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Open-File Report 2012–1125

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Datums

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Abbreviations and Acronyms

AIC	Akaike's Information Criterion
CJS	Cormack-Jolly-Seber models
Kcfs	1,000 ft^3/s
PIT	passive integrated transponder
rkm	river kilometer
TSW	temporary spillway weir

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Abstract

We analyzed 6 years (2004–09) of passage and survival data collected at McNary Dam to examine how spill bay operations affect survival of juvenile salmonids passing through the spillway at McNary Dam. We also examined the relations between spill bay operations and survival through the juvenile fish bypass in an attempt to determine if survival through the bypass is influenced by spill bay operations. We used a Cormack-Jolly-Seber release-recapture model (CJS model) to determine how the survival of juvenile salmonids passing through McNary Dam relates to spill bay operations.

Results of these analyses, while not designed to yield predictive models, can be used to help develop dam-operation strategies that optimize juvenile salmonid survival. For example, increasing total discharge typically had a positive effect on both spillway and bypass survival for all species except sockeye salmon (*Oncorhynchus nerka*). Likewise, an increase in spill bay discharge improved spillway survival for yearling Chinook salmon (*Oncorhynchus tshawytscha*), and an increase in spillway discharge positively affected spillway survival for juvenile steelhead (*Oncorhynchus mykiss*). The strong linear relation between increased spill and increased survival indicates that increasing the amount of water through the spillway is one strategy that could be used to improve spillway survival for yearling Chinook salmon and juvenile steelhead. However, increased spill did not improve spillway survival for subyearling Chinook salmon and sockeye salmon. Our results indicate that a uniform spill pattern would provide the highest spillway survival and bypass survival for subyearling Chinook salmon. Conversely, a predominantly south spill pattern provided the highest spillway survival for yearling Chinook salmon and juvenile steelhead. Although spill pattern was not a factor for spillway survival of sockeye salmon, spill bay operations that optimize passage through the north and south spill bays maximized spillway survival for this species. Bypass survival of yearling Chinook salmon could be improved by optimizing conditions to facilitate bypass passage at night, but the method to do so is not apparent from this analysis because photoperiod was the only factor affecting bypass survival based on the best and only supported model. Bypass survival of juvenile steelhead would benefit from lower water temperatures and increased total and spillway discharge. Likewise, subyearling Chinook salmon bypass survival would improve with lower water temperatures, increased total discharge, and a uniform spill pattern.

Introduction

As juvenile salmon *Oncorhynchus spp.* and steelhead *O. mykiss* migrate downriver to the ocean, they are subject to natural and human-induced mortality. Predators contribute to total natural mortality along with other factors (Vigg and others, 1991; Collis and others, 2001). Impoundments caused by hydroelectric dams on the Snake and Columbia Rivers may indirectly contribute to mortality by slowing the migration of juvenile salmonids (Raymond, 1968, 1979; Plumb and others, 2006), thereby increasing energy expenditure during migration and allowing greater opportunity for predation. Further, passage through dams can be a major source of direct mortality (Mesa 1994; Whitney and others, 1997) that is cumulative for populations negotiating multiple dams.

Studies monitoring fish movements near McNary Dam were conducted annually from 2004 to 2009 to assess how dam operations or fish passage structures influence passage and survival of juvenile salmonids migrating through the hydroelectric system in a particular year. Although the McNary Dam studies provided valuable information for developing management strategies, some important questions remain unanswered. Managers often are interested in understanding how rates of survival and passage vary with environmental conditions, such as total river discharge or distribution of discharge across possible passage routes. Consistently similar conditions are favorable when the goal is point estimation under a given condition, but understanding how survival or passage varies in response to dam operations requires data for a wide range of conditions. Studies conducted in a single year will only consider a narrow range of environmental conditions, due to natural year-to-year variation in the environment. Multi-year analyses are better suited for the development of quantitative relationships than single-year analyses, because operational and environmental variation typically will be higher over a period of 5–10 years than within any given year. Furthermore, multi-year analyses benefit from the large sample sizes over multiple years, which can reduce statistical uncertainty and help identify relations that otherwise might be statistically undetectable. We analyzed 6 years (2004–09) of passage and survival data collected at McNary Dam to examine how spill bay operations affect survival of juvenile salmonids passing through the spillway at McNary Dam. In addition, we examined relations between spill bay operations and survival through the juvenile fish bypass in an attempt to determine if survival through the bypass is influenced by spill bay operations.

Description of Study Area

McNary Dam is the fourth dam on the Columbia River (counting upriver from its terminus with the Pacific Ocean) located 470 river kilometers (rkm) upriver from the Pacific Ocean and 52 rkm downriver from the confluence of the Columbia and Snake Rivers (fig. 1). The reservoir formed by McNary Dam (Lake Wallula) extends 98 rkm upriver to the Hanford Reach of the Columbia River, and impounds 16 rkm of the Snake River downstream of Ice Harbor Dam. John Day Dam is located 123 rkm downriver of McNary Dam and creates Lake Umatilla. Our study area extended from Hat Rock State Park, Oregon, 10 rkm upriver of McNary Dam, to Sundale, Washington, 92 rkm downstream of McNary Dam, where our last acoustic telemetry array was located.

McNary Dam is oriented perpendicular to the river channel and includes a navigation lock, spillway, powerhouse, and earthen dam. The spillway is 399 m long with 22 vertical lift-type spill gates that regulate discharge through the dam. The spillway discharges water at the ogee crest approximately 14 m below the water surface. During the sampling seasons in 2007–09, temporary spillway weirs (TSWs) were installed as part of a strategy to improve fish passage at the dam.

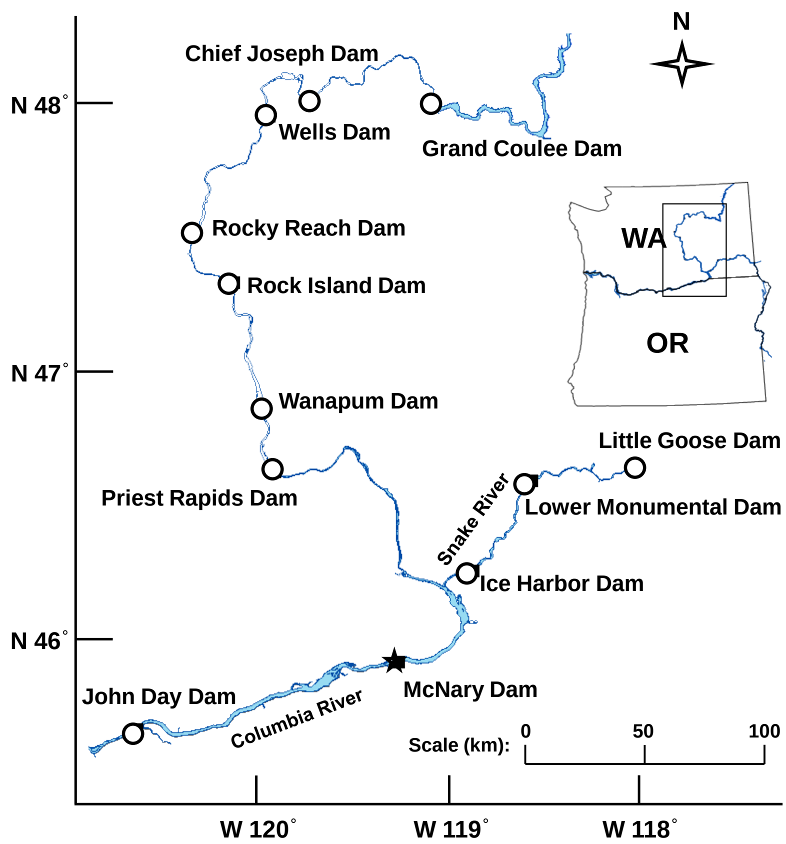

Figure 1. Map showing location of McNary Dam and other major hydroelectric projects on the Columbia and Snake Rivers, Washington and Oregon.

River Conditions

Average daily discharge throughout a season was variable depending upon year. The 10-year average (2000–2009) in mid-April was about 210 kcfs, with discharge increasing to greater than 250 kcfs by late May (fig. 2). River-flows for the 10-year average decreased through June and July to less than 150 kcfs by August. Average daily spill at McNary Dam from 2000 to 2009 followed a similar trend to mean daily outflow (fig. 3). Mean daily spill in mid-April, at the start of the season, averaged 80 kcfs and peaked in late May or early June at 125 kcfs for the 10-year average. During 2004 and 2005, flow through the dam was low compared to the 10-year average. In 2004, very little flow was discharged through the spillway during the summer season. More detailed information regarding average daily discharge, including how discharge varied during the day and night periods, can be found in the annual reports of research (Perry and others, 2006, 2007; Adams and others, 2008; Adams and Counihan, 2009; Adams and Liedtke, 2009, 2010).

Water temperature steadily increased during the study period, from 9°C in April to a peak of about 21°C in late July or early August (fig. 4). Water temperatures were slightly lower (1–2°C) in 2008 than during the other 5 study years. For more detailed information on the environmental conditions and dam operations for individual years included in this analysis, please refer to Adams and Evans (2011).

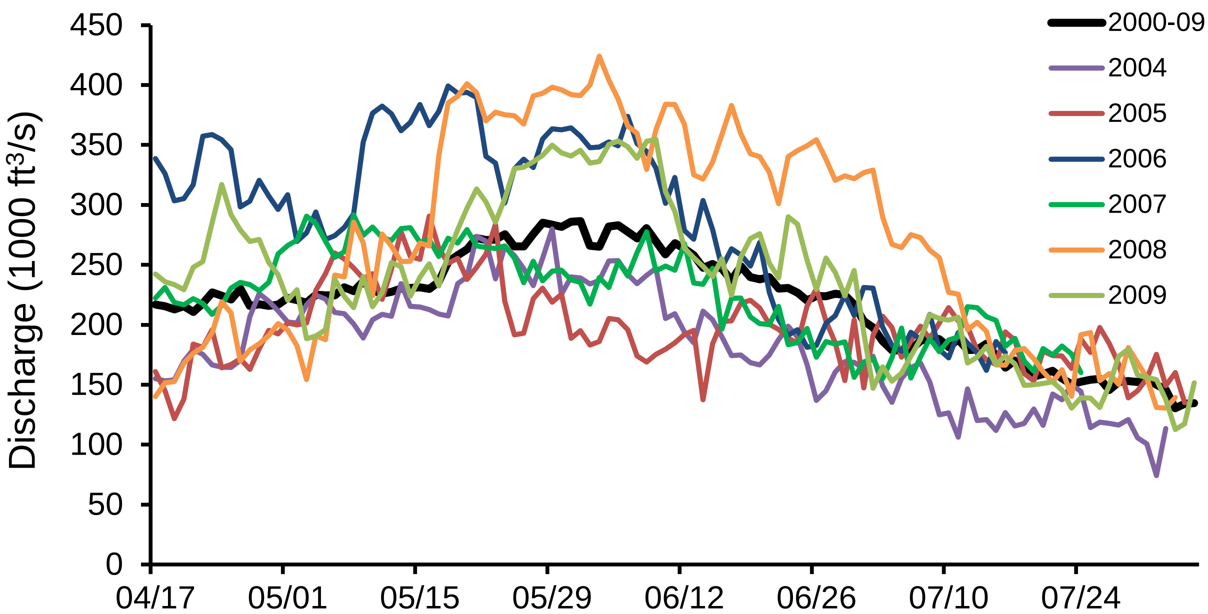

Figure 2. Hydrograph of mean daily project outflow during radio and acoustic telemetry study dates at McNary Dam, 2004–09, and the 10-year average, 2000–09. Data obtained from Columbia River DART website: *http://www.cbr.washington.edu/dart/river.html*.

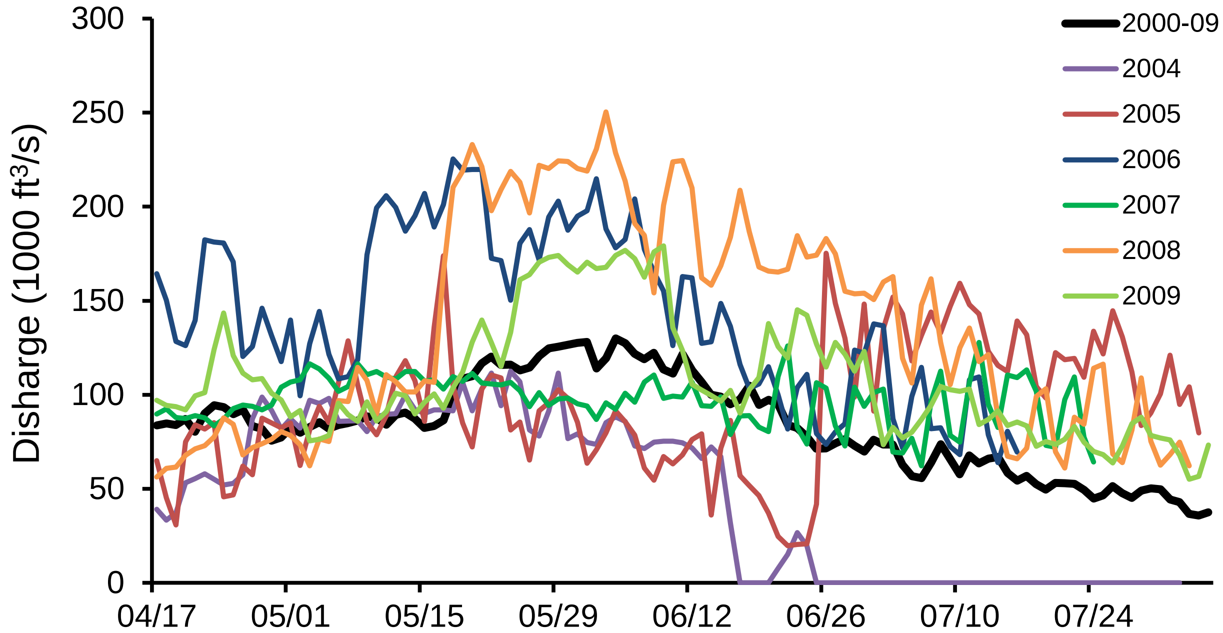

Figure 3. Hydrograph of mean daily project spill during radio and acoustic telemetry study dates at McNary Dam, 2004–09, and the ten year average, 2000–09. Data obtained from Columbia River DART website: *http://www.cbr.washington.edu/dart/river.html*.

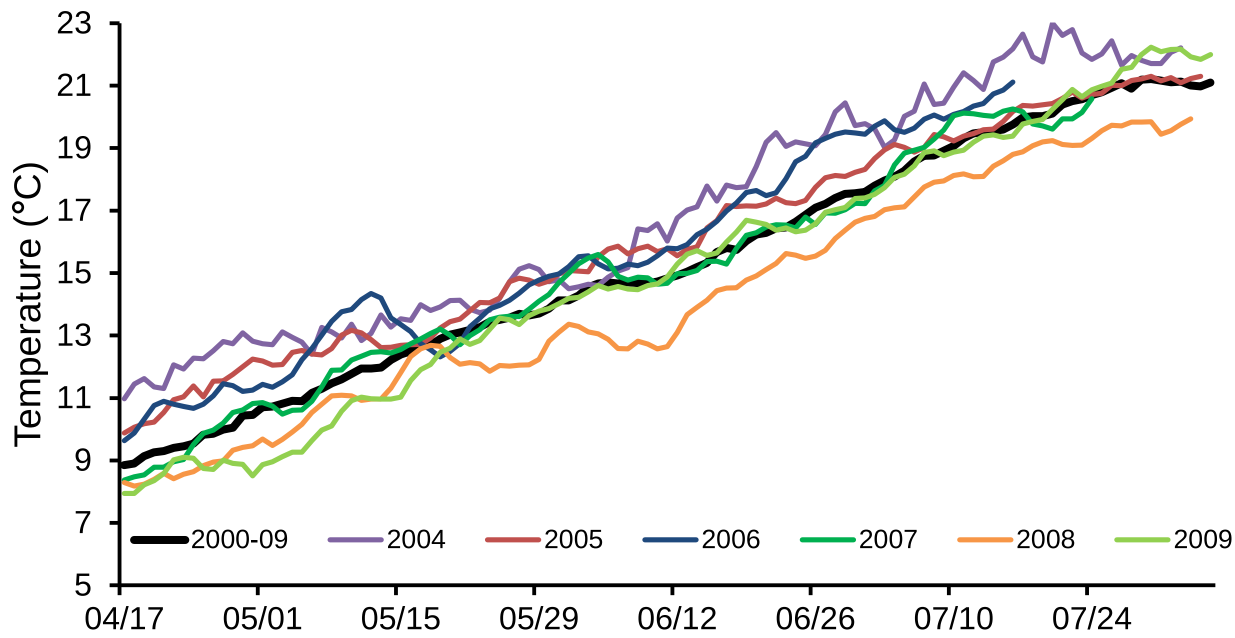

Figure 4. Hydrograph of mean daily water temperature of the Columbia River at McNary Dam during radio and acoustic telemetry study dates, 2004–09, and the 10-year average, 2000–2009. Data obtained from Columbia River DART website: *http://www.cbr.washington.edu/dart/river.html*.

Methods

Data

We analyzed radio and acoustic telemetry data collected during the spring and summer of 2004–09 to examine how spill bay operations affected survival of juvenile salmonids passing through the spillway and the juvenile fish facility bypass. Telemetry equipment was deployed upstream, at, and downstream of McNary Dam to monitor fish movements. During the years included in our analyses, more than 21,000 acoustic-tagged yearling Chinook salmon (*Oncorhynchus tshawytscha*), juvenile steelhead (*Oncorhynchus mykiss*), subyearling Chinook salmon (*Oncorhynchus tshawytscha*), and sockeye salmon (*Oncorhynchus nerka*) were detected passing through the McNary Dam spillway or juvenile bypass (table 1). Yearling Chinook salmon and juvenile steelhead were hatchery-reared, although subyearling Chinook and sockeye salmon were of unknown origin. U.S. Geological Survey personnel tagged and released all yearling and subyearling Chinook salmon and juvenile steelhead used for this analysis. Treatment fish were released 10 km upstream of McNary Dam and control fish were released about 0.5 km downstream of the dam. Sockeye salmon were released in the Mid-Columbia River by personnel from Hydroacoustic Technologies Incorporated, LGL Limited, Chelan County Public Utility District, and Grant County Public Utility District. Specifications for the acoustic transmitters used in the annual studies are provided in table 2. Numbers of each species released, release dates, release sites, passage dates, and percentage of spill during dates of passage are documented in tables 3 and 4. Other details describing tags, tagging, and data-collection methods are given in Adams and others (1998, 2008), Perry and others (2006, 2007), Adams and Counihan (2009), and Adams and Liedtke (2009, 2010).Methods used to tag sockeye salmon are described by Steig and others (2007, 2008, 2009, 2010), Sullivan and others (2009), and Timko and others (2007, 2008, 2010). Survival estimates for all species were assessed from dam passage to a downstream array located from rkm 446 to 448.

Table 1. Number of fish used in this analysis that passed through the McNary Dam spillway or bypass, 2004–09.

[NA, analysis not possible because sockeye salmon were not PIT tagged]

Route	Yearling Chinook salmon	Juvenile steelhead	Subyearling Chinook salmon	Sockeye salmon
Spillway	4,405	3,794	4,213	2,870
Bypass	2,864	1,390	1,835	NA

Table 2. Specifications of transmitters surgically implanted in juvenile salmonids, 2006–09.

[NA, not applicable]

Year	Site	Acoustic transmitter model	Average tag dimensions (millimeters)	Average tag weight in air (grams)	Average tag life (days)	PIT tag model
Yearling Chinook salmon and juvenile steelhead						
2006	Columbia	795-E	6.8 × 21.0	1.5	21	TX1411ST
2007	Columbia	795-E	6.8 × 21.0	1.5	21	TX1411ST
2008	Columbia	795-E	7.1 × 21.9	1.6	18	TX1411ST
2009	Columbia	795-LE	6.7 × 21.1	1.4	28	TX1411ST
Subyearling Chinook salmon						
2006	Columbia	795-M	6.8 × 16.5	0.8	17	TX1411ST
2007	Columbia	795-M	6.8 × 16.5	0.8	17	TX1411ST
2008	Columbia	795-S	6.5 × 22.2	0.7	13	TX1411ST
2009	Columbia	795-LM	6.5 × 16.3	0.7	24	TX1411ST
Sockeye salmon						
2006	Mid-Columbia	795-M	6.8 × 16.5	0.8	14	NA
2007	Mid-Columbia	795-M	6.8 × 16.5	0.8	14	NA
2008	Mid-Columbia	795-M	6.8 × 16.5	0.8	17	NA
2009	Mid-Columbia	795-Lm	5.0 × 17.5	0.7	22	NA

Table 3. Summary statistics of fork length and weight of acoustic-tagged juvenile salmonids released in the Columbia River, by release site, 2006–09.

[Species/age class: Y. Chinook, yearling Chinook salmon; Steelhead, juvenile steelhead; S. Chinook, subyearling Chinook salmon. Release site: HAT, near Hat Rock State Park, Oregon, approximately 10 kilometers upstream of McNary Dam; TAIL, 0.5 kilometers downstream of McNary Dam in the tailrace directly out from the downstream tip of the navigation wall; SAC, intentionally sacrificed fish released at the TAIL release site; RC, Rocky Reach Collector; RR, Rocky Reach Dam; RH, Rock Island Hydro Park; RI, Rock Island Dam; WA, Wanapum Dam; WE, Wells Dam. N, number of fish; Min, minimum; Max, maximum]

Species/ age class	Release site	Release dates	N	Fork length, in millimeters			Weight, in grams		
				Mean	Min	Max	Mean	Min	Max
2006									
Y. Chinook	HAT	4/27–6/4	1,797	149	125	179	31.7	23.0	59.5
Y. Chinook	TAIL	4/27–6/4	1,213	148	133	175	31.3	22.6	49.8
Y. Chinook	SAC	4/30–6/1	49	148	134	174	31.7	23.0	48.7
Steelhead	HAT	4/27–6/1	1,005	209	122	290	78.6	31.0	236.5
Steelhead	SAC	5/4–5/31	50	205	158	267	73.3	30.1	152.6
S. Chinook	HAT	6/20–7/19	1,794	120	104	155	17.5	12.5	44.8
S. Chinook	TAIL	6/20–7/19	1,191	120	108	158	17.4	13.5	44.9
S. Chinook	SAC	6/22–7/11	50	118	112	133	16.7	13.6	25.1
2007									
Y. Chinook	HAT	4/19–6/7	1,973	151	130	222	33.4	23.0	108.4
Y. Chinook	TAIL	4/19–6/7	1,310	151	133	206	33.5	23.0	78.8
Y. Chinook	SAC	4/27–6/4	53	151	135	179	33.2	23.7	49.9
Steelhead	HAT	4/21–6/6	1,118	215	160	292	84.6	27.4	207.7
Steelhead	SAC	4/28–6/2	50	223	178	279	93.4	43.7	166.8
S. Chinook	HAT	6/20–7/25	1,771	118	105	166	17.8	13.2	55.2
S. Chinook	TAIL	6/20–7/25	1,182	118	105	168	17.6	12.8	59.9
S. Chinook	SAC	6/24–7/24	50	118	110	136	17.8	13.5	32.5
2008									
Y. Chinook	HAT	4/19–6/3	1,424	154	131	206	36.0	23.0	147.6
Y. Chinook	TAIL	4/20–6/4	949	153	130	200	35.5	23.0	76.7
Y. Chinook	SAC	4/22–5/31	50	151	134	189	34.2	24.1	63.6
Steelhead	HAT	4/19–6/2	1,186	211	136	289	82.8	27.5	224.0
Steelhead	TAIL	4/20–6/3	785	210	135	294	81.7	25.0	232.7
Steelhead	SAC	4/22–5/31	50	213	171	270	87.2	38.3	179.2
S. Chinook	HAT	6/19–7/28	1,752	116	102	158	17.1	11.8	46.8
S. Chinook	TAIL	6/20–7/29	1,176	117	103	155	17.1	11.8	40.7
S. Chinook	SAC	6/22–7/27	50	117	107	142	17.4	12.4	33.3
2009									
Y. Chinook	HAT	4/18–6/4	1,411	164	134	240	44.4	29.0	119.0
Y. Chinook	TAIL	4/18–6/4	935	164	137	255	44.7	29.0	174.0
Y. Chinook	SAC	4/20–5/29	51	161	143	195	41.9	30.4	75.2
Steelhead	HAT	4/18–6/4	1,176	220	111	280	93.8	32.6	215.4
Steelhead	TAIL	4/18–6/4	785	220	158	283	94.7	32.4	218.0
Steelhead	SAC	4/23–5/29	51	216	156	254	87.4	31.5	130.0
S. Chinook	HAT	6/20–7/30	1,784	121	105	158	20.2	13.5	47.0
S. Chinook	TAIL	6/20–7/30	1,187	122	102	172	20.4	13.5	57.8
S. Chinook	SAC	6/25–7/28	51	118	109	148	18.8	14.0	38.2

Table 4. Number of acoustic-tagged juvenile salmonids released in the Columbia River, number (and percentage of those released) that passed McNary Dam through any route, range of passage dates, and corresponding percentage spill of total project discharge over dates of passage at McNary Dam, by species, 2006–09.

[Species/age class: Y. Chinook, yearling Chinook salmon; Steelhead, juvenile steelhead; S. Chinook, subyearling Chinook salmon. Percentage of spill: Percentage of project discharge spilled includes the water discharged through the temporary spillway weirs]

Species/age class	Number released	Number (%) passed	First passage date	Last passage date	Percentage of spill
			2006		
Y. Chinook	1,797	1,717 (96)	4/27/2006	6/5/2006	50
Steelhead	1,005	944 (94)	4/27/2006	6/2/2006	48
S. Chinook	1,791	1,638 (91)	6/20/2006	7/30/2006	49
Sockeye	3,493	1,339 (38)	5/10/2006	6/11/2006	52
			2007		
Y. Chinook	1,974	1,911 (97)	4/20/2007	6/9/2007	43
Steelhead	1,118	1,086 (97)	4/22/2007	6/9/2007	41
S. Chinook	1,771	1,631 (92)	6/21/2007	8/7/2007	52
Sockeye	2,500	1,224 (49)	5/11/2007	6/14/2007	41
			2008		
Y. Chinook	1,424	1,396 (98)	4/19/2008	6/8/2008	46
Steelhead	1,186	1,186 (100)	4/19/2008	6/3/2008	47
S. Chinook	1,752	1,646 (94)	6/20/2008	8/8/2008	51
Sockeye	2,002	1,084 (54)	5/18/2008	6/21/2008	57
			2009		
Y. Chinook	1,403	1,351 (96)	4/18/2009	6/8/2009	44
Steelhead	1,170	1,107 (95)	4/19/2009	6/4/2009	43
S. Chinook	1,772	1,602 (90)	6/20/2009	8/7/2009	51
Sockeye	3,974	3,578 (90)	5/18/2009	6/20/2009	50

Survival Analysis

We used release-recapture models developed by Cormack (1964), Jolly (1965), and Seber (1965) (hereafter referred to as CJS) to examine how environmental variables and dam operations affect survival of juvenile salmonids passing through the spillway and juvenile fish bypass at McNary Dam. A logit link was used to relate individual and group covariates of environmental variables assigned at dam passage (table 5) to survival. Models were created and parameters estimated in the program MARK (White and Burnham, 1999).

Group covariates for photoperiod, year, passage location, spill bay type, and spill pattern were based on discrete time periods, passage structures, spillway locations, or spillway operations. For photoperiod, dark and light periods were determined using civil twilight for each day. Group covariates for passage location and spill bay type were defined based on consistencies across years so that fish were assigned as passing through a particular part of the spillway or spillway structure (table 6). Spillway passage location generally was assigned as follows: north, spill bays 1–6; middle, bays 7–15; south, bays 16–22. In 2008 it was necessary to include bay 7 in the group of north bays and bay 16 in the group of middle bays. Spill bay type was defined as either a TSW or a standard vertical lift-type spill gate depending on a fish's passage location.

Spill patterns were defined based on the percentage of total spill discharged through the north, middle, and south portions of the spillway during the spring and summer when the study fish passed the dam. The number of spill patterns and their characteristics were determined by cluster analysis using the FASTCLUS procedure in SAS® software (SAS Institute, 2008). Daily percentages of total spill discharged through each portion of the spillway were calculated for two 12-h intervals (0600–1759 and 1800–0559). Because the percentages of total spill discharged through the north and south portions of the spillway were highly correlated, only the percentage of spill for the north and middle spillway were used to create each cluster (spill pattern). The procedure was run repeatedly, allowing the total number of spill patterns defined in each sequential run to incrementally range from 2 to 10. The optimum number of patterns was determined by graphically examining the Cubic Clustering Criterion statistic for where it peaked, and the Approximate Overall R-Squared statistic for where its rate of increase began to level or taper off. Five spill patterns were used for both spring and summer for fish that passed through the spillway (fig. 5), and an additional no-spill category was added for the bypass survival analysis. Twelve-hour intervals with very little total spill discharge (< 20 kcfs) were excluded from the spillway analysis and included in the no-spill category for the bypass analysis.

The individual spill bay discharge covariate for a fish's passage location was determined using the highest resolution of passage location possible given the hydrophone configuration for each year (table 6). When a specific spill bay passage assignment was not possible for a fish passing through one of the standard spill gates, we averaged individual spill bay discharges across two to seven combined spill bays. To minimize measurement error associated with this covariate, we excluded fish if the difference in spill bay discharge among the combined bays was greater than 3 kcfs. As a result, we removed 15 percent of the yearling Chinook salmon, 10 percent of the juvenile steelhead, 7 percent of the subyearling Chinook salmon, and 7 percent of the sockeye from the analysis.

Table 5. List of variables used in survival analyses of fish passing the McNary Dam spillway and bypass, 2004–09.

Type	Name	Definition
Group	Photoperiod	Day, night
Group	[1]Year	yyyy, year of study
Group	Passage location	North, middle, or south passage location at spillway
Group	Bay type	Type of spill bay (conventional or TSW)
Group	Spill pattern	Distribution of spill (north, south, or uniform)
Individual	Temperature	Average daily tailrace water temperature
Individual	Total discharge	Total river discharge at McNary Dam
Individual	Spillway discharge	Discharge through the spillway (all spill bays)
Individual	Spill bay discharge	Discharge through individual spill bays
Individual	Percent spill	Percentage of discharge through the spillway
Individual	Fish weight	Fish weight
Individual	[2]Tag burden	Tag weight/fish weight

[1]A secondary variable used to assess whether year could account for additional variation over and above the effect of other covariates.

[2]A secondary variable used in lieu of fish weight after all other variables were evaluated because of high correlation between tag burden and fish weight.

Table 6. Yearly resolution of spill bay passage location, Temporary Spillway Weir placement (T), and lateral division.

Year	Spill Bay Location																					
	South						Middle									North						
	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
2009			T								Spring								T			
2009			T	T							Summer											
2008			T	T																		
2007	T		T																			
2006																						
2005																						
2004																						

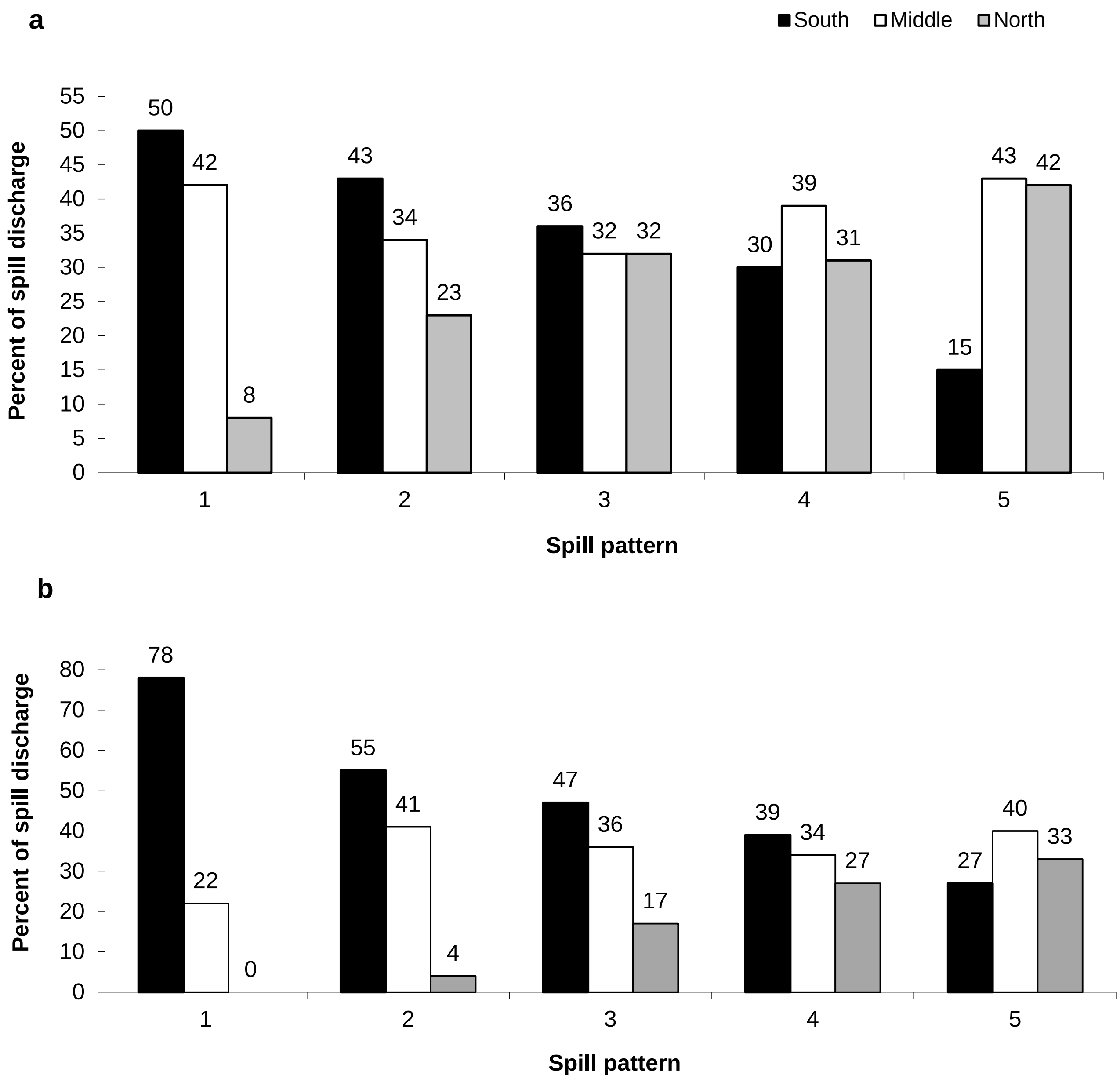

Figure 5. Percentage of spill discharge for each spill pattern during spring (a) and summer (b) study periods at McNary Dam, 2004–09. Black bars represent spill through south spill bays, white bars represent spill through middle spill bays, and gray bars represent spill through north spill bays. Numbers above bars represent percentage of spill discharge.

An initial step in the modeling process was to assign probabilities to detection histories that represent detections of fish downstream. For example, the possible histories for survival in this study included: 111, 101, 110, and 100, where a 1 represents detection at a telemetry array and a 0 represents non-detection. The first digit represents a fish that was released or that passed through a particular passage route, the second digit represents the first downstream detection array, and the last digit represents detection at the last detection array. The probabilities of these capture histories were then incorporated into a multinomial probability model to estimate model parameters using maximum likelihood methods. The model parameters included: $ø$, the probability of survival from dam passage through the spillway or bypass to the first downstream detection array; p, the probability of being detected at the first downstream detection array given the individual survived; and λ, the joint probability of surviving and being detected from the first downstream array to the next downstream array (fig. 6). The probabilities of the possible detection histories can be expressed as:

P_{111}: $ø p \lambda$

P_{101}: $ø(1 - p)\lambda$

P_{110}: $ø p(1 - \lambda)$

P_{100}: $(1 - ø) + ø(1 - p)(1 - \lambda)$, (1)

To express survival as a function of covariates, we used a logit link function, which models the logit of each parameter as a linear function of covariates. For example, a model of survival as a function of photoperiod and a continuous covariate, x, can be expressed as:

$ø(\text{photo} + xi) = \exp(\beta_0 + \beta_{\text{photo}} + \beta_1\, xi) / 1 + \exp(\beta_0 + \beta_{\text{photo}} + \beta_1\, xi)$, (2)

In this expression, β represents the intercept and slope coefficients. The logit link also was used for estimating our detection parameters. The logit link was used to estimate all model parameters because it constrains parameter estimates between 0 and 1, which is appropriate for probabilities. A quadratic term was included in models where there was potential for a unimodal curvilinear response of fish survival to a particular covariate. We found that adding this term to models never resulted in a significant effect, so we did not present the results.

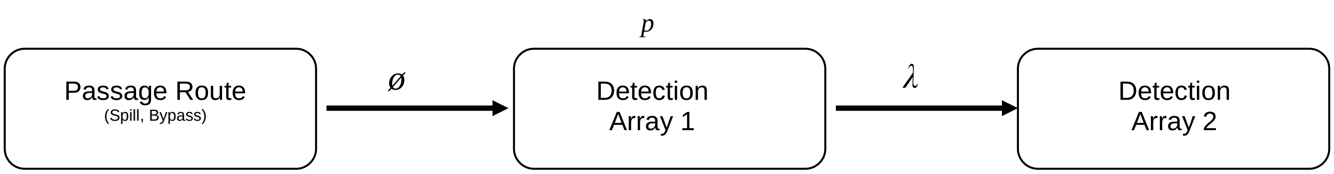

Figure 6. Schematic of the mark-recapture model used to estimate survival ($ø$) and detection probabilities (p) of juvenile salmonids passing through McNary Dam for releases during 2004–09.

To assess how well the covariates or environmental variables explained model parameters, Akaike's Information Criterion (AIC) (Akaike, 1973; Burnham and Anderson, 1998) was used for comparing models. AIC allowed us to measure how well the model fit relative to the number of parameters used in the model:

$$AIC = -2L + 2N, \quad (3)$$

where N is the number of parameters and L is the log-likelihood. Although our sample sizes were large, we used AIC_c

$$AIC_c = -2L + 2N + (2N\,(N + 1)/(n - N - 1))\ , \quad (4)$$

which is a modification for small sample sizes in relation to the number of parameters in a model where n is sample size. When sample sizes are large in relation to the number of parameters in a model, AIC_c is equivalent to AIC, thus AIC_c provides more flexibility when sample size varies over a large range. Further, AIC_c can be used to compare nested and non-nested models, as opposed to strictly using a Likelihood Ratio Test, which is restricted to nested models.

We interpreted ΔAIC_c values based on the recommendations of Burnham and Anderson (1998), where $\Delta AIC_c < 2$ between two models suggests no evidence that one of the models is best; $2 < \Delta AIC_c < 10$ suggests some evidence; and $\Delta AIC_c > 10$ suggests strong evidence that the model with the smaller AIC_c is the best model. Many of our model runs resulted in nested models having a $\Delta AIC_c < 2$. In these cases, candidate models were determined by examining the deviance or likelihood. If nested models differed by only one parameter and the deviance was nearly equal between models, then this suggested the additional parameter did not improve model fit. Therefore, we eliminated the model with the additional parameter from the candidate set. Model selection tables shown in the results of this report contain only models with $\Delta AIC_c<10$; however, appendixes A and B contain all candidate models for survival of fish passing through the spillway and bypass outfall, respectively, regardless of ΔAIC_c value.

We took a hierarchical approach to model selection by evaluating detection parameters and determining the best model using AIC_c similar to the strategy of Lebreton and others (1992). The best model for detection probabilities was used for all other analyses when examining survival. We began our model selection at the farthest downstream parameter, λ, and worked our way upriver (starting with λ and then p). We tested and incorporated the possibility that λ could be related to fish weight or tag burden into the detection probability model where the model fit was improved and then assessed survival of juvenile salmonids as a function of covariates. Various combinations of variables were created for each model to represent potential drivers, or previous hypotheses, as to which factors influence survival of juvenile salmonids as they migrate past McNary Dam. Although hypotheses were developed previously, selection procedures were used conceptually so that important hypotheses were not left out of the model set, which could occur without a systematic approach to hypotheses development (Collett, 2003). The effect of "study year" was then added to the best models to assess additional variation not explained by covariates. Variables that were highly correlated (for example, fish weight and tag burden, total discharge and spill discharge) were substituted into the best models with their correlate to assess which variable was more important or had more influence regarding model fit, but were not kept within the same model if they were highly correlated.

There are assumptions that are made when using mark-recapture models. For CJS models, these assumptions relate to inferences to the population of interest, error in interpreting acoustic signals, and statistical fit of the data to the structure of the model. The assumptions are:

1. Tagged individuals are representative of the population of interest.
2. Survival probabilities of tagged fish are the same as those of untagged fish. For example, the tagging procedures or detection of fish at downstream telemetry arrays should not influence survival or detection probabilities. If the tag negatively affected survival, then estimates of survival rates will be biased accordingly. In this study, tag burden was examined as a covariate.
3. All sampling events are instantaneous. That is, sampling should take place over a short distance relative to the distance between telemetry arrays so that the chance of mortality at a telemetry array is minimized. This assumption is necessary to attribute mortality correctly to a specific river reach. This assumption usually is satisfied by the location of telemetry arrays.
4. The fate of each tagged fish is independent of the fate of other tagged fish. Therefore, survival or mortality of one fish has no effect on the survival or mortality of the other fish.
5. The prior detection history of a tagged fish has no effect on its subsequent survival. This assumption could be violated if parts of the river are not monitored for tagged fish. For acoustic telemetry, this assumption usually is satisfied by the passive nature of detecting acoustic tags, by monitoring all routes of passage at a dam, and by monitoring the entire cross section of the river channel.
6. All tagged fish alive at a sampling location have the same detection probability. This assumption also could be violated as described in assumption 5, but usually is satisfied with acoustic telemetry by monitoring the entire cross section of the river channel.
7. All tags are identified correctly and the status of tagged fish (that is, alive or dead) is known without error. This assumes that fish do not lose their tags and that the tag is functioning when the fish is in the study area. Additionally, the assumption is that all detections are of live fish and that dead fish are not detected and interpreted as live (that is, false-positive detections). This assumption is addressed by releasing tagged, dead fish and seeing if the fish are detected at the detection arrays used to assess survival of juvenile salmonids. Tag life studies are performed in conjunction with field studies.

There are formal ways proposed by Burnham and others (1987) to test some of these assumptions, such as the independence of fate of individuals, fish in a group having equal survival and detection probabilities, and prior recapture history not influencing survival and detection probabilities downstream. However, these tests require three downstream detection sites that we did not have during all study years. Nonetheless, others have found that survival estimates generated using CJS models are robust to many violations of these assumptions (Skalski and others, 1998). Tag life studies and the release of tagged, dead fish were conducted during field studies (Adams and others, 1998, 2008; Adams and Counihan, 2009; Adams and Liedtke, 2009, 2010; Perry and others, 2006, 2007; Timko and others, 2007, 2008, 2010; Steig and others, 2007, 2008, 2009, 2010; and Sullivan and others, 2009).

Results

Yearling Chinook Salmon

Survival Analysis

The best supported spillway and bypass models for *p* and *λ* for yearling Chinook salmon included a year effect for both parameters (table 7). These models of *p* and *λ* were used for all other spillway and bypass survival analyses.

Table 7. Model selection results based on varying *λ* and *p* with respect to year for yearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. The Phi (*ø*) portion of the model was held constant for all models of *λ* and *p*. The best-fit model for *λ* was determined first and then used to assess the best-fit model for *p*. *ø*, the probability of survival from dam passage through a route to the first downstream detection array; *p*, the probability of being detected at the first downstream detection array given the individual survived; *λ*, the joint probability of surviving and being detected from the first downstream array to the next downstream array; g, all combinations of the photoperiod, passage location, bay type, spill pattern, and year group covariates; y, year; AIC_c, Akaike's Information Criterion]

No.	Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
		Spillway			
1	**ø(g) *p*(y) *λ*(y)**	**117**	**8,312.50**	**0.00**	**8,074.82**
2	ø(g) *p*(y) *λ*	112	8,709.94	397.45	8,482.58
3	ø(g) *p* *λ*(y)	112	9,047.15	734.65	8,819.78
		Bypass			
1	**ø(g) *p*(y) *λ*(y)**	**48**	**5,593.62**	**0.00**	**5,496.64**
2	ø(g) *p*(y) *λ*	43	5,727.26	133.64	5,640.47
3	ø(g) *p* *λ*(y)	43	6,168.51	574.88	6,081.71

Spillway survival of yearling Chinook salmon was best explained by the model that included tag burden, spill bay discharge, bay type, temperature, and the interaction between spill bay discharge and bay type (table 8). Tag burden and bay type were both negatively related to spillway survival, and the remaining covariates were positively related to spillway survival (table 9). The model that included tag burden, spill bay discharge, bay type, and temperature (but not the interaction between spill bay discharge and bay type) also was well supported with an AIC_c within 1.38 of the model that included the interaction, indicating no difference between the two models (table 8). Fifteen other models, all of which included tag burden, had AIC_c values within 10 units of the best model and, therefore, provide some explanation of spillway survival for yearling Chinook salmon (table 8). We found that spillway survival increased as spill bay discharge increased for both bay types, and that survival was higher for fish passing through conventional spill bays compared to TSW bays (fig. 7). Similarly, spillway survival increased as total discharge increased for all spill patterns. Survival was highest (94 percent or higher) for spill patterns that discharged the most spill through the north or south portions of the spillway (patterns 1 and 5), and least for spill patterns that discharged water more uniformly through all portions of the spillway (fig. 8).

The best-fit model for survival of fish passing through the juvenile bypass outfall included only the group covariate for photoperiod and was only slightly better (1.12 ΔAIC_c) than the intercept model (table 10). Bypass survival was lower during the day than at night (table 9). The only covariate associated with spill operations that we modeled that provided any support to bypass survival was spill pattern (table 10). The model that included photoperiod and spill pattern had an AIC_c value 5.51 units lower than the model with photoperiod alone, and the model that included only spill pattern had an AIC_c value 6.21 units lower than the best model. Based on these AIC_c values, spill pattern provided little explanation of variation in bypass survival for yearling Chinook salmon.

Table 8. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for yearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Q, discharge]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Tag burden + Spill bay Q + Bay type + Temperature + Spill bay Q*Bay type	**18**	**8,199.62**	**0.00**	**8,163.53**
Tag burden + Spill bay Q + Bay type + Temperature	**17**	**8,201.00**	**1.38**	**8,166.92**
Tag burden + Spill bay Q + Bay type	16	8,201.81	2.18	8,169.73
Tag burden + Total Q + Temperature	16	8,202.53	2.90	8,170.46
Tag burden + Spill bay Q + Temperature	16	8,202.70	3.08	8,170.63
Tag burden + Total Q + Temperature + Passage location	18	8,203.22	3.60	8,,167.13
Tag burden + Temperature	15	8,203.45	3.82	8,173.38
Tag burden + Total Q	15	8,203.86	4.24	8,173.80
Tag burden + Total Q + Passage location	17	8,203.99	4.37	8,169.91
Tag burden + Temperature + Passage location	17	8,204.42	4.80	8,170.34
Tag burden + Total Q + Spill pattern	19	8,205.03	5.40	8,166.93
Tag burden + Spill Q	15	8,206.33	6.71	8,176.27
Tag burden + Spill Q + Passage location	17	8,206.71	7.09	8,172.63
Tag burden + Spill pattern + Temperature	19	8,207.03	7.41	8,168.93
Tag burden + Spill pattern	18	8,207.95	8.32	8,171.86
Tag burden + Spill bay Q	15	8,208.43	8.81	8,178.37
Tag burden + Spill bay Q + Passage location	17	8,209.43	9.81	8,175.35

Table 9. Slope (Beta) coefficients, standard error, and 95-percent confidence limits of model parameters for yearling Chinook salmon passing McNary Dam, 2004–09.

[CL, confidence limit]

Variable	Beta	Standard error	Lower CL	Upper CL
		Spillway		
Intercept	2.338	0.677	1.011	3.666
Tag burden	-0.324	0.084	-0.488	-0.161
Spill bay discharge	0.114	0.049	0.019	0.210
Bay type	-0.992	0.305	-1.590	-0.394
Temperature	0.111	0.059	-0.004	0.227
Bay type*spill bay discharge	0.074	0.038	-0.001	0.149
		Bypass		
Intercept	3.009	0.227	2.563	3.455
Photoperiod (light)	-0.413	0.247	-0.898	0.072

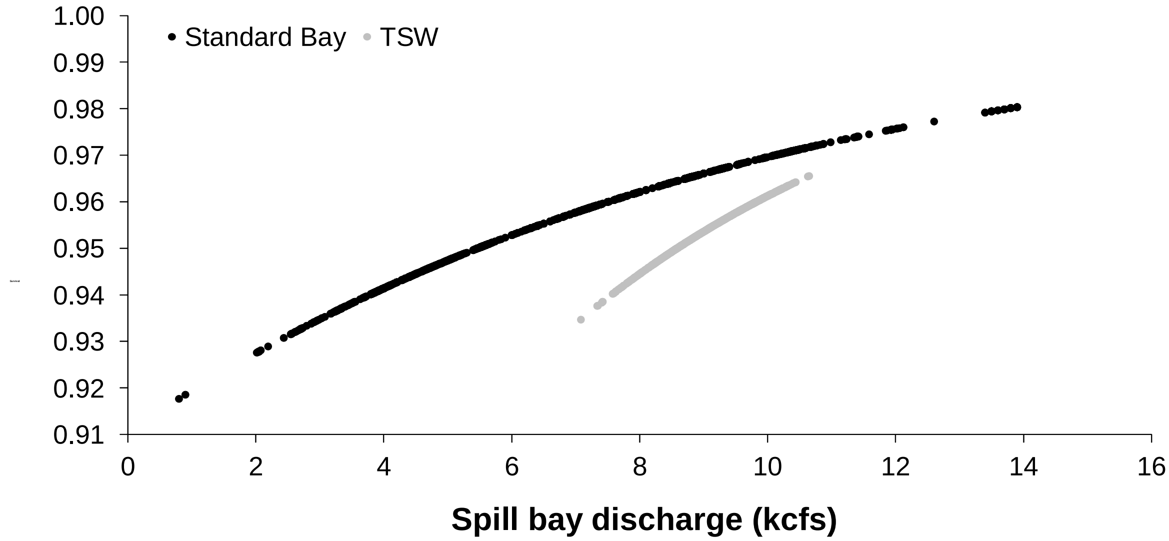

Figure 7. Survival of yearling Chinook salmon that passed through conventional spill bays (black plot) and the TSWs (gray plot) at McNary Dam in relation to spill bay discharge, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest.

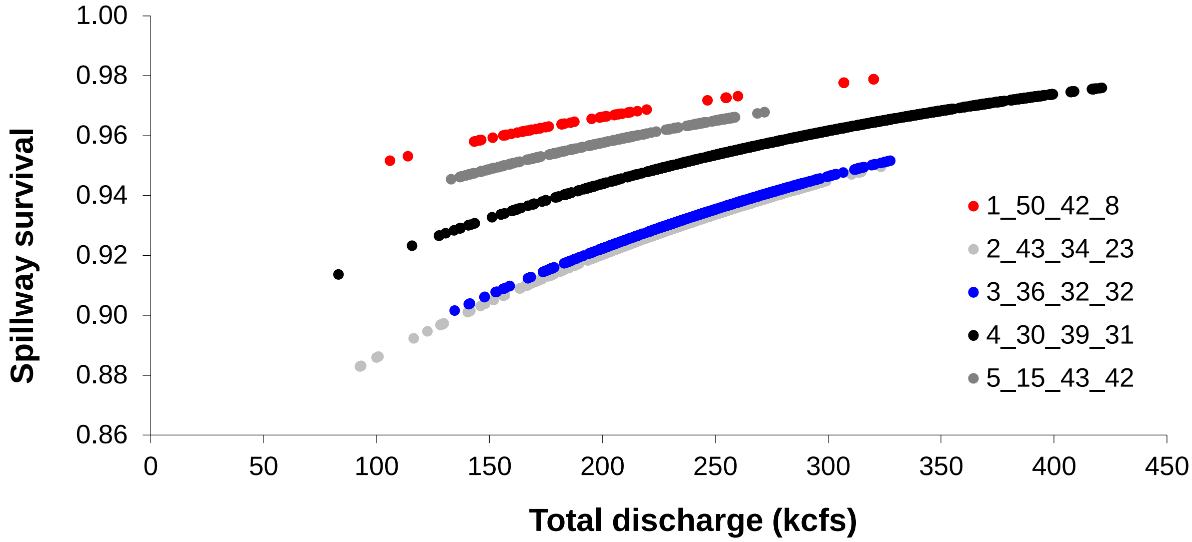

Figure 8. Spillway survival of yearling Chinook salmon in relation to total discharge for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

Table 10. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for yearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Photoperiod	**14**	**5,553.48**	**0.00**	**5,525.39**
Intercept	**13**	**5,554.60**	**1.12**	**5,528.52**
Photoperiod + Spill pattern	19	5,558.99	5.51	5,520.84
Spill pattern	18	5,559.69	6.21	5,523.55

Juvenile Steelhead

Survival Analysis

The best supported models for *p* and *λ* for juvenile steelhead included a year effect for both parameters. The fit of the *λ* models was further improved by the addition of the tag burden covariate for fish that passed through the spillway and the fish weight covariate for fish that passed through the juvenile bypass system (table 11).

The best-fit model for fish passing through the spillway included temperature, spillway discharge, and fish weight (table 12). Survival was negatively related to temperature, but positively related to spillway discharge and fish weight (table 13, fig. 9). The model that replaced spillway discharge with total discharge and spill pattern also was well supported (1.81 ΔAIC_c, table 12). Spillway survival increased as total discharge increased for all spill patterns, and spill patterns one and four provided the highest spillway survival (fig. 10). Four other models, all of which included temperature and fish weight, and three that included at least one covariate related to spillway operations, were within 4.5 AIC_c units, and therefore provided some support to variation in spillway survival. The addition of a year factor to five of the top six models improved the models substantially, decreasing ΔAIC_c by 5.45, 6.88, 7.62, 5.64, and 4.40, respectively (table 12).

The model that best explained survival of juvenile steelhead passing McNary Dam through the juvenile bypass system outfall included temperature and total discharge (table 14). Bypass survival was negatively related to increasing water temperature, but positively related to increasing total discharge (table 13). The second best model included temperature and spill discharge and was within 1.21 AIC_c of the best model (table 14).

Table 11. Model selection results based on varying *λ* and *p* with respect to year for juvenile steelhead at McNary Dam, 2004–09.

[The best-fit models are indicated in bold. The Phi (*ø*) portion of the model was held constant for all models of *λ* and *p*. The best-fit model for *λ* was determined first and then used to assess the best-fit model for *p*. *ø*, the probability of survival from dam passage through a route to the first downstream detection array; *p*, the probability of being detected at the first downstream detection array given the individual survived; *λ*, the joint probability of surviving and being detected from the first downstream array to the next downstream array; g, all combinations of the photoperiod, passage location, bay type, spill pattern, and year group covariates; y, year]

	Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
			Spillway		
1	***ø*(g*t) *p*(y) *λ*(y + tag burden)**	**114**	**6,579.59**	**0.00**	**6,347.36**
2	*ø***(g*t)** *p*(y) *λ*(y)	113	6,605.77	26.18	6,375.61
3	*ø***(g*t)** *p*(y) *λ*	108	6,659.25	79.66	6,439.46
4	*ø***(g*t)** *p* *λ*(y)	108	7,486.42	906.83	7,266.63
			Bypass		
1	***ø*(g) *p*(y) *λ*(y + fish weight)**	**49**	**2,609.71**	**0.00**	**2,509.61**
3	*ø***(g)** *p*(y) *λ*	42	2,663.70	53.99	2,578.16
2	*ø***(g)** *p*(y) *λ*(y)	47	2,694.79	85.08	2,512.35
4	*ø***(g)** *p* *λ*(y)	42	2,865.14	255.43	2,779.60

Table 12. Model selection for fish that passed through the spillway at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for juvenile steelhead, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Temperature + Spill discharge + Fish weight[1]	**17**	**6,464.37**	**0.00**	**6,430.27**
Temperature + Total discharge + Spill pattern + Fish weight[2]	**21**	**6,466.18**	**1.81**	**6,424.04**
Temperature + Total discharge + Percent spill + Fish weight[3]	18	6,466.72	2.35	6,430.61
Temperature + Total discharge + Spill pattern + Total discharge*Spill pattern + Fish weight[4]	25	6,467.26	2.89	6,417.05
Temperature + Spill discharge + Spill pattern + Fish weight	21	6,468.25	3.88	6,426.10
Temperature + Total discharge + Fish weight[5]	17	6,468.82	4.45	6,434.73
Temperature + Spill bay discharge + Spill pattern + Fish weight	21	6,471.93	7.56	6,429.79
Temperature + Spill pattern + Fish weight	20	6,473.18	8.81	6,433.05
Temperature + Spill discharge	16	6,473.82	9.45	6,441.73

[1]Addition of year to this model decreased AIC_c by 5.45.

[2]Addition of year to this model decreased AIC_c by 6.88.

[3]Addition of year to this model decreased AIC_c by 7.62.

[4]Addition of year to this model decreased AIC_c by 5.64.

[5]Addition of year to this model decreased AIC_c by 4.40.

Table 13. Slope (Beta) coefficients, standard error, and 95-percent confidence limits of model parameters for juvenile steelhead passing McNary Dam, 2004–09.

[CL, confidence limit. The addition of year improved model fit for spillway survival]

Variable	Beta	Standard error	Lower CL	Upper CL
Spillway				
Intercept	4.605	0.651	3.329	5.881
Temperature	-0.313	0.053	-0.417	-0.209
Fish weight	0.010	0.003	0.004	0.016
Spill discharge	0.009	0.002	0.004	0.013
Bypass				
Intercept	4.877	1.113	2.696	7.059
Temperature	-0.292	0.092	-0.472	-0.112
Total discharge	0.006	0.002	0.002	0.010

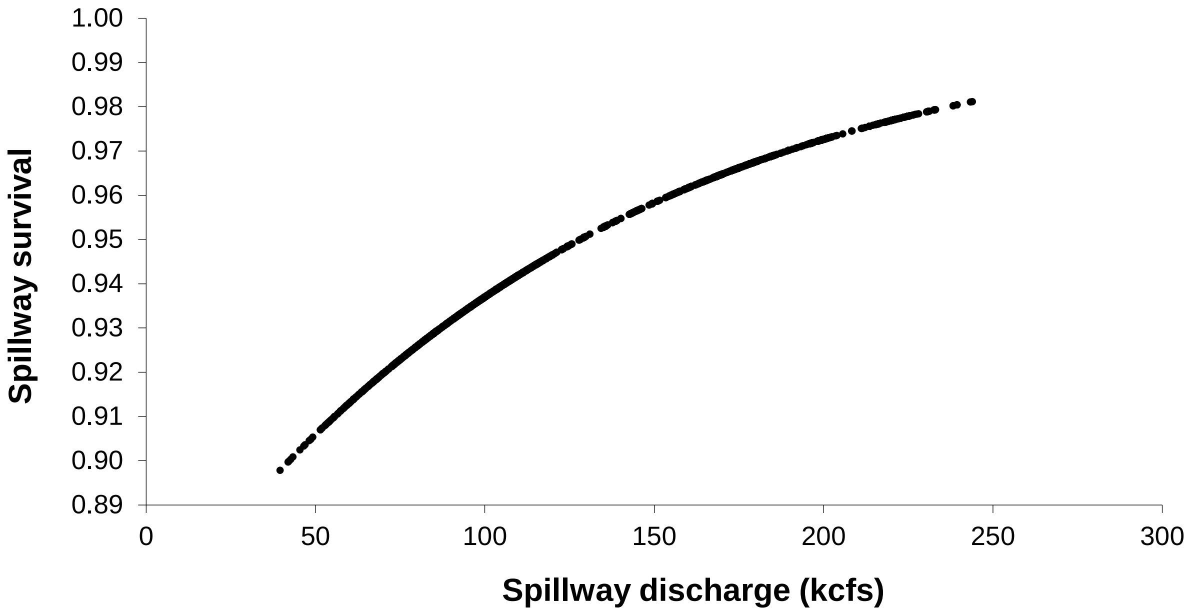

Figure 9. Spillway survival of juvenile steelhead in relation to spillway discharge at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest.

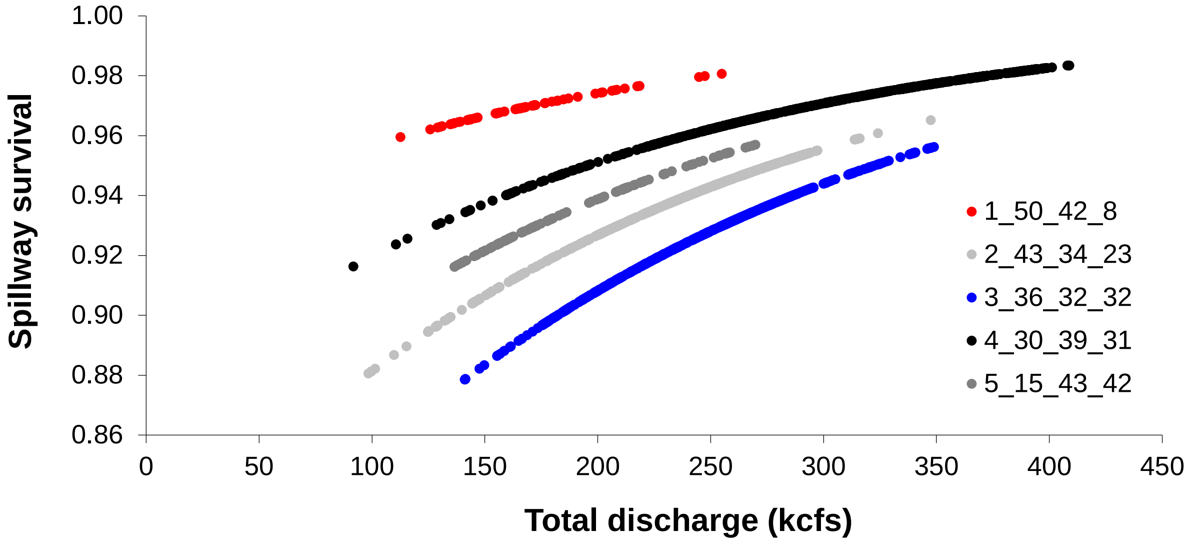

Figure 10. Spillway survival of juvenile steelhead in relation to total discharge for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

Table 14. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for juvenile steelhead, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Temperature + Total discharge	**16**	**2,570.27**	**0.00**	**2,538.04**
Temperature + Spill discharge	**16**	**2,571.48**	**1.21**	**2,539.25**
Temperature + Spill pattern + Total discharge	21	2,573.29	3.02	2,530.90
Temperature + Spill pattern	20	2,575.11	4.84	2,534.75
Temperature + Percent spill	16	2,576.55	6.28	2,544.32
Temperature	15	2,577.33	7.06	2,547.13
Spill discharge	15	2,577.35	7.08	2,547.15
Spill pattern	19	2,578.16	7.89	2,539.84
Spill pattern + Total discharge	20	2,578.49	8.22	2,538.14
Total discharge	15	2,578.69	8.42	2,548.49
Percent spill	15	2,580.22	9.95	2,550.02
Tag burden	15	2,581.26	10.99	2,551.05
Intercept	14	2,581.33	11.06	2,553.16

Subyearling Chinook Salmon

Survival Analysis

The best-supported spillway and bypass models for *p* and *λ* for subyearling Chinook salmon included a year effect for both parameters (table 15). These models of *p* and *λ* were used for all other spillway and bypass survival analyses.

The best model for describing survival of subyearling Chinook salmon passing through the spillway included spill pattern, tag burden, temperature, spill bay discharge, spillway discharge, and percentage of spill (table 16). Spillway survival was positively related to spill pattern 4 and spillway discharge, but negatively related to all other covariates (table 17). Replacing spillway discharge and percentage of spill in the top model with total discharge resulted in essentially equal support (0.33 ΔAIC_c, table 16). Likewise, replacing tag burden with fish weight or spill bay Q with bay type provided models that fit the data well (1.52 ΔAIC_c and 0.68 ΔAIC_c, respectively, table 16). Spillway survival was highest for spill patterns 4 and 5, which distributed spill relatively uniformly among the three portions of the spillway, and lowest for spill patterns that discharged more water through the southern spill bays (figs. 11, 12, and 13). Spillway survival decreased for all spill patterns as percentage of spill and spill bay discharge increased (figs. 11 and 13). Conversely, spillway survival increased for all spill patterns as total discharge increased (fig. 12).

Bypass survival of subyearling Chinook salmon was explained best by the model that included temperature, spill pattern, fish weight, total discharge, and the interaction between spill pattern and total discharge (table 18). Bypass survival was negatively related to temperature, and spill patterns 1, 2, and 5, but was positively related to fish weight, total discharge, and spill patterns 3 and 4 (table 17, figs. 14 and 15). The addition of year to the best model decreased AIC_c by 2.39 units. Bypass survival decreased as total discharge increased for the interaction between spill pattern and total discharge for patterns 3 and 4, increased for patterns 1, 2 and 5, and was constant during no-spill conditions (fig. 14). Bypass survival decreased for all spill patterns as temperature increased, and survival was highest for spill patterns 2 and 4 (fig. 15).

Table 15. Model selection results based on varying *λ* and *p* with respect to year for subyearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. The Phi (*ø*) portion of the model was held constant for all models of *λ* and *p*. The best-fit model for *λ* was determined first and then used to assess the best-fit model for *p*. *ø*, the probability of survival from dam passage through a route to the first downstream detection array; *p*, the probability of being detected at the first downstream detection array given the individual survived; *λ*, the joint probability of surviving and being detected from the first downstream array to the next downstream array; g, all combinations of the photoperiod, passage location, bay type, spill pattern, and year group covariates; y, year]

	Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
			Spillway		
1	***ø*(g) *p*(y) *λ*(y)**	**123**	**8,544.86**	**0.00**	**8,294.55**
2	*ø*(g) *p*(y) *λ*	120	8,621.33	76.46	8,377.23
3	*ø*(g) *p* *λ*(y)	120	9,274.83	729.97	9,030.73
			Bypass		
1	***ø*(g) *p*(y) *λ*(y)**	**57**	**4,124.33**	**0.00**	**4,008.13**
2	*ø*(g) *p*(y) *λ*	52	4,192.13	67.80	4,086.30
3	*ø*(g) *p* *λ*(y)	52	4,391.08	266.75	4,285.25

Table 16. Model selection for fish that passed through the spillway at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for subyearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Q, discharge; PassLoc, passage location; Temp, temperature]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Spill pattern + Tag burden + Temp + Spill bay Q + Spill Q + Percent spill	**20**	**8,406.22**	**0.00**	**8,366.10**
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q	**19**	**8,406.55**	**0.33**	**8,368.45**
Spill pattern + Tag burden + Temp + Spill bay Q + Spill Q + Percent spill + PassLoc	**22**	**8,406.59**	**0.37**	**8,362.45**
Spill pattern + Tag burden + Temp + Bay type + Total Q	**19**	**8,406.90**	**0.68**	**8,368.80**
Spill pattern + Fish weight + Temp + Spill bay Q + Total Q	**19**	**8,407.74**	**1.52**	**8,369.64**
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q + Spill pattern*Total Q	**23**	**8,408.18**	**1.97**	**8,362.03**
Spill pattern + Tag burden + Temp + Total Q	18	8,408.57	2.35	8,372.47
Spill pattern + Tag burden + Temp + Bay type + Total Q + Total Q*spill pattern	23	8,408.65	2.44	8,362.50
Tag burden + Temp + Bay type + Total Q	15	8,410.22	4.00	8,380.15
Spill pattern + Temp + Spill bay Q + Total Q	18	8,410.46	4.25	8,374.37
Spill pattern + Temp + Spill bay Q + Total Q + PassLoc	20	8,410.51	4.29	8,370.39
Spill pattern + Temp + Bay type + Total Q	18	8,410.64	4.42	8,374.54
Spill pattern + Temp + Spill bay Q + Spill Q + Percent spill	19	8,410.67	4.45	8,372.56
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q + Spill pattern*Spill bay Q	23	8,411.15	4.93	8,365.00

Table 16. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for subyearling Chinook salmon, 2004–09.—Continued

[Q, discharge; PassLoc, passage location; Temp, temperature]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Tag burden + Temp + Spill bay Q + Spill Q + Percent spill	16	8,411.27	5.05	8,379.19
Spill pattern + Temp + Bay type + Total Q + PassLoc	20	8,411.31	5.10	8,371.20
PassLoc + Temp + Spill bay Q + Spill Q + Percent spill + Tag burden	18	8,411.64	5.42	8,375.54
Tag burden + Temp + Spill Q + Total Q + PassLoc + PassLoc*Spill Q	19	8,411.67	5.45	8,373.56
Tag burden + Temp + Spill Q + Total Q	15	8,411.74	5.53	8,381.68
Tag burden + Temp + Spill Q + Total Q + PassLoc	17	8,412.35	6.13	8,378.27
Spill pattern + Temp + Total Q	17	8,412.42	6.21	8,378.34
Tag burden + Temp + Spill bay Q + Spill Q + Percent spill + PassLoc + PassLoc*Spill bay Q	20	8,412.64	6.43	8,372.53
Temp + Bay type + Total Q	14	8,414.26	8.04	8,386.20
Temp + Spill bay Q + Spill Q + Percent spill	15	8,415.37	9.15	8,385.30
Temp + Bay type + Total Q + PassLoc	16	8,415.58	9.36	8,383.50
Temp + Spill Q + Total Q + PassLoc + PassLoc*Spill Q	18	8,415.63	9.41	8,379.53
Temp + Spill bay Q + Spill Q + Percent spill + PassLoc	17	8,415.65	9.43	8,381.56

Table 17. Slope (β) coefficients, standard error, and 95-percent confidence limits of model parameters for subyearling Chinook salmon passing McNary Dam, 2004–09.

[CL, confidence limit. The addition of year improved model fit for bypass survival]

Variable	***β***	Standard Error	Lower CL	Upper CL
		Spillway		
Intercept (spill pattern 2)	8.054	1.212	5.679	10.429
Spill pattern 4	0.313	0.173	-0.026	0.651
Spill pattern 5	-0.372	0.172	-0.710	-0.035
Spill pattern 1	-0.480	0.220	-0.912	-0.048
Spill pattern 3	-1.212	0.592	-2.372	-0.052
Temperature	-0.235	0.055	-0.343	-0.128
Spill discharge	0.013	0.004	0.006	0.021
Spill bay discharge	-0.048	0.024	-0.095	0.000
Percent spill	-0.033	0.009	-0.050	-0.016
Tag burden	-0.170	0.068	-0.303	-0.038
		Bypass		
Intercept	9.271	1.901	5.545	12.997
Temperature	-0.434	0.082	-0.595	-0.274
Fish weight	0.025	0.016	-0.007	0.057
Total discharge	0.001	0.004	-0.008	0.009
Spill pattern 1	-0.842	1.758	-4.288	2.604
Spill pattern 2	-1.368	1.178	-3.676	0.941
Spill pattern 3	6.118	7.192	-7.979	20.214
Spill pattern 4	2.807	0.996	0.854	4.759
Spill pattern 5	-0.956	1.227	-3.361	1.450
Spill pattern 1*total discharge	0.003	0.011	-0.018	0.024
Spill pattern 2*total discharge	0.009	0.007	-0.005	0.022
Spill pattern 3*total discharge	-0.038	0.039	-0.113	0.038
Spill pattern 4*total discharge	-0.011	0.005	-0.021	-0.001
Spill pattern 5*total discharge	0.006	0.007	-0.009	0.020

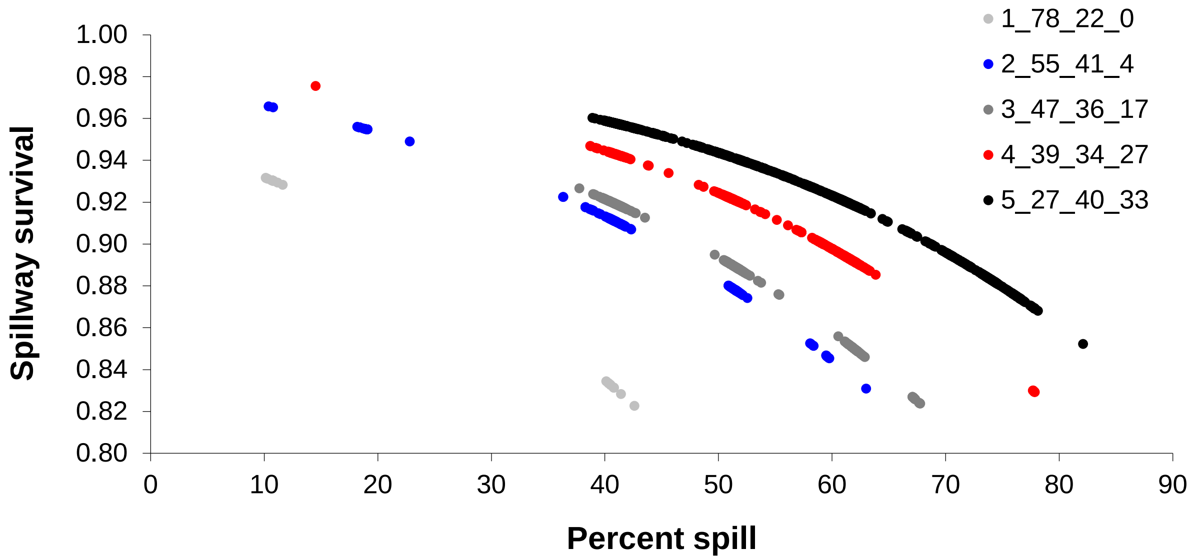

Figure 11. Spillway survival of subyearling Chinook salmon in relation to percent spill for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

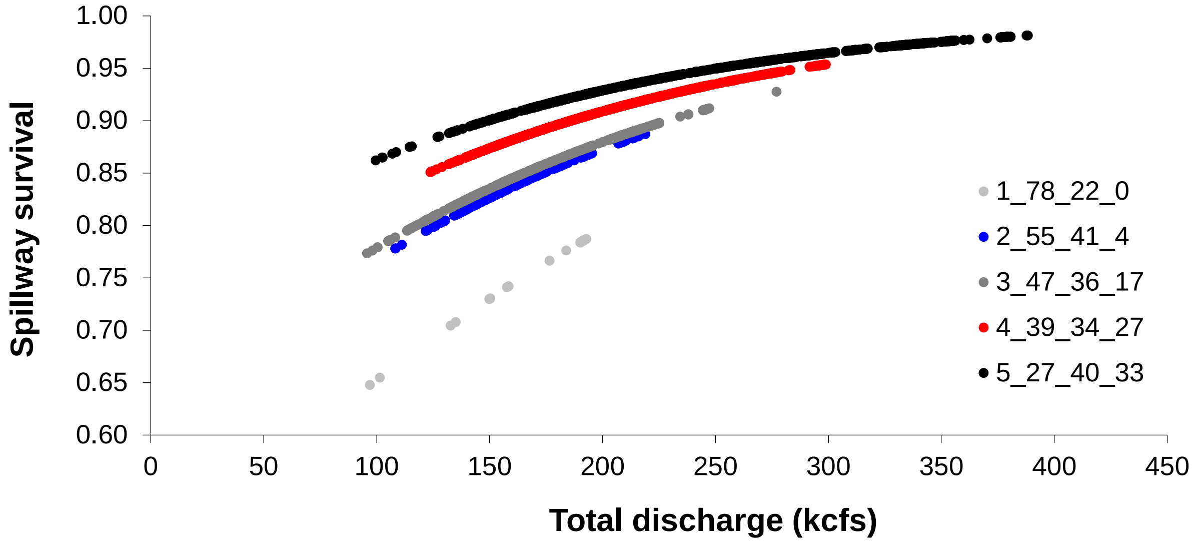

Figure 12. Spillway survival of subyearling Chinook salmon in relation to total discharge for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

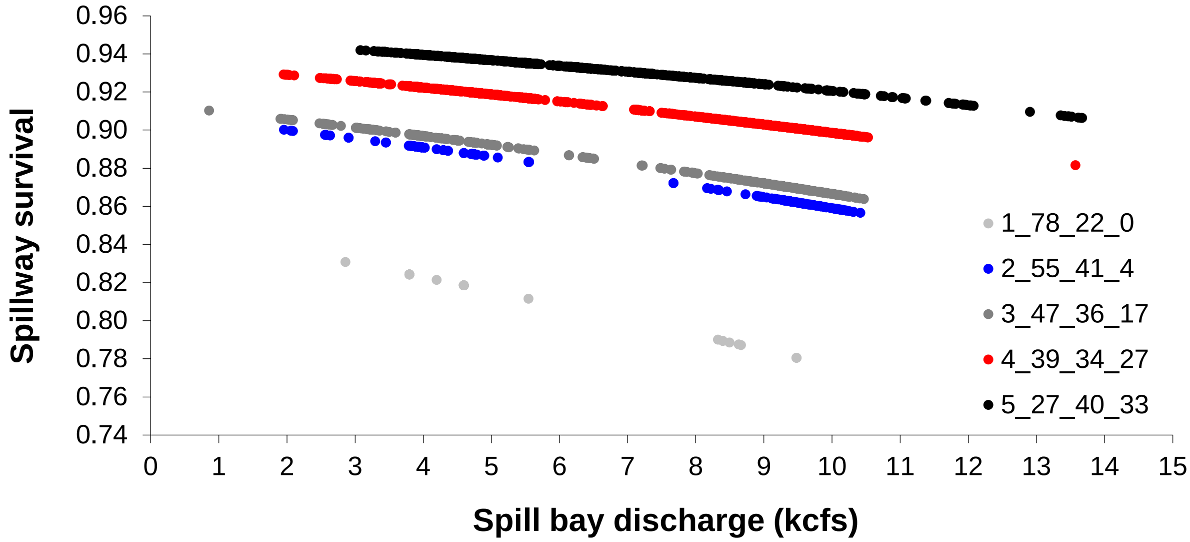

Figure 13. Spillway survival of subyearling Chinook salmon in relation to total discharge for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

Table 18. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for subyearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Q, discharge]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Temperature + Spill pattern + Fish weight + Total Q + Spill pattern*Total Q[1]	**26**	**4,062.74**	**0.00**	**4,010.28**
Temperature + Spill pattern + Total Q + Spill pattern*Total Q	**25**	**4,063.24**	**0.50**	**4,012.81**
Temperature + Spill pattern + Fish weight	20	4,065.41	2.67	4,025.13
Temperature + Spill pattern	19	4,066.09	3.35	4,027.84
Temperature + Fish weight	15	4,067.41	4.67	4,037.25
Temperature	14	4,067.56	4.82	4,039.43

[1]Addition of year to this model decreased AIC_c by 2.39.

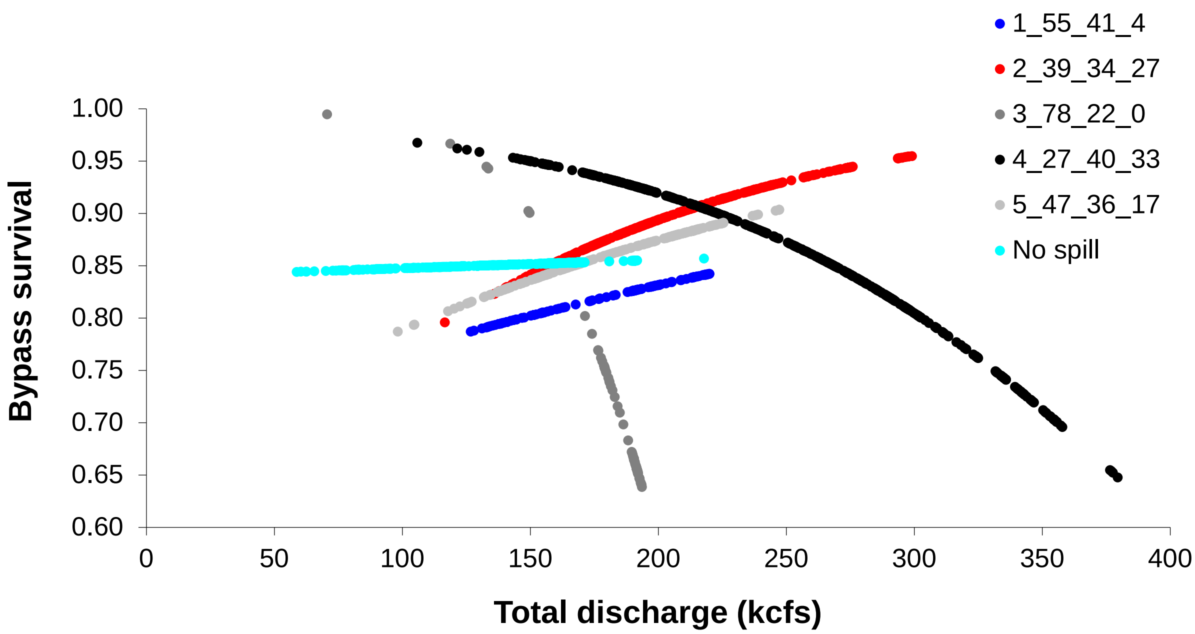

Figure 14. Bypass survival of subyearling Chinook salmon in relation to total discharge, with an interaction between spill pattern and total discharge, for each spill pattern at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

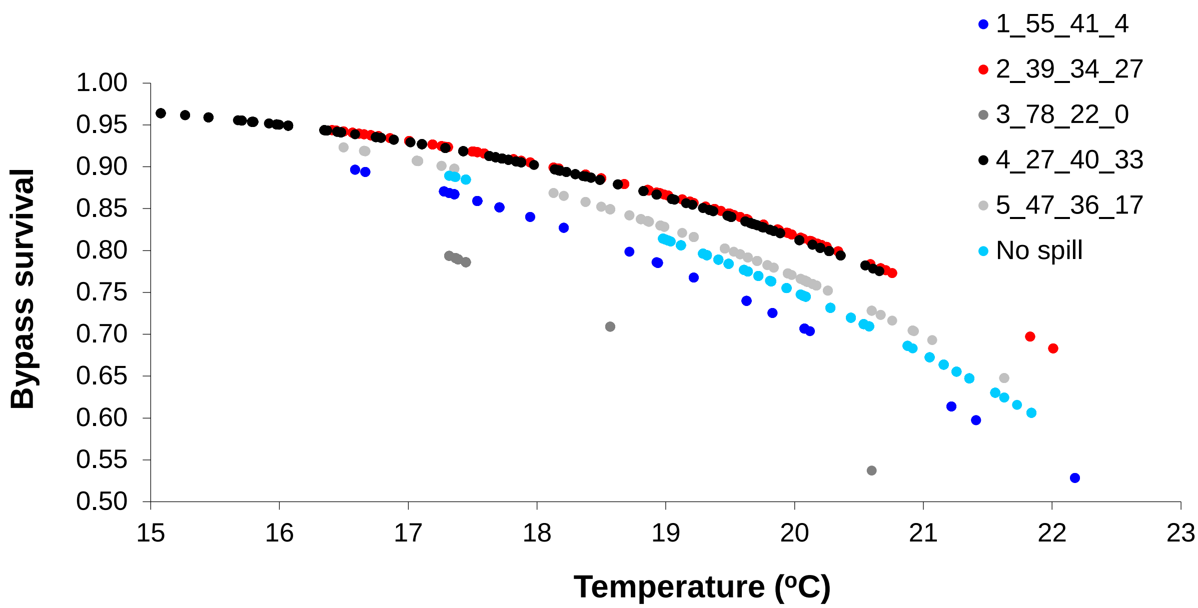

Figure 15. Bypass survival of subyearling Chinook salmon in relation to water temperature at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest. Legend text identifies the spill pattern number followed by the associated percentage of spill discharge through the south, middle, and north portions of the spillway, respectively.

Sockeye Salmon

Survival Analysis

Initial analyses of λ and *p* models for sockeye salmon passing through the spillway indicated that λ was best fit with year and tag burden covariate effects and *p* was best fit with a year effect (table 19). However, because of low downstream detection probabilities for sockeye salmon in most years, survival probabilities for many models, including spill pattern, using this *p* model were not estimable. In order to analyze the effect of spill pattern on survival, we chose to use a model of λ and *p* with only the spill pattern effect for the analyses.

The best model for describing survival of sockeye salmon passing through the spillway included passage location, spill discharge, temperature, and tag burden (table 20). Spillway survival was positively related to passage location and temperature, but negatively related to spill discharge and tag burden (table 21). The model that replaced spill discharge with total discharge and percentage of spill also was well supported (1.83 ΔAIC_c, table 20). The addition of year to the top model improved the model substantially, decreasing ΔAIC_c by 109.61 (table 20). Regardless of spill passage location, spillway survival decreased as spillway discharge or total discharge increased, and survival was highest for fish passing through north spill bays and lowest for fish passing through the middle portion of the spillway (figs. 16 and 17). Spillway survival was more than 98 percent for all spill passage locations at 75 kcfs spillway discharge and decreased to between 81 and 92 percent, depending on spill-passage location (fig. 16). Spillway survival was 96 percent or more for all spill passage locations at about 200 kcfs total discharge, but steadily decreased to between 86 and 94 percent at 425 kcfs (fig. 17).

Table 19. Model selection results for sockeye salmon passing through the spillway based on varying λ and *p* with respect to year, 2004–09.

[The best-fit models are indicated in bold. The Phi (ø) portion of the model was held constant for all models of λ and *p*. The best-fit model for λ was determined first and then used to assess the best-fit model for *p*. ø, the probability of survival from dam passage through a route to the first downstream detection array; *p*, the probability of being detected at the first downstream detection array given the individual survived; λ, the joint probability of surviving and being detected from the first downstream array to the next downstream array; g, all combinations of the photoperiod, passage location, bay type, spill pattern, and year group covariates; y, year]

	Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
1	**ø(g) *p*(y) λ(y + tag burden)**	**54**	**3,945.89**	**0.00**	**3,836.57**
2	ø(g) *p*(y) λ(y)	53	3,949.13	3.25	3,841.87
3	ø(g) *p*(y) λ	50	4,015.40	69.52	3,914.28
4	ø(g) *p* λ(y)	50	5,721.43	1,775.54	5,620.30

Table 20. Model selection for fish that passed through the spillway at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for sockeye salmon, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Passage location + Spill discharge + Temperature + Tag burden[1]	**13**	5,171.48	0.00	5,145.40
Passage location + Total discharge + Temperature + Percent spill + Tag burden	**14**	5,173.31	1.83	5,145.22
Passage location + Total discharge + Temperature + Tag burden	13	5,174.16	2.68	5,148.08
Passage location + Percent spill + Temperature + Tag burden	14	5,175.61	4.13	5,147.52
Passage location + Spill discharge + Tag burden	12	5,178.99	7.51	5,154.92
Spill discharge + Temperature + Tag burden	11	5,179.32	7.84	5,157.26
Total discharge + Temperature + Percent spill + Tag burden	12	5,181.19	9.71	5,157.12

[1]Addition of year to this model decreased AIC_c by 109.606.

Table 21. Slope (β) coefficients, standard error, and 95-percent confidence limits of model parameters for sockeye salmon passing through the spillway at McNary Dam, 2004–09.

[CL, confidence limit]

Variable	β	Standard error	Lower CL	Upper CL
Intercept (middle passage location)	1.517	1.861	-2.130	5.164
North passage location	0.755	0.303	0.162	1.349
South passage location	0.448	0.164	0.127	0.769
Spill discharge	-0.014	0.003	-0.019	-0.008
Temperature	0.379	0.123	0.137	0.621
Tag burden	-0.439	0.082	-0.601	-0.278

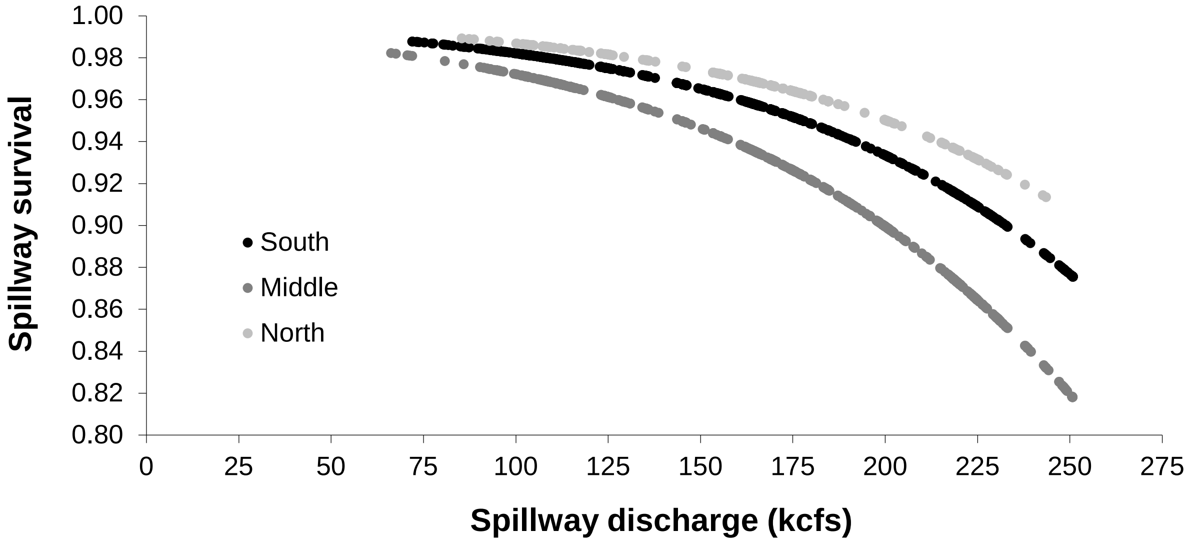

Figure 16. Spillway survival of sockeye salmon in relation to spillway discharge for each spillway passage location at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest.

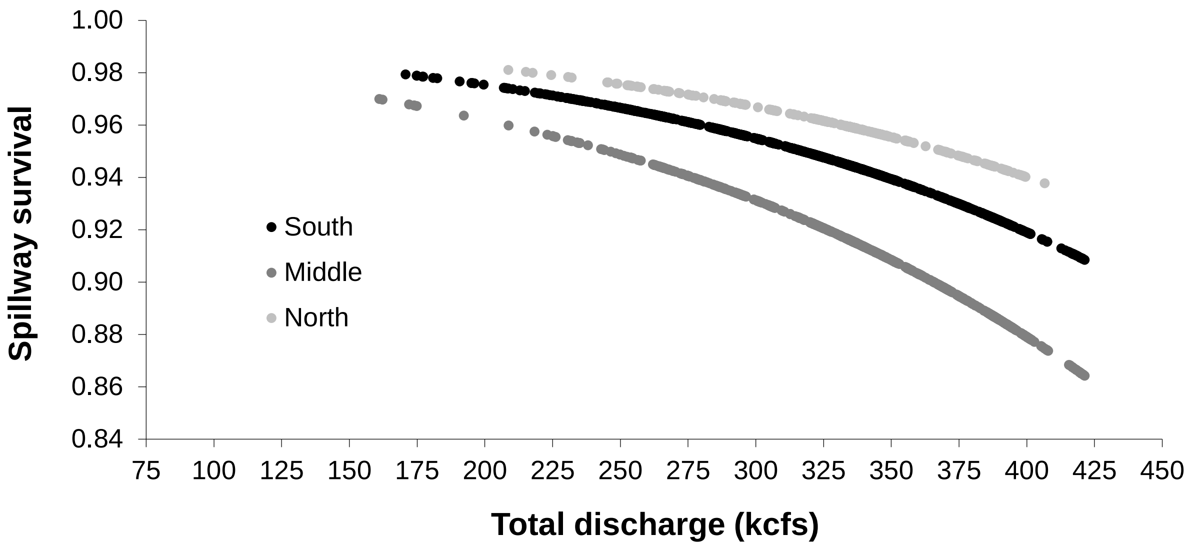

Figure 17. Spillway survival of sockeye salmon in relation to total discharge for each spillway passage location at McNary Dam, 2004–09. Other covariates in the model were held constant at their mean value to examine the relationship to the variable of interest.

Discussion

Spillway Survival

This analysis provided many models that explained variation in spillway survival of juvenile salmonids passing McNary Dam. Models supported by the data included spillway-related variables, as well as other variables. Predominant variables unrelated to spill bay operations that influenced spillway survival were water temperature, tag burden, and total discharge. Water temperature was a factor in nearly all supported models for all species with survival being inversely related to increasing temperatures. Tag burden also was a factor in nearly all supported models for all species except juvenile steelhead, and also was negatively related to survival. Although tag burden was not a supported factor in models for steelhead, fish weight was supported in most models for steelhead. Total discharge was not a factor in the best models for spillway survival for yearling Chinook salmon, but was a factor in many supportive models for juvenile steelhead, subyearling Chinook salmon, and sockeye salmon.

Predominant variables related to spill bay operations that influenced spillway survival were spill pattern, spillway discharge, spill bay discharge, bay type, and spill passage location. The combination of these factors in the models, and the extent to which they influenced survival, varied by species. Both spill bay discharge and bay type were factors in the best three models for yearling Chinook salmon. Spillway survival was positively related to an increase in spill bay discharge. Survival was higher for yearling Chinook salmon passing through conventional spill bays, compared to TSW bays, for all spill bay discharge levels. Although spill pattern was not a factor in models for yearling Chinook salmon, we analyzed spillway survival by spill pattern for comparison with other species and found that spill pattern 1 (predominantly south spill) provided the highest survival, similar to steelhead. The addition of a year factor did not improve any models for yearling Chinook salmon, suggesting that the covariates included in the models adequately captured the factors that cause year-to-year variation in survival.

The best model for steelhead included spillway discharge that was positively related to spillway survival. The next best model (within 1.81 AIC_c) replaced spillway discharge with spill pattern and total discharge. Similar to yearling Chinook salmon, spillway survival increased as total discharge increased, and survival was highest for spill pattern 1, which discharged spill predominantly through the south portion of the spillway. The addition of a year factor improved the top three models for steelhead, indicating there are some other variables not included in our analysis that might be influencing year-to-year variation in survival for steelhead (for example, fish condition or disease).

Spill pattern was the most predominant factor related to spill bay operations in supportive models for subyearling Chinook salmon spillway survival, followed by spill bay discharge, spill discharge, and percentage of spill. We found that spillway survival decreased for subyearling Chinook salmon as percentage of spill or spill bay discharge increased. Conversely, spillway survival increased as total discharge increased. Uniform spill patterns (patterns 4 and 5) provided higher survival than spill patterns that discharged most water through southern spill bays (patterns 1–3), and pattern 5 provided the highest survival. This result for summer migrating subyearling Chinook salmon was the opposite of what we found for spring migrants, which had higher survival for southern spill patterns. The addition of a year factor to the best models did not explain any further variability in spillway survival for subyearling Chinook salmon.

The variables related to spill bay operations that were in the best models for sockeye salmon included spillway passage location and spillway discharge. Spillway survival was negatively related to an increase in both spillway discharge and total discharge. Spillway survival was highest for sockeye salmon passing through the north portion of the spillway, followed by the middle and south locations. The addition of a year factor improved the best model for sockeye salmon, indicating there are some other variables not included in our analysis that might be influencing year-to-year variation in spillway survival. Because sockeye salmon, unlike the other species, were released 167–358 km upstream of McNary Dam, tag life may have been an issue with this species. Obviously, maximum travel times of tagged study fish should be shorter than the minimum tag life of tags used in the study. We found that maximum travel times of fish detected at the first site downstream of McNary Dam did not exceed the expected tag life for tags used in 2008 and 2009 (17 and 22 days, respectively). However, maximum travel times did exceed tag life for tags used in 2006 and 2007 (14 days). This suggests the likelihood that there were some tagged fish for which tags expired prematurely, indicating the potential for bias in survival estimates for sockeye salmon. It also provides a possible explanation for why year improved the best model for spillway survival.

Bypass Survival

Compared to models for spillway survival, fewer models were identified by this analysis that explain variation in survival of juvenile salmonids passing through the juvenile bypass system outfall at McNary Dam. Further, few models contained covariates related to spill bay operations. Photoperiod was the only factor in the best and only model that had support for bypass survival of yearling Chinook salmon. No other models were within 2 AIC_c units except for the intercept model (1.12 ΔAIC_c). Bypass survival of yearling Chinook salmon was lower during the day, compared to night, which is consistent with results reported by Adams and others (2011). Temperature was a predominant variable in all models describing bypass survival for both juvenile steelhead and subyearling Chinook salmon, similar to models for spillway survival. Spillway discharge and spill pattern were the only covariates related to spill bay operations that were present in supportive models for bypass survival of juvenile steelhead and subyearling Chinook salmon, respectively. Spillway discharge was found only in the second-best model for juvenile steelhead, and spill pattern was a predominant factor for subyearling Chinook salmon bypass survival in the top four models.

Spillway and Bypass Survival

The results of these analyses, while they were not designed to yield predictive models, can be used to help develop dam-operation strategies that optimize juvenile salmonid survival. For example, increasing total discharge typically had a positive effect on both spillway and bypass survival for all species except sockeye salmon. Likewise, an increase in spill bay discharge improved spillway survival for yearling Chinook salmon, and an increase in spillway discharge positively affected spillway survival for juvenile steelhead. The strong positive relation between spill and survival indicates that increasing the amount of water through the spillway is one strategy that could be used to improve spillway survival for yearling Chinook salmon and juvenile steelhead. However, increased spill did not improve spillway survival for subyearling Chinook salmon and sockeye salmon. Our results indicate that a uniform spill pattern would provide the highest spillway survival and bypass survival for subyearling Chinook salmon. Conversely, a predominantly south spill pattern provided the highest spillway survival for yearling Chinook salmon and juvenile steelhead. Although spill pattern was not a factor for spillway survival of sockeye salmon, spill bay operations that optimize passage through the north and south spill bays maximized spillway survival for this species. Bypass survival of yearling Chinook salmon could be improved by optimizing conditions to facilitate bypass passage at night, but the method to do so is not apparent from this analysis because photoperiod was the only factor affecting bypass survival based on the best and only supported model. Bypass survival of juvenile steelhead would benefit from lower water temperatures and increased total and spillway discharge. Likewise, subyearling Chinook salmon bypass survival would improve with lower water temperature and increased total discharge with a uniform spill pattern. When total discharge is high (greater than 200 kcfs), there may be a benefit to having more of the flow in the spillway discharged in the bays closest to the powerhouse (south spill). This spill pattern may inhibit the potential for an eddy that could cause fish passing through the bypass pipe to be pulled back upstream into the tailrace of the powerhouse. When total discharge is low (less than 200 kcfs) and the amount of water passing through the powerhouse is proportionally higher than water passing the spillway, survival may be improved by having a uniform spill pattern compared to a pattern that passed more water through the southern spill bays. Having more water passing through the southern spill bays when the predominant flow is being discharged through the powerhouse may cause eddies in the north portion of the spillway and could cause a decrease in survival.

These analyses provided a unique opportunity to examine data from multiple years of research to investigate factors influencing spillway and bypass survival at McNary Dam. By first using statistical models to select among variables hypothesized to influence survival, and then quantifying the magnitude of the effects, we were able to examine how changes to dam operations might positively or negatively influence survival. This is critical information that managers need to develop long-term operational plans. Although development of predictive models was beyond the scope of our analysis, the relations we identified could be used to develop simulation models to gauge the effect of management actions on dam survival.

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Appendix A: All Candidate Models Examined for Spillway Survival

Table A1. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for yearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Q, discharge]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Tag burden + Spill bay Q + Bay type + Temperature + Spill bay Q*Bay type	**18**	**8,199.62**	**0.00**	**8,163.53**
Tag burden + Spill bay Q + Bay type + Temperature	**17**	**8,201.00**	**1.38**	**8,166.92**
Tag burden + Spill bay Q + Bay type	16	8,201.81	2.18	8,169.73
Tag burden + Total Q + Temperature	16	8,202.53	2.90	8,170.46
Tag burden + Spill bay Q + Temperature	16	8,202.70	3.08	8,170.63
Tag burden + Spill bay Q + Bay type + Temperature + Spill bay Q*Bay type + Year	23	8,203.17	3.54	8,157.02
Tag burden + Total Q + Temperature + Passage location	18	8,203.22	3.60	8,167.13
Tag burden + Temperature	15	8,203.45	3.82	8,173.38
Tag burden + Total Q	15	8,203.86	4.24	8,173.80
Tag burden + Total Q + Passage location	17	8,203.99	4.37	8,169.91
Tag burden + Spill bay Q + Bay type + Temperature + Year	22	8,204.20	4.58	8,160.07
Tag burden + Temperature + Passage location	17	8,204.42	4.80	8,170.34
Tag burden + Total Q + Spill pattern	19	8,205.03	5.40	8,166.93
Tag burden + Spill Q	15	8,206.33	6.71	8,176.27
Tag burden + Spill Q + Passage location	17	8,206.71	7.09	8,172.63
Tag burden + Total Q + Temperature + Year	21	8,206.87	7.24	8,164.74
Tag burden + Spill pattern + Temperature	19	8,207.03	7.41	8,168.93
Tag burden + Spill pattern	18	8,207.95	8.32	8,171.86

Table A1. Model selection for fish that passed through the spillway at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for yearling Chinook salmon, 2004–09.—Continued

[Q, discharge]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Tag burden + Spill bay Q	15	8,208.43	8.81	8,178.37
Tag burden + Spill bay Q + Passage location	17	8,209.43	9.81	8,175.35
Spill pattern + Fish weight	18	8,209.85	10.23	8,173.76
Tag burden + Bay type	15	8,211.71	12.09	8,181.65
Tag burden	14	8,212.33	12.71	8,184.28
Tag burden + Passage location	16	8,212.50	12.88	8,180.43
Temperature	14	8,214.55	14.93	8,186.50
Spill bay Q + Bay type	15	8,215.15	15.52	8,185.09
Passage location + Temperature	16	8,215.37	15.74	8,183.30
Bay type + Fish weight	15	8,215.97	16.35	8,185.91
Spill pattern	17	8,216.99	17.36	8,182.91
Fish weight	14	8,217.27	17.64	8,189.21
Total Q	14	8,218.38	18.75	8,190.32
Total Q + Passage location	16	8,218.60	18.98	8,186.53
Spill bay Q	14	8,218.90	19.27	8,190.84
Spill Q	14	8,219.86	20.24	8,191.81
Spill Q + Passage location	16	8,220.08	20.46	8,188.01
Spill bay Q + Passage location	16	8,220.38	20.76	8,188.31
Intercept only	13	8,220.45	20.83	8,194.41
Bay type	14	8,220.58	20.95	8,192.52
Passage location	15	8,220.89	21.26	8,190.82

Table A2. Model selection for fish that passed through the spillway at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for juvenile steelhead, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Temperature + Spill discharge + Fish weight[1]	**17**	**6,464.37**	**0.00**	**6,430.27**
Temperature + Total discharge + Spill pattern + Fish weight[2]	**21**	**6,466.18**	**1.81**	**6,424.04**
Temperature + Total discharge + Percent spill + Fish weight[3]	18	6,466.72	2.35	6,430.61
Temperature + Total discharge + Spill pattern + Total discharge*Spill pattern + Fish weight[4]	25	6,467.26	2.89	6,417.05
Temperature + Spill discharge + Spill pattern + Fish weight	21	6,468.25	3.88	6,426.10
Temperature + Total discharge + Fish weight[5]	17	6,468.82	4.45	6,434.73
Temperature + Spill bay discharge + Spill pattern + Fish weight	21	6,471.93	7.56	6,429.79
Temperature + Spill pattern + Fish weight	20	6,473.18	8.81	6,433.05
Temperature + Spill discharge	16	6,473.82	9.45	6,441.73
Temperature + Spill bay discharge + Bay type + Fish weight	18	6,475.74	11.37	6,439.63
Temperature + Percent spill + Fish weight	17	6,476.07	11.70	6,441.97
Temperature + Spill bay discharge + Fish weight	17	6,476.29	11.92	6,442.19
Temperature + Fish weight	16	6,477.54	13.17	6,445.45
Temperature + Total discharge	16	6,479.48	15.11	6,447.40
Temperature + Spill pattern	19	6,480.42	16.05	6,442.30
Temperature + Tag burden	16	6,481.75	17.38	6,449.66
Temperature + Percent spill	16	6,482.71	18.34	6,450.63
Temperature + Spill bay discharge	16	6,483.19	18.82	6,451.10
Temperature	15	6,484.47	20.10	6,454.39

Table A2. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for juvenile steelhead, 2004–09.—Continued

Model	Number of parameters	AIC*c*	**ΔAIC*c***	Deviance
Fish weight	15	6,490.43	26.06	6,460.36
Tag burden	15	6,492.39	28.02	6,462.31
Spill pattern + Fish weight	19	6,494.81	30.44	6,456.69
Spill pattern + Tag burden	19	6,495.65	31.28	6,457.53
Intercept only	14	6,496.47	32.10	6,468.40
Spill pattern	18	6,500.63	36.26	6,464.52

[1]Addition of year to this model decreased AIC_c by 5.45.

[2]Addition of year to this model decreased AIC_c by 6.88.

[3]Addition of year to this model decreased AIC_c by 7.62.

[4]Addition of year to this model decreased AIC_c by 5.64.

[5]Addition of year to this model decreased AIC_c by 4.40.

Table A3. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for subyearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Temp, temperature; Q, discharge; Passloc, Passage location]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Spill pattern + Tag burden + Temp + Spill bay Q + Spill Q + Percent spill	**20**	**8,406.22**	**0.00**	**8,366.10**
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q	**19**	**8,406.55**	**0.33**	**8,368.45**
Spill pattern + Tag burden + Temp + Spill bay Q + Spill Q + Percent spill + Passloc	**22**	**8,406.59**	**0.37**	**8,362.45**
Spill pattern + Tag burden + Temp + Bay type + Total Q	**19**	**8,406.90**	**0.68**	**8,368.80**
Spill pattern + Fish weight + Temp + Spill bay Q + Total Q	**19**	**8,407.74**	**1.52**	**8,369.64**
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q + Spill pattern*Total Q	**23**	**8,408.18**	**1.97**	**8,362.03**
Spill pattern + Tag burden + Temp + Total Q	18	8,408.57	2.35	8,372.47
Spill pattern + Tag burden + Temp + Bay type + Total Q + Total Q*Spill pattern	23	8,408.65	2.44	8,362.50
Tag burden + Temp + Bay type + Total Q	15	8,410.22	4.00	8,380.15
Spill pattern + Temp + Spill bay Q + Total Q	18	8,410.46	4.25	8,374.37
Spill pattern +Temp + Spill bay Q + Total Q + Passloc	20	8,410.51	4.29	8,370.39
Spill pattern + Temp + Bay type + Total Q	18	8,410.64	4.42	8,374.54
Spill pattern + Temp + Spill bay Q + Spill Q + Percent spill	19	8,410.67	4.45	8,372.56
Spill pattern + Tag burden + Temp + Spill bay Q + Total Q + Spill pattern*Spill bay Q	23	8,411.15	4.93	8,365.00
Percent spill + Tag burden + Temp + Spill bay Q + Spill Q	16	8,411.27	5.05	8,379.19
Spill pattern + Temp + Bay type + Total Q + Passloc	20	8,411.31	5.10	8,371.20
Percent spill + Tag burden + Temp + Spill bay Q + Spill Q + Passloc	18	8,411.64	5.42	8,375.54
Tag burden + Temp + Spill bay Q + Total Q + Passloc + Passloc*Spill bay Q	19	8,411.67	5.45	8,373.56
Tag burden + Temp + Spill bay Q + Total Q	15	8,411.74	5.53	8,381.68
Tag burden + Temp + Spill bay Q + Total Q + Passloc	17	8,412.35	6.13	8,378.27
Spill pattern + Temp + Total Q	17	8,412.42	6.21	8,378.34
Percent spill + Tag burden + Temp + Spill bay Q + Spill Q + Passloc + Passloc*Spill bay Q	20	8,412.64	6.43	8,372.53

Table A3. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for subyearling Chinook salmon, 2004–09.—Continued

[Temp, temperature; Q, discharge; Passloc, Passage location]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Temp + Bay type + Total Q	14	8,414.26	8.04	8,386.20
Temp + Spill bay Q + Spill Q + Percent spill	15	8,415.37	9.15	8,385.30
Temp + Bay type + Total Q + Passloc	16	8,415.58	9.36	8,383.50
Temp + Spill bay Q + Total Q + Passloc + Passloc*Spill bay Q	18	8,415.63	9.41	8,379.53
Temp + Spill bay Q + Spill Q + Percent spill + Passloc	17	8,415.65	9.43	8,381.56
Temp + Spill bay Q + Total Q	14	8,416.54	10.32	8,388.48
Temp + Spill bay Q + Total Q + Passloc	16	8,417.06	10.84	8,384.98
Total Q + Temp + Tag burden	14	8,417.66	11.44	8,389.60
Spill pattern + Tag burden + Temp	17	8,420.34	14.12	8,386.25
Tag burden + Temp + Spill bay Q + Spill Q + Passloc + Passloc*Spill bay Q	19	8,421.54	15.33	8,383.44
Spill pattern + Temp + Percent spill	17	8,421.60	15.38	8,387.51
Spill pattern + Temp + Spill bay Q + Spill Q	18	8,421.96	15.74	8,385.87
Temp + Spill Q + Percent spill	14	8,422.11	15.89	8,394.05
Temp + Spill Q + Total Q	14	8,422.17	15.96	8,394.11
Temp + Total Q	13	8,422.35	16.13	8,396.30
Spill pattern + Temp + Spill bay Q	17	8,423.03	16.81	8,388.94
Temp + Total Q + Passloc	15	8,423.56	17.34	8,393.49
Spill pattern + Temp	16	8,423.82	17.60	8,391.75
Bay type + Temp + Spill Q	14	8,423.93	17.71	8,395.87
Spill pattern + Spill bay Q + Total Q	17	8,424.25	18.03	8,390.16
Temp + Spill bay Q + Spill Q + Passloc	16	8,424.29	18.07	8,392.22
Temp + Spill bay Q + Spill Q	14	8,424.32	18.10	8,396.26

Table A3. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for subyearling Chinook salmon, 2004–09.—Continued

[Temp, temperature; Q, discharge; Passloc, Passage location]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Spill pattern + Total Q	16	8,426.60	20.38	8,394.52
Bay type + Total Q	13	8,428.61	22.40	8,402.56
Spill bay Q + Spill Q + Percent spill + Passloc	16	8,429.64	23.42	8,397.56
Tag burden + Spill bay Q + Total Q	14	8,429.80	23.59	8,401.74
Spill bay Q + Spill Q + Percent spill	14	8,430.01	23.79	8,401.95
Spill bay Q + Total Q	13	8,430.09	23.87	8,404.04
Temp + Spill Q	13	8,431.26	25.04	8,405.21
Temp + Spill Q + Passloc	15	8,432.95	26.74	8,402.89
Spill pattern + Total Q + Spill pattern*Total Q	18	8,432.99	26.77	8,396.89
Tag burden + Total Q	13	8,435.97	29.75	8,409.92
Total Q	12	8,436.17	29.96	8,412.13
Total Q + Passloc	14	8,436.69	30.47	8,408.63
Spill Q + Percent spill	13	8,437.43	31.21	8,411.38
Spill Q + Percent spill + Passloc	15	8,438.13	31.92	8,408.07
Temp + Spill bay Q + Spill Q + Percent spill + Passloc + Passloc*Spill bay Q	19	8,438.92	32.70	8,400.81
Temp + Bay type + Spill bay Q	14	8,440.66	34.45	8,412.61
Temp + Bay type	13	8,441.03	34.82	8,414.98
Tag burden + Temp + Spill bay Q	14	8,446.16	39.94	8,418.10
Temp + Spill bay Q + Percent spill	14	8,449.43	43.21	8,421.37
Temp + Spill bay Q + Percent spill + Passloc	16	8,450.24	44.03	8,418.17
Temp + Spill bay Q	13	8,450.76	44.54	8,424.71
Tag burden + Temp	13	8,450.85	44.64	8,424.80

Table A3. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for subyearling Chinook salmon, 2004–09.—Continued

[Temp, temperature; Q, discharge; Passloc, Passage location]

Model	No. parameters	AIC*c*	ΔAIC*c*	Deviance
Temp + Spill bay Q + Passloc	15	8,451.26	45.04	8,421.20
Photoperiod + Temp + Percent spill	14	8,452.83	46.61	8,424.77
Photoperiod + Temp	13	8,453.80	47.58	8,427.75
Temp + Percent spill	13	8,454.55	48.33	8,428.50
Temp	12	8,455.36	49.15	8,431.32
Temp + Passloc	14	8,455.49	49.27	8,427.43
Spill pattern + Spill bay Q + Spill Q	17	8,456.18	49.96	8,422.09
Spill pattern + Percent spill	16	8,456.58	50.36	8,424.50
Spill pattern + Spill Q + Spill pattern * Spill Q	20	8,458.25	52.04	8,418.14
Spill bay Q + Spill Q + Passloc	15	8,458.80	52.59	8,428.74
Spill pattern + Spill Q	16	8,458.82	52.60	8,426.75
Bay type + Spill Q	13	8,459.42	53.21	8,433.37
Spill bay Q + Spill Q	13	8,459.75	53.53	8,433.70
Spill pattern + Percent spill + Spill pattern*Percent spill	20	8,459.80	53.58	8,419.68
Photoperiod + Spill Q	13	8,466.25	60.03	8,440.20
Spill Q	12	8,467.98	61.77	8,443.94
Spill Q + Passloc	14	8,468.87	62.65	8,440.81
Spill Q + Passloc + Passloc*Spill Q	16	8,469.13	62.92	8,437.06
Spill pattern	15	8,470.29	64.07	8,440.22
Bay type + Spill bay Q + Bay type*Spill bay Q	14	8,495.62	89.40	8,467.56
Bay type + Spill bay Q	13	8,504.48	98.27	8,478.43
Spill bay Q + Passloc + Passloc*Spill bay Q	16	8,506.11	99.89	8,474.03

Table A3. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for subyearling Chinook salmon, 2004–09.—Continued

[Q, discharge; Passloc, Passage location]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Year	15	8,512.36	106.14	8,482.29
Bay type	12	8,515.97	109.75	8,491.93
Photoperiod + Spill bay Q + Photoperiod*Spill bay Q	14	8,519.69	113.47	8,491.63
Photoperiod + Spill bay Q	13	8,529.93	123.71	8,503.87
Photoperiod	12	8,530.45	124.24	8,506.41
Passloc	13	8,534.75	128.53	8,508.70
Passloc + Percent spill	14	8,536.71	130.50	8,508.66
Spill bay Q	12	8,537.19	130.98	8,513.15
Passloc + Percent spill + Passloc*Percent spill	16	8,537.77	131.55	8,505.70
Intercept	11	8,538.06	131.85	8,516.03

Table A4. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for sockeye salmon, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Passage location + Spill discharge + Temperature + Tag burden	**13**	**5,171.48**	**0.00**	**5,145.40**
Passage location + Total discharge + Temperature + Percent spill + Tag burden	**14**	**5,173.31**	**1.83**	**5,145.22**
Passage location + Total discharge + Temperature + Tag burden	13	5,174.16	2.68	5,148.08
Passage location + Percent spill + Temperature + Tag burden	14	5,175.61	4.13	5,147.52
Passage location + Spill discharge + Tag burden	12	5,178.99	7.51	5,154.92
Spill discharge + Temperature + Tag burden	11	5,179.32	7.84	5,157.26
Total discharge + Temperature + Percent spill + Tag burden	12	5,181.19	9.71	5,157.12
Passage location + Total discharge + Percent spill + Tag burden	13	5,181.59	10.11	5,155.51
Percent spill + Temperature + Tag burden	11	5,181.61	10.13	5,159.55
Total discharge + Temperature + Tag burden	11	5,,181.85	10.37	5,159.79
Passage location + Percent spill + Tag burden	12	5,182.51	11.03	5,158.44
Passage location + Total discharge + Tag burden	12	5,183.01	11.53	5,158.94
Passage location + Temperature + Spill bay discharge + Tag burden	13	5,184.03	12.56	5,157.95
Spill discharge + Tag burden	10	5,185.95	14.48	5,165.91
Total discharge + Percent spill + Tag burden	11	5,188.68	17.20	5,166.62
Percent spill + Tag burden	10	5,189.62	18.14	5,169.57
Total discharge + Tag burden	10	5,189.70	18.22	5,169.65
Spill pattern + Passage location + Temperature + Tag burden	14	5,191.75	20.28	5,163.66

Table A4. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for sockeye salmon, 2004–09.—Continued

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Passage location + Spill bay discharge + Tag burden	12	5,193.14	21.66	5,169.07
Spill pattern + Passage location + Spill bay discharge + Tag burden	14	5,194.81	23.33	5,166.72
Spill pattern + + Spill bay discharge + Tag burden	13	5,195.62	24.14	5,169.54
Passage location + Spill discharge + Temperature	12	5,196.39	24.91	5,172.32
Passage location + Total discharge + Temperature	12	5,199.21	27.73	5,175.14
Bay type + Temperature + Spill bay discharge + Tag burden	12	5,201.12	29.64	5,177.05
Spill pattern + Temperature + Tag burden	12	5,201.23	29.75	5,177.16
Temperature + Spill bay discharge + Tag burden	11	5,201.78	30.30	5,179.72
Passage location + Temperature + Tag burden	12	5,202.73	31.26	5,178.67
Passage location + Percent spill + Temperature	12	5,204.49	33.01	5,180.42
Spill discharge + Fish weight	10	5,206.26	34.78	5,186.21
Passage location + Spill discharge	11	5,206.26	34.78	5,184.20
Spill discharge + Temperature	10	5,207.53	36.05	5,187.48
Passage location + Total discharge + Percent spill	12	5,207.76	36.28	5,183.69
Spill pattern + Spill discharge + Temperature	12	5,208.94	37.46	5,184.87
Total discharge + Temperature	10	5,209.46	37.99	5,189.42
Total discharge + Fish weight	10	5,209.64	38.16	5,189.59
Spill pattern + Spill bay discharge + Tag burden	12	5,210.97	39.50	5,186.91

Table A4. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for sockeye salmon, 2004–09.—Continued

Model	Number of parameters	AIC*c*	ΔAIC*c*	Deviance
Passage location + Total discharge	11	5,211.67	40.19	5,189.61
Spill bay discharge + Tag burden	10	5,212.26	40.78	5,192.21
Temperature + Tag burden	10	5,213.08	41.61	5,193.04
Spill pattern + Passage location + Tag burden	13	5,213.84	42.36	5,187.76
Spill pattern + Passage location + Total discharge	13	5,215.50	44.02	5,189.42
Spill pattern + Passage location + Spill bay discharge + Temperature	13	5,216.44	44.97	5,190.36
Spill discharge + Spill bay discharge	10	5,216.70	45.22	5,196.65
Passage location + Percent spill	11	5,216.78	45.30	5,194.72
Percent spill + Temperature	10	5,216.83	45.35	5,196.78
Spill discharge	9	5,217.61	46.13	5,199.57
Passage location + Tag burden	11	5,218.02	46.55	5,195.97
Total discharge + Percent spill	10	5,219.02	47.54	5,198.97
Spill pattern + Tag burden	11	5,221.93	50.45	5,199.87
Total discharge	9	5,222.02	50.55	5,203.99
Tag burden	9	5,227.31	55.84	5,209.27
Percent spill	9	5,229.32	57.84	5,211.28
Spill pattern + Passage location + Temperature	13	5,240.28	68.80	5,214.20
Spill pattern + Passage location + Spill bay discharge	13	5,244.10	72.62	5,218.02

Table A4. Model selection for fish that passed through the spillway at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for sockeye salmon, 2004–09.—Continued

Model	Number of parameters	AIC*c*	**ΔAIC*c***	Deviance
Passage location + Spill bay discharge	11	5,245.67	74.19	5,223.61
Spill pattern + Temperature	11	5,253.62	82.14	5,231.56
Bay type + Temperature + Spill bay discharge	11	5,258.57	87.09	5,236.51
Temperature + Spill bay discharge	10	5,261.55	90.08	5,241.51
Passage location + Temperature	11	5,268.44	96.96	5,246.38
Spill pattern + Bay type + Spill bay discharge	12	5,278.35	106.87	5,254.28
Fish weight	9	5,278.43	106.95	5,260.39
Spill pattern + Spill bay discharge	11	5,280.20	108.73	5,258.15
Bay type + Spill bay discharge	10	5,284.39	112.91	5,264.34
Bay type + Temperature	10	5,288.46	116.98	5,268.41
Temperature	9	5,288.62	117.14	5,270.58
Spill bay discharge	9	5,289.73	118.25	5,271.69
Spill pattern + Passage location	12	5,292.11	120.63	5,268.04
Passage location	10	5,306.96	135.48	5,286.91
Spill pattern	10	5,310.94	139.46	5,290.89
Bay type	9	5,328.93	157.46	5,310.89
Intercept	8	5,329.44	157.96	5,313.41

Appendix B: All Candidate Models Examined for Bypass Survival

Table B1. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for yearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Photoperiod	**14**	**5,553.48**	**0.00**	**5,525.39**
Intercept	**13**	**5,554.60**	**1.12**	**5,528.52**
Photoperiod + Spill pattern	19	5,558.99	5.51	5,520.84
Spill pattern	18	5,559.69	6.21	5,523.55

Table B2. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (ø) as a function of individual and group covariates using the fixed structure of the best model for p and λ parameters for juvenile steelhead, 2004–09.

[The best-fit models are indicated in bold]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Temperature + Total discharge	**16**	**2,570.27**	**0.00**	**2,538.04**
Temperature + Spill discharge	**16**	**2,571.48**	**1.21**	**2,539.25**
Temperature + Spill pattern + Total discharge	21	2,573.29	3.02	2,530.90
Temperature + Spill pattern	20	2,575.11	4.84	2,534.75
Temperature + Percent spill	16	2,576.55	6.28	2,544.32
Temperature	15	2,577.33	7.06	2,547.13
Spill discharge	15	2,577.35	7.08	2,547.15
Spill pattern	19	2,578.16	7.89	2,539.84
Spill pattern + Total discharge	20	2,578.49	8.22	2,538.14
Total discharge	15	2,578.69	8.42	2,548.49
Percent spill	15	2,580.22	9.95	2,550.02
Tag burden	15	2,581.26	10.99	2,551.05
Intercept	14	2,581.33	11.06	2,553.16

Table B3. Model selection for fish that passed through the juvenile bypass system outfall at McNary Dam relating survival (*ø*) as a function of individual and group covariates using the fixed structure of the best model for *p* and *λ* parameters for subyearling Chinook salmon, 2004–09.

[The best-fit models are indicated in bold. Q, discharge]

Model	Number of parameters	AIC_c	ΔAIC_c	Deviance
Temperature + Spill pattern + Fish weight + Total Q + Spill pattern*Total Q[1]	**26**	**4,062.74**	**0.00**	**4,010.28**
Temperature + Spill pattern + Total Q + Spill pattern*Total Q	**25**	**4,063.24**	**0.50**	**4,012.81**
Temperature + Spill pattern + Fish weight	20	4,065.41	2.67	4,025.13
Temperature + Spill pattern	19	4,066.09	3.35	4,027.84
Temperature + Fish weight	15	4,067.41	4.67	4,037.25
Temperature	14	4,067.56	4.82	4,039.43
Total Q	14	4,087.62	24.88	4,059.48
Spill pattern + Total Q + Spill pattern*Total Q	24	4,090.14	27.40	4,041.75
Spill Pattern + Total Q	19	4,091.10	28.36	4,052.85
Spill pattern	18	4,097.98	35.24	4,061.76
Percent spill	14	4,105.97	43.23	4,077.83
Turbine discharge	14	4,118.08	55.34	4,089.94
Intercept	13	4,119.27	56.53	4,093.15

[1]Addition of year to this model decreased AIC_c by 2.39.

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Adams and others—**A Multi-Year Analysis of Spillway Survival for Juvenile Salmonids as a Function of Spill Bay Operations at McNary Dam, Washington and Oregon, 2004–09**—Open-File Report 2012-1125