Attachment 2

Influence of angling methods and terminal tackle on survival of salmon and steelhead caught and released in the Cowlitz River, Washington

Article *in* Fisheries Research · September 2023

DOI: 10.1016/j.fishres.2023.106848

6 authors, including:

Thomas Ward Buehrens
Washington Department of Fish & Wildlife

Sean Gibbs
Mount Hood Environmental

Fisheries Research 268 (2023) 106848

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Full length article

Influence of angling methods and terminal tackle on survival of salmon and steelhead caught and released in the Cowlitz River, Washington

Ian I. Courter[a,*,1], Thomas Buehrens[b,1], Mark Roes[a], Tara E. Blackman[a], Benjamin Briscoe[a], Sean Gibbs[a,2]

[a] Mount Hood Environmental, PO Box 744, Boring, OR 97009, USA
[b] Washington Department of Fish and Wildlife, 1111 Washington St. SE, Olympia, WA 98501, USA

ARTICLE INFO

Handled by A.E. Punt

Keywords:
Catch and Release
Mark-Selective
Angling
Salmon
Steelhead
Survival
Hooking Mortality

ABSTRACT

Efforts to recover depressed stocks of salmon and steelhead trout in North America include implementation of mark-selective recreational fisheries, whereby anglers are allowed to harvest hatchery-origin fish but must release natural-origin fish. Catch and release angling (C&R) is generally thought to be an effective tool for conservation relative to traditional retention fisheries due to high survival of released adult salmon and steelhead in freshwater. Studies designed to estimate C&R mortality have produced highly variable results among species and size classes of fish, gear types, and environmental conditions. Therefore, crude approximations of C&R mortality are commonly used to quantify impacts to natural-origin salmon and steelhead. In addition, managers often restrict use of certain angling methods and terminal tackle that are assumed to result in higher mortality, leading to a multiplicity of different regulatory requirements with limited empirical support. We conducted a novel three-year mark-recapture study in the Cowlitz River, Washington to estimate effects of a variety of factors hypothesized to influence salmon and steelhead C&R survival using a control-treatment design. Three species of anadromous salmonids were captured and released as treatments using various angling techniques and terminal tackle. Fight time, handling time, and water temperature were recorded during each capture event. Non-angled fish were captured in a trap and released back into the fishery to serve as controls. Recovery rates of Coho Salmon differed less than a percent between angled and non-angled fish across multiple gear types, indicating negligible effects of C&R. Angled Spring Chinook Salmon experienced 3.6–10.2 % C&R mortality relative to non-angled control fish, depending on terminal tackle. Barbless hooks were associated with higher survival than barbed hooks for both Chinook and Coho Salmon, although differences were small for Chinook and negligible for Coho. In contrast, steelhead trout angled on barbed hooks were recovered at slightly higher rates than those caught on barbless hooks. We also found evidence for a reduction in landing rates when angling using barbless hooks. Finally, use of bait increased the probability that salmon would be hooked in a critical location such as the esophagus or stomach. Our findings are useful for assessing trade-offs between conservation measures and harvest opportunity when defining fishing regulations in mark-selective salmon and steelhead fisheries.

1. Introduction

Natural-origin Pacific salmon (*Oncorhynchus* spp.) and steelhead trout (*O. mykiss*) abundance has declined throughout western North American (Kendall et al., 2017; National Research Council NRC, 1996; Nehlsen et al., 1991; Welch et al., 2021) leading to widespread protection under the U.S. Endangered Species Act (ESA) (Good et al., 2005) and Canadian Species at Risk Act (Hutchings and Festa-Bianchet, 2009). Efforts to recover depressed stocks include implementation of mark-selective recreational fisheries, whereby anglers are allowed to harvest hatchery-origin fish, but must release natural-origin fish (Johnson, 2004; Zhou, 2002). Catch and release (C&R) is generally thought to have small impacts on salmon and steelhead survival in freshwater (reviewed in Raby et al., 2015) and negligibly impact

* Corresponding author.
E-mail address: ian.courter@mthoodenvironmental.com (I.I. Courter).
[1] Joint first authors contributed equally to this work.
[2] present address: Mount Hood Environmental, 2617 Lowry Avenue NE, Saint Anthony, Minnesota 55418, USA.

https://doi.org/10.1016/j.fishres.2023.106848
Received 24 April 2023; Received in revised form 28 July 2023; Accepted 29 August 2023
Available online 13 September 2023

population productivity (Whitney et al., 2019). However, the practice of C&R has also been shown to occasionally cause mortality of adult fish due to injury and stress, even when adopting best handling and release practices (Brownscombe et al., 2017).

Results of C&R mortality studies have varied among species and by geographic location, with the most robust studies occurring in Alaska and British Columbia, where C&R of natural-origin salmon and steelhead rapidly gained popularity in the 1980s and 1990s. Steelhead C&R mortality in the Keogh and Salmon Rivers, British Columbia was 3.4 % (Hooton, 1987) and 5.4 % (Lirette and Hooton, 1988), respectively. Similarly, steelhead C&R mortality in the Chilliwack River, British Columbia was 3.6 % (Nelson et al., 2005). Pacific salmon studies during the same era of recreational fisheries assessment suggested higher mortality due to C&R relative to steelhead. Coho Salmon (*O. kisutch*) in the Little Susitna and Unalakleet Rivers, Alaska experienced 11.7 % (Vincent-Lang et al., 1993) and 15 % mortality (Stuby, 2002). Bendock and Alexandersdottir (1993) reported 7.6 % mortality for Chinook Salmon (*Oncorhynchus tshawytscha*) released by recreational anglers in the Kenai River. More contemporary studies of C&R impacts on Pacific salmon and steelhead survival in freshwater estimated mortality rates between 1 % and 12 % for Chinook Salmon (Cowen et al., 2007; Fritts et al., 2016; Lindsay et al., 2004), 16 % for Sockeye Salmon (*O. nerka*; Donaldson et al., 2011), and 3–5 % for steelhead (Nelson et al., 2005; Twardek et al., 2018; Whitney et al., 2019).

Approximations of C&R mortality, typically inferred from disparate studies, are used by managers to estimate fishery impacts from C&R and in turn set allowable fish encounters in locations where impacts to natural-origin salmon and steelhead runs are a concern. Population-scale impacts are estimated by multiplying a C&R mortality rate by the number of natural-origin fish encountered in the fishery (Kerns et al., 2012). For example, in the lower Snake River, Washington steelhead fisheries are limited by a 2 % impact rate on late-run steelhead, which is estimated by assuming a 10 % mortality rate on all late-run steelhead caught in the fishery. Similarly, recreational angling seasons on the mainstem Columbia River, and tributaries are limited by C&R of natural-origin steelhead (National Oceanic and Atmospheric Administration NOAA, 2018; Washington Department of Fish and Wildlife (WDFW), 2003).

In addition to setting seasons and monitoring encounter rates, angling techniques and terminal tackle are often regulated as a conservation measure for protected stocks of salmon and steelhead (e.g., Ministry of Forests, 2021). Restricting angling techniques and terminal tackle is thought to reduce C&R impacts on salmonids (Gresswell and Harding, 1997; Hooton, 2001; Muoneke and Childress, 1994) while still affording anglers an opportunity to catch fish with less harmful methods. For example, several Pacific Northwest salmon and steelhead fisheries prohibit the use of bait and/or barbed hooks and hooks with multiple points. These types of regulations are thought to improve survival of fish after release, however empirical evidence to support such claims for adult salmon and steelhead remains limited. Empirical studies of the effects of terminal tackle on salmonid C&R survival in freshwater are rare, and those that have occurred either report low sample sizes (Lindsay et al., 2004; Twardek et al., 2018) or were not conducted on anadromous salmonids (e.g., DuBois and Dubielzig, 2004; DuBois and Kuklinski, 2004).

The dual mandates of many management agencies to conserve salmon and steelhead runs while providing angling opportunity has led to a diverse set of rules governing use of certain types of recreational fishing tackle in Pacific salmon and steelhead fisheries. Review of angling regulations for western North America reveals a general gradient of restrictions from low to high elevation, with the most restrictive regulations occurring at higher elevations proximate to spawning areas. A few exceptions to this general pattern are worth noting, such as barbed hook restrictions in select Lower Columbia River fisheries.

There is a need to improve the accuracy and specificity of C&R survival estimates used to manage Pacific salmon and steelhead recreational fisheries. Indeed, biased estimates of angling impacts may lead to overly constrained fisheries, or alternatively, excessive exploitation of imperiled populations. Ideally, managers would have sufficient empirical information on how C&R survival varies as a function of species, terminal gear type (e.g. bait, lures, treble hooks, and single barbless hooks), angling methods, and environmental variables.

We conducted a three-year study on the Cowlitz River, Washington to evaluate the effects of angling on salmon and steelhead post-release survival. Our study aimed to address limitations of previous work by incorporating a control-treatment design, obtaining large sample sizes, and measuring numerous variables hypothesized to affect C&R mortality. Specifically, we analyzed the effects of terminal tackle and angling technique on Chinook and Coho Salmon and summer and winter-run steelhead trout. We provide relative impact rates as a function of the full suite of variables measured as well as for a subset of variables under regulatory control.

2. Methods

2.1. Study area

The Cowlitz River is a major tributary to the Columbia River draining nearly 6500 square kilometers from the western slopes of the Cascade mountains (Serl et al., 2017; Fig. 1). The river is home to anadromous fish including natural and hatchery origin Coho Salmon, Spring Chinook Salmon, fall Chinook Salmon, winter steelhead trout, coastal cutthroat trout (*O. clarkii)*, hatchery-origin summer steelhead trout and natural origin Chum Salmon (*O. keta*). Occasionally other stray anadromous fish are encountered as well (e.g. Sockeye salmon). The Basin is divided into an upper and lower watershed by the Cowlitz River Hydroelectric Project, comprised of three hydroelectric dams and a large concrete weir known as the Barrier Dam. The Barrier Dam is approximately 80 kilometers upstream from the confluence with the Columbia River and prevents migrating adult salmon and steelhead from entering the Hydroelectric Project area. A trap-and-haul program transports migrating adult fish collected at the Barrier Dam upstream of the Hydroelectric Project.

Thousands of hatchery-origin salmon and steelhead trout migrate back to the lower Cowlitz River annually, supporting a large harvest-oriented recreational fishery. Chinook and Coho Salmon are raised at the Cowlitz Salmon Hatchery (CSH), and summer and winter steelhead trout are raised at the Cowlitz Trout Hatchery (CTH). The CTH is located 11 kilometers downstream of the CSH near the mouth of Blue Creek. A high proportion of migrating adult hatchery-origin salmon and steelhead trout are captured at the Cowlitz Salmon Separator (CSS), a fish sorting facility associated with the Barrier Dam.

2.2. Data collection

A control-treatment study was implemented to assess survival of angled hatchery-origin Spring Chinook Salmon, Coho Salmon, and steelhead trout. Treatment fish were angled using a variety of different methods and gear types and released back into the study area, while non-angled control fish were captured at the CSS, transported downstream, and released back into the study area at several locations in order to disentangle release location effects from angling mortality effects on recovery. The apparent survival of both angled and non-angled fish was monitored using uniquely numbered anchor tags implanted in each treatment and control fish. Recaptured fish were primarily collected at the CSS, however recaptures were also recorded by recreational anglers (self-reporting), or during Washington Department of Fish and Wildlife (WDFW) creel and spawning surveys.

Angling occurred between the Barrier Dam and the city of Toledo from June 1, 2017 to May 31, 2020 with the majority of fish captured between the CTH and the Barrier Dam. Fish were angled from shore or by boat at least two days per week by field biologists, local fishing

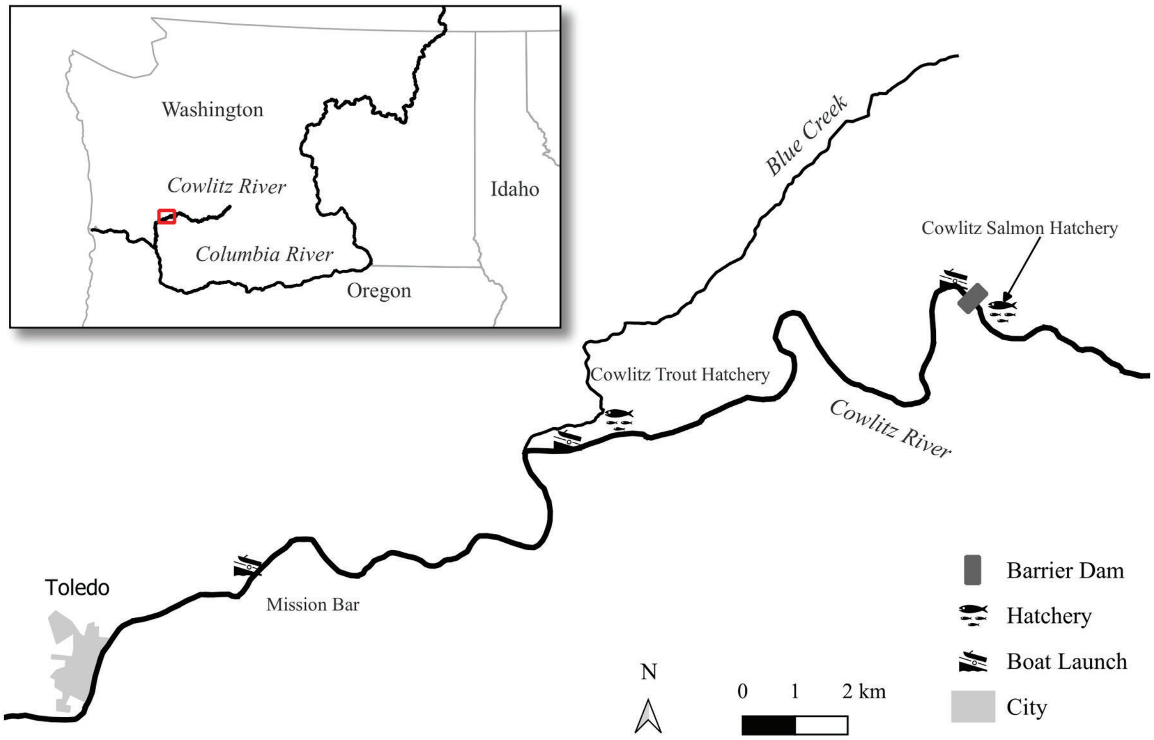


Fig. 1. Map of the study area. Angling occurred in the Cowlitz River between the city of Toledo and the Barrier Dam. Control fish were initially captured at the Cowlitz Salmon Separator, located adjacent to the Barrier Dam, and were subsequently released.

guides, and volunteer anglers. Project personnel conducted tagging and data collection of treatment fish and supervised all angling activities. A variety of hook types (barbed or barbless; single or treble), gear types (bait, lures, jigs, or yarn), and angling methods (bobber, cast, side drifting, or back trolling) were used (Table 1). Gear and method selection was intended to capture a large sample size of fish reflective of common angling practices in the region, while ensuring a reasonable variety of terminal tackle types. All captures followed legal C&R practices for salmon and steelhead in the State of Washington. Accordingly, all captured fish remained submerged in a landing net during handling and data collection. During each capture event, we documented species, origin (hatchery or natural), sex, hooking location (Fig. 2), hook type and size, gear type, angling method, fish condition factors (presence of fungus, percent descaling, net marks, or mammal/lamprey wounds/scars), fish length, surface water temperature, and handling and fight times. Hatchery-origin fish received two t-bar anchor tags (Floy Tag & Mfg, Seattle WA) with unique identification numbers–one implanted on each side of the dorsal fin. Data were also recorded for fish that were hooked for at least three seconds, but not landed. Angling effort was recorded as the number of hours fished per angler.

Non-angled fish were concurrently captured at the CSS to serve as a control group. These fish were anesthetized by electroanesthesia, as is standard practice at the facility for adult salmonids collected for hatchery broodstock and upstream transport, marked with anchor tags, and then transported downstream (Tacoma Power, 2006). Oxygen tanks with diffusers were used to maintain dissolved oxygen levels during transport. Water temperatures and dissolved oxygen levels were continuously monitored to ensure oxygen saturation and minimal change to ambient stream temperatures. The locations of control fish releases were proximal to angling survey locations and included the Mission Bar, Blue Creek, or Barrier Dam boat launches (Fig. 1). Data for all control and treatment fish included field survey data from the initial capture event and any subsequent recapture information including self-reporting by anglers, creel surveys, and spawning ground surveys.

Table 1
Covariates included in the full model and the subset included in regulatory model.

Covariate	Type	Categories	Regulatory model
Treatment	Discrete	Control, treatment	No
Gear type	Discrete	Control, bait, lure, jig, yarn	Yes
Angling method	Discrete	Control, bobber, cast, drift, backtroll	No
Barb type	Discrete	Control, barbless, barbed	Yes
Hook type	Discrete	Control, single hook, multi-hook	Yes
Hook location	Discrete	Control, critical, non-critical	No
Hook removed	Discrete	Control, yes, no	No
Fork length	Continuous	-	No
Fight time	Continuous	-	No
Handling time	Continuous	-	No
Water temperature	Continuous	-	No

2.3. Analytical approach

We used a hierarchical Bayesian mixed-effects modeling approach to quantify Coho Salmon, Chinook Salmon, and steelhead trout mortality due to C&R angling. A Bayesian regression analysis was also conducted to examine the effect of barbed and barbless hooks on landing rates. Because hooking location and handing time cannot be controlled during fish capture events but may influence C&R mortality (Bartholomew and Bohnsack, 2005; Lindsay et al., 2004), we conducted two additional Bayesian regression analyses that examined the factors that influence critical hooking location and handling time. These latter analyses only included Coho Salmon, which had large treatment and control sample sizes compared to other species in this study.

Models were constructed using the ‘brms’ package (Bürkner, 2017) in the program R (R Core Team, 2023). Model outputs were assessed using convergence trace plots, Gelman-Rubin Rhat values (Gelman and Rubin, 1992), inspection of random-effects spline curves, and the

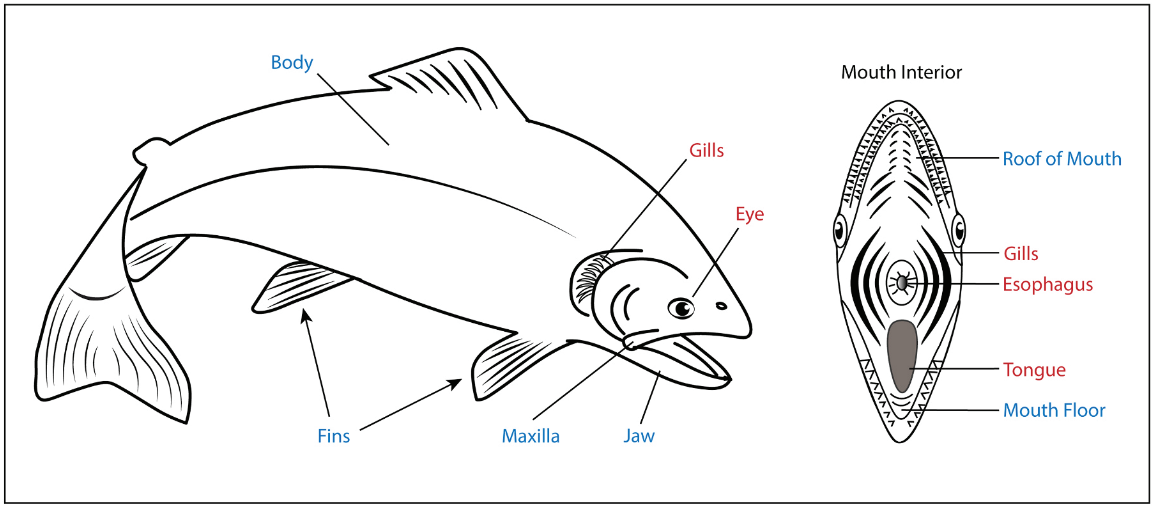


Fig. 2. Critical (red) and non-critical (blue) anatomical hooking locations.

posterior distributions of covariate coefficients along with associated 95 % highest density intervals (HDI). Model predictions for recapture probability were calculated using the 'brmsmargins' package (Wiley, 2022).

2.3.1. Catch and release mortality

Coho Salmon, Chinook Salmon, and steelhead trout mortality due to C&R angling was quantified by comparing the predicted recapture probability between the control and treatment groups using a logit-link regression model. Survival of treatment fish relative to controls was estimated by dividing the inverse-logit transformed predicted recovery rate of treatments by controls. Within this approach, we examined the influence of the method and gear types used for angling and other covariates collected at the time of capture on recapture probability and survival. Models also contained random-effects parameters including a random intercept accounting for unique release and survey events and factor spline terms for the year and day of year a fish was captured or released and the location. The generalized regression formula is given by:

$$R = f(\boldsymbol{Xb} + D_{d,y} + L_{m,y,r} + \gamma_k + \varepsilon_{ijk}) \quad (1)$$

where R is the recapture response variable (whether a fish was recaptured or not) distributed Bernoulli with a logit-link function f. Predicted survival was a function of the product of an n row (observations) by k column (parameter) design matrix $\boldsymbol{X}$, consisting of categorical and continuous covariates, and a vector $\boldsymbol{b}$ of corresponding regression coefficients, including a global intercept. In addition to these linear continuous and categorical effects, the model included smoothing terms $D_{d,y}$ for the estimated date effect as a function of day of year d and study year y, and $L_{m,y,r}$ for the estimated release location effect as a function of river kilometer m, study year y, and run type (i.e., summer and winter steelhead) r. These smoothing terms used factor spline basis functions and were used to estimate non-linear effects of possible nuisance variables and control for spatial and temporal variability. D is the estimated date effect as a function of day of year and study year. L is the estimated release location effect and is a function of river kilometer, study year, and run type (i.e., summer and winter steelhead). The model also included a random effect γ_k with mean zero and variance σ_s^2 to account for the repeated measures variance associated with each unique release event k, and finally, the independent and identically distributed residual error term ε_{ijk}, which was the difference between the logit-transformed prediction and the Bernoulli response.

Separate models were constructed for Coho Salmon, Spring Chinook Salmon, and steelhead trout. Coho Salmon and Spring Chinook Salmon models did not include the location by year factor spline because > 99 % of the releases of control and treatment fish occurred in the vicinity of the Barrier Dam boat launch. Consequently, Coho Salmon and Spring Chinook Salmon released at other locations were excluded from the analysis to eliminate the need to estimate spatial random effects. Spring Chinook Salmon control fish were only available in 2018 therefore modeling only included that year.

The analysis excluded angled fish that were not tagged, and were consequently not available for recapture (e.g., natural origin fish and fish that were not landed). Additionally, control fish that were subsequently recaptured during angling surveys were recorded as control recaptures and were then considered initial captures of treatment fish and released. Recaptured fish that had been formerly converted from control to treatment were recorded as treatment recaptures. Our analysis only considered the first recapture event (within a treatment group) for individual fish that were recaptured multiple times. All recapture events were defined as capture events that occurred at least 24 h after the initial release. Seven treatment Coho were not included in the analysis due to insufficient sample sizes for the gear and methods used during their capture.

Steelhead models did not include control fish, and inferences were therefore limited to relative recovery rates within the treatment component of the study. Despite attempts to release steelhead for use as controls, the downstream location of the steelhead hatchery in the Cowlitz River at Blue Creek caused control fish to avoid our main point of recapture at the Barrier Dam (Fig. 1); this confounded our ability to recapture steelhead control fish and we were unable to devise an analytical solution to address this bias.

For each species, we fit a full model along with a reduced 'regulatory model' that included parameters commonly regulated in C&R fisheries (Table 1). Full models were used to rank the relative importance of covariates on recapture probability, however many of these covariates, such as fight time and hook location, are not under regulatory or angler control (within the study or in a C&R fishery). Therefore, we also fit a model to predict C&R mortality as a function of variables under resource manager control.

Because a fully randomized study design was not intended, we applied a regularized horseshoe prior on the vector of $\boldsymbol{b}$ coefficients, excluding the global intercept (Piironen and Vehtari, 2017). This method was chosen for its robustness to (1) correlation between angling methods, gear selection, and angler success that led to small sample sizes for some combinations of gear types and methods, and (2) the assumption that not all covariate levels will have a strong influence on mortality, and (3) identify a sparse and regularized model that evaluated the relative strength of support for all covariate effects with maximum explanatory power, without either over-fitting, or constructing numerous models comprised of factorial combinations of predictor variables that would be difficult to distinguish with classical model selection approaches (Hooten and Hobbs, 2015). The horseshoe prior was parameterized with the default one degree of freedom of the student-t prior of the local shrinkage parameters and an expected ratio of non-zero to zero coefficient values of 0.5.

To facilitate direct comparison of categorical and continuous covariates, continuous covariates were standardized by two standard deviations as described in Gelman (2008). After standardizing continuous covariates for treatment fish, control fish continuous covariates were set to zero and categorical covariates were designated as the reference level 'control'. Basis functions for the random intercept and spline terms were calculated using the brms package which leverages the 'mgcv' package (Wood, 2017). Spline terms were given the default hyperparameters (e.g., penalty order, knot numbers and locations) from mgcv. Models were run with four chains for 2000 iterations, and 1000 burn-in samples.

2.3.2. Landing probability

The landing probability models for angled Coho Salmon, Spring Chinook Salmon, and steelhead trout were constructed using a similar additive Bayesian regression framework. The response, fish landed or not landed, was treated as a Bernoulli-distributed variable with a logit-link function. All fish successfully identified after being hooked were included in the analyses. Covariates for hook barb type (barbed or barbless) and number of hooks (single or multi-hook) were included with the same regularized horseshoe prior as the C&R mortality model. A random intercept parameter for unique surveys and spline terms for year and time of year did not noticeably affect model fit and were therefore not included. Models were run with four chains of 2000 iterations and 1000 burn-in samples.

2.3.3. Hook location

The critical hook location model for angled Coho Salmon used a similar Bayesian additive regression model framework, and treated whether or not a fish was hooked in a critical location as a Bernoulli-distributed response with a logit-link function. Critical hook location was predicted using a single categorical covariate that described all observed angling method and gear type combinations (Table 1). The same regularized horseshoe prior parameterization as the C&R mortality models was used on this covariate (Eq. 1). Random intercepts for unique surveys and spline terms for year and time of year did not noticeably affect model fit and were therefore not included in the models. The model was run with four chains of 2000 iterations and 1000 burn-in samples.

2.3.4. Handling time

The handling time model for angled Coho Salmon used a similar additive Bayesian regression framework with a gaussian-distributed response for fish handling time (in seconds). Model covariates included critical or non-critical hooking location, barbed or barbless hook, and single or multi-hook type covariates. The same regularized horseshoe prior as the C&R mortality models was applied for these covariates, and a random intercept parameter was applied for unique angling survey events. The model was run with four chains of 2000 iterations and 1000 burn-in samples.

3. Results

From June 1, 2017, to May 31, 2020, more than 7200 rod-hours resulted in angling 2700 salmon and steelhead trout, including non-target species. This resulted in 1446 unique tagged treatment Coho Salmon, Spring Chinook Salmon, and steelhead trout. Concurrent with angling surveys, 3791 fish were trapped at the CSS, tagged, and released into the lower Cowlitz River as control fish (Table 2). Most of these fish were Coho Salmon (n = 1096) and summer (n = 1832) and winter steelhead trout (n = 781). Eighty-two Spring Chinook Salmon were released as control fish. Returns of Spring Chinook Salmon in 2019 and 2020 were not sufficient to allow for control fish releases.

The majority of treatment and control fish were recaptured at the CSS (84.5 %) and by recreational anglers (13.1 %). Other sources of recapture included spawning surveys (<1 %) and out-of-basin fish traps (<1 %). These recapture proportions were similar across species, with the exception of summer steelhead trout; of which 62.5 % were recaptured at the CSS and 35.2 % by anglers. Initial recaptures of treatment fish occurred between 1 and 97 days after capture (median = 18 days; Fig. 3).

3.1. Catch and release mortality

Full and regulatory models were fit for Coho and Chinook Salmon data and effects of covariates on recovery rates and survival relative to controls are reported. For steelhead, model results describe variation in recapture probability only (no inference relative to controls) since the control group was excluded from the analysis. For all models, the

Table 2
Annual totals of tagged control and treatment fish, percentage of recaptures, and returns to the Cowlitz Salmon Hatchery (CSH).

Species	Run Year	Control Release Group		Treatment Release Group		CSH Returns[a]
		Tagged	Recaptured [%]	Tagged	Recaptured [%]	
Coho	2017	316	239 [75.6]	246	180 [73.2]	39,037
	2018	390	277 [71.0]	319	243 [76.2]	12,959
	2019	390	313 [80.3]	369	288 [78.0]	21,337
	Total	1096	829 [75.6]	934	711 [76.1]	
Spring Chinook	2017	8	0 [0]	17	11 [64.7]	9393
	2018	74	56 [75.7]	131	73 [55.7]	2627
	2019	0	0	6	3 [50.0]	1269
	Total	82	56 [68.3]	154	87 [56.5]	
Summer Steelhead[b]	2017	295	148 [50.2]	21	16 [76.2]	1592
	2018	840	466 [55.5]	49	24 [49.0]	2296
	2019	697	338 [48.5]	49	12 [24.5]	1907
	2020	0	0	6	3 [50.0]	-
	Total	1832	952 [52.0]	125	52 [44.0]	
Winter Steelhead	2018	199	112 [56.3]	35	15 [42.9]	2942
	2019	390	205 [52.6]	37	14 [37.8]	1985
	2020	192	104 [54.2]	161	103 [64.0]	4807
	Total	781	421 [53.9]	233	132 [56.5]	

[a] CSH returns are up to date through July 24, 2020.
[b] Control summer steelhead totals includes fish released as part of Tacoma Power's recycling program.

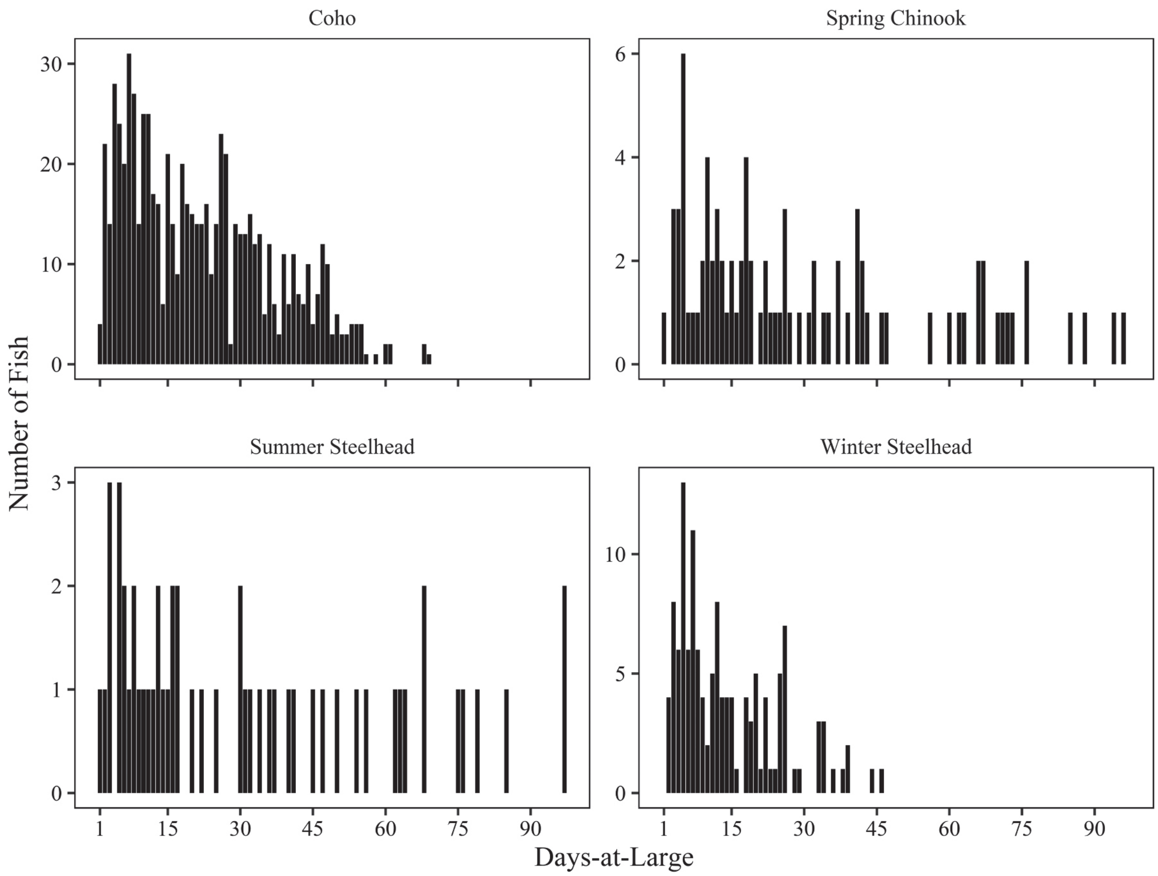


Fig. 3. Frequency of the number of days between capture and initial recapture of treatment fish by species and run type.

horseshoe prior led to β coefficient posterior distributions with clear shrinkage towards zero and long tails when posterior samples were further from zero, as expected. Therefore, the density of posterior distributions was greatest near zero and covariates with evidence for influence on C&R mortality had posterior distributions with strong negative skew. Random effects intercept terms indicated some variation in recapture probability attributed to unique surveys and control releases. Spline terms in the Coho and Chinook models indicated variation in recapture probability based on the day and year of capture or release for control and treatment fish, respectively. The spline terms included in steelhead models indicated variation in recapture probability associated with day of year and year by run type, and river kilometer and run year by run type. Spline functions were consistent within species across models. Trace plots and β parameter Rhat values less than 1.05 indicated that all models converged appropriately.

The Coho full model did not provide clear evidence for covariate effects on recapture probability (Table 3). Handling time and critical hooking location covariates were weakly associated with reduced Coho recapture probability; the probability of a negative effect was 0.61 and 0.58, respectively. Median relative C&R mortality predictions from the regulatory model were less than 1 % (median 95 % HDI −3.2 to 3.2 %), and did not indicate significant differences due to gear, barbs, or single and multiple hook types (Fig. 4).

Spring Chinook models provided minimal evidence for a treatment effect. Lower recovery probabilities were weakly associated with barbed hooks relative to non-barbed, non-critical hooking locations relative to critical hooking locations, and multiple hooks relative to single hooks (Table 4). The overall median predictions of relative mortality from the regulatory model ranged from 3.6 % (95 % HDI −0.6 to 30.1 %) to 10.2 % (95 % HDI −6.9 to 66 %) depending on gear type, barbed or barbless hook, and single or muti-hook type (Fig. 4). In all cases, the 95 % HDI for

Table 3
Coefficient estimates and associated highest density intervals (HDI) from the Coho Salmon catch and release mortality full model. Covariate coefficients are relative to non-angled control fish.

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of negative effect
Handling time	-0.0340	-0.0006	-0.2820	0.0447	0.6135
Critical hook location	-0.0441	-0.0004	-0.3548	0.1246	0.5768
Bobber with bait	-0.0257	-0.0003	-0.2202	0.1017	0.5748
Barbed hook	-0.0024	-0.0001	-0.0679	0.0483	0.5255
Hook removed	-0.0011	0.0000	-0.0628	0.0563	0.5088
Angling effect	-0.0017	0.0000	-0.0727	0.0666	0.5035
Multi-hook	-0.0033	0.0000	-0.0964	0.0679	0.5032
Single hook	0.0012	0.0000	-0.0651	0.0685	0.4958
Backtrolling with bait	0.0047	0.0000	-0.1088	0.1008	0.4948
Hook left in fish	-0.0019	0.0000	-0.1062	0.0893	0.4940
Barbless hook	0.0023	0.0000	-0.0681	0.0661	0.4852
Casting a lure	0.0005	0.0000	-0.0610	0.0694	0.4835
Drifting with bait	0.0064	0.0000	-0.1110	0.0881	0.4808
Casting a jig	0.0032	0.0001	-0.0554	0.0734	0.4690
Fork length	0.0046	0.0001	-0.0443	0.0758	0.4650
Non-critical hook location	0.0072	0.0001	-0.0625	0.0825	0.4582
Temperature	0.0054	0.0001	-0.0624	0.0743	0.4572
Fight time	0.0109	0.0002	-0.0608	0.1191	0.4475

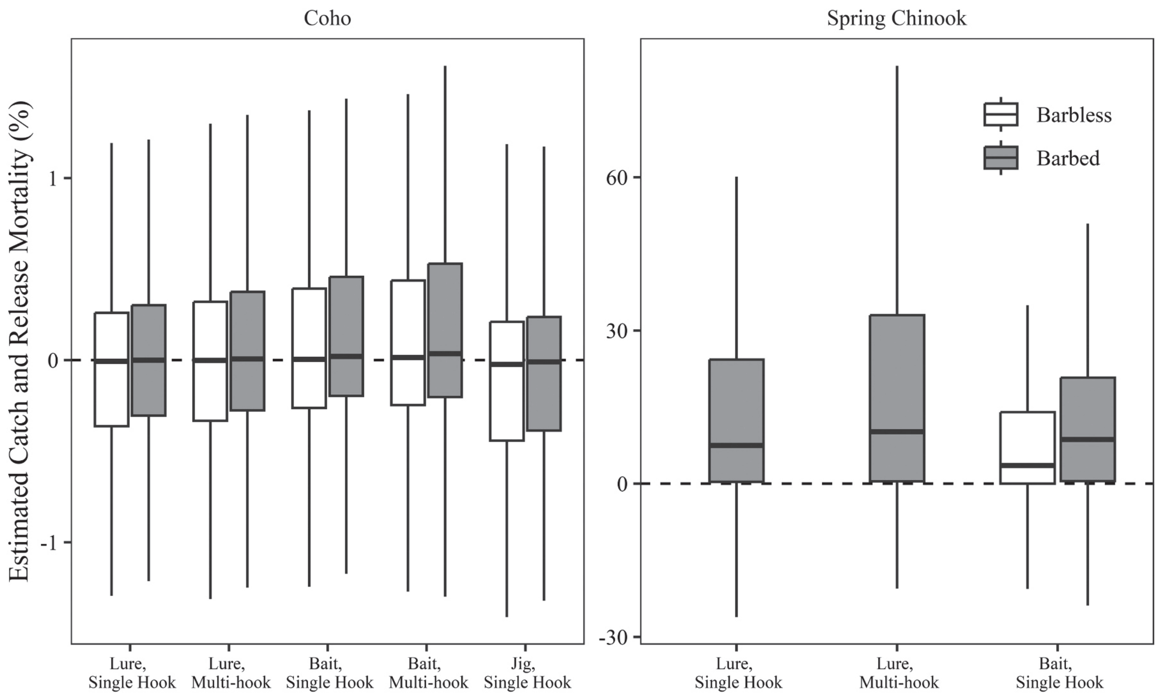


Fig. 4. Estimated catch and release mortality for Coho Salmon and Spring Chinook Salmon, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks.

Table 4
Coefficient estimates and associated highest density intervals (HDI) from the Spring Chinook Salmon catch and release mortality full model. Covariate coefficients are relative to non-angled control fish.

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of negative effect
Angling effect	-0.2609	-0.0204	-1.3995	0.127	0.7048
Barbed hook	-0.0799	-0.0046	-0.6174	0.1854	0.6242
Casting a lure	-0.1101	-0.0023	-0.9708	0.3045	0.5930
Multi-hook	-0.1092	-0.0030	-0.9867	0.2876	0.5918
Hook removed	-0.0385	-0.0016	-0.4630	0.2317	0.5750
Non-critical hook location	-0.0504	-0.0019	-0.508	0.1907	0.5738
Bobber with bait	-0.0343	-0.0010	-0.5184	0.2996	0.5538
Hook left in fish	-0.0378	-0.0009	-0.4749	0.2226	0.5512
Single hook	-0.0324	-0.0009	-0.5277	0.2724	0.5510
Temperature	-0.0263	-0.0008	-0.3822	0.2360	0.5508
Critical hook location	-0.0188	-0.0004	-0.3993	0.2193	0.5295
Barbless hook	-0.0047	0.0000	-0.2763	0.2390	0.502
Handling time	0.0051	0.0001	-0.2496	0.2263	0.488
Fork length	0.0053	0.0003	-0.2354	0.1827	0.474
Fight time	0.0280	0.0011	-0.1623	0.3320	0.4472

estimates of relative mortality included zero.

Steelhead models did not provide any evidence for variation in recapture rates among angled fish. In the full model, posterior distributions of covariate effects all straddled zero. Similarly, recapture probabilities predicted from the regulatory model did not display significant variation for gear, barb, and single or multiple hook type combinations (Fig. 5).

3.1.1. Landing probability

During angling surveys, 2509 Coho Salmon, Spring Chinook Salmon, and steelhead trout were hooked and 2039 were successfully landed. The landing rate models indicated that barbed hooks were likely associated with increased landing probability for all species when compared to barbless hooks, however, the 95 % HDIs overlapped in all cases (Fig. 6). Coefficient estimates for number of hooks were at or near zero and subsequently removed from the models. For Coho Salmon, barbless and barbed hooks were estimated to result in landing probabilities of 0.81 (95 % HDI 0.78 – 0.85) and 0.87 (95 % HDI 0.84 – 0.89), respectively. Barbed hooks were also associated with an increase in landing probability for Spring Chinook Salmon compared to barbless hooks, from 0.75 (95 % HDI 0.65 – 0.86) to 0.89 (95 % HDI 0.82 – 0.94). Similarly, the landing probability for steelhead was lower when barbless hooks were used compared to barbed hooks, estimated at 0.63 (95 % HDI 0.56 – 0.72) and 0.74 (95 % HDI 0.70 – 0.79), respectively.

3.1.2. Hook location

The hook location model for Coho Salmon revealed differences in the probability of hooking Coho in a critical location for some angling method and gear type combinations (Fig. 7). The median probability of critical hook locations while casting with jigs and lures were 0.02 (95 % HDI 0.01 – 0.03) and 0.05 (95 % HDI 0.03 – 0.08), respectively, while using a bobber with bait resulted in a critical hook probability of 0.19 (95 % HDI 0.12 – 0.28). The small sample sizes for angling method and gear type combinations drifting ($n = 11$) and backtrolling ($n = 2$) with bait resulted in limited capacity for inference.

3.1.3. Handling time

The handling time model for Coho Salmon indicated that barbed hooks were the most likely covariate to influence fish handling duration. Barbed hooks were associated with a three second median increase in handling time (mean = 95 s; 95 % HDI −0.58 to 8.52) compared with barbless hooks, and a 0.91 probability that the effect was positive. Critical hook location and multi-hooks were predicted to marginally increase handling time, however the 95% HDIs straddled zero (critical hook location −2 to 7.14; multi-hook −2.36 to 6.26) and the probabilities of positive effect were 0.69 and 0.67, respectively.

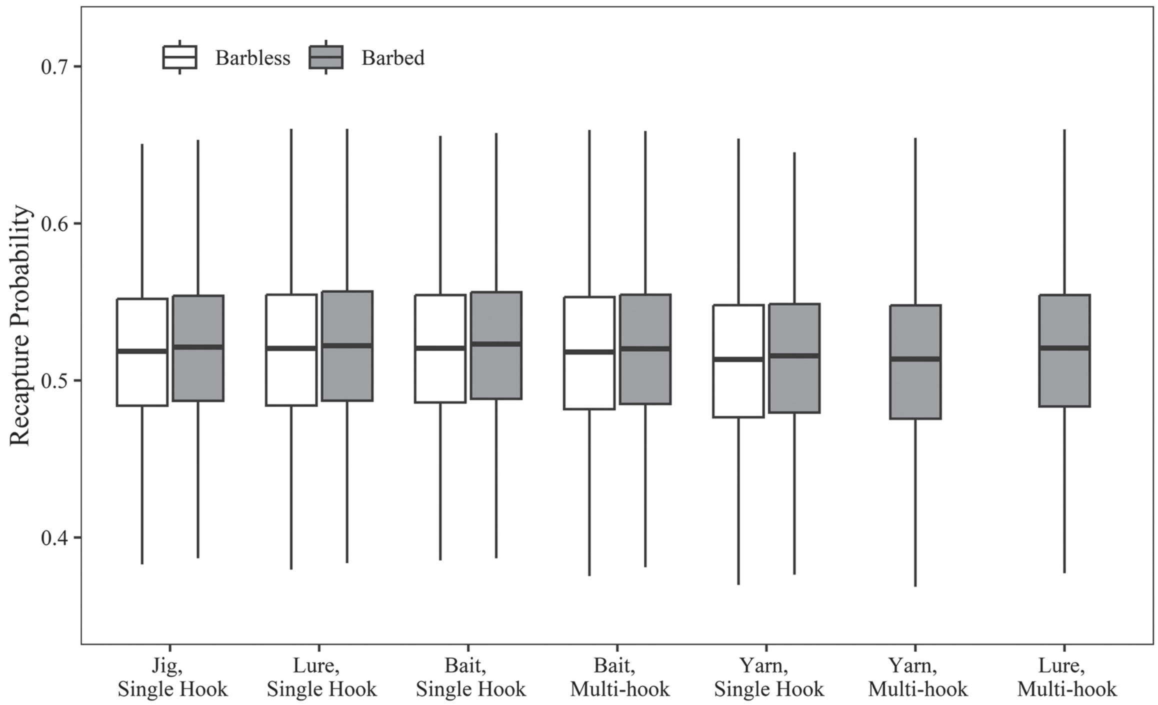


Fig. 5. Estimated variation in recapture probability for angled steelhead trout, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks.

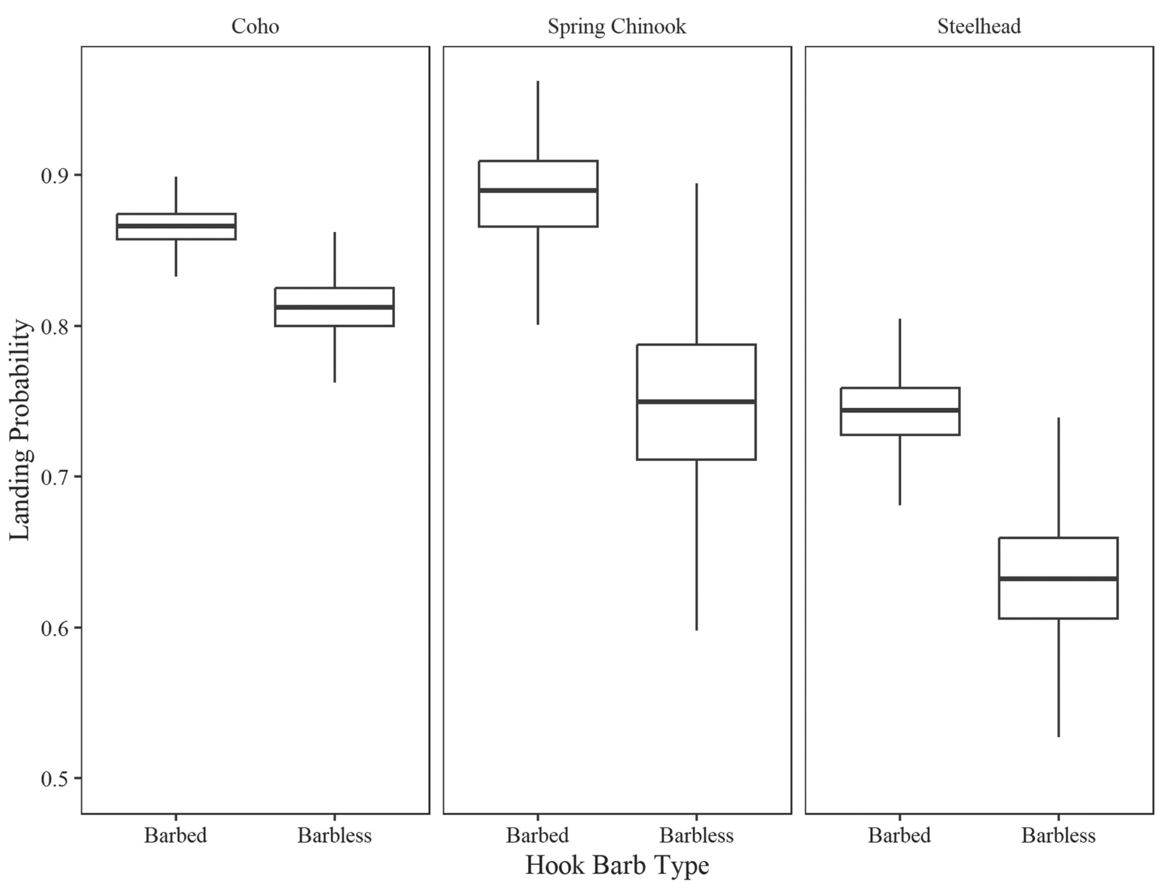


Fig. 6. Landing probability for Coho Salmon, Spring Chinook Salmon, and steelhead trout, given barbed and barbless hook types.

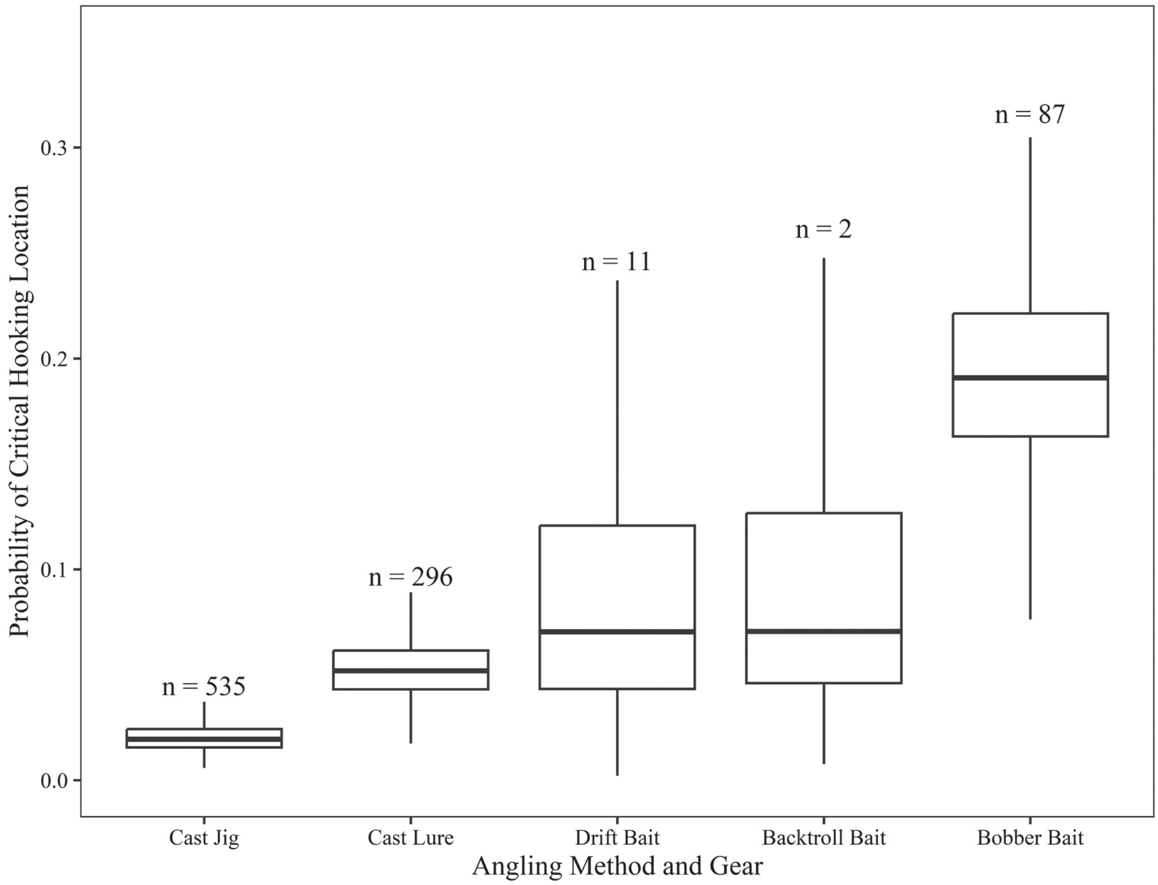


Fig. 7. Critical hook probability for Coho Salmon by combinations of angling method and gear type. n = sample sizes for each angling method and gear type combination.

4. Discussion

C&R survival studies have been conducted on recreational salmon and steelhead fisheries in Alaska, British Columbia, and the Pacific Northwest, but these evaluations were typically limited to a single species. Moreover, few studies of salmon and trout C&R survival were designed to quantify the influence of terminal tackle and angling methods. Existing fish capture facilities, abundance of hatchery-origin fish, and anadromous fish species diversity made the Cowlitz River an ideal location for implementing a C&R survival study on multiple anadromous salmonid species. Our dataset also proved useful for examining effects of terminal gear type and fishing methods, fight time, handling time, and hook location.

Coho Salmon survival was high after C&R with no clear evidence for differences in recapture rates between control and treatment fish. Stuby (2002) reported 15 % C&R mortality for Coho Salmon caught on lures, but our results suggest C&R recreational fisheries that primarily target Coho Salmon with lures and jigs should be expected to have negligible impacts on prespawning survival. It was unclear whether Coho Salmon fisheries that rely on bait should be expected to increase prespawning mortality because we angled few Coho Salmon with bait, which was less effective in the fishery. However, we did find indirect evidence that terminal tackle may influence Coho Salmon survival. Specifically, use of bait increased the probability of hooking fish in critical locations. Vincent-Lang et al. (1993) estimated 11.7 % C&R mortality for Coho Salmon angled using bait and found hook location significantly affected survival rates.

Unlike our results for Coho Salmon, we found evidence for C&R effects on Spring Chinook Salmon, which experienced 3.6–10.2 % mortality relative to non-angled control fish, depending on terminal tackle. These results are similar to those of previous studies that estimated Chinook Salmon C&R mortality between 7.6 % and 12.2 % (Bendock and Alexandersdottir, 1993; Fritts et al., 2016; Lindsay et al., 2004), but differ from the 0.9% mortality reported by Cowen et al. (2007). It is reasonable to assume that higher rates of mortality for Spring Chinook in our study relative to Coho Salmon could have been attributed to preferential use of bait while targeting Chinook in the fishery. Despite Spring Chinook being most-frequently angled using bait, median survival rates were similar to Chinook angled with lures.

Terminal tackle are commonly regulated to reduce impacts of C&R. Therefore, we tested the efficacy of purported conservation measures, such as restricting use of barbed hooks. Lower recapture probabilities were weakly associated with barbed hooks relative to barbless hooks. These results corroborate previous meta-analyses that indicate negligible differences in survival for adult anadromous fish angled with barbed and barbless hooks (Schill and Scarpella, 1997), but differ from other studies that reported barbless hooks result in higher C&R survival of Coho Salmon (Gjernes et al., 1993) and resident trout (Taylor and White, 1992). We found secondary evidence that use of barbed hooks increased handling time, which has been associated with higher mortality in Atlantic Salmon recreational fisheries (Thorstad et al., 2003).

Although salmon and steelhead caught on barbed and barbless hooks were recaptured at nearly indistinguishable rates, there were substantial differences in landing probabilities between the two hook types. Similar to Bloom (2013), DuBois and Dubielzig (2004), and Meka (2004), we found that angling with barbless hooks resulted in lower landing probabilities. This was an important finding that should be useful to managers when assessing trade-offs between conservation and harvest opportunity within recreational fisheries. For example, restricting anglers to use of barbless hooks in hatchery-supplemented fisheries may substantially impact harvest rates without providing a significant conservation benefit. Conversely, it may be prudent to restrict barbed hooks in C&R fisheries where fish retention is not allowed, and the intent is to minimize impacts on natural-origin fish.

Surprisingly, we did not find that increased surface water temperature at capture negatively affected salmon and steelhead C&R survival as was reported by Bartholomew and Bohnsack (2005) and Bentley and Rawding (2016). We suspect this was because temperatures in the Cowlitz River remain within the physiological optima for salmonids. Reservoirs in the Basin moderate river temperature conditions such that peak summer temperatures rarely exceed 16 degrees Celsius and winter temperatures remain above 10 degrees Celsius. We expect that temperature effects are stronger in rivers where water temperatures approach and surpass critical stress thresholds for salmonids–approximately 18 degrees Celsius or higher.

Some researchers have reported relatively high C&R mortality for resident salmonids (Huhn and Arlinghaus, 2011). This may be because resident fish are generally smaller than anadromous fish, and smaller salmonids can be more vulnerable to mortality due to serious injury from handling and hook removal (Meka, 2004; Schisler and Bergersen, 1996). Furthermore, small fish need to recover and continue actively feeding, whereas adult salmon and steelhead undergo prolonged fasting prior to spawning (Penney and Moffitt, 2014). Given differences in life-history and size of resident and anadromous salmonids, it is reasonable to expect that specific terminal tackle types, such as barbed hooks, may have greater impacts on smaller salmonids relative to what we observed for adult anadromous salmonids.

Our study addressed a key shortcoming of previous research by documenting recapture rates of non-angled fish to serve as controls. However, these control fish were imperfect surrogates for other non-angled fish in the population. Impacts of electro-immobilization, handling, and transport of control fish could have positively biased survival estimates for angled fish. We believe these impacts were minimal because CSS operators routinely assesses mortality for hatchery broodstock, and impacts of electro-immobilization at the CSS were found to be negligible (Nguyen et al., 2018). Future C&R survival studies should consider marking outmigrating juvenile fish with Passive Integrated Transponder tags so they can be detected without capture and handling when they reenter the study area as adults. This would allow for survival estimation methods similar to those described by Skalski et al. (2010).

Generally, effects of C&R, angling methods, and terminal tackle were small, with relatively high levels of uncertainty. As such, implementing angling restrictions to minimize impacts of C&R may be less effective than other conservation actions. Previous research has shown that when C&R mortality is low, recreational angling impacts are minimal, even during years of low abundance (McCormick et al., 2021). Correspondingly, liberalizing gear regulations should not be expected to appreciably impact salmon and steelhead populations. Anadromous salmonids are known to respond to density such that small changes in C&R survival will not likely result in changes in population-level abundance or long-term persistence relative to other factors, such as spawning and rearing habitat conditions, predation, migration impediments, and ocean conditions (Nehlsen et al., 1991).

We designed our study to address mortality as the primary experimental endpoint. However, sublethal impacts of angling on anadromous salmon and steelhead is also a management concern. Changes in reproductive success, migratory behavior, or rates of iteroparity could have significant biological consequences. While difficult to assess, these types of sublethal impacts, if they occur because of angling, may be more consequential to population productivity than effects of angling on prespawning survival, and warrant further evaluation.

Funding

Funding for this work was provided by the Washington Department of Fish and Wildlife's Columbia River Salmon and Steelhead Enhancement Fund and an appropriation from the Washington State Legislature.

CRediT authorship contribution statement

Ian I. Courter: Funding acquisition, Conceptualization, Methodology, Investigation, Project administration, Writing – original draft, Writing – review and editing. **Thomas Buehrens:** Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Mark Roes:** Formal analysis, Visualization, Writing – original draft, Visualization, Investigation. **Tara E. Blackman:** Data curation, Methodology, Visualization, Writing – original draft, Writing – review and editing. **Benjamin Briscoe:** Investigation. **Sean Gibbs:** Investigation, Writing – original draft, Writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank Tacoma Power staff for their support of this research. Specifically, Scott Gibson, Jamie Murphy, and Missy Baier who recorded tag numbers from recaptured fish at the Salmon Separator. Tacoma Power staff also tagged, transported, and released hundreds of fish into our study area for use as controls. We thank Forrest Carpenter, formerly Mount Hood Environmental, for fieldwork coordination and many hours in the field angling treatment fish. We also thank WDFW hatchery staff, creel surveyors, and spawning ground surveyors for reporting tag numbers from recovered study fish. Volunteer anglers Don Johnson, Jack Tipping, and Terry Carlson regularly participated in our angling surveys and caught numerous fish, as did fishing guide Andy Coleman who provided invaluable knowledge of the fishery. Columbia River Salmon/Steelhead Recreational Advisory Board members Stan Bartle, Ed Wickersham, and Rick Graser all contributed by supporting our proposal during the funding process. Cowlitz River Ad Hoc Advisory Board member, Bob Reed provided a letter of support at the outset of our proposal effort. Finally, we owe a special thanks to Jon Vigre, Cowlitz River Ad Hoc Advisory Board member, who generously allowed our field crew to lodge at his property for nearly three years.

References

Bartholomew, A., Bohnsack, J.A., 2005. A review of catch-and-release angling mortality with implications for no-take reserves. Rev. Fish. Biol. Fish. 15, 129–154.

Bendock, T., Alexandersdottir, M., 1993. Hooking mortality of chinook salmon released in the Kenai River, Alaska. North Am. J. Fish. Manag. 13, 540–549. https://doi.org/10.1577/1548-8675(1993)013<0540:HMOCSR>2.3.CO;2.

Bentley, K., Rawding, D., 2016. Development of a catch and release mortality model for recreational steelhead fisheries.

Bloom, R.K., 2013. Capture efficiency of barbed versus barbless artificial flies for trout. North Am. J. Fish. Manag. 33, 493–498. https://doi.org/10.1080/02755947.2013.769920.

Brownscombe, J.W., Danylchuk, A.J., Chapman, J.M., Gutowsky, L.F.G., Cooke, S.J., 2017. Best practices for catch-and-release recreational fisheries – angling tools and tactics. Fish. Res. 186, 693–705. https://doi.org/10.1016/j.fishres.2016.04.018.

Bürkner, P.-C., 2017. brms: An R package for Bayesian multilevel models using stan. J. Stat. Soft 80. https://doi.org/10.18637/jss.v080.i01.

R. Core Team, 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria.

Cowen, L., Trouton, N., Bailey, R.E., 2007. Effects of angling on Chinook Salmon for the Nicola River, British Columbia, 1996–2002. North Am. J. Fish. Manag. 27, 256–267. https://doi.org/10.1577/M06-076.1.

Donaldson, M.R., Hinch, S.G., Patterson, D.A., Hills, J., Thomas, J.O., Cooke, S.J., Raby, G.D., Thompson, L.A., Robichaud, D., English, K.K., Farrell, A.P., 2011. The

consequences of angling, beach seining, and confinement on the physiology, post-release behaviour and survival of adult sockeye salmon during upriver migration. Fish. Res. 108, 133–141. https://doi.org/10.1016/j.fishres.2010.12.011.
DuBois, R.B., Dubielzig, R.R., 2004. Effect of hook type on mortality, trauma, and capture efficiency of wild stream trout caught by angling with spinners. North Am. J. Fish. Manag. 24, 609–616. https://doi.org/10.1577/M02-171.1.
DuBois, R.B., Kuklinski, K.E., 2004. Effect of hook type on mortality, trauma, and capture efficiency of wild, stream-resident trout caught by active baitfishing. North Am. J. Fish. Manag. 24, 617–623. https://doi.org/10.1577/M02-172.1.
Fritts, A., Temple, G., Lillquist, C., Rawding, D., 2016. Post-release survival of yakima river spring chinook salmon associated with a mark-selective fishery.
Gelman, A., 2008. Scaling regression inputs by dividing by two standard deviations. Stat. Med. 27, 2865–2873. https://doi.org/10.1002/sim.3107.
Gelman, A., Rubin, D., 1992. Inference from iterative simulation using multiple sequences. Stat. Sci. 7, 457–472. https://doi.org/10.1214/ss/1177011136.
Gjernes, T., Kronlund, A.R., Mulligan, T.J., 1993. Mortality of Chinook and Coho Salmon in their first year of ocean life following catch and release by anglers. North Am. J. Fish. Manag. 13, 524–539. https://doi.org/10.1577/1548-8675(1993)013<0524:MOCACS>2.3.CO;2.
Good, T.P., Waples, R.S., Adams, P., 2005. NOAA Technical Memorandum NMFS-NWFSC-66, Updated Status of Federally Listed ESUs of West Coast Salmon and Steelhead 637 pp.
Gresswell, R.E., Harding, R.D., 1997. The role of special angling regulations in management of coastal cutthroat trout. In: Sea-Run Cutthroat Trout: Biology, Management, and Future Conservation. American Fisheries Society, Corvallis, OR, pp. 151–156.
Hooten, M.B., Hobbs, N.T., 2015. A guide to Bayesian model selection for ecologists. Ecol. Monogr. 85, 3–28. https://doi.org/10.1890/14-0661.1.
Hooton, R.S., 1987. Catch and release as a management strategy for steelhead in British Columbia. In: Barnhart, R.A., Roelofs, T.D. (Eds.), Catch-and-Release Fishing: A Decade of Experience. California Cooperative Fishery Research Unit, Arcata, pp. 143–156.
Hooton, R.S., 2001. Facts and Issues Associated with Restricting Terminal Gear Types in the Management of Sustainable Steelhead Sport Fisheries in British Columbia. Ministry of Environment, Lands, and Parks,, Nanaimo, BC.
Huhn, D., Arlinghaus, R., 2011. Determinants of Hooking Mortality in Freshwater Recreational Fisheries: A Quantitative Meta-Analysis. American Fisheries Society Symposium,, pp. 141–170.
Hutchings, J.A., Festa-Bianchet, M., 2009. Canadian species at risk (2006–2008), with particular emphasis on fishes. Environ. Rev. 17, 53–65. https://doi.org/10.1139/A09-003.
Johnson, J.K., 2004. Regional Overview of Coded Wire Tagging of Anadromous Salmon and Steelhead in Northwest America (Updated from original 1989 version). American Fisheries Society Symposium,, pp. 782–816.
Kendall, N.W., Marston, G.W., Klungle, M.M., 2017. Declining patterns of Pacific Northwest steelhead trout (Oncorhynchus mykiss) adult abundance and smolt survival in the ocean. Can. J. Fish. Aquat. Sci. 74, 1275–1290. https://doi.org/10.1139/cjfas-2016-0486.
Kerns, J.A., Allen, M.S., Harris, J.E., 2012. Importance of assessing population-level impact of catch-and-release mortality. Fisheries 37, 502–503. https://doi.org/10.1080/03632415.2012.731878.
Lindsay, R.B., Schroeder, R.K., Kenaston, K.R., Toman, R.N., Buckman, M.A., 2004. Hooking mortality by anatomical location and its use in estimating mortality of spring chinook salmon caught and released in a river sport fishery. North Am. J. Fish. Manag. 24, 367–378. https://doi.org/10.1577/M02-101.1.
Lirette, M.G., Hooton, R.S., 1988. Telemetric Investigations of Winter Steelhead in the Salmon River, Vancouver Island (Fisheries Technical Circular No. 82).
McCormick, J.L., Dobos, M.E., Bowersox, B.J., Copeland, T., 2021. Evaluation of management strategies for an incidental catch-and-release steelhead fishery. North Am. J. Fish. Manag. 41, 498–512. https://doi.org/10.1002/nafm.10558.
Meka, J.M., 2004. The influence of hook type, angler experience, and fish size on injury rates and the duration of capture in an Alaskan catch-and-release rainbow trout fishery. North Am. J. Fish. Manag. 24, 1309–1321. https://doi.org/10.1577/M03-108.1.
Ministry of Forests, 2021. 2021–23 B.C. Freshwater Fishing Regulations Synopsis.
Muoneke, M.I., Childress, W.M., 1994. Hooking mortality: a review for recreational fisheries. Rev. Fish. Sci. 2, 123–156. https://doi.org/10.1080/10641269409388555.
National Oceanic and Atmospheric Administration (NOAA), 2018 Endangered Species Act (ESA) Section 7(a)(2) Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Response Consultation on effects of the 2018–2027 U.S. v. Oregon Management Agreement. (No. NMFS Consultation Number: WCR-2017–7164.).
National Research Council (NRC), 1996. Upstream: Salmon and Society in the Pacific Northwest. National Academies Press, Washington, D.C. https://doi.org/10.17226/4976.
Nehlsen, W., Williams, J.E., Lichatowich, J.A., 1991. Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington 16, 18 pp.
Nelson, T.C., Rosenau, M.L., Johnston, N.T., 2005. Behavior and survival of wild and hatchery-origin winter steelhead spawners caught and released in a recreational fishery. North Am. J. Fish. Manag. 25, 931–943. https://doi.org/10.1577/M04-192.1.
Nguyen, P.L., Haman, K., Carstensen, L., McKlveen, T., Cooney, P., Gibson, S., 2018. Evaluation of three electrical outputs in an electro-immobilization system to reduce induction time during routine handling of fish at a hatchery. North Am. J. Aquac. 80, 239–248. https://doi.org/10.1002/naaq.10023.
Penney, Z.L., Moffitt, C.M., 2014. Histological assessment of organs in sexually mature and post-spawning steelhead trout and insights into iteroparity. Rev. Fish. Biol. Fish. 24, 781–801. https://doi.org/10.1007/s11160-013-9338-2.
Piironen, J., Vehtari, A., 2017. Sparsity information and regularization in the horseshoe and other shrinkage priors. Electron. J. Stat. 11, 5018–5051. https://doi.org/10.1214/17-EJS1337SI.
Raby, G.D., Donaldson, M.R., Hinch, S.G., Clark, T.D., Eliason, E.J., Jeffries, K.M., Cook, K.V., Teffer, A., Bass, A.L., Miller, K.M., Patterson, D.A., Farrell, A.P., Cooke, S. J., 2015. Fishing for effective conservation: context and biotic variation are keys to understanding the survival of pacific salmon after catch-and-release. Integr. Comp. Biol. 55, 554–576. https://doi.org/10.1093/icb/icv088.
Schill, D.J., Scarpella, R.L., 1997. Barbed hook restrictions in catch-and-release trout fisheries: a social issue. North Am. J. Fish. Manag. 17, 873–881. https://doi.org/10.1577/1548-8675(1997)017<0873:BHRICA>2.3.CO;2.
Schisler, G.J., Bergersen, E.P., 1996. Postrelease hooking mortality of rainbow trout caught on scented artificial baits. North Am. J. Fish. Manag. 16, 570–578. https://doi.org/10.1577/1548-8675(1996)016<0570:PHMORT>2.3.CO;2.
Serl, J., Gleizes, C., Nissell, C., Zimmerman, M., Glaser, B., 2017. Lower Cowlitz River monitoring and evaluation, 2016.
Skalski, J.R., Townsend, R.L., Steig, T.W., Hemstrom, S., 2010. Comparison of two alternative approaches for estimating dam passage survival of salmon smolts. North Am. J. Fish. Manag. 30, 831–839. https://doi.org/10.1577/M09-103.1.
Stuby, L., 2002. An investigation of how catch-and-release mortality of coho salmon in the Unalakleet River varies with distance from Norton Sound 41 pp.
Tacoma Power , 2006. Anadromous Fish Trap and Haul Plan.
Taylor, M.J., White, K.R., 1992. A meta-analysis of hooking mortality of nonanadromous trout. North Am. J. Fish. Manag. 12, 760–767. https://doi.org/10.1577/1548-8675(1992)012<0760:AMAOHM>2.3.CO;2.
Thorstad, E., Næsje, T., Fiske, P., Finstad, B., 2003. Effects of hook and release on Atlantic salmon in the River Alta, northern Norway. Fish. Res. 60, 293–307. https://doi.org/10.1016/S0165-7836(02)00176-5.
Twardek, W.M., Gagne, T.O., Elmer, L.K., Cooke, S.J., Beere, M.C., Danylchuk, A.J., 2018. Consequences of catch-and-release angling on the physiology, behaviour and survival of wild steelhead Oncorhynchus mykiss in the Bulkley River, British Columbia. Fish. Res. 206, 235–246. https://doi.org/10.1016/j.fishres.2018.05.019.
Vincent-Lang, D., Alexandersdottir, M., McBride, D., 1993. Mortality of coho salmon caught and released using sport tackle in the Little Susitna River, Alaska. Fish. Res. 15, 339–356. https://doi.org/10.1016/0165-7836(93)90085-L.
Washington Department of Fish and Wildlife (WDFW), 2003. Fishery Management and Evaluation Plan: Lower Columbia River Region. Olympia, Washington.
Welch, D.W., Porter, A.D., Rechisky, E.L., 2021. A synthesis of the coast-wide decline in survival of West Coast Chinook Salmon (*Oncorhynchus tshawytscha,* Salmonidae). Fish Fish. 22, 194–211. https://doi.org/10.1111/faf.12514.
Whitney, D.W., Meyer, K.A., McCormick, J.L., Bowersox, B.J., 2019. Effects of fishery-related fight time and air exposure on prespawn survival and reproductive success of adult hatchery steelhead. North Am. J. Fish. Manag. 39, 372–378. https://doi.org/10.1002/nafm.10275.
Wiley, J.F., 2022. brmsmargins: Bayesian Marginal Effects for "brms" Models.
Wood, S.N., 2017. Generalized Additive Models: An introduction with R, second. ed. Chapman and Hall/CRC, New York.
Zhou, S., 2002. Uncertainties in estimating fishing mortality in unmarked salmon in mark-selective fisheries using double-index-tagging methods. North Am. J. Fish. Manag. 22, 480–493.

Catch and Release as a Management Strategy for Steelhead in British Columbia

R.S. Hooton[1]
British Columbia Ministry of Environment and Parks
Smithers, B.C.

Abstract

In British Columbia the most frequent application of catch and release has been on heavily used steelhead streams in the populated southwestern management regions. Seven years of data compiled since the first broad scale implementation of catch and release on Vancouver Island in 1980 indicated that the regulation was effective in reversing declining catch trends but that recovery from the sharp initial reductions in licence sales and angler days was slow and mostly related to the recent availability of hatchery steelhead. Hooking mortality associated with catch and release angling was low and survival through spawning for released fish was normal.

Introduction

British Columbia with its thousands of miles of coastline contains a dazzling array of steelhead streams. Each year over 200 streams sustain some recorded angler effort and catch (Steelhead Harvest Analysis 1968-1987) while at least that many more support steelhead but are not fished. Streams range from smaller outer coast winter and/or summer steelhead producers to the large interior tributaries of major river systems such as the Fraser, Skeena, Nass, Stikine and Taku. Many of these latter tributaries—the Kispiox, Babine, Sustut, and Thompson—are world renowned for their exceptionally large, wild summer steelhead.

By fisheries management policy the steelhead streams of British Columbia are categorized as hatchery, augmented, or wild according to their natural ability to produce wild steelhead. With one exception the 22 augmented streams and 4 hatchery streams are located in the heavily populated southwest corner of the province. Wild streams, which clearly dominate the total provincial picture occur throughout the coast from the U.S. Border to southeast Alaska and in the interior (Fig. 1).

Present address: B.C. Fish and Wildlife Branch, 3726 Alfred Avenue, Smithers, British Columbia V0J 2N0

A common feature of a large majority of British Columbia's steelhead streams is their low productivity. The smolt yield capacity is generally well below levels experienced in more southerly environments such as the Columbia basin, the historic center of steelhead abundance. Regulations governing steelhead harvest in British Columbia must therefore be relatively restrictive. Catch and release has become a major management tool to deal with low productivity streams and the cumulative effect on such waters of competing habitat uses, heavy sportfishing pressure and/or high exploitation by commercial and Indian food fisheries. Generally these streams are located in southwestern British Columbia in Management Regions 1 and 2 (Fig. 1). Most of the provincial data base associated with evaluation of catch and release has been compiled in Region 1 (Vancouver Island). For this reason the present report will focus on the Vancouver Island experience.

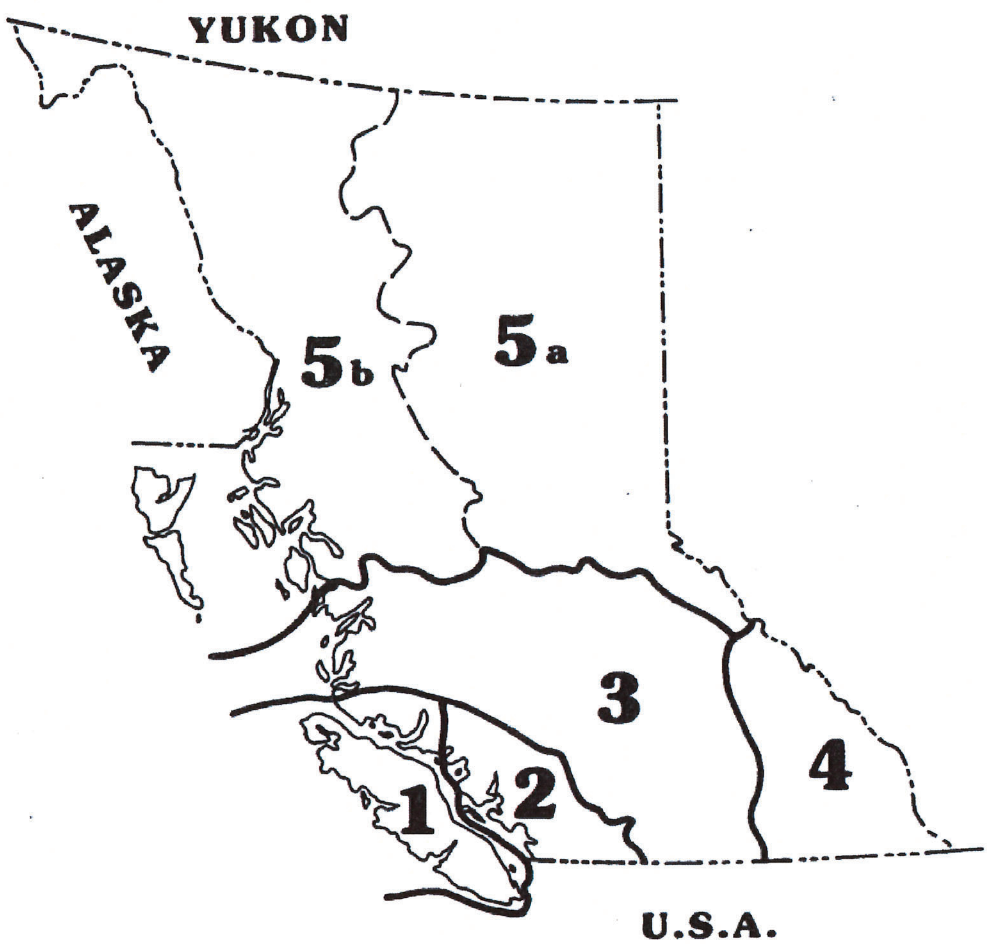


Figure 1. British Columbia resource management regions. Steelhead regions include 1 (Vancouver Island), 2 (Lower Mainland), 3 (Thompson-Cariboo) and 5b (Skeena).

The Vancouver Island Study Area

The Steelhead Fishery

Vancouver Island, a large coastal island adjacent to the heavily populated lower Fraser River valley, contains approximately 35% of the provincial total of streams which sustain measurable steelhead angler effort and catch annually. In recent years the Island has supported 20% of the days fished, 25% of the wild steelhead catch, and more than 60% of the hatchery steelhead catch for all of British Columbia (Steelhead Harvest Analysis, 1968-1987). In the 1986-87 season 5000 steelhead licences were sold to Island residents and angler days totalled 57,000.

Stream specific steelhead catches on Vancouver Island range from tens to thousands. Recently, more than half of the annual catch of 50-60,000 steelhead has occurred in only five streams and approximately 90% in not more than ten. The days fished pattern was similar. Hatchery steelhead are available in 11 streams but in most of these only since the early 1980's. Wild steelhead dominate the total angler catch.

Regulations History

Regulations governing wild steelhead harvest were uniformly liberal across all of British Columbia from the earliest days of provincial fisheries management until the late 1970's. At that time, under the sponsorship of the Salmonid Enhancement Program, many first ever investigations of steelhead stock size and exploitation revealed the necessity for major reductions in daily and season catch limits. On Vancouver Island these reductions were scheduled to take effect in 1980. Further restrictions included catch and release only for all summer steelhead streams and a monthly limit to avoid chronic over-harvest of the early component of the winter steelhead run (Table 1).

Coincident with the agenda to introduce reduced catch limits in April 1980 came a disastrous winter steelhead season in 1979-80. This necessitated an emergency catch and release regulation which was subsequently included in the formal regulations from 1980-84 (Table 1). During the latter four years, hatchery programs were coming on line rapidly and anglers were provided the opportunity to harvest marked hatchery fish throughout the year. By 1985 hatchery production goals were realized and wild steelhead harvest was eliminated entirely.

Table 1. Summary of major regulation changes governing wild steelhead harvest on Vancouver Island streams, pre - 1959 to present.

Years	Steelhead Harvest Quotas Per Day	Per Month	Per Year	Per River
Pre - 1959	3			
1959 - 1961	3		40	
1962 - 1976	2		40	
1977 - 1979	2		20	10
1980 - 1984*	1	2	5	
1985 - Present	0	0	0	

*Further restriction included wild steelhead release Dec. 1 - Mar.1.

Evaluation of the Regulations

The objective of the wild steelhead catch and release regulation on Vancouver Island was to stabilize and, hopefully, reverse a steadily declining catch trend. Data were available from annual mailed questionnaire sampling of licences to compare effort and catch success in the "pre" and "post" catch and release years. These data provided a basis for assessing the efficacy of the regulation.

A common criticism of catch and release was that it was "unsafe" because steelhead subjected to such treatment would die or be weakened to a point where successful reproduction would not occur. To investigate these issues a study was designed to determine the mortality rate among steelhead caught and released on popular terminal tackle and to assess the spawning success of these fish relative to a control group. The research was conducted at Keogh River, an intensively monitored stream on northern Vancouver Island. Complete results of the Keogh study will be reported separately but important features are included here. A further indication of the consequences of catch and release was available from records on steelhead angled for brood stock for hatchery programs.

Results and Discussion

Angler Participation and Catch

The immediate response of anglers to the wild steelhead catch and release, first imposed mid-way through the 1979-80 winter steelhead season, was a 50% reduction in days fished (Fig. 2). In the following licence year (ending in 1981) there was a similar decline in the number of licences sold (Fig. 2). The number of days fished remained at historic lows for three years after which a strong upward trend developed. By 1985 the pre-catch and release angler days total was surpassed (Fig. 2). Licence sales, though increasing remained 20% below the pre-regulation level (Fig. 2). These data indicated that under catch and release angling effort increased from an average of 10 days per licencee to 12.

Retrospective analysis of the circumstances surrounding initiation of catch and release in 1980 left a clear impression that the need to acquaint licencees and the supporting services industry with the full rationale for catch and release was underestimated. If a professional public relations capability had been employed to sell the catch and release concept, the observed declines in licence sales and days fished would likely have been far less dramatic.

Licence sales and days fished over the 1983-87 period was undoubtedly influenced by the rapid growth of the hatchery steelhead program. The extent of this influence as opposed to a growing acceptance of catch and release is unknown but evidence presented below suggests the availability of hatchery steelhead was the dominant factor.

The number of wild steelhead retained by Vancouver Island anglers displayed a declining trend for more than a decade before any catch and release restrictions (Fig. 3). This was due, in part, to growing perceptions of some anglers that their ability to harvest fish had been underestimated, that the regulations were too liberal, and that steelhead abundance was declining. The total catch of wild steelhead over the 1971-79 period strongly supported a declining abundance theory (Fig. 4).

In the years 1980-84 the seasonal catch and release regulations reduced the wild steelhead kill to approximately one third of the preceeding three-year average. This was followed by a further decline after 1985 when year round catch and release came into effect (Fig. 4). The fact that some wild steelhead kill was reported in those years when harvest was illegal probably resulted from errors in catch reporting, misidentification of hatchery fish and/or deliberate non-compliance.

Total catch of wild steelhead increased sharply during the catch and release period and remained well above previous peaks (Fig. 4). Tagging studies revealed that a substantial portion (>30%) of the increase could be attributed to repeat captures (Hooton and Lirette 1986; Hooton 1979; unpublished Fish and Wildlife Branch data). It must be noted, however, that

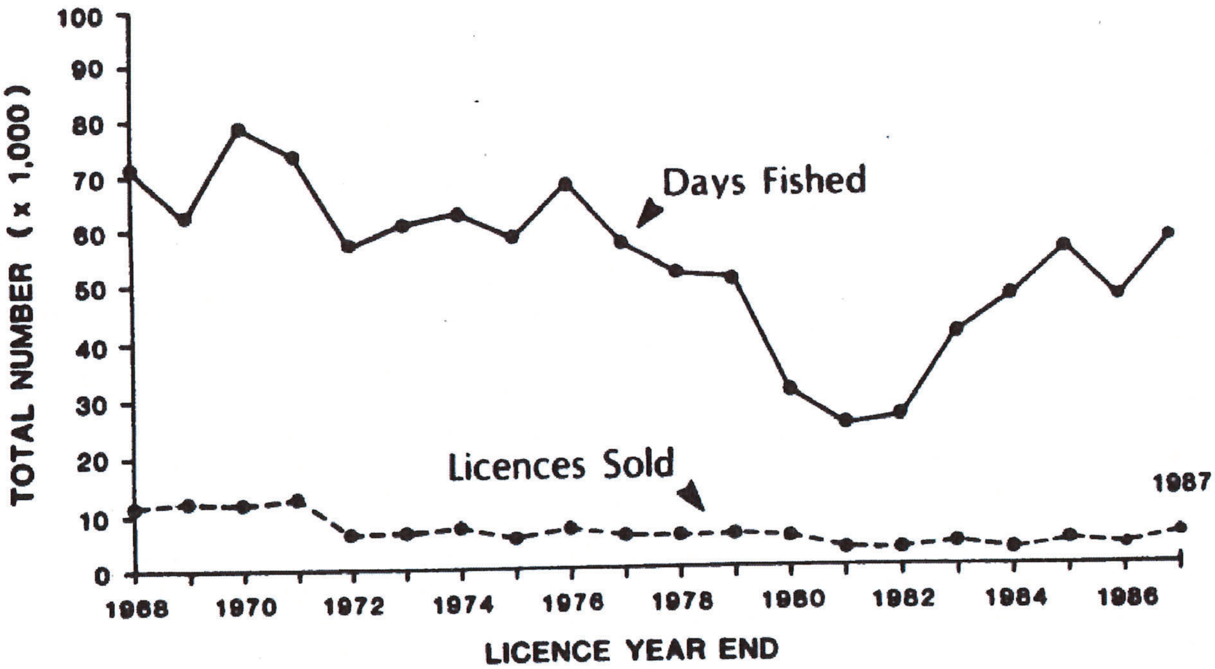


Figure 2. Number of days fished and steelhead angling licences sold, Vancouver Island, 1968 through 1987.

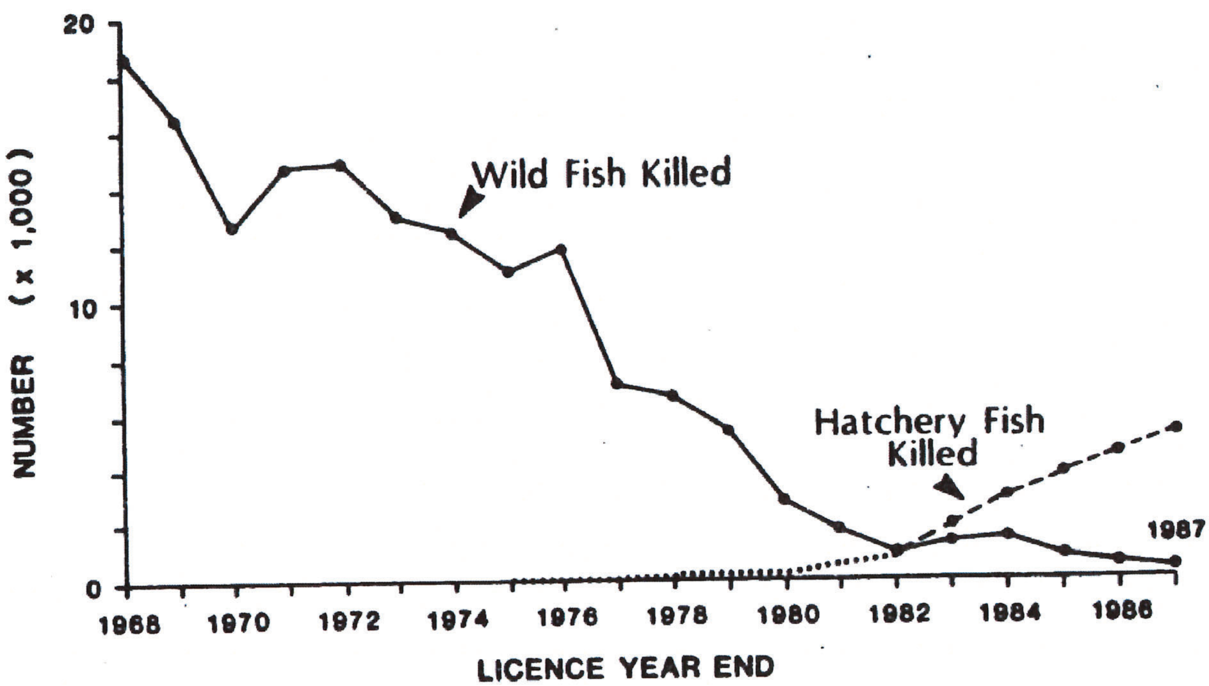


Figure 3. Number of wild and hatchery steelhead killed by anglers on Vancouver Island streams, 1968 through 1987.

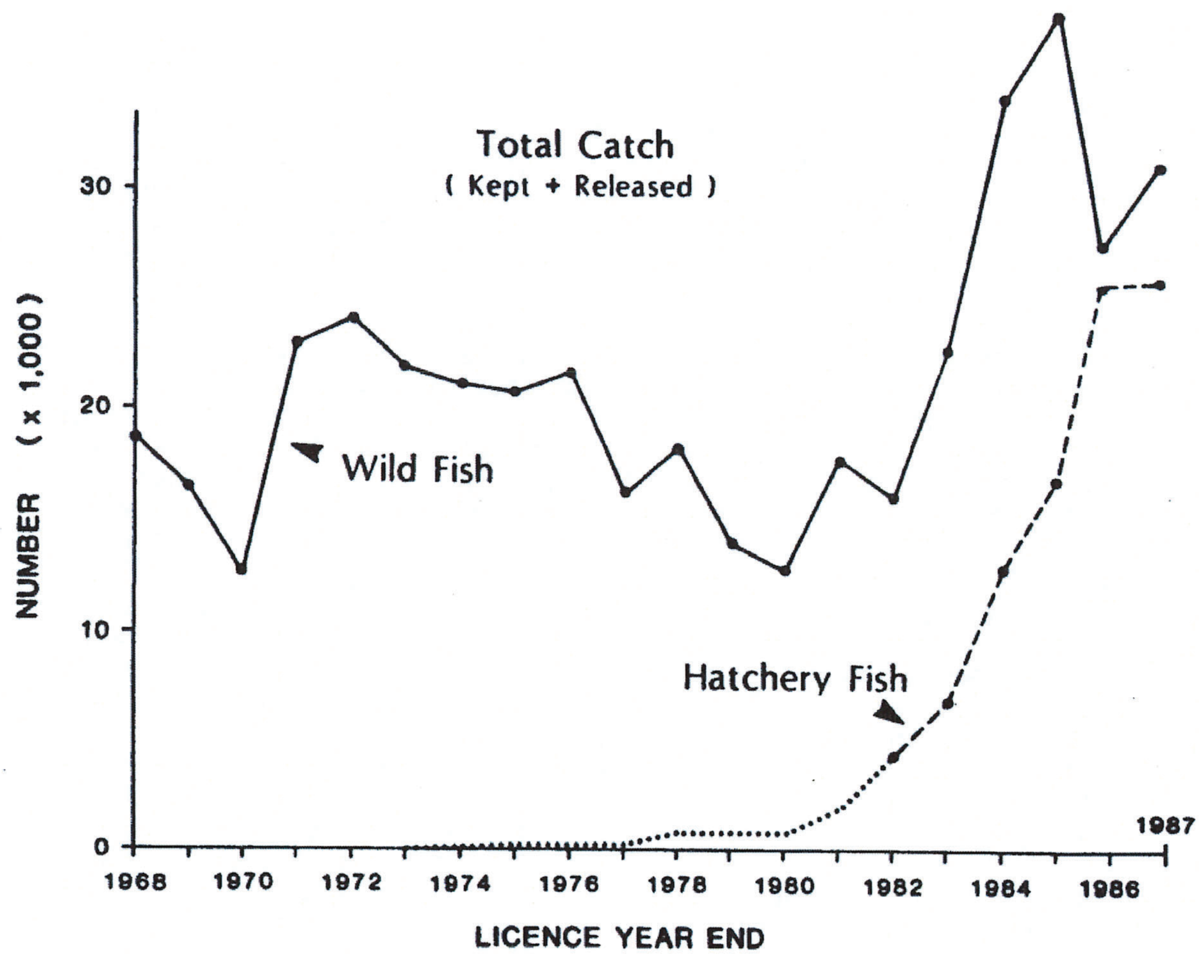


Figure 4. Total angler catch (kill and release) of wild and hatchery steelhead on Vancouver Island streams, 1968 through 1987.

catches were also responsive to an unusually high abundance of wild steelhead in 1984 and 1985, a phenomenon that was observed elsewhere in British Columbia and thoughout the steelhead range.

The response in wild steelhead recruitment from increased escapements which followed catch and release has not been measured and, in fact, could not be separated from environmental influences and the contribution of hatchery adults which spawned naturally. However, the subjective interpretation of the author is that wild steelhead recruitment (i.e. abundance and catch) will continue to fluctuate annually in response to these other variables but at a substantially higher level than would have occurred in the absence of catch and release.

Angler preference studies conducted on Vancouver Island in the mid 1970's determined that, under the circumstances of the day (i.e. liberal catch limits, relatively stable total catch, little hatchery production) catch and release was not a popular regulations option (Hooton 1982). Empirical evidence from the catch and release period confirmed that attitude despite changes in wild steelhead stock status and increasing hatchery steelhead availability. At Gold River, the most prolific wild steelhead only stream in the region, angler days were declining during the 1976-79 period (Fig. 5). The decline continued through 1980 when catch and release came into effect. However, despite catch and catch per unit effort figures which reached record highs in the 1983-87 period, angler days remained well below previous levels (Fig. 5). In contrast, the experience on four popular steelhead streams where anglers had the option of fishing for both hatchery and wild steelhead, the number of angler days and the percent of the total Vancouver Island steelhead angler days increased steadily through the pre and post 1980 period as the supply of hatchery steelhead increased to target levels (Fig. 6). Clearly, the pattern has been one of relatively low and stable angling effort on "wild" streams and deflection of anglers toward "augmented" steams where harvest opportunity remained.

Hooking Mortality and Spawning Success

The opinions that released steelhead die or do not spawn successfully, commonly heard from critics and opponents of catch and release, were refuted by data compiled from hooking mortality studies. Among 3715 steelhead angled on conventional tackle (bait, barbed hooks) to provide brood stock for hatchery programs, only 127 (3.4%) mortalities occurred (Table 2). A large majority of these fish subsequently survived the stress of frequent handling, transport, and lengthy confinement in hatchery facilities before maturing and being spawned. Virtually the entire Vancouver Island (and elsewhere in British Columbia) hatchery steelhead program was built around and continues to operate with these procedures.

At Keogh River where hooking mortality was studied more rigorously, similarly high survivals were noted. Among 336 steelhead angled on various combinations of popular terminal gear (Table 3) the mortality for the combined samples was 5.1% (Table 4). Use of natural bait produced higher

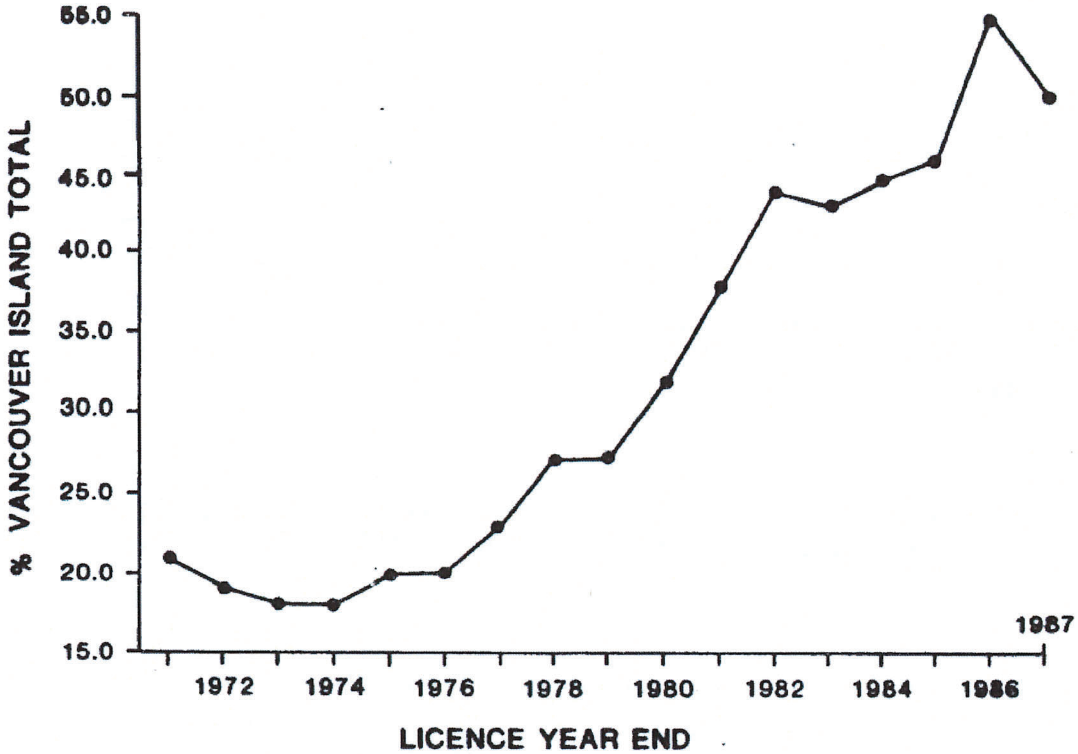


Figure 5. Percent of total Vancouver Island steelhead angler days expended on four popular hatchery steelhead streams, 1971 through 1987.

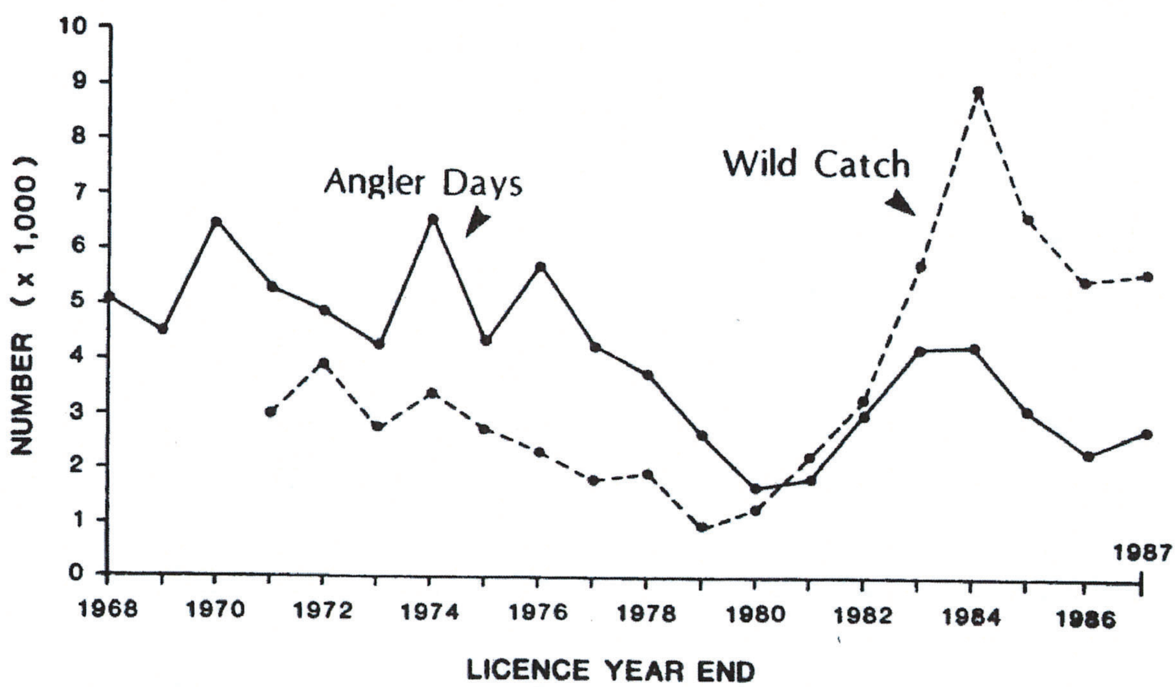


Figure 6. Number of steelhead angler days and total wild steelhead catch (kill plus release), Gold River, 1968 through 1987.

mortality (5.6%) than did artificial lures (3.8%) (Table 4). Also, mortality while using barbed hooks was higher (7.3%) than for barbless hooks (2.9%) regardless of whether bait or artificial lure was employed (Table 4). Analysis of the number of steelhead landed per hour fished on each gear combination indicated that bait was approximately 60% more efficient than artificial lure. This figure was probably minimal, however, because a high proportion of the angling sessions commenced with artificial lures and the number of catchable fish was likely much reduced before bait was employed.

Table 2. Stock specific hooking mortality among steelhead angled for brood stock purposes, Vancouver Island, 1981 - 1987.

Stock	Years of Record	Number of Steelhead Angled	Number (Percent) Hooking Mortalities
Cowichan	7	509	16 (3.1)
Englishman	5	240	9 (3.8)
Heber	1	70	3 (4.3)
Gold	1	30	0 (0)
Nanaimo	7	378	7 (1.9)
Puntledge	7	481	9 (1.9)
Salmon	6	464	27 (5.8)
San Juan	2	49	3 (6.1)
Somass	7	1174	43 (3.7)
Tsitika	7	320	10 (3.1)
All	N/A	3715	127 (3.4)

Table 3. Number of steelhead captured on various terminal gear types, Keogh River hooking mortality study, 1985 and 1986.

Year	Gear Type*								
	BB	BA	NBB	NBA	All	BB + NBB	BA + NBA	BB + BA	NBB + NBA
1985	48	26	56	0	130	104	26	74	56
1986	51	40	77	38	206	128	78	91	115
1985 + 1986	99	66	133	38	336	232	104	165	171

* BB = barbed hook, bait
BA = barbed hook, artificial
NBB = barbless hook, bait
NBA = barbless hook, artificial

Table 4. Number (percent) of hooking mortalities on various terminal gear types, Keogh River, 1985 and 1986.

Year	Gear Type								
	BB	BA	NBB	NBA	ALL	BB + NBB	BA + NBA	BB + BA	NBB+ NBA
1985	6(12.5)	2(7.7)	2(3.6)	0(0)	10(7.7)	8(7.7)	2(7.7)	8(10.8)	2(3.6)
1986	3(5.9)	1(2.5)	2(2.6)	1(2.6)	7(3.4)	5(3.9)	2(2.6)	4(4.4)	3(2.6)
1985 +1986	9(9.1)	3(4.5)	4(3.0)	1(2.6)	17(5.1)	13(5.6)	4(3.8)	12(7.3)	5(2.9)

The survival through spawning of angled and released Keogh River steelhead was similar to that of steelhead which were captured at a weir at the same location 400 m. upstream from the ocean. The number of steelhead caught immediately downstream from the weir, tagged, released immediately upstream, and later trapped as emigrating post-spawners represented 27.5% of the available population. This was only 5.4% lower than the recovery rate for fish which were not angled (Table 5). This margin may have been attributable to additional handling stress endured by the angled fish.

Comparison of the degree of hooking injury with mortality rates revealed, not unexpectedly, that mortality was highest among fish which sustained severe blood loss when the hook pierced or tore a major blood vessel (Table 6). An instructive feature of the data was that, despite extensive blood loss, 47% of the most seriously injured fish recovered and were released in what appeared to be a healthy condition (Table 6). Interestingly, while the number of fish in the most severe injury groups (i.e. categories 2 and 3) was small, their recovery as post-spawners did not differ substantially from the least injured fish. Again this refuted claims that caught and released steelhead were effectively lost from the population.

Conclusions

1. Catch and release is an effective mechanism for maintaining angling opportunity without negatively impacting stock recruitment.

2. A significant proportion of the angling public does not participate in purely catch and release fisheries, especially in the absence of any organized, advance promotion of such regulations.

3. Blanket catch and release restrictions are not necessary on some relatively healthy and/or remote wild steelhead streams (stocks) on Vancouver Island. However, relaxation of the existing regulation on a small number of streams would concentrate anglers and increase harvest beyond tolerable limits, thus re-creating the circumstances which demanded catch and release initially. The management strategy on these exceptional streams must therefore be rigidly enforced stock specific harvest quotas.

4. Catch and release management of wild steelhead stocks will become an increasing biological necessity in British Columbia as competing user groups strengthen their claims to the resource, as the stream habitat base is eroded by the inexorable forces of population growth and resource development, as angler efficiency increases, and as lobby pressures demand. The Fish and Wildlife Branch will be required to play an advocacy role in this evolutionary process.

Table 5. Number (percent) of hooking mortality study (HMS) and non-hooking mortality study (NHMS) steelhead recovered as emigrating post-spawners, Keogh River, 1985 and 1986.

Year	HMS Fish Recovered as Kelts	NHMS Fish Recovered as Kelts
1985	25 (22.3)	56 (24.03)
1986	59 (30.6)	403 (34.7)
1985 + 1986	84 (27.5)	459 (32.9)

Table 6. Number (percent) of hooking mortalities among steelhead of various hook injury categories and the percent of individuals of each category recovered as emigrating post-spawners, Keogh River, 1985 and 1986 data combined.

Hook Injury*	Fish Landed	Hooking Mortalities (%)	Potential Spawning Population	Number (Percent) Post-Spawners Recovered
1	257	0(0)	247	51(20.6)
2	49	1(2.0)	44	7(15.9)
3	30	16 (53.3)	14	4(28.6)
All	336	17 (5.1)	305	84(27.5)**

* 1=Superficial wound, no blood loss
2=Moderate wound, some blood loss but no major blood vessel ruptured
3=Severe blood loss associated with rupture of major blood vessel

** Includes 22 HMS kelts which had lost tags.

Acknowledgements

The author wishes to thank M.G. Lirette for assistance in compiling some of the data used in this report. G. Hodge drafted the figures and provided his usual invaluable service in preparing visual aids for the symposium presentation. E. Bouvier and F. Lee typed the report.

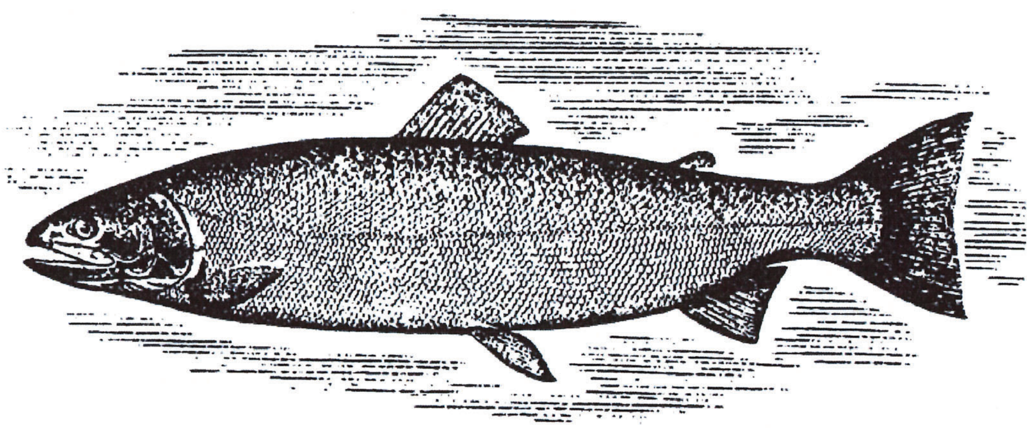
Literature Cited

Anon. 1968-1987. Steelhead Harvest Analysis. Ministry of Environment and Parks, Victoria, B.C.

Hooton, R.S. 1979. Preliminary report of a tagging program designed to investigate certain elements of the Campbell/Quinsam steelhead fishery. MS Rep., Ministry of Environment and Parks, Nanaimo, B.C.

Hooton, R.S. 1982. A questionnaire survey of Vancouver Island steelhead anglers' opinions and preferences on management issues. Master's thesis. University of Idaho, Moscow, Idaho.

Hooton, R.S., and M.G. Lirette. 1986. Telemetric studies of winter steelhead, Gold River, 1982-83. Ministry of Environment and Parks, Fish. Mgmt. Rep. No. 86, Victoria, B.C.



North American Journal of Fisheries Management 24:367–378, 2004

Hooking Mortality by Anatomical Location and Its Use in Estimating Mortality of Spring Chinook Salmon Caught and Released in a River Sport Fishery

ROBERT B. LINDSAY,[1] R. KIRK SCHROEDER,* AND KENNETH R. KENASTON

Oregon Department of Fish and Wildlife, 28655 Highway 34, Corvallis, Oregon 97333, USA

ROBERT N. TOMAN

Toman's Guide Service LLC, 1872 South East Semple Road, Clackamas, Oregon 97015, USA

MARY A. BUCKMAN

Oregon Department of Fish and Wildlife, 28655 Highway 34, Corvallis, Oregon 97333, USA

Abstract.—We estimated the hooking mortality of spring Chinook salmon *Oncorhynchus tshawytscha* that were caught and released to determine whether selective fishing on hatchery Chinook salmon would reduce harvest mortality of wild fish in a sport fishery in the lower Willamette River, Oregon. Hooking mortality in the fishery was estimated from hooking mortality rates for each of five anatomical locations (jaw, 2.3%; tongue, 17.8%; eye, 0.0%; gills, 81.6%; and esophagus–stomach, 67.3%) and from the frequency of these anatomical locations in the sport fishery (jaw, 81.5%; tongue, 5.1%; eye, 0.4%; gills, 5.1%; and esophagus–stomach, 7.8%). Mortality rates by anatomical location were estimated from recaptures of 869 tagged fish that were experimentally angled and of 825 tagged controls that were trapped in a nearby fishway. Anatomical hook locations in the lower Willamette River sport fishery were determined with creel surveys. We estimated hooking mortality rates of 12.2% for wild Chinook salmon caught and released in the sport fishery and 3.2% for the entire run of wild Chinook salmon based on a mean encounter rate of 26%. Hook location was the primary factor affecting recapture of hooked fish, but fish length, gear type, bleeding, and the elapsed time to unhook fish were also significant factors. A selective sport fishery in the lower Willamette River can be used to reduce harvest mortality on runs of wild Chinook salmon while maintaining fishing opportunity on hatchery Chinook salmon. The effect of selective fisheries for Chinook salmon in other rivers would depend on the frequency distribution of anatomical hook locations and on river-specific encounter rates.

Selective fisheries for anadromous salmonids are rapidly becoming a standard management tool to reduce harvest mortality of wild fish while maintaining angling opportunity. Regulating agencies often mandate selective fisheries to target abundant hatchery fish while reducing effects on wild fish. Anglers also voluntarily catch and release fish to select for an attribute, such as large size, where creel limits are low (Bendock and Alexandersdottir 1993). Selective fisheries are currently being used in Oregon to target hatchery Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, and steelhead *O. mykiss*. Because many wild populations of these species in Oregon are in low abundance and are listed under the Endangered Species Act, angling opportunity is being maintained by requiring anglers to release wild fish, but allowing them to keep marked hatchery fish—usually identified by an excised adipose fin. This strategy assumes that mortality from the catch and release of fish is low.

Few studies have been published on hooking mortality of anadromous Pacific salmon in selective sport fisheries in freshwater (Bendock and Alexandersdottir 1993). Studies of hooking mortality in hook-and-line salmon fisheries in saltwater are more common (Wertheimer 1988; Gjernes et al. 1993; Lawson and Sampson 1996; Grover et al. 2002) and have found that mortality is largely dependent on fishing technique and anatomical hook location. In general, hooking mortality in commercial troll fisheries is higher than that in saltwater sport fisheries (CTC 1997), except in ocean sport fisheries off California where a drift-mooching technique was used (Grover et al. 2002). Sev-

* Corresponding author: schroedk@fsl.orst.edu
[1] Retired.

Received September 3, 2002; accepted May 23, 2003

eral studies have examined catch-and-release fishing for steelhead in freshwater (Pettit 1977; Hooton 1987) and for trout species (Mongillo 1984; Muoneke and Childress 1994). Most of these studies estimate hooking mortality over short periods and lack controls.

We began a study in 1998 to estimate the hooking mortality that would occur on wild spring Chinook salmon if they were caught and released in a selective sport fishery for hatchery salmon (marked with an adipose fin clip) in the Willamette River, Oregon. The study focused on the large, main-stem fishery below Willamette Falls at river kilometer (rkm) 43, which provided 171,000 angler-days and accounted for about 70% of the Willamette basin catch of spring Chinook salmon annually from 1981 to 1995 (calculated from Foster and Boatner 2002). Smaller fisheries occur in tributaries and in the main stem above the falls. Fisheries for spring Chinook salmon are supported by annual releases of about 5 million hatchery juveniles, which mitigate for dams that block access to or inundate natural production areas in the Willamette basin. Natural spawning still occurs in most large tributaries and in a few smaller ones that drain the Cascade Mountains. Subsequent to the initiation of our study, wild spring Chinook salmon in the Willamette River were listed as a threatened species under the Endangered Species Act (NMFS 1999), in part because of concern about excessive harvest.

Study Site

The Willamette River is the largest interior river in Oregon and flows north through the Willamette River valley, the most populated region in the state, entering the Columbia River near Portland, Oregon (Figure 1). The river drains a basin 31,080 km^2, bounded on the west by the Coast Range and on the east by the Cascade Mountains. Annual flows in the Willamette River (measured at Salem, Oregon, 92 rkm above Willamette Falls) range from 200 m^3/s in summer to 3,640 m^3/s during floods. Flows ranged from 306 to 1,215 m^3/s during our study in late April and May, but we could not sample at Willamette Falls when flows exceeded about 850 m^3/s. Water temperatures ranged from 9°C to 18°C during our study, the highest temperatures occurring in 1998. Spring Chinook salmon spawn in September and October in most of the large, east-side tributaries to the Willamette River. All of the hatcheries in the Willamette River basin are located on these tributaries (Figure 1).

The Willamette River is divided into upper and lower reaches by Willamette Falls. The height (12.5 m) and horseshoe shape of the falls concentrate adult Chinook salmon before they negotiate a fishway to continue their upstream migration. A counting chamber equipped with a video camera at the head of the fishway provides complete counts of fish runs above Willamette Falls. Most of our experimental fish migrated above the falls and were recaptured at hatcheries 212–290 rkm upstream. Others were recaptured above the falls in tributary fisheries, in traps operated at diversion dams on two large tributaries (114–296 rkm upstream of the falls), and on spawning grounds. A few were recaptured in the Clackamas River, a tributary that enters the Willamette River about 3 rkm below the falls. The creel survey of the sport fishery below the falls is divided into three sections: lower (rkm 0–10), middle (rkm 10–32) and upper (rkm 32–43; Figure 1). The lower survey section includes a heavily fished side channel (Multnomah Channel, 35 rkm long).

Methods

Our study was composed of two parts. First, we estimated hooking mortality rates of adult spring Chinook salmon caught and released in an experimental fishery at Willamette Falls for each of five hook locations: jaw, tongue, eye, gills, and esophagus–stomach. Hook location is a significant factor affecting hooking mortality of salmon that are caught and released (Wertheimer 1988; Wertheimer et al. 1989; Bendock and Alexandersdottir 1993; CTC 1997; Grover et al. 2002). Secondly, we surveyed the sport fishery in the lower Willamette River and estimated the frequency that harvested fish were hooked in each of the five hook locations. We applied these frequencies to the hooking mortality rates by hook location to calculate hooking mortality for fish caught and released in the sport fishery. The effect of catch-and-release fishing on the wild run was determined by multiplying the hooking mortality rate by the mean encounter rate of wild and hatchery fish in 1981–1995 in the lower Willamette River sport fishery. We assumed this encounter rate was applicable to wild fish in a selective fishery, although wild and hatchery fish could not be separated in 1981–1995 because most hatchery fish were not marked.

Mortality in the Experimental Fishery

Tagging and recapture.—The Willamette River offered a unique opportunity to estimate hooking mortality of spring Chinook salmon caught and released. Virtually all fish migrate through the fish-

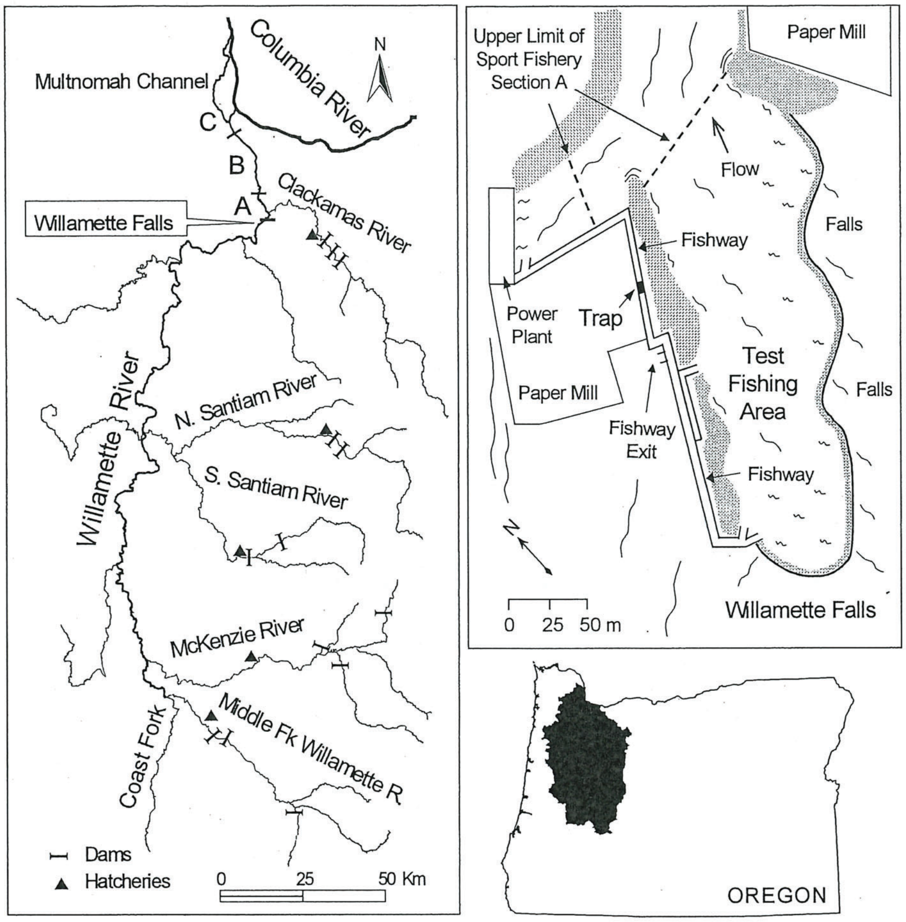


FIGURE 1.—Map of the Willamette River basin, Oregon, showing spring Chinook salmon hatcheries; Willamette Falls test fishing and trapping areas; and the upper (A), middle (B), and lower (C) creel survey sections of the lower Willamette River sport fishery.

way at Willamette Falls, and most enter upriver hatcheries weeks later. The concentration of Chinook salmon at the falls allowed us to tag a large number of fish that we caught with sportfishing gear. Concurrently, we captured and tagged a control group of salmon in the nearby fishway. We adjusted the recapture rate of tags from hooked groups by the recapture rate of tags from control groups to estimate hooking mortality by hook location. We tagged adult spring Chinook salmon at the falls from late April to late May during their upstream migration.

During the 3 years of the study we angled 869 Chinook salmon with a variety of terminal gear—prawn, salmon eggs, spinner, plug, wobbler—each including a variety of hooks (Table 1). We generally fished near the apex of the falls, an area closed to public boating and fishing (Figure 1). A fishing guide provided the boat, sport fishing tackle, and the expertise for catching fish. Two members of the public fished on the boat each day. Two biologists on the boat handled the fish caught, recorded data, and fished when there was opportunity.

Fish were played and netted in a normal manner. Netted fish were lifted into the boat and placed into a 190-L tank partially filled with water. One biologist removed hooks with needle-nosed pliers and removed the fish from the net. We cut the line and left hooks in place when a fish was hooked on bait in the gills or in the esophagus–stomach, assuming that leaving hooks in place would cause less damage than removal (Muoneke and Childress 1994; Schill 1996; Schisler and Bergersen 1996). Most anglers would accept cutting off an inexpensive hook if it improved the chance that a re-

TABLE 1.—Numbers of spring Chinook salmon caught on various types of gear, tagged, and released in an experimental fishery at Willamette Falls, Oregon, to evaluate hooking mortality, 1998–2000.

Terminal gear type	Hook type (all barbed)	Number of hooks	Hook size	Number of fish caught
Prawn[a]	Single	1	4/0, 5/0	82
		2	4/0-4/0, 3/0–5/0	110
Salmon eggs	Single	1	4/0, 5/0	203
Spinner	Single	1	3/0, 6/0	12
	Treble	1	2, 1/0, 2/0	140
Plug	Single	1	2/0, 3/0	17
		2	2/0-2/0	1
	Treble	1	3, 2, 1/0	34
		2	5-5, 4-4, 3-3, 2-2, 1-1, 5-3, 4-3, 1/0-1/0	165
Wobbler	Single	1	3/0	62
	Treble	1	1, 2	43

[a] Vernacular of Oregon anglers for northern shrimp.

leased fish would survive. Lures were always removed regardless of where a fish was hooked. We did not tag fish that were foul hooked or had a severe injury unrelated to hooking. We placed the unanesthetized fish headfirst into a round, plastic cylinder mounted in the bottom of the tank. To calm the fish, the cylinder was darkened with a rubber covering. Fish were then tagged, swabbed with iodine at the tag insertion point to reduce the risk of infection, and released. Fish were tagged at the base of the dorsal fin with a heavy-duty, T-anchor tag (Floy FD-94) that was individually numbered and included an Oregon Department of Fish and Wildlife (ODFW) telephone number. The time to tag, measure, and release a hooked fish (process time) averaged 40 s (range 11–126 s).

We recorded the tag number, hook location, bleeding, fork length (cm; Figure 2), bait type (spinner, salmon eggs, etc.), and hook type (single or treble, number of hooks, and size). For the few fish simultaneously hooked in more than one hook

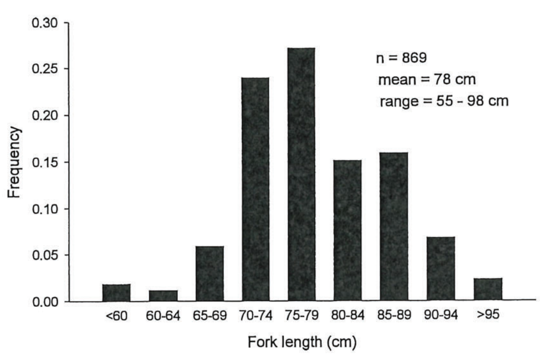


FIGURE 2.—Length-frequency histogram of spring Chinook salmon caught, tagged, and released in the experimental fishery for spring Chinook salmon at Willamette Falls, Willamette River, Oregon, 1998–2000.

location on gear with two hooks, we recorded the hook location that would most likely cause the greatest reduction in survival (e.g., gills more likely than tongue). Fish hooked in the maxillary bone or the roof of the mouth were included with those hooked in the jaw. We recorded the elapsed time to unhook and remove the fish from the net once the fish was in the tank (unhook time) for a subsample of fish in 1999 and 2000. Sex of fish was not recorded because it could not be externally determined.

We tagged a control group of 825 Chinook salmon captured in the fishway at Willamette Falls during the same time that hooked groups were caught. One control group of 395 fish were trapped in the fishway and returned to the river (river control) in the same area that hooked groups were caught. Because we were uncertain how returning these fish to the river might affect their behavior, a second control group of 430 was released directly into the fishway (fishway control). The fishway trap had a small viewing window and pneumatically operated gates, which allowed us to shunt Chinook salmon into a cage or to pass them up the fishway if they were severely injured or already tagged. Trapped salmon ascended an aluminum steep pass (Clay 1995) into a water-filled, wooden trough 3.7 m long × 0.6 m deep. We gently herded individual fish into the narrow end of the trough (0.3 m wide) and into a V-shaped metal insert fitted with handles and a rubber hood. We processed the fish without anesthetic and in the same manner as the hooked group. We lifted the fish with the metal insert and slid them through a plastic tube back into the fishway above the trap (fishway control) or into an aluminum tube partially filled with water for transport to the river (river control). Fish in the fishway control group slid into a tank suspended in the

TABLE 2.—Recapture of adult spring Chinook salmon (N) tagged at Willamette Falls, Oregon, and the number of days from tagging to recapture, 1998–2000.

Recapture		Proportion recaptured by site		Days from tagging to recapture	
Sites	N	Control	Hooked	Median	Range
Hatcheries	508	0.74	0.78	64	13–152
Traps	61	0.11	0.07	57	10–168
Fisheries	88	0.13	0.13	30	1–95
Spawning grounds	13	0.02	0.02	146	118–168
Combined	670[a]				

[a] Of the 670 recaptures, 22 were recaptured below Willamette Falls, of which 14 were in the Clackamas River.

fishway. Fish in the river control group were transported by hand truck about 40 m along the top of the fishway and lowered into a tank suspended in the river. Fish in both groups volitionally swam out of the tanks after recuperating.

Length measurements of control fish may have been underestimated during the study because the V-shaped insert (with measuring scale attached) could easily slide away from the end of the trough while processing fish. The end of the trough formed the stop for the snout of the fish, and any movement of the insert would underestimate length. The magnitude of the measurement error could not be determined and precluded estimating lengths of control groups.

Three biologists tagged all fish and each tagged a similar number of hooked and control fish during sampling periods. We assessed tag loss in 1998 by tagging each fish with an additional filament tag (Floy FD-67F). Of 220 tagged fish examined in 1998, 1% had lost the numbered tag and 6% had lost the filament tag. Consequently, only a single, numbered tag was used to tag Chinook salmon after 1998.

A tagged Chinook salmon was considered a survivor if it was recaptured, regardless of the number of days after tagging. Fish from hooked and control groups were recaptured primarily at hatcheries (Table 2) because hatchery spring Chinook salmon compose a high percentage of Chinook salmon in the Willamette River. Tags were also collected from fish caught by anglers in the main stem and in tributaries, at traps on two tributaries, and on spawning grounds. The proportions of hooked and control fish recaptured were not significantly different among recapture sites ($\chi^2 = 2.55$, df $= 3$, $P = 0.47$).

Statistical analyses.—Hooking mortality by hook location was estimated from combined 1998–2000 data. We used a chi-square test to compare recapture rates of river control fish with those of fishway controls and found no significant difference within years ($P = 0.07$, 0.20, and 0.93 for 1998–2000, respectively) or among years ($P = 0.82$). Recapture rates of the combined control groups were also not different among years ($P = 0.19$). Based on the homogeneity of recapture rates of control fish, we pooled hooked fish over years, assuming that any differences in recapture rates were the result of factors associated with their catch and release.

We estimated a hooking mortality rate for each hook location ($\hat{m}_l$) with the equation

$$\hat{m}_l = 1 - (a_l/b), \qquad (1)$$

where a_l is the proportion of hooked fish recaptured for hook location l, and b is the proportion of control fish recaptured. The variance of ($\hat{m}_l$) was estimated by methods described by Grover et al. (2002). If the 95% confidence interval (CI) calculated from this variance included zero, we concluded that mortality was not significantly different than zero.

We applied point estimates of hooking mortality by hook location in equation (1) to the frequency of those hook locations in the sport fishery by making two assumptions. First, we assumed that anatomical hook location is the primary factor affecting mortality of fish caught and released. Second, we assumed that fish hooked in the same hook location would suffer similar mortality regardless of the terminal gear used to hook the fish. This assumption was necessary because the terminal gear used in the experimental fishery did not cover the range of gear used by anglers in the sport fishery. To test these assumptions we used logistic regression models and the likelihood-ratio chi-square statistic (Agresti 1990; SAS Institute 2000) to identify factors that affected recapture rates. For factors with complete data sets (hook location, bleeding, gear type, fish length, and river flow;

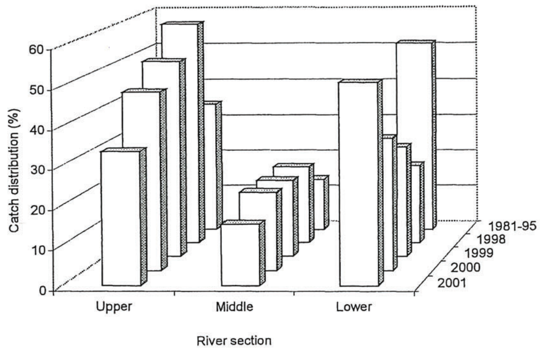


FIGURE 3.—Distribution of the angler catch of spring Chinook salmon in three creel survey sections of the Willamette River below Willamette Falls, 1998–2001, and the mean distribution in 1981–1995 (calculated from Foster and Boatner 2002). Additional angling regulations were enacted in 1998–2000 because of low run sizes.

N = 869) we used forward stepwise regression. For partial data sets (unhook time N = 465, processing time N = 252, and river temperature N = 643) we used individual logistic regressions. We also used logistic regressions to determine if river flow and river temperature affected recapture rates of the control group.

Hooking Mortality in the Sport Fishery

Anatomical hook locations of spring Chinook salmon caught in the general sport fishery were determined for 1998–2001 via creel surveys of anglers conducted by ODFW in three sections of the lower Willamette River (Foster and Boatner 2002). Creel clerks recorded the hook location of caught salmon, the type of gear used by anglers, and the number of hours different types of gear were used.

The distribution of sport catch among the three survey sections has historically differed (Foster and Boatner 2002), but was atypical in 1998–2000, 3 of the 4 years we monitored hook locations in the sport fishery (Figure 3). Additional regulations were enacted in these 3 years because of low run sizes of wild fish. Mean frequency distributions of hook locations in 1998–2001 also differed among the three survey sections because anglers used different types of gear. Consequently, to obtain a single frequency distribution of hook locations that would represent a typical fishing season in the lower river, we calculated a mean frequency weighted by catch ($\hat{w}_l$) for each hook location l with the equation

$$\hat{w}_l = \sum_{k=1}^{3} \left[\left(\frac{1}{4} \sum_{t=1998}^{2001} f_{tkl} \right) \left(\frac{1}{15} \sum_{t=1981}^{1995} c_{tk} \right) \right], \quad (2)$$

where f_{tkl} is the frequency that Chinook salmon in the sport fishery were hooked in anatomical location l in survey section k in year t, and c_{tk} is the proportion of sport catch in survey section k in year t (1981–1995 data from Foster and Boatner 2002).

Equations (1) and (2) were used to estimate a hooking mortality rate for Chinook salmon caught and released ($\hat{s}$) in the lower Willamette River sport fishery as

$$\hat{s} = \sum_{l=1}^{5} \hat{w}_l \hat{m}_l. \quad (3)$$

Hooking mortality relative to the run of wild fish ($\hat{q}$) was then estimated as

$$\hat{q} = \hat{s} \left(\frac{1}{15} \sum_{t=1981}^{1995} h_t \right), \quad (4)$$

where h_t is the encounter rate in the sport fishery in year t (data from Foster and Boatner 2002). Encounter rates do not include sport fisheries in tributaries or in the main stem above Willamette Falls or account for multiple angler encounters with fish caught and released. The hooking mortality estimates of equations (3) and (4) also assume that wild Chinook salmon caught and released in a selective fishery would have the same distribution of hook locations as hatchery and wild Chinook salmon caught and kept in 1998–2001.

Confidence intervals for hooking mortality estimates ($\hat{s}$) and ($\hat{q}$) were calculated from bootstrap estimates of standard errors (Efron and Tibshirani 1993). Estimates of $\hat{s}_{\text{boot}}$ and $\hat{q}_{\text{boot}}$ were generated (1,000 repetitions) by resampling binomial distributions defined by $\{N, p\}$ for each of a_l and b in equation (1), where N is the number of fish tagged, and p is the proportion of tagged fish recaptured; and by resampling from original data sets of f, c, and h in equation (2) and equation (4). Confidence intervals (95%) were estimated as $\hat{s}$ and $\hat{q} \pm 2$ SE_{boot}. Bootstrap estimates were normally distributed and bias between bootstrap means and original estimates of $\hat{s}$ and $\hat{q}$ were negligible (−0.02 and −0.01, respectively).

We compared the effects on hooking mortality of additional regulation of fishing seasons in 1998–2000 with those in a typical season represented by 1981–1995 data. Additional regulations in 1998–2000 included early closures when catch quotas were reached, restricted days of the week, and reduced daily and annual creel limits. Regulations returned to normal in 2001, except that regulations

TABLE 3.—Mortality rates by hook location of spring Chinook salmon that were caught in the experimental sport fishery, tagged, and released at Willamette Falls, Oregon, 1998–2000. Recapture of control groups, 1998–2000, is shown for reference.

Group	Number tagged	Number recaptured	Mortality rate (95% confidence interval)
Hooked			
Jaw	633	270	0.023 (−0.068–0.113)
Tongue	39	14	0.177 (−0.103–0.458)
Eye	15	7	0.000[a] (−0.564–0.425)
Gills	112	9	0.816 (0.725–0.907)
Esophagus–stomach	70	10	0.673 (0.523–0.822)
Control	825	360	

[a] Mortality estimates less than zero were assumed to be zero.

required the release of unmarked Chinook salmon. We calculated a single frequency distribution of hook locations for 1998–2000 by weighting the mean frequency distributions of hook locations for each of the three survey sections by the mean proportion of catch in each section over the 3 years. Hooking mortality and bootstrap confidence intervals were calculated in the same manner as that for a typical fishing season described above.

Results

Mortality in the Experimental Fishery

Because of confounding effects and small sample size, hooking mortality rates in the experimental fishery at Willamette Falls could not be isolated by the hook characteristics (i.e., hook type, number, size; Table 1) or by the five gear types. Therefore, terminal gear was grouped into only two gear types, bait (prawn, salmon eggs) and lure (spinner, plug, wobbler), and their significance in the stepwise model was examined.

Hooking mortality rates were lowest for Chinook salmon hooked in the jaw and highest for those hooked in the gills and in the esophagus–stomach (Table 3). Estimated mortality rates of fish hooked in the jaw, tongue, and eye were not significantly different from zero ($P = 0.71$, 0.34, 0.81, respectively), although sample size for fish hooked in the eye was small (Table 3). Mortality rates of fish hooked in the gills and in the esophagus–stomach were significantly greater than zero ($P < 0.001$).

TABLE 4.—Summary of the stepwise logistic regression analysis of explanatory factors on recapture rates of spring Chinook salmon caught and released in the experimental fishery at Willamette Falls, 1998–2000.

Factor	−2 Log likelihood	df	Chi-square value	*P*
Intercept	1,132.332			
Hook location	1,055.515	4	76.817	<0.0001
Length	1,046.670	1	8.845	0.0029
Gear	1,040.588	1	6.082	0.0137
Bleeding	1,034.742	1	5.846	0.0156
River flow	1,034.387	1	0.355	0.5513

Anatomical hook location was the primary factor affecting recapture of fish in the stepwise regression model (Table 4). Hook location accounted for 79% of the variation explained by the model, which validated one of the underlying assumptions of the study. Fish length, gear type, and bleeding were also significant factors in the model, but not river flow (Table 4). For partial data sets, processing time ($P = 0.42$) and river temperature ($P = 0.53$) were unrelated to recapture rates, but unhook time was significantly related ($\chi^2 = 4.8$, df $= 1$, $P = 0.0339$). The mean time to unhook fish was lower for fish recaptured (34 s, SE = 2) than for those not recaptured (39 s, SE = 1). River flow ($P = 0.68$) and river temperature ($P = 0.64$) were not significant factors in the recapture of the control group.

The significance of gear type in the stepwise regression model invalidated our assumption of similar mortality within hook locations regardless of the gear used. To determine the potential effect on estimates of hooking mortality, we examined each hook location separately (logistic regression) to identify hook locations where recapture rates were significantly affected by gear. We found that gear type was not related to recapture of fish hooked in the eye ($P = 0.20$), in the tongue ($P = 0.48$) or in the gills ($P = 0.42$), but was related to recapture of fish hooked in the jaw ($P = 0.004$). Fish hooked in the jaw on lures were recaptured at a lower rate than those caught on bait, although fish hooked in the jaw had low mortality (2.3%) overall. Fish hooked on lures took longer to un-

TABLE 5.—Mean (SE) frequency distributions of hook locations by creel survey section for spring Chinook salmon caught in the lower Willamette River, Oregon, sport fishery, 1998–2001. The frequency distribution for combined sections was calculated by weighting each section distribution by 0.348 (SE = 0.020), 0.138 (SE = 0.009), and 0.514 (SE = 0.026), the mean proportions of total catch estimated annually in the upper, middle, and lower sections, respectively, in 1981–1995 (calculated from Foster and Boatner 2002).

	Creel survey section			
Hook location	Upper	Middle	Lower	Combined[a]
Jaw	0.782 (0.051)	0.725 (0.048)	0.862 (0.002)	0.815 (0.021)
Tongue	0.046 (0.015)	0.074 (0.006)	0.049 (0.025)	0.051 (0.014)
Eye	0.007 (0.005)	0.007 (0.004)	0.002 (0.002)	0.004 (0.003)
Gills	0.071 (0.024)	0.057 (0.015)	0.036 (0.016)	0.051 (0.005)
Esophagus–stomach	0.095 (0.033)	0.138 (0.038)	0.051 (0.014)	0.078 (0.011)
Sample size	790	508	732	2030

[a] Bootstrap estimate of standard error.

hook (mean = 42 s, SE = 2) than did fish hooked on bait (mean = 30 s, SE = 2; t-test, $P < 0.001$), which may have contributed to the lower recapture of fish hooked on lures. No fish were hooked in the esophagus–stomach on lures.

Hooking Mortality in the Sport Fishery

We examined the anatomical hook locations of 2,030 spring Chinook salmon caught by sport anglers in the lower Willamette River in 1998–2001. Most of these fish (81.5%) were hooked in the jaw (Table 5). Fish hooked in locations producing high mortality (gills or esophagus–stomach), composed 12.9% of the catch. Based on hook location frequencies in the sport fishery and the corresponding hooking mortality rates for each hook location in the experimental fishery, we estimated a hooking mortality rate of 12.2% (95% CI = 1.8–22.6%) for wild spring Chinook salmon that would be caught and released in a selective sport fishery in the lower Willamette River. Hooking mortality relative to the run of wild Chinook salmon in the Willamette River was 3.2% (CI = 0.5–5.9%) based on a mean encounter rate of 26% (SE = 1%) in 1981–1995 (calculated from Foster and Boatner 2002).

The frequency distribution of hook locations varied among survey sections (Table 5) and was generally associated with differences in the type of gear anglers used to catch Chinook salmon (Table 6). Bait predominated in all survey sections, but Pacific herring *Clupea pallasi* was most commonly used in the lower section and prawns (vernacular of Oregon anglers for northern shrimp *Pandalus borealis*) or ghost shrimp *Callianassa* sp. were most commonly used in the upper section. Anglers who used prawns or ghost shrimp generally hooked more fish in the gills and esophagus–stomach and fewer in the jaw than did anglers who used Pacific herring or lures (Table 7).

When additional regulations were enacted in 1998–2000, the catch distribution of Chinook salmon shifted from the lower survey section to upper survey sections compared with 1981–1995 and with 2001 (Figure 3). Because anglers in upper sections used a higher proportion of gear that

TABLE 6.—The mean (SE) frequency distribution of hours that anglers used different types of gear to fish for spring Chinook salmon in each of three creel survey sections of the lower Willamette River, Oregon, 1998–2001. Frequencies may not add to 1.00 due to rounding.

	Mean (SE) frequency of gear usage by survey section		
Gear type	Upper	Middle	Lower
Pacific herring[a]	0.06 (0.01)	0.52 (0.06)	0.74 (0.05)
Prawn or ghost shrimp	0.53 (0.04)	0.38 (0.05)	0.06 (0.01)
Salmon eggs[b]	0.06 (0.02)	<0.01 (0.00)	<0.01 (0.00)
Spinner	0.13 (0.00)	0.05 (0.01)	0.10 (0.02)
Plug	0.07 (0.02)	0.04 (0.01)	0.08 (0.02)
Wobbler	0.05 (0.02)	0.01 (0.00)	0.01 (0.00)
Winged attractor	0.10 (0.05)	<0.01 (0.00)	<0.01 (0.00)
Miscellaneous	0.01 (0.00)	<0.01 (0.00)	0.01 (0.00)

[a] Includes a few northern anchovies *Engraulis mordax*, Pacific sardines *Sardinops sagax*, and eulachons *Thaleichthys pacificus*.

[b] Includes salmon eggs used in combination with prawns or ghost shrimp.

TABLE 7.—Frequency distributions of hook locations for the three most common types of gear used to catch spring Chinook salmon in the lower Willamette River, Oregon, sport fishery, 1998–2001.

	Location					
Year	Jaw	Tongue	Eye	Gills	Esophagus–stomach	Sample size
			Pacific herring			
1998[a]	0.84	0.15	0.00	0.00	0.02	117
1999	0.83	0.04	0.00	0.06	0.06	309
2000	0.85	0.03	0.01	0.03	0.08	349
2001	0.82	0.06	0.01	0.05	0.06	86
			Prawn or ghost shrimp			
1998	0.58	0.05	0.00	0.15	0.22	81
1999	0.84	0.03	0.00	0.03	0.10	213
2000	0.71	0.07	0.01	0.07	0.14	364
2001	0.72	0.11	0.01	0.11	0.05	117
			Spinner			
1998	0.96	0.04	0.00	0.00	0.00	23
1999	0.89	0.03	0.00	0.03	0.05	37
2000	0.83	0.08	0.04	0.04	0.02	52
2001	0.85	0.03	0.00	0.09	0.03	59

[a] Includes one fish caught on a northern anchovy.

hooked fish in the gills and esophagus–stomach (Tables 6, 7), hooking mortality estimates increased from 12.2% for typical years (1981–1995) to 14.3% (CI = 3.5–25.0%) in 1998–2000. However, the increased hooking mortality in 1998–2000 was offset by a reduction in mean encounter rate from 26% in 1981–1995 to 11% (SE = 3%) in 1998–2000 (calculated from Foster and Boatner 2002). The addition of catch-and-release regulations for Chinook salmon in 2001 did not change the catch distribution among survey sections compared with the distribution in 1981–1995 (Figure 3).

Discussion

We found that hooking mortality of spring Chinook salmon caught and released in the lower Willamette River sport fishery is largely dependent on anatomical hook location, which is consistent with other hooking mortality studies on salmon (Wertheimer 1988; Bendock and Alexandersdottir 1993; Gjernes et al. 1993; Grover et al. 2002). Length, gear type, bleeding, and unhook time were also significantly related to recapture of hooked fish. Other studies have shown that bleeding is a significant factor in survival of fish caught and released (Wertheimer 1988; Bendock and Alexandersdottir 1993). The significance of length in our study was difficult to interpret because of the absence of length data for the control group. Size effects could be a function of natural mortality above Willamette Falls or of being caught and released. Natural differences in size-related mortality are unknown but could have affected estimates of hooking mortality if lengths differed between hooked and control groups. The significance of gear type invalidated our assumption that fish hooked in the same anatomical location would suffer similar mortality regardless of the gear used because fish hooked in the jaw with lures had lower recapture rates than those hooked in the jaw on bait. Fish hooked on lures took longer to unhook than fish hooked on bait, and unhook time was inversely related to recapture rates.

Because about 60% of the jaw-hooked fish caught in our experimental fishery were hooked on lures compared with about 20% in the sport fishery, we may have overestimated hooking mortality for the jaw. Had we used the same ratio of lures and bait as in the sport fishery, hooking mortality would have been reduced from 12.2% to 10.3% for fish caught and released and from 3.2% to 2.7% relative to the run. However, bait (prawns and salmon eggs) and lures (spinners and plugs) were broad categories within which components (hook types, hook sizes and body styles, etc.) could not be isolated in our study. In addition, the range and intensity of use of specific types of terminal gear differed between the sport fishery and the experimental fishery. For example, Pacific herring was not used in the experimental fishery but was common in the sport fishery and had a hook location profile more similar to lures than to bait. Therefore, the adjustments in hooking mortality estimates because of differences between bait and lures should be viewed with caution.

Our estimate of 3.2% hooking mortality for wild spring Chinook salmon in the lower Willamette River sport fishery does not include fisheries in the main stem above Willamette Falls or in tributaries, which accounted for about 30% of the total annual harvest in 1981–1995 (calculated from Foster and Boatner 2002). Combining all fisheries, we estimate that sport anglers would encounter 37% of the wild spring Chinook salmon in the Willamette Basin. Assuming the hooking mortality rate of 12.2% estimated in the lower river fishery is applicable to other fisheries in the basin and by using a 6.4% multiple encounter rate for fish previously caught and released (ODFW 2001), we estimate the basinwide mortality for the run of wild spring Chinook salmon would be 4.8% in a catch-and-release fishery. This estimate assumes that the frequency distribution of hook locations in the main stem above the falls and in tributaries is the