Prepared in cooperation with the Bureau of Reclamation

Estimating Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) Abundance from Beach Seine Data Collected in the Sacramento–San Joaquin Delta and San Francisco Bay, California

Open-File Report 2016–1099

U.S. Department of the Interior
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Cover: Beach seine sampling (top) without a block-net (open sampling) and (bottom) with a block-net (closed sampling).
Photographs courtesy of Jacob B. Osborne, U.S. Fish and Wildlife Service.

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

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By Russell W. Perry[1], Joseph E. Kirsch[2], and A. Noble Hendrix[3]

Abstract

Resource managers rely on abundance or density metrics derived from beach seine surveys to make vital decisions that affect fish population dynamics and assemblage structure. However, abundance and density metrics may be biased by imperfect capture and lack of geographic closure during sampling. Currently, there is considerable uncertainty about the capture efficiency of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) by beach seines. Heterogeneity in capture can occur through unrealistic assumptions of closure and from variation in the probability of capture caused by environmental conditions. We evaluated the assumptions of closure and the influence of environmental conditions on capture efficiency and abundance estimates of Chinook salmon from beach seining within the Sacramento–San Joaquin Delta and the San Francisco Bay. Beach seine capture efficiency was measured using a stratified random sampling design combined with open and closed replicate depletion sampling. A total of 56 samples were collected during the spring of 2014. To assess variability in capture probability and the absolute abundance of juvenile Chinook salmon, beach seine capture efficiency data were fitted to the paired depletion design using modified N-mixture models. These models allowed us to explicitly test the closure assumption and estimate environmental effects on the probability of capture. We determined that our updated method allowing for lack of closure between depletion samples drastically outperformed traditional data analysis that assumes closure among replicate samples. The best-fit model (lowest-valued Akaike Information Criterion model) included the probability of fish being available for capture (relaxed closure assumption), capture probability modeled as a function of water velocity and percent coverage of fine sediment, and abundance modeled as a function of sample area, temperature, and water velocity. Given that beach seining is a ubiquitous sampling technique for many species, our improved sampling design and analysis could provide significant improvements in density and abundance estimation.

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Introduction

Fishery scientists and managers often rely on abundance or density metrics derived from beach seining to monitor fish population dynamics and inform decisions that affect fish population viability and assemblage structure. Beach seining has been used to resourcefully collect spatially explicit fish count data for more than 100 years throughout the world's freshwater, estuarine, and marine environments (Pierce and others, 1990; Murphy and Willis, 1996; Bayley and Herendeen, 2000). Because mark-recapture methods are often too invasive, costly, and difficult to implement (Royle, 2004a; Chandler and others, 2011), beach seine surveys operating over large spatial and temporal extents typically quantify fish abundance or density metrics using count data of unmarked individuals. However, count data can underestimate fish abundance and distribution metrics to varying degrees in time and space owing to imperfect capture (false absences) of fishes (Bayley and Peterson, 2001; Chandler and others, 2011). Heterogeneity in capture can vary among beach seine sampling methods, environmental conditions, and fish species and sizes (Murphy and Willis, 1996). Furthermore, failure to account for this sampling bias can introduce systematic error into the data, obfuscate important ecological relations, and negatively influence a manager's ability to make effective resource management decisions (Price and Peterson, 2010).

Beach seine sample bias can be minimized by adjusting count data from unmarked fish with estimates of capture probability (Murphy and Willis, 1996; Peterson and Paukert, 2009). Capture efficiency of beach seines has been estimated using a variety of gear calibration methods (for example Weinstein and Davis, 1980; Lyons, 1986; Parsley and others, 1989; Bayley and Dowling, 1990; Pierce and others, 1990; Allen and others, 1992; Bayley and Herendeen, 2000; Kanou and others, 2004). However, there are relatively few beach seine efficiency models available for fish sampling within estuaries (Weinstein and Davis, 1980; Allen and others, 1992; Rozas and Minello, 1997; Kanou and others, 2004) or large rivers (Bayley and Herendeen, 2000) and no models have been evaluated for juvenile salmonids within the Western United States.

Gear calibration methods require comparing the number of fish captured with beach seines to the known number or an unbiased estimate of the number of fish present in the sample area (Peterson and Paukert, 2009; Price and Peterson, 2010). A primary assumption of most fish abundance estimators (for example, removal or depletion methods; Parsley and others, 1989; Pierce and others, 1990) and all gear calibration methods is that the population is geographically closed while sampling (no immigration or emigration; Peterson and Paukert, 2009). This assumption may be violated when sampling mobile fishes (Bayley and Herendeen, 2000; Chandler and others, 2011). Beach seine efficiency studies have traditionally used block-nets to enclose fishes within a sample area and ensure geographic closure; however, the use of block-nets requires considerable effort (Lyons, 1989; Bayley and Herendeen, 2000).

A class of models known as N-mixture models has recently been developed to simultaneously estimate true abundance (or density) and capture probability using spatially replicated count data from unmarked individuals (Royle 2004a, 2004b). Recent extensions of these models have allowed for lack of geographic closure (allowing for temporary emigration or immigration; Chandler and others, 2011). While allowing for openness among groups of repeated samples, the N-mixture models still assume closure within groups of repeated samples (within multiple passes of a depletion sampling design). Here, we extend this N-mixture approach to estimate and evaluate the variability of site-specific fish abundance or density, probability of capture, and temporary immigration or emigration rates within repeated beach seine hauls. We then apply the approach to evaluate the probability of capture and abundance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) while beach seining within an estuary in the Western U.S.

Methods

Study Area

We evaluated the efficiency of beach seines to capture juvenile Chinook salmon within the Sacramento-San Joaquin Delta and San Francisco Bay (referred to as "Delta" hereinafter) in the Central Valley of California. The Delta consists of approximately 1,100 km^2 of tidal freshwater channels within the upper or landward part of the San Francisco Estuary where the Sacramento, San Joaquin, and other rivers coalesce (Brown and Michniuk, 2007). The climate is classified as Mediterranean and is characterized by wet winters and dry summers (Nichols and others, 1986). In general, the Delta and its surrounding landscapes have been substantially altered by levees, dams, land reclamation, intrabasin water conveyance, and out-of-basin water export (Nichols and others, 1986). Currently, the Delta and its watershed are primarily managed and engineered to supply freshwater for export through thousands of small siphons and pumps for local irrigation, and the Central Valley Project and State Water Project pumping plants in the southern Delta (Kimmerer, 2004). As a result, the Delta is actively managed to maintain low salinity, even during the summers of drought years (Brown and Michniuk, 2007). Annual water temperatures within the Delta can range from 6 to 28 °C and water velocities are largely influenced by tidal flow (Kjelson and others, 1982; Kimmerer, 2004). Delta littoral habitats include submerged (for example *Egeria densa*) and emergent aquatic vegetation (for example *Scirpus* spp. and *Typha* spp.), large woody debris, unobstructed beaches dominated by sand or silt, and extensive riprap on levees (Brown and Michniuk, 2007).

Beach seining has been conducted within the Delta since the late 1970s by the U.S. Fish and Wildlife Service's Delta Juvenile Fish Monitoring Program (DJFMP) to monitor and assess the effects of water operations on the inter- and intra-annual abundance and distribution of juvenile Chinook salmon occurring in mostly unobstructed nearshore habitats (for example beaches and boat ramps; Kjelson and others, 1982). In general, the DJFMP samples 53 fixed monitoring sites distributed among 6 geographic regions distributed throughout the Delta and lower rivers (fig. 1). Each monitoring site is sampled weekly or bi-weekly using a single beach seine haul during the daytime (Speegle and others, 2013). For each sample, the count of fish captured and volume sampled are recorded to calculate an index of site-specific fish density, which is used as a measure of relative abundance.

Sampling Design

Beach seine efficiency sampling was conducted in collaboration with the DJFMP's beach seine project. Sampling occurred from February to May 2014 to account for the out-migrating juvenile Chinook salmon within the Delta. We randomly selected a total of five sites within each of the DJFMP's six geographic beach seine regions using a stratified random sample design to represent the range of site conditions occurring across the beach seine monitoring sites within the Delta and lower rivers (fig. 1). We attempted to sample each site on two separate occasions to assess geographic closure. These sites were sampled on one occasion using a block net to enforce geographic closure and were sampled on another occasion without a block net to allow for geographic openness (fig. 2). The time between the two sampling occasions was approximately 24 hours to allow fish to recolonize the site and minimize the changing of site conditions from variations in river and tidal flows.

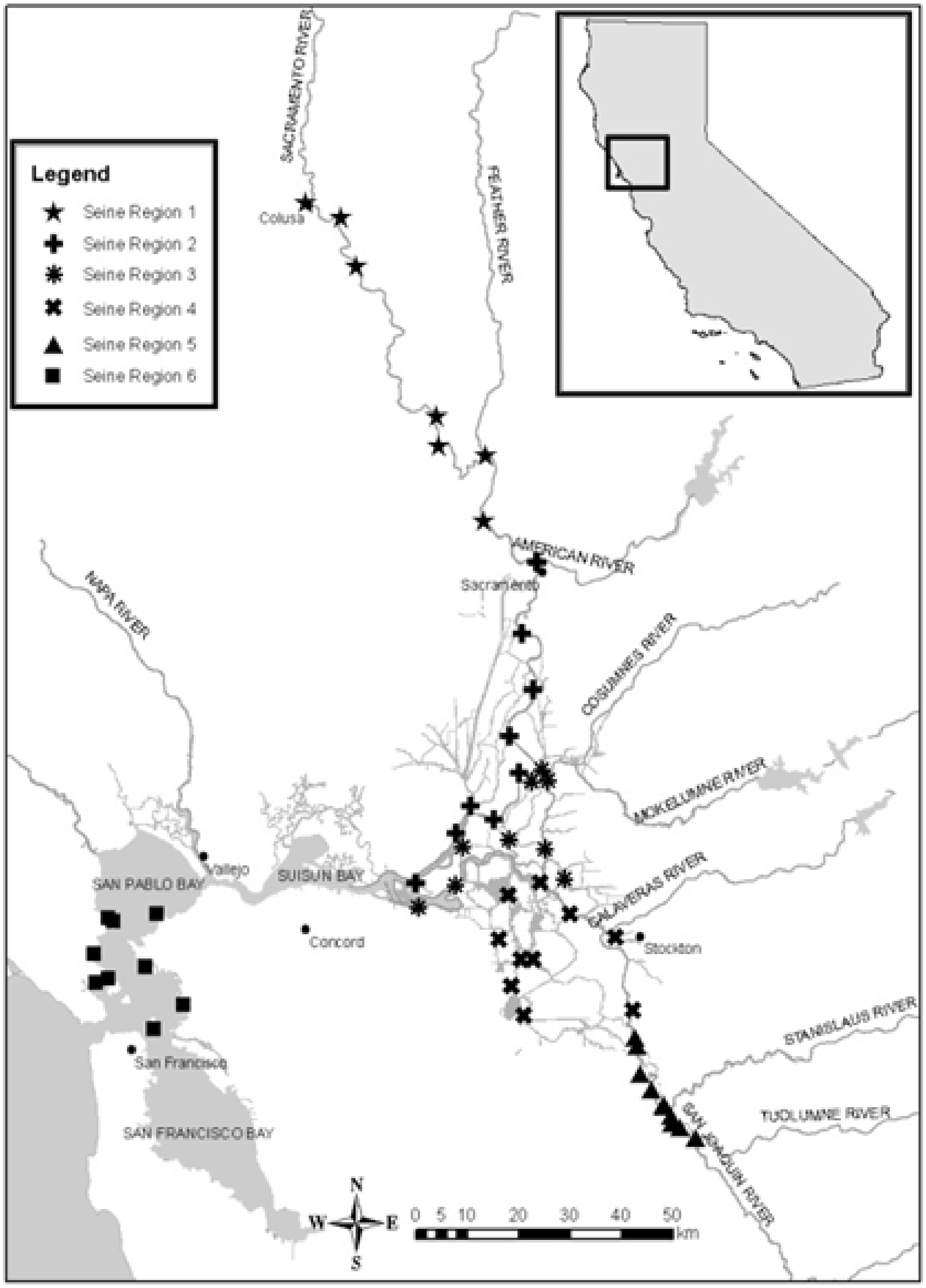

Figure 1. Location of beach seine monitoring sites distributed among six regional strata and randomly selected for sampling within the Sacramento-San Joaquin Delta and San Francisco Bay, California.

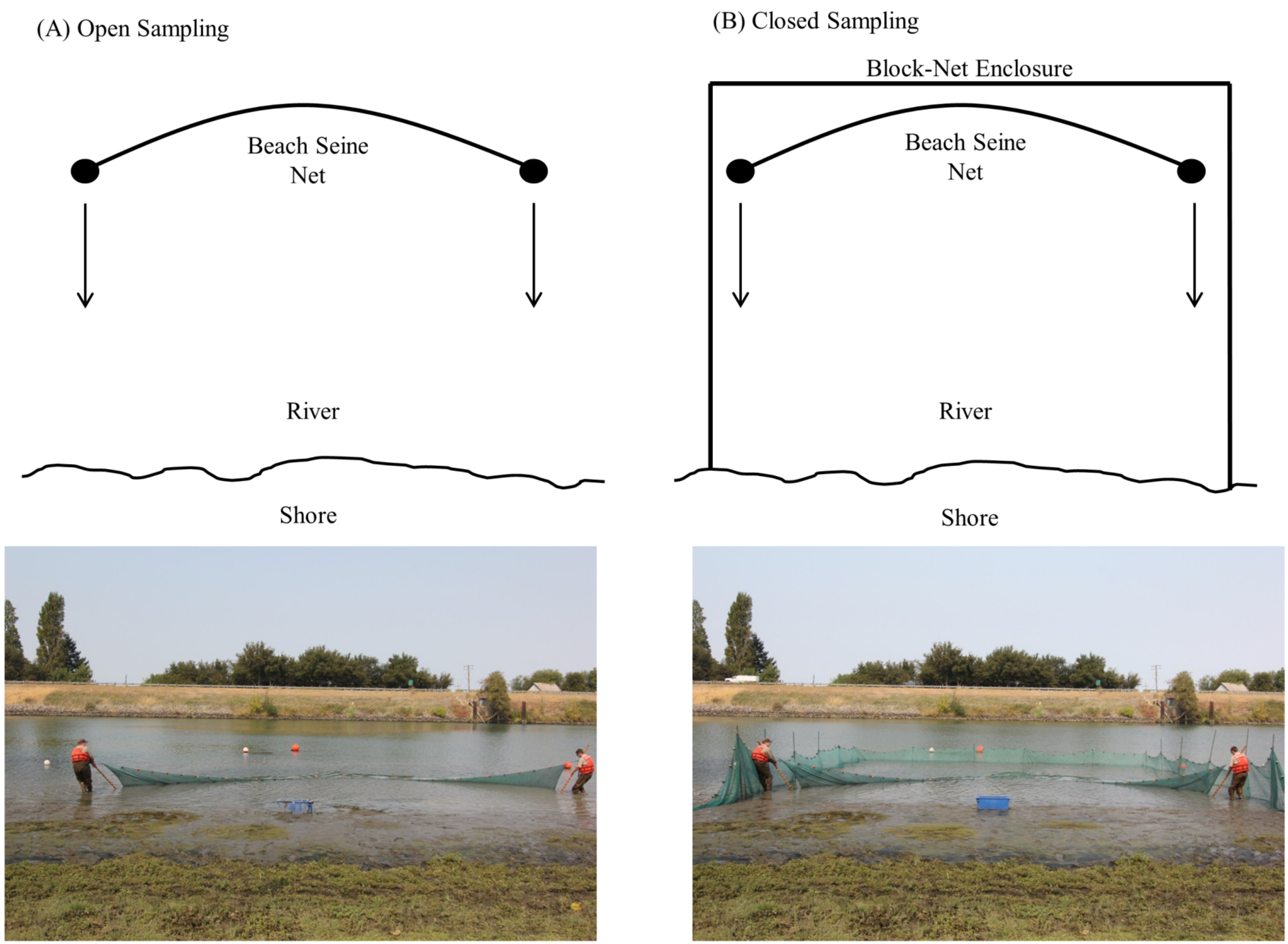

Figure 2. Schematics and photographs of beach seine sampling (A) without a block-net (open sampling) and (B) with a block net (closed sampling). (Photographs courtesy of Jacob B. Osborne, U.S. Fish and Wildlife Service).

The block-net used in this study was composed of one 50 × 2-m block-net (3 mm delta square mesh) with a lead line bottom and the top line attached to numerous 2-m tall stakes installed around each site (fig. 2). We installed the stakes approximately 2 hours prior to any fish sampling to minimize the effects of disturbance. The number of stakes installed and the distance between them were selected to ensure that the block-net would not influence the site area during fish sampling despite variations in wind and water velocities. In general, the ends of the block-net were secured to the shoreline ($\leq$ 15 m apart), and the block-net was hoisted and held above the water surface using custom hinges attached to each stake. The block-net was held above the water surface for at least 1 hour prior to any fish sampling to allow fish to recolonize the site. Thereafter, the block-net was released remotely minutes prior to fish sampling, allowing the bottom of the block net to sink to the substrate and fully enclose the fishes inside the site. Block-nets remained in position until sampling was concluded for each sampling occasion.

Fish Sampling

We sampled fish between sunrise and sunset using a standard 15.2 × 1.3-m beach seine (3 mm delta square mesh) with a continuous lead bottom line, foam floats along the top line, and a 1.2 m^3 bag in the center of the net. To estimate site-specific capture probability and abundance, six replicate beach seine hauls were conducted consecutively at each site during every sampling occasion. The time was recorded at the start of each replicate beach seine haul. During each replicate seine haul, we moved the beach seine into the water, perpendicular from the shoreline, at the downstream part of the site. The beach seine was taken to a depth of 1.2 m or a maximum distance of 15 m from the shoreline, deployed parallel to the shoreline, and then pulled toward the shoreline (fig. 2). The beach seine was continuously pulled towards the shoreline until the lead line of the beach seine’s bag was on shore. After each replicate seine haul was completed, we removed all fish from the bag and other parts of the seine and placed them in a separate holding container filled with river water for processing. During sampling, the width of the beach seine fully deployed parallel to the shoreline (site width) and the distance sampled from the shore (site length) were measured to the nearest 0.5 m using a standard measuring tape. We also noted the condition of each beach seine haul as normal (defined as no net twists, snags, or tears in the net, and the seine was pulled steadily while keeping the lead line in contact with the substrate and float line at or above the water surface); fair (defined as partial net twists, snags, or small tears in the net, but the seine was pulled steadily while keeping the lead line in contact with the substrate and float line at or above the water surface); or poor (defined as complete net twists, snags, or large tears in the net, the seine was not pulled steadily, the lead line was not in contact with the substrate, or float line was below the water surface). All fish collected in each replicate seine haul were identified to species, measured for fork length to the nearest millimeter, examined for fin clips, and held until the completion of all replicate beach seine hauls (removed from the site). After the last replicate seine haul was completed at a site during a sampling occasion, we removed the block net if present and returned all fish captured during sampling back into the site.

Physicochemical Data Collection

Water quality and physical in-stream habitat characteristics hypothesized to influence either abundance or capture probability of juvenile Chinook salmon were measured within each site during each sampling occasion. After beach seine efficiency sampling, water quality characteristics were measured 1 m upstream of the site using calibrated meters at each site to prevent any sample contamination. We measured water temperature to the nearest 0.1 ºC and specific conductance to the nearest 0.01 µS/cm using an YSI® Pro2030 meter (YSI Inc., Yellow Springs, Ohio). We measured turbidity using an HACH® 2100P turbidity meter (HACH Company, Loveland, Colorado) to the nearest 0.01 Nephelometric Turbidity Unit (NTU).

Immediately after the last seine haul was completed at a site, physical instream habitat characteristics were measured or estimated. We measured the maximum depth of a site using a 2-m top-set rod. Mean water velocity was estimated by averaging measurements taken at 3–5 m randomly selected locations within the site at a water depth of 0.6 m using a Marsh McBirney Flo-Mate™ model 2000 flow meter (HACH Company, Loveland, Colorado) in conjunction with a 2-m top-set rod. We also estimated the mean volume of the site sampled by multiplying the site length by the width and by the maximum depth divided by two, assuming a constant gradient. The area of each site was estimated by multiplying the site width by site length. We estimated the mean shoreline gradient by dividing the site length by the maximum depth. Substrate composition within the sample area was quantified visually, as percentages, by two or more crewmembers and averaged. We estimated substrate composition from 10 random substrate samples taken within a site by a small ponar or shovel. Substrate composition was categorized based on particle diameter as fine sediment (< 0.5 mm; clay and silt), sand (0.5–5 mm), gravel (6–50 mm), coarse (> 50 mm), and pavement (modified from Dunne and Leopold, 1978). We quantified wood debris density by counting the pieces of large wood within the site that were greater than 50 cm in length and greater than 10 cm in diameter or aggregates of smaller pieces of wood with comparable volume and dividing by the site area. Submerged, emergent, and floating aquatic vegetation within the sampled area also were quantified visually, as percentage of the site area present, by two or more crewmembers and averaged.

Model Development

To explicitly estimate the degree to which non-enclosure samples were geographically closed, we developed hierarchical N-mixture models that allowed for open and closed population samples. First, for samples where block-nets were used to enforce closure, we used the multinomial-Poisson mixture model (Royle, 2004b; Royle and Dorazio, 2006) as implemented by the “multinomPois” function of the “unmarked” package in R (Fiske and Chandler, 2011). In this hierarchical model, site-specific abundance is viewed as being drawn from a Poisson distribution:

$$N_i \sim \text{Poisson}(\mu) \tag{1}$$

where N_i is the number of individuals within the block-net enclosure at each of $i = 1, \ldots, R$ sites, and μ is the mean abundance across all sites. A multi-pass depletion sample performed on N_i yields a vector of sample counts, $\mathbf{y}_i$, following a multinomial distribution:

$$y_{i1}, \ldots, y_{iJ} \sim \text{Multinomial}(N_i, \pi_{i1}, \ldots, \pi_{iJ}) \tag{2}$$

where y_{ij} is the number of individuals sampled by the beach seine at site i on pass j (j = 1, …, J), and π_{ij} is the multinomial cell probability associated with the probability of first capturing an individual on pass j. For a multi-pass removal sample at site i,

$$\pi_{ij} = p(1-p)^{j-1} \tag{3}$$

where p is the probability of capturing an individual on each seine haul.

The integrated likelihood function for this multinomial-Poisson mixture model has a convenient computational form that reduces to the product of conditionally independent Poisson distributions (Royle, 2004b):

$$f(\mathbf{y}_i \mid \mu, p) = \prod_i \prod_j \text{Poisson}(\mu_i \pi_{ij}) \,. \tag{4}$$

This likelihood function is implemented in the multinomPois function of the unmarked package (Fiske and Chandler, 2011).

For samples without block-nets where fish were free to move in and out of the sampling area, we added a third level to the hierarchical model that explicitly accounted for lack of closure. Following Chandler and others (2011), let M_i be the superpopulation at site i, defined to be the total number of unique individuals that are available to be captured over all seine hauls at site i. Thus M_i will be greater than N_{ij} when the sampling area is not geographically closed. With this additional level to the hierarchy, we now view M_i as being drawn from a Poisson distribution,

$$M_i \sim \text{Poisson}\left(\frac{\mu}{\phi}\right) \tag{5}$$

and N_{ij} as being drawn from a binomial distribution, conditional on M_{ij}:

$$N_{ij} \mid M_{ij} \sim Binomial(M_{ij}, \phi) \,. \tag{6}$$

Here, M_{ij} is the superpopulation at site i on pass j, and ϕ is the probability that an individual in the superpopulation is available to be captured on each beach seine pass (hereafter referred to as the "availability" parameter). The multiple-pass depletion sample is now performed on the superpopulation, resulting in a progressively smaller superpopulation on each subsequent pass, such that $M_i = M_{i1} \geq M_{i2} \geq M_{i3} \geq, \ldots, \geq M_{iJ}$. Consequently, although the vector of sample counts, $\mathbf{y}_i$, remains multinomially distributed, conditional on M_i, the multinomial cell probabilities are now a function of ϕ and p:

$$\pi_{ij} = \phi p(1-\phi p)^{j-1} \,. \tag{7}$$

The likelihood function for this model is identical to that under the closed model (equation 4) with the exception that the distribution of sample counts depends on all parameters of the three-level model:

$$f(\mathbf{y}_i \mid \mu, \phi, p) = \prod_i \prod_j \text{Poisson}\left(\frac{\mu_i}{\phi_i}\pi_{ij}\right) \,. \tag{8}$$

Note that when ϕ = 1, the population is closed by definition and the three-level model described in equations 5–8 reduces to the standard multinomial-Poisson mixture model presented in equations 1–4.

In our three-level model, ϕ and p are confounded and only their product is estimable as a model parameter. However, all model parameters become estimable when the two models previously described for closed and open samples are combined using the joint likelihood of equations 4 and 8. Under this approach, p is estimated from information in the closed samples, and then conditional on p, ϕ becomes identifiable in the open samples. The primary assumption behind this approach is that the capture process is identical between open and closed samples, conditional on fish being available for capture. Fulfillment of this assumption was facilitated by our sampling protocol that collected open and closed samples on consecutive days. This protocol ensured that open and closed samples at a given site were collected under similar fish abundance and environmental conditions that influenced probability of capture.

Model Fitting and Selection

To fit alternative models to beach seine sampling data, we modified the multinomPois function to accommodate the model structure previously described and then used the unmarked package in R for model fitting and selection (Fiske and Chandler, 2011). The primary goals of model fitting and selection were to (1) evaluate whether the closure assumption was valid for non-enclosure samples, and (2) identify which environmental variables influenced fish abundance (μ), capture probabilities (p), and availability for capture (ϕ). Because p and ϕ are probabilities that vary between zero and one, a logit link function was used to express these parameters as functions of covariates. A log link function was used with covariates for abundance to constrain μ to be positive. Because the area sampled by the beach seine varied among sites and sampling occasions, we normalized for sampling area by estimating fish density (number per square meter) rather than absolute abundance. To estimate density using the unmarked package, the logarithm of area was included as an offset (a covariate with its slope fixed to one) in all abundance models.

We used an information theoretic approach (Burnham and Anderson, 2002) to evaluate the relative importance of physicochemical factors on juvenile Chinook salmon abundance (μ), availability (ϕ), and detection (p). We developed candidate models that contained different combinations of predictor variables corresponding to *a priori* hypotheses about the influence of physicochemical factors on juvenile Chinook salmon abundance (μ), availability (ϕ), and detection (p; table 1). We avoided multicollinearity by including only uncorrelated variables ($r^2 < 0.4$) in the same candidate models.

We assessed the fit of each candidate model using Akaike Information Criteria (AIC) with a small sample bias adjustment (Akaike, 1973; Hurvich and Tsai, 1989). The small sample bias adjustment was used based on the relatively large number of model parameters in comparison to the sample size (Hurvich and Tsai, 1989). We determined the best fitting candidate models by calculating Akaike weights (w_i), which could range from zero to one, with the highest weight being associated with the best fitting model in the model set (Burnham and Anderson, 2002). We assessed the amount of support one candidate model had over another by using the ratios of delta AICc and Akaike weights (Burnham and Anderson, 2002). Prior to model selection, all physicochemical data were standardized to have a mean of zero and standard deviation of one to facilitate model fitting.

We evaluated the support for geographic closure by comparing the fit of the best fitting candidate model, assuming geographic openness, to a comparable candidate model, assuming geographic closure ($\phi = 1$). Each candidate model was fitted with the same abundance and detection sub-models. We interpreted differences in model fit between the two models as evidence for or against geographic closure when sampling without a block-net.

Table 1. Hypotheses and corresponding predictor variables used to estimate the abundance (μ), availability (ϕ), and capture probability (p) of juvenile Chinook salmon using beach seine methodology within the Sacramento-San Joaquin Delta and San Francisco Bay, California.

Response variable	Predictor variable	Hypothesis
Abundance/Density	Temperature	Water temperature affects juvenile Chinook salmon occupancy by influencing fish physiology.
	Day of year	Abundance varies with time as the juvenile salmon population migrates through the Sacramento-San Joaquin Delta towards the ocean.
	Water velocity	Water velocity affects juvenile Chinook salmon occupancy by influencing migration rates or metabolic activity.
Availability	Water velocity	Water velocity affects juvenile Chinook salmon availability by influencing migration rates of fish traveling with the water current.
Capture	Fine sediment	Percent coverage of fine sediment affects juvenile Chinook salmon detection by influencing the amount of interstitial space among substrata, and between the seine's lead-line and substrata.
	Water velocity	Water velocity affects juvenile Chinook salmon detection by influencing how the seine is distributed throughout the water column.

Results

Data Collection

We sampled 30 sites from February to May 2014. Four of these sites were not sampled using a block-net because of logistical constraints or alterations in site conditions between sampling occasions and thus were only sampled on a single occasion without a block-net. Samples were collected during the second year of a critical drought and represented a wide range of physicochemical conditions (table 2). Of the 30 sites sampled, 8 (27 percent) sites were on boat ramps and 22 (73 percent) sites were on beaches adjacent to levees. A total of 3,675 unmarked juvenile Chinook salmon were collected during our study. Juvenile Chinook salmon averaged 40.14 mm fork length (standard deviation [SD] = 8.74) and ranged from 27 to 218 mm. Most individuals (99.1 percent) were collected at sites on the lower Sacramento River during February and March, and nearly all samples in the central and southern Delta had zero catches of Chinook salmon. Consequently, we restricted our analysis to the 11 sites and 22 sampling occasions in the northern Delta that had non-zero catches of Chinook salmon. During this period, mean daily Sacramento River discharge at Freeport, California, varied considerably based on the occurrence of two storms and subsequent freshets (mean = 365.7 m^3/s, SD = 177.9, range = 186.3–785.9 m^3/s; California Department of Water Resources, 2014). No juvenile Chinook salmon were collected in 12 sites, which were all within the lower San Joaquin River, southern Delta, and Liberty Island (fig. 1). In general, the amount of time spent constructing block-nets and waiting for the disturbance to subside averaged 117 minutes (range = 90–210 minutes) and required 3–4 staff. The time spent conducting replicate beach seine hauls averaged 31 minutes (range = 14–123 minutes) and required 2 staff.

Table 2. Mean and range of physicochemical conditions in sites sampled within the Sacramento-San Joaquin Delta and San Francisco Bay, California, spring 2014.

[SD, standard deviation; °C, degree Celsius; m, meter; m/s, meter per second; m^2, square meter; m^3, cubic meter; µS/cm, microsiemens per centimeter; NTU, Nephelometric Turbidity Unit]

Variable	Mean (SD)	Range
Temperature (°C)	16.1 (2.358)	12.7–21
Conductivity (µS/cm)	364.46 (295.392)	73.2–1342
Turbidity (NTU)	43.85 (66.197)	4.28–433
Coarse sediment (percent)	0.08 (0.573)	0–4.286
Gravel sediment (percent)	3.58 (8.756)	0–38.125
Sand sediment (percent)	49.34 (38.896)	0–100
Fine sediment (percent)	24.38 (26.437)	0–100
Pavement (percent)	22.61 (38.819)	0–100
Mean velocity (m/s)	0.06 (0.097)	0–0.456
Aquatic vegetation coverage (percent)	5.71 (16.718)	0–100
Woody debris (number/m^2)	0.01 (0.023)	0–0.125
Mean max depth (m)	0.88 (0.223)	0.45–1.2
Gradient	0.105 (0.052)	0.03–0.317
Seine width (m)	9.04 (4.099)	3–15
Site area (m^2)	8.34 (3.276)	1.5–16.5
Site volume (m^3)	36.8 (22.095)	8.25–107.25
Day of year	March 26, 2014 (23.3)	Feb. 13–May 8

Model Selection

The best fitting model included capture probability modeled as a function of water velocity and percent coverage of fine sediment; abundance modeled as a function of temperature, water velocity, and sampling date; and availability modeled as constant across sites (table 3). The next best model included the same variables except for the exclusion of temperature effect on abundance. The lowest-AICc model was strongly supported relative to the second best model ($\Delta AIC_C = 10.6$) with essentially all of the weight assigned to this model ($w_i = 0.995$).

Table 3. Predictor variables, number of parameters (K), AIC_C, ΔAIC_C, and Akaike weights (*w*) for the 10 best fitting candidate models (*i*) predicting juvenile Chinook salmon abundance (μ), availability (ϕ), and detection (*p*) within the Sacramento-San Joaquin Delta and San Francisco Bay, California, spring 2014.

[AIC_C, Akaike Information Criterion, >, greater than; <, less than]

Candidate model	K	AIC_C	ΔAIC_C	*wi*
$\mu = f$(intercept + temperature + velocity + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment + velocity)	8	3,947.60	0.00	>0.995
$\mu = f$(intercept + velocity + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment + velocity)	7	3,958.16	10.56	<0.005
$\mu = f$(intercept + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment + velocity)	6	3,971.92	24.32	0
$\mu = f$(intercept + temperature + velocity + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment)	6	4,095.91	148.31	0
$\mu = f$(intercept + velocity + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment)	7	4,116.76	169.16	0
$\mu = f$(intercept + date) $\phi = f$(intercept) $p = f$(intercept + fine sediment)	6	4,368.80	421.20	0
$\mu = f$(intercept + temperature + velocity) $\phi = f$(intercept) $p = f$(intercept + fine sediment + velocity)	7	4,760.72	813.12	0
$\mu = f$(intercept + temperature) $\phi = f$(intercept + velocity) $p = f$(intercept + fine sediment + velocity)	5	4,790.62	843.02	0
$\mu = f$(intercept + temperature + velocity) $\phi = f$(intercept) $p = f$(intercept + velocity)	6	4,829.33	881.73	0
$\mu = f$(intercept + temperature) $\phi = f$(intercept) $p = f$(intercept + fine sediment + velocity)	6	4,829.95	882.35	0

The best candidate model estimated that the probability of capturing a juvenile Chinook salmon was positively related to fine sediment cover and negatively related to water velocity (table 4, figs. 3 and 4). The abundance of juvenile Chinook salmon was inversely related to sampling date and water velocity and positively related to water temperature (table 4, figs. 5–7).

The best model for predicting juvenile Chinook salmon detection and abundance indicated considerable lack of geographic closure for beach samples without block-nets. The identical model that assumed geographic closure ($\phi = 1$) fit considerably worse than the model that allowed for geographic openness ($\Delta AIC_C = 393.19$), strongly rejecting the closure assumption for beach seine samples without block nets. The estimate of ϕ indicated that the probability of an individual juvenile Chinook salmon being available for capture during a replicate sample was, on average, 48.9 percent (table 4).

Table 4. Parameter estimates, upper and lower 95-percent confidence intervals for variables included in the best approximating abundance (μ), availability (ϕ), and capture (p) model for juvenile Chinook salmon within the Sacramento-San Joaquin Delta and San Francisco Bay, California.

[SE, standard error]

Parameter	Estimate (SE)	Lower	Upper
Abundance (log scale)			
Intercept	0.182 (0.026)	0.132	0.232
Temperature	0.142 (0.036)	0.072	0.212
Water velocity	-0.105 (0.020)	-0.144	-0.067
Sampling date	-0.830 (0.030)	-0.888	-0.773
Availability (logit scale)			
Intercept	-0.044 (0.056)	-0.153	0.066
Detection (logit scale)			
Intercept	1.27 (0.066)	1.138	1.395
Fine sediment	0.68 (0.102)	0.475	0.875
Water velocity	-0.49 (0.038)	-0.569	-0.418

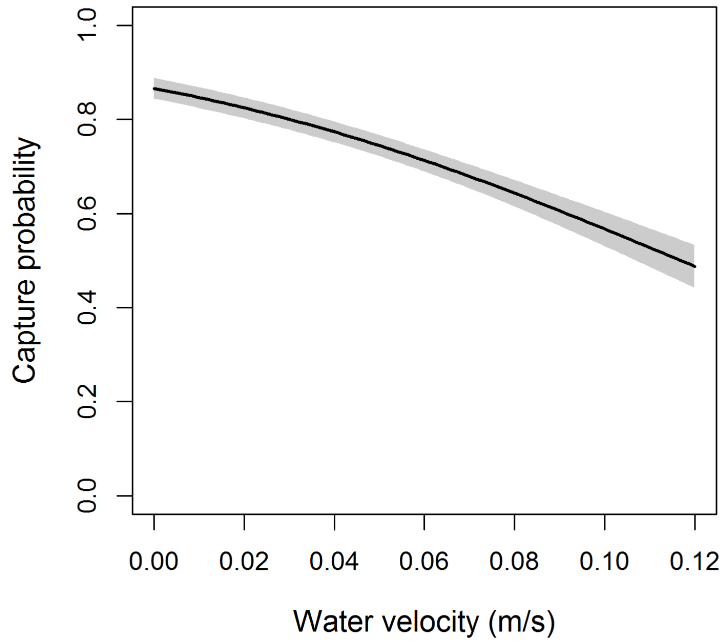

Figure 3. Relations between capture probabilities (*p*) and mean water velocity for juvenile Chinook salmon while beach seining within the Sacramento-San Joaquin Delta and San Francisco Bay, California. The mean capture probability (solid line) and 95-percent confidence limits (gray fill) were estimated with the other covariates set to their mean. (m/s; meter per second)

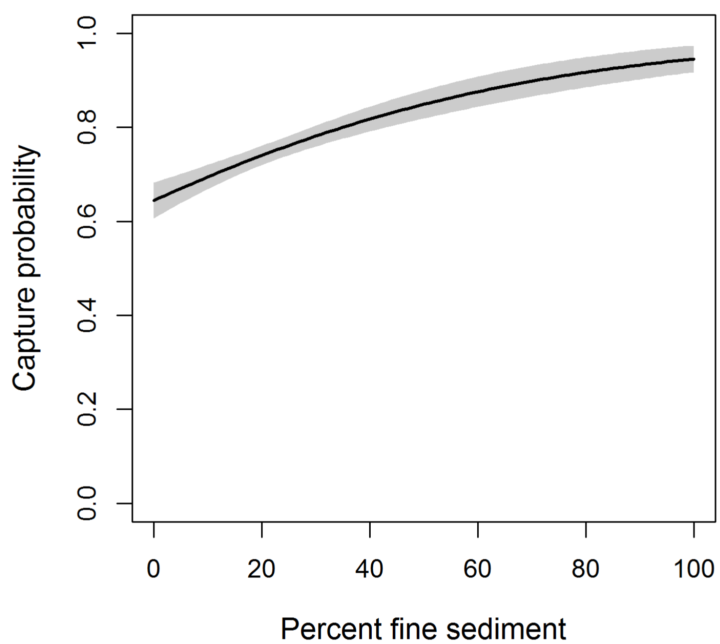

Figure 4. Relations between conditional capture probabilities (*p*) and fine sediment cover for juvenile Chinook salmon while beach seining within the Sacramento-San Joaquin Delta and San Francisco Bay, California. The mean detection (solid line) and 95-percent confidence limits (gray fill) were estimated with the other covariates set to their mean.

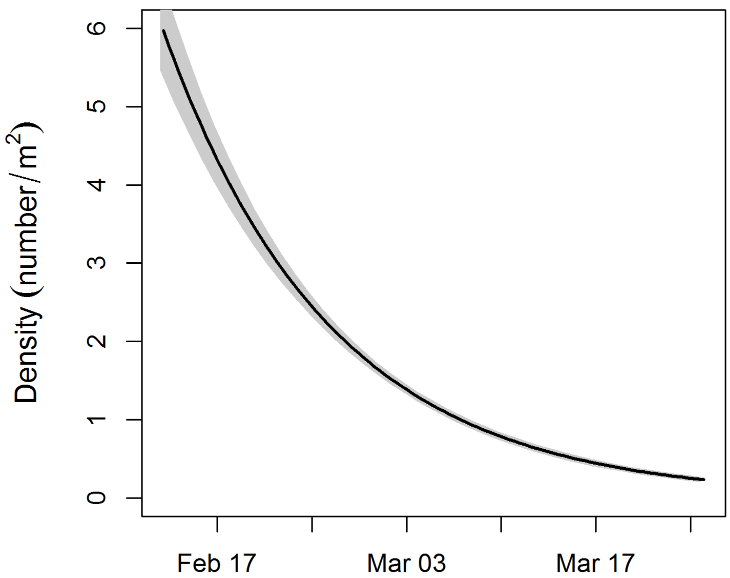

Figure 5. Relations between juvenile Chinook salmon density (abundance/area sampled) and sampling date within the Sacramento-San Joaquin Delta and San Francisco Bay, California. The mean density (solid line) and 95-percent confidence limits (gray fill) were estimated with the other covariates set to their mean.

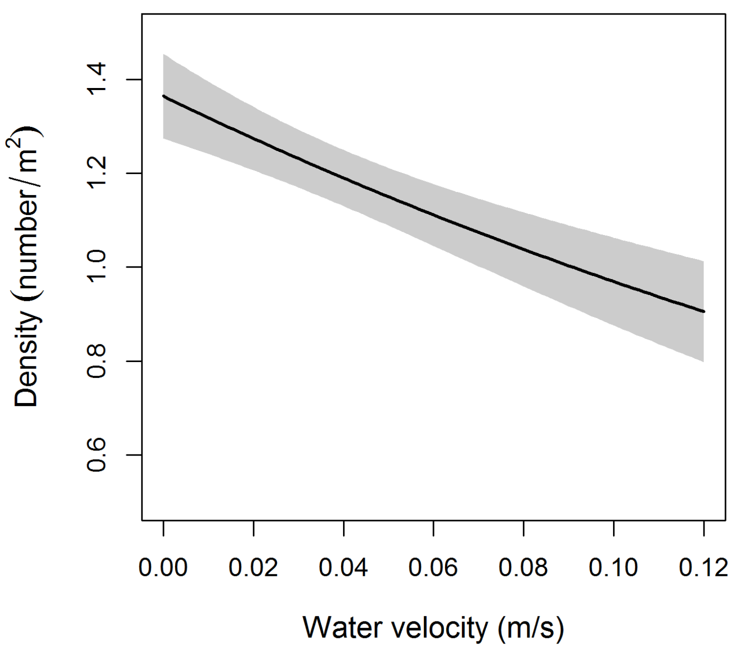

Figure 6. Relations between juvenile Chinook salmon density (abundance/area sampled) and water velocity within the Sacramento-San Joaquin Delta and San Francisco Bay, California. The mean density (solid line) and 95-percent confidence limits (gray fill) were estimated with the other covariates set to their mean. (m/s, meter per second)

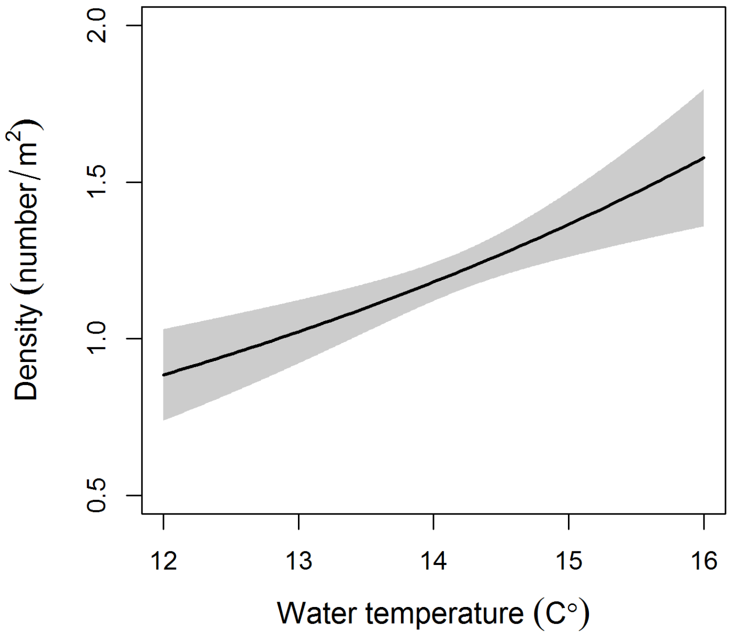

Figure 7. Relations between juvenile Chinook salmon density (abundance/area sampled) and temperature within the Sacramento-San Joaquin Delta and San Francisco Bay, California. The mean density (solid line) and 95-percent confidence limits (gray fill) were estimated with the other covariates set to their mean.

Discussion

We determined that sampling date, water velocity, and temperature were the most important factors affecting juvenile Chinook salmon density at long-term monitoring beach seine sites within the San Francisco Estuary and lower Sacramento and San Joaquin Rivers. However, we also observed more juvenile Chinook salmon within the mainstem Sacramento River during periods of increased river discharge. These findings are consistent with several studies (Kjelson and others, 1982; Stevens and Miller, 1983; Brandes and McClain, 2001). In general, juvenile Chinook production is considerably higher within the Sacramento River Basin relative to the San Joaquin River Basin (Williams, 2006) and only a relatively small proportion of juveniles from the Sacramento River Basin migrate through the interior Delta (Perry and others, 2010). Furthermore, increases in river discharge can influence immigration rates into the Delta through causing displacement or dispersal of juvenile salmon (Kjelson and others, 1982; Williams, 2006). Stevens and Miller (1983) demonstrated that juvenile Chinook salmon densities were positively associated with increases in river discharge and hypothesized that the increase in density was the result of dispersal to avoid density dependent mortality. Because our study occurred during the second year of a critical drought, the probability of density dependence (mortality or growth) occurring within the San Francisco Estuary and its watershed may be higher relative to wetter water years (Williams, 2006) and may have limited residency times within the Delta. The strong effect of sampling date on abundance captured the seasonal pulse of the juvenile salmon population moving through the Delta. At a smaller scale, we observed that juvenile salmon density was positively and inversely related to water velocity among the monitoring sites, a finding that is consistent with habitat use of juvenile Chinook salmon.

We also determined that juvenile Chinook salmon density was positively related to water temperature over the range of temperatures observed in our study (12–16 °C). Over a wider range of water temperature, Kjelson and others (1982) reported higher occurrence rates and catch densities of juvenile Chinook salmon within the Sacramento-San Joaquin Delta at locations and times dominated by cooler water temperatures. In general, elevated water temperatures can influence the density of juvenile Chinook at monitoring locations by affecting migratory rates (Giorgi and others, 1997) or survival (Kjelson and Brandes, 1989; Newman and Rice, 2002). Studies have demonstrated that water temperatures greater than 23–24 °C can negatively affect the survival of juvenile salmon by exceeding the upper physiological limits (Brett, 1952; Baker and others, 1995; Marine and Cech, 2004). Conversely, juvenile Chinook reared in 21–24 °C water temperatures can experience decreased growth rates, impaired smoltification, and increased predation vulnerability (Marine and Cech, 2004; Myrick and Cech, 2004). If water temperatures in our study had encompassed a wider range, exceeding the thermal optima of juvenile Chinook salmon, we would not expect abundance to continue to be positively related to water temperature.

Our N-mixture model requires a number of assumptions to estimate the availability parameter, ϕ. Recall that capture probability (p) and availability (ϕ) are confounded in samples that are geographically open, but p can be estimated when closure is enforced with block-nets. Because all the information about capture probability comes from the closed samples, our model assumes that the capture process is the same between open and closed samples, given that fish are available to be captured. In other words, factors that affect capture probability should act similarly to influence capture probability regardless of whether the beach samples are geographically open or enclosed with a block-net. Although we have little reason to believe that factors such as water velocity and substrate composition affect capture probability differently between open and closed samples, violation of this assumption would induce bias in our estimates of availability.

We also assume that beach seines conducted within enclosures are indeed geographically closed. The underlying assumption is that $\phi = 1$ within enclosures, but if some fish within the block nets are unavailable for capture, then $\phi < 1$ and our estimate of capture probability will be biased low. Bias of this nature would also propagate bias in our estimates of ϕ in the open samples. For example, if some areas of the block-net do not rest flush against the substrate, fish may be able to escape from the enclosure making them unavailable for sampling. Although we cannot rule out this possibility, we believe bias of this nature is negligible in our study.

Our model also assumes a simple binomial process for modeling the probability of fish being available for capture on each beach seine pass. The primary assumptions of the binomial model are that (1) the act of sampling does not influence the probability of being available for capture, and (2) every fish has the same probability of being available for capture. These assumptions are likely to be violated to some degree. First, sampling with a beach seine disturbs the environment and probably elicits a behavioral avoidance response from individuals within the sampling area. Alternatively, fish outside the sampling area may be attracted to the sampling area if sampling increases suspended detritus. These behavioral responses could affect the probability of fish being available for sampling on each subsequent beach seine pass. The degree to which these processes bias estimates from our model remain unknown but will likely depend on the size of the sampling area, swimming velocities of fish, and the time required to complete a multiple-pass removal sample at a particular site.

Individuals are also likely to vary in their probability of being available for capture. Fish near the edge of the sampling area could be less likely to be available for capture on subsequent beach seine passes relative to fish near the center of the sampling area. Chandler and others (2011) simulated this type of process using a Gaussian movement kernel to represent home ranges of animals juxtaposed against the sampling area. They showed that parameter estimates remained unbiased when availability varied among individuals. In our case, juvenile Chinook salmon probably follow more complex movement patterns than simply occupying a home range. Juvenile Chinook salmon sampled in our study are migrating towards the ocean, rearing and feeding as they move downstream. Although beyond the scope of our analysis, a useful extension of our work would be to replace the simple binomial model with an advection-diffusion movement model that explicitly accounts individuals moving into and out of the sampling area.

Our N-mixture model also assumes that the paired open-closed samples are statistically independent. However, we expect there to be within-site correlation because we purposefully sampled each site on consecutive days to ensure that open and closed samples were collected during similar environmental conditions and site-specific abundance. Lack of independence of this nature would be unlikely to bias parameter estimates, but could affect the estimates of uncertainty about the parameter estimates. A model that included site as a random effect would appropriately account for the within-site correlation. However, the unmarked package does not implement random-effects N-mixture models. Random effects N-mixture models can be implemented in a Bayesian framework, which would be a useful extension of our model in the future.

We developed a novel approach for explicitly estimating the degree of closure in beach seine samples, allowing us to estimate absolute abundance (or density) of juvenile Chinook salmon for beach seine samples without enclosures. Although block-nets enforce closure, their use as a standard monitoring protocol is hampered by the amount of time required to deploy a block net (only two sites per day could be sampled in our study). Our sampling and analysis design with open and closed samples can be used as a calibration technique to develop models for non-enclosure samples that allow abundance to be estimated while explicitly accounting for lack of closure. Such an approach still requires a subset of samples with block-nets but also allows abundance to be estimated from non-enclosure samples that require much less sampling effort. Inferences about abundance often are based on count data that may be biased due to heterogeneity in capture and availability. Given the ubiquity of beach seines for sampling fish populations, novel techniques that account for imperfect capture and availability are needed to avoid bias in abundance estimates. Our study takes an important step toward this end.

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