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DISCRIMINATION OF CHINOOK (*Oncorhynchus tshawytscha*) AND COHO (*O. kisutch*) SALMON AND STEELHEAD (*O. mykiss*) REDDS AND EVALUATION OF THE USE OF REDD DATA FOR ESTIMATING ESCAPEMENT IN SEVERAL UNREGULATED STREAMS IN NORTHERN CALIFORNIA

PROJECT 1d2

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ABSTRACT

I developed and evaluated a stratified index redd area method to estimate Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) and steelhead (*O. mykiss*) escapement in several coastal streams in Northern California based on the assumption that redd size is related to the number of redds a female builds. Sources of error in redd counts were identified and reduced including the use of logistic regression to classify redd species, necessary due to temporal overlap in the spawning of these species in coastal Northern California. Redd area escapement estimates were compared to estimates from more conventional methods and releases above a counting structure. Observer efficiency in redd detection ranged from 0.64 (S.E. = 0.10) to 0.75 (S.E. = 0.14) and was significantly associated with stream flow and water visibility (ANOVA $f = 41.8$, $p < 0.001$). Logistic regression significantly reduced uncertainty in redd identification. Redd area and date observed were significant in predicting coho salmon and steelhead redd species (Wald's $z = 11.9$ and 18.09, respectively, $p < 0.001$). Pot substrate and redd area were significant in classifying Chinook and coho salmon redds (Wald's $z = 5.88$ and 4.03, $p = 0.015$ and 0.04, respectively). Stratified index redd area escapement estimates and capture-recapture, area-under-the-curve, and known releases above the counting structure (coho salmon only) were not significantly different (ANOVA $f < 13.6$, $p > 0.06$). Escapement estimates assuming one redd per female were only significantly different from other methods for steelhead (ANOVA $f = 13.11$, $p = 0.006$). Redd counts were significantly correlated with escapement estimates ($r > 0.82$, $p < 0.04$). Reduction of counting errors and uncertainty in redd identification, biweekly surveys throughout the spawning period, and the use of redd areas in a stratified index sampling design produced precise, reliable, and cost effective escapement estimates for Chinook and coho salmon and steelhead.

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INTRODUCTION

Accurate estimates of escapement are essential for effective management and conservation of salmonids (Busby et al. 1996, McElhany et al. 2000). In Northern California coastal Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) and steelhead (*O. mykiss*) are listed as threatened species under the U. S. Endangered Species Act (Federal Register 1997, 1999, 2000). Delisting criteria will presumably depend on whether important populations have reached abundance thresholds. There is a need for reliable, cost effective, and precise techniques for monitoring salmonid escapement.

While redd counts are commonly used to index adult escapement and assess population trends (Beland 1996, Rieman and Myers 1997, Isaak et al. 2003), their accuracy as a measure of abundance has rarely been evaluated (Dunham et al. 2001). As the product only of reproductive adults, redd counts provide an index of effective population size (Meffe 1986). Maxell (1999) suggests that the sources of counting errors involved in redd counts be identified and reduced before they will be useful for long term monitoring. Dunham et al. (2001) suggest that redd counts are less intrusive and expensive than tagging, trapping, underwater observation, weirs, and genetics for inventorying bull trout populations and that with limited resources more populations can be inventoried over a longer period. However, they conclude that substantial improvements are needed to reduce counting errors before redd counts will be useful for population monitoring. The use of redd counts for population monitoring may be further complicated if females make more than one redd. Crisp and Carling (1989) found that female salmonids occasionally make more than one redd and Reingold (1965) documents a steelhead making two redds in different locations within a stream. Salmonids may also make false or “test” redds, which are abandoned before eggs are deposited (Crisp and Carling 1989).

The use of redd counts for population monitoring may be further complicated if there is uncertainty in redd species identification. Identification of Chinook and coho salmon and steelhead redds in coastal northern California streams is difficult because of overlap in spawning time and redd sizes. Chinook and coho spawn from late-October through January and steelhead spawn from December through March in coastal Northern California (Weitkamp et al. 1995, Busby et al. 1996, Myers et al. 1998). Chinook salmon redd surface areas range from 0.84 to 15 m^2, coho range from 0.80 to 8.4 m^2 (Burner 1951), and steelhead range from 2.4 to 11.2 m^2 (Orcutt et al. 1968). Thus to use redd counts for population monitoring in coastal Northern California it was necessary to develop a technique to distinguish redd species.

To resolve some of the weaknesses listed above I evaluated the amount of bias in estimates due to errors in redd species identification, detection of redds, and duration under variable survey conditions. I used data collected over two years in four rivers and three creeks to develop a logistic regression model based on physical redd characteristics and spawning time to distinguish between coho salmon and steelhead redds and tested it with data collected in the third year of the study. To distinguish between Chinook and coho salmon redds, a similar model was developed and evaluated with data collected in two rivers during one year. I evaluated the validity and some sources of bias involved with using redd counts and redd sizes to estimate escapement by estimating surveyor efficiency, the duration redds remain visible, and the influence of stream flow and water visibility on redd detection. To determine if redd-based estimates differed from conventional escapement approaches, I examined the relationship between these estimates and estimates based on capture recapture experiments, Area-Under-the-Curve (AUC) estimates, and counts at the Noyo River Egg Collecting Station (ECS) between 2000-01 and 2002-03. To test if coho and steelhead redd counts and redd based escapement estimates are related to abundance, I examined the relationship between these data collected over four years in one river (steelhead only) and three years in two rivers and three creeks. To examine the idea that female salmonids make more than one redd I compared the number of redds observed to our AUC and capture-recapture estimates of the number of females. The purpose of this study was to determine if escapement estimates, based on redd counts or on the assumption that redd size is related to the number of redds a female salmonid makes, can be applied to all three species, and if they are more reliable, cost effective, and precise than conventional approaches.

MATERIALS AND METHODS

Study Area and Data Collection

The streams studied were Caspar, Hare, and Pudding creeks, and the Albion, Little, Noyo, and Ten Mile rivers (Figure 1). These streams range in drainage area from 13-296 km^2, flow directly into the ocean, are unregulated, and are surface and groundwater fed with peak flows occurring in winter following heavy rains.

All available spawning habitat in Caspar, Hare, and Pudding creeks and Little River was surveyed approximately bi-weekly from early-December 2000 to mid-February 2001, from early-December 2001 to mid-April 2002, and approximately weekly from mid-December 2002 to mid-April 2003. The entire extent of spawning habitat in the Noyo River was surveyed biweekly from late-February 2000 to late-April 2000 and from early-December to mid-April during 2000-01 and 2001-02. During 2002-03 nine segments ranging from two to eight km were surveyed weekly in the Noyo River. The Albion and Ten Mile rivers were surveyed sporadically between 2000 and 2002-03.

Crews of two walked or kayaked two to nine km long stream reaches searching for redds, live fish, and carcasses. Stream flow (m^3/s) was estimated from flow rated staff gages and water visibility quantified as the maximum depth (m) the stream substrate was visible. All redds observed were measured and uniquely marked with labeled flagging, tied to the nearest branch directly upstream of the pot, to avoid double counting. Live tagged and untagged fish were identified to species, counted, and fork length and sex visually estimated. Carcasses were identified to species and sex, measured, inspected for tags, marks, and fin clips and unmarked carcass were uniquely marked with numbered metal tags. To insure consistency in data collection and identification of redds and fish, surveyors were provided with four hours of laboratory training and two hours field training at the beginning of each season. In addition, surveyors were rotated so that experienced and inexperienced surveyors were paired.

All newly constructed redds observed were identified to species, treated as unknown, or denoted as test or redds under construction; marked with flagging; counted; and measured during each visit. Tests (redds which appeared incomplete to the observers) and redds under construction were reexamined on consecutive surveys and were reclassified when possible based on their apparent completion. Redd measurements consisted of area, substrate, and depth. Pot length (measured parallel to stream flow), pot width (perpendicular to the length axis), and pot depth (the maximum depth of the excavation relative to the undisturbed stream bed) were measured and the dominant pot substrate was visually estimated using a modified Brusven index (Platts et al. 1983). Tail spill length (longitudinally parallel to stream flow) and tail spill width at 1/3 and 2/3 from the downstream edge of the pot to the end of the tailspill (perpendicular to the length axis) were measured and the dominant tail spill substrate was visually estimated as the undisturbed substrate upstream of the pot following Gallagher and Gard (1999) from December 2000 to April 2001 and in the middle of the tail spill during following years. Redd areas were the sum of pot and tailspill areas calculated by treating the pot as a circle or ellipse and the tailspill as square, rectangle, or triangle. Redd locations were recorded on field maps.

To assess redd longevity and observer efficiency all flagged and newly constructed redds were examined during each survey during 2002-03. To examine redd longevity, redds were classified as new, measurable, no longer measurable, or no longer apparent. Weekly observer efficiency was estimated as the percentage of known flagged redds (minus those classified as no longer apparent) observed during each survey. Weekly flag observer efficiency for each species was averaged for all survey segments in each stream throughout the season to estimate total efficiency for the season. Multiple regression was used to examine the relationship between weekly flag based observer efficiency, stream flow, and water visibility. To further examine observer efficiency, on two occasions during early-March 2003, four crews of two followed each other on one survey segment and recorded only newly constructed redds. Average field observer efficiency was calculated by assuming the largest number of redds observed by any one crew was the known number and the totals from each survey crew observing fewer redds was divided by this number and these averaged.

Classification of Redd Species

Examination of the number of known redds (redds which were positively identified with one species or another building or guarding them) observed by week indicated a large overlap in the timing of spawning among the three species of salmonids in this study (Figure 2).

Known coho salmon and steelhead redd data were used as a training data set in logistic regression analysis to differentiate redds by species using data collected in three creeks and four rivers during 2000-01 and 2001-02 (Tables 1 and 2). To develop a training data set for discrimination, the redd data from each river was examined and all known redds identified. Because so few steelhead were observed on redds (Table 1), the number of known steelhead redds in the training data set was increased so that the number of coho and steelhead redds was equal. To do this, a subset of all field identified steelhead redds containing only redds field identified as steelhead after 16 February (the last date which live or dead coho adults were observed) was developed. From this data set, field identified steelhead redds from each river each year were randomly selected until number of steelhead and known coho redds per river was equal. Because no steelhead redds were observed in the Albion and Ten Mile rivers during 2001-02, due to the surveys ending in mid-February, more late-season field identified steelhead redds were randomly selected from the other rivers to equalize the number of known redds (Table 1).

In logistic regression analysis the species making a redd was the dependent variable and variables in Tables 1 and 2 were independent variables. Survey date was changed to day with the first survey date set as one. Modeling with logistic regression continued iteratively, removing those variables least significantly associated with predicting species and rerunning the regression. The final model was tested by applying it to all known redds observed during 2002-03 and further evaluated by applying it to known steelhead redds measured in the American River during 2002-03 (J. Hannon, U.S. Bureau of Reclamation, 2800 Cottage Way, Sacramento, CA 95825, unpublished data). The following equation (Equation 1) was applied to all redds observed to reclassify them as steelhead or Coho/Chinook.

Equation 1:

Logit P = -4.074+(0.13*Day)-(0.918*Redd Area), ∃0.5 Steelhead; otherwise Coho or Chinook.

Chinook salmon redds were only positively identified during 2002-03. Equation 1 predicted all known Chinook redds observed during 2002-03 to be coho. All known Chinook and coho redds during 2002-03 were used in logistic regression analysis following a procedure similar to that used to develop Equation 1. The resulting equation (Equation 2) was used to classify redds as Chinook or coho. This model was evaluated by comparing the number of known redds in the original data set misclassified by Equation 2.

Equation 2:

Logit P = -5.962+(0.441*Pot Substrate)+(0.253*Redd Area), ∃0.5 Chinook; otherwise coho.

Escapement Estimates

Capture-Recapture

Steelhead escapement in the Noyo River was estimated using the Petersen capture-recapture method during 2000, 2000-01, 2001-02, and 2002-03 (Krebs 1989). During 2000 steelhead were captured, marked, and recaptured using gill nets set in the lower river, at the ECS, in fyke traps set throughout the river, and by anglers. During 2000-01 a weir was operated in the lower river and fish were captured, marked, and recaptured at the weir, at the ECS, in fyke traps set throughout the river, by anglers, and during spawning surveys. During 2001-02 and 2002-03 steelhead were captured, marked, and recaptured by angling, at the ECS, in fyke traps set throughout the river, and during spawning surveys.

Coho populations were estimated by capture and recapture of carcasses during spawning surveys in all streams following the Jolly-Seber method, or the Schnabel method when recaptures were less than seven (Krebs 1989). During 2002-03 live coho salmon were captured and tagged in the lower Noyo River using gill nets and recaptured during spawning surveys and escapement estimated using the Peterson method. Known numbers of coho were released above the Noyo River ECS during 2000-01, 2001-02, and 2002-03.

AUC

Spawning population estimates each year were also derived from live fish observations using the AUC (English et al. 1992, Hilborn et al. 1999). Steelhead stream residence time (rt) was estimated separately for tributaries and main stem sections by averaging observations of fish on redds, time between capture and recapture of tagged fish, and from data from Shapovalov and Taft (1954) and Kormen et al. (2002) and was 12.6 and 41.3 days, respectively. Coho rt was 11 days (Beidler and Nickelson 1980). Chinook rt of 9.3 days was the average of values presented by Parken et al. (2003) and Neilson and Geen (1981). Observer efficiency (v), the ratio of total fish seen to the total present (Korman et al. 2002), was estimated by dividing the total number of fish of each species observed during spawning surveys by the capture recapture estimates each season. Thus confidence intervals for AUC and capture-recapture estimates were interrelated.

Redd Area

Escapement estimates based on redd data were made by expanding total redd counts by the male to female ratio and by a method which assumes the number of redds a female makes is related to the size of the redd (redd area method). Escapement estimates assuming one redd per female were made by multiplying the number of redds by the male to female ratio observed in each river and summing this with the number of redds. Because Susac and Jacobs (1999) found steelhead redds per female to range from 0.5 to 4.45 and results reported herein were within this range, I assumed the number of redds per steelhead female to range from one to four.

To estimate the number of female steelhead based on redd area and a range of one to four redds per female, I estimated the number of females from redd area by multiplying the maximum sized known steelhead redd by three quarters, half, and one quarter. Redds > 4.6 m^2 were assumed to represent one female. Each redd between 3.05 and 4.6 m^2 was assumed to represent three quarters of a female, redds between 1.52 and 3.04 m^2 were assumed to represent one half of a female, and redds < 1.52 m^2 were assumed to represent one quarter of a female. Coho redd area escapement estimates were based on findings from releases above the ECS during 1996, where it was estimated that females make between one and four redds and redd areas > 5.1 m^2 represent one female, redds between 2.1 and 5.0 m^2 represent one half a female, and redds < 2.0 m^2 represent one quarter of a female (M. Maahs, Salmon Trollers Marketing Association, P.O. Box 137, Fort Bragg, CA 95437, unpublished data). Female coho and steelhead redd area escapement estimates were multiplied by the male per female ratio observed in each stream each year and summed with female estimates to estimate populations. Observer efficiency estimated during 2002-03 and predicted for 2000-01 and 2001-02 was used to expand redd counts and redd area estimates. Uncertainty in redd identification was derived from logistic regression and field uncertainty was calculated from observer uncertainty in species making redds.

To determine if escapement estimates could be made with reduced sampling effort using a stratified index approach (Irvine et al. 1992), steelhead and coho redd area densities in the Noyo River during 2001-02 were plotted against sample reach (Figure 3a). Figure 3a indicated that after nine reaches the variance around the mean did not substantially decrease. Nine reaches were selected and the average density calculated and multiplied by the total length of spawning habitat in each category to estimate steelhead escapement for 2000, 2000-01, and 2001-02. Coho salmon escapement was estimated by the stratified index approach for the Noyo River during 2001-02. Coho and steelhead escapement was estimated with a stratified index approach in Caspar, Hare, and Pudding creeks and Little River for 2001-02 by dividing the streams into 0.5 km segments, developing performance curves of redd area densities (Figure 3b-e), randomly selecting the number of segments indicated by the performance curves, and multiplying the average density by the length of spawning habitat in each stream. These estimates were compared to estimates from surveying the entire river and capture recapture estimates. To further evaluate this method during 2002-03, only nine reaches were surveyed in the Noyo River and resulting escapement estimates compared to capture recapture estimates.

Data Analysis

Physical characteristics of redds and associated variables were compared using correlation, logistic regression, and Mann-Whitney U or t-tests. Significance of variables in predicting redd species was based on examination of the significance of Wald's z-values. Population estimates were compared with ANOVA or the Kruskal-Wallis ANOVA on ranks when Standard Kurtosis p-values were < 0.05. Correlation was used to determine if redd counts or redd area escapement estimates were related to capture-recapture or AUC escapement estimates by treating year and river specific data for each species as samples. Relationships between redd sizes and female fork lengths were examined by correlation. Statistical significance was accepted at $p < 0.05$.

RESULTS

Steelhead redd observer efficiency based on flag recaptures during 2002-03 was 0.74 (S.E. = 0.02) and was very similar to field observer efficiency of 0.75 (S.E. = 0.14). Coho salmon redd observer efficiency based on flag recaptures was 0.64 (S.E. = 0.10). There was no difference in the percentage of redds $< 1.5\ m^2$ and redds $>1.5m^2$ observed more than once ($t = 1.06$, $p = 0.31$), however the power of this test was low ($\alpha = 0.06$). Weekly stream flow and water visibility were significant in predicting weekly flag based observer efficiency (ANOVA $F = 41.8$, $p < 0.001$) and the resulting equation (Equation 3) was used to predict observer efficiency for 2000-01 and 2001-02. Predicted observer efficiency for 2000-01 was 0.74 (S.E = 0.03) and for 2001-02 was 0.67 (S.E. = 0.02). Treating weeks as samples, predicted and estimated observer efficiency was not different among years (ANOVA $H = 3.62$, $p = 0.17$).

Equation 3:

Observer Efficiency = 0.435-(0.00278*stream flow)+(0.256* visibility)

The percentage of steelhead redds still measurable after two weeks was 73.4% whereas only 39% of coho redds and 43% of Chinook redds were still measurable after two weeks during 2002-03. If surveys were conducted monthly only 25% of steelhead redds, 18% of coho redds, and 14% of Chinook redds would still have been measurable. After eight weeks only 1% of steelhead, 0.2% of coho, and no Chinook redds were still measurable.

Classification of Redd Species

Logistic regression reduced uncertainty in redd identification. Field uncertainty in redd identification was 16% during 2000, 22.4% during 2000-01, 18.2% during 2001-02, and 11.1% during 2002-03. The apparent error rate from logistic regression was 3.9% (i.e. in the training data set known species redds, Tables 1 and 2, only eight out of 204 redds were misclassified by logistic regression). When this model (Equation 1) was applied to all redds observed during 2000-01 and 2001-02, no redds were classified as coho after 16 February, the last day live or carcass coho were observed. All known steelhead and coho salmon redds observed during 2002-03 were correctly predicted to species by Equation 1. Three of 44 known steelhead redds (6.8%) observed in the American River during 2002-03 were misclassified by Equation 1.

For discrimination of steelhead and coho, only redd area and the date redds were observed were significantly associated with predicting species (Wald's $z = 11.9$ and 18.09, respectively, $p < 0.001$). Year and river were not significantly associated with predicting species (Wald's $z = 0.02$, $p = 0.88$ and $z = 0.08$, $p > 0.93$, respectively). Distance from the river mouth was not significant in predicting species (Wald's $z = 0.53$, $p = 0.47$). For redds where fish were observed in enough detail to estimate fish length, fork length was not significantly correlated with pot size ($r = 0.05$, $p = 0.62$) or redd size ($r = 0.06$, $p = 0.57$) and was not significantly associated with predicting species (Wald's $z = 0.98$, $p = 0.32$). Steelhead and coho salmon fork lengths were not different in 2000-01 ($u = 6787$, $p = 0.05$) nor in 2001-02 ($t = 1.27$, $p = 0.21$, Table 2), were not normally distributed (K-S = 0.15, $p < 0.001$, and K-S = 0.12, $p < 0.009$, respectively), and were skewed towards larger size fish (Figure 4a). Steelhead and coho salmon redd sizes were not normally distributed (K-S < 0.11, $p < 0.02$) and were skewed towards smaller redds (Figure 4b).

The apparent error rate for classification of Chinook and coho salmon redds (Equation 2) was 5.9%. Only pot substrate and redd area were significant in classifying Chinook and coho salmon redds (Wald's $z = 5.88$ and 4.03, $p = 0.015$ and 0.04, respectively). Only five Chinook redds were positively identified during 2002-03, so it was not possible to examine river and year affects on predicting redd species or relationships between redd size and female size. The low number of known redds used in the training data set for logistic regression and the lack of multiple years' data limited the evaluation of this model.

Escapement Estimates

The uncertainty associated with each method of estimating coho salmon escapement, while generally higher for capture-recapture and AUC estimates, overlap the point estimates, suggesting all methods were reasonable (Figure 5a-d). Treating years as samples known numbers of coho salmon released above the ECS were not significantly different than AUC and redd area escapement estimates (ANOVA $f = 6.54$, $p = 0.06$, Figure 5a) nor were they different than estimates based on assuming one redd per female (ANOVA $f = 6.30$, $p = 0.06$). However the power of these tests was low ($\alpha = 0.51$, 0.50, respectively). The coho salmon carcass based capture-recapture estimate above the ECS, made only during 2002-03 due to low numbers of recaptures in other years, was much lower than the known release and other estimates (Figure 5a). Treating years as samples and including data from all streams, coho salmon carcass based population estimates were not significantly different than redd area estimates (Figure 5b-d, ANOVA $f = 3.13$, $p = 0.12$). The power of this test ($\alpha = 0.24$) was low. Coho salmon carcass based estimates were significantly lower than assuming one redd per female (ANOVA $f = 13.57$, $p = 0.04$, $\alpha = 0.90$). Coho salmon AUC and redd area estimates did not significantly differ (ANOVA $f = 0.35$, $p = 0.57$), but the power was low ($\alpha = 0.05$). Escapement estimates based on one redd per female were not different than AUC estimates (ANOVA $f = 3.39$, $p = 0.09$), yet the power of this test was low ($\alpha = 0.05$). Treating rivers as samples stratified index based escapement estimates for coho salmon during 2001-02 were not significantly different than AUC estimates (Figure 5b, ANOVA $f = 0.41$, $p = 0.54$, $\alpha = 0.05$).

The uncertainty associated with estimating steelhead escapement by capture-recapture and the AUC was large and overlaps that of other methods suggesting all methods gave similar results (Figure 6a-c). Treating years as samples steelhead capture-recapture escapement estimates in the Noyo River (Figure 6a) were not significantly different than redd area or stratified index based estimates (ANOVA $f = 1.20$ and 0.15, $p = 0.35$ and 0.73, respectively). The power of these tests was low ($\alpha < 0.06$). Steelhead capture-recapture estimates were significantly different than those based on one redd per female (ANOVA $f = 11.85$, $p = 0.04$), but the tests power was low ($\alpha = 0.60$). The AUC escapement estimates from the Noyo River were not significantly different from redd area (ANOVA $f = 0.64$, $p = 0.48$), assuming one redd per female (ANOVA $f = 7.88$, $p = 0.07$), or stratified index estimates (ANOVA $f = 0.19$, $p = 0.69$). However, the power of these tests was low ($\alpha < 0.44$). Treating years as samples and including all streams data, AUC escapement estimates were not significantly different than redd area estimates (Figure 6a-c, ANOVA $f = 0.64$, $p = 0.48$). The AUC estimates were significantly different than assuming one redd per female (ANOVA $f = 13.11$, $p = 0.006$, $\alpha = 0.88$). The AUC escapement estimates were not significantly different from stratified index estimates (ANOVA f = 0.04, p = 0.85). However, the power of this tests was low (α = 0.05).

Similar to coho and steelhead escapement estimates, uncertainty associated with the different Chinook salmon escapement estimate methods overlapped, were large for capture-recapture and AUC, and indicate all methods produced reasonable estimates (Figure 7). Chinook salmon were only observed in the Albion (2002-03 only) and Noyo rivers. The Albion River was not surveyed completely in 2002-03 such that it was not possible to make escapement estimates. Only two Chinook salmon carcasses were marked and none recaptured during 2000-01, such that capture-recapture estimates were not made for this season. Although sample sizes were small (n = 2), treating years as samples Chinook salmon capture-recapture estimates did not differ significantly from redd area (ANOVA f = 0.36, p = 0.66) or from estimates based on one redd per female (ANOVA f = 1.86, p = 0.40). The power of these tests was low (α = 0.05 and 0.11, respectively).

Based on capture-recapture and AUC estimates, Coho salmon and steelhead females appear to make more than one redd. Coho salmon females released above the ECS averaged 1.25 (S.E. = 0.15) redds per female (range 1.02-1.54) over three years. Based on capture-recapture of coho carcasses the average number of redds per female over three years in all streams was 4.61 (range 1.80-7.04). The average number of redds per coho salmon female based on AUC estimates over three years in all streams was 1.70 and ranged from 0.50 to 3.19. The average number of steelhead redds per female over three years, based on capture-recapture estimates was 1.93 (S.E. = 0.47) and ranged from 1.02 to 2.43. The average number of steelhead redds per female based on AUC estimates over three years in all streams was 3.46 and ranged from 1.80 to 6.91. In the Noyo River over two years Chinook salmon averaged one redd per female.

Redd counts significantly reflect Chinook and coho salmon and steelhead escapement (Figure 8a-c). Treating years as samples, coho salmon redd counts and known numbers of females above the ECS were significantly correlated (r = 0.99, p = 0.04). Treating years as samples and including all streams data, coho salmon redd counts and capture-recapture escapement estimates were significantly correlated (Fig 8a, $r = 0.83$, $p = 0.001$, $n = 11$). Similarly, coho salmon redd counts were significantly correlated with AUC escapement estimates ($r = 0.83$, $p < 0.001$, $n = 14$). Treating years as samples and including data from all streams, steelhead redd counts were significantly correlated with AUC escapement estimates (Figure 8b. $r = 0.82$, $p = 0.003$). With only two years data for Chinook salmon it was not possible to correlate redd counts with capture-recapture estimates, although they appear related (Figure 8c).

DISCUSSION

We were able to account for and reduce many sources of bias and uncertainty in redd counts. By marking redds and reexamining flagged redds on subsequent surveys I was able to account for under counting errors (i.e. missed redds). Because flag and field observer efficiency was not different, it appears that marked (flagged) and unmarked (no flags and assumed to be new) redds are equally detectable. Small and large redds were also, based on flag observer efficiency, equally detectable. Rather than examine sources of individual variation in redd counts, I estimated it for all surveys and averaged it for the season, which tends to cancel out individual errors (Krebs 1989). Dunham et al. (2001) attributed variability in redd counts to differences among individual surveyors and redd and habitat characteristics, yet did not examine the affect of stream flow or turbidity. In this study, water visibility and stream flow had a strong effect on redd detection and I was able to use these variables to predict observer efficiency for years it was not field estimated. Although I did not account for over counting redds (false identifications), several factors suggest this type of error was minimal. The survey protocol had a redd classification category called test and surveyors were instructed to use this for redds or channel features that looked like redds but there was uncertainty if these features actually were redds. Redds classified as test were reexamined on subsequent surveys and if they had not changed were left in this category; these redds were not included in further analysis. Field crews worked in pairs and were instructed to confer on redd species identification. All redds, including those field classified as test, were measured, and as part of the measuring process, surveyors examined redds in some detail and were less likely to include channel features which were not actually redds.

The length of time redds remain visible and measurable can cause counting errors and may effect the use of redd counts for population monitoring. Dunham et al. (2001) found redd age was significantly associated with counting errors and some redds in their study were over four weeks old. They and other researchers (Beland 1996, Rieman and Myers 1997, Isaak et al. 2003) counted redds once or twice at the assumed end of the spawning season. In this study we surveyed weekly or biweekly throughout the season such that the oldest redds encountered would have been aged less than 13 days. Observer efficiency was not different between years and escapement estimates based on redd counts were not different from AUC or capture-recapture among years suggesting that biweekly surveys encountered redds as well as weekly surveys. Since redds disappeared and a large percentage were not measurable after as little as two weeks I recommend that surveys be conducted less than 13 days apart or as soon after large flow events as possible throughout the spawning season. Surveying weekly rather than biweekly will increase the cost of these surveys. Survey periodicity should be within the residence time of the species of interest so that AUC can also be estimated. Surveying once at the end of the spawning season for all species (over four months) would not produce realistic results. Even if surveys were conducted once after Chinook and coho salmon spawning occurred and again at the end of steelhead spawning, the results would be of little use. A larger percentage of steelhead redds remained measurable longer than Chinook and coho salmon redds because most steelhead spawn later than coho and Chinook salmon, after the usual time of large stream flow events.

Classification of Redd Species

The discrimination function from logistic regression reduced species uncertainty by an average of 15% and thus decreased this source of error in the use of redd counts for population monitoring. The apparent error rate from logistic regression of 3.9% was lower than that reported by other researchers using multivariate techniques to classify salmonid redds. Fukushima and Smoker (1998) found water depth and velocity and stream gradient significant in discriminating sockeye and pink salmon redds, but report an error rate of 33%. Zimmerman and Reeves (2000) found water depth and substrate significant in separating anadromous and resident steelhead redds using stepwise discrimination and report an error rate of > 28%.

The model based on steelhead and coho salmon redd area and date of spawning appears spatially and temporally robust for distinguishing between the two species and may be applicable to other streams where these species co-occur. All known steelhead and coho salmon redds observed during 2002-03 were correctly classified by Equation 1 and only 6.8% of known steelhead redds in the American River were misclassified. Year and river were not significant in predicting redd species. The physical features of redds which contribute to species identification (i.e. size and date of spawning) appear to be consistent over a large geographic area suggesting they are driven by some biologically inherent characteristics of the species and not by stream geomorphic or watershed features. Steelhead redds may be smaller than coho and Chinook redds because steelhead are iteroparous. Female steelhead and coho salmon fork lengths were not significantly different and redd sizes were not related to fish size. Female steelhead may not expend all their energy making redds because they survive to spawn again in later years, where as coho and Chinook salmon die after spawning. Burner (1951) observed that salmon continue to dig above the nest pockets of redds after spawning activity ceased. Whereas Briggs (1953) states that both male and female steelhead drift downstream after spawning is complete.

The logistic regression equation developed to distinguish between Chinook and coho salmon redds was encouraging and, although more known redd data will likely improve this relationship, it appears that these species redds can be identified based on physical characteristics. Chinook and coho salmon redds differed in pot substrate and redd size. The difference in redd size may be because Chinook salmon are larger than coho. Although I found that steelhead and coho salmon fork lengths and redd sizes were not related, I was unable to examine this relationship for Chinook salmon because so few fish were observed on redds. The difference in pot substrate size between these species may be because Chinook excavate their nests deeper than coho (DeVries 1997) or that they prefer different substrate sizes (Hampton and Aceituno 1988). However, pot depths were not different between the two species in this study (Table 2). Redd size and substrate used to differentiate Chinook and coho salmon redds were not different than reported in other areas (Burner 1951) suggesting that Equation 2 may be useful in other areas where these species overlap. This model will need further evaluation and more data to validate its applicability over multiple years or in other systems.

Escapement Estimates

Redd Area

Although I did not quantitatively evaluate the assumption that redd size is related to the number of redds a female salmonid makes (e.g. the redd area method), several of the results suggest this was valid. Redd area escapement estimates were not different than known numbers of coho salmon released above the ECS. The redd area and stratified redd area escapement estimates were not significantly different than other methods, except assuming one redd per female which overestimated escapement. The number of redds per female was > 1.0 for all methods and were within the range used in the redd area method. Redd size was not related to female size. Fork lengths were not normally distributed and were skewed towards larger fish whereas redd sizes were skewed towards smaller redds (Figure 4), suggesting redd size is related to female effort. The redd area method accounts for multiple redds per female and smaller redds have lower importance in escapement estimates.

The redd area method is sensitive to the female to male ratio, the range of size of redds, and errors in counting and measuring redds. I used female to male ratios based on live fish observations in each stream, or when too few fish were observed, assumed it was one to one. Average coho and steelhead redd sizes were very similar each year and I only used known redd areas for estimating the female effort ranges. Training of surveyors and efforts to reduce redd counting errors described above likely helped reduce these potential sources of error.

Of the methods examined in this study, Chinook and coho salmon and steelhead escapement was most precisely, cost effectively, and reliably estimated using redd areas in a stratified index approach. Irvine et al. (1992) found that stratified index estimates were always similar to capture-recapture estimates. Stratified index escapement estimates were not significantly different than redd area, capture-recapture, or AUC estimates, but were significantly different from estimates assuming one redd per female for steelhead. When tested in the third year of the study, stratified index estimates were not different than AUC, capture-recapture, or redd area escapement estimates. Although the power of these tests was low and the uncertainty associated with the point estimates high, they overlapped for all escapement estimates except for the steelhead estimates that assumed one redd per female (Figures 5-6). Uncertainty associated with the stratified index estimates was lower than that of AUC and capture-recapture estimates. The one redd per female and redd area estimates were total counts and their uncertainty was that associated with redd identification such that these methods did not provide statistical descriptions of uncertainty. Krebs (1989) states that total counts are often of dubious reliability and recommends sample counts for population estimation. The stratified index estimates can be viewed as a specialized form of block sampling where the stream segments are blocks and the entire length of spawning habitat in a stream is the census zone. The mean and variance is calculated from the blocks and multiplied by the census zone. The use of performance curves reduced cost by reducing the amount of the census zone (i.e. spawning habitat in each stream) by about 60% allowing more coverage with the same effort while reducing variance in escapement estimates. This method was shown to work for a variety of water years and streams, is not susceptible to mechanical failure, and fish are not handled, tagged, or their movements impeded. This approach may be useful and applicable to examine and monitor metapopulation dynamics (Rieman and Mcintyre 1996) important for recovery of these threatened species (Isaak et al. 2003). Redd counts and escapement from stratified redd areas was significantly correlated with fish released above the ECS (coho) and capture recapture estimates, thus these estimates appear to track population trends accurately (Figure 8). Accurate estimates combined with reduced uncertainty from improvements in redd counts and redd identification and confidence bounds estimated from the stratified index approach, suggests this approach will be useful for monitoring and detecting long term trends (Maxell 1999).

Capture-Recapture

The capture-recapture estimates had large confidence bounds due to low numbers of marked and recaptured fish, and carcass based estimates appeared to underestimate populations (Figs. 5-7). Carcass population estimates require unique individual marks, high capture-recapture rates, a short duration between surveys, and the entire river be surveyed to increase the reliability of the resulting estimates. Increasing the periodicity of surveys during 2002-03 allowed coho carcass based estimates above the ECS, yet still drastically underestimated escapement and did not greatly increase the reliability of the escapement estimates for other streams (Figure 5). To observe, tag, and recover enough carcasses to reduce the uncertainty with these estimates might require surveys on a daily basis because high flows between surveys can bury, wash away, or otherwise decrease the chance of finding carcasses (Cederholm et al. 1989). Too few steelhead carcasses were observed to estimate escapement using capture-recapture methods. Live fish capture-recapture programs require active capture techniques which are susceptible to mechanical failure in moderate to high water years, require fish are tagged, handled, and their movements impeded. Permanent or temporary counting structures are expensive to build, maintain, and operate, are susceptible to mechanical failure and coupled with extensive permitting and access requirements, limit their use over a large geographic area. High stream flows limited trap operation in Waddell Creek, California (Shapovalov and Taft 1954) and beach seining to capture steelhead in the Rouge River, Oregon (Everest 1973).

AUC

The AUC estimates were not different from total counts of coho above the ECS or from capture-recapture estimates of Chinook, coho, and steelhead. This suggests the use of residence time from the literature for Chinook and coho and estimated for steelhead in the Noyo and applied to other streams in this study was realistic. However, observer efficiency and residence time should be estimated annually for each stream and estimated throughout each season (English et al. 1992, Manske and Schwarz 2000) because the AUC method is very sensitive to these variables (Hilborn et al. 1999). English et al. (1992) found the AUC method is also sensitive to variability in survey time. The AUC confidence bounds in this study were estimated from observer efficiencies which were tied to the capture-recapture estimates. One of the major short comings of the AUC is that it lacks a rigorous statistical method for calculating confidence bounds and when estimated requires intensive bootstrap computer simulation and independent capture-recapture estimates for their calculation (Korman et al. 2002, Parkin et al. 2003). Where the AUC has been used to estimate salmonid escapement, residence time and observer efficiency have been estimated using independent capture-recapture programs (Shardlow et al. 1987, Jones et al 1998, Korman et al. 2002, Parken et al. 2003) which are capable of estimating escapement without the use of the AUC. Due to the need to better define estimates of residence time and observer efficiency (Manske and Schwarz 2000) and the need for intensive simulation to estimate statistical descriptors of uncertainty, the AUC appears to cumbersome for use in long term monitoring of salmonids in coastal Northern California.

RECCOMENDATIONS

Reduction of counting errors and uncertainty in redd identification combined with biweekly surveys throughout the spawning period of Chinook and coho salmon and steelhead allowed us to estimate escapement in a stratified index sampling design using redd areas. This resulted in precise, reliable, and cost effective escapement estimates compared to more conventional approaches. I recommend that surveys be conducted 7 to 13 days apart, that observer efficiency in redd counts be estimated for each survey and averaged for the season, that redd identification be based on the logistic regression models presented here (with continued development and testing of the Chinook-coho model as data become available), and that escapement be estimated using redd areas in a stratified index approach. The relationship between redd size and the number of redds a female builds needs further evaluation. This approach appears promising for long term monitoring of individual populations and metapopulations (Isaak et al 2003) in a randomized block design similar to that applied to salmonids in Oregon (Jacobs et al. 2001). Evaluations of the power of the data from stratified index redd area escapement estimates for long term trend detection should be conducted.

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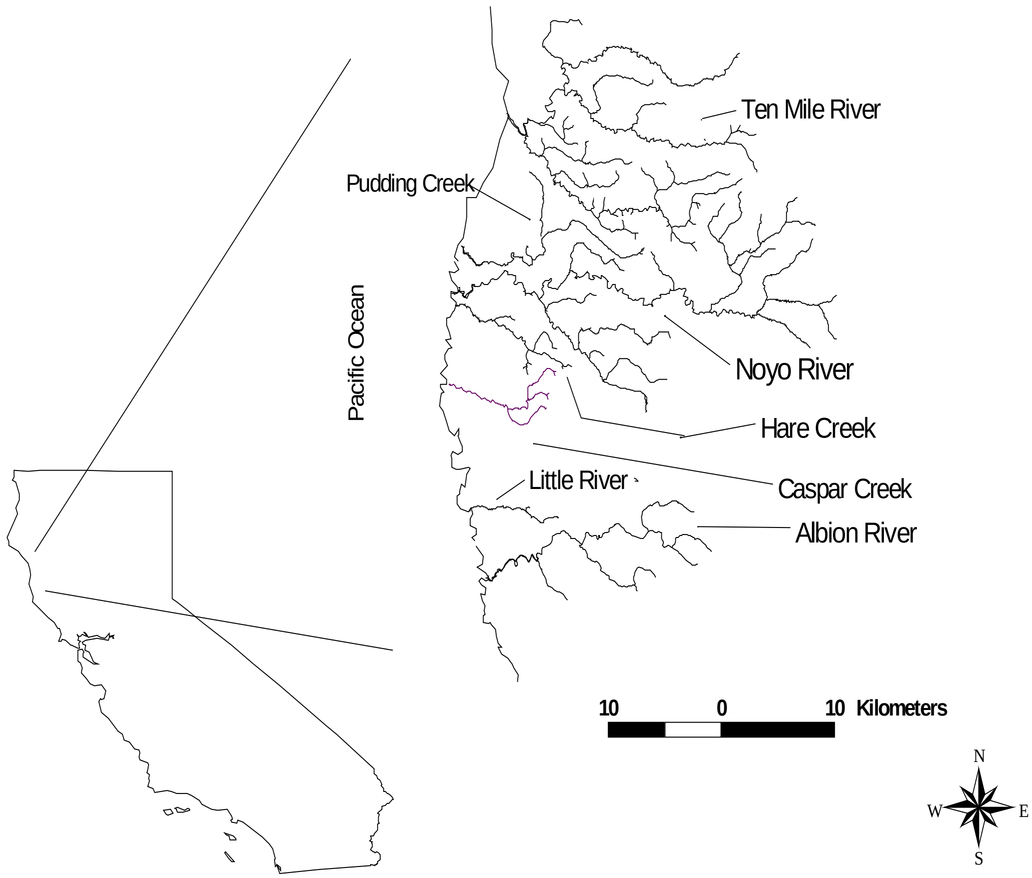


Figure 1. Location of the streams surveyed during this study in coastal Mendocino County, California.

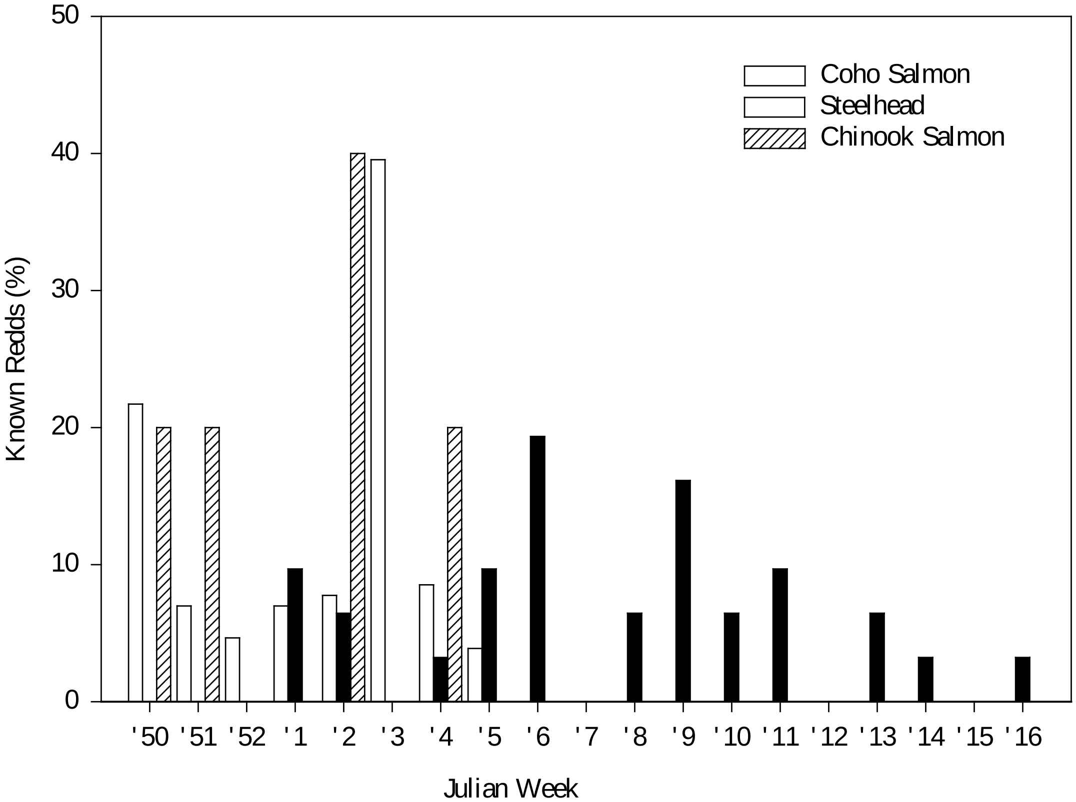


Figure 2. Percent of positively identified Chinook and coho salmon and steelhead redds observed by week in several Coastal Mendocino County streams 2001-2003.

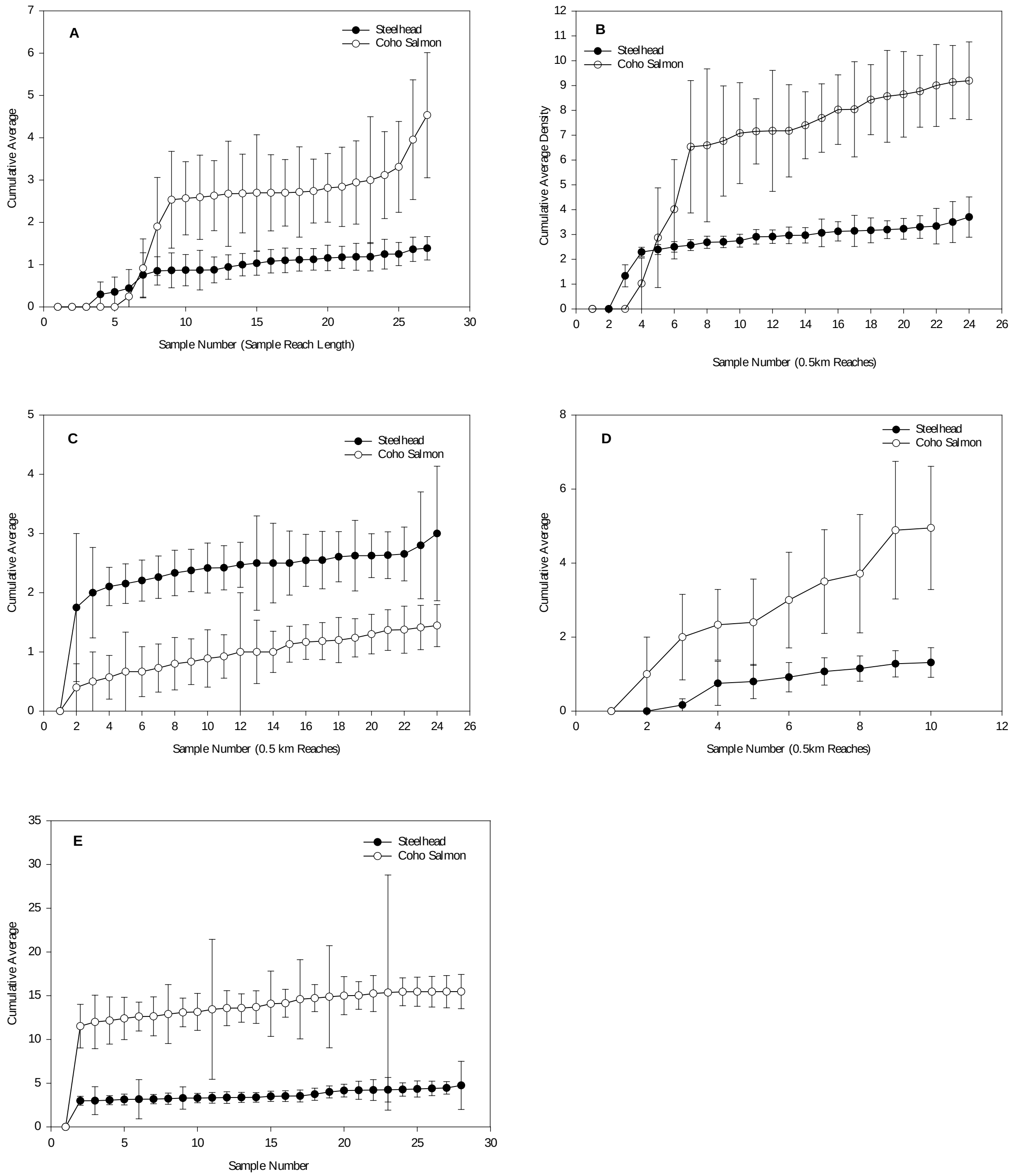


Figure 3. Cumulative mean density of coho salmon and steelhead ± S.E. plotted against the number of sample reaches. (a). Noyo River. (b). Caspar Creek. (c). Hare Creek. (d). Little River. (e). Pudding Creek.

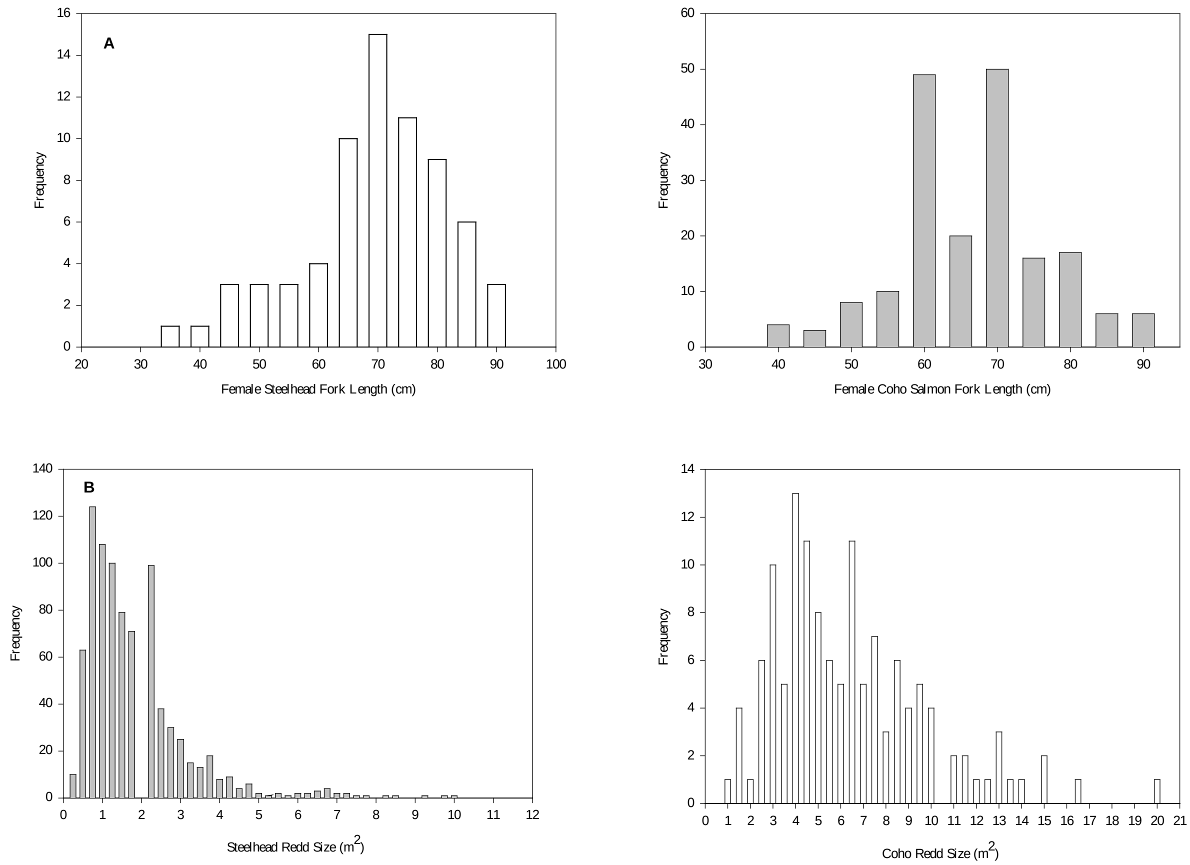


Figure 4. Coho salmon and steelhead female fork length and redd frequencies observed in several coastal Mendocino County streams 2001-2003. (a). Female fork length frequencies. (b). Redd size frequencies.

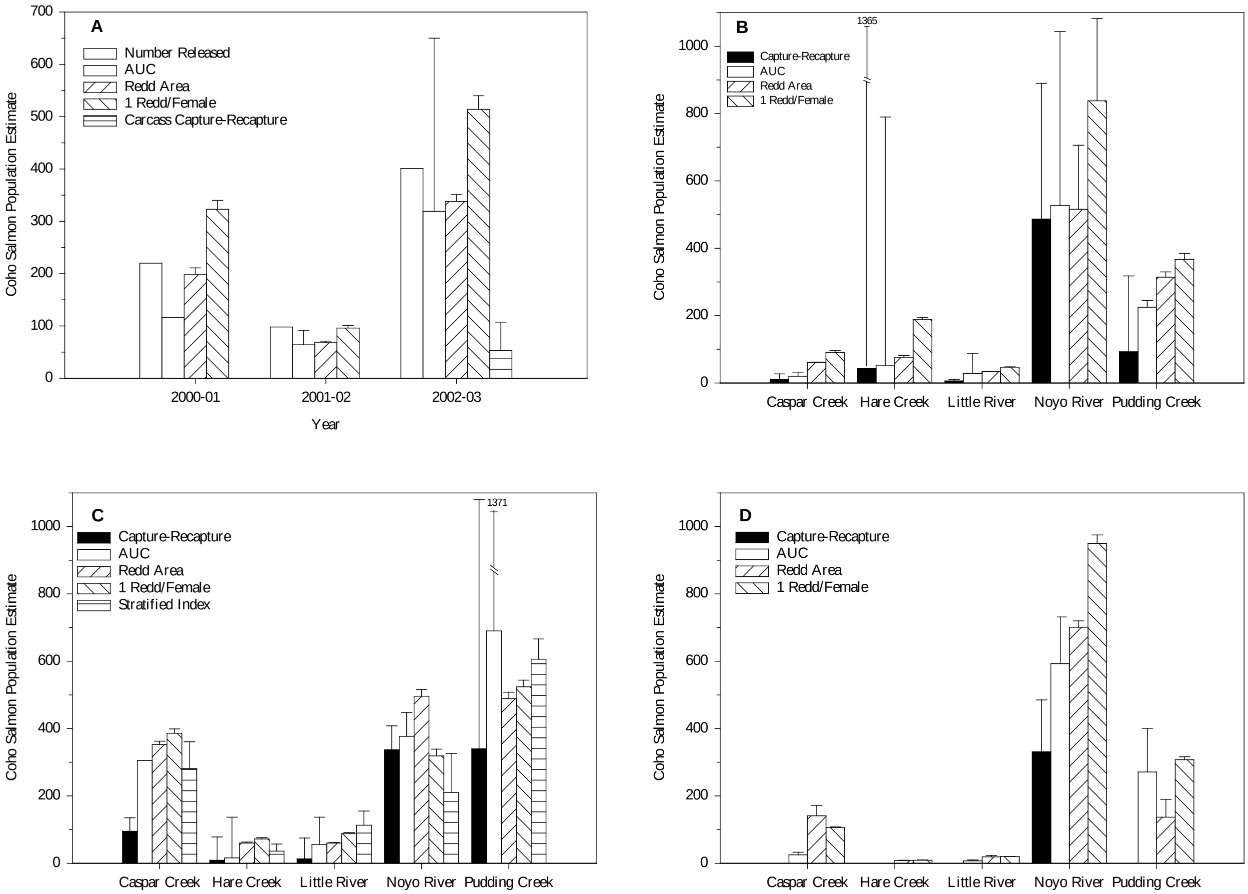
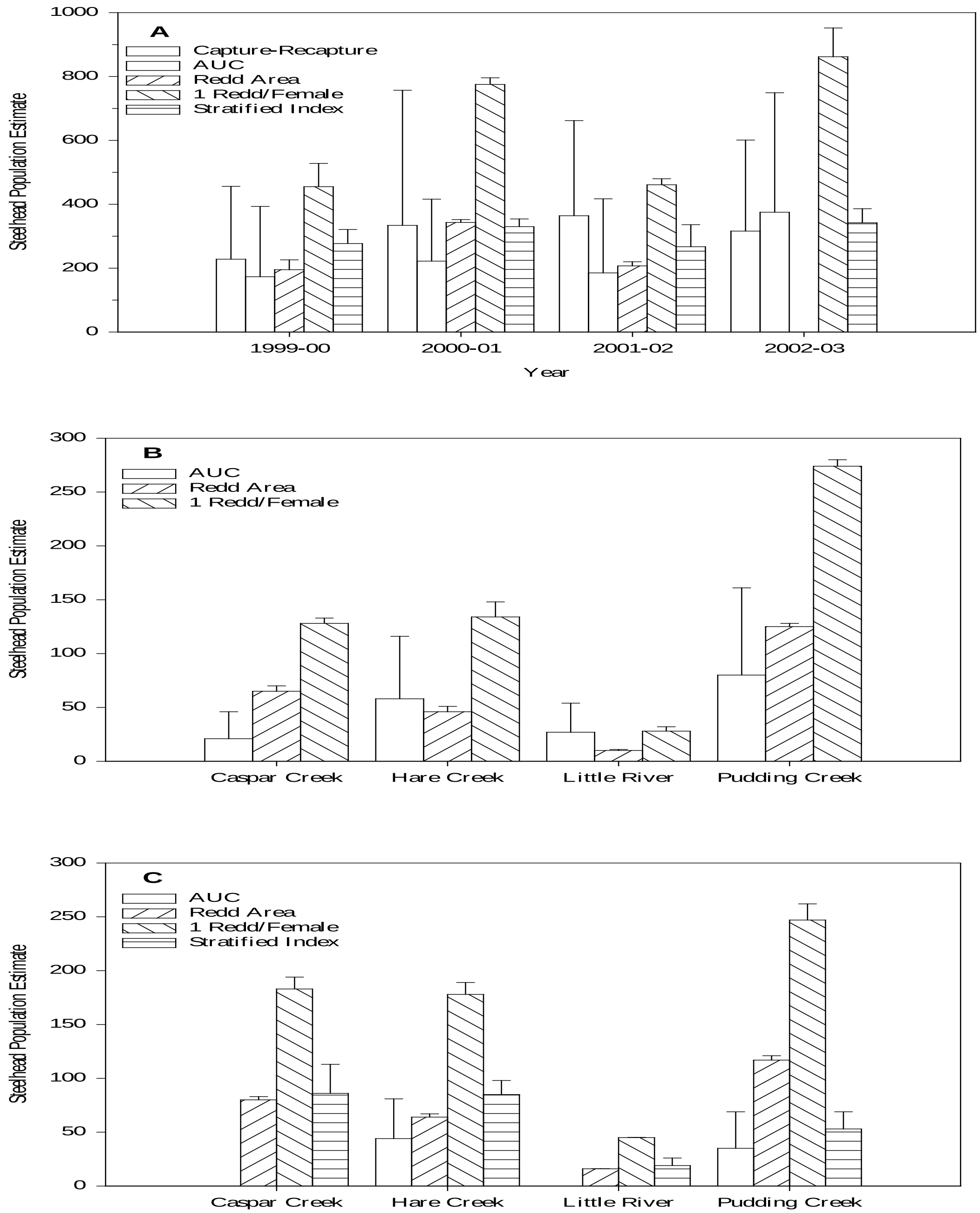


Figure 5. Coho salmon escapement estimates in several coastal Mendocino County streams 2000-01 to 2002-03. (a) Above the Noyo River Egg Collecting Station. (b) 2002-03. (c) 2001-02. (d) 2000-01. Thin lines are 95% CI for carcass capture-recapture and observer uncertainty in AUC, uncertainty in redd identification for redd area and one redd per female, and S.E. for stratified index redd area estimates.



[redacted]igure 6. Ste[redacted]ead populat[redacted]n estimates i[redacted]several Mendocino county streams. (a) [redacted]oyo River 1[redacted]9-00 to 2002[redacted]3. (b) Fou[redacted]treams 2002-03. (c) Four streams 2001-02. Thin lines are[redacted]5% CI for ca[redacted]ure-recaptur[redacted]and AUC, uncertainty in redd identification for redd area and one redd per female, and S.E. for stratified index redd area estimates.

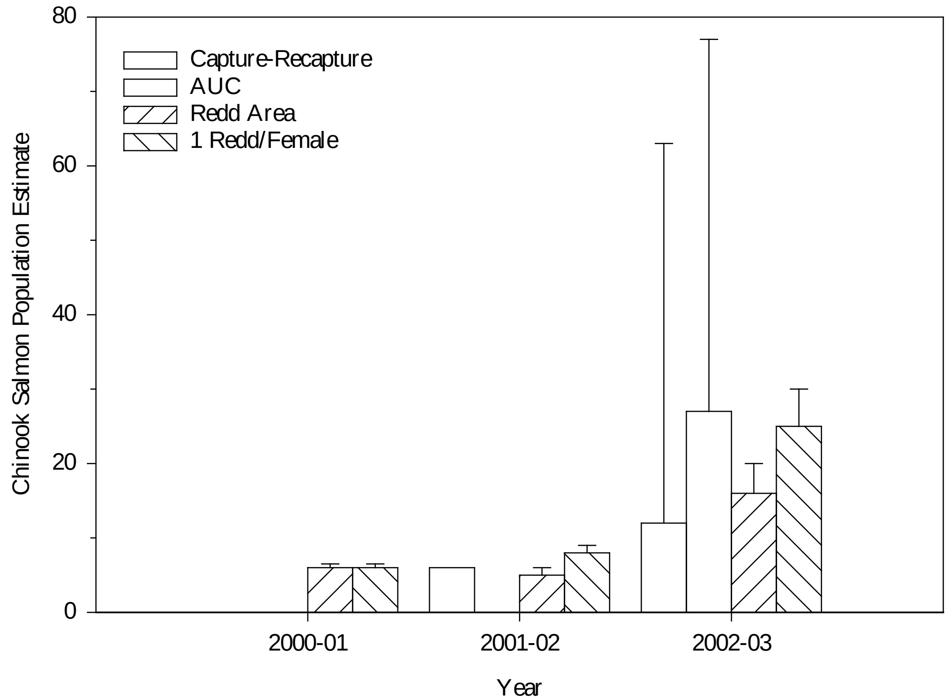


Figure 7. Chinook salmon population estimates in the Noyo River 2000-01 to 2002-03. Thin lines are 95% CI for capture-recapture and AUC and uncertainty in redd identification for redd area and one redd per female.

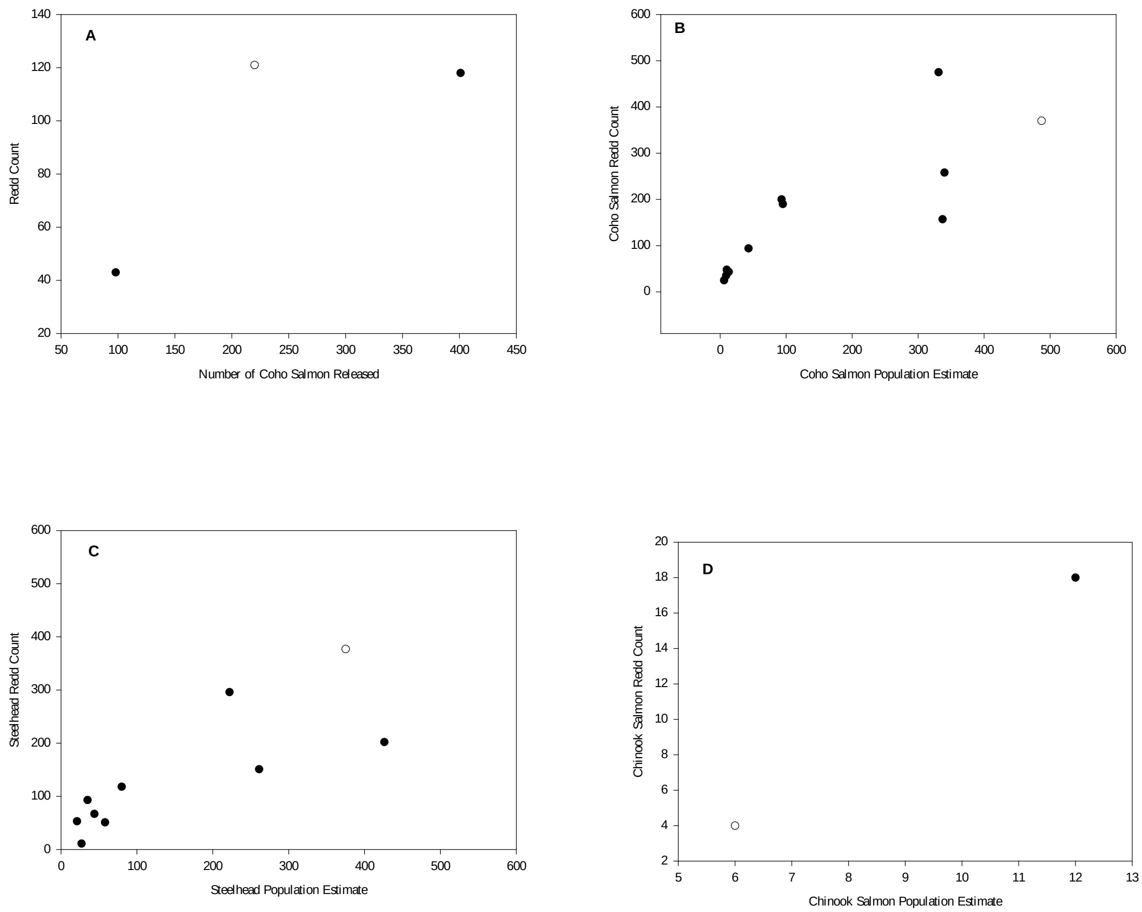


Figure 8. Relationship between redd counts and salmonid escapement estimates in several Mendocino County streams 2000-01 to 2002-03. (a) Coho salmon released above the Noyo River Egg Collecting Station 2000-01 to 2002-03. (b) Coho salmon carcasses capture-recapture estimated escapement from five streams 2000-01 to 2002-03. (c) Steelhead AUC estimated escapement in five streams 2000-01 to 2002-03. (d). Chinook salmon carcass capture-recapture estimated escapement 2001-02 to 2002-03.

Table 1. Number of known coho salmon and steelhead redds observed by river and year used as training data set for logistic regression analysis. Numbers in parentheses are assumed known steelhead redds (based on date) added to increase training data set.

River	2000-01		2001-02	
	Coho Salmon	Steelhead	Coho Salmon	Steelhead
Albion River	1	3	10	0
Caspar Creek	3	0	11	(14)
Hare Creek	0	0	2	1 (5)
Little River	0	0	5	0 (8)
Noyo River	26	7 (13)	11	9 (33)
Pudding Creek	12	0	2	0 (6)
Ten Mile River	0	0	24	0

Table 2. Average and S.E. of Chinook and coho salmon and steelhead redd variables used in training data set for logistic regression.

	Coho Salmon			Steelhead			Chinook Salmon		
Variable	Average	SE	N	Average	SE	N	Average	SE	N
Day	32.4	1.6	102	101.8	2.6	102	28	10.1	5
Distance from Ocean (km)	14.4	0.7	86	24.3	1.4	99	40.9	3.2	5
Fork Length (cm)	67.9	1.1	81	71.7	2.9	20	-	-	-
Pot Depth (m)	0.21	0.01	95	0.14	0.01	102	0.12	0.01	5
Pot Substrate (cm)	2.1-4.5	na	102	2.1-4.5	na	102	15.2	1.3	5
Redd Area (m^2)	6.03	0.34	102	1.78	0.14	102	6.72	0.87	5
Tail Spill Substrate (cm)*	2.0-4.5	na	61	1.3-3.7	na	75	6.75	0.99	5

APPENDIX I

Other Findings of Note

Historical Antecedents

The number of coho salmon and steelhead currently returning to Caspar Creek to spawn is not different than it was during the early 1960's. During the 1960-61 season Kabel and German (1967?) counted coho salmon and steelhead entering Caspar Creek at a mill pond fish ladder which was removed in late-1961. Although not clearly stated in their report, assuming that all fish entering the stream were counted at this ladder, there were a total of 322 coho salmon and 92 steelhead in Caspar Creek in 1960-61. Following a strict three year life cycle the offspring of the 1961 coho salmon reproduction would be encountered 13 generations later in 2001-02. In 2001-02 Gallagher (2003) estimated using the AUC that there were 381 (range 305-565) coho salmon in Caspar Creek. Using redd areas, Gallagher (2003) estimated there were 265 (uncertainty of ± 10) Coho salmon and 60 (± 2) steelhead in Caspar Creek during 2001-02. Looking at redd data, there were 145 coho redds and 68 steelhead redds in Caspar Creek in 2001-02. Assuming a 1:1 male to female ratio would double the redd numbers for an estimate of escapement. If the carcass capture-recapture estimates of Gallagher (2003) correctly estimated the number of Coho salmon in Caspar Creek in 2001-02 (95 ± 40), there were significantly fewer Coho salmon than during the 1950's. However, Gallagher (2003) stated there were some problems with carcass mark-recapture estimates in Capsar Creek during 2001-02 due to low numbers of marked and recaptured fish. During 2002-03 there were an estimated 25-120 coho and 25-75 steelhead in Caspar Creek. No data exist for comparison for this year class of coho or steelhead. Gallagher (2003) states that coho salmon and steelhead populations in coastal Mendocino County, based on redd density patterns, appeared relatively constant over the last 12 years. Figures 5-6 indicate that populations do fluctuate from year to year but year class strength, based on the above, appears rather consistent over time.

Examining the trapping records for adult fish at the Pudding Creek Egg Collecting Station (ECS), while unreliable due to lack of complete records of operation and knowledge of the trapping efficiency, is interesting. In 1957-58 (the earliest record for the corresponding generation to the 2002-03 year class), 368 adult and 260 "grilse" coho salmon and 239 steelhead were captured. Of these a maximum of 256 adults and 260 "grilse" were allowed to escape. In 2002-03 160-410 coho salmon and 75- 260 steelhead were estimated to have returned to Pudding Creek. If trapping at the Pudding Creek ECS was 100% efficient, there is likely no difference in coho and steelhead populations between then and now. Especially, if it is assumed that all "grilse" encountered where returning hatchery plants. Apparently it was common practice to stock waters where egg collecting activities were planned for a number of years prior to egg taking (M. Knechlte, Personal Communication). However, it is very unlikely that 100% of fish entering Pudding Creek during 1957-58 were captured and that the majority of "grisle" were actually returning hatchery fish. During 2003-04 about one in 12 coho salmon entering Pudding Creek were captured at the fish ladder (G. Neillands, Personal communication). It is unknown what the effort was, how the ladder and dam were operated, and what the actual trap consisted of in 1957-58. If trapping efficiency during 1957-58 was similar to 2003-04, there were perhaps up to 12 times as many coho salmon in Pudding Creek in the 1950's as there are today.

Carcass Capture-Recapture

Boydstun (1987) evaluated estimation procedures for Chinook salmon carcass surveys and found that both the Schaefer (a closed population model) and the Jolly-Seber (an open population model) produced estimates similar to known numbers released past a counting structure. However, the Jolly-Seber performed better and Boydstun (1987) recommended its use for future carcass surveys in California. During this study, in most cases too few carcasses were marked and/or recovered to use the Jolly-Seber method. In the few cases it was applicable; it appears to slightly underestimate population numbers compared to other methods (Figure 5). It greatly underestimated the known number of coho salmon released above the Noyo River ECS (Figure 5a). When tested in a stratified index approach on the Noyo River during 2002-03, too few carcasses were encountered and the resulting population estimate, both from the Schaefer and Jolly-Seber methods, suggested there were fewer coho salmon in this river than were known from releases from the ECS in the South Fork. The Jolly-Seber method did work in to Noyo River for Chinook salmon and produced estimates similar to AUC and redd based methods. Carcass based population estimates are not feasible for steelhead because they are iteroparous (Gallagher 2003). Although the Jolly-Seber is probably the correct statistical method for use in carcass mark-recapture programs, its applicability to coho salmon in coastal streams where carcass capture-recaptures were very low was shown not to work.

Hatchery/Wild Interactions Above the ECS

In the South Fork Noyo River, hatchery coho salmon appear to reproduce successfully, which is contrary to some accounts in the literature. The percentage of known wild and hatchery females released above the ECS (36.5% and 63.5%, respectively) is almost exactly the same as the percentage of known wild and hatchery fish observed spawning (36.4 and 63.6, respectively). Since releases and redd counts above the ECS were significantly correlated (Figure 8) and it is likely that marked wild and hatchery coho salmon are equally detectable during spawning surveys, it appears that hatchery coho salmon were successfully spawning. Berejiikian et al. (1997) states that wild males dominant in 86% of spawning interactions with hatchery males and that hatchery females make 62.5% as many redds as wild fish. Numerous other studies suggest that hatchery fish reproduce less successfully that wild fish (Fleming et al. 1992, 1993, 1994). These studies were generally conducted in artificial channels and/or in somewhat controlled situations. The wild fish observed during 2002-03 above the ECS were the progeny of wild fish as no hatchery fish were released the previous years (M. Knechtle, Personal Communication). The hatchery fish were reared at Mad River Hatchery for about one year, held at the Noyo River ECS for about one week, and released. Although the wild fish above the ECS could possibly be the progeny of hatchery fish. Estimates of the number of redds per female above the ECS could be suspect due to the history of hatchery influences on these fish.

Chinook Salmon Observations

Chinook salmon populations in the Noyo River appear to be on the increase (Figure 7). This is likely because spawning surveys had not been conducted on this stream in the past and it was assumed that Chinook salmon did not inhabit the Noyo River. Or it may be that conditions are improving in the ocean and freshwater habitats of other streams and these fish are expanding their range (i.e. the metapopulation concept). Another possible explanation is that spring-run Chinook salmon were planted in the Ten Mile River in the early 1990's and these fish might be strays and or progeny from this effort.

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