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The Delta Passage Model

by

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1/24/2011

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Introduction

The Delta Passage Model (DPM) simulates migration of juvenile Chinook salmon entering the Delta from the Sacramento and San Joaquin Rivers and estimates relative survival to Chipps Island. Although the DPM is primarily based on studies of winter-run Chinook surrogates (late fall-run Chinook), we applied it here for winter-run, spring-run and fall-run Chinook salmon by adjusting emigration timing and by assuming that all migrating Chinook salmon will respond similarly to Delta conditions. The biological functionality of the DPM is based upon the foundation provided by Perry et al. (2009) as well as other acoustic tagging based studies (Perry 2010; SJRGA 2008; SJRGA 2010; Holbrook et al. 2009) and coded wire tag (CWT) based studies (Newman and Brandes 2009; Newman 2008). Uncertainty is explicitly modeled in the DPM by incorporating environmental stochasticity and estimation error for most model functions. Where empirical information was lacking, parameter values were informed by data inference from the relevant scientific literature. A detailed sensitivity analysis of the current form of the DPM model has yet to be completed.

Survival estimates generated by the DPM are not intended to predict future outcomes or to predict actual survival. Rather, DPM provides an estimate of relative of survival (or survival index) which is useful for making comparisons between proposed operation alternatives. While DPM has been calibrated to the best available information, in most cases it is not possible to validate DPM results against actual fish abundance or survival values because such data does not exist. Where suitable data is available (e.g. spawning escapement abundance) observed values are the result of past habitat conditions, predator abundance and other factors which are not representative of expected future conditions. Generally, DPM results are appropriately reported as averages or as probability distributions by years, by months, and/or by Water Year Type, but not as comparisons between specific days, months or years.

Site Description

The transition between freshwater rivers, the low salinity Delta, and the fully marine waters of the San Francisco Bay (Bay) varies daily and seasonally as a function of tides, flows, and export diversions. As in previous Delta salmon studies (e.g., Brandes and McClain 2001; Perry et al. 2009) we defined the Bay as the area West of Chipps Island, and the Delta as the area East of Chipps Island (see Figure 1).

Model Description

The DPM is based on a detailed accounting of migratory pathways and reach-specific mortality as Chinook salmon smolts travel through a simplified network of reaches and junctions in the Delta. The DPM is composed of 10 reaches and four junctions (Figure 1; Table 1) selected to represent primary salmonid migration corridors where high quality fish and hydrodynamic data were available. For simplification, Sutter Slough and Steamboat Slough are combined as the reach SS and the forks of the Mokelumne River and Georgiana Slough are combined as Geo/DCC. The Geo/DCC reach can be entered by Mokelumne River fall-run at the head of the South and North Forks of the Mokelumne River or by Sacramento runs through the combined junction of Georgiana Slough and Delta Cross Channel (Junction C). The Interior Delta reach can be entered from three different pathways: 1) Geo/DCC, 2) SJ2, or 3) Old

River Junction (Junction D). The four distributary junctions depicted in the DPM are: A) Sacramento River at Freemont Weir (head of Yolo Bypass), B) Sacramento River at head of Sutter and Steamboat Sloughs, C) Sacramento River at the combined junction with Georgiana Slough and Delta Cross Channel, and D) San Joaquin River at the head of Old River (Figure 1; Table 1).

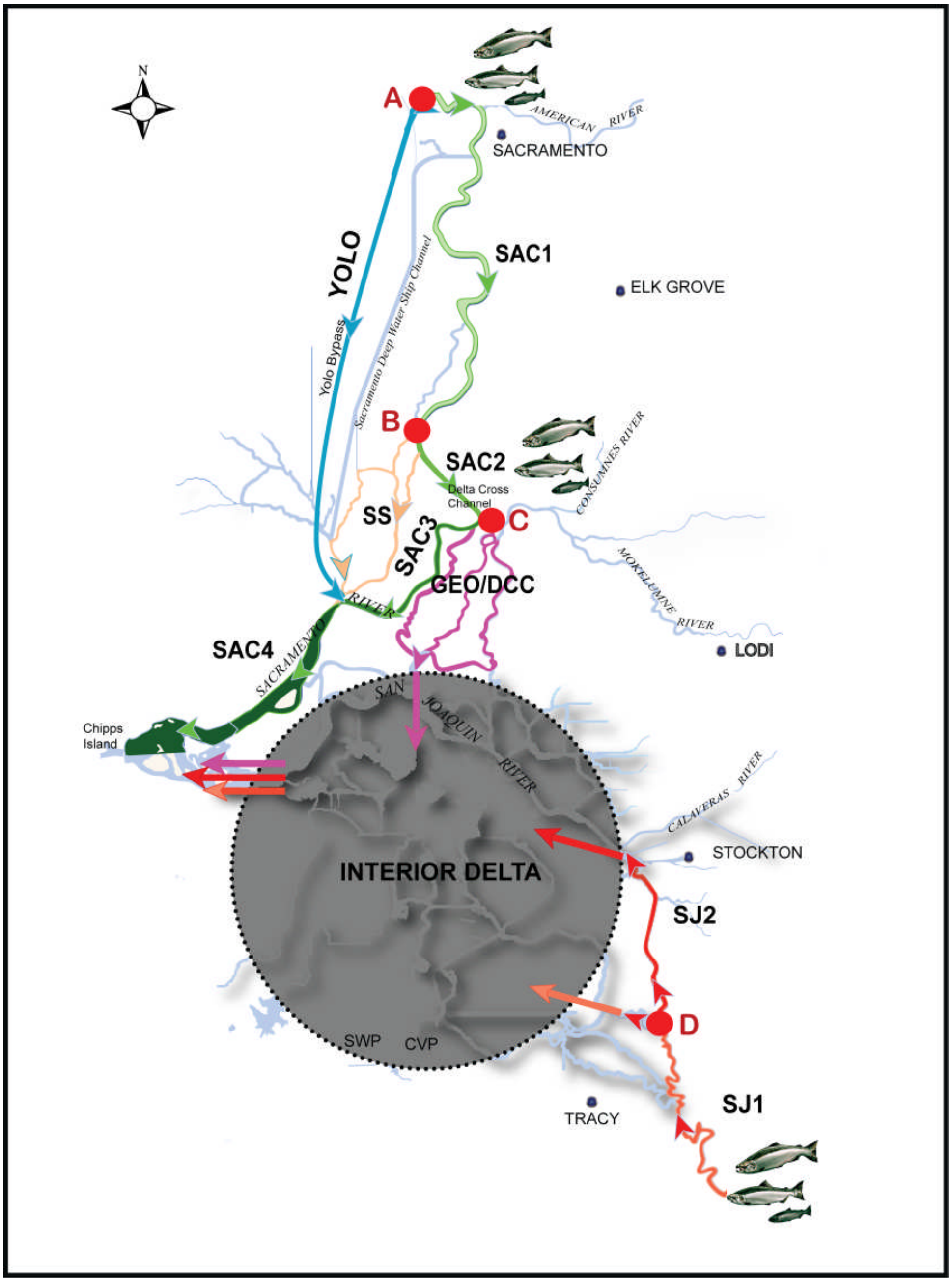

Figure 1. Map of the Sacramento-San Joaquin Delta showing the modeled reaches and junctions of the Delta. Colored river channels are modeled reaches and red circles are junctions. Salmonid icons indicate locations where juvenile salmonids enter the Delta in the DPM.

Table 1. Description of modeled reaches and junctions in the Delta Passage Model.

Reach/Junction	Description
Sac1	Sacramento River from Freeport to junction with Sutter Slough
Sac2	Sacramento River from Sutter Slough junction to junction with Delta Cross Channel
Sac3	Sacramento River from Delta Cross Channel junction to Rio Vista, CA
Sac4	Sacramento River from Rio Vista, CA to Chipps Island
Yolo	Yolo Bypass from entrance at Fremont Weir to Rio Vista, CA
SS	Combined reach of Sutter Slough and Steamboat Slough ending at Rio Vista, CA
Geo/DCC	Combined reach of Georgiana Slough, Delta Cross Channel, and South and North Forks of the Mokelumne River ending at confluence with the San Joaquin River
SJ1	San Joaquin River from Mossdale to confluence with the Old River
SJ2	San Joaquin River from confluence with Old River to confluence with the Deep Water Ship Canal
Interior Delta	Begins at end of reaches Geo/DCC or SJ2, or through Old River Junction (D) and ends at Chipps Island
A	Junction of the Yolo Bypass and the Sacramento River
B	Combined junction of Sutter Slough and Steamboat Slough with the Sacramento River
C	Combined junction of the Delta Cross Channel and Georgiana Slough with the Sacramento River
D	Junction of the Old River with the San Joaquin River

The DPM, as applied here, assesses the migrations of four Central Valley California Chinook Salmon runs: Sacramento River spring-run, fall-run, and winter-run, and San Joaquin River fall-run. Sacramento River winter-run, spring-run, and fall-run are introduced into the model at Freeport on the Sacramento River while San Joaquin River fall-run are introduced into the model at Mossdale on the San Joaquin River.

The DPM operates on a daily time step using simulated daily average flows and Delta exports as model inputs. The DPM does not attempt to represent sub-daily flows or diel salmon smolt behavior in response to the interaction of tides, flows and specific channel features. The DPM is intended to represent the net outcome of migration and mortality occurring over days, not three dimensional movements occurring over minutes or hours like that described in Blake and Horn (2003).

Flow Data

With the exception of exports from the SWP and CVP pumping plants, water movement though the Delta was modeled using daily (tidally averaged) flow output from the hydrology module of the Delta Simulation Model II (DSM2-HYDRO; http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/). Export flow into the CVP and SWP pumping plants was modeled using monthly flow output from the hydrologic simulation tool CALSIM II (Ferreira 2005) that are disaggregated into mean daily flows based on historical patterns. The nodes in the DSM2-HYDRO and CALSIM II models that were used to provide flow for specific reaches in the DPM are shown in Table 2. Technical details for DSM2-Hydro and CALSIM II models are described in Kimmerer and Nobriga (2008). DSM2 flow data output was used to inform the daily conditions experienced by migrating salmonids in the model.

Table 2. DPM reaches and associated channels from DSM2-HYDRO and CALSIM II models.

DPM Reach	DSM2 Hydro/CALSIM Channels
Sac1	RSAC155
Sac2	SAC DS STMBTSL
Sac3	RSAC123
Sac4	RSAC101
Yolo	D160 + D166A
SS	SUTR SL + STMB SL
Geo/DCC	DCC + GEORG SL
SJ1	RSAN112
SJ2	RSAN063
Exports	TOTAL_EXP

Delta Entry Timing

The best available, most recent sampling data on Delta entry timing of emigrating juvenile smolts for each of the 4 Chinook salmon runs were used to inform the daily proportion of juveniles entering the Delta for each run (Table 3). For each race we examined each brood year's catch distribution and visually approximated an average timing distribution which was then applied in the model (Figure 2). For winter-run Chinook and for San Joaquin basin fall-run Chinook, we observed two general patterns of emigration across years, represented by two separate curves within each race (Figure 2A and 2D). For spring-run Chinook a single distribution pattern was indicated (Figure 2B), while for Sacramento basin fall-run Chinook there was a single (but bimodal) distribution. For each Chinook race and within each model realization-year, a single emigration distribution was used. If more than one distribution was available (as it was with winter-run and San Joaquin River fall-run Chinook salmon) then the distribution used (within each model realization-year) was selected at random.

Table 3. Sampling gear used to create juvenile Delta entry timing distributions for each Central Valley run of Chinook salmon.

Run	Gear	Agency	Brood Years
Sacramento River Winter-Run	Trawls at Sacramento, CA	USFWS	1995-2005
Sacramento River Spring-Run	Trawls at Sacramento, CA	USFWS	1995-2005
Sacramento River Fall-Run	Trawls at Sacramento, CA	USFWS	1995-2005
San Joaquin River Fall-Run	Kodiak Trawl at Mossdale, CA	CDFG	1996-2009

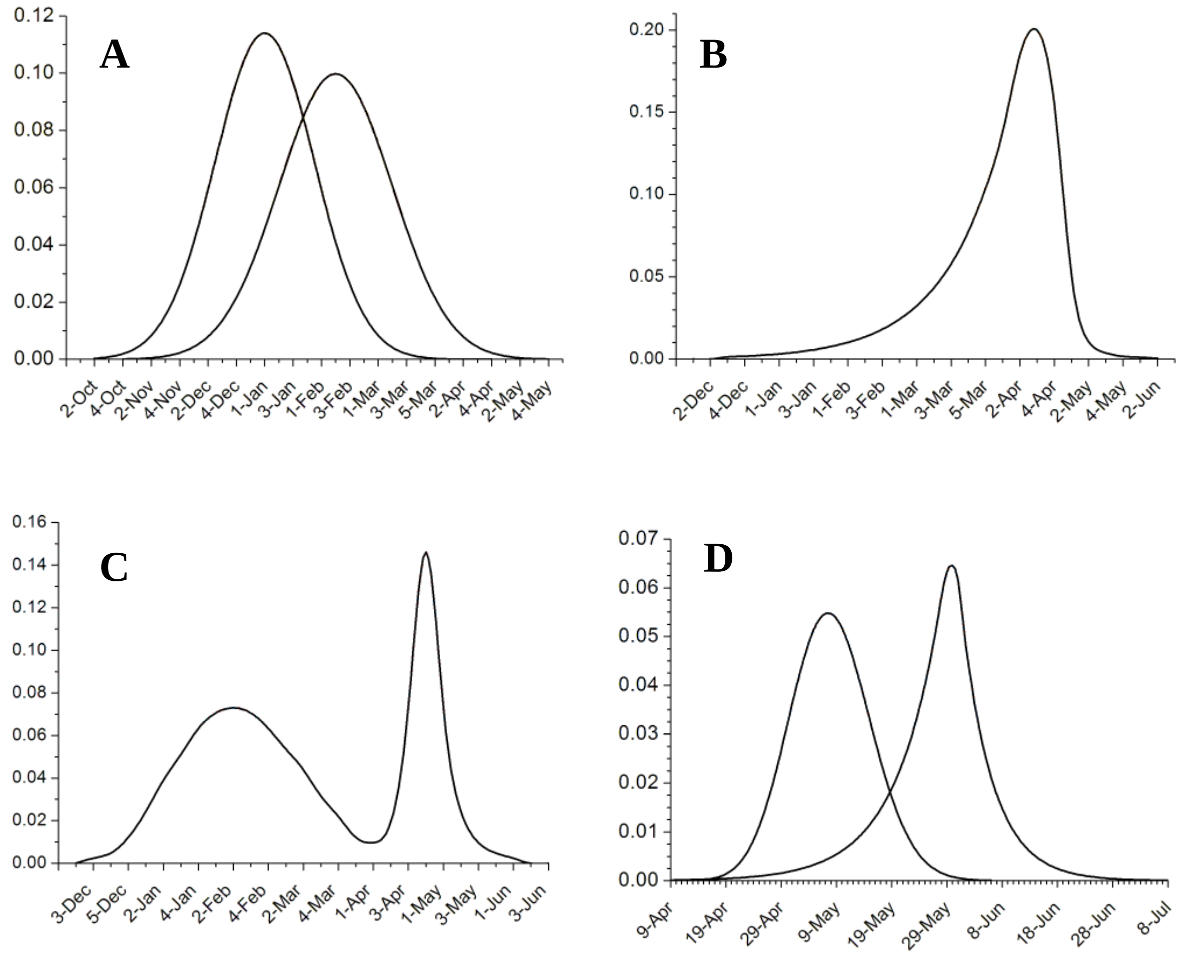

Figure 2. Delta Entry distributions for juvenile Sacramento River winter-run (A), Sacramento River spring-run (B), Sacramento River fall-run (C), and San Joaquin River fall-run (D).

Migration Speed

Smolt movement in the DPM occurs daily and is a function of reach-specific length and migration speed as developed from acoustic tagging results. The DPM assumes a net daily movement of smolts in the downstream direction. The rate of smolt movement in the DPM affects the timing of arrival at Delta junctions and reaches which can affect route selection and survival if flow conditions or water project operations are changing rapidly. However, since migration speed only affects route selection or survival indirectly, its influence will be minor relative to other factors.

For north Delta reaches Sac1, Sac2, Sac3, SS, and Geo/DCC mean migration speed is predicted as a function of flow. Many studies have found a positive relationship between Juvenile Chinook salmon migration rate and flow in the Columbia River Basin (Raymond 1968, Berggren and Filardo 1993, Schreck et al. 1994), with Berggren and Filardo (1993) finding a logarithmic relationship for Snake River yearling Chinook salmon. We used observed flows and migration speeds from Vogel (2008) north Delta acoustic study for reach Sac1 to create a best-fit logarithmic relationship:

1) $$y = 0.4296\ln(x) - 3.5193;$$

where y is migration speed (mph) and x is flow (in cfs) into Sac1. We found a positive, significant relationship between migration speed and flow (ANOVA; F = 22.6; df = 144; p < 0.001), with flow explaining 13% of the variation in migration speed. This function is applied north Delta-wide because migration speed data is unavailable for all other north Delta reaches. Due to assumed strong tidal influences in reach Sac4 (between Rio Vista and Chipps Island) we chose to have mean migration speed independent of reach inflow in Sac4. For reach Sac4, mean migration speed was set at 22.6 km/day, the average speed of acoustic tagged smolts in the Sac1 reach (Vogel 2008). Average migration speeds observed in San Joaquin River juvenile Chinook salmon acoustic studies (SJRGA 2008) were used to set mean migration speed for San Joaquin River reaches SJ1 and SJ2.

Variance in migration speed was modeled using error estimates from acoustic tracking experiments. Migration speed variance from acoustic study data was used along with mean migration speed to define a normal probability distribution that was sampled from each day to determine the daily migration speed in each reach (Table 4).

Table 4. Mean and standard deviations used to define a normal probability distribution that was sampled from each day to determine the daily migration speed in each reach.

Reach	Mean (km/day)	Standard Deviation
Sac1	Linear function of flow	9.1
Sac2	Linear function of flow	9.1
Sac3	Linear function of flow	9.1
SS	Linear function of flow	9.1
Sac4	22.6	9.1
Geo/DCC	Linear function of flow	9.1
SJ1	30.9	0.27
SJ2	21.6	0.41

Migration Pathways

Perry et al. (2010) found that acoustically tagged smolts arriving at Delta junctions exhibited inconsistent movement patterns in relation to the flow being diverted. For junction B, Perry et al. (2010) found that smolts consistently entered downstream reaches in proportion to the flow being diverted. Therefore, smolts arriving at junction B in our model move proportionally with flow. Similarly, given the lack of additional data to inform the nature of the relationship, we also applied a proportional relationship between flow and fish movement for junction D and junction A.

For junction C, Perry (2010) found a linear, non-proportional relationship between flow and fish movement. We applied his relationship for junction C in our model:

$$y = 0.22 + 0.47x;$$

where y is the proportion of fish diverted into Geo/DCC and x is the proportion of flow diverted into Geo/DCC.

Reach-Specific Survival

Reach-specific survival data and associated error estimates were obtained from four separate Delta acoustic tagging studies (Perry 2010; SJRGA 2008; SJRGA 2010; Holbrook et al. 2009; Table 6). These studies primarily released large (>150mm) late-fall hatchery Chinook. Given the importance of acoustic data, the DPM is probably most applicable to large smolts (>100mm), but model results may also be representative for steelhead smolts and smaller salmon smolts. Salmon juveniles less than 80mm are more likely to exhibit rearing behavior in the Delta (Moyle 2002), and thus will likely be poorly represented by the DPM. The degree to which tagged hatchery fish are representative of natural origin, untagged and volitionally migrating Chinook is largely unknown, but studies increasingly show that hatchery raised juvenile salmonids suffer greater mortality in the wild than do naturally-produced smolts (Kostow 2004; Araki et al. 2007). These factors illustrate again that survival values estimated by the DPM should be interpreted cautiously and only to make comparison between alternatives.

For all reaches except the Yolo Bypass, mean reach survival was used along with reach-specific standard deviation to define a normal probability distribution that was sampled from each day to determine the survival rate at each reach (Table 5a). For reaches where literature showed support for reach-level responses to environmental variables, mean survival was predicted as a function of reach-specific flow (Sac3, SS, SJ1, and SJ2) or Delta exports (Interior Delta for Sacramento River runs). For all other reaches, mean reach survival was calculated from acoustic tagging studies (Table 5a; Table 5b). For all reaches, the standard deviation of the estimated survival estimates was used to inform uncertainty in our model (Table 5a; Table 5b).

Table 5a. Reach-specific mean survival and associated standard deviation for each Chinook salmon run used in the model to define a normal probability distribution that was sampled from each day to determine the survival rate at each reach.

Reach	Chinook Salmon Run	Mean	Standard Deviation
Sac1	All Sacramento runs	0.845	0.058
Sac2	All Sacramento runs	0.928	0.032
Sac3	All Sacramento runs	function of flow	0.105
Sac4	All Sacramento runs	0.698	0.153
Yolo	All Sacramento runs	user-defined	N/A
SS	All Sacramento runs	function of flow	0.15
Geo/DCC	Mokelumne Fall-run	0.407	0.209
	All Sacramento runs	0.65	0.126
SJ1	San Joaquin Fall-run	function of flow	0.1
SJ2	San Joaquin Fall-run	function of flow	0.124
Interior Delta	All Sacramento runs	function of exports	0.089
	San Joaquin Fall-run via Old River	0.061	0.002
	San Joaquin Fall-run via SJ2	0.132	0.041

Table 5b. Individual release-group survival estimates and associated calculations used to inform reach-specific mean survival and standard deviation used in the DPM model.

DPM Reach	Survival	Release Dates	Source	Survival Calculation	Mean	Std. Dev
Sac1	0.844	12/5/06	Perry 2010	$S_{A1}*S_{A2}$	0.845	0.058
Sac1	0.876	1/17/07	Perry 2010	$S_{A1}*S_{A2}$		
Sac1	0.874	12/4/07-12/6/07	Perry 2010	$S_{A1}*S_{A2}$		
Sac1	0.892	1/15/08-1/17/08	Perry 2010	$S_{A1}*S_{A2}$		
Sac1	0.822	11/31/08-12/06/08	Perry 2010	$S_{A1}*S_{A2}$		
Sac1	0.760	1/13/09-1/19/09	Perry 2010	$S_{A1}*S_{A2}$		
Sac2	0.947	12/5/06	Perry 2010	S_{A3}	0.928	0.032
Sac2	0.976	1/17/07	Perry 2010	S_{A3}		
Sac2	0.919	12/4/07-12/6/07	Perry 2010	S_{A3}		
Sac2	0.915	1/15/08-1/17/08	Perry 2010	S_{A3}		
Sac2	0.928	11/31/08-12/06/08	Perry 2010	S_{A3}		
Sac2	0.881	1/13/09-1/19/09	Perry 2010	S_{A3}		
Sac3	0.691	12/5/06	Perry 2010	$S_{A4}*S_{A5}$	.680[a]	0.105
Sac3	0.703	1/17/07	Perry 2010	$S_{A4}*S_{A5}$		
Sac3	0.620	12/4/07-12/6/07	Perry 2010	$S_{A4}*S_{A5}*S_{A6}$		
Sac3	0.627	1/15/08-1/17/08	Perry 2010	$S_{A4}*S_{A5}*S_{A6}$		
Sac3	0.600	11/31/08-12/06/08	Perry 2010	$S_{A4,\ open}$		
Sac3	0.901	11/31/08-12/06/08	Perry 2010	$S_{A4,\ closed}$		
Sac3	0.616	1/13/10-1/19/10	Perry 2010	$S_{A4,\ closed}$		
Sac4	0.714	12/5/06	Perry 2010	$S_{A6}*S_{A7}$	0.698	0.153
Sac4	0.858	1/17/07	Perry 2010	$S_{A6}*S_{A7}$		
Sac4	0.548	12/4/07-12/6/07	Perry 2010	$S_{A7}*S_{A8}$		
Sac4	0.488	1/15/08-1/17/08	Perry 2010	$S_{A7}*S_{A8}$		
Sac4	0.731	11/31/08-12/06/08	Perry 2010	$S_{A7}*S_{A8}$		
Sac4	0.851	1/13/09-1/19/09	Perry 2010	$S_{A7}*S_{A8}$		
SS	0.389	12/5/06	Perry 2010	S_{B1}	.510[b]	0.150
SS	0.681	1/17/07	Perry 2010	S_{B1}		
SS	0.274	12/4/07-12/6/07	Perry 2010	$\Psi_{B11}/(\Psi_{B11+}\Psi_{B21})*(\Phi_{B11,B12}S_{B12}S_{B13}+\Phi_{B11,B22}S_{B22}S_{B23})+\Psi_{B21}/(\Psi_{B21+}\Psi_{B11})*(S_{B21}S_{B22}S_{B23})$		
SS	0.576	1/15/08-1/17/08	Perry 2010	$\Psi_{B11}/(\Psi_{B11+}\Psi_{B21})*(\Phi_{B11,B12}S_{B12}S_{B13}+\Phi_{B11,B22}S_{B22}S_{B23})+\Psi_{B21}/(\Psi_{B21+}\Psi_{B11})*(S_{B21}S_{B22}S_{B23})$		
SS	0.600	11/31/08-12/06/08	Perry 2010	$\Psi_{B11}/(\Psi_{B11}+\Psi_{B21})*(\Phi_{B11,B12}S_{B12}S_{B13}+\Phi_{B11,B22}S_{B22}S_{B23})+\Psi_{B21}/(\Psi_{B21}+\Psi_{B11})*(\Phi_{B21,B22}S_{B21}S_{B22}S_{B23}+\Phi_{B21,B12*}S_{B12*}S_{B13})$		
SS	0.539	1/13/09-1/19/09	Perry 2010	$\Psi_{B11}/(\Psi_{B11}+\Psi_{B21})*(\Phi_{B11,B12}S_{B12}S_{B13}+\Phi_{B11,B22}S_{B22}S_{B23})+\Psi_{B21}/(\Psi_{B21}+\Psi_{B11})*(\Phi_{B21,B22}S_{B21}S_{B22}S_{B23}+\Phi_{B21,B12*}S_{B12*}S_{B13})$		

Table 5b (continued). Individual release-group survival estimates and associated calculations used to inform reach-specific mean survival and standard deviation used in the DPM model.

Geo/DCC - Mok Fall-run	0.648	12/5/06	Perry 2010	$S_{C1}*S_{C2}$	0.407	0.209
Geo/DCC - Mok Fall-run	0.286	12/4/07-12/6/07	Perry 2010	S_{C1}		
Geo/DCC - Mok Fall-run	0.286	11/31/08-12/06/08	Perry 2010	S_{C1}		
Geo/DCC - Sacramento runs	0.648	12/5/06	Perry 2010	S_{D1}	0.650	0.126
Geo/DCC - Sacramento runs	0.600	12/4/07-12/6/07	Perry 2010	$S_{D1,Sac}*S_{D2}$		
Geo/DCC - Sacramento runs	0.762	1/15/08-1/17/08	Perry 2010	$S_{D1,Sac}*S_{D2}$		
Geo/DCC - Sacramento runs	0.774	11/31/08-12/06/08	Perry 2010	$S_{D1,Sac}*S_{D2}$		
Geo/DCC - Sacramento runs	0.467	1/13/09-1/19/09	Perry 2010	$S_{D1,Sac}*S_{D2}$		
SJ1	0.700	5/3/07	SJRGA 2007	N/A	.704[c]	0.100
SJ1	0.620	5/10/07	SJRGA 2007	N/A		
SJ1	0.782	4/29/08	Holbrook et al. 2009	$\sigma_{a1}*\sigma_{a2}$		
SJ1	0.826	5/6/08	Holbrook et al. 2009	$\sigma_{a1}*\sigma_{a2}$		
SJ1	0.593	4/22/09-05/13/09	SJRGA 2010	$S_{A1}*S_{A2}$		
SJ2	0.816	4/29/08	Holbrook et al. 2009	$\sigma_{a3}*\sigma_{a4}$	.662[d]	0.124
SJ2	0.623	5/6/08	Holbrook et al. 2009	$\sigma_{a3}*\sigma_{a3}$		
SJ2	0.519	4/22/09-05/13/09	SJRGA 2010	$S_{A3}*S_{A4}$		
SJ2	0.688	4/22/09-05/13/09	SJRGA 2010	$S_{A3}*S_{A4}$		
Int. Delta via Geo/DCC	0.571	12/5/06	Perry 2010	$S_{D2}S_{D3}$	0.470	0.089
Int. Delta via Geo/DCC	0.505	12/4/07-12/6/07	Perry 2010	$S_{D3}*S_{D4}*S_{D5}*S_{D6}*S_{D7}$		
Int. Delta via Geo/DCC	0.510	1/15/08-1/17/08	Perry 2010	$S_{D3}*S_{D4}*S_{D5}*S_{D6}*S_{D7}$		
Int. Delta via Geo/DCC	0.419	11/31/08-12/06/08	Perry 2010	$S_{D2}*S_{D4}*S_{D7}$		
Int. Delta via Geo/DCC	0.343	1/13/09-1/19/09	Perry 2010	$S_{D2}*S_{D4}*S_{D7}$		
Int. Delta via Old River	0.063	4/29/08	Holbrook et al. 2009	$\varphi_{b1,e1}\sigma_{e1}+\varphi_{b1,a7}\sigma_{a7}+\varphi_{b1,b2}\sigma_{b2}\sigma_{b3}+\varphi_{b1,d1}\sigma_{d1}$	0.061	0.002
Int. Delta via Old River	0.059	5/6/08	Holbrook et al. 2009	$\varphi_{b1,e1}\sigma_{e1}+\varphi_{b1,a7}\sigma_{a7}+\varphi_{b1,b2}\sigma_{b2}\sigma_{b3}+\varphi_{b1,d1}\sigma_{d1}$		
Int. Delta via SJ2	0.103	4/29/08	Holbrook et al. 2009	$\sigma_{a5}(\Psi_{a2}(\varphi_{a6,e1}\sigma_{e1}+\varphi_{a6,a7}\sigma_{a7}+\varphi_{a6,b2}\sigma_{b2}\sigma_{b3}+\varphi_{a6,d1}\sigma_{d1})+\Psi_{c2}(\varphi_{c1,e1}\sigma_{e1}+\varphi_{c1,a7}\sigma_{a7}+\varphi_{c1,b2}\sigma_{b2}\sigma_{b3}+\varphi_{c1,d1}\sigma_{d1}))$	0.132	0.041
Int. Delta via SJ2	0.161	5/6/08	Holbrook et al. 2009	$\sigma_{a5}(\Psi_{a2}(\varphi_{a6,e1}\sigma_{e1}+\varphi_{a6,a7}\sigma_{a7}+\varphi_{a6,b2}\sigma_{b2}\sigma_{b3}+\varphi_{a6,d1}\sigma_{d1})+\Psi_{c2}(\varphi_{c1,e1}\sigma_{e1}+\varphi_{c1,a7}\sigma_{a7}+\varphi_{c1,b2}\sigma_{b2}\sigma_{b3}+\varphi_{c1,d1}\sigma_{d1}))$		

a,b,c,d = Calculated mean survival for reaches Sac3, SS, SJ1, and SJ2 were not used in the model. Instead, mean reach survival was calculated as a function of flow.

River Flow-Survival

Perry (2010) evaluated the relationship between survival among acoustically tagged Sacramento River juvenile Chinook and river flow and found a significant relationship between survival and flow during the migration period for smolts that migrated through Sutter and Steamboat Sloughs to Chipps Island (SS and Sac4 combined) and smolts that migrated from Georgiana Slough to Chipps Island (Sac3 and Sac4 combined). Therefore, for reaches SS and Sac3 we used the logit survival function from Perry (2010) to predict mean reach survival (*S*) from reach flow (*flow*):

$$S = \frac{e^{(\beta_0+\beta_1 flow)}}{1+e^{(\beta_0+\beta_1 flow)}};$$

where β_0 (SS = -0.175, Sac3 = -0.121) is the reach coefficient and β_1 (0.52) is the flow coefficient. All the benefits of increased flow observed by Perry (2010) are accounted for the in relationships we have applied for reaches SS and Sac3. In order to avoid overestimation of the flow-effect on survival in our model, we modeled reach Sac4 as being uninfluenced by flow (mean survival from the acoustic studies is applied). Estimated mean reach survival was then used along with the reach-specific standard deviation from the acoustic studies to define a normal probability distribution that was sampled from each day to determine the reach-specific survival rate.

In lieu of an acoustic tagging analysis comparable to Perry (2010) for the South Delta, for SJ1 and SJ2 we assume a logarithmic relationship between river flow and survival which is supported by Newman (2008). To estimate reach-specific relationships between survival and flow for SJ1 and SJ2, we used the following linear regression model:

$$y_{i,k} = \beta_{0,i} * reach_i + \beta_1 \log(flow_{i.k}) + e_{i,k} ;$$

where subscripts *i* and *k* denote the ith reach and kth replicate estimate of survival rate, and residual errors (*e*) are assumed to be normally distributed. The variable reach is a factor or "dummy variable" designating the specific reaches. To better normalize the data and ensure that predicted survival rates were bounded between 0 and 1, we used the logit transformation (Dobson 2002) of the observed survival rates (*s*) as the independent variable:

$$y_{i.k} = \text{logit}(s_{i.k}) = \log\left(\frac{s_{i.k}}{1-s_{i.k}}\right) .$$

Thus, we assumed in the regression model that the effect of flow (β_1) on survival had the same function form (i.e., slope) in both SJ1 and SJ2, but that reach-specific survival rates varied above or below the average relationship as defined by reach-specific intercepts ($\beta_{0i,}$; e.g. due to differences in reach length, predation effects, etc.). Ideally, we would like to obtain (and test) reach-specific estimates for both the intercept and slope of the survival-flow relationship; however, there were far too few data points and insufficient contrast among flow observations to estimate such a model.

The estimated coefficients (β) provide predicted values of survival rate via the following back-transformation of the logit function:

$$\hat{s}_{i,k} = \frac{1}{1+\exp(-[\hat{\beta}_{0,i} + \hat{\beta}_1 * \log(flow_{i,k})])} .$$

The overall effect of the *reach* was highly significant (ANOVA; F = 8.52; df = 16; $p < 0.001$). However, the estimated effect of log(*flow*) was very imprecise and not significant (t-test; t = 0.71; df = 16; $p = 0.48$). Thus, while there is clear evidence of reach-specific differences in mean survival, the effect of flow is highly uncertain. However, strong support exists among studies of San Joaquin River salmon survival for a positive relationship between survival and flow for out-migrating juvenile Chinook salmon (Newman 2008, CDFG 2005). Since our limited dataset and lack of contrast among flow observations limited our ability to find a flow effect on survival, we decided to retain flow as an independent variable in our final model.

Combined stochasticity and uncertainty about Delta survival predictions was modeled using error estimates from the acoustic study data. The mean daily survival calculated from the reach-specific survival-flow curves was used along with the reach-specific standard deviation to define a normal probability distribution that was sampled from each day to determine the reach-specific survival rate for SJ1 and SJ2.

Export Loss

Survival estimates for Chinook salmon entering the Interior Delta from the San Joaquin River are consistent with the findings of Newman (2008) and do not include a relationship between exports and survival. However, as migratory juvenile salmon enter the Interior Delta from Geo/DCC for Sacramento races or Mokelumne River fall-run, they transition to an area strongly influenced by tides and where exports may influence survival. To account for this, we applied the export-survival relationship described by Newman and Brandes (2009) as:

$$S = -0.000024 * Exports + 0.625;$$

where S is Interior Delta mean survival and the slope (-0.000024) is from the relationship between survival and Delta exports (*Exports*) for smolts migrating through the interior Delta from Newman and Brandes (2009; Figure 3). The intercept from Newman and Brandes (2009) was adjusted from 0.58 to 0.625 so that the regression line passes the point (6,500, 0.47), where 6,500 is the mean export level (cfs) observed during the acoustic studies and 0.47 is the mean survival rate observed during the acoustic studies (Figure 3). In effect, we used the slope of the relationship between survival and exports as estimated by Newman and Brandes (2009) as a scalar on the survival rates as observed from acoustic tagging studies. Estimated mean survival was then used along with the standard deviation of survival estimates from the acoustic studies to inform a normal probability distribution that was sampled from each day to determine Interior Delta survival.

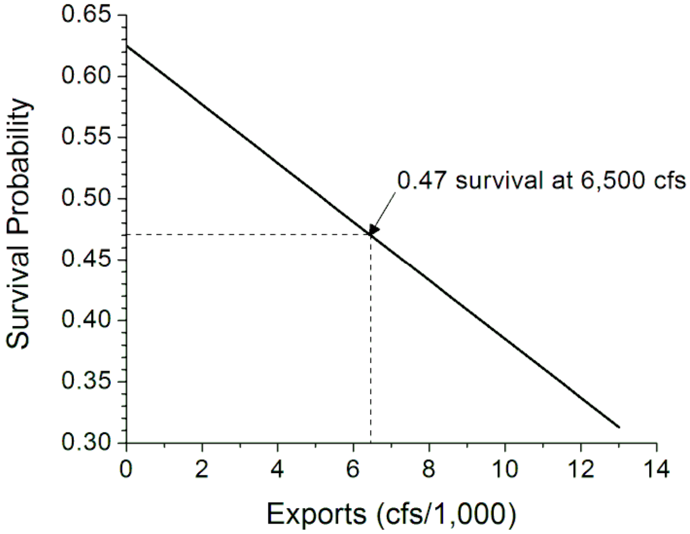

Figure 3. Linear function used to predict mean interior Delta survival from Delta exports for Mokelumne River fall-run and Sacramento River runs. The slope of the relationship is from Newman and Brandes (2009), and the intercept was set so that the regression line passes the point (6,500, 0.47), where 6,500 is the mean export level (cfs) observed during the acoustic studies and 0.47 is the mean survival rate observed during the acoustic studies. Estimated mean survival was then used along with the standard deviation of survival estimates from the acoustic studies to inform a normal probability distribution that was sampled from each day to determine Interior Delta survival.

Sensitivity Analysis

Through-Delta Survival for Different Water Years

We assessed the influence of reservoir storage and precipitation on DPM results by grouping the results of DPM model runs by water year type. Overall through-Delta survival varied considerably among each of the five water year types (Figure 4). Survival was highest in “wet” years and lowest in “critically dry” years. Similar patterns were apparent in examining survival through Sutter-Steamboat Slough (Figure 5) and mainstem Sacramento River routes (Figure 6).

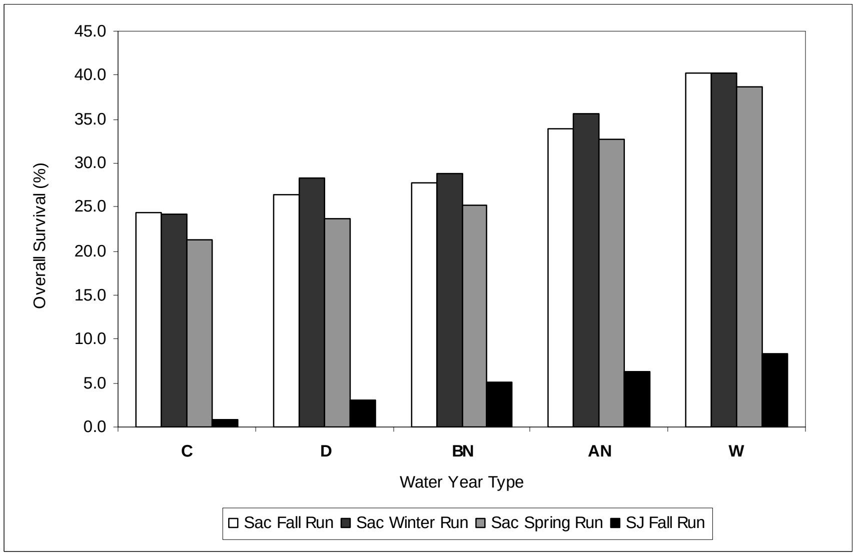

Figure 4. Juvenile Chinook salmon through-Delta survival percentages by water year type and run. Water year types are: C=Critical, D=Dry, B=Below Normal, AN=Above Normal, and W=Wet.

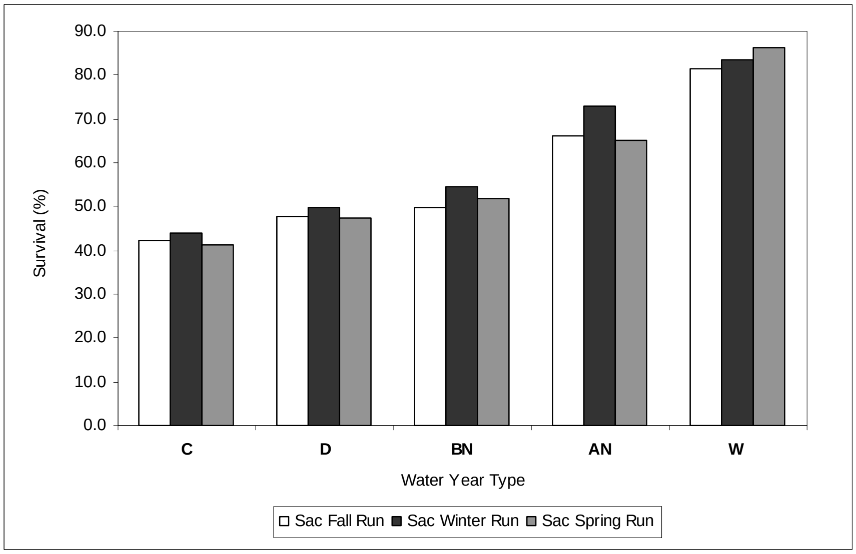

Figure 5. Sacramento Chinook smolt survival percentages in the SS reach by water year type and run. Water year types are: C=Critical, D=Dry, B=Below Normal, AN=Above Normal, and W=Wet.

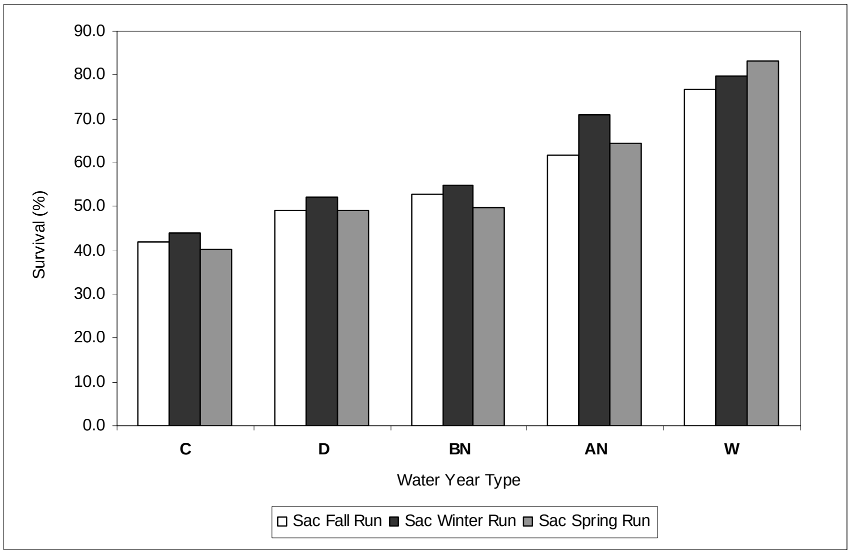

Figure 6. Sacramento Chinook smolt survival percentages in the SAC3 reach by water year type and run. Water year types are: C=Critical, D=Dry, B=Below Normal, AN=Above Normal, and W=Wet.

Survival in San Joaquin Reaches for Different Water Years

We assessed the influence of reservoir storage and precipitation on DPM results by grouping the results of DPM model runs by water year type. Overall through-Delta survival on the San Joaquin River varied considerably among each of the five water year types (Figure 7). Patterns were similar to those observed on the Sacramento River, but with an even large difference between survival in “wet” years and survival in “critically dry” years.

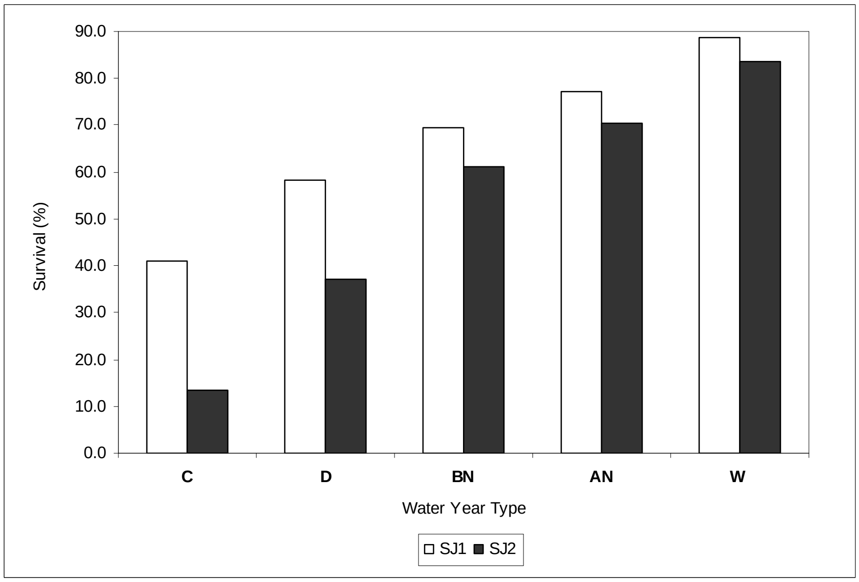

Figure 7. San Joaquin fall-run Chinook smolt survival percentages in the SJ1 and SJ2 reaches by water year type. Water year types are: C=Critical, D=Dry, B=Below Normal, AN=Above Normal, and W=Wet.

Effect of Yolo Bypass Access on Through-Delta Survival

We assessed the effect of juvenile Chinook salmon using Yolo Bypass by using the Delta Passage Model to estimate through-Delta survival with the Yolo Bypass "open" vs. "closed". For the "open" condition, juvenile Chinook were allowed to enter Yolo Bypass in proportion to Sacramento River flows. For the "closed" condition, juvenile Chinook were not allowed to enter Yolo Bypass regardless of flows. Fish using Yolo Bypass were assumed to survive at a 10% higher rate than fish remaining in the Sacramento River. Results for fall-run Chinook and winter-run Chinook indicate a small improvement in through-Delta survival when fish are allowed to access Yolo Bypass (Figure 8 and Figure 9). Spring-run Chinook also showed some benefits from access to Yolo Bypass (Figure 10), but somewhat less than that observed for fall-run and winter-run Chinook. Observed differences between races of Chinook salmon are due to the correspondence (or lack of correspondence) between events flooding Yolo Bypass and the peak emigration of juvenile Chinook salmon.

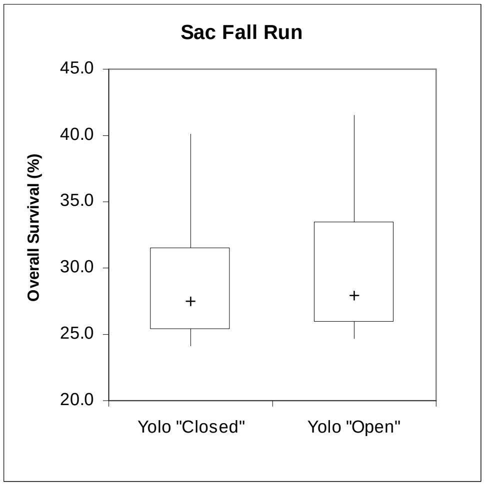

Figure 8. Sacramento fall-run Chinook through-Delta smolt survival as estimated by the DPM with Yolo Bypass closed vs. open. Plot shows survival distribution across all study years. Median is marked with "+", upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

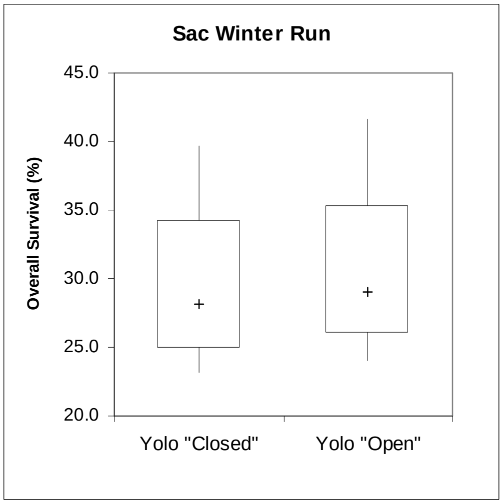

Figure 9. Sacramento winter-run Chinook through-Delta smolt survival as estimated by the DPM with Yolo Bypass closed vs. open. Plot shows survival distribution across all study years. Median is marked with “+”, upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

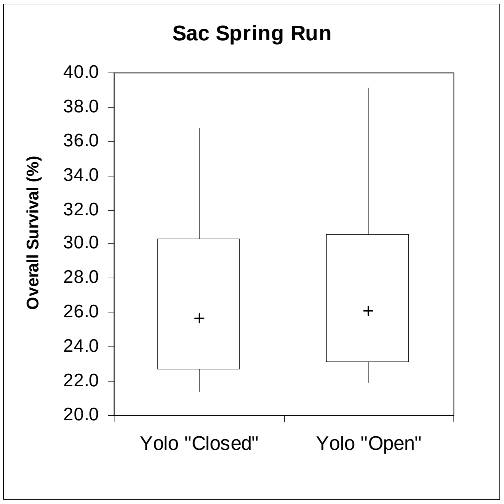

Figure 10. Sacramento spring-run Chinook through-Delta smolt survival as estimated by the DPM with Yolo Bypass closed vs. open. Plot shows survival distribution across all study years. Median is marked with “+”, upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

Effect of Barriers Reduction on Through-Delta Survival

We used the Delta Passage Model to evaluate potential benefits of non-physical barriers operated at Georgiana Slough and at the Head of Old River. We evaluated six levels of deterrence effectiveness ranging between 0% and 100% and estimated resulting through-Delta survival. With a barrier reduction (or deterrence) of 0%, then juvenile salmon would continue to enter Georgiana Slough or Old River as though no non-physical barrier was present. With a barrier reduction (or deterrence) of 100%, then all juvenile salmon would be prevented from entering Georgiana Slough or Old River. Our assessment assumed operation of non-physical barriers would not exacerbate predation mortality.

A non-physical barrier at the head of Old River, provided very small improvements (~0.1%) San Joaquin fall-run (Figure 11).

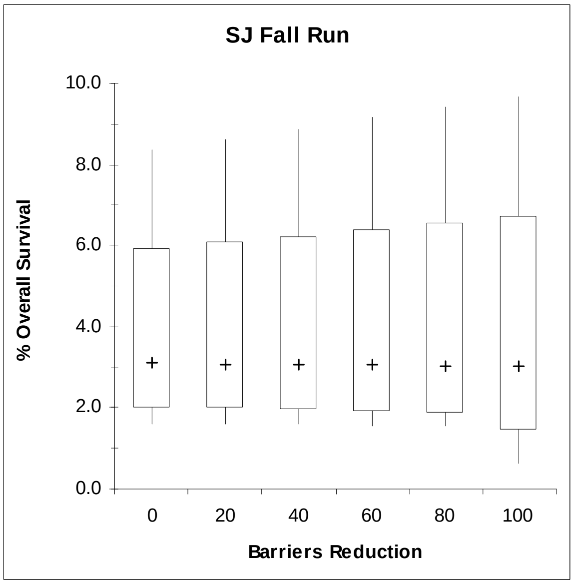

Figure 11. San Joaquin fall-run Chinook through-Delta smolt survival as estimated by the DPM with different GEO/DCC and old river junction barriers reduction percentages. Plot shows survival distribution across all study years. Median is marked with "+", upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

Effect of Increasing Exports on Through-Delta Survival

We estimated through-Delta survival for Sacramento River fall-run Chinook to illustrate the influence of exports. Through-Delta survival declined by approximately 2% as exports increased from zero to 10,000 cfs (Figure 12). Though not presented here, similar results were obtained for Sacramento River spring-run and winter-run Chinook salmon.

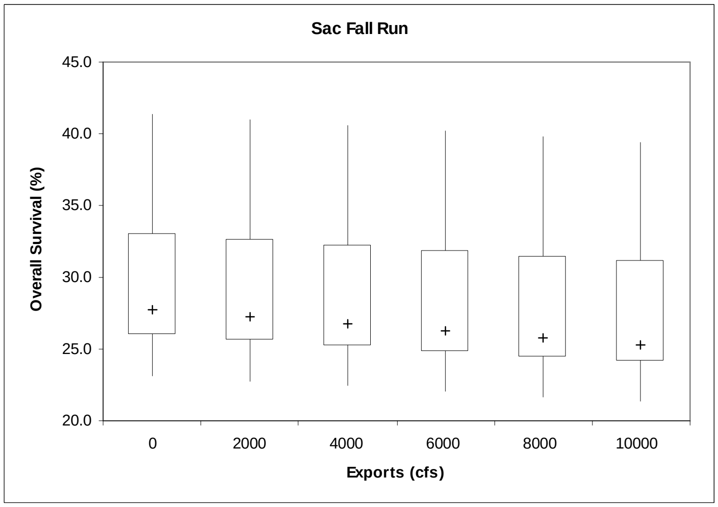

Figure 12. Sacramento fall-run Chinook through-Delta smolt survival as estimated by the DPM with different export volumes in cubic feet per second. Plot shows survival distribution across all study years. Median is marked with "+", upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

Effect of Reach Conservation on Through-Delta Survival

In order to illustrate the potential benefits of conservation measures we modeled through-Delta survival with a range of 1% improvements in survival. As might be expected, incremental improvement in reach specific survival which might result from habitat enhancements or predator control efforts yield corresponding incremental improvements in through-Delta survival (Figure 13).

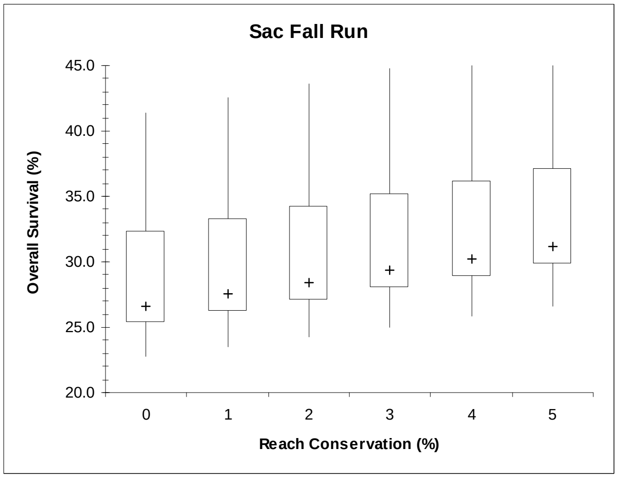

Figure 13. Sacramento fall-run Chinook through-Delta smolt survival as estimated by the DPM with different reach conservation percentages. Plot shows survival distribution across all study years. Median is marked with "+", upper and lower boundaries of the box indicate 75th and 25th percentiles, upper and lower whiskers indicate max and min percentage survival.

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