach Dam forebay release		Rocky Reach Dam tailrace release		Rock Island Dam tailrace release	
Date	χ^2	P value	χ^2	P value	χ^2	P value	χ^2	P value
15 Apr	7.800	0.253	no release		0.557	0.757	5.820	0.054
16 Apr	4.300	0.636	no release		2.349	0.309	1.115	0.573
17 Apr	no release		6.338	0.386	0.560	0.756	0.355	0.837
18 Apr	6.047	0.418	no release		1.892	0.388	1.564	0.457
21 Apr	1.763	0.779	no release		2.374	0.305	1.388	0.500
22 Apr	no release		4.577	0.599	0.480	0.787	5.047	0.080
23 Apr	7.685	0.262	no release		4.599	0.100	5.006	0.082
24 Apr	2.675	0.848	no release		6.095	0.047	0.977	0.614
25 Apr	no release		2.690	0.847	0.228	0.892	0.033	0.984
28 Apr	5.716	0.456	no release		3.918	0.141	2.039	0.361
29 Apr	6.985	0.137	no release		1.232	0.540	0.189	0.910
30 Apr	no release		14.231	0.027	0.411	0.814	0.947	0.623
1 May	9.320	0.054	no release		1.268	0.530	5.037	0.081
2 May	12.419	0.053	no release		0.533	0.766	0.089	0.956
5 May	no release		11.388	0.077	0.069	0.966	1.212	0.546

Table 8. Test statistics and P values for Burnham et al. (1987) TEST 2 for Rocky Reach Dam tailrace and Rock Island Dam tailrace release groups. All tests have one degree of freedom. Shaded cells indicate significant tests (significance level $\alpha = 0.10$).

	TEST 2 (Rocky Reach Dam tailrace release)		TEST 2 (Rock Island Dam tailrace release)	
Date	χ^2	P value	χ^2	P value
15 Apr	0.223	0.637	3.036	0.081
16 Apr	1.196	0.274	0.392	0.531
17 Apr	0.006	0.938	0.172	0.678
18 Apr	0.141	0.707	1.057	0.304
21 Apr	0.678	0.410	0.065	0.799
22 Apr	0.055	0.815	2.334	0.127
23 Apr	3.189	0.074	4.463	0.035
24 Apr	6.040	0.014	0.742	0.389
25 Apr	0.228	0.633	0.026	0.872
28 Apr	3.841	0.050	1.590	0.207
29 Apr	1.102	0.294	0.188	0.665
30 Apr	0.041	0.840	0.001	0.975
1 May	0.267	0.605	0.040	0.841
2 May	0.214	0.644	0.055	0.815
5 May	0.062	0.803	0.906	0.341

Table 9. Test statistics and P values for Burnham et al. (1987) TEST 3 for Rocky Reach Dam tailrace and Rock Island Dam tailrace release groups. All tests had one degree of freedom. Shaded cells indicate significant tests (significance level $\alpha = 0.10$).

	TEST 3 (Rocky Reach Dam tailrace release)		TEST 3 (Rock Island Dam tailrace release)	
Date	χ^2	P value	χ^2	P value
15 Apr	0.334	0.563	2.784	0.095
16 Apr	1.153	0.283	0.723	0.395
17 Apr	0.554	0.457	0.183	0.669
18 Apr	1.751	0.186	0.507	0.476
21 Apr	1.696	0.193	1.323	0.250
22 Apr	0.425	0.514	2.713	0.101
23 Apr	1.410	0.235	0.543	0.461
24 Apr	0.055	0.815	0.235	0.628
25 Apr	0.000	1.000	0.007	0.933
28 Apr	0.077	0.781	0.449	0.503
29 Apr	0.130	0.718	0.001	0.975
30 Apr	0.370	0.543	0.946	0.331
1 May	1.001	0.317	4.997	0.025
2 May	0.319	0.572	0.034	0.854
5 May	0.007	0.933	0.306	0.580

Table 10. Survival estimates from Wells Dam tailrace to Rocky Reach Dam tailrace based on Paired-Release Model. Estimates derived from both parallel-Single-Release Model and model selection process are given. Abbreviations: RRT-Rocky Reach Dam tailrace; MCN-McNary Dam tailrace.

	Based on parallel SR Model			Based on selected PR model			
Date	Wells-MCN $(\hat{S}_{T1})$	RRT-MCN $(\hat{S}_{R11})$	Wells-RRT Ratio $(\hat{S})$	Model Selected	Wells-MCN $(\hat{S}_{T1})$	RRT-MCN $(\hat{S}_{R11})$	Wells-RRT Ratio $(\hat{S})$
15 Apr	0.472 (0.056)	0.658 (0.074)	0.717 (0.117)	M_{1S}	0.514 (0.042)	0.649 (0.050)	0.792 (0.089)
16 Apr	0.724 (0.119)	0.741 (0.109)	0.977 (0.216)	M_{2P}	0.724 (0.116)	0.741 (0.107)	0.977 (0.211)
18 Apr	0.531 (0.087)	0.886 (0.141)	0.599 (0.137)	M_{1S}	0.594 (0.072)	0.816 (0.095)	0.728 (0.122)
21 Apr	0.762 (0.206)	0.644 (0.070)	1.183 (0.345)	M_{2S}	0.762 (0.206)	0.642 (0.059)	1.187 (0.339)
23 Apr	0.565 (0.093)	0.680 (0.090)	0.831 (0.175)	M_{2P}	0.551 (0.078)	0.678 (0.077)	0.813 (0.147)
24 Apr	0.676 (0.133)	0.662 (0.102)	1.021 (0.255)	M_{1S}	0.601 (0.078)	0.741 (0.094)	0.811 (0.147)
28 Apr	0.709 (0.145)	0.623 (0.088)	1.138 (0.283)	M_{3S}	0.707 (0.120)	0.625 (0.088)	1.131 (0.249)
29 Apr	0.719 (0.157)	0.745 (0.114)	0.965 (0.257)	M_{2P}	0.720 (0.075)	0.748 (0.091)	0.963 (0.154)
1 May	0.524 (0.104)	0.761 (0.135)	0.689 (0.183)	M_{1S}	0.552 (0.077)	0.734 (0.100)	0.752 (0.147)
2 May	0.808 (0.217)	0.656 (0.098)	1.232 (0.379)	M_{3S}	0.818 (0.221)	0.750 (0.110)	1.091 (0.335)
Weighted geometric mean			**0.867 (0.065)**				**0.859 (0.042)**

Table 11. Survival estimates from Rocky Reach Dam forebay to Rocky Reach Dam tailrace based on Paired-Release Model. Estimates derived from both parallel-Single-Release Model and model selection process are given. Abbreviations: RRF-Rocky Reach Dam forebay; RRT-Rocky Reach Dam tailrace; MCN-McNary Dam tailrace.

	Based on parallel SR Model			Based on selected PR model			
Date	RRF-MCN ($\hat{S}_{T1}$)	RRT-MCN ($\hat{S}_{R!1}$)	RRF-RRT Ratio ($\hat{S}$)	Model Selected	RRF-MCN ($\hat{S}_{T1}$)	RRT-MCN ($\hat{S}_{R!1}$)	RRF-RRT Ratio ($\hat{S}$)
17 Apr	0.536 (0.064)	0.602 (0.071)	0.890 (0.149)	M_{1S}	0.547 (0.050)	0.591 (0.053)	0.926 (0.119)
22 Apr	0.691 (0.098)	0.650 (0.083)	1.063 (0.203)	M_{1P}	0.689 (0.072)	0.651 (0.066)	1.058 (0.154)
25 May	0.791 (0.148)	0.709 (0.108)	1.116 (0.269)	M_{1S}	0.710 (0.088)	0.773 (0.095)	0.918 (0.160)
30 Apr	0.527 (0.067)	1.344 (0.373)	0.392 (0.120)	M_{2S}	0.542 (0.056)	1.000 (0.373)	0.542 (0.210)
5 May	0.600 (0.114)	0.540 (0.078)	1.111 (0.265)	M_{1S}	0.517 (0.063)	0.605 (0.072)	0.855 (0.146)
Weighted geometric mean			**0.922 (0.138)**				**0.924 (0.068)**

Table 12. Survival estimates from Rocky Reach Dam tailrace to Rock Island Dam tailrace based on Paired-Release Model. Estimates derived from both parallel-Single-Release Model and model selection process are given. Abbreviations: RRT-Rocky Reach Dam tailrace; RIT-Rock Island Dam tailrace; MCN-McNary Dam tailrace.

	Based on parallel SR Model			Based on selected PR model			
Date	RRT-MCN ($\hat{S}_{T1}$)	RIT-MCN ($\hat{S}_{R11}$)	RRT-RIT Ratio ($\hat{S}$)	Model Selected	RRT-MCN ($\hat{S}_{T1}$)	RIT-MCN ($\hat{S}_{R11}$)	RRT-RIT Ratio ($\hat{S}$)
15 Apr	0.658 (0.074)	0.938 (0.115)	0.701 (0.117)	M_{2P}	0.681 (0.074)	0.938 (0.115)	0.726 (0.118)
16 Apr	0.741 (0.109)	0.846 (0.100)	0.876 (0.165)	M_{1S}	0.698 (0.069)	0.884 (0.085)	0.790 (0.109)
17 Apr	0.602 (0.071)	0.707 (0.096)	0.851 (0.153)	M_{1S}	0.646 (0.049)	0.654 (0.049)	0.988 (0.105)
18 Apr	0.886 (0.141)	0.643 (0.068)	1.378 (0.263)	M_{2P}	0.886 (0.141)	0.653 (0.068)	1.357 (0.258)
21 Apr	0.644 (0.070)	0.676 (0.078)	0.953 (0.151)	M_{1S}	0.658 (0.056)	0.663 (0.056)	0.992 (0.119)
22 Apr	0.650 (0.083)	0.991 (0.133)	0.656 (0.122)	M_{1P}	0.686 (0.069)	0.938 (0.092)	0.731 (0.103)
23 Apr	0.680 (0.090)	0.750 (0.100)	0.907 (0.170)	M_{1S}	0.704 (0.062)	0.727 (0.067)	0.968 (0.123)
24 Apr	0.662 (0.102)	0.775 (0.090)	0.854 (0.165)	M_{3S}	0.662 (0.102)	0.775 (0.090)	0.854 (0.165)
25 Apr	0.709 (0.108)	1.183 (0.211)	0.599 (0.141)	M_{2S}	0.709 (0.108)	1.000 (0.211)	0.709 (0.185)
28 Apr	0.623 (0.088)	0.781 (0.116)	0.798 (0.164)	M_{2P}	0.623 (0.088)	0.781 (0.116)	0.798 (0.164)
29 Apr	0.745 (0.114)	0.796 (0.120)	0.936 (0.201)	M_{1S}	0.750 (0.085)	0.793 (0.089)	0.946 (0.151)
30 Apr	1.344 (0.373)	0.875 (0.140)	1.536 (0.492)	M_{2S}	1.000 (0.373)	0.875 (0.140)	1.143 (0.464)
1 May	0.761 (0.135)	0.708 (0.115)	1.075 (0.259)	M_{1S}	0.723 (0.090)	0.743 (0.093)	0.973 (0.172)
2 May	0.656 (0.098)	0.888 (0.146)	0.739 (0.164)	M_{1S}	0.723 (0.077)	0.808 (0.090)	0.895 (0.138)
5 May	0.540 (0.078)	0.821 (0.134)	0.658 (0.143)	M_{3S}	0.540 (0.078)	0.868 (0.134)	0.624 (0.132)
Weighted geometric mean			**0.854 (0.051)**				**0.893 (0.039)**

Table 13. Estimates of survival and detection probabilities for groups released from Wells Dam tailrace and Rocky Reach Dam forebay. Estimates based on Single-Release Model. Standard errors in parentheses. Abbreviations: Rel-Release site; MCN-McNary Dam tailrace; JDA-John Day Dam tailrace.

	Survival Probability		Detection Probability		Capture/Survival
Date	Rel-MCN	MCN-JDA	MCN	JDA	Below JDA
Wells Dam tailrace release groups					
15 Apr	0.472 (0.056)	1.0[a] (0.300)	0.196 (0.027)	0.179 (0.042)	0.101 (0.025)
16 Apr	0.724 (0.119)	0.970 (0.305)	0.123 (0.022)	0.153 (0.042)	0.069 (0.020)
18 Apr	0.531 (0.087)	1.0[a] (0.479)	0.147 (0.027)	0.116 (0.039)	0.067 (0.023)
21 Apr	0.762 (0.206)	0.425 (0.162)	0.078 (0.023)	0.227 (0.063)	0.091 (0.027)
23 Apr	0.565 (0.093)	1.0[a] (0.578)	0.150 (0.028)	0.107 (0.041)	0.050 (0.020)
24 Apr	0.676 (0.133)	0.863 (0.322)	0.112 (0.024)	0.145 (0.048)	0.064 (0.022)
28 Apr	0.709 (0.145)	0.989 (0.396)	0.107 (0.024)	0.113 (0.040)	0.059 (0.022)
29 Apr	0.719 (0.157)	0.728 (0.257)	0.091 (0.022)	0.167 (0.048)	0.078 (0.024)
1 May	0.524 (0.104)	0.624 (0.188)	0.114 (0.025)	0.271 (0.064)	0.099 (0.026)
2 May	0.808 (0.217)	0.514 (0.180)	0.060 (0.018)	0.230 (0.054)	0.099 (0.025)
Rocky Reach Dam forebay release groups					
17 Apr	0.536 (0.064)	1.0[a] (0.306)	0.208 (0.028)	0.182 (0.047)	0.075 (0.021)
22 Apr	0.691 (0.098)	0.626 (0.138)	0.150 (0.024)	0.253 (0.046)	0.142 (0.027)
25 May	0.791 (0.148)	1.0[a] (0.463)	0.108 (0.022)	0.113 (0.040)	0.048 (0.018)
30 Apr	0.527 (0.067)	0.925 (0.216)	0.179 (0.026)	0.217 (0.045)	0.116 (0.026)
5 May	0.600 (0.114)	0.841 (0.349)	0.149 (0.030)	0.136 (0.052)	0.059 (0.023)

a. Model-based estimate greater than 1.0.

Table 14. Estimates of survival and detection probabilities for groups released from Rocky Reach Dam tailrace. Estimates based on Single-Release Model. Standard errors in parentheses. Abbreviations: Rel-Rocky Reach Dam tailrace; MCN-McNary Dam tailrace; JDA-John Day Dam tailrace.

	Survival Probability		Detection Probability		Capture/Survival
Date	Rel-MCN	MCN-JDA	MCN	JDA	Below JDA
15 Apr	0.658 (0.074)	1.0[a] (0.269)	0.198 (0.025)	0.163 (0.037)	0.092 (0.022)
16 Apr	0.741 (0.109)	0.552 (0.132)	0.162 (0.026)	0.250 (0.050)	0.126 (0.027)
17 Apr	0.602 (0.071)	0.895 (0.223)	0.205 (0.027)	0.211 (0.048)	0.090 (0.022)
18 Apr	0.886 (0.141)	0.778 (0.228)	0.133 (0.023)	0.149 (0.038)	0.086 (0.023)
21 Apr	0.644 (0.070)	1.0[a] (0.253)	0.205 (0.026)	0.186 (0.042)	0.086 (0.021)
22 Apr	0.650 (0.083)	0.749 (0.184)	0.195 (0.028)	0.219 (0.048)	0.105 (0.025)
23 Apr	0.680 (0.090)	0.777 (0.179)	0.153 (0.023)	0.260 (0.051)	0.099 (0.022)
24 Apr	0.662 (0.102)	0.867 (0.256)	0.154 (0.026)	0.169 (0.044)	0.089 (0.024)
25 Apr	0.709 (0.108)	0.879 (0.232)	0.126 (0.022)	0.190 (0.043)	0.091 (0.022)
28 Apr	0.623 (0.088)	0.687 (0.161)	0.161 (0.026)	0.241 (0.048)	0.126 (0.027)
29 Apr	0.745 (0.114)	0.525 (0.120)	0.136 (0.023)	0.319 (0.056)	0.120 (0.024)
30 Apr	1.0[a] (0.373)	0.442 (0.180)	0.064 (0.019)	0.143 (0.044)	0.071 (0.023)
1 May	0.761 (0.135)	1.0[a] (0.378)	0.117 (0.023)	0.131 (0.043)	0.053 (0.018)
2 May	0.656 (0.098)	1.0[a] (1.183)	0.150 (0.025)	0.067 (0.032)	0.026 (0.013)
5 May	0.540 (0.078)	0.859 (0.246)	0.179 (0.029)	0.194 (0.050)	0.092 (0.025)

a. Model-based estimate greater than 1.0.

Table 15. Estimates of survival and detection probabilities for groups released from Rock Island Dam tailrace. Estimates based on Single-Release Model. Standard errors in parentheses. Abbreviations: Rel-Rock Island Dam tailrace; MCN-McNary Dam tailrace; JDA-John Day Dam tailrace.

	Survival Probability		Detection Probability		Capture/Survival
Date	Rel-MCN	MCN-JDA	MCN	JDA	Below JDA
15 Apr	0.938 (0.115)	0.675 (0.155)	0.165 (0.023)	0.224 (0.045)	0.090 (0.020)
16 Apr	0.846 (0.100)	0.783 (0.169)	0.169 (0.022)	0.200 (0.038)	0.112 (0.022)
17 Apr	0.707 (0.096)	0.773 (0.190)	0.159 (0.024)	0.218 (0.047)	0.097 (0.022)
18 Apr	0.643 (0.068)	1.0[a] (0.246)	0.205 (0.025)	0.202 (0.044)	0.084 (0.020)
21 Apr	0.676 (0.078)	0.826 (0.170)	0.181 (0.024)	0.237 (0.043)	0.119 (0.023)
22 Apr	0.991 (0.133)	0.633 (0.142)	0.144 (0.021)	0.232 (0.043)	0.105 (0.021)
23 Apr	0.750 (0.100)	0.834 (0.210)	0.156 (0.023)	0.208 (0.046)	0.083 (0.020)
24 Apr	0.775 (0.090)	0.608 (0.109)	0.167 (0.022)	0.311 (0.046)	0.149 (0.024)
25 Apr	1.0[a] (0.211)	0.479 (0.127)	0.106 (0.020)	0.202 (0.041)	0.112 (0.024)
28 Apr	0.781 (0.116)	0.696 (0.179)	0.135 (0.022)	0.242 (0.053)	0.082 (0.020)
29 Apr	0.796 (0.120)	0.778 (0.203)	0.125 (0.021)	0.213 (0.047)	0.082 (0.020)
30 Apr	0.875 (0.140)	0.537 (0.133)	0.128 (0.022)	0.250 (0.050)	0.110 (0.024)
1 May	0.708 (0.115)	0.754 (0.233)	0.145 (0.026)	0.193 (0.052)	0.073 (0.021)
2 May	0.888 (0.146)	0.639 (0.175)	0.119 (0.021)	0.211 (0.048)	0.085 (0.021)
5 May	0.821 (0.134)	1.0[a] (0.630)	0.139 (0.025)	0.088 (0.037)	0.034 (0.015)

a. Model-based estimate greater than 1.0.

Table 16. Estimates of survival and detection probabilities for groups released from Wells Dam tailrace and Rocky Reach Dam forebay. Estimates based on Single-Release Model using detections at Rocky Reach Dam. Standard errors in parentheses. Abbreviations: Rel-Release site; RRT-Rocky Reach Dam tailrace; MCN-McNary Dam tailrace.

	Survival Probability		Detection Probability
Date	Rel-RRT	RRT-MCN	Rocky Reach
Wells Dam tailrace release groups			
15 Apr	0.825 (0.118)	0.581 (0.107)	0.103 (0.017)
16 Apr	0.993 (0.172)	0.729 (0.174)	0.073 (0.014)
18 Apr	0.649 (0.089)	0.821 (0.174)	0.125 (0.020)
21 Apr	0.842 (0.168)	0.904 (0.304)	0.086 (0.019)
23 Apr	0.731 (0.118)	0.754 (0.171)	0.097 (0.018)
24 Apr	0.926 (0.162)	0.729 (0.192)	0.091 (0.018)
28 Apr	0.829 (0.143)	0.855 (0.228)	0.090 (0.017)
29 Apr	0.995 (0.205)	0.724 (0.217)	0.069 (0.016)
1 May	0.887 (0.159)	0.591 (0.158)	0.097 (0.019)
2 May	0.856 (0.149)	0.956 (0.306)	0.096 (0.019)
Rocky Reach Dam forebay release groups			
17 Apr	1.0[a] (0.144)	0.534 (0.099)	0.101 (0.016)
22 Apr	1.0[a] (0.231)	0.669 (0.176)	0.042 (0.011)
25 May	1.0[a] (0.325)	0.581 (0.177)	0.047 (0.012)
30 Apr	0.978 (0.174)	0.536 (0.117)	0.071 (0.014)
5 May	0.844 (0.098)	0.716 (0.159)	0.189 (0.025)

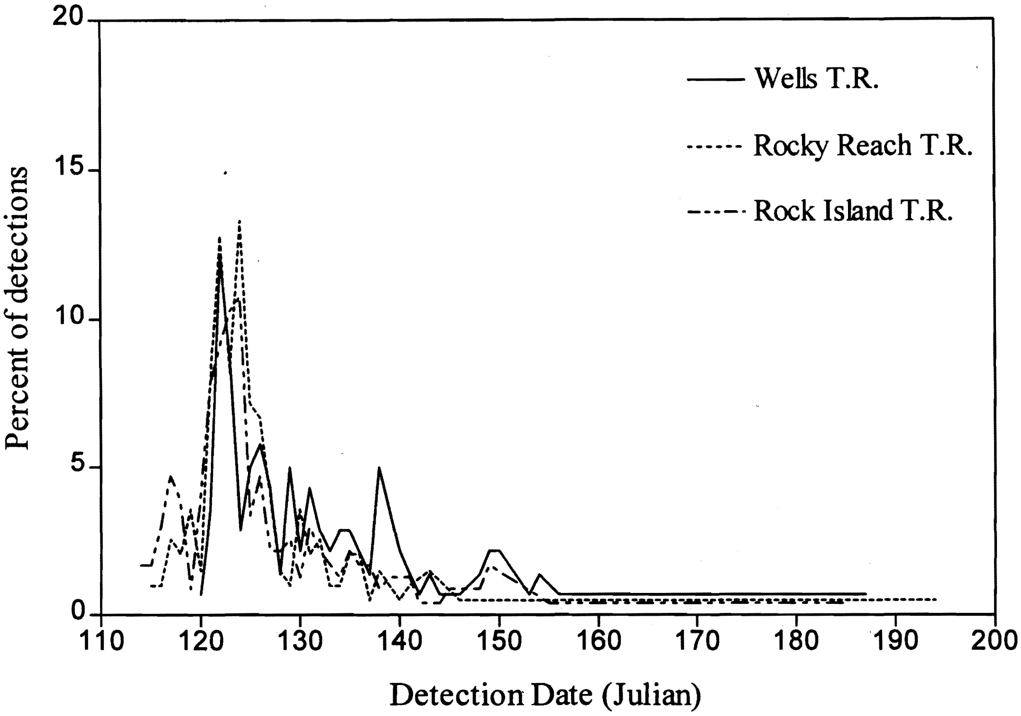
a. Model-based estimate greater than 1.0.

Table 17. Summary of mean survival estimates, mid-Columbia River survival study, 1998. Standard errors are in parentheses. Estimates from preferred method are in shaded cells. Abbreviations: PR-Paired Release; SR-Single Release; WEL-Wells Dam tailrace; RRT-Rocky Reach Dam tailrace; MCN-McNary Dam tailrace; RRF-Rocky Reach Dam forebay; RIT-Rock Island Dam tailrace.

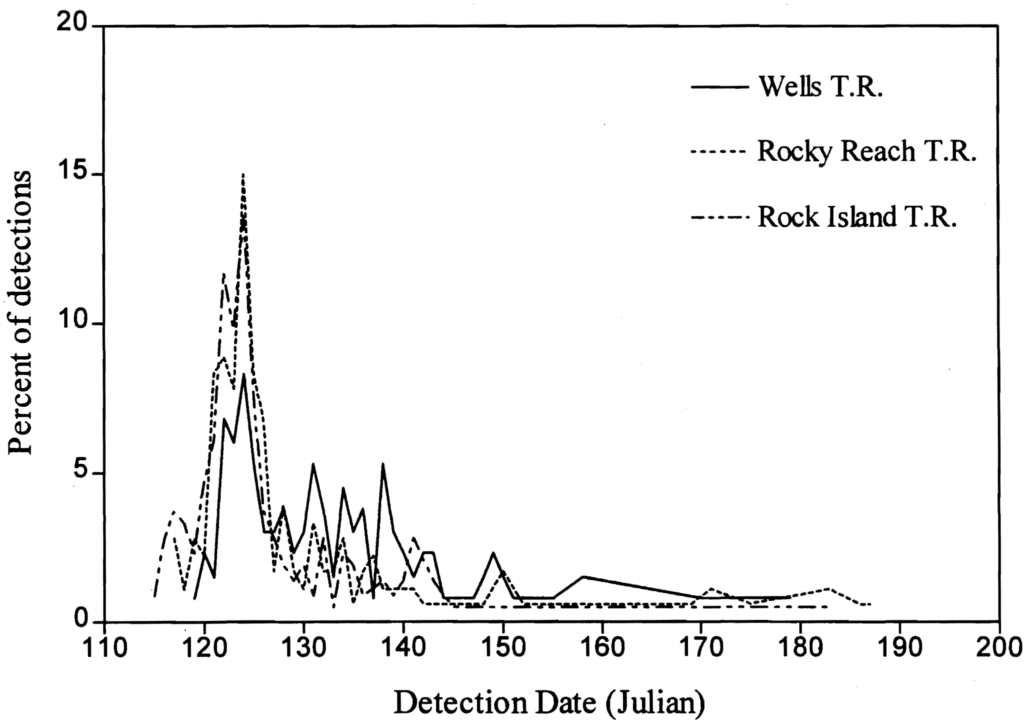
Reach	Selected PR Model	Parallel-SR Model	SR Model	Discussion
WEL-RRT	0.859 (0.042)	0.867 (0.065)	0.835 (0.036)	0.869 (0.053)[a] 0.848 (0.075)[b] 0.872[c]
WEL-MCN	NA	NA	0.606 (0.085)	NA
RRF-RRT	0.924 (0.068)	0.922 (0.138)	0.974 (0.100)	0.966 (0.044)[a] 0.993 (0.069)[b]
RRF-MCN	NA	NA	0.604 (0.124)	NA
RRT-RIT	0.893 (0.039)	0.854 (0.051)	NA	0.919 (0.053)[a] 0.888 (0.072)[b]
RRT-MCN	NA	NA	0.683 (0.051)	NA
RIT-MCN	NA	NA	0.806 (0.035)	NA

a. Selected PR Model excluding pairs with significant violation of goodness-of-fit test.
b. Parallel-SR Model excluding pairs with significant violation of goodness-of-fit test.
c. Single-Release Model estimate adjusted for 4.2% estimated handling mortality/tag loss.

Replicate #1 (Release Date 4/15)

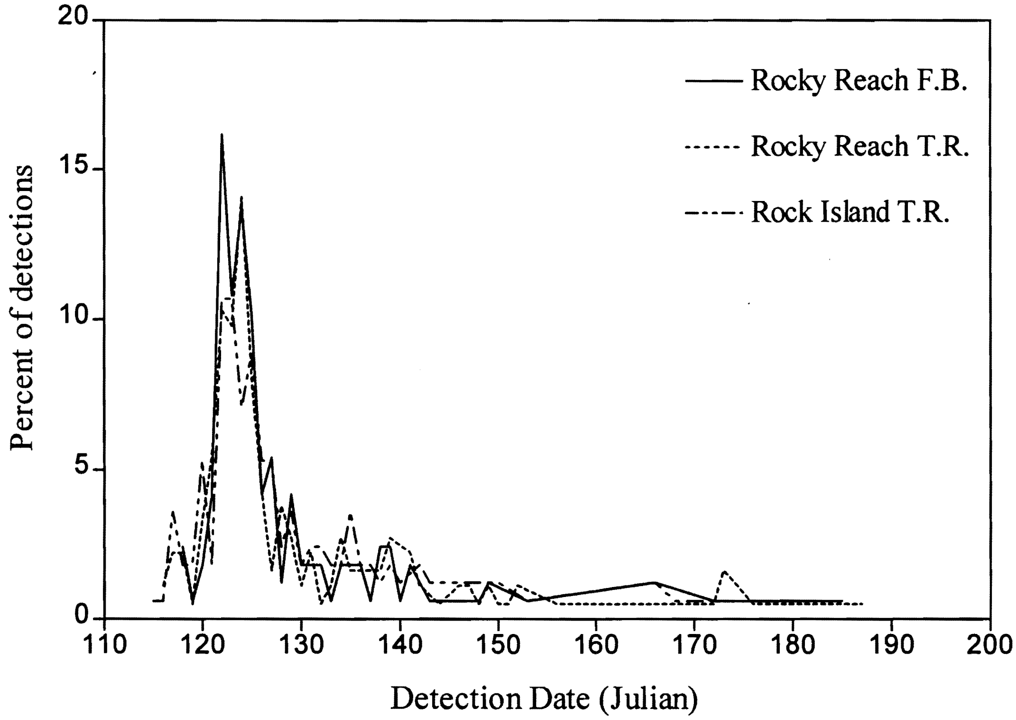


Replicate #2 (Release Date 4/16)

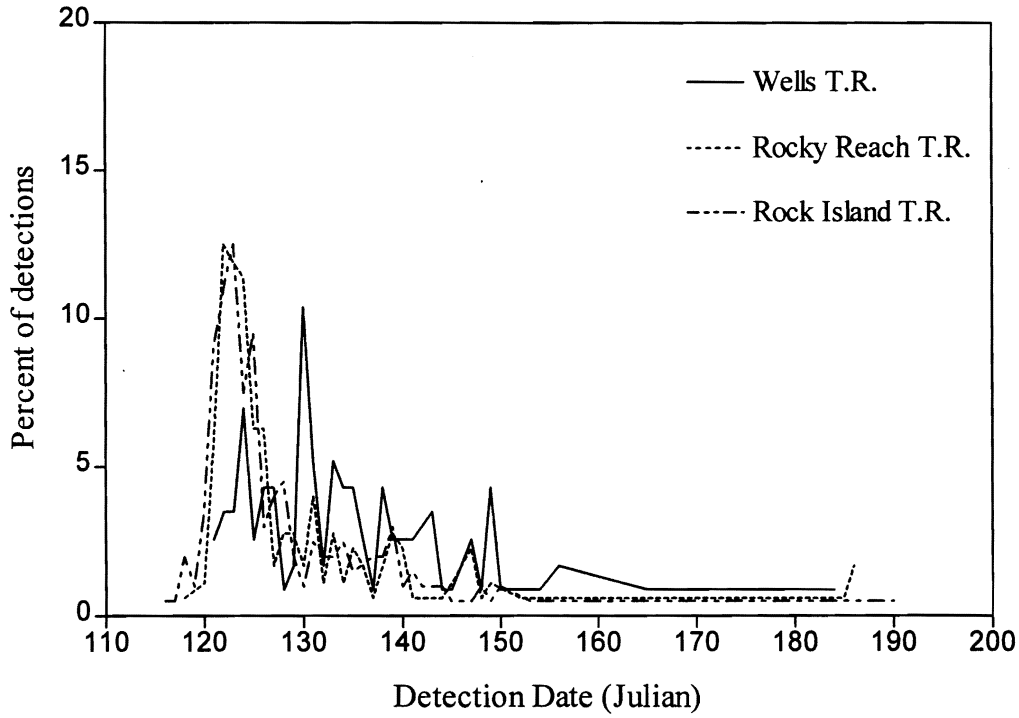


Appendix Figure 1. Passage distributions at McNary Dam for PIT-tagged hatchery yearling fall chinook salmon released for the Mid-Columbia survival study, 1998.

Replicate #3 (Release Date 4/17)

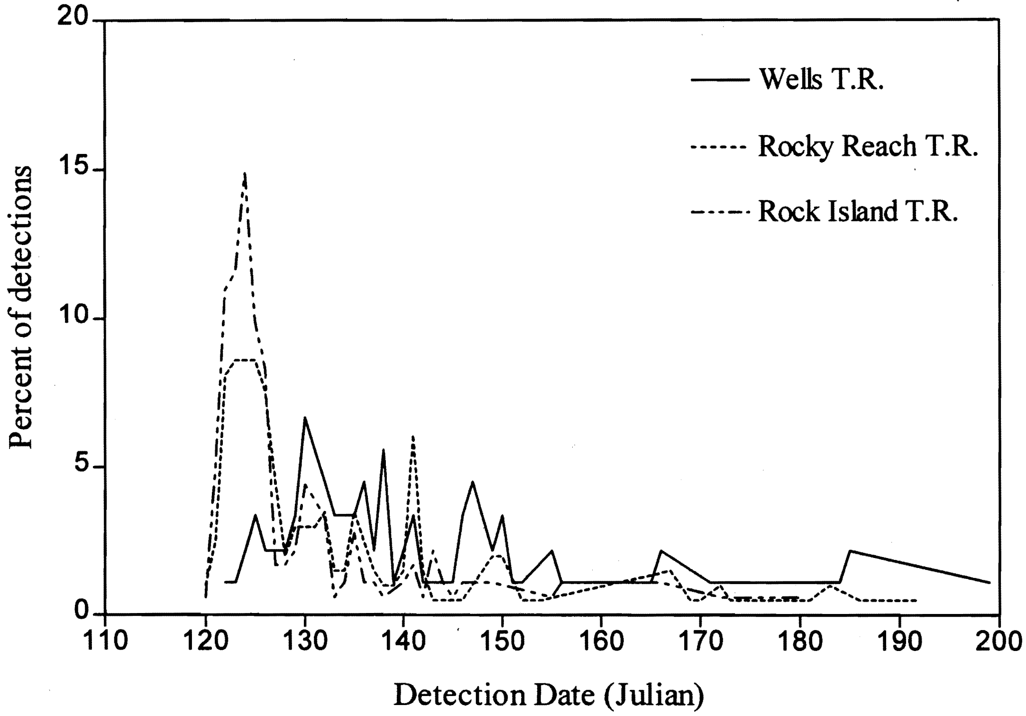


Replicate #4 (Release Date 4/18)

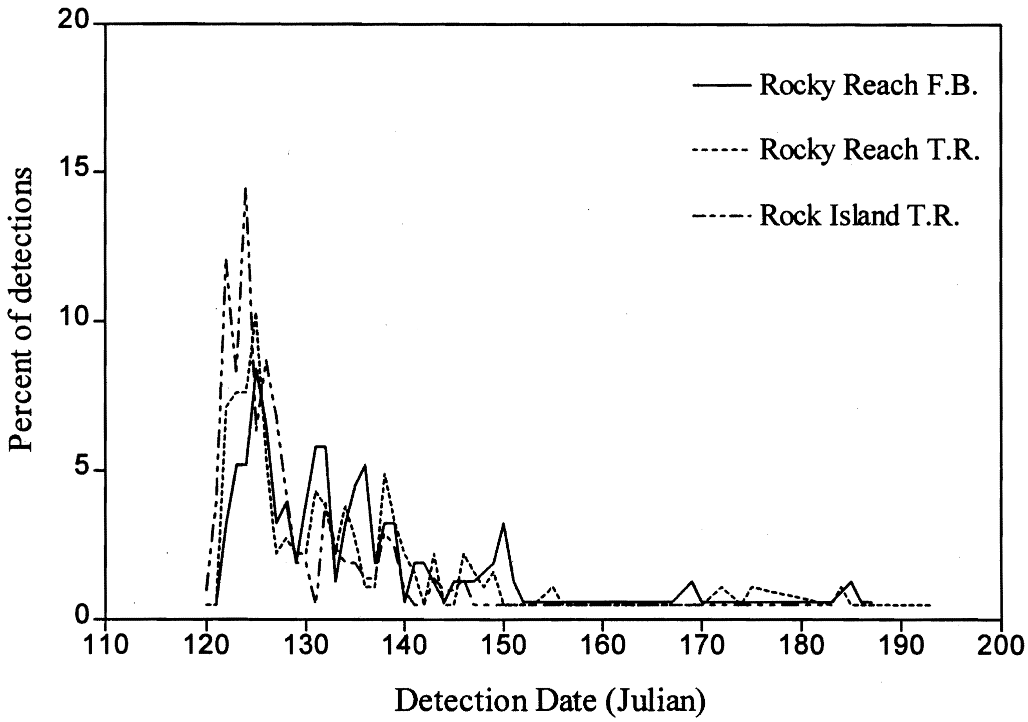


Appendix Figure 1. Continued.

Replicate #5 (Release Date 4/21)

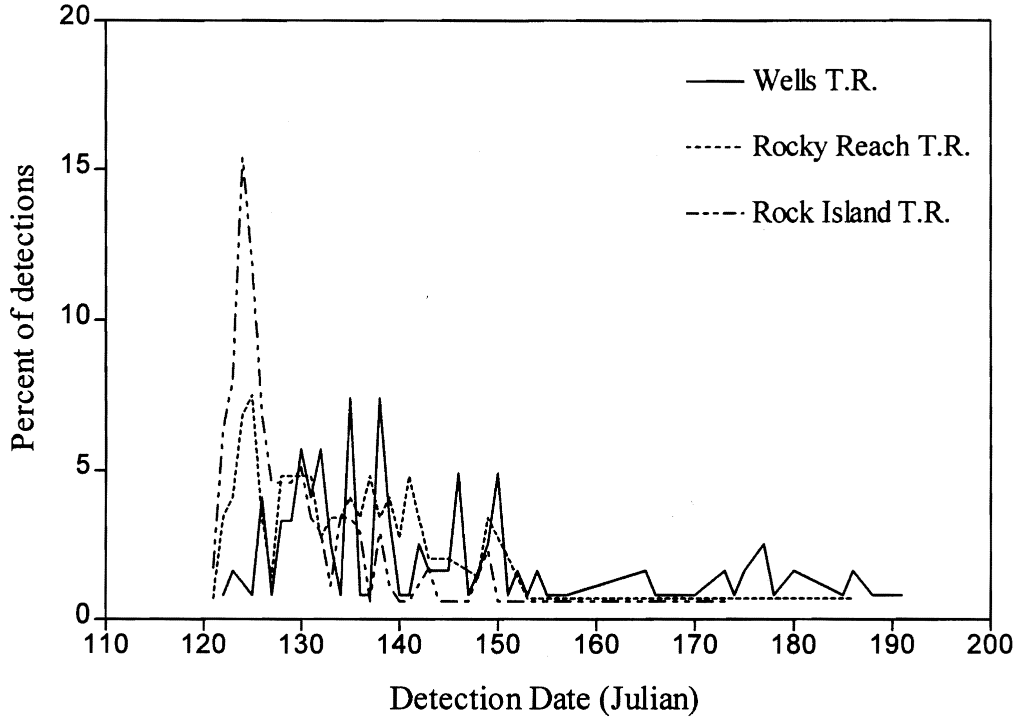


Replicate #6 (Release Date 4/22)

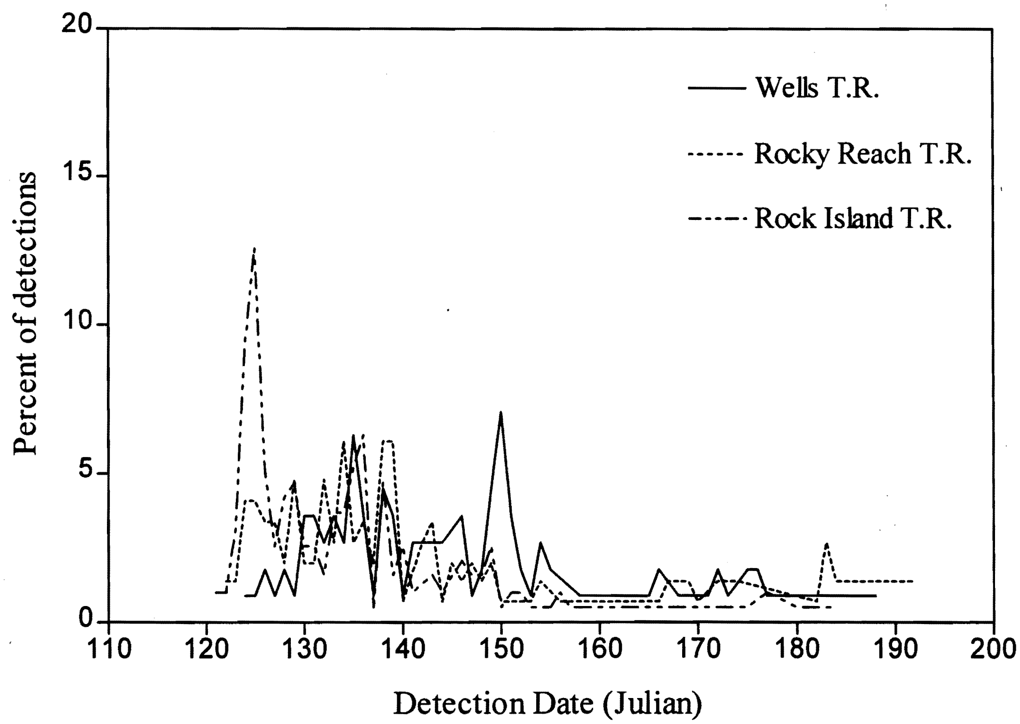


Appendix Figure 1. Continued.

Replicate #7 (Release Date 4/23)

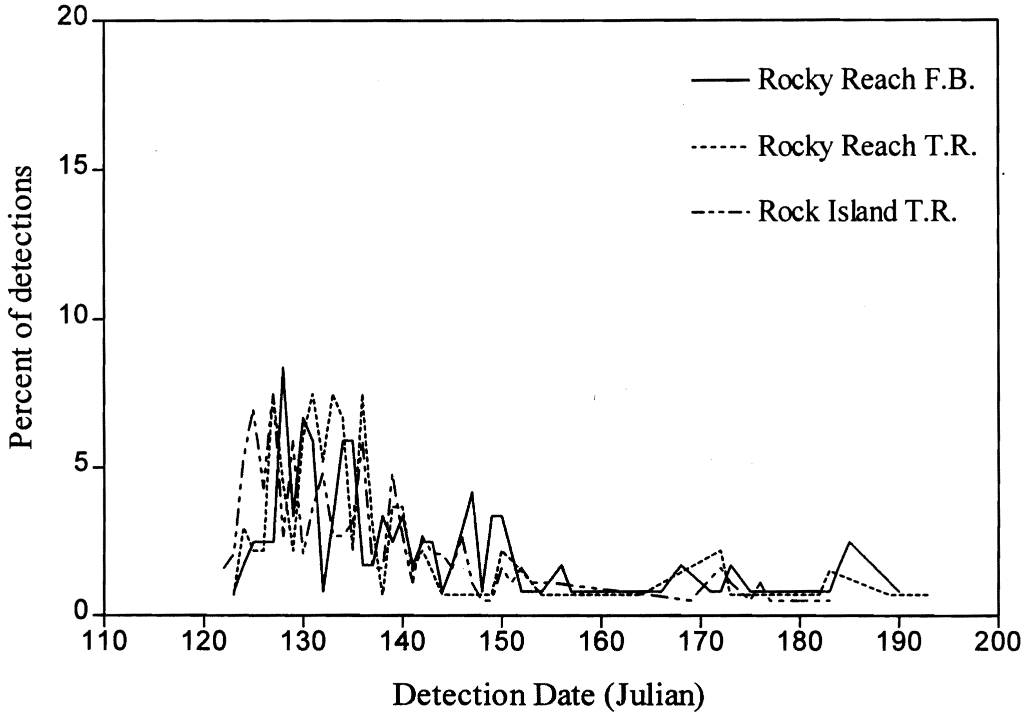


Replicate #8 (Release Date 4/24)

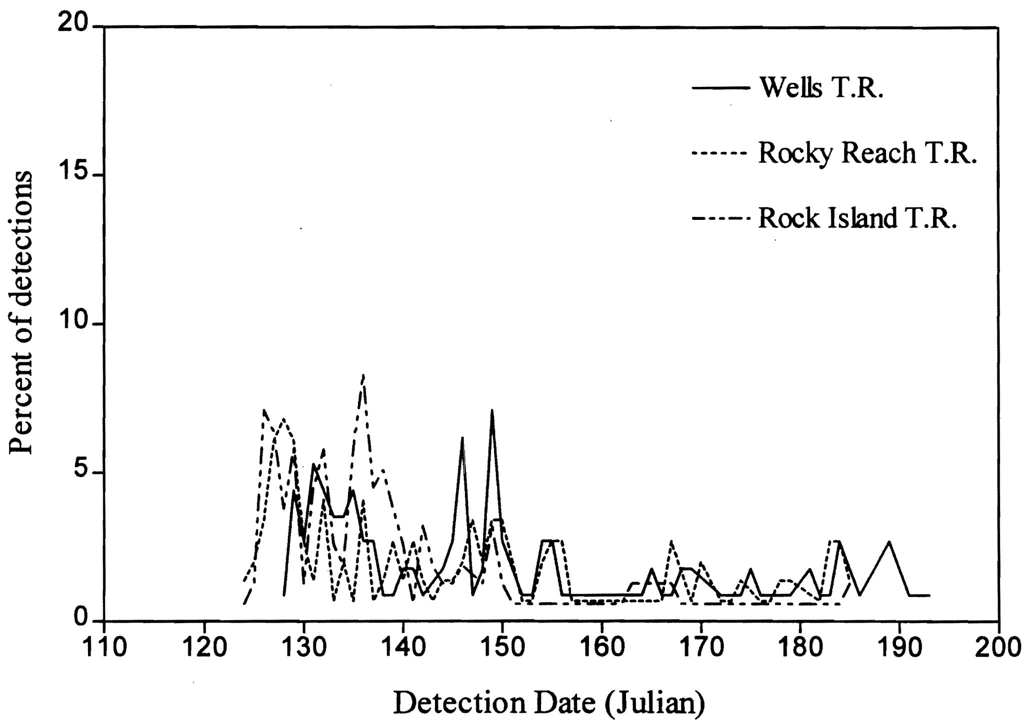


Appendix Figure 1. Continued.

Replicate #9 (Release Date 4/25)

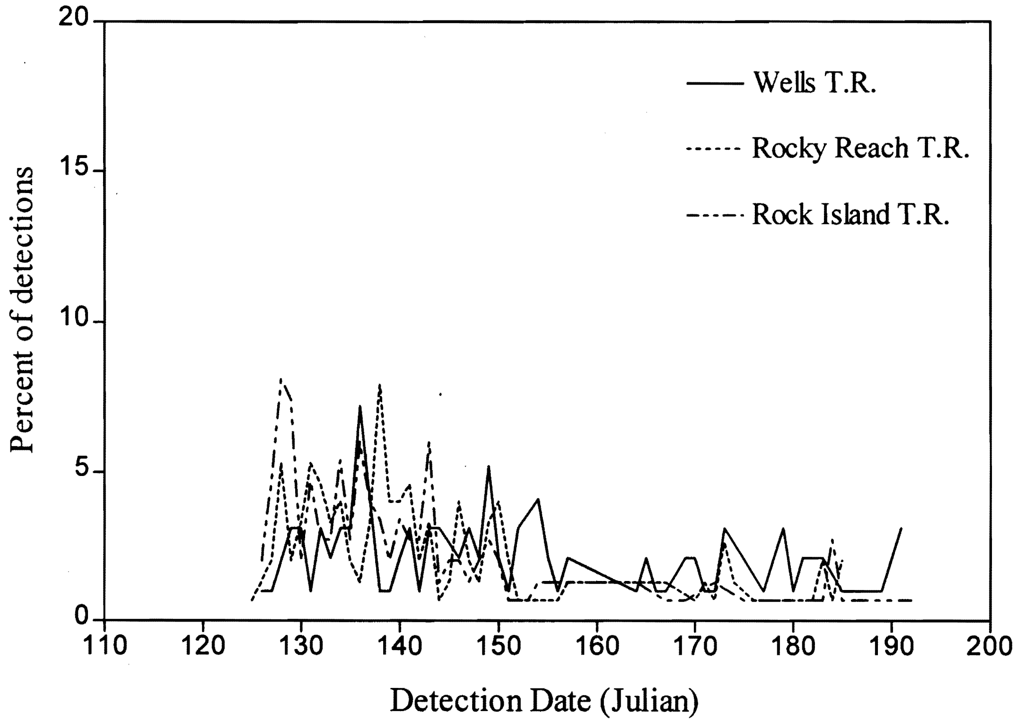


Replicate #10 (Release Date 4/28)

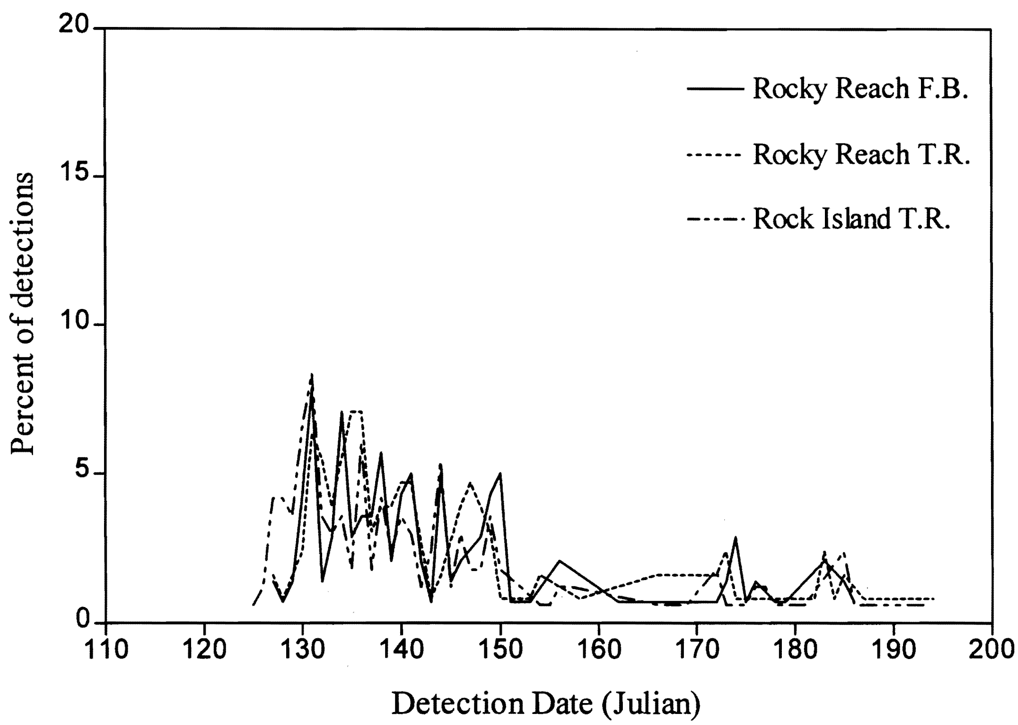


Appendix Figure 1. Continued.

Replicate #11 (Release Date 4/29)

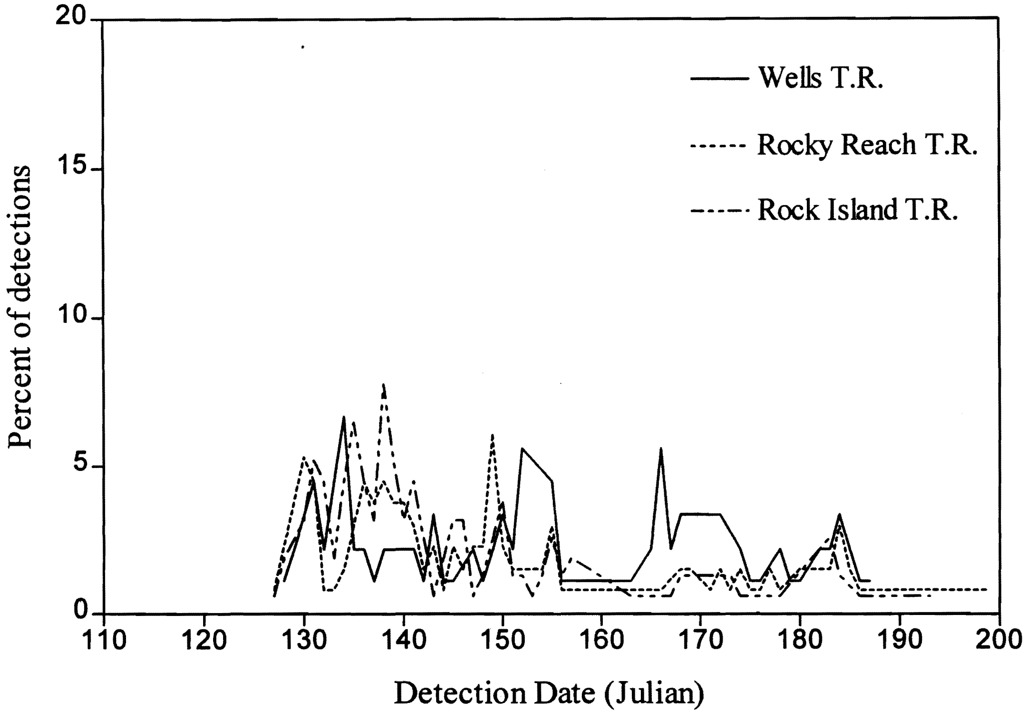


Replicate #12 (Release Date 4/30)

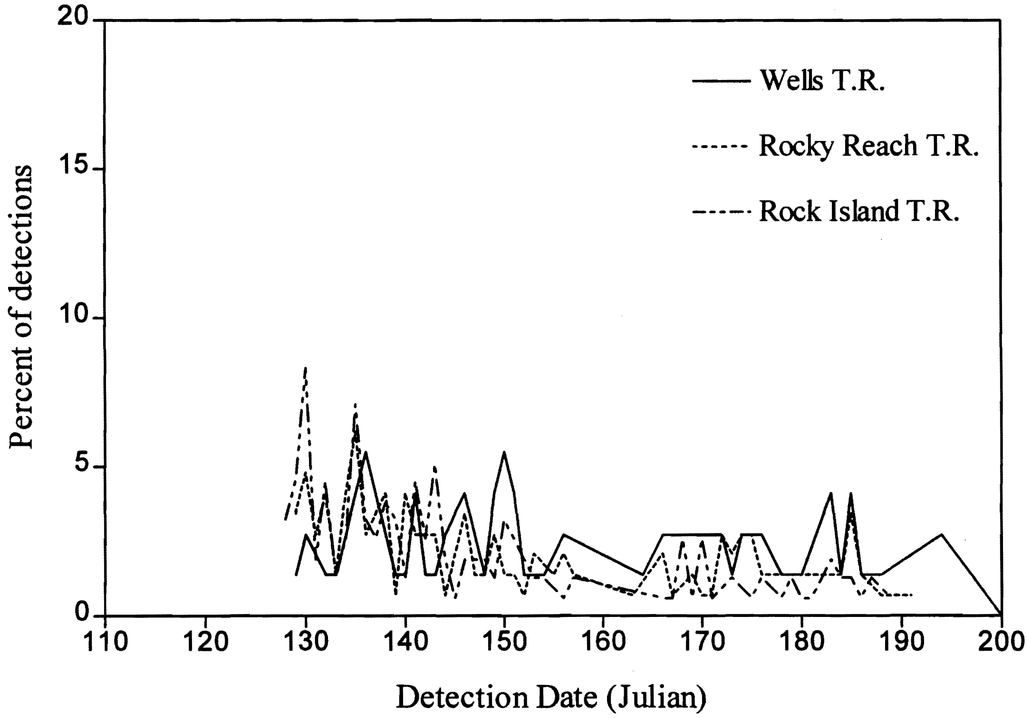


Appendix Figure 1. Continued.

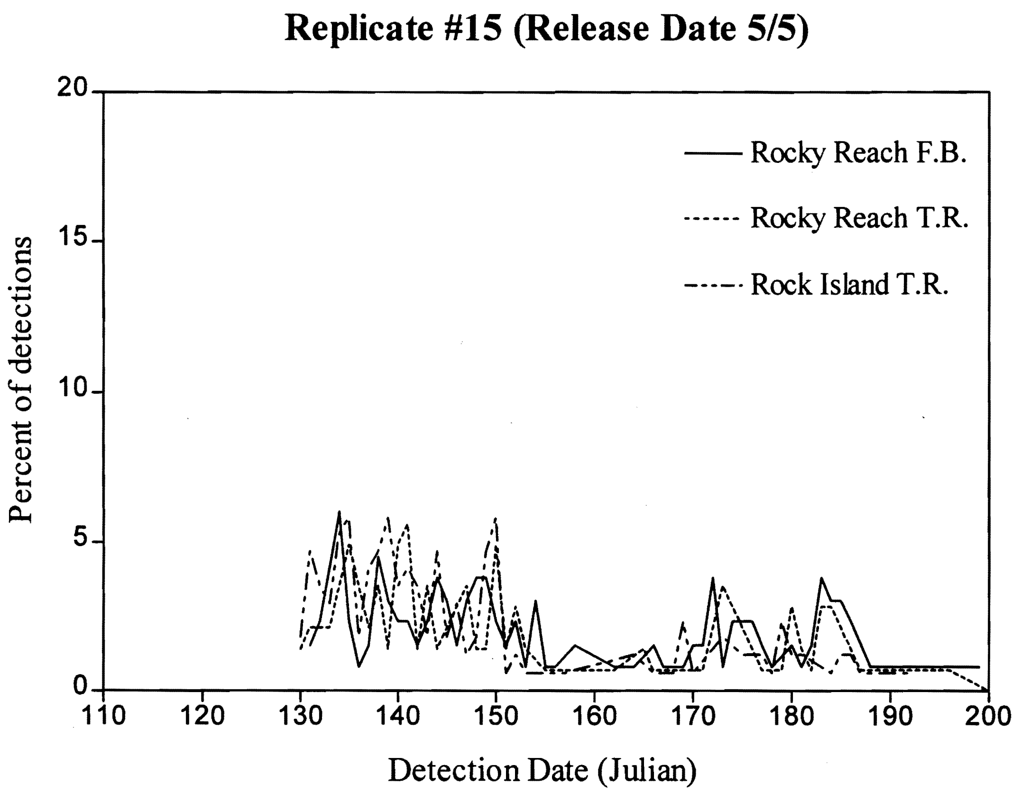
Replicate #13 (Release Date 5/1)



Replicate #14 (Release Date 5/2)

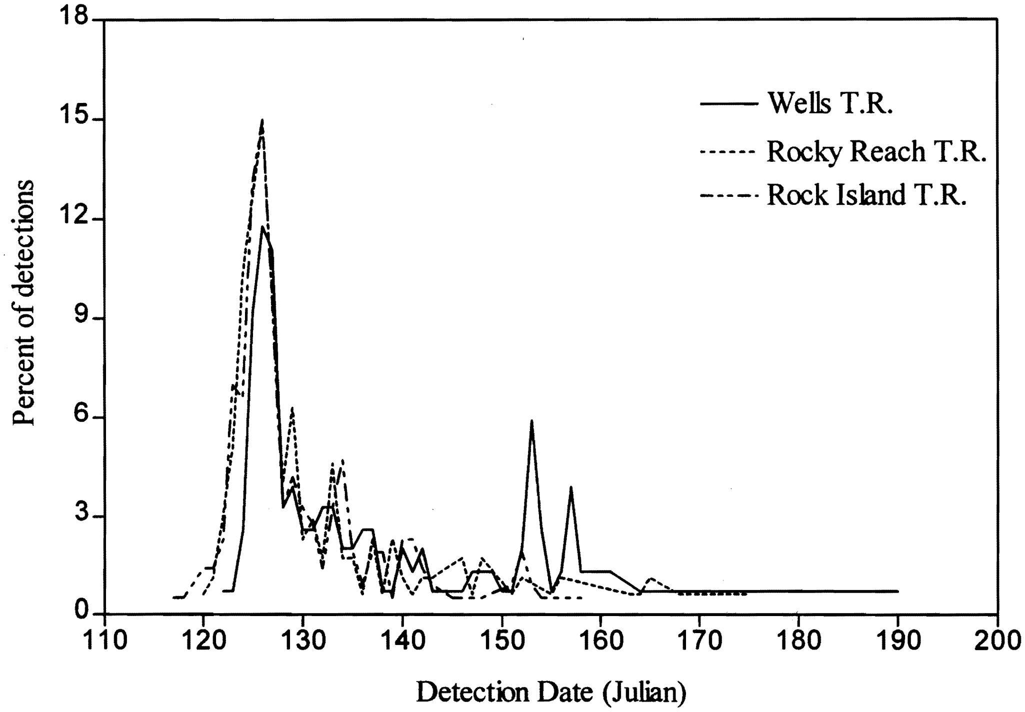


Appendix Figure 1. Continued.

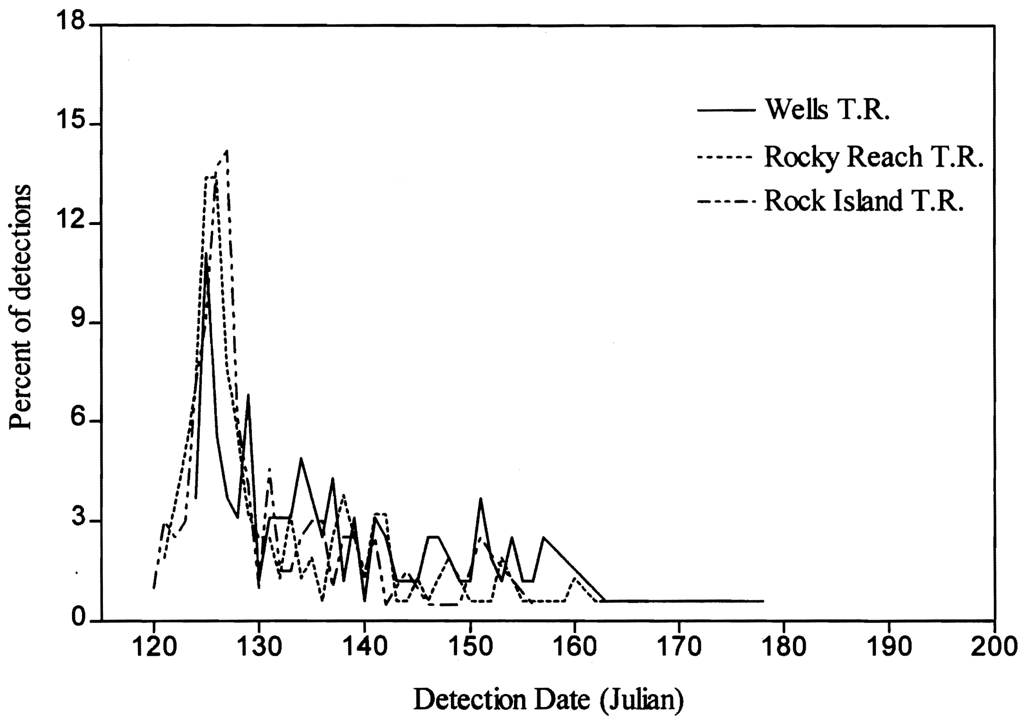


Appendix Figure 1. Continued.

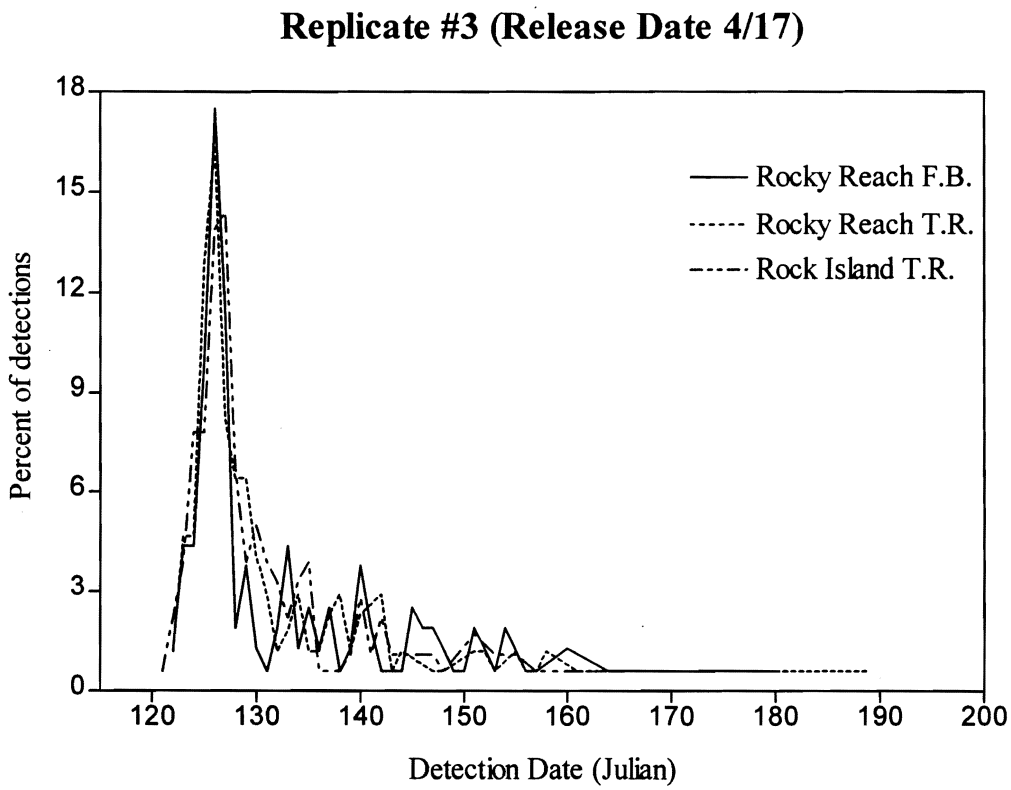
Replicate #1 (Release Date 4/15)

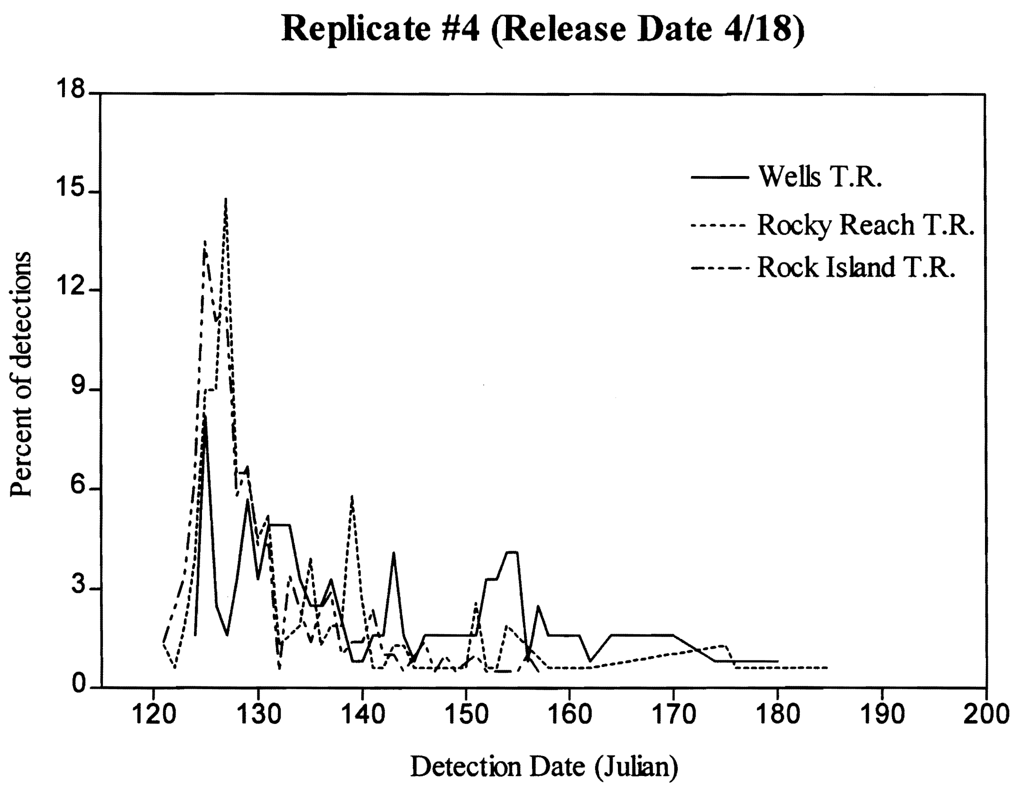


Replicate #2 (Release Date 4/16)



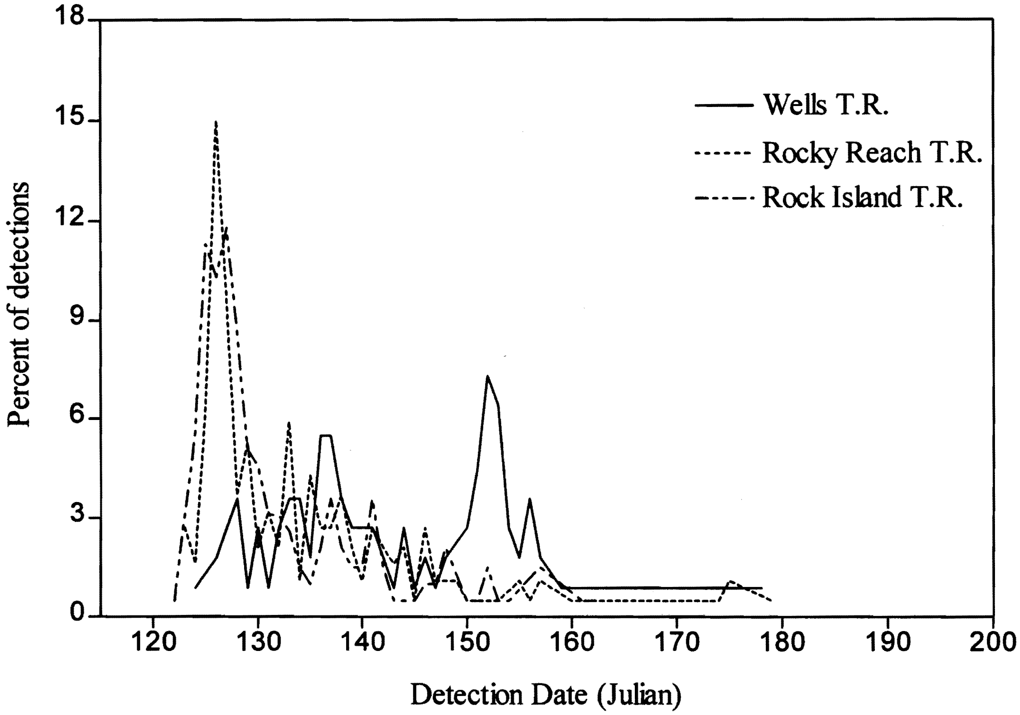
Appendix Figure 2. Passage distribution at John Day Dam for PIT-tagged hatchery yearling fall chinook salmon released for the Mid-Columbia survival study, 1998



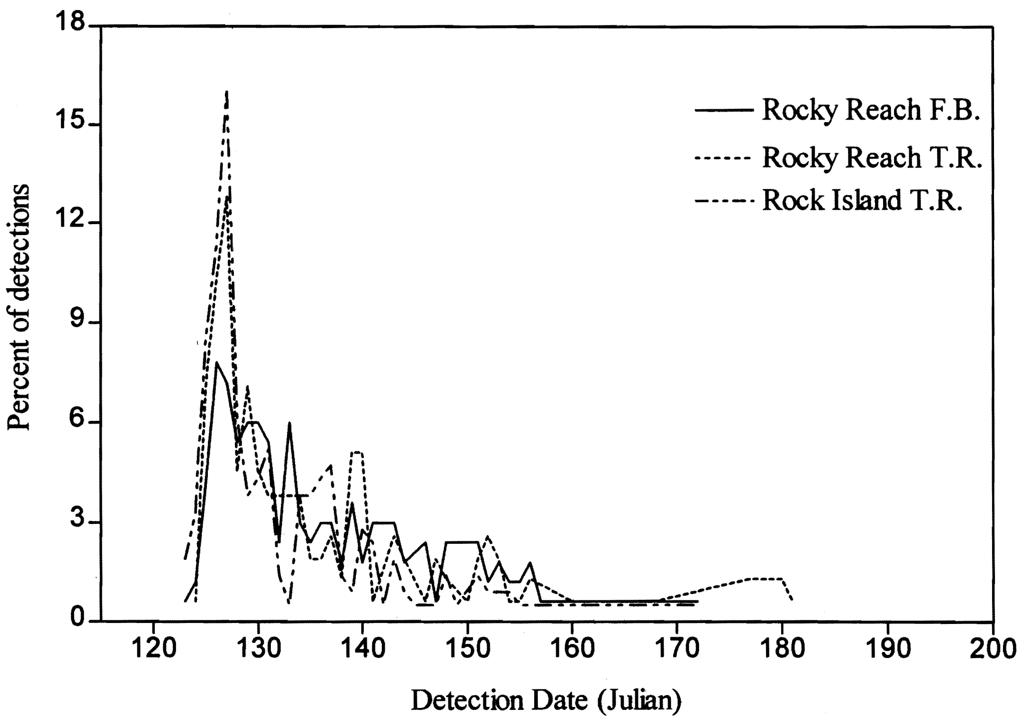


Appendix Figure 2. Continued.

Replicate #5 (Release Date 4/21)

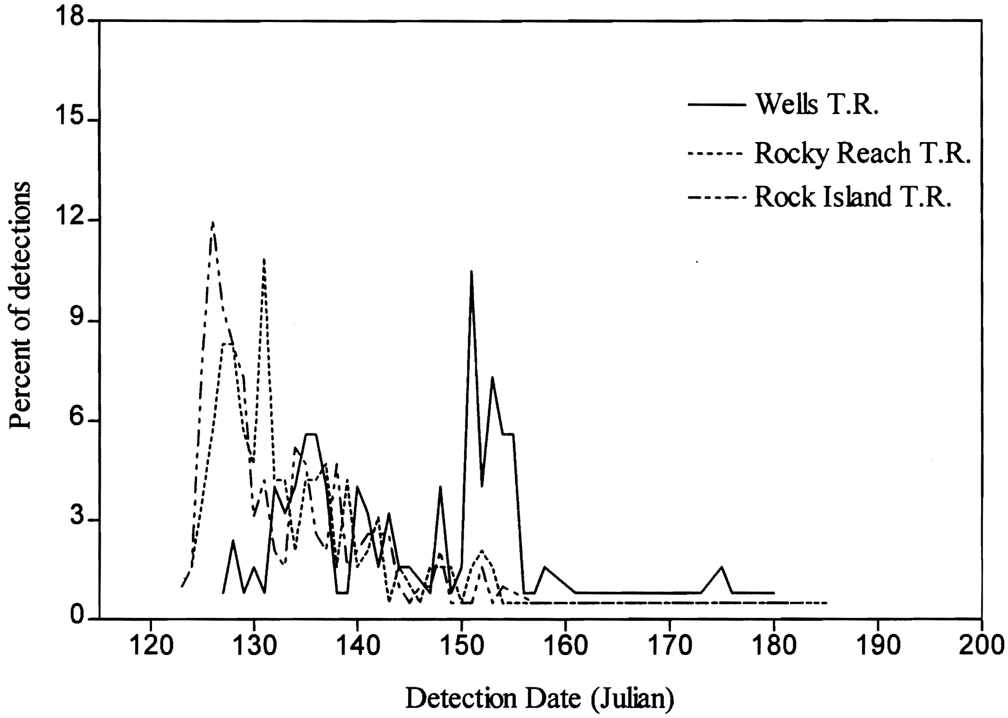


Replicate #6 (Release Date 4/22)

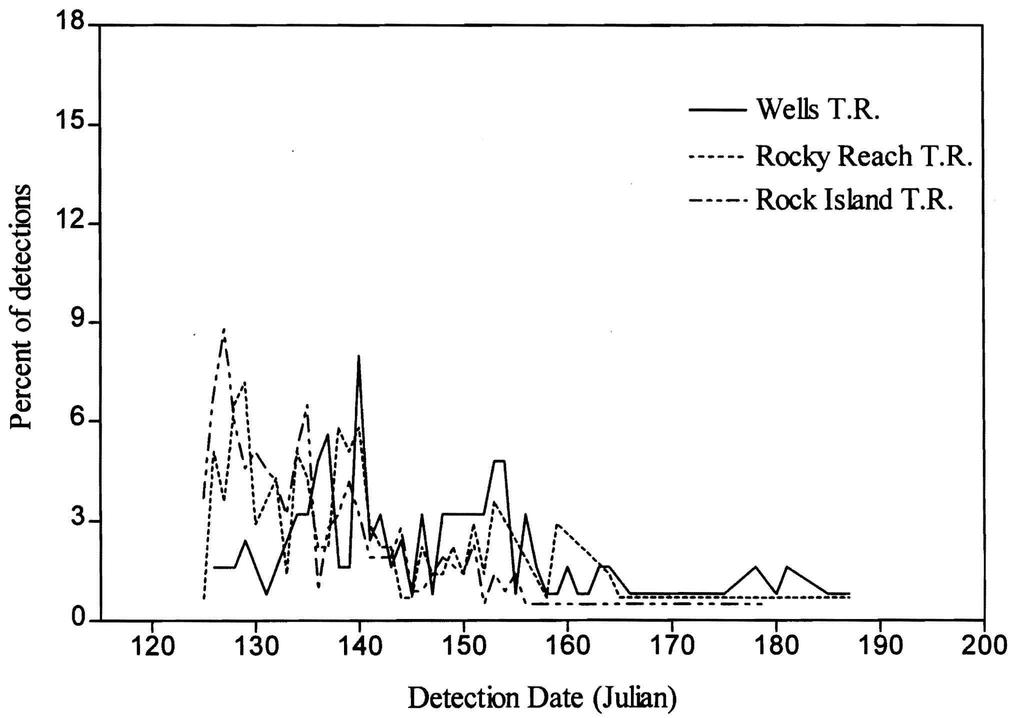


Appendix Figure 2. Continued.

Replicate #7 (Release Date 4/23)

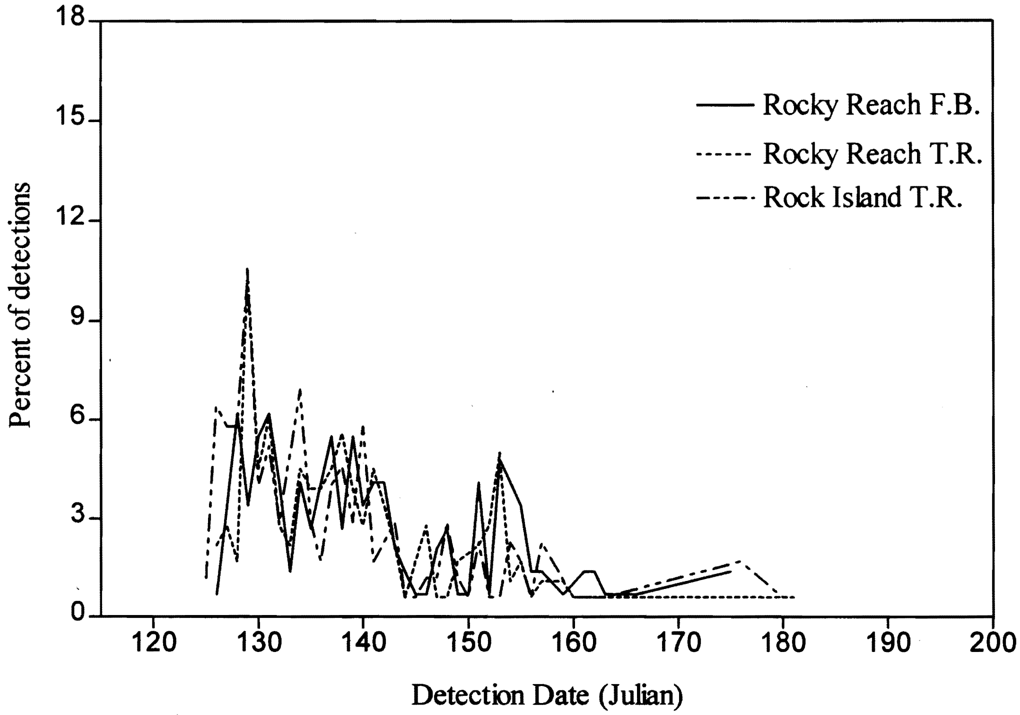


Replicate #8 (Release Date 4/24)

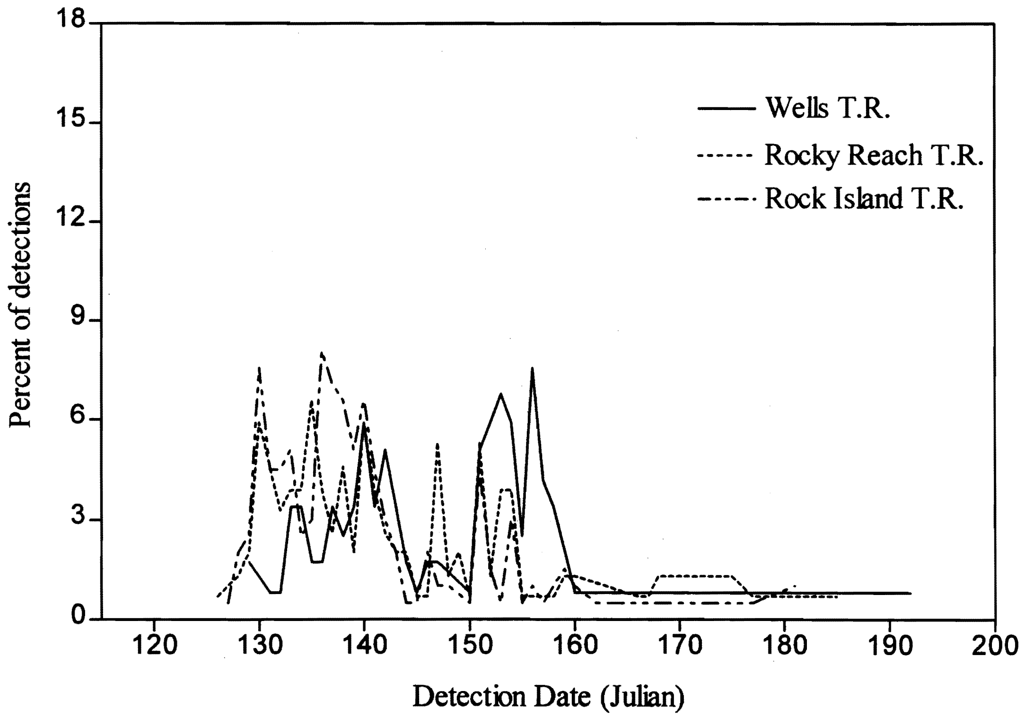


Appendix Figure 2. Continued.

Replicate #9 (Release Date 4/25)

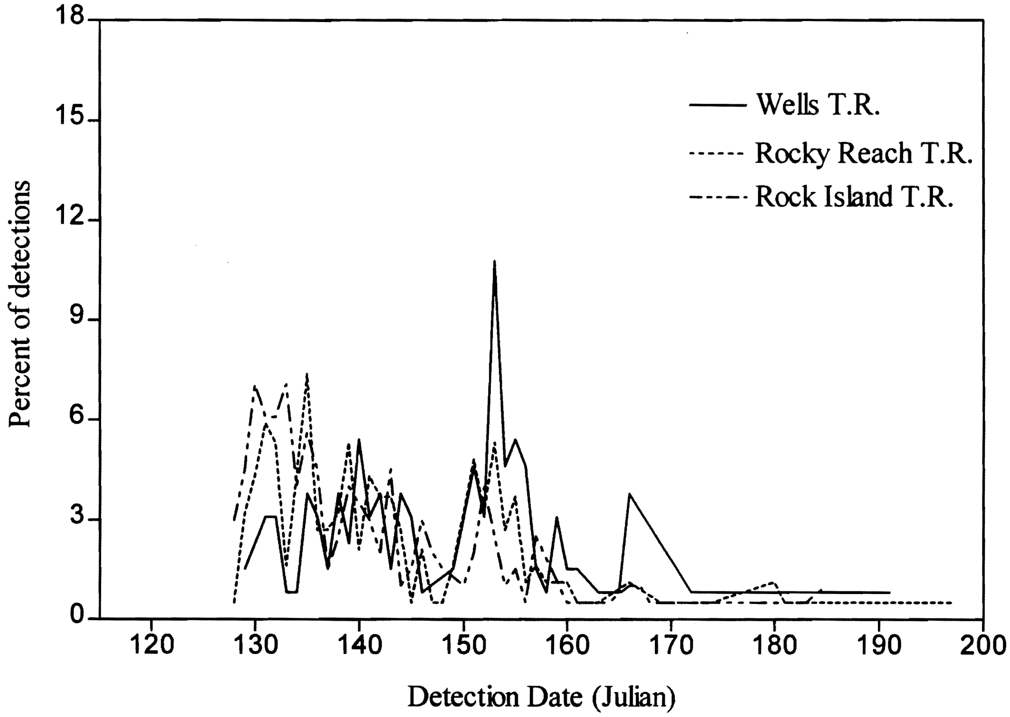


Replicate #10 (Release Date 4/28)

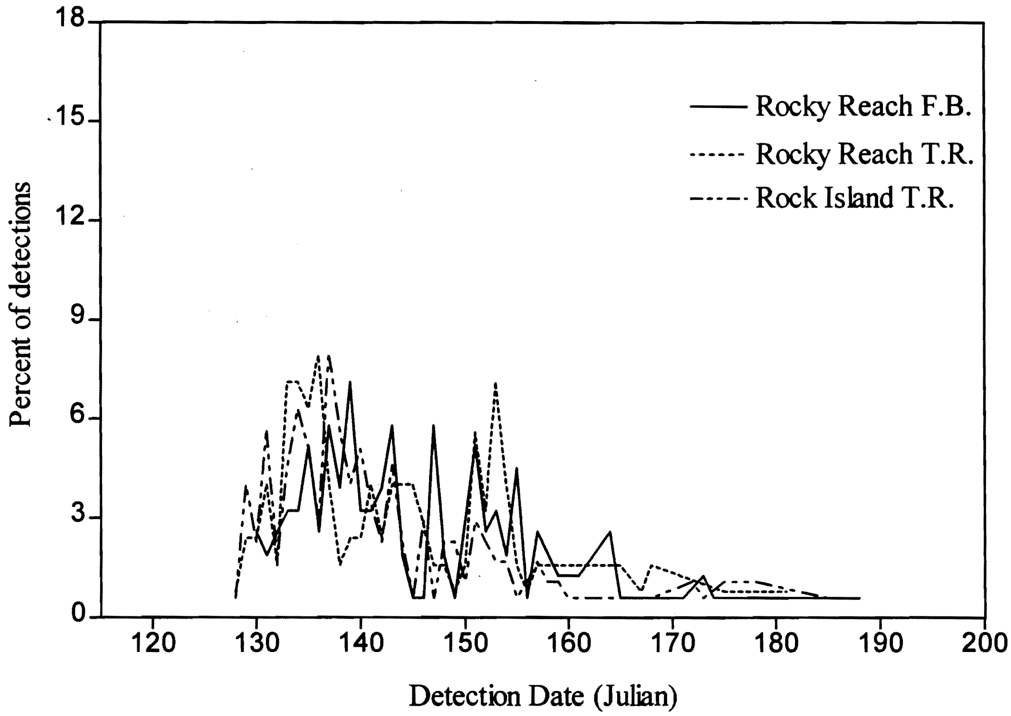


Appendix Figure 2. Continued.

Replicate #11 (Release Date 4/29)

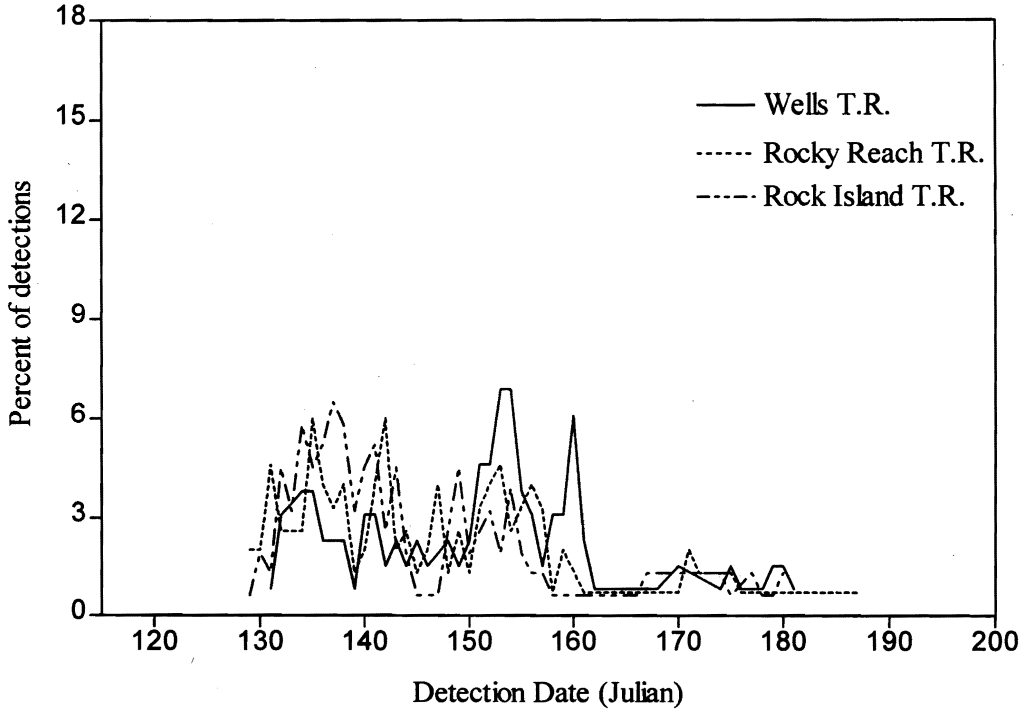


Replicate #12 (Release Date 4/30)

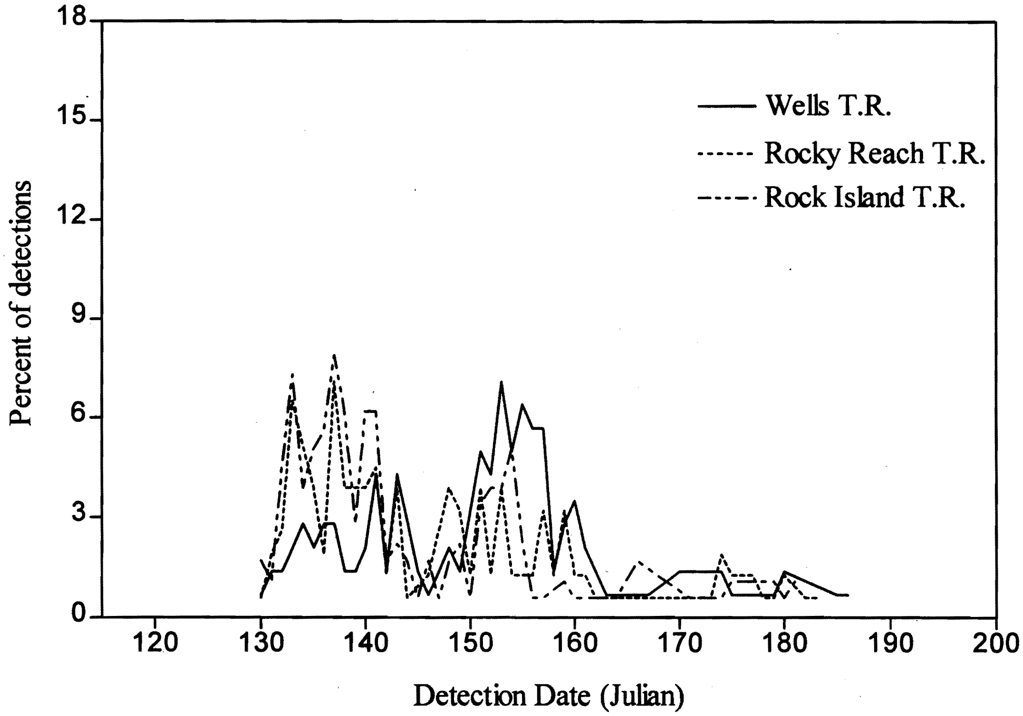


Appendix Figure 2. Continued.

Replicate #13 (Release Date 5/1)

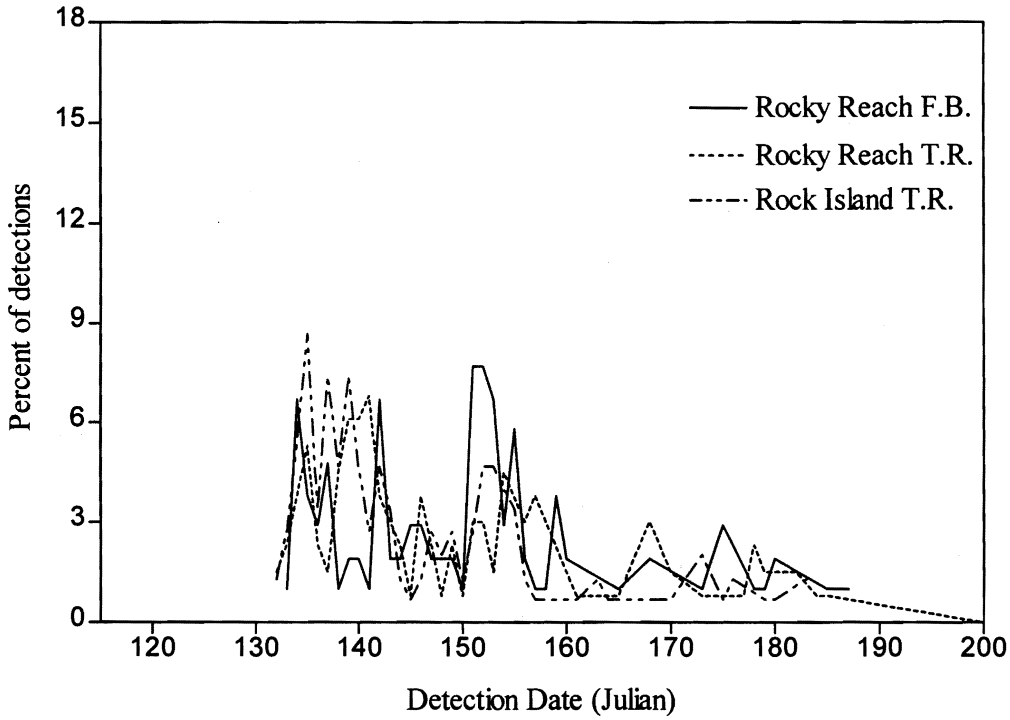


Replicate #14 (Release Date 5/2)



Appendix Figure 2. Continued.

Replicate #15 (Release Date 5/5)



Appendix Figure 2. Continued.