

# Hierarchical modeling of juvenile chinook salmon survival as a function of Sacramento-San Joaquin Delta water exports

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## Abstract

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2 A multi-year study in the Sacramento-San Joaquin Delta system was carried out to exam-  
3 ine the relationship between the survival of out-migrating Chinook salmon *Oncorhynchus*  
4 *tshawytscha* and the amount of water exported from the system by the two major pumping  
5 stations in the southern portion of the Delta. Paired releases of groups of coded-wire-tagged  
6 juvenile late-fall run Chinook salmon were made at two locations in the Delta, one in the  
7 main stem Sacramento River and one in the interior portion of the Delta where they were  
8 more likely to be directly affected by the pumping stations. Shortly after release, fish were  
9 recovered downstream by a mid-water trawl, and, over a two to four year period, fish were  
10 recovered in samples of ocean fishery catches and from spawning ground surveys. A Bayesian  
11 hierarchical model for the recoveries was fit which explicitly accounted for between release  
12 variation in survival and capture probabilities as well as sampling variation in the recoveries.  
13 Survival of the interior Delta releases was considerably lower than the survival of main stem  
14 releases (mean ratio of survival probabilities was 0.35). The ratio of survival probabilities  
15 was negatively associated with water export levels, but various model selection criteria gave  
16 more, or nearly equal, weight to simpler models which excluded exports. The signal-to-noise  
17 ratio, as defined in terms of the export effect relative to environmental variation, however,  
18 was very low, and could explain indeterminacy in the results of model selection procedures.  
19 Many more years of data would be needed to more precisely estimate the export effect.  
20 Whatever the factors are that adversely affect survival through the interior Delta, to deter-  
21 mine the overall effect on out-migrating Sacramento river Chinook salmon the fraction of  
22 out-migrants that enter the interior Delta needs to be estimated.

# 1 Introduction

Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) survival experiments have been conducted in the Sacramento-San Joaquin Delta of California since the early 1970s (Kjelson, et al. 1981 and 1982; Kjelson and Brandes 1989; Brandes and McLain 2001). The experiments have involved the release, at multiple locations throughout the Delta, of marked and tagged hatchery-reared juvenile salmon followed by later recovery of these salmon. Survival of juvenile salmon through the Delta is of particular interest because of the Delta's role in water management in California. Two large pumping facilities, the Central Valley Project's C. W. "Bill" Jones Pumping Plant (CVP) and the State Water Project's Harvey Banks Pumping Plant (SWP), are located in the south Delta (Figure 1) and provide water, to over 23 million people, for municipal, agricultural and domestic purposes throughout central and southern California. The Delta is critical for Sacramento-San Joaquin origin salmon survival as all juvenile salmon must migrate through the Delta to reach the Pacific Ocean. There are two races of Central Valley Chinook salmon listed under the Endangered Species Act, winter run as endangered (NMFS 1997) and spring run as threatened, with the other two races, fall and late-fall run, considered species of concern. The role of CVP and SWP exports on juvenile salmon survival through the Delta is of great interest to managers and stake-holders and this interest has been a primary reason for the salmon survival experiments.

Previous analyses of some of these survival experiments, using juvenile fall run Chinook salmon (Kjelson, et al. 1981; Brandes and McLain 2001; Newman and Rice 2002; Newman 2003) which out-migrate through the Delta from March through June (Yoshiyama, et al. 1998), have suggested that survival is negatively associated with water exports. These analyses included data from a very spatially-dispersed set of release locations where many

46 variables other than export levels potentially affected survival.

47 In this paper we analyze release-recovery data from a more narrowly focused study of ex-  
48 port effects, where factors other than exports were to some degree controlled for by temporal  
49 pairing of releases. Paired releases of juvenile late-fall run Chinook salmon were made simul-  
50 taneously in the interior Delta and in the main stem of the Sacramento River downstream of  
51 the Delta Cross Channel and Georgiana Slough (Figure 1). The interior Delta is an area of  
52 the Delta that out-migrating juvenile salmon can enter from the Sacramento River through  
53 either the Delta Cross Channel, when the Delta Cross Channel gates are open, or Georgiana  
54 Slough. Fish released directly into the interior Delta are presumably more vulnerable to the  
55 influence of the CVP and SWP pumping facilities than fish released in the main stem. In  
56 contrast to fall run experiments (Newman and Rice 2002), the temporal pairing of releases  
57 controlled for the effects of all factors other than release location and exports on survival.  
58 One limitation of the study, however, is that levels of exports cannot be fixed or controlled  
59 by researchers due to the precedence of water demands. Another limitation is that the over-  
60 all effect of exports on out-migrating salmon cannot be determined without knowing the  
61 proportion of out-migrating salmon that enter the interior Delta.

62 Brandes and McLain (2001) analyzed paired release-recovery data that included releases  
63 of late-fall run fish and fall run fish. Their analysis procedure was to first calculate freshwa-  
64 ter recovery fractions (adjusted for estimates of capture efficiency) and then to regress the  
65 fractions against export levels. Based on the data available at the time, they found a sta-  
66 tistically significant negative association between the survival of Georgiana Slough releases  
67 relative to the survival of Ryde releases and export levels (Figure 1).

68 One purpose of this paper is to update the analyses of Brandes and McLain (2001)

69 incorporating the since-gathered data but only using late-fall run stock. Late-fall run fish  
70 are potential surrogates for winter run salmon (Brandes and McLain 2001), since both runs  
71 out-migrate from November through May (Yoshiyama, et al. 1998). A second purpose is  
72 to compare results for the Brandes and McLain approach with results based on Bayesian  
73 hierarchical models (Carlin and Louis 1996; Gelman, et al. 2004; for a fisheries release-  
74 recovery application, Newman 2003). Hierarchical models offer several potential advantages  
75 for analyzing multi-release studies. One advantage is parsimony; rather than estimating  
76 release-pair specific effects independently, e.g.,  $n$  independent estimates of relative survival  
77 for  $n$  release pairs, a single distribution for the effects underlying the results for all release  
78 pairs is specified. Another advantage is that such a *random effects* distribution characterizes  
79 the environmental variation in survival probabilities, and the hierarchy makes this variation  
80 distinct from sampling variation. A third advantage is that a hierarchical model provides  
81 a sensible means of combining data from multiple year studies, in this case multiple sets of  
82 paired releases with associated recoveries, e.g., giving release-pairs with fewer fish released  
83 less weight than those with more fish released.

84 The paired release-recovery experiment design and the statistical models used for analysis  
85 are described in Section 2. Results are given in Section 3. We close with a discussion (Section  
86 4) of the management implications of the results.

## 87 2 Methods

### 88 2.1 Data

89 The paired release-recovery data, including numbers released, numbers recovered at various  
90 locations, and the water export levels at time of release, are given in Table 1. Fifteen paired  
91 groups of juvenile late-fall run Chinook salmon yearlings (mean size  $> 100$  mm), reared at  
92 Coleman National Fish Hatchery, were released between 1993 and 2005 during the months of  
93 December and January. At the hatchery, each fish had its adipose fin clipped and a coded-  
94 wire-tag was inserted into its snout; to read such tags after implantation requires sacrificing  
95 the fish. The tag codes were batch-specific, i.e., the same codes were used for thousands of  
96 fish, with unique tag codes for each release location. The fish were trucked from the hatchery  
97 to the interior Delta (Georgiana Slough) and the main stem Sacramento River (at Ryde or  
98 Isleton) (Figure 1), and releases were made at both locations with a day or two.

99 Within a few weeks of release, recoveries were made in freshwater by a mid-water trawl  
100 operating near Chipps Island (Figure 1). The trawl was towed at the surface almost daily  
101 for four to six weeks after the fish were released. Typically, ten, twenty minute tows were  
102 made each day between roughly 7 AM and noon. Juvenile fish were also recovered at fish  
103 facilities located in front of the pumping plants at CVP and SWP. These recovered salmon  
104 were transported by truck and released at locations north of the pumps and nearer to the  
105 main stem of the Sacramento River upstream of Chipps Island, where they could potentially  
106 be caught by the mid-water trawl at Chipps Island. Then over a three to four year period,  
107 adult fish were recovered from samples of landings from ocean fisheries. The total number of  
108 ocean fishery recoveries, summed over many landing areas and years, was estimated from a

109 spatially and temporally stratified random sample of landings and catches. The percentage  
110 of ocean catch that is sampled is roughly 20-25%. Additional recoveries of adult fish were  
111 made in freshwater fisheries, at hatcheries, and on spawning grounds (inland recoveries).  
112 The expanded ocean and inland recoveries were retrieved from a web-based database query  
113 system administered by Pacific States Marine Fisheries Commission ([www.rmfc.org](http://www.rmfc.org)). The  
114 straying proportions, i.e., the fraction of inland recoveries that were not recovered at Coleman  
115 National Fish Hatchery, for Georgiana Slough and Ryde releases varied considerably between  
116 release pairs, but within release pairs the proportions were quite similar.

117 The combined water export levels, hereafter referred to as exports, from both the SWP  
118 and the CVP were averaged over a three day period starting the day after release in Georgiana  
119 Slough. The choice of three days was somewhat arbitrary, although linear correlations of  
120 three day average export levels with averages for 10 and 17 days were quite high ( $r=0.94$   
121 for 10 days and  $r=0.91$  for 17 days). There is a certain degree of imprecision to defining an  
122 export variable with regard to fish outmigration because some fish take longer to out-migrate  
123 than others and the degree of exposure to the area influenced by the pumps will vary; e.g.,  
124 the Georgiana Slough release in group 1 had one recovery at the SWP fish facility three  
125 months after release. Furthermore, export levels are not necessarily constant, even within  
126 a three day period, and day to day variation in export level is not captured by the use  
127 of an average. Water volumes entering the interior Delta are also affected by the position  
128 of the Delta Cross Channel gates, which when open increase the flow of water from the  
129 Sacramento River into the interior Delta. The gates were open on the day of the Georgiana  
130 Slough releases in the first two years of the study (1993 and 1994), and for one of the 1999  
131 releases (Group 10), but otherwise closed for all other releases. Recognizing that it might be  
132 the amount of exports relative to total inflow from the Sacramento River (at Freeport) that

133 could be more important than absolute exports, the export to flow ratio was also examined  
134 as a covariate; the relationship between the ratios and the absolute values, however, was  
135 positive and linear ( $r=0.83$ ).

## 136 **2.2 Assumptions and notation**

137 Within and between releases, the fate of an individual fish, e.g., live or die, caught or not, was  
138 assumed independent of the fate of any other fish. For all fish released from one location at  
139 the same time, the survival and capture probabilities were assumed identical. In recognition  
140 of the paired release aspect of the studies, we further assumed that within a release pair  
141 the probability of capture at Chipps Island, and the recovery probabilities (a complicated  
142 combination of survival and capture probabilities) in the ocean fishery and inland areas were  
143 identical. For example, for release pair 1 (Table 1) the capture probability for a Ryde fish or  
144 a Georgiana Slough fish that has survived to Chipps Island is the same, but that probability  
145 can differ from that for release pair 2.

146 We further assumed that only fish released in Georgiana Slough were affected by exports.  
147 Ryde is located 2.5 miles downstream of the location on the main stem where water is diverted  
148 into the Georgiana Slough and releases at Ryde are further removed geographically from the  
149 export facilities. However, for two years there were sizeable numbers of Ryde fish recovered  
150 at the fish facilities (Table 1); these were potentially situations where flood tides carried  
151 some of the Ryde releases into the interior Delta at some upstream or downstream locations,  
152 e.g., Three Mile Slough (Figure 1), a channel several miles downstream that connects the  
153 Sacramento and San Joaquin Rivers in the Delta.

154 For a given release pair  $t$ , the numbers released at Ryde and Georgiana Slough are



155 denoted  $R_{Ry,t}$  and  $R_{GS,t}$  and the associated recoveries at Chipps Island are  $y_{Ry \rightarrow CI,t}$  and  
 156  $y_{GS \rightarrow CI,t}$ . Expanded ocean recoveries are  $\hat{y}_{Ry \rightarrow Oc,t}$  and  $\hat{y}_{GS \rightarrow Oc,t}$ , and similarly expanded  
 157 inland recoveries are  $\hat{y}_{Ry \rightarrow IL,t}$  and  $\hat{y}_{GS \rightarrow IL,t}$ . Recovery fractions, defined as the ratios of  
 158 number of recoveries to number released, will be denoted  $\hat{r}$ , with subscripts indicating release  
 159 and recovery locations; e.g.,  $\hat{r}_{Ry \rightarrow Oc,t} = \hat{y}_{Ry \rightarrow Oc,t} / R_{Ry,t}$ . Combined recovery fractions for more  
 160 than one recovery location are denoted similarly; e.g.,  $\hat{r}_{Ry \rightarrow CI+Oc+IL,t} = (y_{Ry \rightarrow CI,t} + \hat{y}_{Ry \rightarrow Oc,t} +$   
 161  $\hat{y}_{Ry \rightarrow IL,t}) / R_{Ry,t}$ .

162 Notation for the probability that a Ryde release is recovered at Chipps Island is  $r_{Ry \rightarrow CI,t}$   
 163 and the recovery probability for ocean fisheries and inland recoveries combined is  $r_{Ry \rightarrow Oc+IL,t}$ .  
 164 The corresponding probabilities of recovery for Georgiana Slough releases are denoted  $\theta_t r_{Ry \rightarrow CI,t}$   
 165 and  $\theta_t r_{Ry \rightarrow Oc,t}$ , where  $\theta_t$  is a release pair-specific constant. Given the assumption that within  
 166 a release pair, the capture probabilities at Chipps Island are the same,  $\theta_t$  is the ratio of the  
 167 survival probability between Georgiana Slough and Chipps Island to the survival probability  
 168 between Ryde and Chipps Island. How  $\theta_t$  relates to export levels is the primary management  
 169 question.

## 170 2.3 Non-Bayesian, non-hierarchical models

171 Two non-hierarchical models were fit. Both somewhat mimic Brandes and McLain's (2001)  
 172 analyses in that a two step procedure was used: (a) an estimate of  $\theta_t$  is calculated; (b)  
 173 the estimate is regressed against exports. The first model is quite similar to Brandes and  
 174 McLain's analysis in that only recoveries at Chipps Island are used, i.e.,  $\theta_t$  is estimated as  
 175 the the ratio of recovery fractions at Chipps Island for Georgiana Slough and Ryde releases,

$$176 \hat{\theta}_{1,t} = \frac{\hat{r}_{GS \rightarrow CI,t}}{\hat{r}_{Ry \rightarrow CI,t}} \quad (1)$$

177 In contrast to Brandes and McLain (2001), recoveries were not scaled by estimated gear  
 178 efficiency, because of the assumption that capture probabilities were identical within a release  
 179 pair. A simple linear regression model using standardized exports was fit:

$$180 \quad \hat{\theta}_{1,t} \sim \text{Normal}(\beta_0 + \beta_1 \text{Exp}_t^*, \sigma^2), \quad (2)$$

181 where  $\text{Exp}_t^* = (\text{Exp}_t - \overline{\text{Exp}})/s_{\text{Exp}}$ ,  $\text{Exp}_t$  is the exports at time  $t$ ,  $\overline{\text{Exp}}$  is the average export  
 182 level, and  $s_{\text{Exp}}$  is the standard deviation of exports. Assuming independence and identical  
 183 probabilities of survival and capture for all fish in a single release, the number of fish recovered  
 184 at Chipps Island is a binomial random variable, e.g.,  $y_{Ry \rightarrow CI,t} \sim \text{Binomial}(R_{Ry,t}, r_{Ry \rightarrow CI,t})$ .  
 185 Given  $R_{Ry,t}$  and  $y_{Ry \rightarrow CI,t}$ ,  $\hat{r}_{Ry \rightarrow CI,t}$  is the maximum likelihood estimate (mle) of  $r_{Ry \rightarrow CI,t}$ ;  
 186 similarly,  $\hat{r}_{GS \rightarrow CI,t}$  is the mle of  $\theta_t r_{Ry \rightarrow CI,t}$ , and  $\hat{\theta}_{1,t}$  is the mle for  $\theta_t$  based on Chipps Island  
 187 recoveries alone.

188 For the second non-hierarchical model,  $\theta_t$  was estimated using Chipps Island, ocean, and  
 189 inland recoveries combined,

$$190 \quad \hat{\theta}_{2,t} = \frac{\hat{r}_{GS \rightarrow CI + Oc + IL,t}}{\hat{r}_{Ry \rightarrow CI + Oc + IL,t}}. \quad (3)$$

191 Implicit to this calculation is the assumption that within a release pair the Chipps Island  
 192 capture probabilities, the ocean recovery probabilities, and the inland recovery probabilities  
 193 are identical. If total ocean and inland recoveries were known exactly and not estimated,  
 194 the joint distribution of Chipps Island recoveries and combined ocean and inland recoveries  
 195 would be multinomial, and  $\hat{\theta}_{2,t}$  would be the mle for  $\theta_t$ . However, with expanded recoveries,  
 196 the distribution is more complex. To account for differences in sampling variation and to  
 197 somewhat duplicate the hierarchical model, a weighted regression of the log of  $\hat{\theta}_{2,t}$  against  
 198 standardized exports was fit:

$$199 \quad \ln(\hat{\theta}_{2,t}) \sim \text{Normal}(\beta_0 + \beta_1 \text{Exp}_t^*, se_{\ln[\hat{\theta}_{2,t}]}^2 \sigma^2). \quad (4)$$

200 The weights were the inverse of the square of the standard errors of  $\ln[\hat{\theta}_{2,t}]$ ,  $se_{\ln[\hat{\theta}_{2,t}]}$ , which  
201 were calculated using the delta method (cf Section 10.5, Stuart and Ord, 1987). The log  
202 transformation ensures that  $\theta_{2,t}$  remains non-negative.

203 The primary inferential aim, for both models (Equations 2 and 4), is to estimate the  
204 slope coefficient  $\beta_1$  and its standard error.

## 205 **2.4 Hierarchical models**

206 Hierarchical models (Carlin and Louis 1996) consist of two or more levels, each level ac-  
207 counting for a different type of variation. For these data, the first level accounts for sampling  
208 variation in the recoveries conditional on survival and capture probabilities, while the second  
209 level accounts for between release pair variation in the survival and capture probabilities.  
210 The second level reflects what is sometimes referred to as random effects. The prior distri-  
211 butions for the fixed and unknown parameters of the model (in the second level) make up  
212 the third level of the model.

### 213 **2.4.1 Bayesian hierarchical model**

214 A Bayesian hierarchical model (BHM) was formulated for the joint distribution of Chipps  
215 Island recoveries and the combined ocean and inland recoveries. The statistical distributions  
216 for each of the levels of the hierarchical model are shown below. The first level distributions  
217 are conditional on the second level variables, and similarly the second level is conditional on  
218 the third level.

219 Level 1:

$$220 \quad y_{GS \rightarrow CI,t}, \hat{y}_{GS \rightarrow Oc+IL,t} \sim \text{Multinomial}(R_{GS,t}, \theta_{3,t} r_{Ry \rightarrow CI,t}, \theta_{3,t} r_{Ry \rightarrow Oc+IL,t}) \quad (5)$$

$$221 \quad y_{Ry \rightarrow CI,t}, \hat{y}_{Ry \rightarrow Oc+IL,t} \sim \text{Multinomial}(R_{Ry,t}, r_{Ry \rightarrow CI,t}, r_{Ry \rightarrow Oc+IL,t}) \quad (6)$$

222 Level 2:

$$223 \quad \ln(\theta_{3,t}) \sim \text{Normal}(\beta_0 + \beta_1 \text{Exp}^*, \sigma_\theta^2) \quad (7)$$

$$224 \quad \text{logit}(r_{Ry \rightarrow CI,t}) \sim \text{Normal}(\mu_{r_{Ry \rightarrow CI}}, \sigma_{r_{Ry \rightarrow CI}}^2) \quad (8)$$

$$225 \quad \text{logit}(r_{Ry \rightarrow Oc+IL,t}) \sim \text{Normal}(\mu_{r_{Ry \rightarrow Oc+IL}}, \sigma_{r_{Ry \rightarrow Oc+IL}}^2) \quad (9)$$

226 Level 3:

$$227 \quad \beta_0, \beta_1, \mu_{Ry \rightarrow CI}, \mu_{Ry \rightarrow Oc+IL} \sim \text{Normal}(0, 1.0E + 6) \quad (10)$$

$$228 \quad \sigma_\theta, \sigma_{r_{Ry \rightarrow CI}}, \sigma_{r_{Ry \rightarrow Oc+IL}} \sim \text{Uniform}(0, 20) \quad (11)$$

229 As noted previously the joint distributions for Chipps Island recoveries and combined ex-  
 230 panded ocean and inland recoveries cannot be multinomial due to estimation error in the  
 231 expansions, thus the Level 1 formulation is an approximation. The log transformation of  $\theta_{3,t}$   
 232 (in the Level 2 model) ensures that  $\theta_{3,t}$  is non-negative. The logit transformations at Level  
 233 2 bounds  $r_{Ry \rightarrow CI,t}$  and  $r_{Ry \rightarrow Oc+IL,t}$  between 0 and 1; however, the resulting probabilities are  
 234 so small that log transformations would have the same practical effect.

235 In contrast to the likelihood framework, the inferential objective in the Bayesian setting  
 236 is to calculate the posterior distribution for the unknown parameters (Gelman, et al. 2004),  
 237 i.e., to calculate

$$238 \quad p(\Theta | \text{Data}) \propto p(\text{Data} | \Theta) p(\Theta)$$

239 where  $\Theta$  is the vector of unknown constants, such as  $\beta_0$  and  $\beta_1$ , and unknown random  
 240 variables, such as  $\theta_t$ , and  $p(\Theta)$  is the prior distribution (here defined by Level 3). In this case

241 primary interest is in the posterior distribution for  $\beta_1$  and the probability that  $\beta_1$  is negative  
242 is a measure of the degree of a negative association between exports and the relative survival  
243 of Georgiana Slough releases.

## 244 2.4.2 Sensitivity analysis

245 Sensitivity of the BHM to the choice of distributions and functional forms was assessed by  
246 alternative formulations for each level. At Level 1, to allow for possible dependence between  
247 fish within a release as well as extra-multinomial variation due to the fact that ocean and  
248 inland recoveries are sample expansions, negative binomial distributions were used for the  
249 Chipps Island and expanded ocean and inland recoveries from a given release. For example,  
250 the negative binomial model for recoveries at Chipps Island of releases from Ryde is the  
251 following.

$$252 \quad y_{Ry \rightarrow CI} \sim \text{Negative Binomial} \left( k_{CI}, \frac{k_{CI}}{R_{Ry} r_{Ry \rightarrow CI} + k_{CI}} \right),$$

253 where  $k_{CI}$  is a non-negative constant that affects the degree of overdispersion (relative to a  
254 Poisson, or indirectly a Binomial, random variable). The larger  $k_{CI}$  is, the less the overdis-  
255 persion.

256 At Level 2, several alternative models were fit. One model removed exports from the  
257 model for  $\ln(\theta_{3,t})$ . A second used a logistic transformation of  $\theta_{3,t}$ , ensuring  $0 \leq \theta_{3,t} \leq 1$ , i.e.,  
258 the Georgiana Slough to Chipps Island survival probability cannot exceed Ryde to Chipps  
259 Island survival probability. A third alternative was a multivariate normal distribution for  
260 the joint distribution of  $\theta_{3,t}$ ,  $r_{Ry \rightarrow CI,t}$ , and  $r_{Ry \rightarrow Oc+IL,t}$ , which allowed for correlation among  
261 these parameters within each release pair. In particular,  $\theta_{3,t}$  was log transformed and, largely  
262 to facilitate fitting, an extension of a logistic model was used to transform  $r_{Ry \rightarrow CI,t}$  and

263  $r_{Ry \rightarrow Oc+IL,t}$ , i.e., dropping the subscript  $t$  to reduce notation,

$$264 \begin{bmatrix} \theta^1 \\ \theta^2 \\ \theta^3 \end{bmatrix} \sim \text{MVN} \left( \begin{bmatrix} \beta_0 + \beta_1 \text{Exp}^* \\ \mu_{Ry \rightarrow CI} \\ \mu_{Ry \rightarrow Oc} \end{bmatrix}, \Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_{1,2} & \sigma_{1,3} \\ \sigma_{2,1} & \sigma_2^2 & \sigma_{2,3} \\ \sigma_{3,1} & \sigma_{3,2} & \sigma_3^2 \end{bmatrix} \right)$$

265 where

$$266 \begin{aligned} \theta^1 &= \ln(\theta_3) \\ 267 \theta^2 &= \ln \left( \frac{r_{Ry \rightarrow CI}}{1 - r_{Ry \rightarrow CI} - r_{Ry \rightarrow Oc+IL}} \right) \\ 268 \theta^3 &= \ln \left( \frac{r_{Ry \rightarrow Oc+IL}}{1 - r_{Ry \rightarrow CI} - r_{Ry \rightarrow Oc+IL}} \right). \end{aligned}$$

269 A fourth alternative was to use the fraction of exports relative to total river flow, ex-  
270 ports/flow, instead of the absolute level of exports. A fifth alternative was to remove random  
271 effects, i.e., the Level 2 models were deterministic.

272 For Level 3, various prior distributions were tried for the Level 2 fixed parameters. We  
273 used the inverse gamma distributions instead of uniform distributions (equation 11) for the  
274 variances of the random effects, i.e.,  $\sigma_\theta^2$ ,  $\sigma_{r_{Ry \rightarrow CI}}^2$ , and  $\sigma_{r_{Ry \rightarrow Oc+IL}}^2$ . For the multivariate normal  
275 model, an inverse Wishart distribution was used as the prior for the variance-covariance  
276 matrix,  $\Sigma$ .

277 Not all possible combinations of models for each level were fit. During the fitting process  
278 it became clear that certain options at one level led to clearly poor fitting models; e.g.,  
279 removing random effects at level 2 led to a drastic drop in model fit no matter what options  
280 were selected at other levels.

### 281 **2.4.3 Model fitting, assessment, and comparison**

282 To fit the BHMs we used the program WinBUGS (Lunn, et al. 2003), which generated samples  
283 from the joint posterior distribution for the parameters, random effects, and expected num-  
284 bers of recoveries. WinBUGS is based on a technique known as Markov chain Monte Carlo,  
285 MCMC (Gilks, Richardson, and Spiegelhalter 1996), which is a computer simulation method  
286 where samples are generated from a Markov chain which has a limiting distribution equal  
287 to the distribution of interest, in this case the joint posterior distribution.

288 By a limiting distribution it is meant that the samples do not initially come from the  
289 desired distribution, but once “enough” samples are generated, the so-called burn-in period,  
290 all additional samples do come from the desired distribution. WinBUGS includes measures,  
291 e.g., the Brooks-Gelman-Rubin statistic (Brooks and Gelman,1998), based upon the results  
292 of simulating from multiple Markov chains with differing initial values, for determining an  
293 adequate burn-in period. Informally stated, given widely different starting values, the point  
294 at which the chains begin to overlap, i.e., begin mixing, is the necessary burn-in period,  
295 presumably the samples are coming from the limiting distribution and are not stuck at  
296 some local mode of the posterior distribution. Values near 1.0 for the Brooks-Gelman-Rubin  
297 statistic are evidence for convergence, with values below 1.1 often adequate (Gelman, et al.  
298 2004, page 297). Three different chains, with differing initial values, were run in parallel and  
299 the summary statistics are based on the pooled output following burn-in.

300 Goodness of model fit, for a given model, was assessed by calculating Bayesian P-values  
301 (Gelman, et al. 2004) for each of the observations. The P-value is the proportion of time a  
302 predicted value exceeds the observed value:

$$303 \quad \text{Bayesian P-value} = \frac{1}{L} \sum_{l=1}^L I(y_l^{pred} \geq y),$$

304 where  $I()$  is an indicator function equaling 1 when the condition inside  $()$  is met. The

305 predicted value,  $y_i^{pred}$  is found by simulating  $y$  from its probability distribution evaluated at  
306 the  $l^{th}$  parameter value in the MCMC sample. Ideally, the observed values will lie in the  
307 central portion of the simulated posterior predictive distribution, equally distributed around  
308 the median predicted values. A Bayesian P-value near 0 or 1 is indicative of a poor fit for  
309 the particular observation.

310 All the models were compared using the deviance information criterion, DIC (Spiegel-  
311 halter, et al. 2002). DIC can be viewed as a measure of overall model fit while penalizing  
312 for model complexity. When comparing two models, the model with the lower DIC value is  
313 estimated to have better predictive capabilities. Reversible jump MCMC (RJMCMC, Green  
314 1995) was used to compare two models, one model with exports as a covariate (equation  
315 (7)) and one without exports. Given the data, a set of models, and a corresponding set of  
316 prior probabilities that a given model is the correct model (the prior model probability),  
317 RJMCMC calculates posterior model probabilities.

### 318 **3 Results**

319 The recovery fractions for Georgiana Slough releases were consistently less than the fractions  
320 for Ryde releases, with the exception of the fraction recovered at the fish facilities (Figure  
321 2). The means of the ratios of recovery fractions equalled 0.26, 0.46, and 0.37 for Chipps  
322 Island, ocean fisheries, and inland recoveries, respectively. Conversely, at the fish facilities,  
323 Georgiana Slough releases were about 16 times more likely to be recovered. Also, the recovery  
324 fraction of fish facility recoveries from the Georgiana Slough releases tended to increase,  
325 from about 0.001 to 0.025 , as exports went from 2000 cfs to 10000 cfs, although there was  
326 considerable variability at any given level of exports (Figure 3). This suggested a higher



327 probability of ending up at the pumps with increasing exports. In contrast, the fraction of  
 328 Ryde releases ending up at the fish facilities, with group 3 an exception and a case with high  
 329 exports, was less than 0.001 (generally supportive of the assumption that Ryde releases were  
 330 unaffected by exports).

### 331 3.1 Non-hierarchical analyses

332 The release pair specific point estimates,  $\hat{\theta}_1$  and  $\hat{\theta}_2$ , and corresponding standard errors are  
 333 shown in Table 2. As expected, given the additional information provided by ocean and  
 334 inland recoveries, the standard errors for  $\hat{\theta}_2$  tended to be smaller than those for  $\hat{\theta}_1$ . That  
 335 difference in standard errors was smaller for the most recent releases (groups 14 and 15)  
 336 which likely have incomplete inland recovery information for older aged returns. Between  
 337 release group variation in the estimates of  $\theta_t$  was quite large, with values ranging from 0.13  
 338 to 0.80 (based on  $\hat{\theta}_2$ ).

339 The fitted models of  $\theta_t$  as a function of exports (equations 2 and 4) are the following:

$$340 \quad \hat{\theta}_{1,t} \approx \text{Normal}\left(0.265 - 0.086Exp_t^*, 0.18^2\right)$$

$$341 \quad \ln(\hat{\theta}_{2,t}) \approx \text{Normal}\left(-0.935 - 0.214Exp_t^*, 3.88^2\right).$$

342 P-values for a one-sided test of significance of the slope coefficient for exports, with the  
 343 alternative  $H_1 : \beta_1 < 0$ , are 0.05 for the  $\hat{\theta}_1$  model and 0.04 for the  $\ln(\hat{\theta}_2)$  model. Neither  
 344 model fit particularly well, however; the  $R^2$  values were 0.19 and 0.21 for the  $\hat{\theta}_1$  and  $\ln(\hat{\theta}_2)$   
 345 models, respectively.

### 346 3.2 Bayesian hierarchical model

347 For each model the burn-in time was 50,000 iterations, per chain, a further 150,000 iterations,  
348 per chain, were carried out, and every tenth realization was used for the posterior samples.  
349 The negative binomial model was an exception, due to somewhat slow computational speed,  
350 burn-in was 50,000 iterations followed by 50,000 sample iterations. Evidence for conver-  
351 gence to the posterior distribution were Brooks-Gelman-Rubin statistics for all parameters  
352 between 1.0 and 1.03, plots of the parameters for the three chains against simulation number  
353 (traceplots) that showed considerable overlap and movement in chain values (consistent with  
354 good mixing), and DIC values that were stable between different runs.

355 All the BHMs with a multinomial distribution for the observations (Level 1) and random  
356 effects (Level 2) had nearly equal DIC values (Models #1-#6 in Table 3). Spiegelhalter,  
357 et al. (2002) support the rule of thumb that models within 1-2 of the minimal DIC value  
358 deserve consideration (as used by Burnham and Anderson (1998) for AIC). Notably, this set  
359 included a model without exports. The results were robust to the choice of the prior for the  
360 random effects standard deviation ( $\sigma$ ), either uniform or inverse gamma. Either covariate,  
361 exports or exports/flow, led to equivalent DIC values. Posterior means for  $\theta_{3,t}$  were much  
362 the same for these models.

363 The Bayesian P-values were essentially identical for these multinomial, random effect  
364 models. Fifty-three of the 60 total observations, 88%, had Bayesian P-values that fell in-  
365 side of the middle 90% of posterior predictive distributions. There were too few observed  
366 recoveries ( $P=0.02$  to  $0.04$ ) for two cases ( $y_{Ry \rightarrow CI,1}$  and  $y_{Ry \rightarrow CI,6}$ ), and too many observed  
367 recoveries ( $P=0.95$  to  $1.00$ ) for five others ( $y_{GS \rightarrow CI,5}$ ,  $y_{GS \rightarrow CI,9}$ ,  $y_{GS \rightarrow CI,12}$ ,  $\hat{y}_{Ry \rightarrow Oc+IL,14}$  and  
368  $\hat{y}_{GS \rightarrow Oc+IL,14}$ ).

369 Replacing the multinomial distribution with the negative binomial distribution (Model

370 #7) or excluding random effects (Model #8) led to sizeable increases in DIC values (Table  
371 3), especially for the latter model. Many of the Bayesian P-values for the non-random effects  
372 model were close to 0 or 1. The negative binomial model's parameters,  $k_{CI}$  and  $k_{Oc}$  were  
373 quite large (posterior means of 214 and 279), indicating little evidence for overdispersion.

374 Referring now to model #1 (although the results are nearly identical for models #2-#6),  
375 the recovery probabilities for Ryde releases at Chipps Island were an order of magnitude  
376 lower than those for the ocean fisheries and inland recoveries; the median for  $r_{Ry \rightarrow CI}$  was  
377 0.0004 versus 0.0038 for  $r_{Ry \rightarrow Oc+IL}$ . Given that recovery probabilities are the product of  
378 survival and capture probabilities,  $r_{Ry \rightarrow CI} \approx 0.0004$  seems reasonable for the Chipps Island  
379 trawl based on independent estimates of Chipps Island trawl capture probabilities on the  
380 order of 0.001 to 0.002 (Newman 2003). The correlations between  $\theta$ ,  $r_{Ry \rightarrow CI}$ , and  $r_{Ry \rightarrow Oc}$ ,  
381 on the transformed scales, were weakly positive: between  $\theta$  and  $r_{Ry \rightarrow CI}$  the posterior mean  
382 for  $\sigma_{1,2}$  was 0.21, between  $\theta$  and  $r_{Ry \rightarrow Oc}$   $E[\sigma_{1,3}]$  was 0.18, and between  $r_{Ry \rightarrow CI}$  and  $r_{Ry \rightarrow Oc}$   
383  $E[\sigma_{2,3}]$  was 0.25. Thus, within a release pair, when survival was higher for one segment, it  
384 tended to be higher for the other segments.

385 For all models with exports the posterior mean value for  $\beta_1$  was negative, indicative of  
386 a negative association between  $\theta$  and exports. For Models #1-#5,  $\Pr(\beta_1 < 0)$  ranged from  
387 0.86 to 0.92. The variation in the relationship with exports, however, was quite large as both  
388 the size of  $E[\sigma_\theta]$  and the plot of predicted  $\theta$  values against exports (Figure 4) indicate. While  
389 the plot shows the decline in mean  $\theta$  as exports increases (e.g., when exports are at 2000 cfs,  
390 mean  $\theta$  is 0.54, and when exports are at 10,000 cfs, mean  $\theta$  is 0.34), the range of individual  
391 values is very wide. Upper bounds on  $\theta$  for export levels less than 7200 exceed 1.0, allowing  
392 for the possibility that Georgiana Slough releases could occasionally have higher survival  
than Ryde releases.

393 Given the similarity in DIC values amongst Models #1 - #6, and primary interest being  
394 the effect of exports, reversible jump MCMC was applied to just two models differing only  
395 in terms of the inclusion (Model #2) or exclusion (Model #6) of exports . The posterior  
396 probability for the model including exports was only 1% compared to 99% probability for  
397 the model without exports, thus apparently scant evidence for a relationship between  $\theta$  and  
398 exports. However, such results could be due to the low signal-to-noise ratio, as measured by  
399 the posterior mean for  $\beta_1$  to the posterior means for  $\sigma_\theta$ ,  $\sigma_{r_{Ry \rightarrow CI}}$ , and  $\sigma_{r_{Ry \rightarrow OC+IL}}$ . Repeated  
400 simulations of 15 sets of recoveries with the actual release numbers and export levels were  
401 made using Model #2 (equations 5-11) with the posterior mean values for the parameters  
402 (e.g.,  $E[\beta_1] = -0.17$ ). Despite the fact that the true model did have  $\theta$  as a function of exports,  
403 RJMCMC typically yielded the posterior probabilities for this model in the range of 1-3%.  
404 Even doubling the number of release pairs and extending the range of export levels to plus  
405 or minus two standard deviations of observed values did not change these results. However,  
406 if the environmental variation was artificially decreased (e.g., by an order of magnitude),  
407 then RJMCMC gave posterior probabilities for the correct model (the model with exports)  
408 ranging from 90 to 99%.

### 409 3.3 Non-hierarchical versus hierarchical

410 The posterior means and standard deviations of  $\theta_t$  from the BHMs (#1-#6) were quite similar  
411 to the (approximate) maximum likelihood estimates,  $\hat{\theta}_{2,t}$ , and the standard errors (Table 2).  
412 This indicates that the influence of the prior distributions on the Bayesian results was slight.  
413 The posterior standard deviations of  $\theta_t$  were generally slightly less than the standard errors,  
414 presumably a result of the “borrowing of strength” from other release-recovery data that

415 informs the estimates.

416 Model-based predictions of  $\theta_t$  as a function of exports were quite similar for the BHM  
417 (equations 5-11) and the non-hierarchical model (equation (4)), but the prediction intervals  
418 for the BHM were considerably wider (Figure 4). The observed variation in estimates of  $\theta_t$   
419 (shown in Figure 4) seems more consistent with the wider BHM prediction intervals than  
420 the non-hierarchical model intervals.

## 421 **4 Discussion**

422 We conclude that, for a paired release, the survival to Chipps Island of Georgiana Slough  
423 releases is considerably less than the survival to Chipps Island of Ryde releases. The ratios  
424 of recovery fractions to Chipps Island, ocean fisheries, and inland sites for Georgiana Slough  
425 releases to Ryde releases were consistently much less than 1.0 (Figure 2), and the posterior  
426 means and the maximum likelihood estimates of  $\theta_t$  were at most 0.8 (Table 2). The posterior  
427 median of  $\theta_t$  was 0.35 (from a model without exports, BHM #6).

428 Factors in addition to exports that could cause lower relative survival for Georgiana  
429 Slough releases include water temperature, predation, and pollution (Moyle 1994). Increasing  
430 water temperatures have been associated with increasing mortality through the Delta (Baker,  
431 et al. 1995). For the paired releases we have analyzed, however, water temperatures at release  
432 were very similar at Ryde and Georgiana Slough within a release pair. Regarding predation,  
433 Stevens (1966) found more salmon in the stomachs of striped bass located in the so-called  
434 flooded islands portion of the Delta (south of the Georgiana Slough release point) relative  
435 to that for the stomachs of striped bass in the Sacramento River.

436 Regarding the relationship between the relative survival and export levels, the point  
437 estimates of export effects were consistently negative, and for the BHMs, the probability  
438 that the effects are negative was 86 to 92%. However, the signal-to-noise ratio is low enough  
439 that DIC values and posterior model probabilities indicate that the predictive ability of  
440 models without exports is equivalent to that of models which include exports. Environmental  
441 variation is large enough that a failure to find a stronger association could be a function  
442 of inadequate sample size. Previous analyses (Newman 2008, page 72) of the relationship  
443 between number of paired releases and precision of the estimated slope parameter for exports  
444 showed that 100 paired releases were needed (based on  $\beta_1 = -0.57$  for a logistic transformation  
445 of  $\theta$ ) to yield a coefficient of variation of 20%. The RJMCMC analysis of simulated data  
446 were consistent with those findings.

447 Exports do affect Georgiana Slough releases more than Ryde releases as the fraction of  
448 Georgiana Slough releases recovered at the CVP and SWP fish salvage facilities increases  
449 with increasing exports (Figure 2). The intent of the salvage operations is to increase survival  
450 by relocating those fish away from the pumping facilities, and perhaps there is in fact some  
451 mitigating effect. However, at the SWP facilities there is an enclosed area, Clifton Court  
452 Forebay, where fish suffer mortality, due at least to predators (Gingras 1997), prior to entering  
453 the salvage facilities. Experiments with marked salmon in the vicinity of the SWP fish facility  
454 have yielded estimates of “pre-salvage” mortality in the range of 63-99%, with an average of  
455 85% (Gingras 1997), although the quality of these estimates has been called into question  
456 (Kimmerer 2008).

457 A tangential question is whether or not the fish facility recovery fractions are related to  
458 exports or the export to flow ratio, i.e., the absolute or the relative level of exports. Over  
459 the range of values observed in these studies, exports and export/flow are linearly associated

460 (Pearson correlation coefficient = 0.83), thus it is difficult to disentangle the effects of the  
461 two factors. Deliberate fixing of export levels at varying levels of flows would be one means  
462 of trying to determine if it is the absolute level or the relative level of exports that affects the  
463 fraction of Georgiana Slough releases recovered at the fish salvage facilities. Current water  
464 management policies and operational standards, however, make such manipulations difficult  
465 to conduct. Export levels are largely determined by state and federal water project agencies  
466 based on water demand, Delta conditions, Delta water quality and operational standards as  
467 well as endangered species biological opinions. Due to this lack of randomization of export  
468 levels and the relatively low numbers of releases, the effect of exports may be confounded  
469 by other conditions that cause survival to increase or decrease. The pairing aspect of the  
470 design does potentially control such confounding factors.

471       Given the low signal-to-noise ratio, instead of repeating coded-wire-tag release-recovery  
472 experiments for many more years, releases of fish with acoustic tags combined with strategi-  
473 cally placed receivers, is recommended. Such a system could provide more precise information  
474 about when and where mortality is occurring, yielding estimates of reach-specific survival  
475 (Muthukumarana, Schwarz, and Swartz, 2008). How much of an effect the interior Delta  
476 mortality has on the total population of Sacramento River juvenile Chinook salmon, what-  
477 ever the causes, depends upon the fraction of the out-migrating population that moves into  
478 the interior Delta. Using coded-wire-tag release-recovery data, Kimmerer (2008) estimated  
479 that the overall mortality is 10% at the highest export levels assuming a pre-salvage mortal-  
480 ity of 80% at the fish facilities. Pilot studies using acoustic tags have recently been carried  
481 out to estimate the proportion of out-migrants entering the Delta (Perry, et al., xxxx), and  
482 once this proportion is identified, the benefits of preventing fish from entering the interior  
483 Delta can be estimated more accurately.

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Table 1: Release and recovery data.  $R$  are the number released,  $CI$  and  $\widehat{Oc}$  refers to observed recoveries at Chipps Island and expanded recoveries in the ocean fisheries.  $\widehat{FF}$  refers to expanded recoveries at fish salvage facilities and  $\widehat{IL}$  are expanded inland recoveries. Ryde releases were occasionally made at Isleton (denoted by \*). Exports are a three day average (cfs) for the sum of water exported from SWP and CVP and E/F is the export to flow ratio over that same period.

Release		Tag Codes		Georgiana Slough					Ryde					E/F	Exports
Date	Pair	Georg.Sl.	Ryde	$R$	$CI$	$\widehat{Oc}$	$\widehat{FF}$	$\widehat{IL}$	$R$	$CI$	$\widehat{Oc}$	$\widehat{FF}$	$\widehat{IL}$	E/F	Exports
12/02/93	1	06-45-21	06-45-22	33,668	5	79	248	12	34,650	37	293	10	36	0.68	10,434
12/05/94	2	05-34-25	05-34-26*	31,532	4	11	87	8	30,220	15	28	6	13	0.22	5,988
01/04-05/95	3	06-25-25	06-25-24*	31,328	2	102	837	53	31,557	13	266	231	138	0.40	10,403
01/10-11/96	4	05-41-13	05-41-14	33,670	5	146	768	9	30,281	21	239	12	23	0.55	9,523
12/04-05/97	5	05-50-50	05-50-60	61,276	2	7	153	4	46,756	22	42	18	11	0.51	10,570
01/13-14/97	6	05-50-49	05-50-62	66,893	18	240	24	51	49,059	48	167	0	70	0.06	3,887
12/01-02/98	7	05-23-08	05-23-20	69,180	12	172	28	44	48,207	30	183	0	102	0.04	1,868
12/29-30/98	8	05-23-12	05-23-21	68,843	12	151	48	54	48,804	17	156	0	88	0.09	1,984
12/10-11/99	9	05-51-30	05-51-32*	65,517	3	43	24	9	53,426	16	129	0	20	0.18	3,237
12/20-21/99	10	05-51-31	05-51-33*	64,515	21	149	82	32	49,341	19	160	4	66	0.26	4,010
01/03-05/02	11	05-07-76	05-07-67	77,053	18	240	390	116	52,327	34	521	18	418	0.12	7,789
12/05-06/02	12	05-10-98	05-11-67	90,219	1	68	700	11	49,629	18	148	42	34	0.46	5,007
			05-11-68												
12/09-10/03	13	05-17-71:72	05-17-81:82	68,703	5	51	306	8	45,981	13	127	24	69	0.18	4,016
12/08-09/04	14	05-22-92:93	05-22-80:81	72,082	10	11	0	1	50,397	28	20	0	0	0.25	6,092
12/08-09/05	15	05-27-84:87	05-27-88:91	70,414	6	35	165	1	51,017	23	49	12	1	0.68	10,837

Table 2: Comparison of release pair-specific fitted values of  $\theta$ , the ratio of the Georgian Slough survival probability to the Ryde survival probability. The non-Bayesian, non-hierarchical results are the maximum likelihood estimates and standard errors based on the Chipps Island recoveries alone ( $\hat{\theta}_1$ ) and combined Chipps Island, ocean, and inland recoveries ( $\hat{\theta}_2$ ). The Bayesian hierarchical values are the posterior distribution means and standard deviations from the BHM with a multivariate normal distribution at Level 2 and  $\theta$  modeled as a function of exports.

Group	Non-Bayesian				Bayesian	
	Non-Hierarchical				Hierarchical	
	$\hat{\theta}_1$	SE	$\hat{\theta}_2$	SE	E[ $\theta_{3,t}$  Data]	SD
1	0.14	0.07	0.27	0.031	0.28	0.031
2	0.26	0.14	0.39	0.097	0.38	0.084
3	0.15	0.12	0.38	0.035	0.38	0.035
4	0.21	0.11	0.51	0.050	0.50	0.049
5	0.07	0.05	0.13	0.040	0.16	0.041
6	0.28	0.08	0.80	0.065	0.79	0.064
7	0.28	0.10	0.50	0.044	0.51	0.043
8	0.50	0.19	0.59	0.054	0.58	0.052
9	0.15	0.10	0.27	0.042	0.28	0.041
10	0.85	0.27	0.63	0.060	0.62	0.057
11	0.36	0.10	0.26	0.016	0.26	0.016
12	0.03	0.03	0.22	0.029	0.23	0.029
13	0.26	0.14	0.20	0.029	0.22	0.029
14	0.25	0.09	0.32	0.082	0.32	0.076
15	0.19	0.09	0.42	0.081	0.38	0.070

Table 3: Summary of Bayesian hierarchical models. Level 1 column specifies distributions (Mn = Multinomial and NB = Negative Binomial). Level 2 column has models for  $\theta_{3,t}$  with N denoting Normal distribution; models for  $r_{Ry \rightarrow CI,t}$  and  $r_{Ry \rightarrow CI,t}$  were those shown in Equations (8) and (9) except for Multivariate Normal (MVN) and model without random effects. Level 3 column specifies prior distribution for the random effects variance;  $\sigma$  (U for Uniform),  $\sigma^2$  (IG for Inverse Gamma), and  $\Sigma$  in the MVN model (IW[I,4] for Inverse Wishart with I=Identity matrix).

#	Level 1	Level 2	Level 3	E[ $\beta_1$ ]	Pr( $\beta_1 < 0$ )	E[ $\sigma_\theta$ ]	DIC
1	Mn	$\ln(\theta_{3,t}), \dots \sim \text{MVN}(\beta_0 + \beta_1 \text{Exp}_t^*, \dots, \Sigma)$	$\Sigma \sim \text{IW}[I,4]$	-0.194	0.92	0.53	460.0
2	Mn	$\ln(\theta_{3,t}) \sim \text{N}(\beta_0 + \beta_1 \text{Exp}_t^*, \sigma_\theta^2)$	$\sigma \sim \text{U}(0,20)$	-0.170	0.89	0.50	460.0
3	Mn	$\ln(\theta_{3,t}) \sim \text{N}(\beta_0 + \beta_1 \frac{\text{Exp}}{\text{Flow}_t}, \sigma_\theta^2)$	$\sigma \sim \text{U}(0,20)$	-0.706	0.86	0.51	460.0
4	Mn	$\ln(\theta_{3,t}) \sim \text{N}(\beta_0 + \beta_1 \text{Exp}_t^*, \sigma_\theta^2)$	$\sigma^2 \sim \text{IG}(0.001,0.001)$	-0.166	0.90	0.48	459.9
5	Mn	$\text{logit}(\theta_{3,t}) \sim \text{N}(\beta_0 + \beta_1 \text{Exp}_t^*, \sigma_\theta^2)$	$\sigma \sim \text{U}(0,20)$	-0.297	0.88	0.89	460.0
6	Mn	$\ln(\theta_{3,t}) \sim \text{N}(\beta_0, \sigma_\theta^2)$	$\sigma \sim \text{U}(0,20)$	NA	NA	0.51	460.1
7	NB	$\ln(\theta_{3,t}) \sim \text{N}(\beta_0 + \beta_1 \text{Exp}_t^*, \sigma_\theta^2)$	$\sigma \sim \text{U}(0,20)$	-0.168	0.89	0.46	487.0
8	Mn	$\ln(\theta_{3,t}) = \beta_0 + \beta_1 \text{Exp}_t^*$	NA	-0.079	0.99	NA	4281.8

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Figure 1: Map of the Ryde and Georgiana Slough release locations and the Chipps Island recovery location.

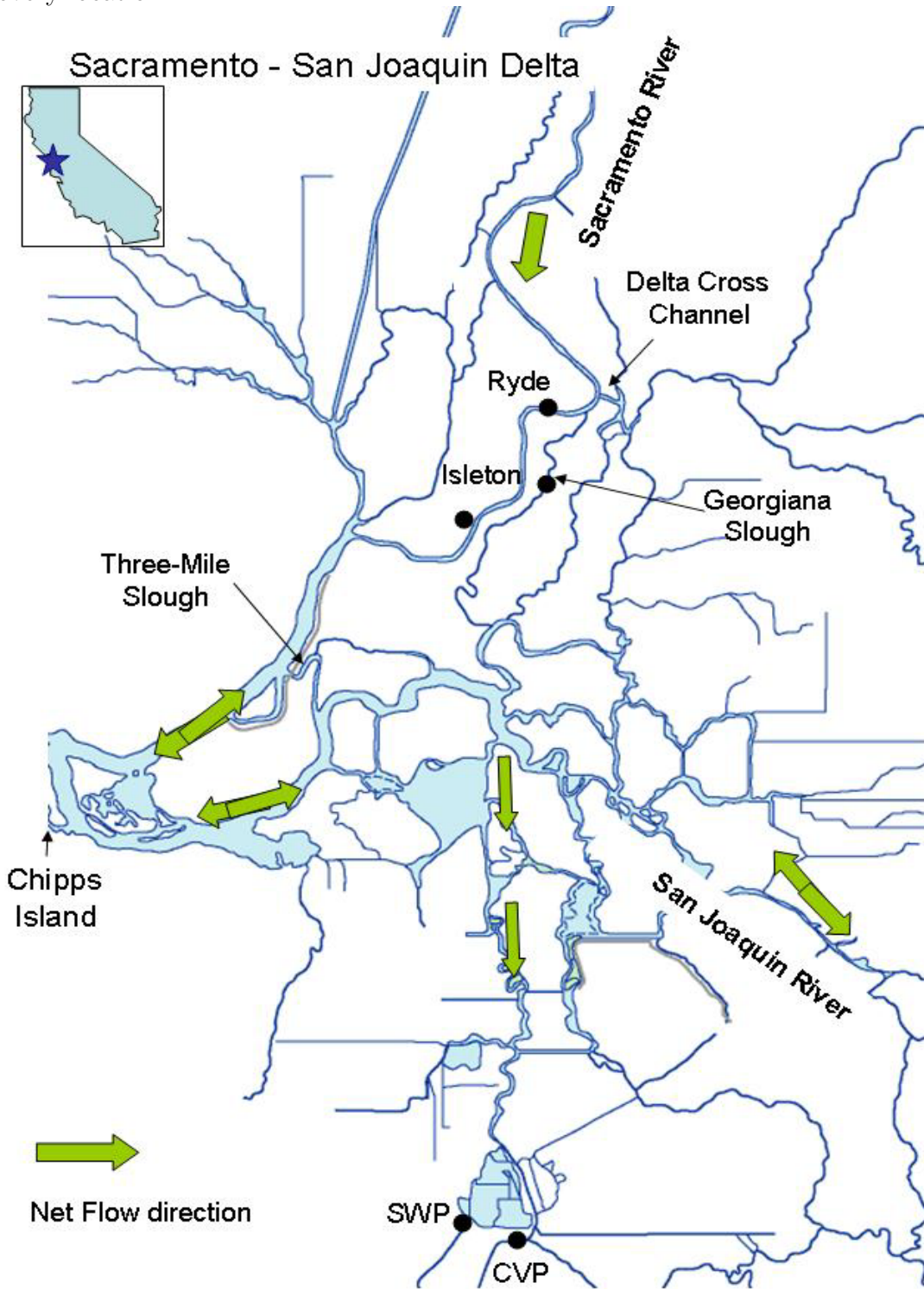




Figure 2: Comparison of recovery fractions at Chipps Island, in the ocean fisheries, in fish facility salvage, and from inland recoveries for Georgiana Slough and Ryde releases by release pair. Straight lines on plots have slope equal to mean of the ratios of recovery fractions.

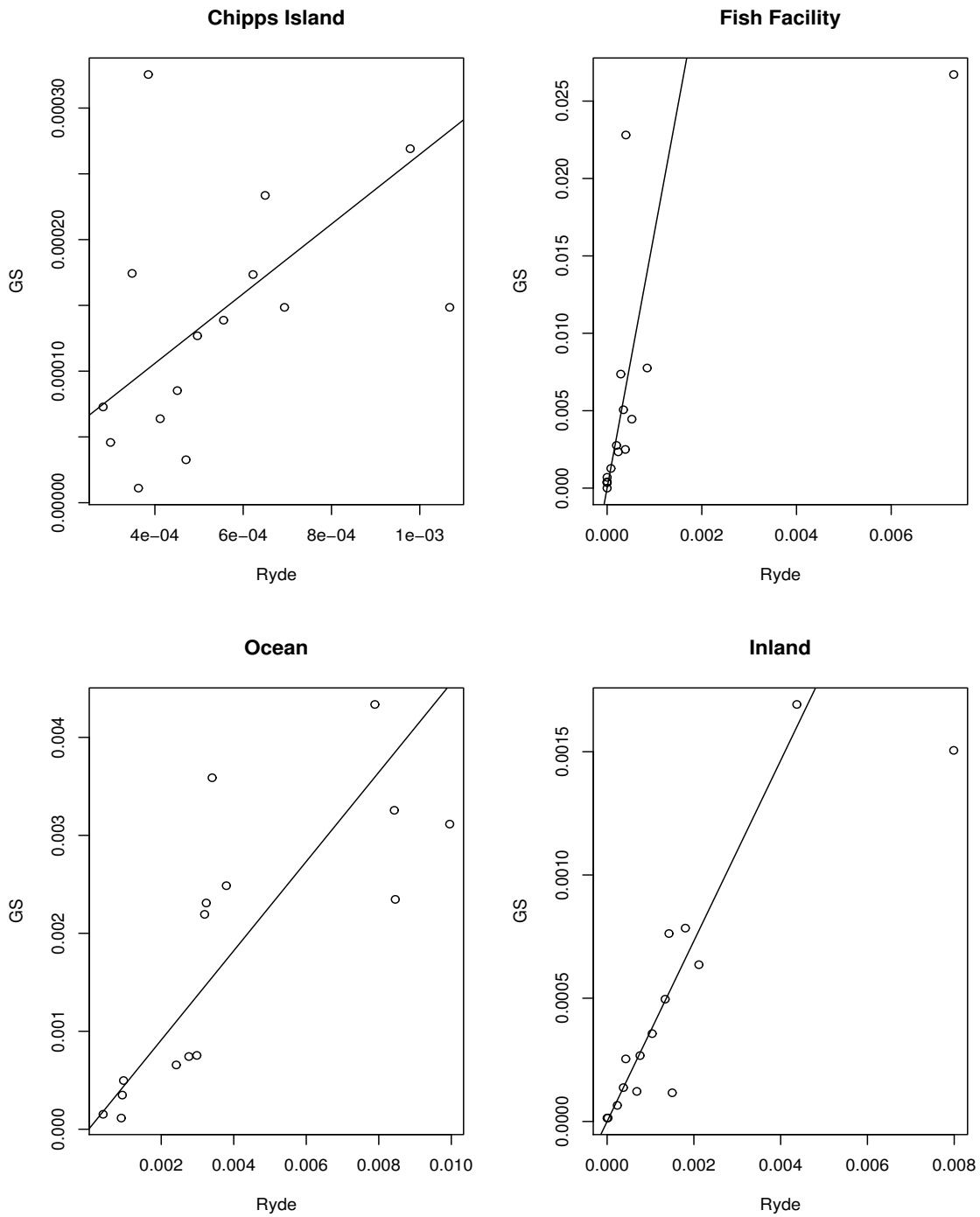


Figure 3: Expanded recovery fractions at the fish facilities near SWP and CVP plotted against the export level. Lines drawn on the plot are scatterplot smooths (dashed for Georgiana Slough; solid for Ryde).

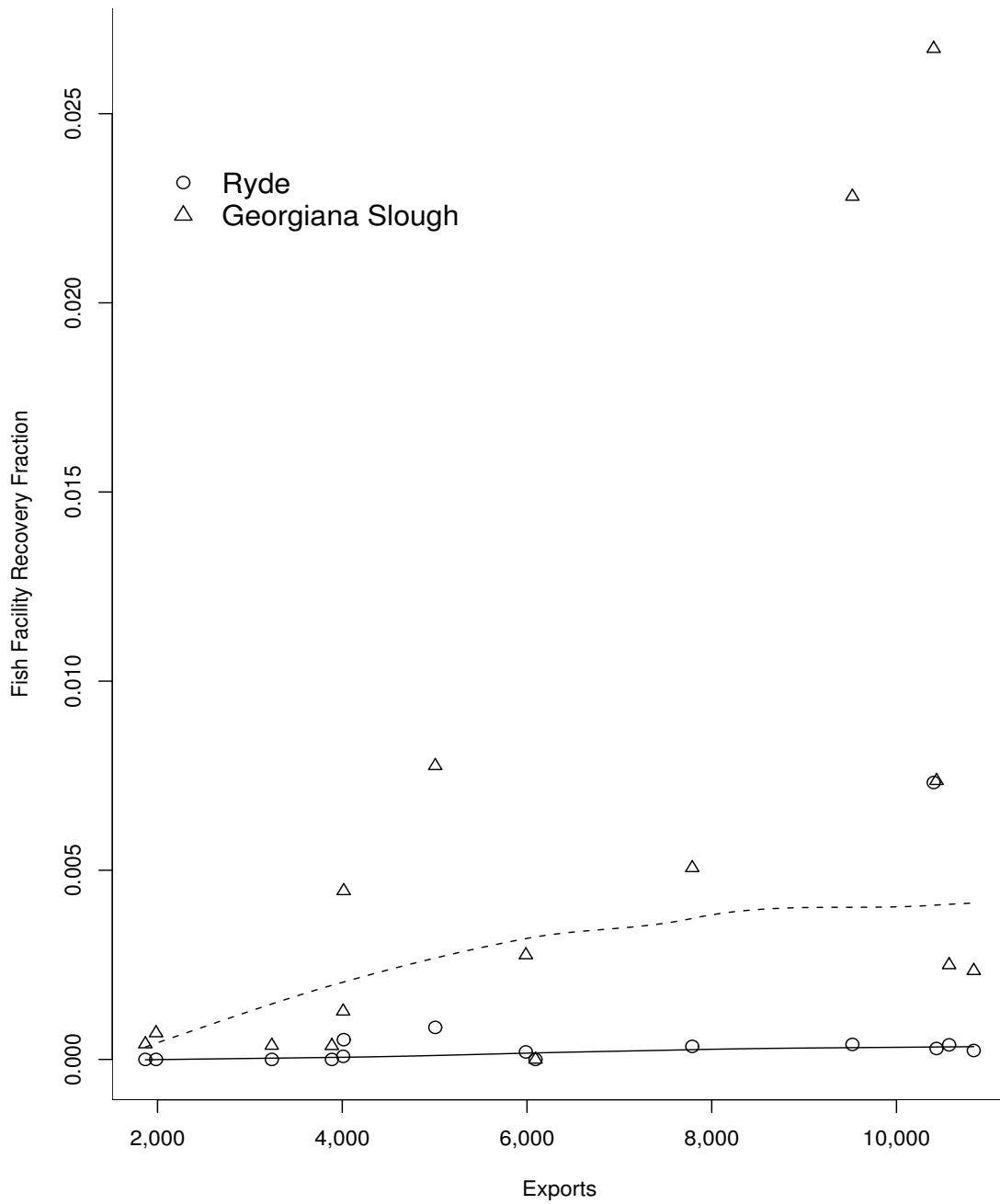


Figure 4: Expected values, and 2.5% and 97.5% prediction intervals, for  $\theta$  at different levels of exports for Bayesian Hierarchical Model #1 (solid lines) and the non-hierarchical model (dashed lines) using Chipps Island recoveries and combined ocean and inland recoveries (equation (4)). Circles are posterior mean fitted values for  $\theta$  from the BHM and triangles are the maximum likelihood estimates based on combined Chipps Island, ocean, and inland recoveries.

