

What caused the Sacramento River fall Chinook stock collapse?

S. T. Lindley, C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, , D. L. Bottom, C. A. Busack, T. K. Collier, J. Ferguson, J. C. Garza, A. M. Grover, D. G. Hankin, R. G. Kope, P. W. Lawson, A. Low, R. B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F. B. Schwing, J. Smith, C. Tracy, R. Webb, B. K. Wells, T. H. Williams

Pre-publication report to the Pacific Fishery Management Council

March 18, 2009

Contents

1	Executive summary	4
2	Introduction	7
3	Analysis of recent broods	10
3.1	Review of the life history of SRFC	10
3.2	Available data	11
3.3	Conceptual approach	11
3.4	Brood year 2004	15
3.4.1	Parents	15
3.4.2	Eggs	16
3.4.3	Fry, parr and smolts	17
3.4.4	Early ocean	21
3.4.5	Later ocean	30
3.4.6	Spawners	32
3.4.7	Conclusions for the 2004 brood	32
3.5	Brood year 2005	33
3.5.1	Parents	33
3.5.2	Eggs	33
3.5.3	Fry, parr and smolts	33
3.5.4	Early ocean	34
3.5.5	Later ocean	35
3.5.6	Spawners	35
3.5.7	Conclusions for the 2005 brood	35
3.6	Prospects for brood year 2006	36
3.7	Is climate change a factor?	36
3.8	Summary	37
4	The role of anthropogenic impacts	38
4.1	Sacramento River fall Chinook	38
4.2	Other Chinook stocks in the Central Valley	43
5	Recommendations	47
5.1	Knowledge Gaps	47
5.2	Improving resilience	48
5.3	Synthesis	49

List of Figures

1	Sacramento River index.	8
2	Map of the Sacramento River basin and adjacent coastal ocean.	13
3	Conceptual model of a cohort of fall-run Chinook.	14
4	Discharge in regulated reaches of the Sacramento River, Feather River, American River and Stanislaus River in 2004-2007.	16
5	Daily export of freshwater from the Delta and the ratio of exports to inflows.	18
6	Releases of hatchery fish.	19
7	Mean annual catch-per-unit effort of fall Chinook juveniles at Chipps Island by USFWS trawl sampling.	20
8	Cumulative daily catch per unit effort of fall Chinook juveniles at Chipps Island by USFWS trawl sampling in 2005.	20
9	Relative survival from release into the estuary to age two in the ocean for Feather River Hatchery fall Chinook.	22
10	Escapement of SRFC jacks.	22
11	Conceptual diagram displaying the hypothesized relationship between wind-forced upwelling and the pelagic ecosystem.	24
12	Sea surface temperature (colors) and wind (vectors) anomalies for the north Pacific for Apr-Jun in 2005-2008.	25
13	Cumulative upwelling index (CUI) and anomalies of the CUI.	27
14	Sea surface temperature anomalies off central California in May-July of 2003-2006.	28
15	Surface particle trajectories predicted from the OSCURS current model	29
16	Length, weight and condition factor of juvenile Chinook over the 1998-2005 period.	31
17	Changes in interannual variation in summer and winter upwelling at 39°N latitude.	37
19	The fraction of total escapement of SRFC that returns to spawn in hatcheries.	42
20	Escapement trends in various populations of Central Valley Chinook.	45
21	Escapement trends in the 1990s and 2000s of various populations of Chinook.	46

List of Tables

1	Summary of data sources used in this report.	12
---	--	----

1 Executive summary

2 In April 2008, in response to the sudden collapse of Sacramento River fall Chi-
3 nook salmon (SRFC) and the poor status of many west coast coho salmon popula-
4 tions, the Pacific Fishery Management Council (PFMC) adopted the most restric-
5 tive salmon fisheries in the history of the west coast of the U.S. The regulations
6 included a complete closure of commercial and recreational Chinook salmon fish-
7 eries south of Cape Falcon, Oregon. Spawning escapement of SRFC in 2007 is es-
8 timated to have been 88,000, well below the PFMC's escapement conservation goal
9 of 122,000-180,000 for the first time since the early 1990s. The situation was even
10 more dire in 2008, when 66,000 spawners are estimated to have returned to natural
11 areas and hatcheries. For the SRFC stock, which is an aggregate of hatchery and
12 natural production, many factors have been suggested as potential causes of the poor
13 escapements, including freshwater withdrawals (including pumping of water from
14 the Sacramento-San Joaquin delta), unusual hatchery events, pollution, elimination
15 of net-pen acclimatization facilities coincident with one of the two failed brood
16 years, and large-scale bridge construction during the smolt outmigration (CDFG,
17 2008). In this report we review possible causes for the decline in SRFC for which
18 reliable data were available.

19 Our investigation was guided by a conceptual model of the life history of fall
20 Chinook salmon in the wild and in the hatchery. Our approach was to identify where
21 and when in the life cycle abundance became anomalously low, and where and when
22 poor environmental conditions occurred due to natural or human-induced causes.
23 The likely cause of the SRFC collapse lies at the intersection of an unusually large
24 drop in abundance and poor environmental conditions. Using this framework, all of
25 the evidence that we could find points to ocean conditions as being the proximate
26 cause of the poor performance of the 2004 and 2005 broods of SRFC. We recognize,
27 however, that the rapid and likely temporary deterioration in ocean conditions is
28 acting on top of a long-term, steady degradation of the freshwater and estuarine
29 environment.

30 The evidence pointed to ocean conditions as the proximate cause because con-
31 ditions in freshwater were not unusual, and a measure of abundance at the entrance
32 to the estuary showed that, up until that point, these broods were at or near normal
33 levels of abundance. At some time and place between this point and recruitment to
34 the fishery at age two, unusually large fractions of these broods perished. A broad
35 body of evidence suggests that anomalous conditions in the coastal ocean in 2005
36 and 2006 resulted in unusually poor survival of the 2004 and 2005 broods of SRFC.
37 Both broods entered the ocean during periods of weak upwelling, warm sea surface
38 temperatures, and low densities of prey items. Individuals from the 2004 brood
39 sampled in the Gulf of the Farallones were in poor physical condition, indicating
40 that feeding conditions were poor in the spring of 2005 (unfortunately, comparable
41 data do not exist for the 2005 brood). Pelagic seabirds in this region with diets sim-
42 ilar to juvenile Chinook salmon also experienced very poor reproduction in these
43 years. In addition, the cessation of net-pen acclimatization in the estuary in 2006
44 may have contributed to the especially poor estuarine and marine survival of the

45 2005 brood.

46 Fishery management also played a role in the low escapement of 2007. The
47 PFMC (2007) forecast an escapement of 265,000 SRFC adults in 2007 based on
48 the escapement of 14,500 Central Valley Chinook salmon jacks in 2006. The real-
49 ized escapement of SRFC adults was 87,900. The large discrepancy between the
50 forecast and realized abundance was due to a bias in the forecast model that has
51 since been corrected. Had the pre-season ocean abundance forecast been more ac-
52 curate and fishing opportunity further constrained by management regulation, the
53 SRFC escapement goal could have been met in 2007. Thus, fishery management,
54 while not the cause of the 2004 brood weak year-class strength, contributed to the
55 failure to achieve the SRFC escapement goal in 2007.

56 The long-standing and ongoing degradation of freshwater and estuarine habitats
57 and the subsequent heavy reliance on hatchery production were also likely contrib-
58 utors to the collapse of the stock. Degradation and simplification of freshwater
59 and estuary habitats over a century and a half of development have changed the
60 Central Valley Chinook salmon complex from a highly diverse collection of nu-
61 merous wild populations to one dominated by fall Chinook salmon from four large
62 hatcheries. Naturally-spawning populations of fall Chinook salmon are now ge-
63 netically homogeneous in the Central Valley, and their population dynamics have
64 been synchronous over the past few decades. In contrast, some remnant populations
65 of late-fall, winter and spring Chinook salmon have not been as strongly affected
66 by recent changes in ocean conditions, illustrating that life-history diversity can
67 buffer environmental variation. The situation is analogous to managing a financial
68 portfolio: a well-diversified portfolio will be buffeted less by fluctuating market
69 conditions than one concentrated on just a few stocks; the SRFC seems to be quite
70 concentrated indeed.

71 Climate variability plays an important role in the inter-annual variation in abun-
72 dance of Pacific salmon, including SRFC. We have observed a trend of increasing
73 variability over the past several decades in climate indices related to salmon sur-
74 vival. This is a coast-wide pattern, but may be particularly important in California,
75 where salmon are near the southern end of their range. These more extreme climate
76 fluctuations put additional strain on salmon populations that are at low abundance
77 and have little life-history or habitat diversity. If the trend of increasing climate
78 variability continues, then we can expect to see more extreme variation in the abun-
79 dance of SRFC and salmon stocks coast wide.

80 In conclusion, the development of the Sacramento-San Joaquin watershed has
81 greatly simplified and truncated the once-diverse habitats that historically supported
82 a highly diverse assemblage of populations. The life history diversity of this histor-
83 ical assemblage would have buffered the overall abundance of Chinook salmon in
84 the Central Valley under varying climate conditions. We are now left with a fish-
85 ery that is supported largely by four hatcheries that produce mostly fall Chinook
86 salmon. Because the survival of fall Chinook salmon hatchery release groups is
87 highly correlated among nearby hatcheries, and highly variable among years, we
88 can expect to see more booms and busts in this fishery in the future in response
89 to variation in the ocean environment. Simply increasing the production of fall

90 Chinook salmon from hatcheries as they are currently operated may aggravate this
91 situation by further concentrating production in time and space. Rather, the key to
92 reducing variation in production is increasing the diversity of SRFC.

93 There are few direct actions available to the PFMC to improve this situation,
94 but there are actions the PFMC can support that would lead to increased diversity
95 of SRFC and increased stability. Mid-term solutions include continued advocacy
96 for more fish-friendly water management and the examination of hatchery prac-
97 tices to improve the survival of hatchery releases while reducing adverse interac-
98 tions with natural fish. In the longer-term, increased habitat quantity, quality, and
99 diversity, and modified hatchery practices could allow life history diversity to in-
100 crease in SRFC. Increased diversity in SRFC life histories should lead to increased
101 stability and resilience in a dynamic, changing environment. Using an ecosystem-
102 based management and ecological risk assessment framework to engage the many
103 agencies and stakeholder groups with interests in the ecosystems supporting SRFC
104 would aid implementation of these solutions.

2 Introduction

In April 2008 the Pacific Fishery Management Council (PFMC) adopted the most restrictive salmon fisheries in the history of the west coast of the U.S., in response to the sudden collapse of Sacramento River fall Chinook (SRFC) salmon and the poor status of many west coast coho salmon populations. The PFMC adopted a complete closure of commercial and recreational Chinook fisheries south of Cape Falcon, Oregon, allowing only for a mark-selective hatchery coho recreational fishery of 9,000 fish from Cape Falcon, Oregon, to the Oregon/California border. Salmon fisheries off California and Oregon have historically been robust, with seasons spanning May through October and catches averaging over 800,000 Chinook per year from 2000 to 2005. The negative economic impact of the closure was so drastic that west coast Governors asked for \$290 million in disaster relief, and the U.S. Congress appropriated \$170 million.

Escapement of several west coast Chinook and coho salmon stocks was lower than expected in 2007 (PFMC, 2009), and low jack escapement in 2007 for some stocks suggested that 2008 would be at least as bad (PFMC, 2008). The most prominent example is SRFC salmon, for which spawning escapement in 2007 is estimated to have been 88,000, well below the escapement conservation goal of the PFMC (122,000–180,000 fish) for the first time since the early 1990s (Fig. 1). While the 2007 escapement represents a continuing decline since the recent peak escapement of 725,000 spawners in 2002, average escapement since 1983 has been about 248,000. The previous record low escapement, observed in 1992, is believed to have been due to a combination of drought conditions, overfishing, and poor ocean conditions (SRFCRT, 1994). Although conditions have been wetter than average over the 2000-2005 period, the spawning escapement of jacks in 2007 was the lowest on record, significantly lower than the 2006 jack escapement (the second lowest on record), and the preseason projection of 2008 adult spawner escapement was only 59,000¹ despite the complete closure of coastal and freshwater Chinook fisheries.

Low escapement has also been documented for coastal coho salmon during this same time frame. For California, coho salmon escapement in 2007 averaged 27% of parent stock abundance in 2004, with a range from 0% (Redwood Creek) to 68% (Shasta River). In Oregon, spawner estimates for the Oregon Coast natural (OCN) coho salmon were 30% of parental spawner abundance. These returns are the lowest since 1999, and are near the low abundances of the 1990s. Columbia River coho and Chinook stocks experienced mixed escapement in 2007 and 2008.

For coho salmon in 2007 there was a clear north-south gradient, with escapement improving to the north. California and Oregon coastal escapement was down sharply, while Columbia River hatchery coho were down only slightly (PFMC, 2009). Washington coastal coho escapement was similar to 2006. Even within the OCN region, there was a clear north-south pattern, with the north coast region (predominantly Nehalem River and Tillamook Bay populations) returning at 46%

¹Preliminary postseason estimate for 2008 SRFC adult escapement is 66,000.

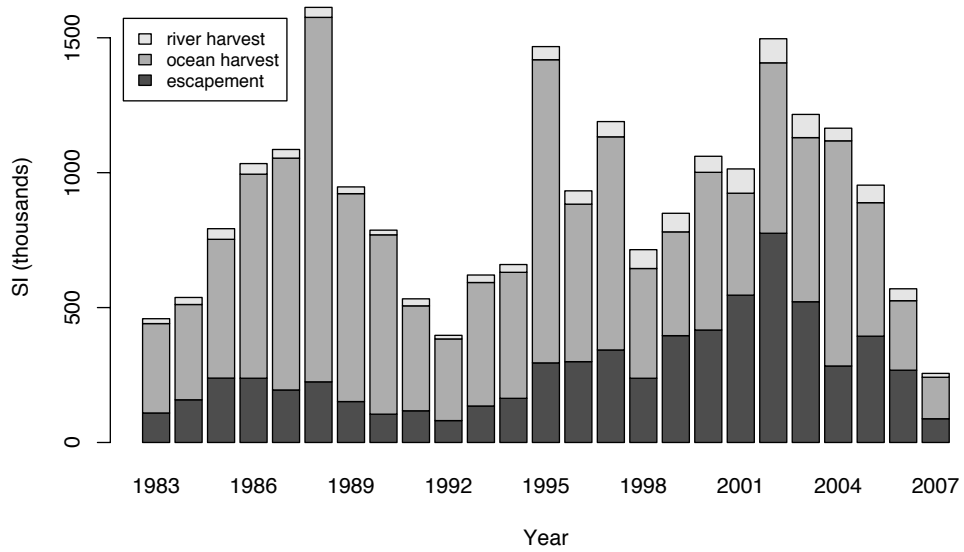


Figure 1: Sacramento River fall Chinook escapement, ocean harvest, and river harvest, 1983–2007. The sum of these components is the Sacramento Index (SI). From O’Farrell et al. (2009).

147 of parental abundance while the mid-south coast region (predominantly Coos and
148 Coquille populations) returned at only 14% of parental abundance. The Rogue
149 River population was only 21% of parental abundance. Low 2007 jack escapement
150 for these three stocks in particular suggests a continued low abundance in 2008.
151 In addition, Columbia River coho salmon jack escapement in 2007 was also near
152 record lows.

153 There have been exceptions to these patterns of decline. Klamath River fall
154 Chinook experienced a very strong 2004 brood, despite parent spawners being well
155 below the estimated level necessary for maximum production. Columbia River
156 spring Chinook production from the 2004 and 2005 broods will be at historically
157 high levels, according to age-class escapement to date. The 2008 forecasts for
158 Columbia River fall Chinook “tule” stocks are significantly more optimistic than
159 for 2007. Curiously, Sacramento River late-fall Chinook escapement has declined
160 only modestly since 2002, while the SRFC in the same river basin fell to record low
161 levels.

162 What caused the observed general pattern of low salmon escapement? For the
163 SRFC stock, which is an aggregate of hatchery and natural production (but prob-
164 ably dominated by hatchery production (Barnett-Johnson et al., 2007)), freshwater
165 withdrawals (including pumping of water from the Sacramento-San Joaquin Delta),
166 unusual hatchery events, pollution, elimination of net-pen acclimatization facilities
167 coincident with one of the two failed brood years, and large-scale bridge construc-
168 tion during the smolt outmigration along with many other possibilities have been
169 suggested as prime candidates causing the poor escapement (CDFG, 2008).

170 When investigating the possible causes for the decline of SRFC, we need to rec-
171 ognize that salmon exhibit complex life histories, with potential influences on their
172 survival at a variety of life stages in freshwater, estuarine and marine habitats. Thus,
173 salmon typically have high variation in adult escapement, which may be explained
174 by a variety of anthropogenic and natural environmental factors. Also, environ-
175 mental change affects salmon in different ways at different time scales. In the short
176 term, the dynamics of salmon populations reflect the effects of environmental vari-
177 ation, e.g., high freshwater flows during the outmigration period might increase
178 juvenile survival and enhance recruitment to the fishery. On longer time scales,
179 the cumulative effects of habitat degradation constrain the diversity and capacity of
180 habitats, extirpating some populations and reducing the diversity and productivity
181 of surviving populations (Bottom et al., 2005b). This problem is especially acute in
182 the Sacramento-San Joaquin basin, where the effects of land and water development
183 have extirpated many populations of spring-, winter- and late-fall-run Chinook and
184 reduced the diversity and productivity of fall Chinook populations (Myers et al.,
185 1998; Good et al., 2005; Lindley et al., 2007).

186 Focusing on the recent variation in salmon escapement, the coherence of varia-
187 tions in salmon productivity over broad geographic areas suggests that the patterns
188 are caused by regional environmental variation. This could include such events
189 as widespread drought or floods affecting hydrologic conditions (e.g., river flow
190 and temperature), or regional variation in ocean conditions (e.g., temperature, up-
191 welling, prey and predator abundance). Variations in ocean climate have been in-

192 creasingly recognized as an important cause of variability in the landings, abun-
193 dance, and productivity of salmon (e.g, Hare and Francis (1995); Mantua et al.
194 (1997); Beamish et al. (1999); Hobday and Boehlert (2001); Botsford and Lawrence
195 (2002); Mueter et al. (2002); Pyper et al. (2002)). The Pacific Ocean has many
196 modes of variation in sea surface temperature, mixed layer depth, and the strength
197 and position of winds and currents, including the El Niño-Southern Oscillation, the
198 Pacific Decadal Oscillation and the Northern Oscillation. The broad variation in
199 physical conditions creates corresponding variation in the pelagic food webs upon
200 which juvenile salmon depend, which in turn creates similar variation in the popula-
201 tion dynamics of salmon across the north Pacific. Because ocean climate is strongly
202 coupled to the atmosphere, ocean climate variation is also related to terrestrial cli-
203 mate variation (especially precipitation). It can therefore be quite difficult to tease
204 apart the roles of terrestrial and ocean climate in driving variation in the survival
205 and productivity of salmon (Lawson et al., 2004).

206 In this report we review possible causes for the decline in SRFC, limiting our
207 analysis to those potential causes for which there are reliable data to evaluate. First,
208 we analyze the performance of the 2004, 2005 and 2006 broods of SRFC and look
209 for corresponding conditions and events in their freshwater, estuarine and marine
210 environments. Then we discuss the impact of long-term degradation in freshwater
211 and estuarine habitats and the effects of hatchery practices on the biodiversity of
212 Chinook in the Central Valley, and how reduced biodiversity may be making Chi-
213 nook fisheries more susceptible to variations in ocean and terrestrial climate. We
214 end the report with recommendations for future monitoring, research, and conser-
215 vation actions. The appendix answers each of the more than 40 questions posed to
216 the committee and provides summaries of most of the data used in the main report
217 (CDFG, 2008).

218 **3 Analysis of recent broods**

219 **3.1 Review of the life history of SRFC**

220 Naturally spawning SRFC return to the spawning grounds in the fall and lay their
221 eggs in the low elevation areas of the Sacramento River and its tributaries (Fig. 2).
222 Eggs incubate for a month or more in the fall or winter, and fry emerge and rear
223 throughout the rivers, tributaries and the Delta in the late winter and spring. In May
224 or June, the juveniles are ready for life in the ocean, and migrate into the estuary
225 (Suisun Bay to San Francisco Bay) and on to the Gulf of the Farallones. Emigra-
226 tion from freshwater is complete by the end of June, and juveniles migrate rapidly
227 through the estuary (MacFarlane and Norton, 2002). While information specific to
228 the distribution of SRFC during early ocean residence is mostly lacking, fall Chi-
229 nook in Oregon and Washington reside very near shore (even within the surf zone)
230 and near their natal river for some time after ocean entry, before moving away
231 from the natal river mouth and further from shore (Brodeur et al., 2004). SRFC
232 are encountered in ocean salmon fisheries in coastal waters mainly between cen-

233 tral California and northern Oregon (O’Farrell et al., 2009; Weitkamp, In review),
234 with highest abundances around San Francisco. Most SRFC return to freshwater to
235 spawn after two or three years of feeding in the ocean.

236 A large portion of the SRFC contributing to ocean fisheries is raised in hatcheries
237 (Barnett-Johnson et al., 2007), including Coleman National Fish Hatchery (CNFH)
238 on Battle Creek, Feather River Hatchery (FRH), Nimbus Hatchery on the Amer-
239 ican River, and the Mokelumne River Hatchery. Hatcheries collect fish that as-
240 cend hatchery weirs, breed them, and raise progeny to the smolt stage. The state
241 hatcheries transport >90% of their production to the estuary in trucks, where some
242 smolts usually are acclimatized briefly in net pens and others released directly into
243 the estuary; Coleman National Fish Hatchery (CNFH) usually releases its produc-
244 tion directly into Battle Creek.

245 **3.2 Available data**

246 A large number of datasets are potentially relevant to the investigation at hand.
247 These are summarized in Table 1.

248 **3.3 Conceptual approach**

249 The poor landings and escapement of Chinook in 2007 and the record low escape-
250 ment in 2008 suggests that something unusual happened to the SRFC 2004 and
251 2005 broods, and more than forty possible causes for the decline were evaluated
252 by the committee. Poor survival of a cohort can result from poor survival at one or
253 more stages in the life cycle. Life cycle stages occur at certain times and places, and
254 an examination of possible causes of poor survival should account for the temporal
255 and spatial distribution of these life stages. It is helpful to consider a conceptual
256 model of a cohort of fall-run Chinook that illustrates how various anthropogenic
257 and natural factors affect the cohort (Fig. 3). The field of candidate causes can be
258 narrowed by looking at where in the life cycle the abundance of the cohort became
259 unusually low, and by looking at which of the causal factors were at unusual levels
260 for these broods. The most likely causes of the decline will be those at unusual
261 levels at a time and place consistent with the unusual change in abundance.

262 In this report, we trace through the life cycle of each cohort, starting with the
263 parents of the cohort and ending with the return of the adults. Coverage of life stages
264 and possible causes for the decline varies in depth, partly due to differences in the
265 information available and partly to the committee’s belief in the likelihood that
266 particular life stages and causal mechanisms are implicated in the collapse. Each
267 potential factors identified by CDFG (2008) is, however, addressed individually in
268 the Appendix. Before we delve into the details of each cohort, it is worthwhile to
269 list some especially pertinent observations relative to the 2004 and 2005 broods:

- 270 • Near-average numbers of fall Chinook juveniles were captured at Chipps Is-
271 land

Table 1: Summary of data sources used in this report.

Data type	Period	Source
Time series of ocean harvest, river harvest and escapement	1983-2007	PFMC
Coded wire tag recoveries in fisheries and hatcheries	1983-2007	PSMFC
Fishing effort	1983-2007	PSMFC
Bycatch of Chinook in trawl fisheries	1994-2007	NMFS
Hatchery releases and operations	varies	CDFG, USFWS
Catches of juvenile salmon in survey trawls near Chipps Island	1977-2008	USFWS
Recovery of juvenile salmon in fish salvage operations at water export facilities	1997-2007	DWR
Time series of river conditions (discharge, temperature, turbidity) at various points in the basin	1990-2007	USGS, DWR
Time series of hydrosystem operations (diversions and exports)	1955-2007	DWR, USBR
Abundance of striped bass	1990-2007	CDFG
Abundance of pelagic fish in Delta	1993-2007	CDFG
Satellite-based observations of ocean conditions (sea surface temperature, winds, phytoplankton biomass)	various	NOAA, NASA
Observations of estuary conditions (salinity, temperature, Chl, dissolved O ₂)	1990-2007	USGS
Zoolankton abundance in the estuary	1990-2007	W. Kimmerer, SFSU
Ship-based observations of physical and biological conditions in the ocean (abundance of salmon prey items, mixed layer depth)	1983-2007	NOAA
Ocean winds and upwelling	1967-2008	NMFS
Abundance of marine mammals	varies	NMFS
Abundance of groundfish	1970-2005	NMFS
Abundance of salmon prey items	1983-2005	NMFS
Condition factor of juvenile Chinook in estuary and coastal ocean	1998-2005	NOAA
Seabird nesting success	1971-2005	PRBO

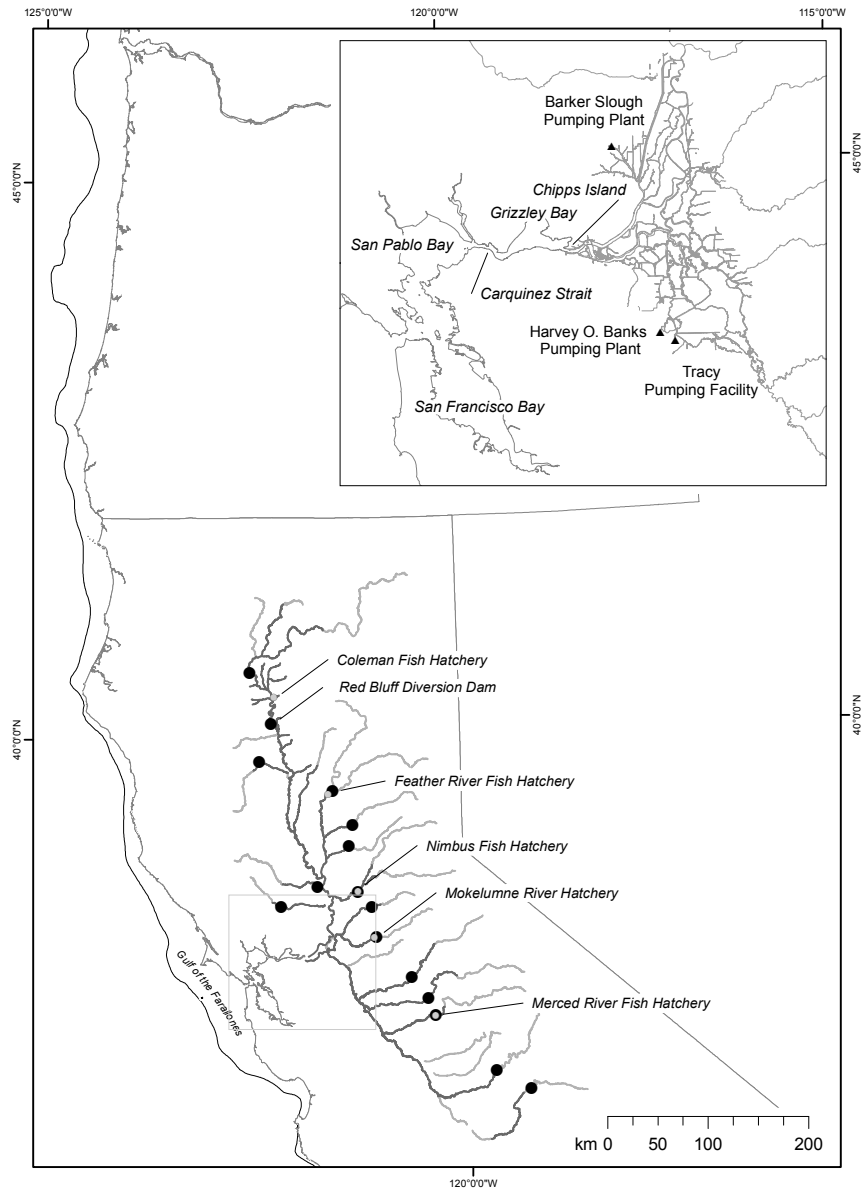


Figure 2: Map of the Sacramento River basin and adjacent coastal ocean. Inset shows the Delta and bays. Black dots denote the location of impassable dams; black triangle denote the location of major water export facilities in the Delta. The contour line indicates approximately the edge of the continental shelf.

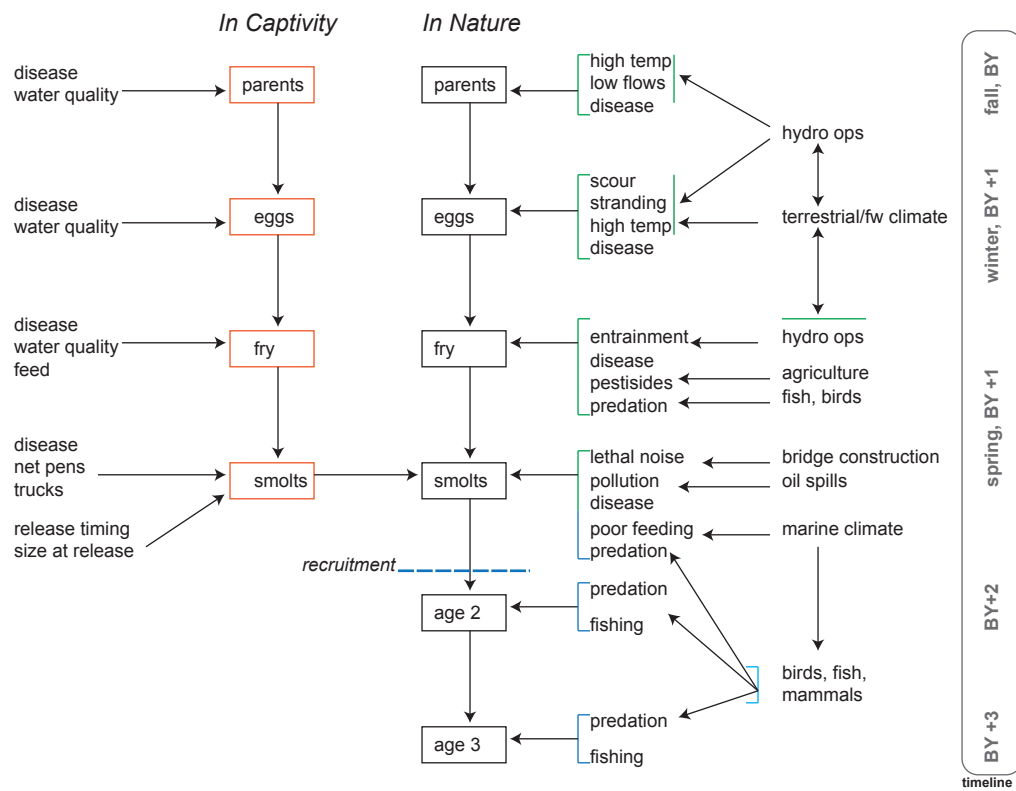


Figure 3: Conceptual model of a cohort of fall-run Chinook and the factors affecting its survival. Orange boxes represent life stages in the hatchery, and black boxes represent life stages in the wild.

- 272 • Near-average numbers of SRFC smolts were released from state and federal
273 hatcheries
- 274 • Hydrologic conditions in the river and estuary were not unusual during the
275 juvenile rearing and outmigration periods (in particular, drought conditions
276 were not in effect)
- 277 • Although water exports reaches record levels in 2005 and 2006, these lev-
278 els were not reached until June and July, a period of time which followed
279 outmigration of the vast majority of fall Chinook salmon smolts from the
280 Sacramento system
- 281 • Survival of Feather River fall Chinook from release into the estuary to re-
282 cruitment to fisheries at age two was extremely poor
- 283 • Physical and biological conditions in the ocean appeared to be unusually poor
284 for juvenile Chinook in the spring of 2005 and 2006
- 285 • Returns of Chinook and coho salmon to many other basins in California,
286 Oregon and Washington were also low in 2007 and 2008.

287 From these facts, we infer that unfavorable conditions during the early marine
288 life of the 2004 and 2005 broods is likely the cause of the stock collapse. Fresh-
289 water factors do not appear to be implicated directly because of the near average
290 abundance of smolts at Chipps Island and because tagged fish released into the es-
291 tuary had low survival to age two. Marine factors are further implicated by poor
292 returns of coho and Chinook in other west coast river basins and numerous obser-
293 vations of anomalous conditions in the California Current ecosystem, especially
294 nesting failure of seabirds that have a diet and distribution similar to that of juvenile
295 salmon.

296 In the remainder of this section, we follow each brood through its lifecycle,
297 bringing relatively more detail to the assessment of ocean conditions during the
298 early marine phase of the broods. While we are confident that ocean conditions are
299 the proximate cause of the poor performance of the 2004 and 2005 broods, human
300 activities in the freshwater environment have played an important role in creating a
301 stock that is vulnerable to episodic crashes; we develop this argument in section 4.

302 **3.4 Brood year 2004**

303 **3.4.1 Parents**

304 The possible influences on the 2004 brood of fall-run Chinook began in 2004, with
305 the maturation, upstream migration and spawning of the brood's parents. Most sig-
306 nificantly, 203,000 adult fall Chinook returned to spawn in the Sacramento River
307 and its tributaries in 2004, slightly more than the 1970-2007 mean of 195,000; es-
308 capement to the Sacramento basin hatcheries totaled 80,000 adults (PFMC, 2009).
309 In September and October of 2004, water temperatures were elevated by about

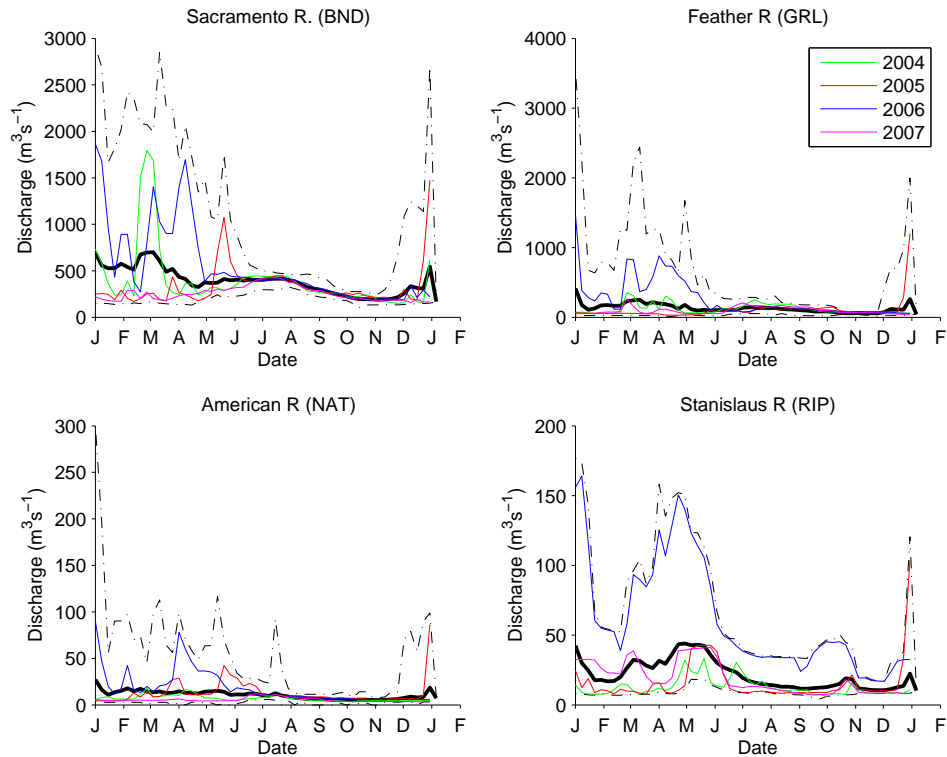


Figure 4: Discharge in regulated reaches of the Sacramento River, Feather River, American River and Stanislaus River in 2004-2007. Heavy black line is the weekly average discharge over the period of record for the stream gage (indicated in parentheses in the plot titles); dashed black lines indicate weekly maximum and minimum discharges. Data from the California Data Exchange Center, <http://cdec.water.ca.gov>.

310 1°C above average at Red Bluff, but remained below 15.5°C. Temperatures inhibit-
 311 ing the migration of adult Chinook are significantly higher than this (McCullough,
 312 1999). Flows were near normal through the fall and early winter (Fig. 4). Es-
 313 capement to the hatcheries was near record highs, and no significant changes to
 314 broodstock selection or spawning protocols occurred. Carcass surveys on the Sacra-
 315 mento River showed very low levels of pre-spawning mortality in 2004 (D. Killam,
 316 CDFG, unpublished data). It therefore appears that factors influencing the parents of
 317 the 2004 brood were not the cause of the poor performance of that brood.

318 3.4.2 Eggs

319 The naturally-spawned portion of the 2004 brood spent the egg phase in the gravel
 320 from October 2004 through March 2005 (Vogel and Marine, 1991). Water tempera-
 321 tures at Red Bluff were within the optimal range for egg incubation for most of this
 322 period, with the exception of early October. Flows were below average throughout
 323 the incubation period, but mostly above the minimum flow levels observed for the
 324 last 20 years or so. It is therefore unlikely that the eggs suffered scouring flows; we
 325 have no information about redd dewatering, although flows below the major dams

326 are regulated to prevent significant redd dewatering.

327 In the hatcheries, no unusual events were noted during the incubation of the
328 eggs of the 2004 brood. Chemical treatments of the eggs were not changed for the
329 2004 brood.

330 **3.4.3 Fry, parr and smolts**

331 As noted above, flows in early 2005 were relatively low until May, when conditions
332 turned wet and flows rose to above-normal levels (Fig. 4). Higher spring flows
333 are associated with higher survival of juvenile salmon (Newman and Rice, 2002).
334 Water temperature at Red Bluff was above the 1990-2007 average for much of the
335 winter and spring, but below temperatures associated with lower survival of juvenile
336 life stages (McCullough, 1999). In 2005, the volume of water pumped from the
337 Delta reached record levels in January before falling to near-average levels in the
338 spring, then rising again to near-record levels in the summer and fall (Fig. 5,top), but
339 only after the migration of fall Chinook smolts was nearly complete (Fig. 8). Water
340 diversions, in terms of the export:inflow ratio (E/I), fluctuated around the average
341 throughout the winter and spring (Fig. 5,bottom). Statistical analysis of coded-
342 wire-tagged releases of Chinook to the Delta have shown that survival declines
343 with increasing exports and increasing E/I at time of release (Kjelson and Brandes,
344 1989; Newman and Rice, 2002).

345 Releases of Chinook smolts were at typical levels for the 2004 brood, with a
346 high proportion released into the bay, and of these, a not-unusual portion acclima-
347 tized in net pens prior to release (Fig. 6). No significant disease outbreaks or other
348 problems with the releases were noted.

349 Systematic trawl sampling near Chipps Island provides an especially useful
350 dataset for assessing the strength of a brood as it enters the estuary². The US-
351 FWS typically conducts twenty-minute mid-water trawls, 10 times per day, 5 days
352 a week. An index of abundance can be formed by dividing the total catch per day by
353 the total volume swept by the trawl gear. Fig. 7 shows the mean annual CPUE from
354 1976 to 2007; CPUE in 2005 was slightly above average. The timing of catches
355 of juvenile fall Chinook at Chipps Island was not unusual in 2005 (Fig. 8). Had
356 the survival of the 2004 brood been unusually poor in freshwater, catches at Chipps
357 Island should have been much lower than average, since by reaching that location,
358 fish have survived almost all of the freshwater phase of their juvenile life.

359 There are two reasons, however, that apparently normal catches at Chipps Island
360 could mask negative impacts that occurred in freshwater. One possibility is that
361 catches were normal because the capture efficiency of the trawl was much higher
362 than usual. The capture efficiency of the trawl, as estimated by the recovery rate
363 of coded-wire-tagged Chinook, is variable among years, but the recovery rate of
364 Chinook released at Ryde in 2005 was about average (P. Brandes, USFWS, un-
365 published data). This suggests that the actual abundance of fall Chinook passing

²Catches at Chipps Island include naturally-produced fish and CNFH hatchery fish released at Battle Creek; almost all fish from the state hatcheries are released downstream of Chipps Island.

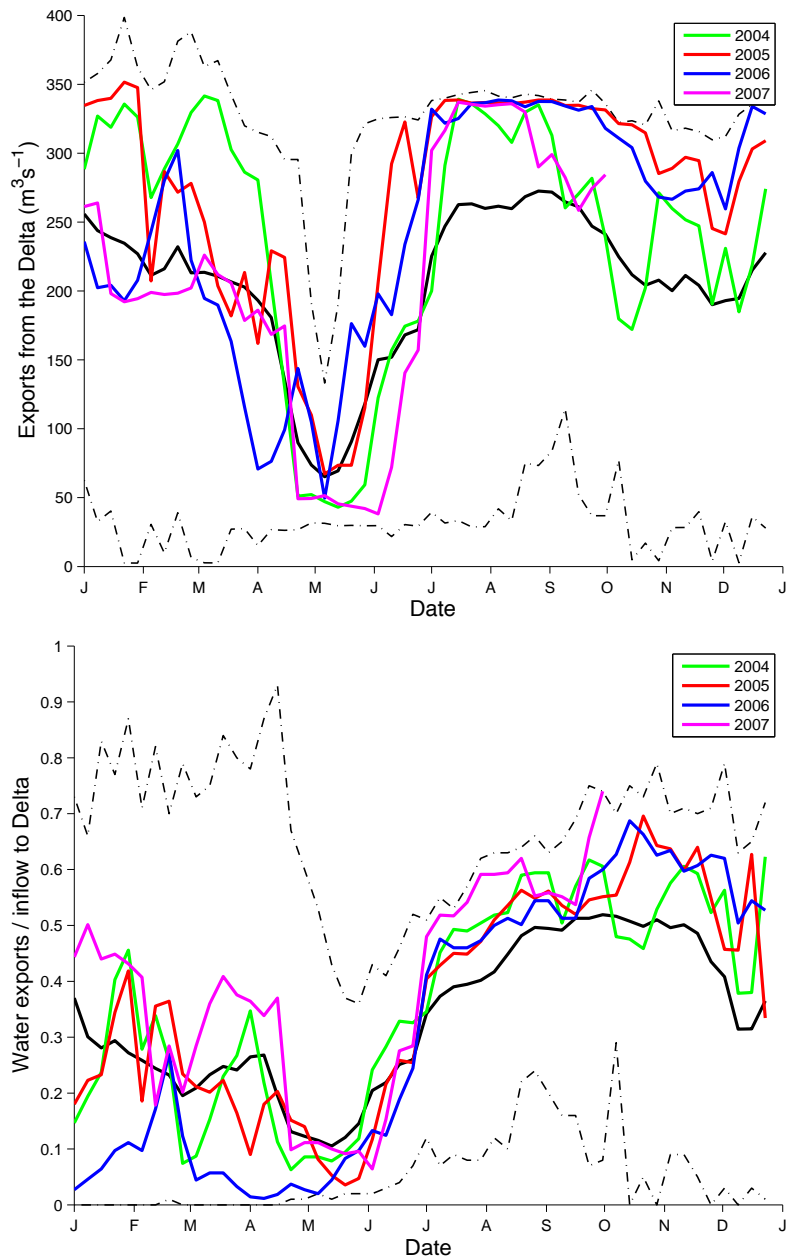


Figure 5: Weekly average export of freshwater from the Delta (upper panel) and the ratio of exports to inflows (bottom panel). Heavy black line is the weekly average discharge over the 1955-2007 period; dashed black lines indicate maximum and minimum weekly average discharges. Exports, as both rate and proportion, were higher than average in all years in the summer and fall, but near average during the spring, when fall Chinook are migrating through the Delta. Flow estimates from the DAYFLOW model (<http://www.iep.ca.gov/dayflow/>).

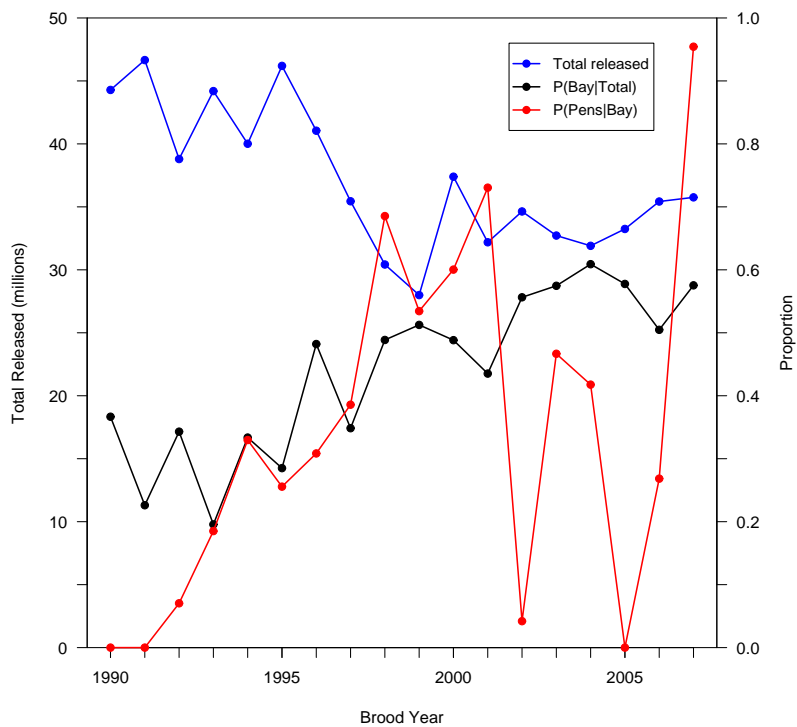


Figure 6: Total releases of hatchery fall Chinook, proportion of releases made to the bay, and the proportion of bay releases acclimatized in net pens. Unpublished data of CDFG and USFWS.

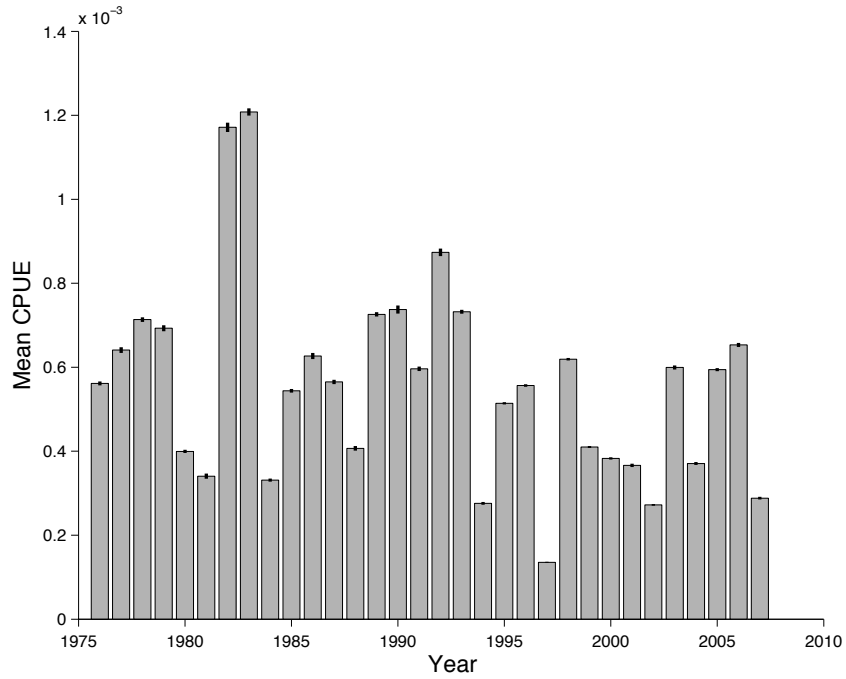


Figure 7: Mean annual catch-per-unit effort of fall Chinook juveniles at Chipps Island by USFWS trawl sampling conducted between January 1 and July 18. Error bars indicate the standard error of the mean. USFWS, unpublished data.

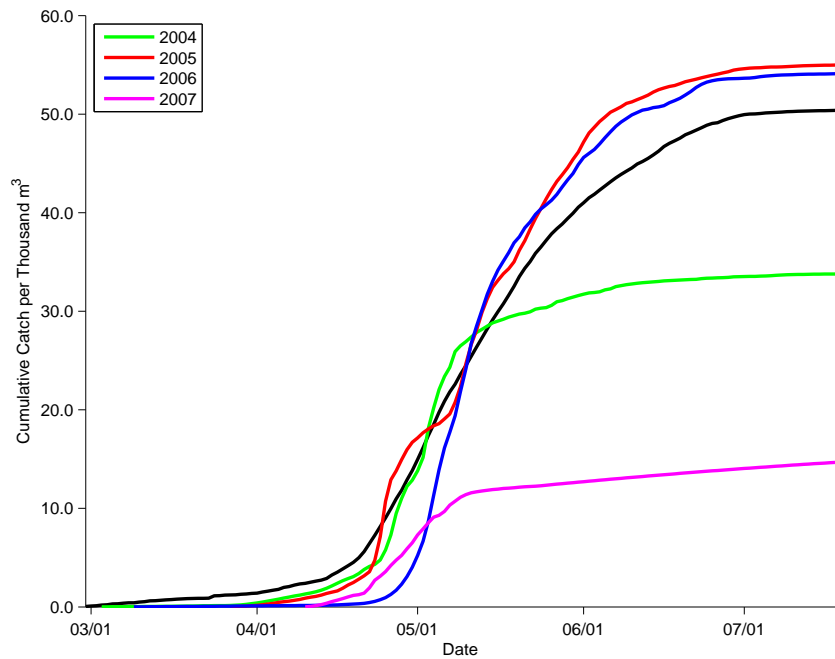


Figure 8: Cumulative daily catch per unit effort (CPUE) of fall Chinook juveniles at Chipps Island by USFWS trawl sampling. Black line shows the mean cumulative CPUE for 1976-2007.

366 Chipps Island was not low. The other explanation is that the effects of freshwa-
367 ter stressors result in delayed mortality that manifests itself after fish pass Chipps
368 Island. Delayed mortality from cumulative stress events has been hypothesized to
369 explain the relatively poor survival to adulthood of fish that successfully pass more
370 hydropower dams on the Columbia River (Budy et al., 2002). However, there is no
371 *direct* evidence, to date, for delayed mortality in Chinook from the Columbia River
372 (ISAB, 2007), and its causes remain a mystery. In any case, we do not have the data
373 to test this hypothesis for SRFC.

374 **3.4.4 Early ocean**

375 Taken together, two lines of evidence suggest that something unusual befell the
376 2004 brood of fall Chinook in either the bay or the coastal ocean. First, near-
377 average numbers of juveniles were observed at Chipps Island (Fig. 8), and the state
378 hatcheries released normal numbers of smolts into the bay. Second, survival of FRH
379 smolts to age two was very low for the 2004 brood, only 8% that of the 2000 brood
380 (Fig. 9; see the appendix for the rationale and details behind the survival rate index
381 calculations), and the escapement of jacks from the 2004 brood was also very low in
382 2006 (Fig. 10). The Sacramento Index of for 2007 was quite close to that expected
383 by the escapement of jacks in 2006 (see appendix), indicating that the unusual mor-
384 tality occurred after passing Chipps Island and prior to recruitment to the fishery at
385 age two. Environmental conditions in the bay were not unusual in 2005 (see ap-
386 pendix), suggesting that the cause of the collapse was likely in the ocean. Before
387 reviewing conditions in the ocean, it is helpful to consider a conceptual model of
388 physical and biological processes that characterize upwelling ecosystems, of which
389 the California Current is an example.

390 Rykaczewski and Checkley (2008) provides such a model (Fig. 11). Several
391 factors, operating at different scales, influence the magnitude and distribution of
392 primary and secondary productivity³ occurring in the box. At the largest scale, the
393 winds that drive upwelling ecosystems are generated by high-pressure systems cen-
394 tered far offshore that generate equator-ward winds along the eastern edge of the
395 ocean basin (Barber and Smith, 1981). The strength and position of pressure sys-
396 tems over the globe change over time, which is reflected in various climate indices
397 such as the Southern Oscillation Index and the Northern Oscillation index (Schwing
398 et al., 2002), and these large-scale phenomena have local effects on the California
399 Current. One effect is determining the source of the water entering the northern
400 side of the box in Fig. 11. This source water can come from subtropical waters
401 (warmer and saltier, with subtropical zooplankton species that are not particularly
402 rich in lipids) or from subarctic waters (colder and fresher, with subarctic zooplank-
403 ton species that are rich in lipids) (Hooff and Peterson, 2006). Where the source
404 water comes from is determined by physical processes acting at the Pacific Ocean
405 basin scale. The productivity of the source water entering the box is also influenced
406 by coastal upwelling occurring in areas to the north.

³Primary production is the creation of organic material by phytoplankton; secondary production is the creation of animal biomass by zooplankton.

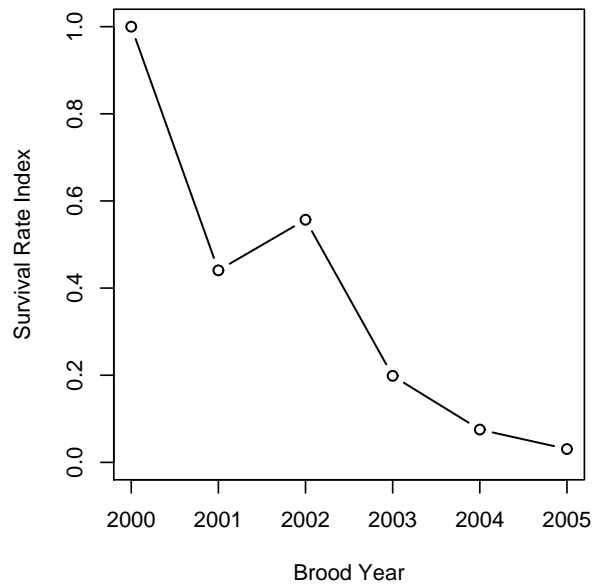


Figure 9: Index of FRH fall Chinook survival rate between release in San Francisco Bay and age two based on coded-wire tag recoveries in the San Francisco major port area recreational fishery; brood years 2000-2005. The survival rate index is recoveries of coded-wire tags expanded for sampling divided by the product of fishing effort and the number of coded-wire tags released, relative to the maximum value observed (brood year 2000).

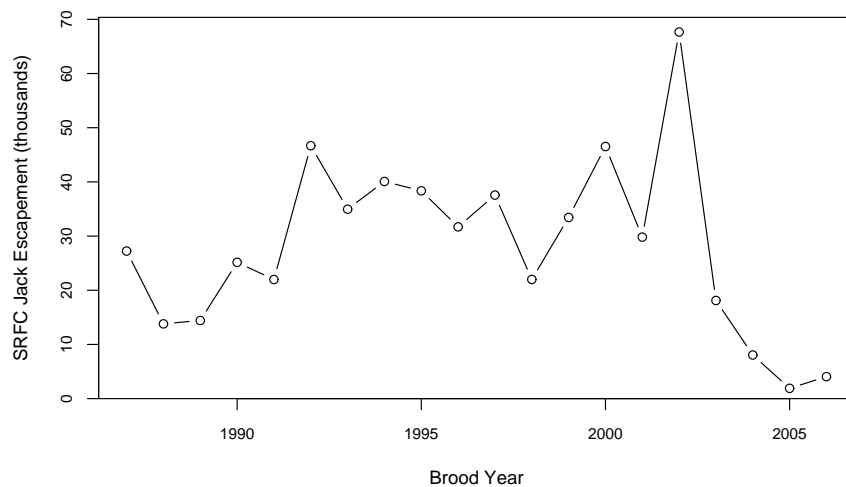


Figure 10: Escapement of SRFC jacks. Escapements in 2006 (brood year 2004) and 2007 (brood year 2005) were record lows at the time. Escapement estimate for 2008 (brood year 2006) is preliminary.

407 Within the box, productivity also depends on the magnitude, direction, spatial
408 and temporal distribution of the winds (e.g., Wilkerson et al., 2006). Northwest
409 winds drive surface waters away from the shore by a process called Ekman flow,
410 and are replaced from below by colder, nutrient-rich waters near shore through the
411 process of coastal upwelling. Northwest winds typically become stronger as one
412 moves away from shore, a pattern called positive windstress curl, which causes
413 offshore upwelling through a processes called Ekman pumping. The vertical ve-
414 locities of curl-driven upwelling are generally much smaller than those of coastal
415 upwelling, so nutrients are supplied to the surface waters at a lower rate by Ekman
416 pumping (although potentially over a much larger area). Calculations by Dever et al.
417 (2006) indicate that along central California, coastal upwelling supplies about twice
418 the nutrients to surface waters as curl-driven upwelling. The absolute magnitude of
419 the wind stress also affects mixing of the surface ocean; wind-driven mixing brings
420 nutrients into the surface mixed layer but deepens the mixed layer, potentially lim-
421 iting primary production by decreasing the average amount of light experienced by
422 phytoplankton.

423 Yet another factor influencing productivity is the degree of stratification⁴ in the
424 upper ocean. This is partly determined by the source waters– warmer waters in-
425 crease the stratification, which impedes the effectiveness of wind-driven upwelling
426 and mixing. The balance of all of these processes determines the character of the
427 pelagic food web, and when everything is “just right”, highly productive and short
428 food chains can form and support productive fish populations that are characteristic
429 of coastal upwelling ecosystems (Ryther, 1969; Wilkerson et al., 2006).

430 It is also helpful to consider how Chinook use the ocean. Juvenile SRFC typ-
431 ically enter the ocean in the springtime, and are thought to reside in near shore
432 waters, in the vicinity of their natal river, for the first few months of their lives in
433 the sea (Fisher et al., 2007). As they grow, they migrate along the coast, remaining
434 over the continental shelf mainly between central California and southern Wash-
435 ington (Weitkamp, In review). Fisheries biologists believe that the time of ocean
436 entry is especially critical to the survival of juvenile salmon, as they are small and
437 thus vulnerable to many predators (Percy, 1992). If feeding conditions are good,
438 growth will be high and starvation or the effects of size-dependent predation may
439 be lower. Thus, we expect conditions at the time of ocean entry and near the point
440 of ocean entry to be especially important in determining the survival of juvenile fall
441 Chinook.

442 The timing of the onset of upwelling is critical for juvenile salmon that migrate
443 to sea in the spring. If upwelling and the pelagic food web it supports is well-
444 developed when young salmon enter the sea, they can grow rapidly and tend to
445 survive well. If upwelling is not well-developed or if its springtime onset is delayed,
446 growth and survival may be poor. As shown next, most physical and biological
447 measures were quite unusual in the northeast Pacific, and especially in the Gulf of
448 the Farallones, in the spring of 2005, when the 2004 brood of fall Chinook entered
449 the ocean.

⁴Stratification is the layering of water of different density.

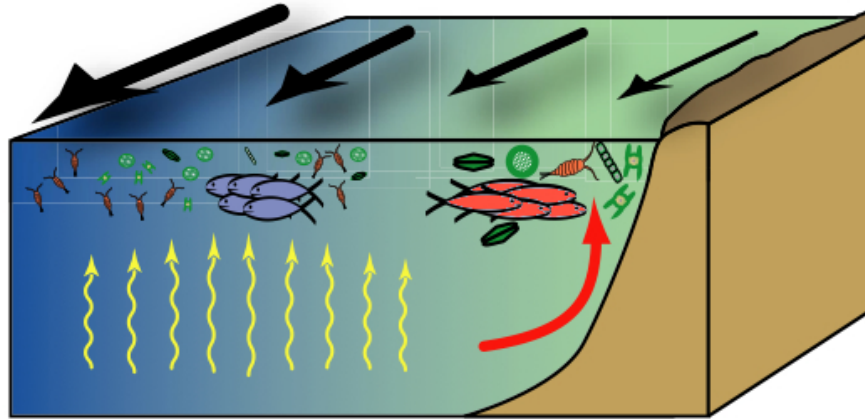


Figure 11: Conceptual diagram displaying the hypothesized relationship between wind-forced upwelling and the pelagic ecosystem. Alongshore, equatorward wind stress results in coastal upwelling (red arrow), supporting production of large phytoplankters and zooplankters. Between the coast and the wind-stress maximums, cyclonic wind-stress curl results in curl-driven upwelling (yellow arrows) and production of smaller plankters. Black arrows represent winds at the ocean surface, and their widths are representative of wind magnitude. Young juvenile salmon, like anchovy (red fish symbols), depend on the food chain supported by large phytoplankters, whereas sardine (blue fish symbols) specialize on small plankters. Growth and survival of juvenile salmon will be highest when coastal upwelling is strong. Redrawn from Rykaczewski and Checkley (2008).

450 Figure 12 shows temperature and wind anomalies for the north Pacific in the
 451 April-June period of 2005-2008. There were southwesterly anomalies in wind
 452 speed throughout the California Current in May of 2005, and sea surface tempera-
 453 ture (SST) in the California Current was warmer than normal. This indicates that
 454 upwelling-inducing winds were abnormally weak in May 2005. By June of 2005,
 455 conditions off of California were more normal, with stronger than usual northwesterly
 456 winds along the coast.

457 Because Fig. 12 indicates that conditions were unusual in the spring of 2005
 458 throughout the California Current and also the Gulf of Alaska, we should expect
 459 to see wide-spread responses by salmon populations inhabiting these waters at this
 460 time. This was indeed the case. Fall Chinook in the Columbia River from brood
 461 year 2004 had their lowest escapement since 1990, and coastal fall Chinook from
 462 Oregon from brood year 2004 had their lowest escapement since either 1990 or the
 463 1960s, depending on the stock. Coho salmon that entered the ocean in the spring of
 464 2005 also had poor escapement.

465 Conditions off north-central California further support the hypothesis that ocean
 466 conditions were a significant reason for the poor survival of the 2004 brood of fall
 467 Chinook salmon. The upper two panels of Fig. 13 show a cumulative upwelling
 468 index (CUI; Schwing et al. (2006)), an estimate of the integrated amount of up-
 469 welling for the growing season, for the nearshore ocean area where fall Chinook
 470 juveniles initially reside (39°N) and the coastal region to the north, or “upstream”

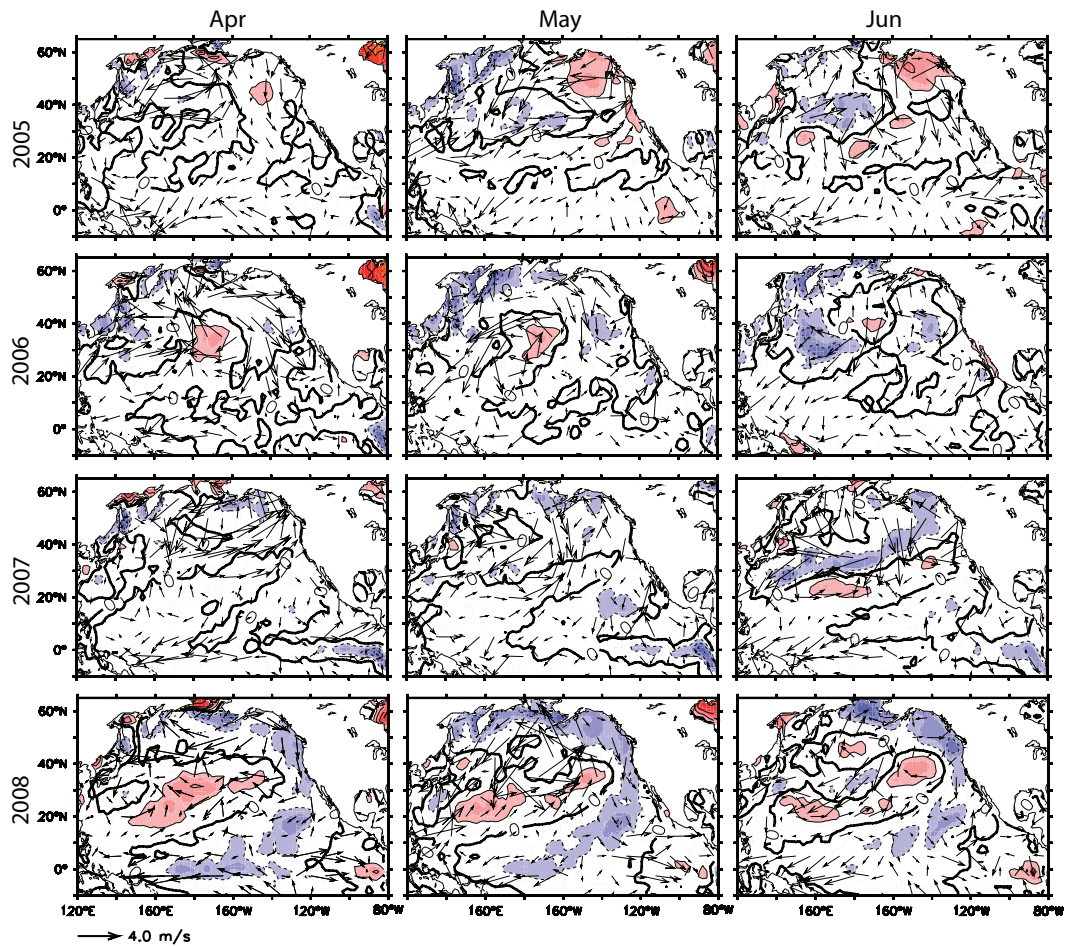


Figure 12: Sea surface temperature (colors) and wind (vectors) anomalies for the north Pacific for April-June in 2005-2008. Red indicates warmer than average SST; blue is cooler than average. Note the southwesterly wind anomalies (upwelling-suppressing) in May 2005 and 2006 off of California, and the large area of warmer-than-normal water off of California in May 2005. Winds and surface temperatures returned to near-normal in 2007, and become cooler than normal in spring 2008 along the west coast of North America.

471 (42°N). Typically, upwelling-favorable winds are in place by mid-March, as shown
472 by the start dates of the CUI. In 2005, upwelling-favorable winds were unseason-
473 ably weak in early spring, and did not become firmly established until late May and
474 June further delayed to the north. The resulting deficit in the CUI (Fig. 13, lower
475 two panels) is thought to have resulted in a delayed spring bloom, reduced biologi-
476 cal productivity, and a much smaller forage base for Chinook smolts. The low and
477 delayed upwelling was also expressed as unusually warm sea-surface temperatures
478 in the spring of 2005 (Fig. 14).

479 The anomalous spring conditions in 2005 and 2006 were also evident in surface
480 trajectories predicted from the OSCURS current simulations model⁵. The model
481 computes the daily movement of water particles in the North Pacific Ocean surface
482 layer from daily sea level pressures (Ingraham and Miyahara, 1988). Lengths and
483 directions of trajectories of particles released near the coast are an indication of
484 the strength of offshore surface movement and upwelling. Fig. 15 shows particle
485 trajectories released from three locations March 1 and tracked to May 1 for 2004,
486 2005, 2006 and 2007. In 2005 and 2006 trajectories released south of 42°N stayed
487 near coast; a situation suggesting little upwelling over the spring.

488 The delay in 2005 upwelling to the north of the coastal ocean habitat for these
489 smolts is particularly important, because water initially upwelled off northern Cali-
490 fornia and Oregon advected south, providing the source of primary production that
491 supports the smolts prey base. Transport in spring 2005 (Fig. 15b) supports the con-
492 tention that the water encountered by smolts emigrating out of SF Bay originated
493 from off northern California, where weak early spring upwelling was particularly
494 notable.

495 Some of the strongest evidence for the collapse of the pelagic food chain comes
496 from observations of seabird nesting success on the Farallon Islands. Nearly all
497 Cassin's auklets, which have a diet very similar to that of juvenile Chinook, aban-
498 doned their nests in 2005 because of poor feeding conditions (Sydeman et al., 2006;
499 Wolf et al., 2009). Other notable observations of the pelagic foodweb in 2005 in-
500 clude: emaciated gray whales (Newell and Cowles, 2006); sea lions foraging far
501 from shore rather than their usual pattern of foraging near shore (Weise et al., 2006);
502 various fishes at record low abundance, including common salmon prey items such
503 as juvenile rockfish and anchovy (Brodeur et al., 2006); and dinoflagellates be-
504 coming the dominant phytoplankton group in Monterey Bay, rather than diatoms
505 (MBARI, 2006). While the overall abundance of anchovies was low, they were
506 captured in an unusually large fraction of trawls, indicating that they were more
507 evenly distributed than normal (NMFS unpublished data). The overall abundance
508 of krill observed in trawls in the Gulf of the Farallones was not especially low, but
509 krill were concentrated along the shelf break and sparse inshore.

510 Observations of size, condition factor (K, a measure of weight per length) and
511 total energy content (kilojoules (kJ) per fish, from protein and lipid contents) of
512 juvenile salmon offer direct support for the hypothesis that feeding conditions in

⁵Live access to OSCURS model, Pacific Fisheries Environmental Laboratory. Available at www.pfeg.noaa.gov/products/las.html. Accessed 26 December 2007.

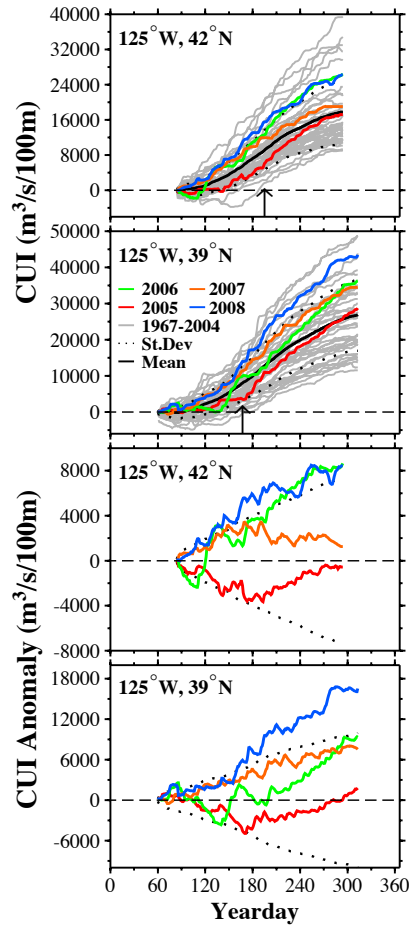


Figure 13: Cumulative upwelling index (CUI) and anomalies of the CUI at 42°N (near Brookings, Oregon) and 39°N (near Pt. Arena, California). Gray lines in the upper two panels are the individual years from 1967-2004. Black line is the average, dashed lines show the standard deviation. Arrow indicates the average time of maximum upwelling rate. The onset of upwelling was delayed in 2005 and remained weak through the summer; in 2006, the onset of upwelling was again delayed but became quite strong in the summer. Upwelling in 2007 and 2008 was stronger than average.

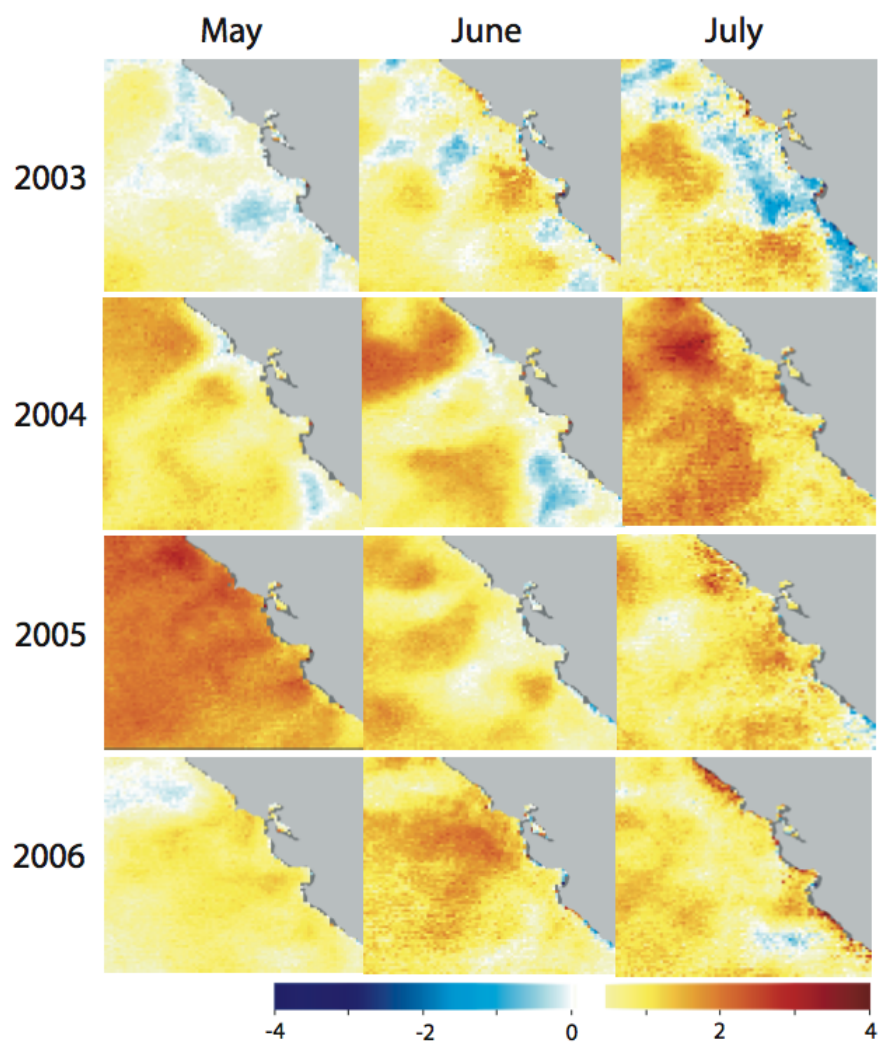


Figure 14: Sea surface temperature anomalies off central California in May-July of 2003-2006.

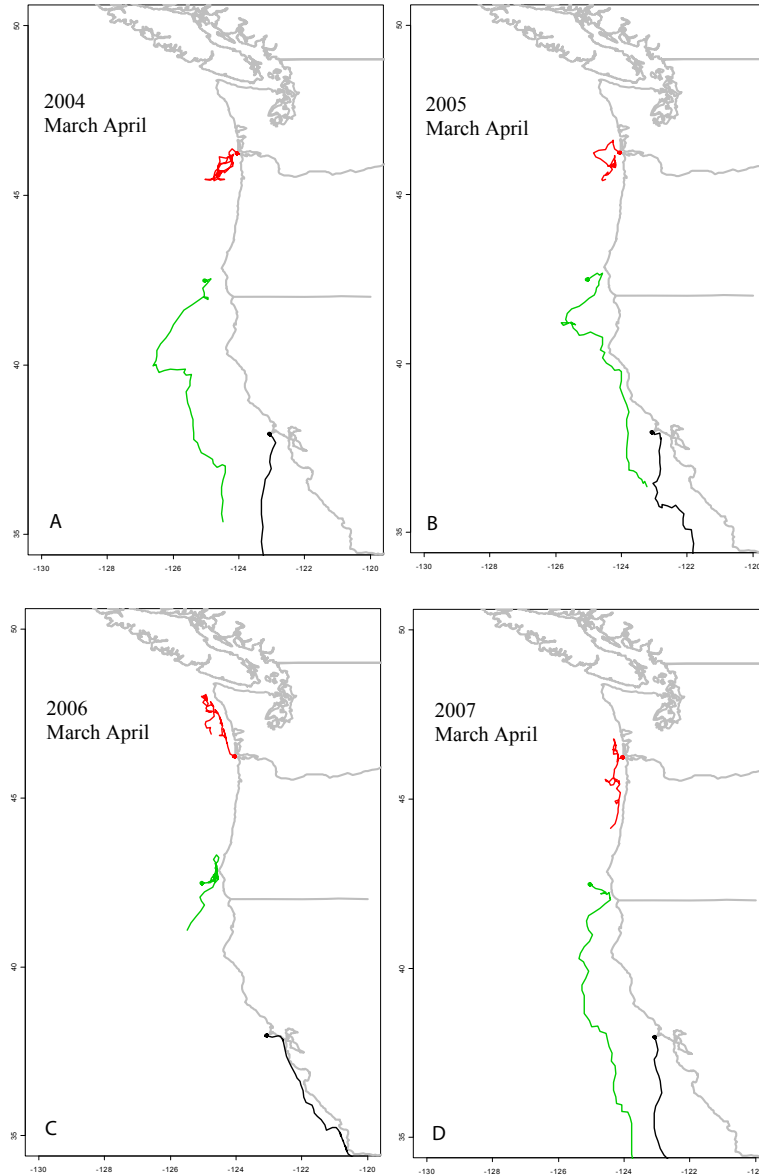


Figure 15: Surface particle trajectories predicted from the OSCURS current model. Particles released at 38°N, 43°N and 46°N (dots) were tracked from March 1 through May 1 (lines) for 2004-2007.

513 the Gulf of the Farallones were poor for juvenile salmon in the summer of 2005.
514 Variation in feeding conditions for early life stages of marine fishes has been linked
515 to subsequent recruitment variation in previous studies, and it is hypothesized that
516 poor growth leads to low survival (Houde, 1975). In 2005, length, weight, K, and
517 total energy content of juvenile Chinook exiting the estuary during May and June,
518 when the vast majority of fall-run smolts enter the ocean, was similar to other ob-
519 servations made over the 1998-2005 period (Fig. 16). However, size, K, and total
520 energy content in the summer of 2005, after fish had spent approximately one month
521 in the ocean, were all significantly lower than the mean of the 8-year period. These
522 data show that growth and energy accumulation, processes critical to survival dur-
523 ing the early ocean phase of juvenile salmon, were impaired in the summer, but
524 recovered to typical values in the fall. A plausible explanation is that poor feeding
525 conditions and depletion of energy reserves in the summer produced low growth
526 and energy content, resulting in higher mortality of juveniles at the lower end of the
527 distribution. By the fall, however, ocean conditions and forage improved and size,
528 K, and total energy content had recovered to typical levels in survivors.

529 Taken together, these observations of the physical and biological state of the
530 coastal ocean offer a plausible explanation for the poor survival of the 2004 brood.
531 Due to unusual atmospheric and oceanic conditions, especially delayed coastal up-
532 welling, the surface waters off of the central California coast were relatively warm
533 and stratified in the spring, with a shallow mixed layer. Such conditions do not
534 favor the large, colonial diatoms that are normally the base of short, highly produc-
535 tive food chains, but instead support greatly increased abundance of dinoflagellates
536 (MBARI, 2006; Rykaczewski and Checkley, 2008). The dinoflagellate-based food
537 chain was likely longer and therefore less efficient in transferring energy to juve-
538 nile salmon, juvenile rockfish and seabirds, which all experienced poor feeding
539 conditions in the spring of 2005. This may have resulted in outright starvation of
540 young salmon, or may have made them unusually vulnerable to predators. What-
541 ever the mechanism, it appears that relatively few of the 2004 brood survived to
542 age two. These patterns and conditions are consistent with Gargett's (1997) "opti-
543 mal stability window" hypothesis, which posits that salmon stocks do poorly when
544 water column stability is too high (as was the case for the 2004 and 2005 broods)
545 or too low, and with Rykaczewski and Checkley's (2008) explanation of the role
546 of offshore, curl-driven upwelling in structuring the pelagic ecosystem of the Cal-
547 ifornia Current. Strong stratification in the Bering Sea was implicated in the poor
548 escapement of sockeye, chum and Chinook populations in southwestern Alaska in
549 1996-97 (Kruse, 1998).

550 **3.4.5 Later ocean**

551 In the previous section we presented information correlating unusual conditions
552 in the Gulf of the Farallones, driven by unusual conditions throughout the north
553 Pacific in the spring of 2005, that caused poor feeding conditions for juvenile fall
554 Chinook. It is possible that conditions in the ocean at a later time, such as the spring
555 of 2006, may have also contributed to or even caused the poor performance of the

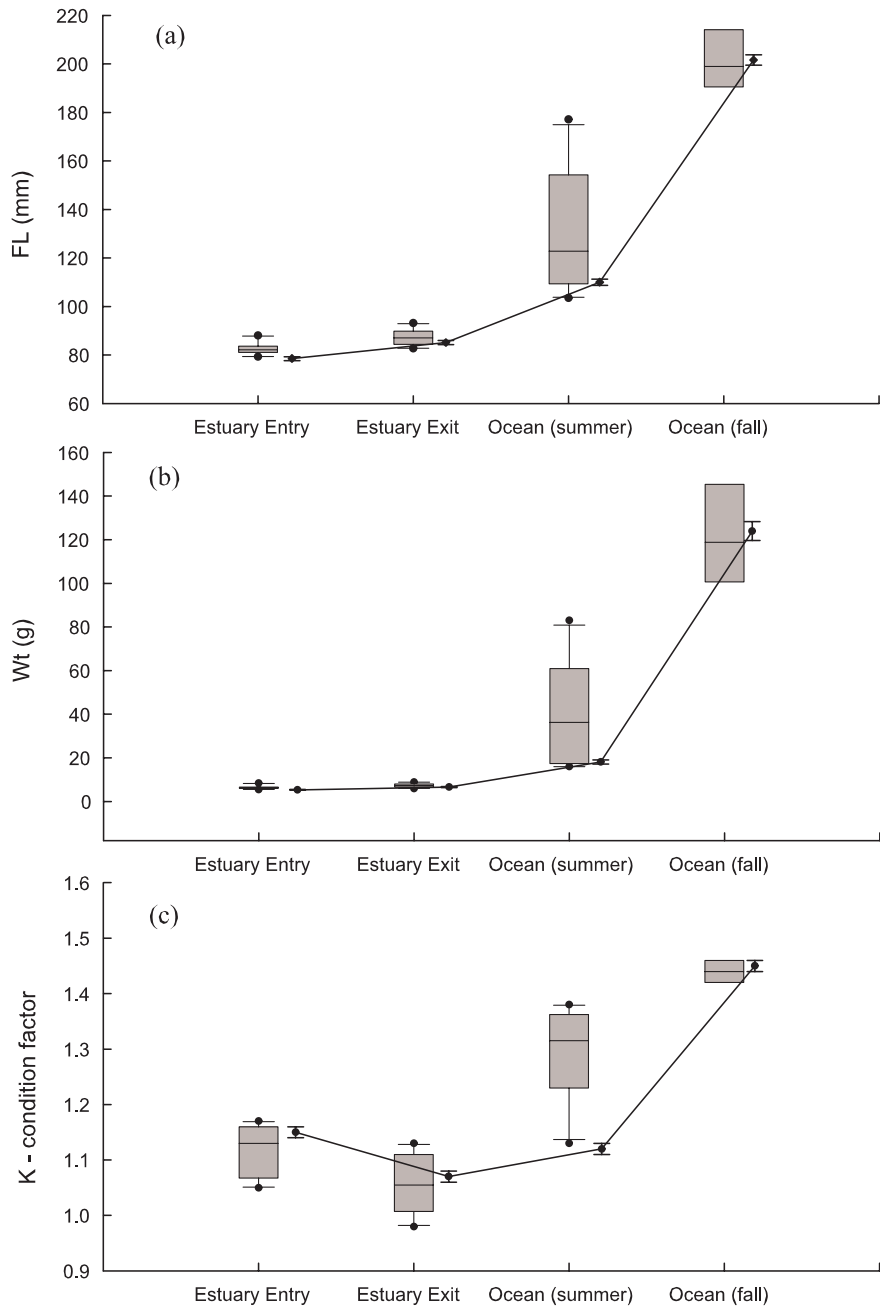


Figure 16: Changes in (a) fork length, (b) weight, and (c) condition (K) of juvenile Chinook salmon during estuarine and early ocean phases of their life cycle. Boxes and whiskers represent the mean, standard deviation and 90% central interval for fish collected in San Francisco Estuary (entry = Suisun Bay, exit = Golden Gate) during May and June and coastal ocean between 1998-2004; points connected by the solid line represent the means (± 1 SE) of fish collected in the same areas in 2005. Unpublished data of B. MacFarlane.

556 2004 brood. This is because fall Chinook spend at least years at sea before returning
557 to freshwater, and thus low jack escapement could arise due to mortality or delayed
558 maturation caused by conditions during the second year of ocean life. While it
559 is generally believed that conditions during early ocean residency are especially
560 important (Pearcy, 1992), work by Kope and Botsford (1990) and Wells et al. (2008)
561 suggests that ocean conditions can affect all ages of Chinook. As discussed below
562 in section 3.5.4, ocean conditions in 2006 were also unusually poor. It is therefore
563 plausible that mortality of sub-adults in their second year in the ocean may have
564 contributed to the poor escapement of SRFC in 2007.

565 Fishing is another source of mortality to Chinook that could cause unusually
566 low escapement (discussed in more detail in the appendix). The PFMC (2007)
567 forecasted an escapement of 265,000 SRFC adults in 2007 based on the escape-
568 ment of 14,500 Central Valley Chinook jacks in 2006. The realized escapement of
569 SRFC adults was 87,900. The error was due mainly to the over-optimistic forecast
570 of the pre-season ocean abundance of SRFC. Had the pre-season ocean abundance
571 forecast been accurate and fishing opportunity further constrained by management
572 regulation in response, so that the resulting ocean harvest rate was reduced by half,
573 the SRFC escapement goal would have been met in 2007. Thus, fishery manage-
574 ment, while not the cause of the 2004 brood weak year-class strength, contributed
575 to the failure to achieved the SRFC escapement goal in 2007.

576 **3.4.6 Spawners**

577 Jack returns and survival of FRH fall Chinook to age two indicates that the 2004
578 brood was already at very low abundance before they began to migrate back to
579 freshwater in the fall 2007. Water temperature at Red Bluff was within roughly
580 1°C of normal in the fall, and flows were substantially below normal in the last 5
581 weeks of the year. We do not believe that these conditions would have prevented
582 fall Chinook from migrating to the spawning grounds, and there is no evidence
583 of significant mortalities of fall Chinook in the river downstream of the spawning
584 grounds.

585 **3.4.7 Conclusions for the 2004 brood**

586 All of the evidence that we could find points to ocean conditions as being the proxi-
587 mate cause of the poor performance of the 2004 brood of fall Chinook. In particular,
588 delayed coastal upwelling in the spring of 2005 meant that animals that time their
589 reproduction so that their offspring can take advantage of normally bountiful food
590 resources in the spring, found famine rather than feast. Similarly, marine mammals
591 and birds (and juvenile salmon) which migrate to the coastal waters of northern
592 California in spring and summer, expecting to find high numbers of energetically-
593 rich zooplankton and small pelagic fish upon which to feed, were also impacted.
594 Another factor in the reproductive failure and poor survival of fishes and seabirds
595 may have been that 2005 marked the third year of chronic warm conditions in the
596 northern California Current, a situation which could have led to a general reduction

597 in health of fish and birds, rendering them less tolerant of adverse ocean conditions.

598 **3.5 Brood year 2005**

599 **3.5.1 Parents**

600 In 2005, 211,000 adult fall Chinook returned to spawn in the Sacramento River
601 and its tributaries to give rise to the 2005 brood, almost exactly equal to the 1970-
602 2007 mean (Fig. 1). Pre-spawning mortality in the Sacramento River was about
603 1% of the run (D. Killam, CDFG, unpublished data). River flows were near normal
604 through the fall, but rose significantly in the last weeks of the year. Escapement to
605 Sacramento basin hatcheries was near record highs, but this did not result in any
606 significant problems in handling the broodstock.

607 **3.5.2 Eggs**

608 Flows in the winter of 2005-2006 were higher than usual, with peak flows around
609 the new year and into the early spring on regulated reaches throughout the basin.
610 Flows generally did not reach levels unprecedented in the last two decades (Fig. 4;
611 see appendix for more details), but may have resulted in stream bed movement
612 and subsequent mortality of a portion of the fall Chinook eggs and pre-emergent
613 fry. Water temperature at Red Bluff in the spring was substantially lower than
614 normal, probably prolonging the egg incubation phase, but not so low as to cause
615 egg mortality (McCullough, 1999).

616 **3.5.3 Fry, parr and smolts**

617 The spring of 2006 was unusually wet, due to late-season rains associated with a
618 cut-off low off the coast of California and a ridge of high pressure running over
619 north America from the southwest to the northeast. This weather pattern gener-
620 ated high flows in March and April 2006 (Fig. 4) and a very low ratio of water
621 exports to inflows to the Delta (Fig. 5). Water temperatures in San Francisco Bay
622 were unusually low, and freshwater outflow to the bay was unusually high (see ap-
623 pendix). These conditions, while anomalous, are not expected to cause low survival
624 of smolts migrating through the bay to the ocean. It is conceivable that the wet
625 spring conditions had a delayed and indirect negative effect on the 2005 brood. For
626 example, surface runoff could have carried high amounts of contaminants (pesti-
627 cide residues, metals, hydrocarbons) into the rivers or bay, and these contaminants
628 could have caused health problems for the brood that resulted in death after they
629 passed Chipps Island. However, since both the winter and spring had high flows
630 the concentrations of pollutants would likely have been at low levels if present. We
631 found no evidence for or against this hypothesis.

632 Total water exports at the state and federal pumping facilities in the south Delta
633 were near average in the winter and spring, but the ratio of water exports to inflow to
634 the Delta (E/I) was lower than average for most of the winter and spring, only rising

635 to above-average levels in June. Total exports were near record levels throughout
636 the summer and fall of 2006, after the fall Chinook emigration period.

637 Catch-per-unit-effort of juvenile fall Chinook in the Chipps Island trawl sam-
638 pling was slightly higher than average in 2006, and the timing of catches was very
639 similar to the average pattern, with perhaps a slight delay (roughly one week) in
640 migration timing.

641 Releases from the state hatcheries were at typical levels, although in a poten-
642 tially significant change in procedure, fish were released directly into Carquinez
643 Strait and San Pablo Bay without the usual brief period of acclimatization in net
644 pens at the release site. This change in procedure was made due to budget con-
645 straints at CDFG. Acclimatization in net pens has been found to increase survival
646 of release groups by a factor of 2.6, (CDFG, unpublished data) so this change may
647 have had a significant impact on the survival of the state hatchery releases. CNFH
648 released near-average numbers of smolts into the upper river, with no unusual prob-
649 lems noted.

650 Conditions in the estuary and bays were cooler and wetter in the spring of 2006
651 than is typical. Such conditions are unlikely to be detrimental to the survival of
652 juvenile fall Chinook.

653 **3.5.4 Early ocean**

654 Overall, conditions in the ocean in 2006 were similar to those in 2005. At the
655 north Pacific scale, northwesterly winds were stronger than usual far offshore in the
656 northeast Pacific during the spring, but weaker than normal near shore (Fig. 12).
657 The seasonal onset of upwelling was again delayed in 2006, but this anomaly was
658 more distinct off central California (Fig. 13). Unlike 2005, however, nearshore
659 transport in 2006 was especially weak (Fig. 15b). In contrast to 2005, conditions
660 unfavorable for juvenile salmon were restricted to central California, rather than be-
661 ing a coast-wide phenomenon (illustrated in Fig. 13, where upwelling was delayed
662 later at 39°N than 42°N). Consequently, we should expect to see corresponding
663 latitudinal variation in biological responses in 2006.

664 These relatively poor conditions, following on the extremely poor conditions
665 in 2005, had a dramatic effect on the food base for juvenile salmon off central
666 CA. Once again, Cassin's auklets on the Farallon Islands experienced near-total
667 reproductive failure. Krill, which were fairly abundant but distributed offshore near
668 the continental shelf break in 2005, were quite sparse off central California in 2006
669 (see appendix). Juvenile rockfish were at very low abundance off central California,
670 according to the NMFS trawl surveys (see appendix). These observations indicate
671 feeding conditions for juvenile salmon in the spring of 2006 off central California
672 were as bad as or worse than in 2005.

673 Consistent with the alongshore differences in upwelling and SST anomalies, and
674 with better conditions off of Oregon and Washington, abundance of juvenile spring
675 Chinook, fall Chinook and coho were four to five times higher in 2006 than in 2005
676 off of Oregon and Washington (W. Peterson, NMFS, unpublished data from trawl
677 surveys). Catches of juvenile spring Chinook and coho salmon in June 2005 were

678 the lowest of the 11 year time series; catches of fall Chinook were the third lowest.
679 Similarly, escapement of adult fall Chinook to the Columbia River in 2007 for the
680 fish that entered the sea in 2005 was the lowest since 1993 but escapement in 2008
681 was twice as high as in 2007. A similar pattern was seen for Columbia River spring
682 Chinook. Cassin's auklets on Triangle Island, British Columbia, which suffered
683 reproductive failure in 2005, fared well in 2006 (Wolf et al., 2009).

684 Estimated survival from release to age two for the 2005 brood of FRH fall Chi-
685 nook was 60% lower than the 2004 brood, only 3% of that observed for the 2000
686 brood (Fig. 9). We note that the failure to acclimatize the bay releases in net pens
687 may explain the difference in survival of the 2004 and 2005 Feather River releases,
688 but would not have affected survival of naturally produced or CNFH smolts. Jack
689 escapement from the 2005 brood in 2007 was extremely low. Unfortunately, lipid
690 and condition factor sampling of juvenile Chinook in the estuary, bays and Gulf
691 of the Farallones was not conducted in 2006 due to budgetary and ship-time con-
692 straints.

693 **3.5.5 Later ocean**

694 Ocean conditions improved in 2007 and 2008, with some cooling in the spring in
695 the California Current in 2007, and substantial cooling in 2008. Data are not yet
696 available on the distribution and abundance of salmon prey items, but it is likely
697 that feeding conditions improved for salmon maturing in 2008. However, improved
698 feeding conditions appear to have had minimal benefit to survival after recruitment
699 to the fishery, because the escapement of 66,000 adults in 2008 was very close to
700 the predicted escapement (59,000) based on jack returns in 2007. Fisheries were
701 not a factor in 2008 (they were closed).

702 **3.5.6 Spawners**

703 As mentioned above, about 66,000 SRFC adults returned to natural areas and hatcheries
704 in 2008. Although detailed data have not yet been assembled on freshwater and
705 estuarine conditions for the fall of 2008, the Sacramento Valley has been experi-
706 encing severe drought conditions, and river temperatures were higher than normal
707 and flows have been lower than normal. Neither of these conditions are beneficial
708 to fall Chinook and may have impacted the reproductive success of the survivors of
709 the 2005 brood.

710 **3.5.7 Conclusions for the 2005 brood**

711 For the 2005 brood, the evidence suggests again that ocean conditions were the
712 proximate cause of the poor performance of that brood. In particular, the cessation
713 of coastal upwelling in May of 2006 was likely a serious problem for juvenile fall
714 Chinook entering the ocean in the spring. In contrast to 2005, anomalously poor
715 ocean conditions were restricted to central California. The poorer performance of

716 the 2005 brood relative to the 2004 brood may be partly due to the cessation of
717 net-pen acclimatization of fish from the state hatcheries.

718 **3.6 Prospects for brood year 2006**

719 In this section, we briefly comment on some early indicators of the possible per-
720 formance of the 2006 brood. The abundance of adult fall Chinook escaping to the
721 Sacramento River, its tributaries and hatcheries in 2006 had dropped to 168,000, a
722 level still above the minimum escapement goal of 122,000. Water year 2007 (which
723 started in October 2006) was categorized as “critical”⁶, meaning that drought con-
724 ditions were in effect during the freshwater phase of the 2006 brood. While the
725 levels of water exports from the Delta were near normal, inflows were below nor-
726 mal, and for much of the winter, early spring, summer and fall of 2007, the E/I ratio
727 was above average. During the late spring, when fall Chinook are expected to be
728 migrating through the Delta, the E/I ratio was near average. Ominously, catches of
729 fall Chinook juveniles in the Chipps Island trawl survey in 2007 were about half
730 that observed in 2005 and 2006. A tagging study conducted by NMFS and UC
731 Davis found that survival of late-fall Chinook from release in Battle Creek (upper
732 Sacramento River near CNFH) to the Golden Gate was roughly 3% in 2007; such
733 survival rates are much lower than have been observed in similar studies in the
734 Columbia River (Williams et al., 2001; Welch et al., 2008).

735 Ocean conditions began to improve somewhat in 2007, with some cooling evi-
736 dent in the Gulf of Alaska and the eastern equatorial Pacific. The California Current
737 was roughly 1°C cooler than normal in April and May, but then warmed to above-
738 normal levels in June-August 2007. The preliminary estimate of SRFC jack escape-
739 ment was 4,060 (Fig. 10, PFMC (2009)), double that of the 2005 brood, but still the
740 second lowest on record and a level that predicts an adult escapement in 2009 at the
741 low end of the escapement goal absent any fishing in 2009. A survival rate estimate
742 from release to age two is not possible for this brood due to the absence of a fishery
743 in 2008, but jack returns will provide some indication of the survival of this brood⁷.

744 **3.7 Is climate change a factor?**

745 An open question is whether the recent unusual conditions in the coastal ocean are
746 the result of normal variation or caused in some part by climate change. We tend
747 to think of the effects of climate change as a trajectory of slow, steady warming.
748 Another potential effect is an increased intensity and frequency of many types of
749 rare events (Christensen et al., 2007). Along with a general upward trend in sea
750 surface temperatures, the variability of ocean conditions as indexed by the Pacific
751 Decadal Oscillation, the North Pacific Gyre Oscillation, and the NINO34 index
752 appears to be increasing (N. Mantua, U. Washington, unpublished data).

⁶California Department of Water Resources water year hydrological classification indices,
<http://cdec.water.ca.gov/cgi-progs/iodir2/WSIHIST>

⁷Proper cohort reconstructions are hindered because of inadequate sampling of tagged fish in the hatchery and on the spawning grounds, and high rates of straying.

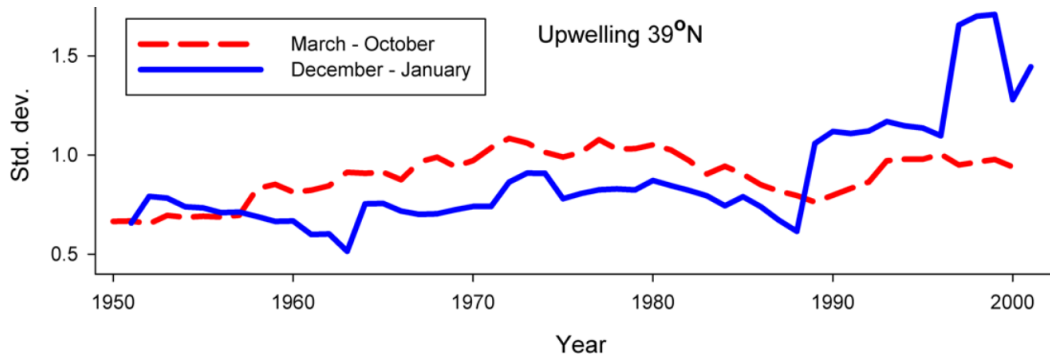


Figure 17: Changes in interannual variation in summer and winter upwelling at 39°N latitude, 1946 - 2007. Summer upwelling shows a possible decadal-scale oscillation. Winter upwelling (downwelling) shows a sharp increase starting in the late 1980s. The graph shows 11-year moving average standard deviations of standardized time series.

753 Winter upwelling at 39°N, off the California coast, took a jump upward in the
 754 late 1980s (Fig. 17). Whether there is a direct causative relationship between this
 755 pattern and recent volatility in SRFC escapement is a matter for further investi-
 756 gation, but there is a similar pattern of variability in environmental indices and
 757 salmon catch and escapement coast wide. While not evident in all stocks (Sacra-
 758 mento River winter Chinook escapement variability is going down, for example)
 759 the general trend for salmon stocks from California to Alaska is one of increasing
 760 variability (Lawson and Mantua, unpublished data). The well-recognized relation-
 761 ship between salmon survival and ocean conditions suggests that the variability in
 762 SRFC escapement is at least partly linked to the variability in ocean environment.

763 In the Sacramento River system there are other factors leading to increased vari-
 764 ability in salmon escapements, including variation in harvest rates, freshwater habi-
 765 tat simplification, and reduced life history diversity in salmon stocks (discussed in
 766 detail in the section 4). In addition, freshwater temperature and flow patterns are
 767 subject to the same forces that drive variability in the ocean environment (Lawson
 768 et al., 2004), although they are modified significantly in the Central Valley by the
 769 water projects. These factors, in combination with swings in ocean survival, would
 770 tend to increase the likelihood of extreme events such as the unusually high escape-
 771 ments of the early 2000s and the recent low escapements that are the subject of this
 772 report.

773 3.8 Summary

774 A broad body of evidence suggests that anomalous conditions in the coastal ocean
 775 in 2005 and 2006 resulted in unusually poor survival of the 2004 and 2005 broods
 776 of SRFC. Both broods entered the ocean during periods of weak upwelling, warm
 777 sea surface temperatures, and low densities of prey items. Pelagic seabirds with
 778 diets similar to juvenile Chinook also experienced very poor reproduction in these
 779 years. A dominant role for freshwater factors as proximate causes of poor survival
 780 for the 2004 and 2005 broods were ruled out by observations of near-normal fresh-

781 water conditions during the period of freshwater residency, near-normal numbers of
782 juvenile fall-run Chinook entering the estuary, and typical numbers of juvenile fall
783 Chinook released from hatcheries. However, as Lawson (1993) reasoned, long-term
784 declines in the condition of freshwater habitats are expected to result in increasingly
785 severe downturns in abundance during episodes of poor ocean survival (Fig. 18). In
786 the following section, we explain how human activities may be making the Central
787 Valley Chinook salmon stock complex more susceptible to natural stressors.

788 **4 The role of anthropogenic impacts**

789 So far, we have restricted our analysis to the question of whether there were un-
790 usual conditions affecting Sacramento River fall-run Chinook from the 2004 and
791 2005 broods that could explain their poor performance, reaching the conclusion
792 that unfavorable ocean conditions were the proximate cause. But what about the
793 ultimate causes?

794 **4.1 Sacramento River fall Chinook**

795 With regard to SRFC, anthropogenic effects are likely to have played a signifi-
796 cant role in making this stock susceptible to collapse during periods of unfavorable
797 ocean conditions. Historical modifications have eliminated salmon spawning and
798 rearing habitat, decreased total salmon abundance, and simplified salmon biodi-
799 versity (McEvoy, 1986; Yoshiyama et al., 1998, 2001; Williams, 2006a). To the
800 extent that these changes have concentrated fish production and reduced the ca-
801 pacity of populations to spread mortality risks in time and space, we hypothesize
802 that the Central Valley salmon ecosystem has become more vulnerable to recurring
803 stresses, including but not limited to periodic shifts in the ocean environment.

804 Modifications in the Sacramento River basin since early in the nineteenth cen-
805 tury have reduced the quantity, quality, and spatial distribution of freshwater habitat
806 for Chinook. Large dams have blocked access to spawning habitat upriver and
807 disrupted geomorphic processes that maintain spawning and rearing habitats down-
808 stream. Levees have disconnected flood plains, and bank armoring and dewatering
809 of some river reaches have eliminated salmon access to shallow, peripheral habitats.
810 By one estimate at least 1700 km or 48% of the stream lengths available to salmon
811 for spawning, holding, and migration (not including the Delta) have been lost from
812 the 3500 km formerly available in the Central Valley (Yoshiyama et al., 2001).

813 One of the most obvious alterations to fall Chinook habitat has been the loss
814 of shallow-water rearing habitat in the Delta. Mid-nineteenth century land surveys
815 suggest that levee construction and agricultural conversion have removed all but
816 about 5% of the 1,300 km² of Delta tidal wetlands (Williams, 2006a). Because
817 growth rates in shallow-water habitats can be very high in the Central Valley (Som-
818 mer et al., 2001; Jeffres et al., 2008), access to shallow wetlands, floodplains and
819 stream channel habitats could increase the productive capacity of the system. From
820 this perspective, the biggest problem with the state and federal water projects is not

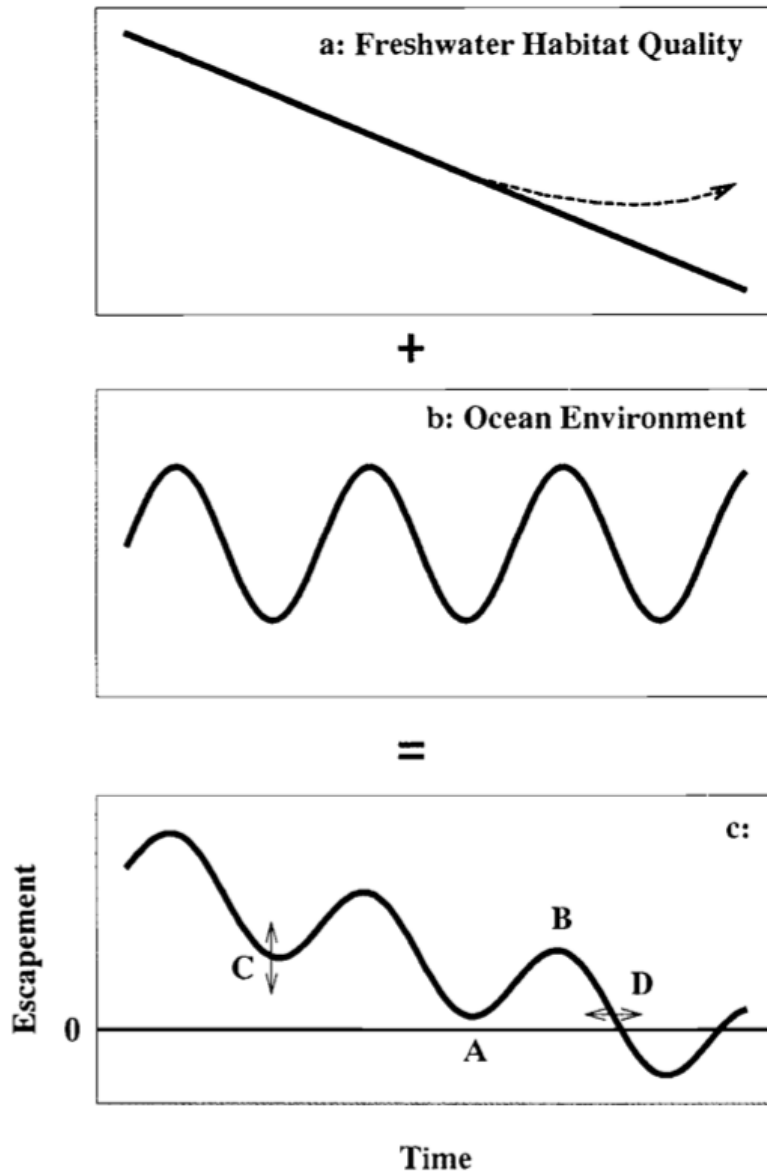


Figure 18: Conceptual model of effects of declining habitat quality and cyclic changes in ocean productivity on the abundance of salmon. a: trajectory over time of habitat quality. Dotted line represents possible effects of habitat restoration projects. b: generalized time series of ocean productivity. c: sum of top two panels where letters represent the following: A = current situation, B = situation in the future, C = change in escapement from increasing or decreasing harvest, and D = change in time of extinction from increasing or decreasing harvest. Copied from Lawson (1993).

821 that they kill fish at the pumping facilities, but that by engineering the whole system
822 to deliver water from the north of the state to the south while preventing flooding,
823 salmon habitat has been greatly simplified.

824 Although historical habitat losses undoubtedly have reduced salmon production
825 in the Central Valley ecosystem, other than commercial harvest records, quantita-
826 tive abundance estimates did not become available until the 1940s, nearly a century
827 after hydraulic gold mining, dam construction, and other changes had drastically
828 modified the habitat landscape. Harvest records indicate that high volumes of fish
829 were harvested by nineteenth-century commercial river fisheries. From the 1870s
830 through early 1900s, annual in-river harvest in the Central Valley often totaled four
831 to ten million pounds of Chinook, approaching or exceeding the total annual harvest
832 by statewide ocean fisheries in recent decades (Yoshiyama et al., 1998). Maximum
833 annual stock size (including harvest) of Central Valley Chinook salmon before the
834 twentieth century has been estimated conservatively at 1-2 million spawners with
835 fall-run salmon totals perhaps reaching 900,000 fish (Yoshiyama et al., 1998). In re-
836 cent decades, annual escapement of SRFC, which typically accounts for more than
837 90% of all fall Chinook production in the Central Valley, has remained relatively
838 stable, totaling between 100,000 and 350,000 adults in most years from the 1960s
839 through the 1990s. However, escapement began to fluctuate more erratically in the
840 present decade, climbing to a peak of 775,000 in 2002 but then falling rapidly to
841 near-record lows thereafter (Fig. 1).

842 Beyond the effects of human activities on production of SRFC are the less obvi-
843 ous influences on biodiversity. The diversity of life histories in Chinook (variations
844 in size and age at migration, duration of freshwater and estuarine residency, time
845 of ocean entry, etc.) has been described as a strategy for spreading mortality risks
846 in uncertain environments (Healey, 1991). Diverse habitat types allow the expres-
847 sion of diverse salmon rearing and migration behaviors (Bottom et al., 2005b), and
848 life history diversity within salmon stocks allows the stock aggregate to be more
849 resilient to environmental changes (Hilborn et al., 2003).

850 Juvenile SRFC have adopted a variety of rearing strategies that maximize use
851 of the diverse habitat types throughout the basin, including: (1) fry (< 50 mm fork
852 length) migrants that leave soon after emergence to rear in the Delta or in the es-
853 tuarine bays; (2) fingerling migrants that remain near freshwater spawning areas
854 for several months, leaving at larger sizes (> 60 mm fork length) in the spring but
855 passing quickly through the Delta; and (3) later migrants, including some juveniles
856 that reside in natal streams through the summer or even stay through the winter
857 to migrate as yearlings (Williams, 2006a). Today most SRFC exhibit fry-migrant
858 strategies, while the few yearling migrants occur in areas where reservoir releases
859 maintain unusually low water temperatures. Historical changes reduced or elim-
860 inated habitats that supported diverse salmon life histories throughout the basin.
861 Passage barriers blocked access to cool upper basin tributaries, and irrigation di-
862 versions reduced flows and increased water temperatures, eliminating cool-water
863 refugia necessary to support juveniles with stream-rearing life histories (Williams,
864 2006a). The loss of floodplain and tidal wetlands in the Delta eliminated a con-
865 siderable amount of habitat for fry migrants, a life history strategy that is not very

866 effective in the absence of shallow-water habitats downstream of spawning areas.
867 Similar fresh water and estuarine habitat losses have been implicated in the simplifi-
868 cation of Chinook life histories in the Salmon (Bottom et al., 2005a) and Columbia
869 River basins (Bottom et al., 2005b; Williams, 2006b). In Oregon's Salmon River,
870 an extensive estuarine wetland restoration program has increased rearing opportu-
871 nities for fry migrants, expanding life history diversity in the Chinook population,
872 including the range of times and sizes that juveniles now enter the ocean (Bottom
873 et al., 2005a). Re-establishing access to shallow wetland and floodplain habitats in
874 the Sacramento River and Delta similarly could extend the time period over which
875 SRFC reach sufficient sizes to enter the ocean, strengthening population resilience
876 to a variable ocean environment.

877 Hatchery fish are a large and increasing proportion of SRFC (Barnett-Johnson
878 et al., 2007), and a rising fraction of the population is spawning in hatcheries
879 (Fig. 19). The Central Valley salmon hatcheries were built and operated to miti-
880 gate the loss of habitat blocked by dams, but may have inadvertently contributed to
881 the erosion of biodiversity within fall Chinook. In particular, the release of hatchery
882 fish into the estuary greatly increases the straying of hatchery fish to natural spawn-
883 ing areas (CDFG and NMFS, 2001). Central Valley fall Chinook are almost unique⁸
884 among Chinook ESUs in having little or no detectable geographically-structured ge-
885 netic variation (Williamson and May, 2005). There are two plausible explanations
886 for this. One is that Central Valley fall Chinook never had significant geographical
887 structuring because of frequent migration among populations in response to highly
888 variable hydrologic conditions (on a microevolutionary time scale). The other ex-
889 planation is that straying from hatcheries to natural spawning areas has genetically
890 homogenized the ESU. One implication of the latter explanation is that populations
891 of SRFC may have lost adaptations to their local environments. It is also likely that
892 hatchery practices cause unintentional evolutionary change in populations (Reisen-
893 bichler and Rubin, 1999; Bisson et al., 2002), and high levels of gene flow from
894 hatchery to wild populations can overcome natural selection, reducing the genetic
895 diversity and fitness of wild populations.

896 Another consequence of the hatchery mitigation program was the subsequent
897 harvest strategy, which until the 1990s was focused on exploiting the aggregate
898 stock, with little regard for the effects on naturally produced stocks. For many
899 years, Central Valley Chinook stocks were exploited at rates averaging more than
900 60 percent in ocean and freshwater fisheries (Myers et al., 1998). Such levels may
901 not be sustainable for natural stocks, and could result in loss of genetic diversity,
902 contributing to the homogeneity of Central Valley fall Chinook stocks. Harvest
903 drives rapid changes in the life history and morphological phenotypes of many or-
904 ganisms, with Pacific salmon showing some of the largest changes (Darimont et al.,
905 2009). An evolutionary response to the directional selection of high ocean harvest
906 is expected, including reproduction at an earlier age and smaller size and spawn-
907 ing earlier in the season (reviewed by Hard et al. (2008)). A truncated age structure

⁸The exception to this rule is Sacramento River winter-run Chinook, which now spawn only in the mainstem Sacramento River below Keswick Reservoir.

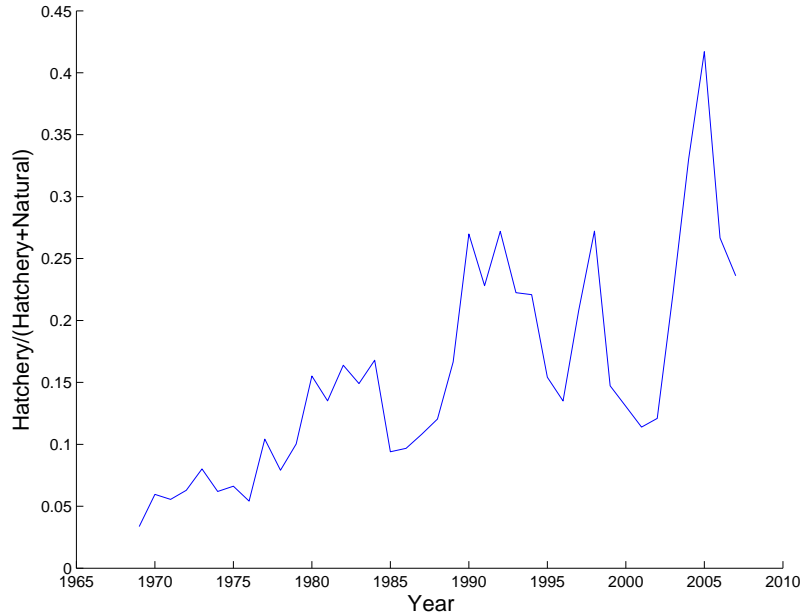


Figure 19: The fraction of total escapement of SRFC that returns to spawn in hatcheries.

908 may also increase variation in population abundance (Huusko and Hyvärinen, 2005;
 909 Anderson et al., 2008).

910 Hatchery practices also may cause the aggregate abundance of hatchery and nat-
 911 ural fish to fluctuate more widely. Increased variability arises in two ways. First,
 912 high levels of straying from hatcheries to natural spawning areas can synchronize
 913 the dynamics of the hatchery and natural populations. Second, hatcheries typically
 914 strive to standardize all aspects of their operations, releasing fish of a similar size
 915 at a particular time and place, which hatchery managers believe will yield high
 916 returns to the fishery on average. Such strategies can have strong effects on age
 917 at maturation through effects on early growth (Hankin, 1990), reducing variation
 918 in age at maturity. A likely product of this approach is that the high variation in
 919 survival among years and high covariation in survival and maturation among hatch-
 920 ery releases within years may create boom and bust fluctuations in salmon returns,
 921 as hatchery operations align, or fail to align, with favorable conditions in stream,
 922 estuarine or ocean environments.

923 Hankin and Logan's (2008) analysis of survival rates from release to ocean
 924 age 2 of fall-run Chinook released from Iron Gate, Trinity River and Cole Rivers
 925 hatcheries provides an example. Survival of 20+ brood years of fingerling releases
 926 ranged from 0.0002 to 0.046, and yearling releases ranged from 0.0032 to 0.26, a
 927 230-fold and 80-fold variation in survival, respectively. Hankin and Logan (2008)
 928 found that survival covaried among release groups, with the highest covariation
 929 between groups released from the same hatchery at nearly the same time, although
 930 covariation among releases from different hatcheries made at similar times was sub-
 931 stantial. Because Central Valley fall Chinook are dominated by hatchery produc-
 932 tion, and Central Valley hatcheries release most of their production at similar times,

933 this finding is significant: very high variation in ocean abundance and escapement
934 *should be expected* from the system as currently operated.

935 A similar mechanism has been proposed to explain the collapse of coho salmon
936 fisheries along the Oregon coast following the 1976 ocean regime shift. Cumulative
937 habitat loss, overharvest, and the gradual replacement of diverse wild populations
938 and life histories with a few hatchery stocks left coho salmon vulnerable to col-
939 lapse when ocean conditions suddenly changed (Lawson, 1993; Lichatowich, 1999;
940 Williams, 2006b)). The situation is analogous to managing a financial portfolio: a
941 well-diversified portfolio will be buffeted less by fluctuating market conditions than
942 one concentrated on just a few stocks; the SRFC seems to be quite concentrated in-
943 deed.

944 **4.2 Other Chinook stocks in the Central Valley**

945 Sacramento River fall Chinook have been the most abundant stock of Chinook
946 salmon off of central California in recent decades, but this has not always been
947 the case. Sacramento River winter Chinook, late-fall Chinook and especially spring
948 Chinook once dominated the production of Chinook from the Central Valley (Fisher,
949 1994), but over the decades have dwindled to a few remnant populations mostly
950 now under the protection of the Endangered Species Act (Lindley et al., 2004). The
951 causes for these declines are the same as those that have affected fall Chinook, but
952 because these other stocks spend some portion of their life in freshwater during
953 the summer, they have been more strongly impacted by impassable dams that limit
954 access to cold-water habitats.

955 Spring-run Chinook were once the most abundant of the Central Valley runs,
956 with large populations in snow-melt and spring-fed streams in the Sierra Nevada
957 and southern Cascades, respectively (Fisher, 1994). Spring-run Chinook have been
958 reduced from perhaps 18 major populations spawning in four distinct ecoregions
959 within the Central Valley to three remnant populations inhabiting a single ecoregion
960 (Lindley et al., 2007). Winter-run Chinook were less abundant than spring Chinook,
961 spawning in summer months in a few spring-fed tributaries to the upper Sacramento
962 River. Perhaps four distinct populations of winter Chinook have been extirpated
963 from their historical spawning grounds, with survivors founding a population in the
964 tailwaters of Shasta Dam (Lindley et al., 2004). The historical distribution of late-
965 fall-run Chinook is less clear, but their life history requires cool water in summer,
966 and thus their distribution has probably also been seriously truncated by impassable
967 dams at low elevations in the larger tributaries.

968 An examination of the population dynamics of extant Central Valley Chinook
969 populations illustrates that if spring, winter and late-fall Chinook contributed sig-
970 nificantly to the fishery, the aggregate abundance of Chinook in central California
971 waters would be less variable. Populations of Central Valley fall-run Chinook ex-
972 hibited remarkably similar dynamics over the past two decades, while other runs
973 of Central Valley Chinook did not (Fig. 20 and 21). Almost all fall Chinook popu-
974 lations reached peak abundances around 2002, and have all been declining rapidly
975 since then. In contrast, late-fall, winter and naturally-spawning spring Chinook

976 populations have been increasing in abundance over the past decade, although es-
977 capement in 2007 was down in some of them and the growth of these populations
978 through the 1990s and 2000s has to some extent been driven by habitat restoration
979 efforts. This begs the question of why have these other stocks responded differently
980 to recent environmental variation.

981 The answer may have two parts. One part has to do with hatcheries. As dis-
982 cussed above, hatcheries may be increasing the covariation of fall Chinook popu-
983 lations by erasing genetic differences among populations that might have caused
984 the populations to respond differently to environmental variation. They may be fur-
985 ther synchronizing the demographics of the naturally-spawning populations through
986 straying of hatchery fish into natural spawning areas, a problem exacerbated by out-
987 planting fish to the Delta and bays. Finally, hatchery practices minimize variation
988 in size, condition and migration timing, which should tend to increase variation in
989 survival rates because “bet hedging” is minimized.

990 The other part of the answer may lie in the observation that the other runs of
991 Chinook have life history tactics that differ in important ways from fall Chinook.
992 While named according to the time of year that adults enter freshwater, each run
993 type of Central Valley Chinook has a characteristic pattern of habitat use across
994 space and time that leads to differences in the time and size of ocean entry. For
995 example, spring-run Chinook juveniles enter the ocean at a broader range of ages
996 (with a portion of some populations migrating as yearlings) than fall Chinook, due
997 to their use of higher elevations and colder waters. Winter run Chinook spawn in
998 summer, and the juveniles enter the ocean at a larger size than fall Chinook, due
999 to their earlier emergence and longer period of freshwater residency. Late-fall-run
1000 Chinook enter freshwater in the early winter, and spawn immediately, but juveniles
1001 migrate as yearlings the following winter. Thus, if ocean conditions at the time
1002 of ocean entry are critical to the survival of juvenile salmon, we should expect
1003 that populations from different runs should respond differently to changing ocean
1004 conditions because they enter the ocean at different times and at different sizes.

1005 In conclusion, the development of the Sacramento-San Joaquin watershed has
1006 greatly simplified and truncated the once-diverse habitats that historically supported
1007 a highly diverse assemblage of populations. The life history diversity of this histor-
1008 ical assemblage would have buffered the overall abundance of Chinook salmon in
1009 the Central Valley under varying climate conditions. We are now left with a fish-
1010 ery that is supported largely by four hatcheries that produce mostly fall Chinook
1011 salmon. Because the survival of fall Chinook salmon hatchery release groups is
1012 highly correlated among nearby hatcheries, and highly variable among years, we
1013 can expect to see more booms and busts in this fishery in the future in response
1014 to variation in the ocean environment. Simply increasing the production of fall
1015 Chinook salmon from hatcheries as they are currently operated may aggravate this
1016 situation by further concentrating production in time and space. Rather, the key to
1017 reducing variation in production is increasing the diversity of SRFC. In the follow-
1018 ing section, we make some recommendations towards this goal.

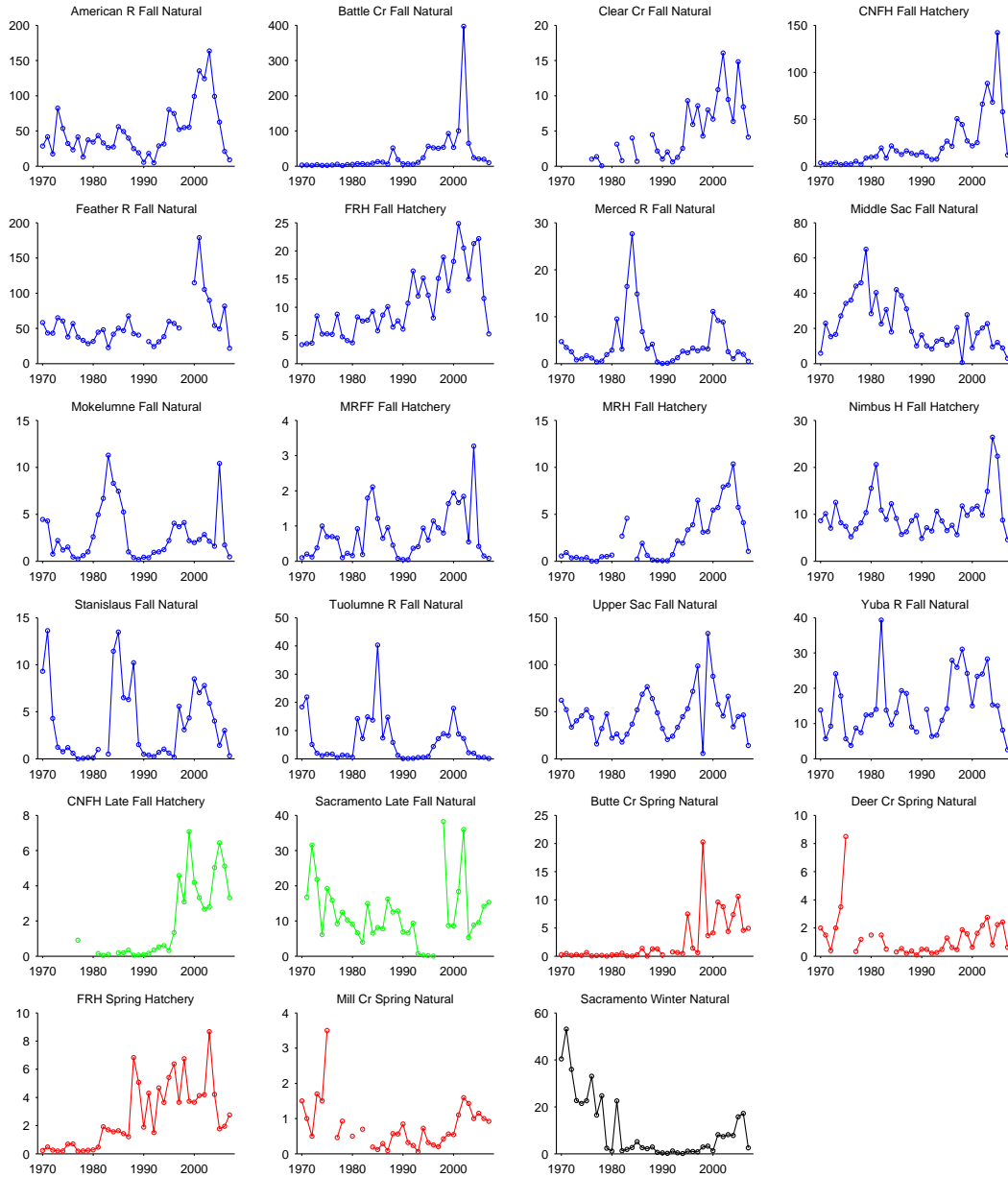


Figure 20: Escapement trends in selected populations of Chinook since 1970. Plots are color-coded according to run timing. Y-axis is thousands of fish; X-axis is year. CNFH = Coleman National Fish Hatchery; FRH = Feather River Hatchery; MRFF = Merced River Fish Facility; MRH = Mokelumne River Hatchery.

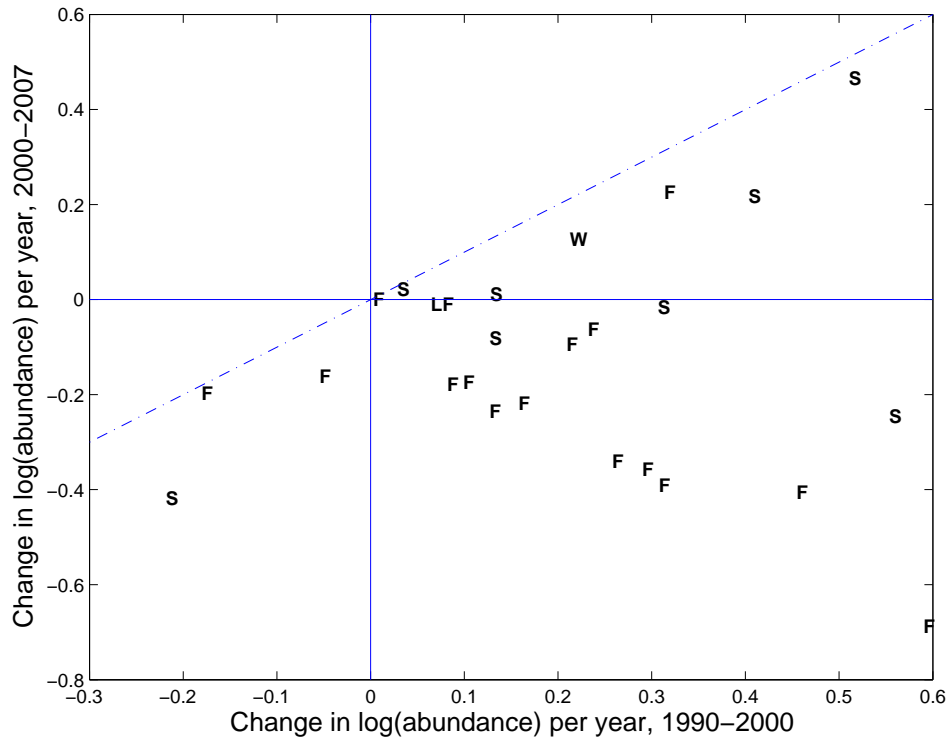


Figure 21: Escapement trends in the 1990s and 2000s of various populations of Chinook. F = fall Chinook, S = spring Chinook, LF= late fall Chinook, W= winter Chinook. If populations maintained constant growth rates over the 1990-2007 period, they would fall along the dashed diagonal line. All populations fall below the diagonal line, showing that growth rates are lower in the 2000s than in the 1990s, and fall Chinook populations have tended to decline the fastest in the 2000s.

1019 **5 Recommendations**

1020 In this section, we offer recommendations in three areas. First, we identify major
1021 information gaps that hindered our analysis of the 2004 and 2005 broods. Filling
1022 these gaps should lead to a better understanding of the linkages between survival
1023 and environmental conditions. Second, we offer some suggestions on how to im-
1024 prove the resilience of SRFC and the Central Valley Chinook stock complex. While
1025 changes in harvest opportunities are unavoidable given the expected fluctuations in
1026 environmental conditions, it is the panel's opinion that reducing the volatility of
1027 abundance, even at the expense of somewhat lower average catches, would benefit
1028 the fishing industry and make fishery disasters less likely. Finally, we point out that
1029 an ecosystem-based management and ecological risk assessment framework could
1030 improve management of Central Valley Chinook stocks by placing harvest man-
1031 agement in the broader context of the Central Valley salmon ecosystem, which is
1032 strongly influenced by hatchery operations and management of different ecosystem
1033 components, including water, habitat and other species.

1034 **5.1 Knowledge Gaps**

1035 We are confident in our conclusion that unusual conditions in the coastal ocean in
1036 2005 and 2006 caused the poor performance of the 2004 and 2005 broods. Our
1037 case could have been strengthened further, however, with certain kinds of informa-
1038 tion that are not currently available. Chief among these is the need for constant
1039 fractional marking and tagging of hatchery production, and adequate sampling of
1040 fish on the natural spawning grounds. Such information would better identify the
1041 contribution of hatcheries to the ocean fishery and natural spawning escapement,
1042 survival rates of different hatchery release groups, and the likely degree to which
1043 hatchery populations are impacting naturally-spawning populations. Central Valley
1044 hatcheries have recently started a constant-fractional marking program for fall Chi-
1045 nook, and CDFG is currently planning how to improve in-river sampling for mark
1046 and tag recovery. These efforts are critical to improved assessment of SRFC in the
1047 future.

1048 CDFG has also recently begun to determine the age of returns to the river, which
1049 will allow stock assessment scientists to produce cohort reconstructions of the nat-
1050 ural stocks in addition to hatchery stocks. Cohort reconstructions provide better
1051 survival estimates than the method used in this report (releases of tagged juvenile
1052 and recovery of tagged fish at age-two in recreational fisheries) because they are
1053 based on many more tag recoveries and provide estimates of fishery mortality and
1054 maturation rates.

1055 In the case of the 2004 and 2005 broods, freshwater factors did not appear to be
1056 the direct cause of the collapse, but future collapses may have multiple contribut-
1057 ing causes of similar importance. In such cases, it would be extremely valuable to
1058 have reach-specific survival rates like those routinely available for several salmonid
1059 species in the Columbia River and recently available for late-fall Chinook and steel-
1060 head in the Sacramento River. This would provide powerful and direct information

1061 about when and where exceptional mortality occurs.

1062 Observations of growth and energetic condition of Chinook in the estuary and
1063 ocean provided valuable evidence for the 2004 brood, but were unavailable for the
1064 2005 and later broods, due to funding limitations.

1065 **5.2 Improving resilience**

1066 It appears that the abundance of SRFC is becoming increasingly variable (Fig. 17).
1067 Exceptionally high abundance of SRFC may not seem like a serious problem (al-
1068 though it does create some problems), but exceptionally low abundances are treated
1069 as a crisis. The panel is concerned that such crises are to be expected at a frequency
1070 much higher than is acceptable, and that this frequency may be increasing with
1071 time due to changes in the freshwater environment, the ocean environment, and the
1072 SRFC stock itself. The main hope of reducing this volatility is increasing the diver-
1073 sity within and among the populations of fall Chinook in the Central Valley. There
1074 are a number of ways to increase diversity.

1075 Perhaps the most tractable area for increasing diversity is in changing hatchery
1076 operations. We recommend that a hatchery science review panel, be formed to
1077 review hatchery practices in the Central Valley. The panel should address a number
1078 of questions, including the following:

- 1079 1. assess impacts of outplanting and broodstock transfers among hatcheries on
1080 straying and population structure and evaluate alternative release strategies
- 1081 2. evaluate alternative rearing strategies to increase variation in timing of out-
1082 migration and age at maturity
- 1083 3. assess whether production levels are appropriate and if they could be adjusted
1084 according to expected ocean conditions

1085 Ongoing efforts to recover listed Chinook ESUs and increase natural production
1086 of anadromous fish in the Central Valley (e.g., the fisheries programs of the Central
1087 Valley Project Improvement Act) are also relevant to the problem and should be
1088 supported. In particular, efforts to increase the quantity and diversity of spawning
1089 and rearing habitats for fall Chinook are likely to be effective in increasing the
1090 diversity of life history tactics in that stock.

1091 The PFMC should consider creating specific conservation objectives for natural
1092 populations of SRFC. Especially in coordination with revised hatchery operations
1093 and habitat restoration, managing for natural production could increase diversity
1094 within Central Valley fall Chinook. Because conditions for reproduction and juve-
1095 nile growth are more variable within and among streams than hatcheries, natural
1096 production can be expected to generate a broader range of outmigration and age-at-
1097 maturity timings. If straying from hatcheries to natural areas is greatly reduced, the
1098 population dynamics of natural populations would be less similar to the dynamics of
1099 the hatchery populations, which would smooth the variation of the stock aggregate.

1100 **5.3 Synthesis**

1101 Addressing hatcheries, habitat and harvest independently would provide benefits
1102 to Central Valley Chinook, but addressing them together within a holistic frame-
1103 work is likely to be much more successful. The fisheries management community
1104 is increasingly recognizing the need to move towards an ecosystem based manage-
1105 ment approach. While there is still much uncertainty about what this should en-
1106 tail, the ecosystem-based management and ecological risk assessment (EBM/ERA)
1107 approach used by the south Florida restoration program (e.g., Harwell et al., 1996;
1108 Gentile et al., 2001) is readily applicable to management of Central Valley Chinook.
1109 That approach could lead stakeholders to a common view of the different problems
1110 afflicting Central Valley Chinook, identify and organize the information needed
1111 to effectively manage the ecosystem, better connect this information to decision-
1112 making, and reduce the uncertainty surrounding our decisions.

1113 At the core of the EBM/ERA approach are conceptual models of how the sys-
1114 tem works. The current fishery management regime for SRFC has some features
1115 of adaptive management, in that there are clearly stated goals and objectives for
1116 the fisheries, monitoring and evaluation programs, and an analytic framework for
1117 connecting the data to decisions about operation of the fishery. If one were to make
1118 explicit the conceptual model underlying SRFC harvest management, it would in-
1119 clude hatcheries that maintain a roughly constant output of fish coupled with ocean
1120 and in-river fisheries operating on aggregate stock abundance. The goal is to max-
1121 imize harvest opportunities in the current year within constraints posed by vari-
1122 ous weak stocks, which do not include naturally-spawning populations of SRFC.
1123 The panel feels that it would be useful to expand this conceptual model to include
1124 naturally-spawning populations, revised hatchery operations, habitat effects, ocean
1125 effects, and climate change. Also, resource managers might consider changing the
1126 goal of management from maximizing harvest opportunity for the current year to
1127 reducing fluctuations in opportunity from year to year and maintaining the stability
1128 of the system for the long term. Both of these goals require viable and productive
1129 populations of wild salmon. Not all of the factors in the revised system would be
1130 subject to control by fisheries managers, but including them in the model would
1131 at least make clear the contribution of these factors to the problem of effectively
1132 managing Chinook salmon fisheries.

1133 The panel is well aware that the resource management institutions are not well-
1134 equipped to pursue this approach, and that many of the actions that could improve
1135 the status and resilience of Central Valley Chinook are beyond the authority of the
1136 PFMC or any other single agency or entity. Nonetheless, significantly improv-
1137 ing the resilience of Central Valley Chinook and the sustainability of California's
1138 Chinook salmon fishery will require resource managers and stakeholders to work
1139 together, and EBM/ERA offers a framework for facilitating such cooperation.

1140 **References**

- 1141 Anderson, C. N. K., C. H. Hsieh, S. A. Sandin, R. Hewitt, A. Hollowed, J. Bed-
1142 dington, R. M. May, and G. Sugihara. 2008. Why fishing magnifies fluctuations
1143 in fish abundance. *Nature* 452:835–839.
- 1144 Barber, R. T. and R. L. Smith. 1981. Coastal upwelling ecosystems. *In* Analysis
1145 of marine ecosystems, A. R. Longhurst, editor, pages 31–68. Academic Press,
1146 London.
- 1147 Barnett-Johnson, R., C. B. Grimes, C. F. Royer, and C. J. Donohoe. 2007b. Iden-
1148 tifying the contribution of wild and hatchery Chinook salmon (*Oncorhynchus*
1149 *tshawytscha*) to the ocean fishery using otolith microstructure as natural tags.
1150 *Canadian Journal of Fisheries and Aquatic Sciences* 64:1683–1692.
- 1151 Beamish, R. J., D. J. Noakes, G. A. McFarlane, L. Klyashtorin, V. V. Ivanov, and
1152 V. Kurashov. 1999. The regime concept and natural trends in the production of
1153 Pacific salmon. *Can. J. Fish. Aquat. Sci.* 56:516–526.
- 1154 Bisson, P. A., C. C. Coutant, D. Goodman, R. Gramling, D. Lettenmaier, J. Licha-
1155 towich, W. Liss, E. Loudenslager, L. McDonald, D. Philipp, and B. Riddell. 2002.
1156 Hatchery surpluses in the Pacific Northwest. *Fisheries* 27:16–27.
- 1157 Botsford, L. W. and C. A. Lawrence. 2002. Patterns of co-variability among Califor-
1158 nia Current chinook salmon, coho salmon, Dungeness crab, and physical oceanog-
1159 raphic conditions. *Progress In Oceanography* 53:283–305.
- 1160 Bottom, D. L., K. K. Jones, T. J. Cornwell, A. Gray, and C. A. Simenstad. 2005a.
1161 Patterns of Chinook salmon emigration and residency in the Salmon River estu-
1162 ary (Oregon). *Estuarine Coastal and Shelf Science* 64:79–93.
- 1163 Bottom, D. L., C. A. Simenstad, J. Burke, A. M. Baptista, D. A. Jay, K. K.
1164 Jones, E. Casillas, and M. H. Schiewe. 2005b. Salmon at river’s end: the role
1165 of the estuary in the decline and recovery of Columbia River salmon. NOAA
1166 Tech. Memo. NMFS-NWFSC-68, U.S. Dept. Commer.
- 1167 Brodeur, R. D., J. P. Fisher, D. J. Teel, R. L. Emmett, E. Casillas, and T. W. Miller.
1168 2004. Juvenile salmonid distribution, growth, condition, origin, and environmen-
1169 tal and species associations in the Northern California Current. *Fishery Bulletin*
1170 102:25–46.
- 1171 Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips.
1172 2006. Anomalous pelagic nekton abundance, distribution, and apparent recruit-
1173 ment in the northern California Current in 2004 and 2005. *Geophysical Research*
1174 *Letters* 33:L22S08.
- 1175 Budy, P., G. P. Thiede, N. Bouwes, C. E. Petrosky, and H. Schaller. 2002. Evidence
1176 linking delayed mortality of Snake River salmon to their earlier hydrosystem
1177 experience. *North American Journal of Fisheries Management* 22:35–51.

- 1178 CDFG (California Department of Fish and Game). 2008. Focus areas of research
1179 relative to the status of the 2004 and 2005 broods of the Central Valley fall Chi-
1180 nook salmon stock. Pacific Fishery Management Council.
- 1181 CDFG and NMFS(California Department of Fish and Game and National Marine
1182 Fisheries Service). 2001. Final report on anadromous salmonid fish hatcheries
1183 in California. Technical report, California Department of Fish and Game and
1184 National Marine Fisheries Service Southwest Region.
- 1185 Christensen, J., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones,
1186 R. K. Kolli, W. T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C. Men-
1187 ndez, J. Räisänen, A. Rinke, S. A., and P. Whetton. 2007. Regional climate
1188 projections. *In* *Climate Change 2007: The Physical Science Basis. Contribution*
1189 *of Working Group I to the Fourth Assessment Report of the Intergovernmental*
1190 *Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Mar-
1191 quis, K. Averyt, M. Tignor, and H. Miller, editors. Cambridge University Press,
1192 Cambridge, United Kingdom and New York, NY, USA.
- 1193 Darimont, C. T., S. M. Carlson, M. T. Kinnison, P. C. Paquet, T. E. Reimchen, and
1194 C. C. Wilmers. 2009. Human predators outpace other agents of trait change in
1195 the wild. *Proceedings of the National Academy of Sciences of the United States*
1196 *of America* 106:952–954.
- 1197 Dever, E. P., C. E. Dorman, and J. L. Largier. 2006. Surface boundary-layer vari-
1198 ability off Northern California, USA, during upwelling. *Deep Sea Research Part*
1199 *II: Topical Studies in Oceanography* 53:2887–2905.
- 1200 Fisher, F. W. 1994. Past and present status of Central Valley chinook salmon. *Con-*
1201 *servation Biology* 8:870–873.
- 1202 Fisher, J. P., M. Trudel, A. Ammann, J. A. Orsi, J. Piccolo, C. Bucher, E. Casillas,
1203 J. A. Harding, R. B. MacFarlane, R. D. Brodeur, J. F. T. Morris, and D. W. Welch.
1204 2007. Comparisons of the coastal distributions and abundances of juvenile Pacific
1205 salmon from central California to the northern Gulf of Alaska. *In* *The ecology*
1206 *of juvenile salmon in the northeast Pacific Ocean: regional comparisons*, C. B.
1207 Grimes, R. D. Brodeur, L. J. Haldorson, and S. M. McKinnell, editors, pages
1208 31–80. American Fisheries Society, Bethesda, MD.
- 1209 Gargett, A. E. 1997. The optimal stability ‘window’: a mechanism underlying
1210 decadal fluctuations in North Pacific salmon stocks? *Fisheries Oceanography*
1211 6:109–117.
- 1212 Gentile, J. H., M. A. Harwell, W. Cropper, C. C. Harwell, D. DeAngelis, S. Davis,
1213 J. C. Ogden, and D. Lirman. 2001. Ecological conceptual models: a framework
1214 and case study on ecosystem management for South Florida sustainability. *Sci-*
1215 *ence of the Total Environment* 274:231–253.

- 1216 Good, T. P., R. S. Waples, and P. Adams. 2005. Updated status of federally listed
1217 ESUs of west coast salmon and steelhead. NOAA Tech. Memo. NMFS-NWFSC-
1218 66, U.S. Dept. Commer.
- 1219 Hankin, D. G. 1990. Effects of month of release of hatchery-reared chinook salmon
1220 on size at age, maturation schedule, and fishery contribution. Information Reports
1221 Number 90-4, Fish Division, Oregon Department of Fish and Wildlife.
- 1222 Hankin, D. G. and E. Logan. 2008. A preliminary analysis of chinook salmon
1223 coded-wire tag recovery data from Iron Gate, Trinity River and Cole Rivers
1224 hatcheries, brood years 1978-2001. Review draft.
- 1225 Hard, J. J., M. R. Gross, M. Heino, R. Hilborn, R. G. Kope, R. Law, and J. D.
1226 Reynolds. 2008. Evolutionary consequences of fishing and their implications for
1227 salmon. *Evolutionary Applications* 1:388–408.
- 1228 Hare, S. R. and R. C. Francis. 1995. Climate change and salmon production in
1229 the Northeast Pacific Ocean. *In* *Climate Change and Northern Fish Popula-*
1230 *tions*. Canadian Special Publications in Fisheries and Aquatic Sciences 121, R. J.
1231 Beamish, editor, pages 357–372.
- 1232 Harwell, M. A., J. F. Long, A. M. Bartuska, J. H. Gentile, C. C. Harwell, V. Myers,
1233 and J. C. Ogden. 1996. Ecosystem management to achieve ecological sustain-
1234 ability: The case of south Florida. *Environmental Management* 20:497–521.
- 1235 Healey, M. C. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*).
1236 *In* *Pacific salmon life histories*, C. Margolis and L. Groot, editors, pages 311–
1237 394. University of British Columbia Press, Vancouver.
- 1238 Hilborn, R., T. P. Quinn, D. E. Schindler, and D. E. Rogers. 2003. Biocomplexity
1239 and fisheries sustainability. *Proceedings of the National Academy of Sciences*,
1240 USA 100:6564–6568.
- 1241 Hobday, A. J. and G. W. Boehlert. 2001. The role of coastal ocean variation in
1242 spatial and temporal patterns in survival and size of coho salmon (*Oncorhynchus*
1243 *kisutch*). *Canadian Journal of Fisheries and Aquatic Sciences* 58:2021–2036.
- 1244 Hooff, R. C. and W. T. Peterson. 2006. Copepod biodiversity as an indicator
1245 of changes in ocean and climate conditions of the northern California current
1246 ecosystem. *Limnology and Oceanography* 51:2607–2620.
- 1247 Houde, E. D. 1975. Effects of stocking density and food density on survival, growth
1248 and yield of laboratory-reared larvae of sea bream *Archosargus rhomboidalis* (L.)
1249 (Sparidae). *Journal of Fish Biology* 7:115–127.
- 1250 Huusko, A. and P. Hyvärinen. 2005. A high harvest rate induces a tendency to
1251 generation cycling in a freshwater fish population. *Journal of Animal Ecology*
1252 74:525–531.

- 1253 ISAB (Independent Scientific Advisory Board). 2007. Latent mortality report: re-
1254 view of hypotheses and causative factors contributing to latent mortality and their
1255 likely relevance to the "below Bonneville" component of the COMPASS model.
1256 ISAB 2007-1. ISAB, Portland, OR.
- 1257 Ingraham, J. W. J. and R. K. Miyahara. 1988. Ocean surface current simulations in
1258 the North Pacific Ocean and Bering Sea (OSCURS – Numerical Models). NOAA
1259 Tech. Memo. NMFS F/NWC-130, U.S. Dept. Commer.
- 1260 Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats
1261 provide best growth conditions for juvenile Chinook salmon in a California river.
1262 *Environmental Biology of Fishes* 83:449–458.
- 1263 Kjelson, M. A. and P. L. Brandes. 1989. The use of smolt survival estimates to
1264 quantify the effects of habitat changes on salmonid stocks in the Sacramento-
1265 San Joaquin rivers, California. *In Proceedings of the National Workshop on the*
1266 *effects of habitat alteration on salmonid stocks*, C. D. Levings, L. B. Holtby,
1267 and M. A. Henderson, editors, *Canadian Special Publications in Fisheries and*
1268 *Aquatic Sciences*, volume 105, pages 100–115.
- 1269 Kope, R. G. and L. W. Botsford. 1990. Determination of factors affecting recruit-
1270 ment of chinook salmon *Oncorhynchus tshawytscha* in central California. *Fish-*
1271 *ery Bulletin* 88:257–269.
- 1272 Kruse, G. H. 1998. Salmon run failures in 1997–1998: a link to anomalous ocean
1273 conditions? *Alaska Fishery Research Bulletin* 5:55–63.
- 1274 Lawson, P. W. 1993. Cycles in ocean productivity, trends in habitat quality, and the
1275 restoration of salmon runs in Oregon. *Fisheries* 18:6–10.
- 1276 Lawson, P. W., E. A. Logerwell, N. J. Mantua, R. C. Francis, and V. N. Agostini.
1277 2004. Environmental factors influencing freshwater survival and smolt produc-
1278 tion in Pacific Northwest coho salmon (*Oncorhynchus kisutch*). *Canadian Journal*
1279 *of Fisheries and Aquatic Sciences* 61:360–373.
- 1280 Lichatowich, J. 1999. *Salmon without rivers: a history of the Pacific salmon crisis*.
1281 Island Press, Washington, DC.
- 1282 Lindley, S. T., R. S. Schick, B. May, J. J. Anderson, S. Greene, C. Hanson,
1283 A. Low, D. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams.
1284 2004. Population structure of threatened and endangered chinook salmon ESUs
1285 in California's Central Valley basin. NOAA Tech. Memo. NMFS-SWFSC-360,
1286 U.S. Dept. Commer.
- 1287 Lindley, S. T., R. S. Schick, E. Mora, P. B. Adams, J. J. Anderson, S. Greene,
1288 C. Hanson, B. P. May, D. McEwan, R. B. MacFarlane, C. Swanson, and J. G.
1289 Williams. 2007. Framework for assessing viability of threatened and endangered
1290 Chinook salmon and steelhead in the Sacramento-San Joaquin basin. *San Fran-*
1291 *cisco Estuary and Watershed Science* 5(1):Article 4.

- 1292 MacFarlane, R. B. and E. C. Norton. 2002. Physiological ecology of juvenile chi-
1293 nook salmon (*Oncorhynchus tshawytscha*) at the southern end of their distribu-
1294 tion, the San Francisco Estuary and Gulf of the Farallones, California. *Fishery*
1295 *Bulletin* 100:244–257.
- 1296 Mantua, N., S. Hare, Y. Zhang, J. Wallace, and R. Francis. 1997. A Pacific inter-
1297 decadal climate oscillation with impacts on salmon production. *Bulletin of the*
1298 *American Meteorological Society* 78:1069–1079.
- 1299 MBARI (Monterey Bay Aquarium Research Institute). 2006. Annual report.
1300 MBARI, Moss Landing, CA.
- 1301 McCullough, D. A. 1999. A review and synthesis of effects of alteration to the
1302 water temperature regime on freshwater life stages of salmonids, with special
1303 reference to chinook salmon. Document 910-R-99010, United States Environ-
1304 mental Protection Agency. Seattle, WA.
- 1305 McEvoy, A. F. 1986. The fisherman’s problem: ecology and law in the California
1306 fisheries. Cambridge University Press, New York, New York.
- 1307 McIsaac, D. O. 2008. Pacific Fishery Management Council request for scientific
1308 review of factors affecting certain west coast salmon stocks. Supplemental Infor-
1309 mational Report 5, Pacific Fishery Management Council. Portland, OR.
- 1310 Mueter, F. J., R. M. Peterman, and B. J. Pyper. 2002. Opposite effects of ocean
1311 temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus*
1312 spp.) in northern and southern areas. *Canadian Journal of Fisheries and Aquatic*
1313 *Sciences* 59:456–463.
- 1314 Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright,
1315 W. S. Grant, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. Sta-
1316 tus review of chinook salmon from Washington, Idaho, Oregon, and California.
1317 NOAA Tech. Memo. NMFS-NWFSC-35, U.S. Dept. Commer.
- 1318 Newell, C. L. and T. J. Cowles. 2006. Unusual gray whale *Eschrichtius robus-*
1319 *tus* feeding in the summer of 2005 off the central Oregon Coast. *Geophysical*
1320 *Research Letters* 33:L22S11.
- 1321 Newman, K. B. and J. Rice. 2002. Modeling the survival of chinook salmon smolts
1322 outmigrating through the lower Sacramento River system. *Journal of the Ameri-*
1323 *can Statistical Association* 97:983–993.
- 1324 O’Farrell, M. R., M. S. Mohr, M. L. Palmer-Zwahlen, and A. M. Grover. 2009. The
1325 Sacramento Index. Report in preparation.
- 1326 Percy, W. G. 1992. Ocean ecology of North Pacific salmonids. University of
1327 Washinton, Seattle, WA.

- 1328 PFMC (Pacific Fishery Management Council). 2007. Preseason report III: Anal-
1329 ysis of council adopted management measures for 2007 ocean salmon fisheries.
1330 Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101,
1331 Portland, Oregon 97220-1384.
- 1332 PFMC (Pacific Fishery Management Council). 2008. Preseason report I: Stock
1333 abundance analysis for 2008 ocean salmon fisheries. Pacific Fishery Management
1334 Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.
- 1335 PFMC (Pacific Fishery Management Council). 2009. Review of 2008 ocean salmon
1336 fisheries. Pacific Fishery Management Council, 7700 NE Ambassador Place,
1337 Suite 101, Portland, Oregon 97220-1384.
- 1338 Pyper, B. J., F. J. Mueter, R. M. Peterman, D. J. Blackbourn, and C. C. Wood.
1339 2002. Spatial covariation in survival rates of Northeast Pacific chum salmon.
1340 Transactions of the American Fisheries Society 131:343–363.
- 1341 Reisenbichler, R. R. and S. P. Rubin. 1999. Genetic changes from artificial prop-
1342 agation of Pacific salmon affect the productivity and viability of supplemented
1343 populations. ICES Journal of Marine Science 56:459–466.
- 1344 Rykaczewski, R. R. and D. J. Checkley. 2008. Influence of ocean winds on the
1345 pelagic ecosystem in upwelling regimes. Proceedings of the National Academy
1346 of Sciences 105:1967–1970.
- 1347 Ryther, J. H. 1969. Photosynthesis and fish production in the sea. Science 166:72–
1348 76.
- 1349 Schwing, F. B., N. A. Bond, S. J. Bograd, T. Mitchell, M. A. Alexander, and
1350 N. Mantua. 2006. Delayed coastal upwelling along the US West Coast in 2005:
1351 A historical perspective. Geophysical Research Letters 33:L22S01.
- 1352 Schwing, F. B., T. Murphree, and P. M. Green. 2002. The Northern Oscillation
1353 Index (NOI): a new climate index for the northeast Pacific. Progress In Oceanog-
1354 raphy 53:115–139.
- 1355 Sommer, T. R., M. L. Nobriga, W. C. Harrel, W. Batham, and W. J. Kimmerer. 2001.
1356 Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and
1357 survival. Can. J. Fish. Aquat. Sci. 58:325–333.
- 1358 SRFCRT (Sacramento River Fall Chinook Review Team). 1994. Sacramento River
1359 Fall Chinook Review Team: An assessment of the status of the Sacramento River
1360 fall chinook stock as required under the salmon fishery management plan. Pacific
1361 Fishery Management Council.
- 1362 Sydeman, W. J., R. W. Bradley, P. Warzybok, C. L. Abraham, J. Jahncke, K. D.
1363 Hyrenbach, V. Kousky, J. M. Hipfner, and M. D. Ohman. 2006. Planktivorous
1364 auklet *Ptychoramphus aleuticus* responses to ocean climate, 2005: Unusual at-
1365 mospheric blocking? Geophysical Research Letters 33:L22S09.

- 1366 Vogel, D. A. and K. R. Marine. 1991. Guide to upper Sacramento chinook salmon
1367 life history. CH2M Hill.
- 1368 Weise, M. J., D. P. Costa, and R. M. Kudela. 2006. Movement and diving behavior
1369 of male California sea lion (*Zalophus californianus*) during anomalous oceano-
1370 graphic conditions of 2005 compared to those of 2004. *Geophysical Research*
1371 *Letters* 33:L22S10.
- 1372 Weitkamp, L. A. In review. Marine distributions of Chinook salmon (*Oncorhynchus*
1373 *tshawytscha*) from the west coast of North America determined by coded wire tag
1374 recoveries.
- 1375 Welch, D. W., E. L. Rechisky, M. C. Melnychuk, A. D. Porter, C. J. Walters,
1376 S. Clements, B. J. Clemens, R. S. McKinley, and C. Schreck. 2008. Survival
1377 of migrating salmon smolts in large rivers with and without dams. *PLoS Biology*
1378 6:2101–2108.
- 1379 Wells, B. K., J. C. Field, J. A. Thayer, C. B. Grimes, S. J. Bograd, W. J. Sydeman,
1380 F. B. Schwing, and R. Hewitt. 2008. Untangling the relationships among climate,
1381 prey and top predators in an ocean ecosystem. *Marine Ecology Progress Series*
1382 364:15–29.
- 1383 Wilkerson, F. P., A. M. Lassiter, R. C. Dugdale, A. Marchi, and V. E. Hogue. 2006.
1384 The phytoplankton bloom response to wind events and upwelled nutrients during
1385 the CoOP WEST study. *Deep Sea Research Part II: Topical Studies in Oceanog-*
1386 *raphy* 53:3023–3048.
- 1387 Williams, J. G. 2006a. Central Valley salmon: a perspective on Chinook and steel-
1388 head in the Central Valley of California. *San Francisco Estuary and Watershed*
1389 *Science* 4(3):Article 2.
- 1390 Williams, J. G., S. G. Smith, and W. D. Muir. 2001. Survival estimates for down-
1391 stream migrant yearling juvenile salmonids through the Snake and Columbia
1392 rivers hydropower system, 1966–1980 and 1993–1999. *North American Jour-*
1393 *nal of Fisheries Management* 21:310–317.
- 1394 Williams, R. N., editor. 2006b. *Return to the river: restoring salmon to the*
1395 *Columbia River*. Elsevier Academic Press, San Diego, CA.
- 1396 Williamson, K. S. and B. May. 2005. Homogenization of fall-run Chinook salmon
1397 gene pools in the Central Valley of California, USA. *North American Journal of*
1398 *Fisheries Management* 25:993–1009.
- 1399 Wolf, S. G., W. J. Sydeman, J. M. Hipfner, C. L. Abraham, B. R. Tershy, and D. A.
1400 Croll. 2009. Range-wide reproductive consequences of ocean climate variability
1401 for the seabird Cassin's Auklet. *Ecology* 90:742–753.

- 1402 Yoshiyama, R. M., F. W. Fisher, and P. B. Moyle. 1998. Historical abundance
1403 and decline of chinook salmon in the Central Valley region of California. *North*
1404 *American Journal of Fisheries Management* 18:487–521.
- 1405 Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2001. Historic
1406 and present distribution of chinook salmon in the Central Valley drainage of Cal-
1407 ifornia. *In* *Fish Bulletin 179: Contributions to the biology of Central Valley*
1408 *salmonids.*, R. L. Brown, editor, volume 1, pages 71–176. California Department
1409 of Fish and Game, Sacramento, CA.