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[Article]

Effects of Reservoir Operations on Hatchery Coastal Rainbow Trout in Lake Roosevelt, Washington

HOLLY J. MCLELLAN,* STEPHEN G. HAYES, AND ALLAN T. SCHOLZ
Department of Biology, Eastern Washington University,
258 Science Building, Cheney, Washington 99004, USA

Abstract.—It is suspected that reservoir operations limit the mitigation fishery for coastal rainbow trout *Oncorhynchus mykiss irideus* in Lake Roosevelt, Washington. Entrainment through Grand Coulee Dam has been suggested as the primary impact of reservoir operations. However, the causal mechanisms and effects of entrainment have been difficult to quantify. A logistic regression model was used to examine the effect of reservoir operations on the coastal rainbow trout tag return probability. Eight independent variables were studied: release location, presence–absence of a tag reward, minimum reservoir elevation (m above mean sea level [msl]) during a sample year, reservoir elevation on the fish release date, mean daily water retention time (d) 2 weeks postrelease, mean daily retention time 4 weeks postrelease, mean annual water retention time, and water year type (associated with shallow, average, or deep drawdown events). Models were selected on the basis of likelihood ratio tests, odds ratio confidence intervals (CIs), and predictive ability. Analyses indicated that the significant independent variables were release location, water year, release elevation, and mean water retention time at 4 weeks postrelease. Angler return of tagged fish was 1.86 times more likely after a shallow drawdown event than after a deep drawdown event (95% profile likelihood CI = 1.15–3.03). The effect of mean water retention time was dependent on reservoir elevation at the time of release. When release elevation was low (366–381 m above msl), increasing mean water retention time increased the probability of tag return. However, when release elevation was high (381–393 m above msl), increasing mean water retention time did not increase the probability of tag return. The logistic regression model can be used by fisheries managers to predict the impacts of hydropower operations on the coastal rainbow trout fishery in Lake Roosevelt, thereby allowing for annual adjustments to release strategies that would maximize harvest potential.

Hydroelectric dams have dramatically altered major river systems across the USA by shifting natural hydrographs, altering sediment transport dynamics, diverting water (Hesse and Mestl 1993; Merz and Setka 2004), and causing changes in biotic (e.g., secondary productivity) and abiotic variables (e.g., temperature; Zale et al. 1990; Haddix and Budy 2005). Some hydroelectric facilities were constructed without fish passage, thereby blocking upstream passage of migratory fish species (Schmetterling and McEvoy 2000; Merz and Setka 2004; Ward and Ward 2004). Managers have attempted to establish recreational fisheries in these new lacustrine habitats. In many western reservoirs, salmonids such as rainbow trout *Oncorhynchus mykiss* and kokanee *O. nerka* (lacustrine sockeye salmon) are often used to create these fisheries (Rieman and Myers 1992; Martinez and Wiltzius 1995; Rieman and Maiolie 1995; Haddix and Budy 2005).

Management of the salmonid fisheries can be difficult due to dynamic environments caused by fluctuating reservoirs. Several studies have demonstrated that alteration of flow regimes in regulated rivers influences fish populations (Stober et al. 1983; Smith and Andersen 1984; Weisberg and Burton 1993; McKinney et al. 2001; Post et al. 2006). Fisheries managers are interested in the relationships between hydrologic variables and fish population effects in regulated rivers because modification of reservoir operations is one of the few options available to managers trying to maintain fisheries (Sammons and Bettoli 2000).

The construction of Grand Coulee Dam created Franklin D. Roosevelt Lake (hereafter, Lake Roosevelt), causing extirpation of anadromous fishes (salmon, steelhead [anadromous rainbow trout], and Pacific lamprey *Lampetra tridentata*; NWPPC 1987). As partial mitigation for this loss, catchable-sized coastal rainbow trout *O. mykiss irideus* (McCloud River strain) have been stocked in the lake since 1987. Currently, 500,000 coastal rainbow trout are stocked annually (Peone 2003), which has created a fishery worth approximately US$6.5 million to the local economies (Lee et al. 2006).

In Lake Roosevelt, stocking strategies and reservoir operations are the two major factors affecting recruitment of coastal rainbow trout into the fishery (Cichosz et al. 1999). Studies suggested that entrainment of coastal rainbow trout was a function of water retention

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* Corresponding author: hmclellan@ewu.edu

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times, drawdown–refill scenarios, and release timing (Cichosz et al. 1999). Recruitment increased by 12% if fish were released when water retention time was 30 d and by 20% if fish were released when water retention time reached 40 d. Therefore, to maximize angler harvest, hatchery coastal rainbow trout release protocols included holding fish until the end of May, when the reservoir reached 384 m above mean sea level (msl). Under normal conditions, it was assumed that the reservoir had stabilized and that water retention time was above 40 d.

Fisheries managers have taken the above steps to reduce the negative impacts of reservoir operations on the fishery. However, reservoir operations vary depending on the type of water year and continue to have a varying effect on the quality of the fishery after the fish are released. Therefore, a tool that assists managers in predicting the magnitude of reservoir operation effects on the fishery during various water years would be valuable. Such a tool would give managers the ability to make changes to stocking procedures when reservoir operations are likely to negatively affect the quality of the coastal rainbow trout fishery. The objective of this study was to develop a model that could be used by fisheries managers to predict coastal rainbow trout tag return probability in Lake Roosevelt based on specific reservoir conditions. Thus, managers would be able to predict the quality of the coastal rainbow trout fishery on an annual basis.

Study Area

In 1942, construction of Grand Coulee Dam impounded the Columbia River in north-central Washington at river kilometer (rkm) 960.5 and formed Lake Roosevelt. The reservoir (at a full-pool elevation of 393 m above msl) inundates 33,490 ha and possesses a storage capacity of more than 11.7×10^9 m^3 and a maximum depth of 122 m (Nigro et al. 1981; Barber et al. 1999; Figure 1). Lake Roosevelt is 243 km long, making it the largest reservoir in Washington and the sixth-largest reservoir in the USA (Lee et al. 2006). Grand Coulee Dam is the largest U.S. producer of hydroelectric energy and provides water that irrigates over 202,343 ha of eastern Washington. The Columbia River provides 87% of the inflow but also receives water from three main tributaries: the Spokane, Kettle, and SanPoil rivers (Barber et al. 1999). Lotic waters predominate in the upper reaches, transitioning to more-lentic waters near Grand Coulee Dam (Lee et al. 2006). The fishery is limnetically driven, as the majority of fishes (including some obligate benthivores) use pelagically fixed carbon (Black et al. 2003). The long-term trend suggests that Lake Roosevelt is changing from a eutrophic–mesotrophic state to an oligotrophic state (Barber et al. 1999).

Grand Coulee Dam is 1 of 14 large-scale, multipurpose facilities that make up the Federal Columbia River Power System (FCRPS). The U.S. Bureau of Reclamation (USBOR) is responsible for construction and operation of the dam. Under the Flood Control Act of 1944 (16USC 460d), the U.S. Army Corps of Engineers is responsible for specific operations concerning flood control. Because of its size and key location, Grand Coulee Dam plays a prominent role in the coordination of the FCRPS for both flood control and power production (FCRPS 2001). Grand Coulee Dam is operated as a storage dam, which typically requires the reservoir to experience a deep drawdown during late winter and early spring to accommodate the large spring freshet. The extent of the spring drawdown in any Columbia River reservoir is the responsibility of the FCRPS-affiliated agencies, which abide by a set of rule curves that have been developed for each reservoir. These curves specify desirable reservoir water levels for each month and provide guidance for meeting project goals. The curves are updated as snowpack and streamflow data become available (FCRPS 2001).

Typically, reservoir operations in January and February are predominately controlled by power production, resulting in low, stable lake elevations. Operations are focused on flood control from mid-February to May, which is thus typically the period of lowest water elevation. Operations during May and June focus on meeting reservoir refill objectives (85% probability of being filled by July 1) and downriver flow targets defined by the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) biological opinion (NMFS 2008) and the U.S. Fish and Wildlife Service biological opinion (USFWS 2000). Flood control operations at Grand Coulee Dam reduce the reservoir water elevation by up to 24 m annually between January and June to create room for spring flows. Spring drawdown events decrease the volume of the reservoir by an average of 55% and decrease reservoir surface area by 45% annually (Beckman et al. 1985).

Methods

Coastal rainbow trout source and production.—The Spokane Tribal Hatchery receives annual egg allotments of approximately 500,000 Spokane stock, diploid coastal rainbow trout from the Washington Department of Fish and Wildlife (WDFW) Spokane Hatchery (McCloud River origin). Coastal rainbow trout eggs were from a procuring brood (fall spawn) held at the Spokane Hatchery. Eggs were incubated and

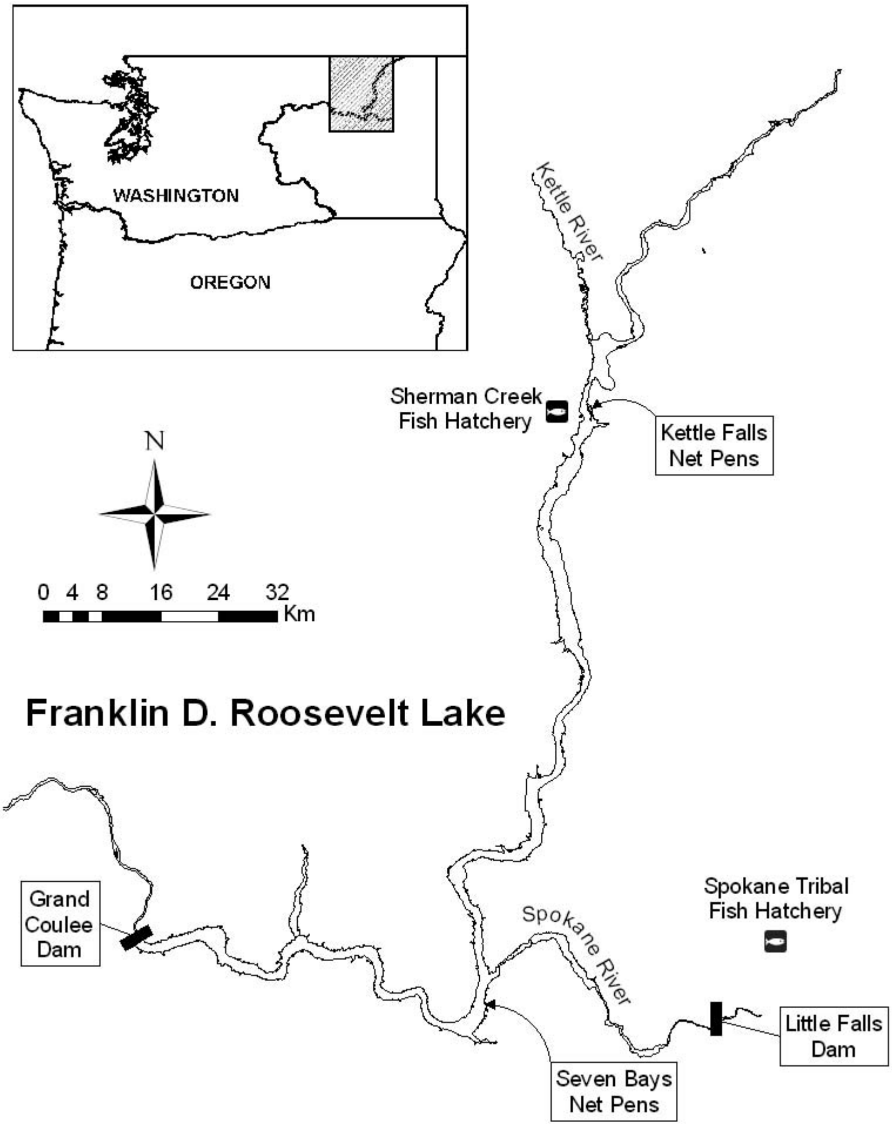

FIGURE 1.—Map of Franklin D. Roosevelt Lake, Washington, located behind Grand Coulee Dam on the Columbia River. Coastal rainbow trout from the Sherman Creek and Spokane Tribal fish hatcheries were held in net-pens and released at two locations on the reservoir (Seven Bays and Kettle Falls) and were used to determine the effect of reservoir operations on the probability of tag return by anglers.

reared at the Spokane Tribal Hatchery until the yearling stage (Peone 2003). Fish destined for midreservoir net-pens were held until fall at the Spokane Tribal Hatchery and then were transferred to the appropriate net-pens for overwinter rearing and subsequent spring release. Fish destined for net-pens in the northern portion of the reservoir were transferred to the WDFW Sherman Creek Hatchery in June for summer rearing in raceways; these fish were then transferred to the net-pen sites in the fall for overwinter rearing and were finally released as yearlings during the subsequent spring (Lovrak and Combs 2003).

Coastal rainbow trout release strategies have varied since the inception of the artificial production program; since 1995, fisheries managers have consistently released 5,000–10,000 marked coastal rainbow trout in the spring (mid-May or early June) at two primary sites: Seven Bays and Kettle Falls (Table 1). One month prior to the expected release date, fish greater than 200 mm total length were affixed with individually numbered Floy tags (Floy Tag, Inc., Seattle, Washington; Model FD-94, 1.905-cm [0.75-in] monofilament, T-shaped anchor). Tags were inserted at the posterior base of the dorsal fin as described by Guy et al. (1996). Each tag was printed with the words "EWU CHENEY" (Eastern Washington University, Cheney) so that anglers would know where to return the tags. Posters were also displayed at all boat launches along the reservoir with instructions for voluntarily returning tag information. Information related to the tagging program was published in local newspapers and on the Lake Roosevelt Forum Web site (LRF 2002).

During fall 2002, a phone number was printed on each tag and a reward program was initiated in an attempt to increase the rate of tag returns by anglers. Drawings were held biannually in April and October. Among the pool of anglers that returned tags, 20 winners were randomly selected to receive $1,100 in gift certificates (ranging from $20 to $200) to a local sporting goods retail store. Angler tag return information was collected by phone, e-mail, letters, or the Lake Roosevelt creel survey. Data collected from anglers included tag color and number, date and location of capture, fish length, fish weight, and angler mailing information.

Statistical methods.—For the logistic regression models, the dependent variable was the probability of tag return by anglers. Independent variable selection focused on encompassing all possible influences on tag return probability without saturating the model. Six reservoir operation variables and two variables unrelated to reservoir operation were studied. The two nonreservoir variables were release location (LOC) and presence–absence of a tag reward (RW; absence: no reward offered during 1996–2001; presence: reward offered from fall 2002 to 2005). Although there were sufficient tag return data from two locations on the reservoir (Seven Bays and Kettle Falls), tag return rates were not necessarily equal between areas. By including LOC in the model, we accounted for bias related to unequal capture probabilities. The Lake Roosevelt tag reward program was initiated in the middle of the study. By including RW in the model, we could determine whether the reward program had a significant effect on tag return probability.

The six reservoir operation variables were minimum reservoir elevation (ME), reservoir elevation at the time of fish release (RE), mean daily water retention time 2 weeks postrelease (WRT_2), mean daily retention time 4 weeks postrelease (WRT_4), mean annual retention time (WRT_52), and water year (WR; categorized as shallow, average, or deep drawdown; Table 2). The ME for each year was derived from a predictive model developed by the USBOR based on the relationship between snowpack and inflow levels. By using this variable, both inflow and snowpack levels were represented in the model. Fish are currently released when the reservoir elevation is approximately 384 m above msl. This usually occurs in late spring when the reservoir is refilling. However, depending on reservoir operations, RE can vary substantially per year. Therefore, we evaluated the effect of RE on tag return probability.

TABLE 1.—Release dates, released number of Floy-tagged coastal rainbow trout, number recaptured, and percentage of tags returned by anglers in Lake Roosevelt, Washington, between 1995 and 2005. Fish were held in net-pens and released at Kettle Falls or Seven Bays.

Release date	Number tagged	Number recaptured	Percent recovered
Kettle Falls			
May 12, 1995	5,000	45	0.90
Apr 29, 1996	4,998	4	0.08
May 19, 1997	7,000	1	0.01
Jun 1, 1997	3,000	1	0.03
May 31, 1998	9,992	379	3.79
May 29, 1999	9,977	40	0.40
Jun 14, 2000	9,999	114	1.14
May 23, 2001	5,000	63	1.26
Jun 3, 2001	5,000	74	1.48
May 29, 2002	9,997	84	0.84
May 25, 2003	6,700	247	3.69
May 26, 2004	6,500	86	1.32
Total	83,163	1,138	1.25
Seven Bays			
May 23, 1995	8,000	91	1.14
Jun 6, 1996	9,950	232	2.33
Jun 3, 1997	10,000	15	0.15
May 28, 1998	9,989	524	5.25
Jun 6, 1999	9,995	66	0.66
Jun 14, 2000	9,968	240	2.41
May 4, 2001	5,000	101	2.02
Jun 8, 2001	4,994	157	3.14
Jun 22, 2001	5,000	152	3.04
May 20, 2002	9,999	55	0.55
May 28, 2003	6,600	311	4.71
May 13, 2004	6,500	233	3.58
Total	95,995	2,177	2.42

Water retention time is a function of reservoir volume and outflow. It was important to utilize WRT variables instead of separate volume and outflow variables, because independently the latter variables were not representative of the actual reservoir environment. For example, the reservoir could have high inflow but low outflow (i.e., during refill), which extends WRT within the reservoir. However, the reservoir could also have high inflow and high outflow (i.e., during a freshet), which would decrease WRT. Therefore, the WRT variables specifically addressed the flow within the reservoir. Water retention time varied daily depending on how the dam was operated. To determine how WRT affected tag return probability,

TABLE 2.—Descriptions of two variables unrelated to reservoir operation (release location and reward for returned tags) and six reservoir operation variables analyzed in logistic regression models predicting the probability of tag return by anglers in the coastal rainbow trout fishery of Lake Roosevelt, Washington, between 1995 and 2005. Fish were held in net-pens prior to release. Shallow, average, and deep drawdown elevation categories (water year type) are described in Methods.

Variable	Code	Description
Release location	LOC	Two release sites (Seven Bays and Kettle Falls)
Reward	RW−	1996–2001; tag return reward was not offered
	RW+	2002–2005; tag return reward was offered
Minimum elevation (m above mean sea level [msl])	ME	Maximum drawdown level per year
Release elevation (m above msl)	RE	Reservoir elevation at the time of fish release
Water retention time (d)	WRT_2	Mean daily water retention time at 2 weeks postrelease
	WRT_4	Mean daily water retention time at 4 weeks postrelease
Annual water retention time (d)	WRT_52	Mean annual water retention time (52 weeks)
Water year type	WR_1	Comparison of shallow versus average drawdown events
	WR_2	Comparison of shallow versus deep drawdown events

we examined the three WRT variables described above.

Hydrologic data were obtained from the Columbia River Data Access in Real Time web site (University of Washington 2006). Reservoir elevation was converted to volume of water stored using a reservoir water storage table (USACE 1981). Reservoir water volume (millions of m^3) was then divided by the outflow (millions of m^3/d) to calculate daily WRT (Table 3). Maximum drawdown elevation between 1989 and 2004 was used to determine the average drawdown (mean ± SD = 15.0 ± 6.1 m), which was subtracted from the full-pool elevation level (393 m above msl) to determine the average drawdown elevation (378.0 ± 6.1 m above msl). A deep drawdown event was classified as a year in which the maximum drawdown elevation was below 372 m (average drawdown elevation − SD). A shallow drawdown event was classified as a year in which the maximum drawdown elevation did not go below

TABLE 3.—Observed values of variables (see Table 2 for explanation of variable codes and units) analyzed in logistic regression models predicting the probability of tag return by anglers in the coastal rainbow trout fishery of Lake Roosevelt, Washington, between 1995 and 2005. Shallow, average, and deep drawdown elevation categories for WR are described in Methods.

Release date	ME	RE	WR type	WRT_2	WRT_4	WRT_52
			Kettle Falls			
May 12, 1995	382.0	382.8	Average	39.87	45.06	46.18
Apr 29, 1996	374.1	375.4	Average	14.86	15.56	32.39
May 19, 1997	368.4	374.3	Deep	11.95	13.28	29.23
Jun 1, 1997	368.4	382.3	Deep	14.47	16.05	29.23
May 31, 1998	381.7	392.2	Average	28.76	33.2	45.12
May 29, 1999	369.8	376.4	Deep	21.17	25.89	32.07
Jun 14, 2000	376.1	383.0	Average	37.95	39.56	39.6
May 23, 2001	370.9	383.2	Deep	80.55	66.53	59.22
Jun 3, 2001	370.9	388.8	Deep	55.95	56.66	59.22
May 29, 2002	370.9	382.2	Average	23.82	24.56	44.85
May 25, 2003	385.6	385.7	Shallow	47.8	37.88	53.72
May 26, 2004	383.5	389.0	Shallow	41.82	28.66	50.02
			Seven Bays			
May 23, 1995	382.0	385.3	Average	48.58	43.61	46.18
Jun 5, 1996	374.1	381.7	Average	20.92	23.3	32.39
Jun 3, 1997	368.4	384.0	Deep	14.46	17.02	29.23
May 28, 1998	381.7	391.5	Average	26.44	32.03	45.12
Jun 6, 1999	369.8	381.4	Deep	25.97	27.62	32.07
Jun 14, 2000	376.1	383.0	Average	37.95	39.56	39.6
May 4, 2001	385.6	373.6	Deep	68.58	78.43	59.22
Jun 8, 2001	370.9	389.5	Deep	16.5	13.9	59.22
Jun 22, 2001	370.9	390.4	Deep	62.82	78.9	59.22
May 20, 2002	378.0	378.0	Average	69.8	24.73	44.85
May 28, 2003	385.6	386.4	Shallow	37.79	36.79	53.72
May 13, 2004	383.5	388.3	Shallow	38.81	39.99	50.02

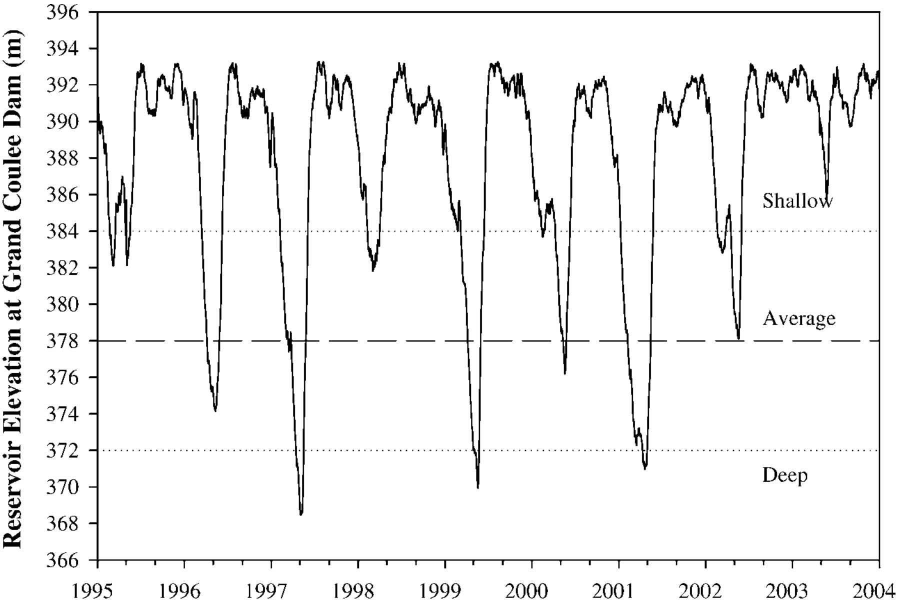

FIGURE 2.—Reservoir elevation (m above mean sea level) of Lake Roosevelt at Grand Coulee Dam on the Columbia River, Washington, between 1995 and 2004. Shallow, average, and deep drawdown elevation categories are described in Methods.

384 m (average drawdown elevation + SD). An average drawdown event was classified as a year in which the maximum drawdown elevation was within 1 SD of the average drawdown elevation (Figure 2).

Logistic regression was used to model the probability of tag return in Lake Roosevelt from coastal rainbow trout released at Kettle Falls and Seven Bays. Prior to model selection, the eight independent variables were screened to determine their individual effects on tag return probability. Variables were retained if they had significant ($\alpha = 0.15$) univariate logistic regressions (LOGISTIC procedure in the Statistical Analysis System [SAS]; SAS Institute 2007) or previously identified biological significance. A liberal type I error rate was used for single-variable screening to ensure that important variables were included in multivariate candidate models (Hosmer and Lemeshow 1989). Collinear variables were identified with rank correlation analysis (CORR procedure in SAS). The negative effects of collinearity were assessed by observing the stability of parameter estimates in multivariate models.

After univariate analyses, the linearity of the logit with each continuous variable was examined. The logit represents the $\log_e$ transformation of the logistic regression probability distribution. The logit is designated as linear in the logistic regression parameters. To check this assumption, quartiles were used to break the range of each continuous variable into four groups; the logit of the group mean was then plotted against the midpoint of the group (Hosmer and Lemeshow 1989).

After removing nonsignificant and collinear variables, all two-way interactions were examined using Wald's chi-square test. Significant interactions ($\alpha = 0.05$) were added, forming a full model. All possible subsets of the full model were evaluated using the likelihood score statistic for each subset model (LOGISTIC procedure in SAS; SELECTION = SCORE). From the group of all possible subsets, 11 models generated large likelihood score statistics that were clustered above those of the other models. These 11 models were placed into the candidate model set.

The final model was selected on the basis of (1) parsimony, (2) odds ratio significance, (3) coefficient and standard error stability, and (4) predictability (McCullagh and Nelder 1983; Myers 1990; Tabachnick and Fidell 1996). Likelihood ratio tests ($\alpha = 0.05$) were used to determine whether more-parsimonious models fit as well as the full model (McCullagh and Nelder 1983). Odds ratio significance was evaluated with 95% profile likelihood confidence intervals (CIs; Hosmer and Lemeshow 1989). Because the experimental units (i.e., release groups) were clusters, the dependence of observations (i.e., fish) within release groups resulted in overdispersion (Williams 1982; McCullagh and Nelder 1983). To account for overdispersion, odds ratio CIs were corrected by rescaling the covariance matrix using Williams' method (LO-

TABLE 4.—Chi-square (χ^2; df = 1) values and significance (P) of variables (see Table 2 for explanation of variable codes and units) considered in univariate logistic regression models predicting the probability of tag return by anglers in the coastal rainbow trout fishery of Lake Roosevelt, Washington, between 1995 and 2005.

Variable code	χ^2	P
WR_1	2.27	0.13
WR_2	5.38	0.02
ME	9.30	<0.01
RE	14.83	<0.01
WRT_2	0.44	0.51
WRT_4	1.54	0.22
WRT_52	7.36	0.01
LOC	3.58	0.06
RW	1.25	0.26

GISTIC procedure; SCALE = W). Coefficient and standard error stability was judged by removing a variable from the model and observing the magnitude of estimate changes from the remaining variables.

Predictive ability regardless of model and variable significance tests was quantified for each candidate model using receiver operating characteristic (ROC) curves and their associated areas (Hanley and McNeil 1982). The area under a ROC curve was quantified using the trapezoidal rule. The area was interpreted as the probability that the model prediction for a randomly chosen returned tag exceeds the model prediction for a randomly chosen unreturned tag (Heagerty et al. 2000). Models with the most discriminatory power were identified based on the magnitude of the area under the ROC curve.

The ROC curves were generated by randomly splitting data into training (80%) and test (20%) groups and then fitting each candidate model with the training data. Predictability was evaluated using test data to generate a ROC curve for each candidate model. The curves were formed by plotting (1 − specificity) values against sensitivity values for a set of cut points (c). Specificity estimates a model's rate of false-positive prediction (i.e., the proportion of unreturned tags that were predicted to be returned). Sensitivity estimates the model's rate of true-positive prediction (i.e., the proportion of returned tags that were predicted to be returned). The c-values convert the predicted logistic probability (π) into a tag return prediction (e.g., $c = 0.5$: if $\pi < 0.5$, then the tag is predicted to be unreturned; if $\pi \geq 0.5$, then the tag is predicted to be returned). A perfect model will produce a ROC curve that instantly rises from (0, 0) when c equals 0 to (0, 1) for all c-values between 0.0 and 1.0. Models that depart from the ideal will only become more sensitive by becoming less specific (i.e., more true positives and more false positives) as c approaches 1.0 (Hanley and McNeil 1982).

The ROC curve depends on the random split of the data; therefore, ROC curve area is a random variable. The mean and standard error of ROC curve area were estimated by bootstrapping the data splitting procedure 500 times for each candidate model (Heagerty et al. 2000). Bootstrap 95% CIs were constructed around each model's mean ROC curve area to identify the best predictive models, which then were interpreted after refitting them with the entire data set. The ROC curve and bootstrap analyses were performed using the IML procedure in SAS.

Results

Between 1995 and 2004, 179,158 Spokane stock coastal rainbow trout yearlings were released in 24 unique groups at Kettle Falls and Seven Bays (Table 1). The recapture database consisted of 3,315 fish that were recaptured between May 1995 and April 2005 (Table 1). These data represent only those fish that were recaptured within the study area (Lake Roosevelt) and do not describe those that were recaptured downstream of Grand Coulee Dam or upstream of the study area (i.e., in Canada). Tagging information related to the experiment was not posted outside the study area; therefore, we could not assume that fish recaptured outside of the study area had equal tag return probabilities. The exclusion of these data is further evaluated in the Discussion. The recapture database was extended into 2005 to cover recruitment of the coastal rainbow trout released in 2004.

Five of the eight independent variables had significant univariate relationships with tag return probability (Table 4). Plots of the logit and continuous variables were linear. Collinearity, which could lead to imprecise estimates of regression coefficients, plagued the data set. Minimum drawdown elevation, WRT_52, and WRT_2 were dropped from analysis because they produced unstable parameter estimates and had significant ($P < 0.01$) rank correlations. The RE variable was retained because it produced a significant univariate logistic regression ($\chi^2 = 14.83$, df = 1, $P < 0.01$) and was not correlated with WRT_4. The RW and WRT_4 variables were not significant in univariate tests (Table 4) but were retained because of their suspected importance.

The initial logistic regression model contained the following uncorrelated variables: LOC, RW, WR_1, WR_2, RE, and WRT_4. The RE × WRT_4 interaction was the only significant two-way interaction ($P < 0.01$) and was therefore added to the full model containing the above six variables. Eleven reduced-variable models were identified using the likelihood

TABLE 5.—Receiver operating characteristic (ROC) curve area (mean of 500 bootstrap replicates) and likelihood ratio (–2 log L; P-values in parentheses represent comparison with model 2 except where indicated) for candidate logistic regression models predicting the probability of tag return by anglers in the coastal rainbow trout fishery of Lake Roosevelt, Washington, between 1995 and 2005. See Table 2 for explanation of variable codes and units.

Model	Variable code(s)	Mean ROC curve area	−2 log L (P)[a]
Full	RW, LOC, RE, WR_1, WR_2, WRT_4, WRT_4 × RE interaction	0.710	975.71
1	LOC, RE, WR_1, WR_2, WRT_4, WRT_4 × RE interaction	0.710	975.83 (0.73)[b]
2	LOC, RE, WR_2, WRT_4, WRT_4 × RE interaction	0.706	977.24 (0.22)[c]
3	LOC, RE, WR_1, WR_2, WRT_4	0.702	983.16 (<0.01)
4	LOC, RE, WR_1, WR_2	0.698	986.98 (<0.01)
5	LOC, RE, WR_2, WRT_4,	0.703	984.82 (<0.01)
6	LOC, RE, WR_2	0.699	988.87 (<0.01)
7	LOC, RE	0.683	994.21 (<0.01)
8	RE, WR_2	0.667	996.44 (<0.01)
9	RE	0.672	1,000.78 (<0.01)
10	WR_2	0.560	1,026.49 (<0.01)
11	LOC	0.562	1,024.64 (<0.01)

[a] Significance of likelihood ratio test comparing reduced and complex models (H_0: reduced model fits as well as the complex model).

[b] Comparison to full model.

[c] Comparison to model 1.

score statistic (Table 5). Likelihood ratio tests showed that model 2 (formed by removing RW and the WR_1 variable, which compared shallow and average drawdown events) did not significantly reduce the likelihood (Table 5). Furthermore, RW and WR_1 did not produce significant odds ratios in the full model or reduced models ($P > 0.05$). All remaining variables produced significant contributions to the likelihood (Table 5) and had significant odds ratios ($P < 0.05$; Table 6). Estimates in model 2 remained stable when variables were removed.

The full model and model 1 generated the largest mean ROC curve areas (0.710 for both; Table 5). The mean area corresponds to each model's predictive ability. For example, if the full model is used to predict tag return probability for a pair of randomly selected tags (one returned and one unreturned), then there is a 71% chance that the full model will produce a greater π for the returned tag than for the unreturned tag. The prediction probabilities (ROC curve areas) for models 2, 3, and 5 were 0.706, 0.702, and 0.703, respectively (Table 5), which were only slightly less (by 0.004–0.008) than those of the full model and model 1. It is difficult to imagine that such small mean differences among models represent biologically distinct predictive abilities.

Despite the nearly equal predictability values among models, the significance of likelihood ratio and odds ratio tests led us to select model 2 as the final model (Table 6; Figure 3). According to this model, the probability of tag return is a function of LOC, RE, WR_2, WRT_4, and the WRT_4 × RE interaction. The interaction means that the effect of RE cannot be determined unless WRT_4 is considered. For example, if reservoir elevation is 372 m above msl at fish release, increasing WRT_4 by 20 d will increase the probability of tag return by a factor of 2.57. At REs greater than 384 m above msl, increases in WRT_4 will have no effect on the probability of tag return (Figure 4).

Water year and LOC had significant main effects. Tag returns were 1.86 times more likely after a shallow drawdown event than after a deep drawdown event (95% profile likelihood CI = 1.15–3.03). Tag returns were also 1.71 times more likely for fish released at

TABLE 6.—Description of logistic regression coefficients (with odds ratio 95% confidence interval [CI] or SE in parentheses) for independent variables included in the final model (model 2 in Table 5) selected from a set of candidate models for predicting the probability of tag return by anglers in the coastal rainbow trout fishery of Lake Roosevelt, Washington, between 1995 and 2005. See Table 2 for explanation of variable codes and units. The 95% CIs were significant ($P < 0.05$) because they did not contain 1.0.

Independent variable	Coefficient
Constant	−88.45
LOC	0.536[a] (1.13–2.59)[b]
WR_2	−0.622 (1.15–3.03)[b]
RE[c]	0.218[d]
WRT_4[e]	0.987[d]
RE × WRT_4 interaction	−0.0025[d]
ROC curve area (SE)[f]	0.706 (0.00052)

[a] Model variable coefficient.

[b] Odds ratio 95% profile likelihood CI.

[c] Odds ratio unit = 3 m.

[d] See Figure 4 for odds ratio 95% CI.

[e] Odds ratio unit = 20 d.

[f] Based on 500 bootstrap replicates.

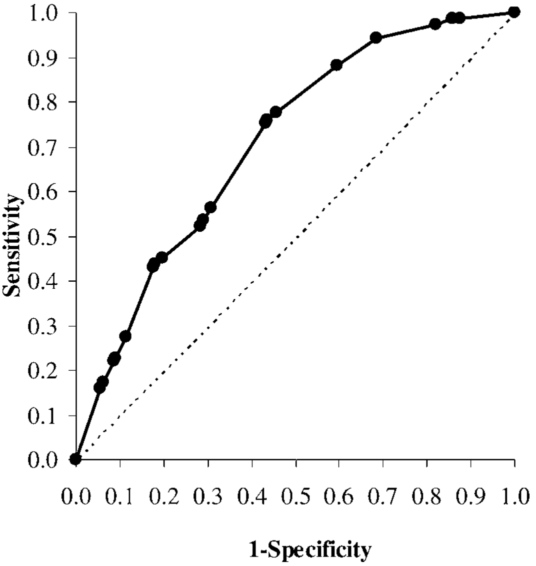

FIGURE 3.—Receiver operating characteristic (ROC) curve (i.e., sensitivity plotted against [1 – specificity]; see Methods) for a model describing the effect of coastal rainbow trout release location and reservoir operating characteristics on the probability of tag return by anglers in Lake Roosevelt, Washington, 1995–2005 (model 2 in Table 5). Coordinates represent the upper and lower standard errors generated from bootstraps of 500 random data splits.

Seven Bays than for fish released at Kettle Falls (95% profile likelihood CI = 1.13–2.59).

The dominance of the RE variable was illustrated by the ROC curve analysis. The single-variable model containing only RE (model 9) predicted the tag return probability nearly as well as the more-complicated models (Table 5). The addition of WR, WRT_4, and the interaction only added 0.038 to the mean area under the ROC curve.

Discussion

The Lake Roosevelt hatchery coastal rainbow trout program was implemented as partial mitigation for the loss of anadromous fish runs caused by construction of Grand Coulee Dam. Our results suggest that operations of the dam negatively affected the coastal rainbow trout fishery in the reservoir. The logistic regression model indicated that LOC, WR (drawdown scenario), WRT_4, and the interaction of WRT_4 and RE were the primary variables affecting the success of the hatchery coastal rainbow trout fishery. We used 10 years of tag return data to choose the best-fitting model according to likelihood ratio tests and significant odds ratios. Our model was cross validated using ROC curve area as an independent measure of goodness of fit.

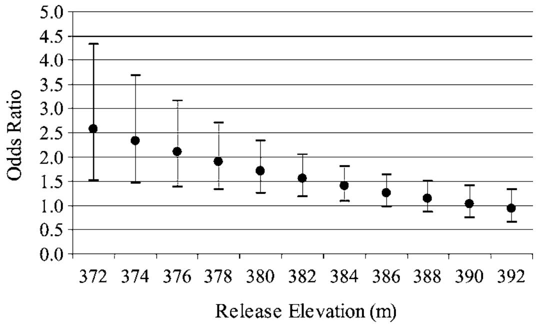

FIGURE 4.—Estimated odds ratio (with 95% profile likelihood confidence interval [CI]) describing the effect of a 20-d increase in reservoir water retention time (measured at 4 weeks postrelease) on the probability of tag return from hatchery coastal rainbow trout released into Lake Roosevelt, Washington, at various reservoir elevations (m above mean sea level). Odds ratio 95% CIs containing 1.0 are not significant.

The logistic regression model indicated that (1) shallow and average drawdown events were not significantly different in their effects on tag return probability and (2) the likelihood of tag return was primarily influenced (i.e., decreased) by the deep drawdown events. During deep drawdown events, conditions in the reservoir were probably unstable by the standard late-May target release date, thereby facilitating an increase in fish entrainment, mortality, or both. The model displayed the importance of RE and of releasing fish when the reservoir is at or above 384 m above msl. Of all the variables tested, the only interaction was between RE and WRT_4. Under average conditions, when the reservoir is at the desired 384-m level, the tag return probability ranged between 0.015 and 0.035 depending on WRT_4. Therefore, increasing WRT during the critical 4 weeks after release can positively affect the coastal rainbow trout fishery. Because WRT is a product of outflow value and reservoir volume, decreasing outflow during the critical period is recommended for protection of the coastal rainbow trout fishery.

The ROC curves, which were used to test the accuracy of the models, further supported our findings. There was a 71% chance that the full model would produce a greater π for a returned tag than for an unreturned tag. The ROC curve area (0.710) estimates the likelihood that the model generates π-values in the correct order for two randomly selected data points (one returned tag and one unreturned tag). Correct ordering occurs when the unreturned tag has a smaller predicted π than the returned tag. If the selected c falls between the two π-values, then one true-positive prediction and one true-negative prediction are made

(Mason and Graham 2002). Therefore, when running data through the model, a true positive was predicted 71% of the time. When ROC curve area values were analyzed for reduced models, it was clear that RE was a primary variable. Using RE alone (model 9), there was a 67% chance that the model would predict a greater π for a returned tag than for an unreturned tag. When analyzed alone, WR_2 (model 10) had a 56% chance of predicting a greater π for a returned tag than for an unreturned tag.

The use of the best-fit model (model 2) for Lake Roosevelt is recommended based on the high likelihood and odds ratio tests. However, the reduced models might be more applicable when attempting to manage highly variable systems and to coordinate with multiple agencies. Resource managers of other fluctuating systems might benefit from the use of models containing variables that play a large role in recruitment, such as drawdown level and WRT. For example, we could simply recommend that a reservoir elevation of 384 m above msl is attained by May 31 of each year to protect the coastal rainbow trout fishery in Lake Roosevelt.

The dynamic environmental conditions that occur in the reservoir during spring runoff challenge fisheries managers on an annual basis. The option to hold fish until reservoir conditions are optimal is not always feasible. For example, during the annual spring freshet period in 1997–2006, total dissolved gas (TDG) levels in the Columbia River exceeded 110% saturation in all years except 2001 (University of Washington 2006). A TDG level of 110% is the maximum permitted by the U.S. Environmental Protection Agency and Washington State Department of Ecology (Rucker and Tuttle 1948; Ryan et al. 2000; Johnson et al. 2005a). The duration for which TDG exceeded the maximum allowable concentration ranged between 39 and 135 d/year, and the excessive TDG level varied between 110% and 200% (University of Washington 2006). Rainbow trout held in net-pens have no way to escape the supersaturated water, which often causes gas bubble trauma that leads to lethal vascular and cardiac blockage or hemorrhaging (Johnson et al. 2005a). In these instances, managers have been forced to choose between holding fish until reservoir conditions stabilize or risk fish exposure to high TDG levels.

The use of reservoir operations to evaluate the success of the fishery was more practical and cost effective than attempting to quantify entrainment. Previous studies have attempted to relate coastal rainbow trout losses specifically to entrainment through Grand Coulee Dam. Such studies can be very difficult and costly (Boreman and Goodyear 1981; Stober et al. 1983; Johnson et al. 1994, 2005b; LeCaire 2000; Maiolie et al. 2001). The model we developed examined the relation between reservoir conditions and tag return probability and does not assume that the impacts are solely related to entrainment. Our model allowed us to predict how reservoir conditions affect the coastal rainbow trout fishery in Lake Roosevelt and encompassed all forms of loss (e.g., entrainment, predation, and gas bubble trauma).

Tagging study methods and biases have been extensively reported (Ebener and Copes 1982; Mourning et al. 1994; Sprankle et al. 1996; Henderson-Arzapalo et al. 1999; Pollock et al. 2001). The present study was not without biases; therefore, we briefly address these biases in relation to several assumptions of our tagging study. We assumed that (1) tagged samples were representative of the target population, (2) there were no tag losses, (3) survival rates were not affected by tagging, (4) tagged fish were independent, and (5) tag-related survival and recovery rates were equal among years.

In our study, tagged and untagged fish were held in similar net-pens, fed the same diet proportions, and released on the same date at each location; this consistency in production characteristics ensured that the tagged fish represented the target population. We acknowledge that there was probably initial and chronic tag loss in our study. Tag retention was not estimated, because we used a long-term data set that lacked a tag retention component. Tag retention rates have been estimated for numerous fish species and vary extensively depending species and tag type (Carline and Brynildson 1972; Tranquilli and Childers 1982; Muoneke 1992; Mourning et al. 1994; Lenarz and Shaw 1997; Fabrizio et al. 1999; Cadigan and Brattey 2003). We assumed that initial tag loss and tag-related mortality were reduced by using similar experienced tagging crews (Cadigan and Brattey 2003), tagging similarly sized fish ($\geq$200 mm total length), and holding the fish for 1 month prior to release. Long-term loss was probably not a factor, because this is a put-and-take coastal rainbow trout fishery and most of the fish are harvested within 6 months of release.

Tag reporting rates have been studied and vary widely (Hearn et al. 1998, 1999; Hoening et al. 1998a; Pollock et al. 2002a; Cadigan and Brattey 2003; Taylor et al. 2006). Variation associated with angler tag return rate was reduced by using data from only those fish that were recaptured in the study area. In addition, creel clerks collected tags from the major boat launches each year. Our modeling effort demonstrated that the likelihood of tag return did not increase after the reward program was established. This suggests that either the tag return rates were already consistently high or the reward was not large enough to generate more angler interest in returning tags (Pollock et al. 2001, 2002b; Taylor et al. 2006).

A coastal rainbow trout harvest that is 1.86 times less than the average harvest could result in a decline in angler trips to Lake Roosevelt. This reduction translates into a loss to local economies. The continued use of Lake Roosevelt water to support downriver interests negatively affects upper Columbia River Native American tribes, anglers, and native fish and wildlife species, all of which lost the benefits associated with anadromous fishes.

We were able to verify and quantify that deep drawdown events, low WRT, and low RE affected the success of the hatchery coastal rainbow trout fishery in Lake Roosevelt. On a regional level, managers will be able to predict impacts to the coastal rainbow trout fishery under various hydropower operation scenarios, use the information to adjust management strategies, and negotiate mitigation packages. Managers could also postpone the release of coastal rainbow trout until reservoir elevation or water retention time attains an optimal level. Additionally, managers will be able to quantify the benefits of keeping the average drawdown level above 15.0 m to maintain a high-quality coastal rainbow trout fishery in Lake Roosevelt.

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