Charles Paulsen
Richard Hinrichsen

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Hatchery Hypothesis: Variation in releases of Snake River hatchery spring/summer chinook is associated with variation in extra mortality of naturally produced Snake River spring/summer chinook.

Management Implication: Reducing hatchery releases would reduce extra mortality, independent of hydrosystem actions.

Introduction

There are a number of possible mechanisms by which releases of hatchery smolts could affect the survival of wild fish. On the one hand, hatchery releases could have a positive affect on wild fish by "swamping" predators. On the other, they could spread disease, compete for food, and stress the natural population. Testing hypotheses regarding hatchery influence is complicated because of the "two-stage" nature of the problem.

For example, assume that fisheries managers are faced with a stock that is declining due to over-harvest, but they are unaware that this is the cause of the decline. Suppose that the managers decide to begin releasing hatchery fish in order to add to the stock available for harvest. As a result, harvest rates increase and the decline of the natural stock accelerates. In this example, the hatchery fish may have had no direct impact (via competition, etc.) on the natural stock, but a stock assessment would show a strong correlation between hatchery releases and the decline of the natural stock. The problem has two "stages". The first is the decline of the stock (due to harvest). In the second stage, a hatchery is built to solve the problem, but there is a feedback loop between the first and second stage.

In the case of Snake River spring/summer chinook, a large number of management actions were taken as the lower Snake River dams were completed. Idaho Power financed the construction of hatcheries to compensate for the spawning areas lost due to the Hells Canyon complex. Similarly, hatcheries were built to compensate for loss of habitat in the Clearwater. In addition, the hatchery program was intended, in part, to help compensate for decreases in migrant survival. Meanwhile, bypass screening, transportation, and spill programs were undertaken at run-of-the-river dams to improve the survival of juvenile migrants.

An unambiguous separation of hatchery releases intended to mitigate for habitat loss and those to mitigate for migration corridor problems is impossible. To the extent that the releases mitigate for passage mortality, this is "controlled" in the Alpha and Delta life-cycle models by using passage model output to backcast passage mortality. Even if hatcheries were intended solely as mitigation for passage problems, these passage problems are accounted for using passage model back-casts. The focus here is on the "extra" mortality not accounted for by passage models. We will attempt to explain a portion of the extra mortality (as distinct from direct passage mortality) as a simple linear function of hatchery releases, *after* accounting for the direct hydrosystem effects the hatcheries were intended to mitigate.

The plan of the paper is as follows. We first re-iterate the structure of the life cycle models, focussing on what extra mortality is and how the models account for it. We next show how the release data is correlated with extra mortality. We conclude with an assessment of how this information might be used in prospective BSM runs, and what the management implications might be.

Methods

The delta model, as currently implemented in the BSM, can be described as follows:

$$\log(R_{t,i}) = \log(S_{t,i}) + a_i - b_i S_t - m_t - n_{t,i} X + d_t + e_{t,i} \quad [1]$$

Where: $R_{t,i}$ = Columbia River "observed" returns (recruitment) originating from Spawning in year t and stock i

$S_{t,i}$	=	"observed" spawning in year t and stock i
a_i	=	Ricker-a parameter, which depends on stock
b_i	=	Ricker-b parameter, which depends on stock
m_t	=	Differential mortality in year t
$n_{t,i}$	=	Number of first level dams (X-dams) stock i must pass in year t
X	=	Dam passage mortality per first level dam
d_t	=	Common year effect for year t
$e_{t,i}$	=	normally distributed mixed process error and recruitment measurement error term N(0,*Ve*) (i.e., it follows a normal distribution with mean zero and variance *Ve*)

For each year of the retrospective study, we estimate the total mortality, *m*, which includes both direct and extra mortalities, using the maximum likelihood estimates of μ_t and X_t.

$$m_t = \mu_t + n_t X \qquad [2]$$

The estimate of extra mortality of in-river fish is then

$$1 - \lambda_{n,t} = 1 - \exp(-m_t)/\omega_t \qquad [3]$$

where ω_t is the system survival supplied by the passage models for each year (1952-1990). The extra mortality of transported fish is then expressed in terms of extra mortality for in-river migrants and D, their ratio:

$$D = \lambda_{t,t} / \lambda_{n,t}$$

$$\lambda_{t,t} = D^* \lambda_{n,t} \qquad [4]$$

Equation [4] is then used calculate delayed mortality (i.e., 1 - delayed survival) of transported fish.

Under the Delta model, one can test if delayed mortality for both transported and non-transported fish is related to the release of hatchery smolts. We used simple bivariate Pearson correlation; obviously other more sophisticated methods could be applied. For the Delta model, we examined the correlations between hatchery releases and extra mortality for inriver migrants, transported fish, and the total extra mortality. We looked at correlations for both 1952-90 and 1975-90 (the latter being the period when extra mortality is believed be higher). In addition, to investigate how annual variation in releases is associated with extra mortality, we detrended the time series. The data (prior to detrending) are shown in Table 1.

The Alpha model can be described as:

$$\log(R_{t,i}) = \log(S_{t,i}) + a_i - b_i S_t - M_{t,i} - \alpha_t + \varepsilon_{t,i} \qquad [5]$$

Where:	$R_{t,i}$	=	Columbia River "observed" returns (recruitment) originating from Spawning in year *t* and stock *i*
	$S_{t,i}$	=	"observed" spawning in year *t* and stock *i*
	a_i	=	Ricker-a parameter, which depends on stock
	b_i	=	Ricker-b parameter, which depends on stock
	α_t	=	Common additional mortality in year *t* for all Snake stocks (sums to zero over 1952-1990).
	$M_{t,i}$	=	Passage mortality for stock i in year t. (Supplied by passage models).
	$\varepsilon_{t,i}$	=	normally distributed mixed process error and

recruitment measurement error term N(0,*Ve*) (i.e., it follows a normal distribution with mean zero and variance *Ve*)

In the version of the alpha model used to date, the series of additional mortalities is described by a linear relationship with further explanatory variables. The retrospective alpha series is modeled in the BSM is as follows:

$$\alpha_t = \beta_1'(1/F_t) + \beta_2'(E_t/F_t) + \beta_3' Step_t - \log(D_t P_t + 1 - P_t) + \beta_0' \quad [6]$$

Where

β_j' = Regression coefficients. The coefficient β_0' is chosen so that the alpha series sums to zero over brood years 1952-1990. This ensures that the a_i represents the average productivity of stock i in the absence of passage mortality.

F_t = Average Flow (in KCFS) at Astoria for year t during April-June.

E_t = Climate index variable (PAPA drift). Represents the latitude of a drifting object after three months drift starting at station PAPA.

$Step_t$ = Step is a factor variable that takes the value zero prior to 1975, and the estimated value STEP afterwards. It is formulated to model the effect of a 1975 (brood year) regime shift.

D_t = Ratio of post-Bonneville transport survival to post-Bonneville inriver survival for year *t*.

P_t = Proportion of fish arriving below Bonneville that were transported for year *t*.

For the hatchery hypotheses, we examine the correlations between the annual average residuals from [6] and hatchery releases.[1] As for the Delta model, we analyze these for 1952-90 and 1975-90, both with and without detrending.

Results

We first examine the "two-stage" problem: that hatchery releases increased (at least in part) to mitigate for the direct effects of the hydrosystem. Figure 1a shows how the direct passage survival including transported fish, exp(-*M*), has decreased over time as hatchery releases have increased. Given this, it is apparent that there is a weak association between hatchery releases of yearling chinook migrants and direct passage survival, again including transported fish. The correlations between passage survival and hatchery releases are 0.13 and -0.08, respectively, for CRiSP and FLUSH. This weak association occurs because of the influence of transported fish, which have high survival to below Bonneville. When we look at the direct survival of fish passing in-river only (Figure 1b), the correlations are -0.69 and -0.83 for CRiSP and FLUSH, respectively. Based solely on this information, one cannot say to what degree hatchery releases are "caused" by decreasing passage survival (i.e. to what extent they are intended to mitigate for the direct effects of the hydrosystem). It is apparent, however, that the two covary over time.

It is important to recall, however, that the focus for our hatchery hypothesis tests is on extra mortality. That is, we would like to know the association (if any) between hatchery releases

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[1] Unlike the Delta model, hatchery releases can easily be incorporated directly in the Alpha model, by adding a term to Eq. 6'. We use the correlation approach to parallel the methods used for the Delta model.

and mortality that is not accounted for by hydrosystem survival, compensatory mortality, year effects common to both upriver and downriver stocks, etc. Put somewhat differently, the Alpha and Delta models "control" for the direct effects of the hydrosystem using passage model output. The "control" variable *Vn* (direct passage survival of in-river migrants) is indeed strongly correlated with hatchery releases, and one could loosely say that the "control" variables are part of the "cause" for increased hatchery releases. What we are interested in, however, is the association, if any, between releases and the unexplained extra mortality. As such, the correlations just noted are not problematic. Therefore, the potential "two-stage problem" noted in the introduction does pose any particular difficulty for the hatchery hypotheses analyzed here.

Delta model correlations between extra mortality and releases are shown in Tables 2 through 5. Table 2 shows correlations between releases and extra mortality for 1952-90, without detrending, while 3 shows correlations for 1975-90.[2] Figures 2 and three display the same information as time series. The highest correlation is for total extra mortality using CRiSP, 1952-90, at 0.714, while the lowest if for FLUSH inriver for 52-90, at 0.054.

Note that there is a clear upward trend in extra mortality, for both periods, models, and fish groups (inriver or transported). Tables 4 and 5, and Figures 4 and 5, show the relationships between extra mortality and releases after detrending the mortality and release series.[3] As one might expect given their common upward trends, the correlations are substantially smaller, ranging from 0.303 to -0.005. One interesting feature is that the correlation between detrended extra mortality for transported fish mortality and releases is stronger than that for inriver migrants. Looking at the figures, one can see covarying patterns between releases and extra mortality, but there are important exceptions as well. For example, in Figure 5b, there is a close correspondence between releases and total extra mortality between 1977 and 1982, but there are several years in the 80's when the pattern breaks down.

Table 6 and Figure 6 show the relationship between the alpha model residuals, which reflect extra mortality of in-river migrants, and hatchery releases. As with the Delta model results, the correlations are weaker for the detrended results.[4] Note that the Alpha model accounts for differential inriver and transport extra mortality by using the log[DP + 1 – P] term directly in Eq. 6.

Biological mechanisms that could explain these results might include horizontal transmission of disease, competition for food or other resources, or hatchery fish may help maintain larger predator populations than would exist otherwise. In addition, stress during transportation may play a role. However, most of these mechanisms cannot be tested with the information available from life-cycle models. The exception is the stress during transport: if this is important, one would expect substantially stronger correlations between releases and extra mortality for transported fish. We do not see consistent, markedly stronger correlations for transported fish than for fish migrating inriver, however. This suggests that whatever underlies the correlations is a result of interactions in other life cycle phases, such as migration from rearing areas down to Lower Granite.

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[2] We omit the 75-90 correlations for transported fish, since the transportation program did not become active until 1969.

[3] To detrend a time series, we mean that one uses the residuals from a regression of the form $y(t) = b0 + b1*t + \varepsilon(t)$. These have any linear relationship with time removed from the series.

[4] If releases are included in Eq. 6, their effects are negative and significant, with "t" values of about 6.

Management Implications and BSM Implementation

If the correlations between hatchery releases and mortality reflect an underlying causal relationship, then reducing hatchery output should reduce extra mortality. The correlation analysis indicates the direction of the hypothesized relationship, but does not say anything about the size of that relationship. For the Delta model, one would need to perform regressions of the following form:

$$EM(t) = b0 + b1(releases) + \varepsilon(t) \qquad [7]$$

Where EM is extra mortality, whether of transported or inriver migrants. It may be desirable to transform the variables in [7] using natural logs. Distributions of the coefficients and their distributions could then be put into the BSM. As noted previously, releases could be included directly into the Alpha model, and estimated coefficient distributions could be carried forward in the BSM, along with projections of hatchery releases.

Table 1. Delta Model Extra Mortality and Hatchery Releases of Spring/Summer Chinook

Brood Yr.	CRISP Extra Mortality - inriver	FLUSH Extra Mortality - inriver	CRISP Extra Mortality, Transported	FLUSH Extra Mortality, Transported	CRISP Total Extra Mortality	FLUSH Total Extra Mortality	Regional Smolt Releases
52	0.120	0.283			0.120	0.283	0.00E+00
53	0.066	0.016			0.066	0.016	0.00E+00
54	0.197	0.335			0.197	0.335	0.00E+00
55	0.329	0.472			0.329	0.472	0.00E+00
56	0.280	0.444			0.280	0.444	0.00E+00
57	0.304	0.387			0.304	0.387	0.00E+00
58	0.208	0.353			0.208	0.353	0.00E+00
59	0.392	0.575			0.392	0.575	0.00E+00
60	0.335	0.522			0.335	0.522	0.00E+00
61	0.287	0.458			0.287	0.458	1.60E+04
62	0.313	0.481			0.313	0.481	0.00E+00
63	0.425	0.565			0.425	0.565	1.05E+04
64	0.326	0.358			0.326	0.358	5.80E+05
65	0.275	0.399			0.275	0.399	4.80E+05
66	0.324	-0.259			0.324	-0.259	1.46E+06
67	0.423	0.693			0.423	0.693	1.06E+06
68	-0.212	0.270			-0.212	0.270	3.34E+06
69	-0.450	0.676	0.748	0.753	0.095	0.680	2.89E+06
70	-0.289	0.175	0.776	0.575	0.097	0.241	3.46E+06
71	0.170	-0.691	0.856	0.645	0.551	0.458	4.90E+06
72	0.779	0.870	0.961	1.000	0.779	0.870	3.16E+06
73	-0.468	0.036	0.745	0.570	0.208	0.343	6.34E+06
74	0.027	0.763	0.831	0.879	0.680	0.808	7.27E+06
75	0.622	0.211	0.934	0.922	0.916	0.916	5.01E+06
76	0.356	0.397	0.888	0.837	0.804	0.800	7.75E+06
77	-0.235	-0.077	0.785	0.742	0.683	0.708	6.37E+06
78	0.781	0.570	0.962	0.885	0.946	0.872	7.35E+06
79	0.665	0.389	0.942	0.844	0.914	0.833	4.04E+06
80	0.088	0.029	0.423	0.566	0.307	0.508	3.82E+06
81	-0.087	-0.256	0.312	0.540	0.167	0.383	6.71E+06
82	0.514	0.404	0.692	0.731	0.642	0.651	8.75E+06
83	0.422	-0.122	0.634	0.700	0.611	0.657	1.09E+07
84	0.795	0.672	0.870	0.892	0.859	0.875	7.22E+06
85	0.872	0.641	0.919	0.929	0.916	0.922	1.16E+07
86	0.661	-0.067	0.785	0.807	0.779	0.798	1.09E+07
87	0.832	0.684	0.894	0.911	0.884	0.896	1.20E+07
88	0.874	0.682	0.920	0.929	0.917	0.924	1.35E+07
89	0.839	0.628	0.898	0.905	0.893	0.896	9.71E+06
90	0.945	0.807	0.965	0.964	0.965	0.963	1.17E+07

Table 2. Delta Model Correlations Between Extra Mortality and Hatchery Releases 1952-90, No Detrending. Correlations between extra mortality and releases are **bolded**

a: Inriver Migrants					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.447	1.000	0.000	0.000
	FLUSH	0.060	0.446	1.000	0.000
	Releases	0.930	**0.435**	**0.054**	1.000
b: Transported Fish (69-90)					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.069	1.000	0.000	0.000
	FLUSH	0.388	0.803	1.000	0.000
	Releases	0.842	**0.198**	**0.398**	1.000
c: Total Extra Mortality					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.728	1.000	0.000	0.000
	FLUSH	0.684	0.835	1.000	0.000
	Releases	0.930	**0.714**	**0.657**	1.000

Table 3. Delta Model Correlations Between Extra Mortality and Hatchery Releases 1975-90, No Detrending

a: Inriver Migrants					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.585	1.000	0.000	0.000
	FLUSH	0.471	0.822	1.000	0.000
	Releases	0.785	**0.548**	**0.416**	1.000
b: Total Extra Mortality					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.241	1.000	0.000	0.000
	FLUSH	0.333	0.980	1.000	0.000
	Releases	0.785	**0.372**	**0.428**	1.000

Table 4. Delta Model Correlations Between Extra Mortality and Hatchery Releases 1952-90, Detrended

a: Inriver Migrants					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.470	1.000	0.000
	Releases	0.000	**0.059**	**-0.005**	1.000
b: Transported (69-90)					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.844	1.000	0.000
	Releases	0.000	**0.261**	**0.143**	1.000
c: Total					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.674	1.000	0.000
	Releases	0.000	**0.144**	**0.078**	1.000

Table 5. Delta Model Correlations Between Extra Mortality and Hatchery Releases 1975-90, Detrended

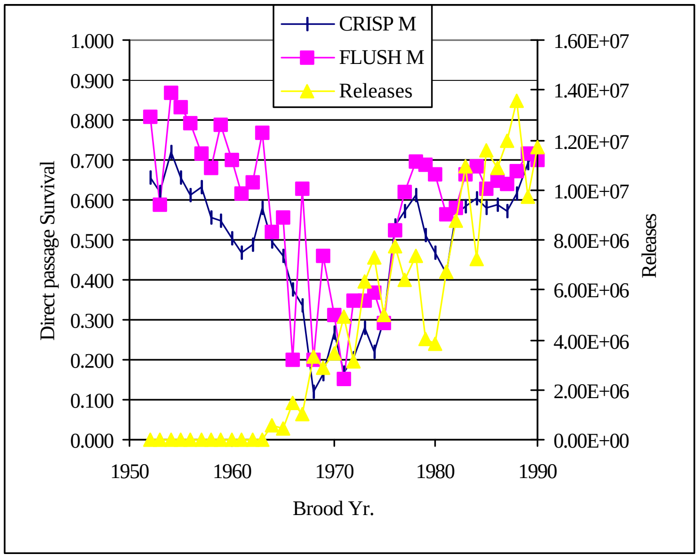
a: Inriver					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.764	1.000	0.000
	Releases	0.000	**0.177**	**0.083**	1.000
b: Total					
		Brood Year	CRiSP	FLUSH	Releases
	Brood Year	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.984	1.000	0.000
	Releases	0.000	**0.303**	**0.284**	1.000

Table 6. Alpha Model Correlations Between α Model Residuals and Hatchery Releases

a: 1952-90, No Detrending					
		Brood Yr.	CRiSP	FLUSH	Releases
	Brood Yr.	1.000	0.000	0.000	0.000
	CRiSP	0.179	1.000	0.000	0.000
	FLUSH	0.302	0.957	1.000	0.000
	Releases	0.930	**0.185**	**0.255**	1.000
b: 1975-90, No Detrending					
		Brood Yr.	CRiSP	FLUSH	Releases
	Brood Yr.	1.000	0.000	0.000	0.000
	CRiSP	0.322	1.000	0.000	0.000
	FLUSH	0.258	0.991	1.000	0.000
	Releases	0.785	**0.193**	**0.158**	1.000
c: 1952-90, Detrended					
		Brood Yr.	CRiSP	FLUSH	Releases
	Brood Yr.	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.962	1.000	0.000
	Releases	0.000	**-0.050**	**0.072**	1.000
d: 1975-90, Detrended					
		Brood Yr.	CRiSP	FLUSH	Releases
	Brood Yr.	1.000	0.000	0.000	0.000
	CRiSP	0.000	1.000	0.000	0.000
	FLUSH	0.000	0.993	1.000	0.000
	Releases	0.000	**0.102**	**0.074**	1.000

Figure 1. Hatchery Releases and Direct Passage Survival, CRiSP and FLUSH, 1952-90

1a. Direct Passage Mortality (Lower Granite to Bonneville) Including Transported Fish



1b. Passage Mortality of Inriver Migrants (Lower Granite to Bonneville)

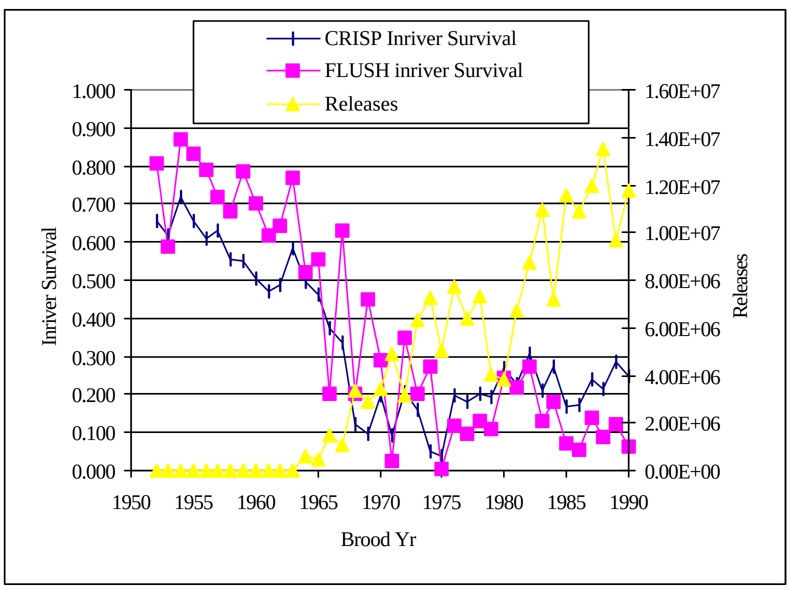
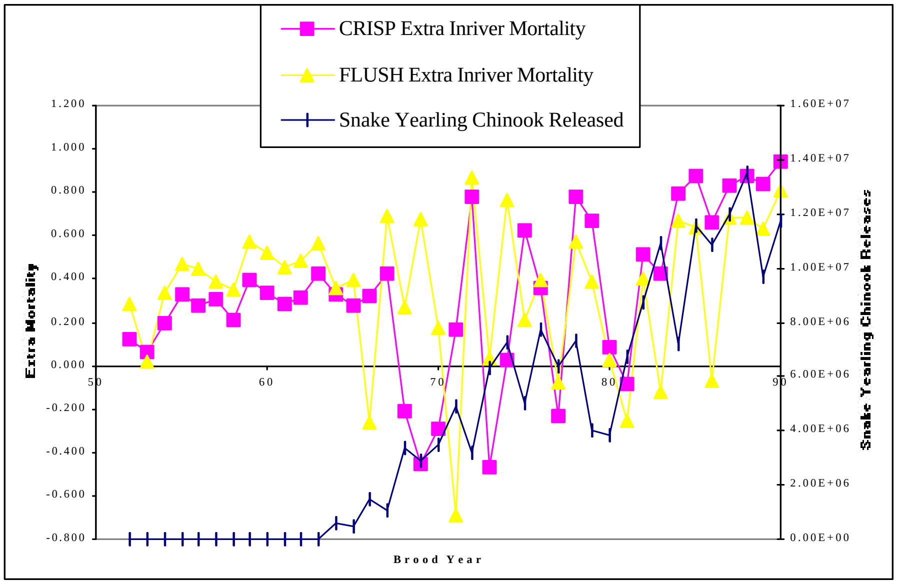
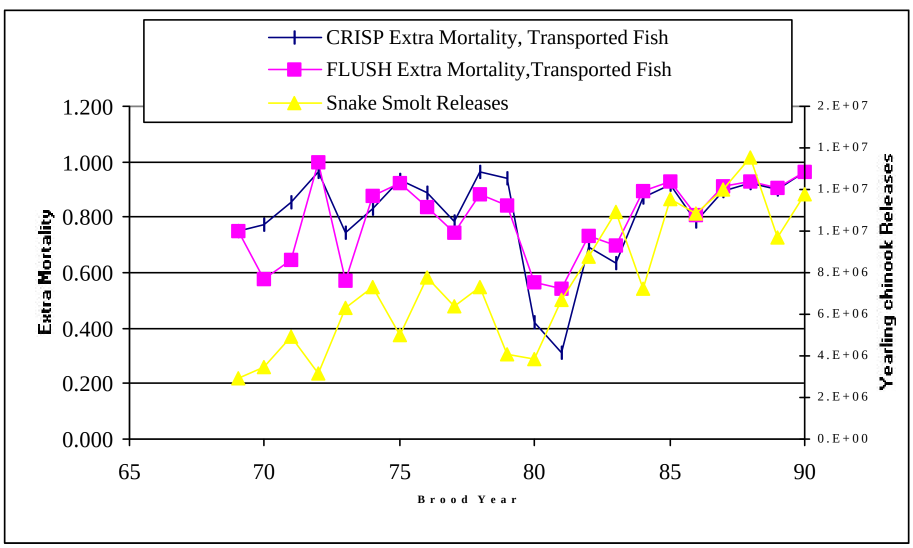


Figure 2. Delta Model Extra Mortalities and Hatchery Releases, 1952-90, No Detrending.

2a. Inriver Migrants



2b. Transported Fish



2c. Total

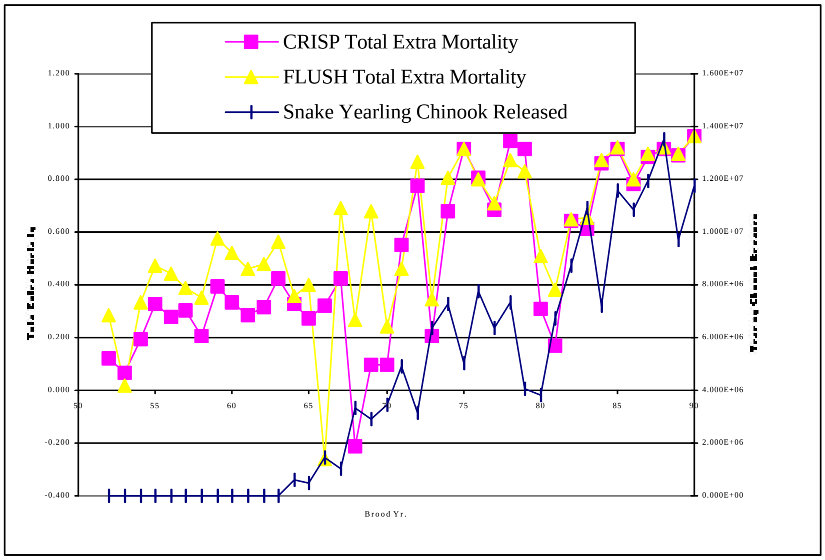
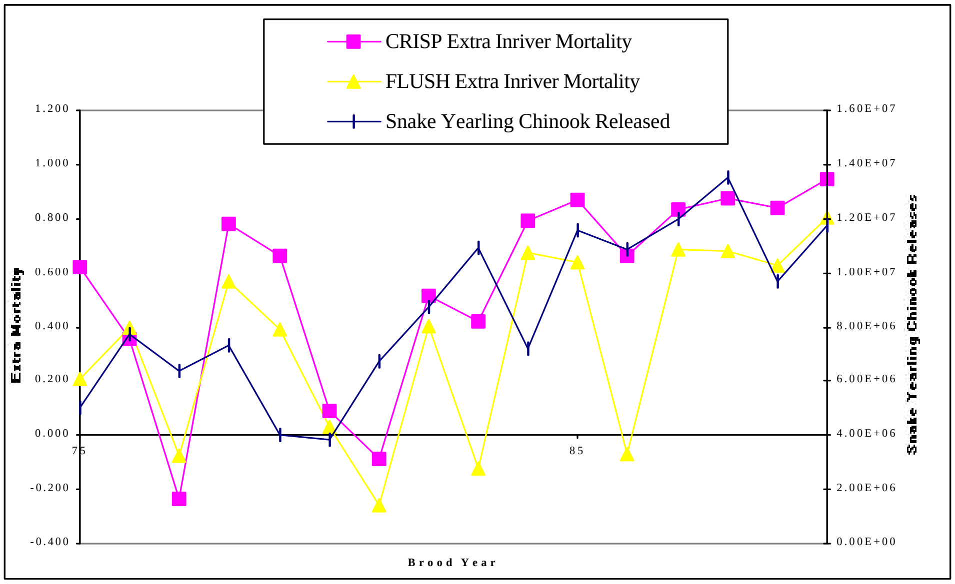

CRISP Total Extra Mortality
FLUSH Total Extra Mortality
Snake Yearling Chinook Released
1.200
1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
1.600E+07
1.400E+07
1.200E+07
1.000E+07
8.000E+06
6.000E+06
4.000E+06
2.000E+06
0.000E+00
50
55
60
65
70
75
80
85
90
Brood Yr.

Figure 3. Delta Model Extra Mortalities and Hatchery Releases, 1975-90, No Detrending.

3a. Inriver Migrants



3b. Total

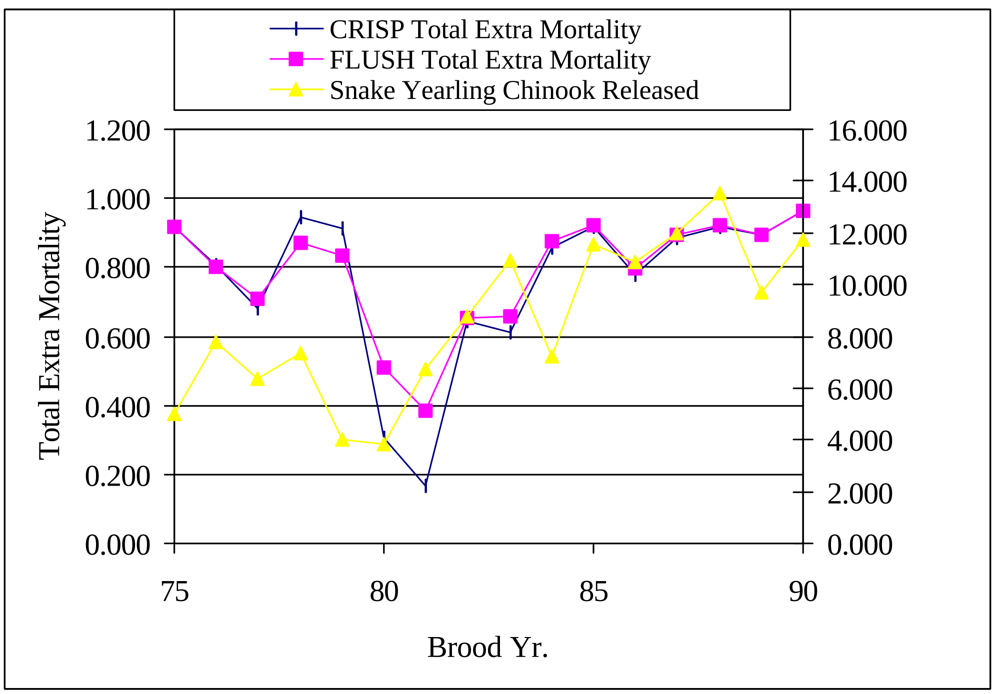
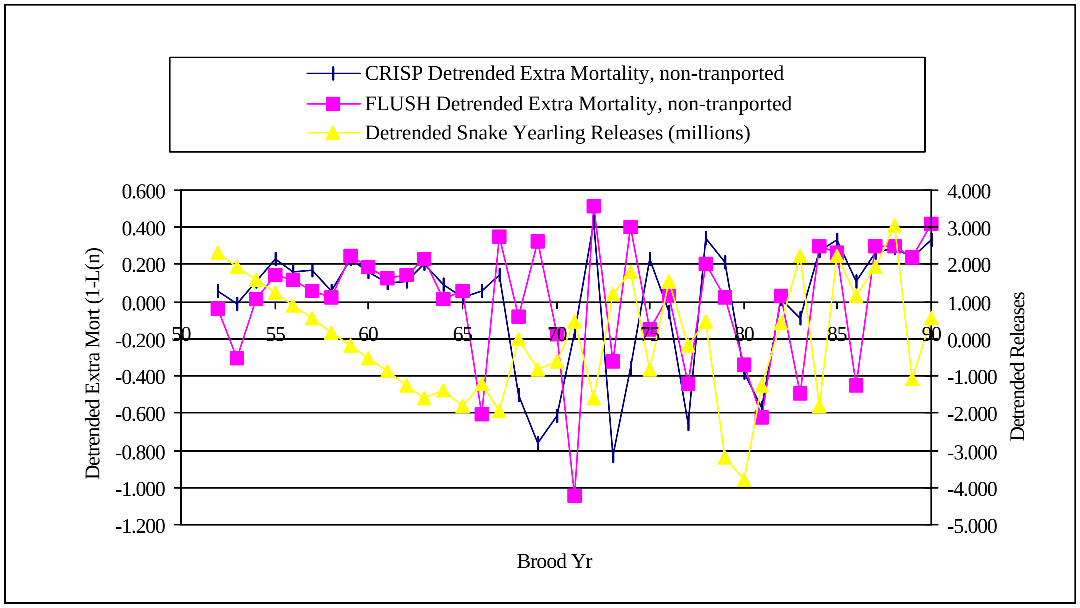
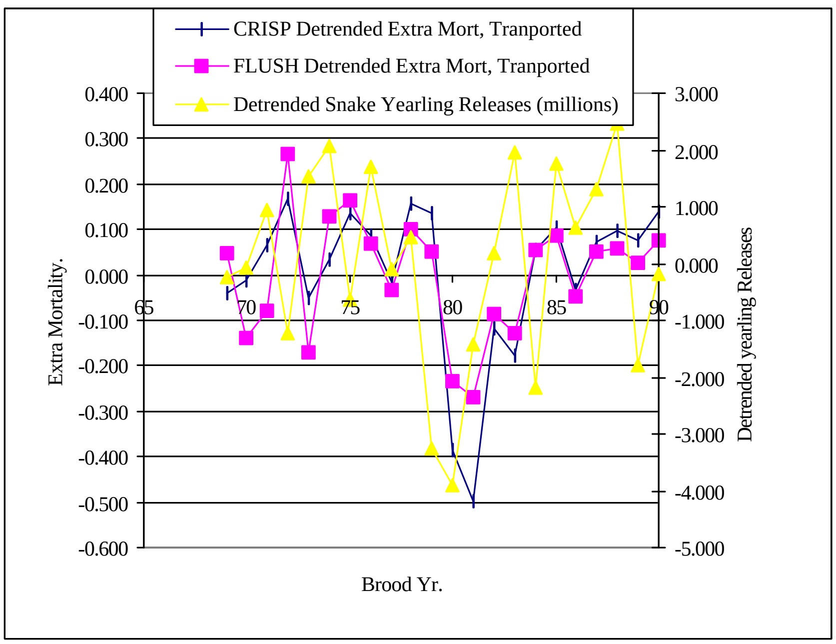


Figure 4. Delta Model Extra Mortalities and Hatchery Releases, 1952-90, Detrended.

4a. Inriver Migrants



4b. Transported Fish



4c. Total

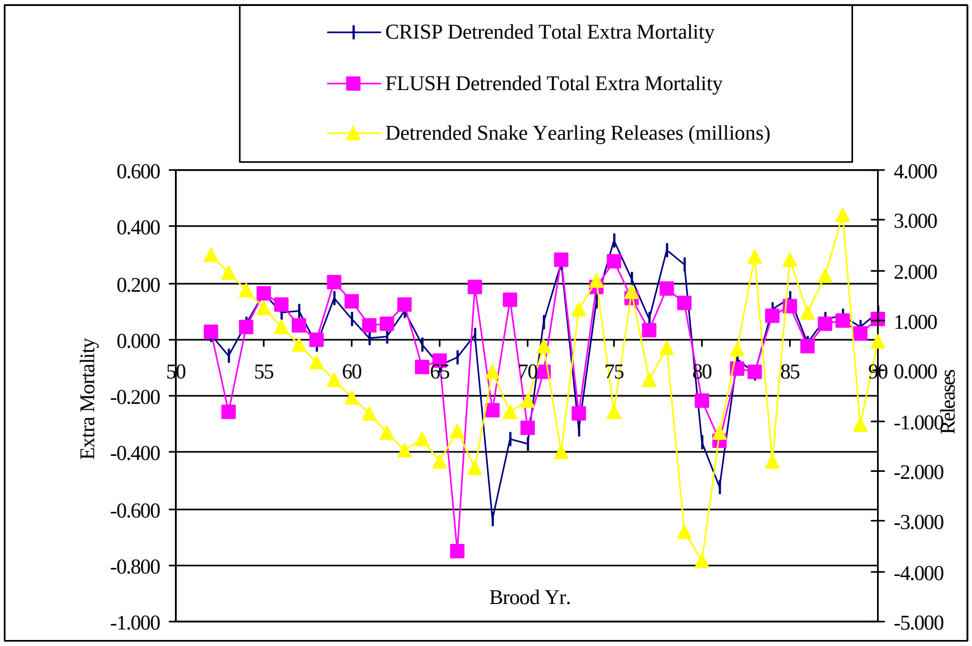
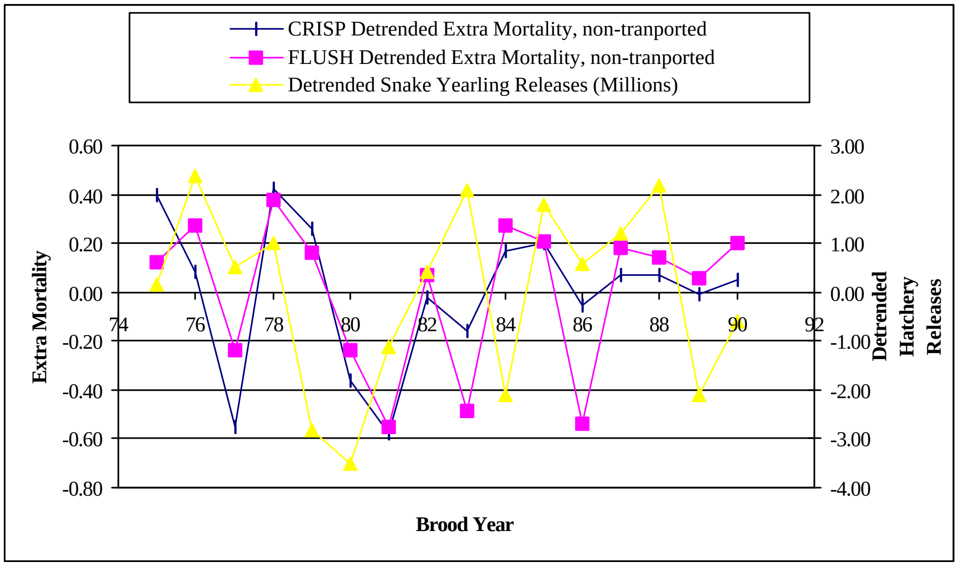

CRISP Detrended Total Extra Mortality
FLUSH Detrended Total Extra Mortality
Detrended Snake Yearling Releases (millions)
Extra Mortality
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
-0.800
-1.000
Releases
4.000
3.000
2.000
1.000
0.000
-1.000
-2.000
-3.000
-4.000
-5.000
50
55
60
65
70
75
80
85
90
Brood Yr.

Figure 5. Delta Model Extra Mortalities and Hatchery Releases, 1975-90, Detrended.

5a. Inriver Migrants



5b. Total

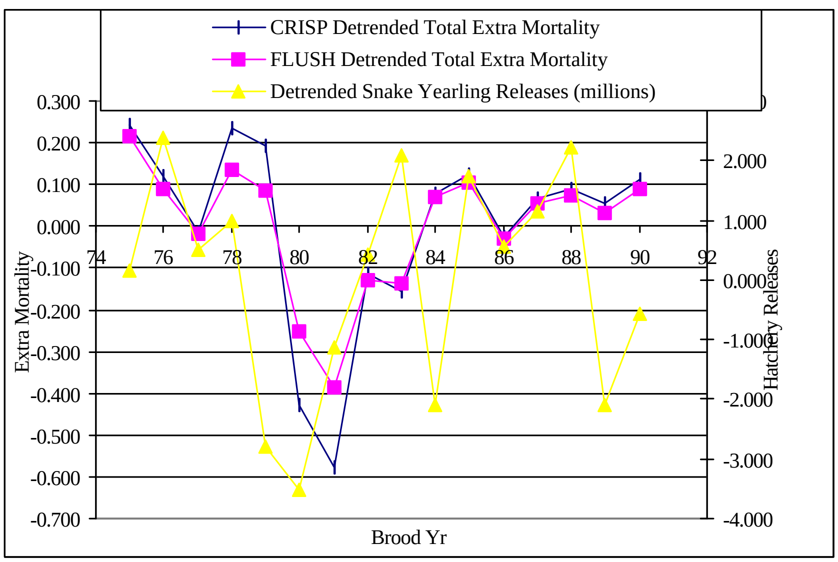
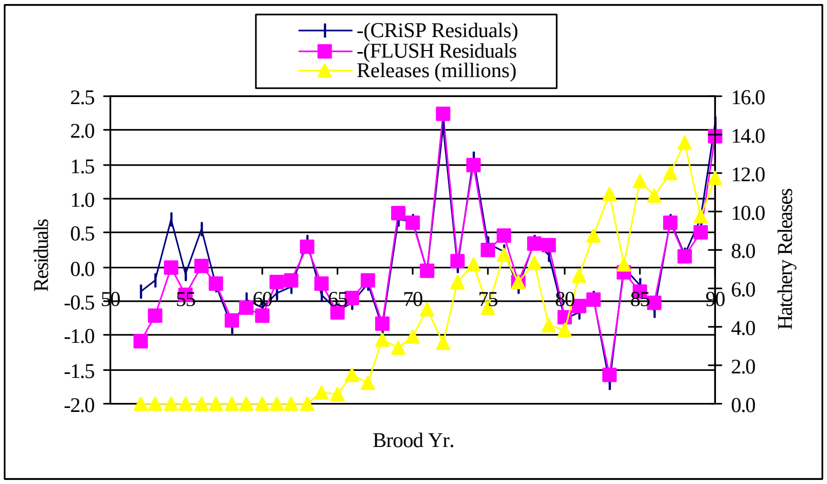
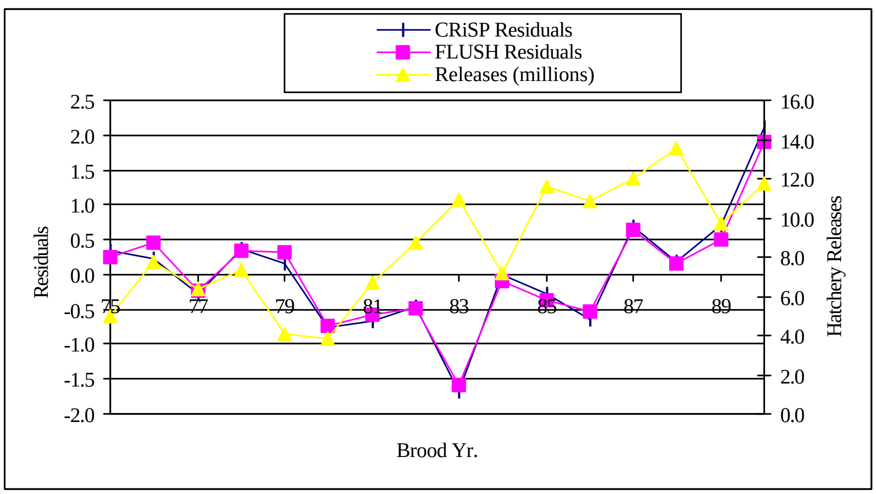


Figure 6. Alpha Model Residuals and Hatchery Releases

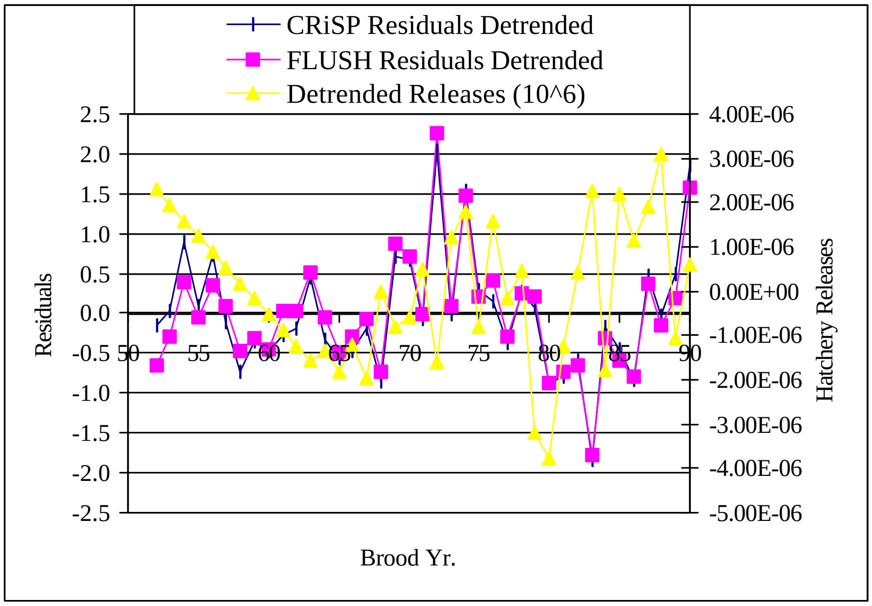
6a. 1952-90, no detrending



6b. 1975-90, no detrending



6c. 1952-90, detrended



6d. 1975-90, detrended