Prospective analysis for the alpha model

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This paper details a model (alpha model) used to analyze factors contributing to the decline of Columbia River spring chinook (retrospective analysis) and evaluate options for stock recovery (prospective analyses). The alternative model framework developed by Wilson Schaller, Weber and Petrosky (19970 we will refer to as the *delta model* in that it attributes the same climate effect to upstream and down stream stocks through δ. The α model described herein is an extension of the model proposed by Deriso et al. (1996), which was modified to better represent specific passage issues that may be used in stock recovery options and to articulate hypotheses on the competing impacts of the climate and post-Bonneville Dam impacts of the hydrosystem. The paper presents two hypotheses for stock decline: (H1) a hydrosystem caused decline and (H2) a climate caused decline.

Stock Recruitment equation

The alpha model is based on a Ricker stock-recruitment model using both stock-recruitment data and smolt passage survival estimated by a juvenile passage model. The model separates mortality factors into five components: a despensation factor, a density independent survival factor, a density dependent survival factor, a juvenile passage mortality, the remaining additional mortality from natural and anthropogenic causes, and an error term. The equation can be applied to a single region such as the endangered wild Snake River chinook. The equation is

$$\ln \mathrm{R}_{y,\,i} \;=\; (1+p)\ln S_{y,\,i} + a_i - b_i S_{y,\,i} - M_{y,\,i} - \alpha_{y,\,j} + \varepsilon_{y,\,i} \tag{1}$$

where

- y = brood year, i = stock
- j = region, 1 = Snake river, 2 = Lower Columbia, 3 = Mid Columbia
- $R_{y,i}$ = observed returns of stock i in brood year y
- $S_{y,i}$ = observed spawning population of stock i for brood year y
- $M_{y,i}$ = log of juvenile passage survival from tributary or head of Lower Granite pool to Bonneville dam tailrace of stock i for brood year y estimated from passage model
- a_i = Ricker density independent parameter for stock i
- b_i = Ricker density dependent parameter or stock i
- p = depensation parameter (p >0)

$\alpha_{y,j}$ = additional mortality factor for region *j* which by definition sums to zero over the data set

$\varepsilon_{y,i}$ = normally distributed mixed process and recruitment measurement error

(In the following work most parameters have year and region subscripts that are deleted unless required to distinguish specific regional or yearly measures.)

Note that the productivity parameters, a_i, includes effects of the hydrosystem and climate. Extracting these effects to estimate the true intrinsic productivity requires that we develop hypotheses on how these factors affect alpha. Also note this model is different from the delta model in that it need have not assumed common year effect between regions. To proceed, we define the elements in the additional mortality term, alpha. We apply the alpha model to stocks from three regions: the Snake River, the Lower Columbia and the Mid Columbia as illustrated in Fig. 1. The delta model can only be applied to two regions, the lower Columbia and the Snake.

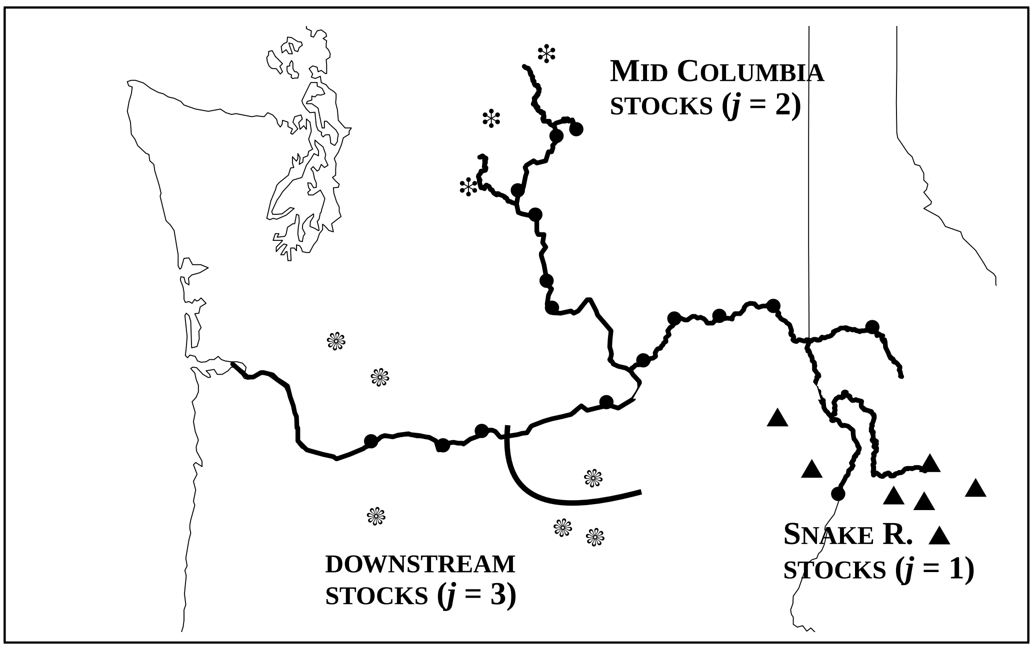

Fig. 1 Location of Snake (▲), Mid Columbia (✻) and Downstream stocks (❁).

A schematic of the mortality elements in eq(1) are illustrated in Fig. 2. Note that the direct hydrosystem mortality of fish travelling via various transport routes is defined as well as the portion of fish in Bonneville Tailrace that were from transport and non transport passage routes. More detail could be defined for the hydrosystem passage, but it is not required since our approach for post-hydrosystem mortality only categorizes stocks according to transport and nontransport origins. Also note that the additional mortality includes processes that occur in the estuary and ocean and reflects any differential differences of post-hydrosystem mortality of fish transported and not transported as juveniles. The definition of the stock and recruitment populations is for fish returning to Bonneville dam. The survival of adults through the hydrosystem was calculated outside the model and is reflected in the estimates of $S_{y,i}$ and $R_{y,i}$.

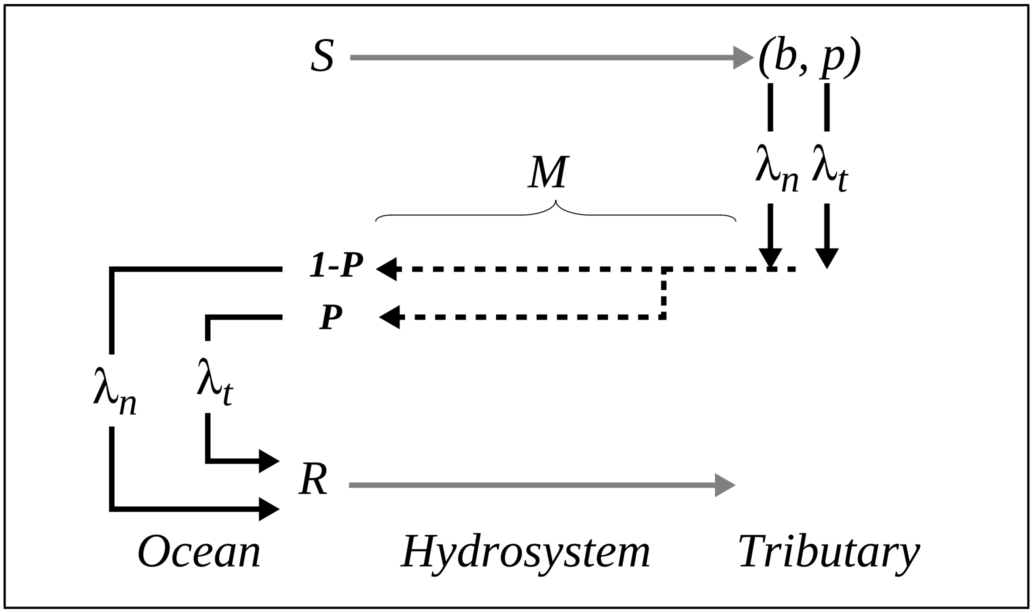

Fig. 2 Mortality factors for fish with transport and in-river juvenile migration paths. The solid lines represent stages affected by additional mortality. Dotted lines represent the juvenile hydrosystem passage state. Total juvenile mortality is M, and P is the fraction of juveniles in Bonneville dam tailrace that arrive through transportation. S and R are stock and recruitment numbers at Bonneville dam, respectively. Additional mortality of non transported and transported fish are designated λ_n and λ_t, respectively.

Model Equivalences and Constraints

An alternative form of the alpha model has been presented in PATH that includes the assumption of a common year effect. This model, denoted the *delta model,* takes the form

$$\ln \mathrm{R}_{y,\,i} \;=\; (1+p)\ln S_{y,\,i} + a'_i - b'_i S_{y,\,i} - M_{y,\,i} - \Delta m_{y,\,i} + \delta_y + \varepsilon'_{y,\,i} \qquad (1.a)$$

where

$\Delta m_{y,\,i}$= delayed mortality

δ_y = year affect

In this alternative model, the parameters for a given region rely on estimates of parameters from other regions. This model can be related to the alpha model described in eq(1). To begin, we must write the constraints of the two models, namely

$$\sum_y \alpha_{y,\,j} \;=\; 0 \qquad \sum_y \delta_y \;=\; 0\,, \qquad (2)$$

which are the constraints for eq(1) and eq(1.a), respectively.

Some further constraints have been imposed on the delta model, but we will discuss these later. Earlier numerical work by Deriso revealed that the estimates of the b parameters in the two models are similar. Therefore, subtracting equations (1.a) and (1) yields

$$0 = a_i - a'_i + \alpha_{y,j} - (-\Delta m_{y,i} + \delta_y) + (\varepsilon_{y,i} - \varepsilon'_{y,i}) \tag{3}$$

Taking the average of both sides of eq(3), and noting that the δs and the αs sum to zero over a given region gives

$$a_i = a'_i - \overline{\Delta m_i} \tag{4}$$

This demonstrates that estimates of the Ricker-a parameter in the two models differs by the average delayed mortality.

The relationship between the additional mortality components of the alpha and delta-model's can be obtained by substituting eq(4) into eq(3) to give

$$\alpha_{y,j} = \Delta m_{y,i} - \overline{\Delta m_i} - \delta_y + (\varepsilon_{y,i} - \varepsilon'_{y,i}) \tag{5}$$

for stocks i within region j. Given a one-to-one match between the parameters of the eqs (1) and (1.a) (i.e., additional constraints of the delta model are applied to the delta model below), the residuals of the two models will be the same, making the right hand error term zero.

<u>Additional constraints on the delta model</u>

As the delta and alpha models stand, they have more parameters than justified by the AIC or BIC, in fact, the delta model contains more parameters than observations. To solve this overparameterization difficulty, some constraints were added to the model parameters based on parameter estimates of the retrospective analysis in Chapter 5 by Deriso et al. (1996). These constraints are

$$\Delta m_{y,i} = n_{y,i}X + \mu_{y,j} - M_{y,i} \tag{6}$$

$$\mu_{y,j} = 0 \qquad \text{for } y \le 1969 \text{ or } j = 2 \tag{7}$$

The equivalences allow us to test a hypotheses stated within one model structure in the alternative model. Equivalent assumptions on the alpha model become:

$$\alpha_{y,j} + \overline{\Delta m_i} + \delta_y = \Delta m_{y,i} = n_{y,i}X + \mu_{y,j} - M_{y,i}, \tag{8}$$

which yields

$$\alpha_{y,j} = n_{y,i}X + \mu_{y,j} - M_{y,i} - (\overline{n_{y,i}X + \mu_{y,j} - M_{y,i}} + \delta_y), \tag{9}$$

where eq(7) is assumed to hold.

Difficulties with a further constraint on Δm.

The constraints detailed above allow one to reduce the number of parameters, but caution is warranted when imposing further constraints. For example, it has been suggested that the delayed mortality of the Lower Columbia River stocks is zero (i.e., $\Delta m_{y,i} = 0$ for the John Day, Warm Springs, Klickitat, and Wind stocks). The difficulty with this constraint is that eq(6) becomes

$$0 = n_{y,i}X + 0 - M_{y,i} \text{ (for Lower Columbia stocks),}$$

so that the passage mortality M is assumed to be equal to the dam mortality nX from the retrospective model. No such equivalence has been demonstrated, and is unlikely to hold, even approximately, since M varies with flow, temperature, and river operations, while nX does not. In reality, we must recognize that the Lower River stocks will suffer some delayed mortality due to lower river dam passage (the John Day Stocks, for example must pass three dams enroute to the ocean), just as the Snake River stocks are assume to suffer delayed mortality at these dams. To remedy this problem, we should not assume $\Delta m_{y,i} = 0$ for the Lower Columbia stocks, but simply approximate $\Delta m_{y,i}$ for the Lower Columbia stocks through eq(6), where $\mu_{y,j} = 0$ (for downriver stocks, j=2).

Additional mortality

Within the alpha model, assumptions on the cause of the decline of stocks and actions for their recovery will involve understanding the factors controlling the additional mortalities as expressed through the α terms for each region. The additional mortality is developed as follows. The term α expresses the additional mortalities (systematic region-specific and year-to-year mortalities not explained by the imbedded Ricker model or the passage models) from all sources and we must account for the possibility that juvenile salmon arriving below Bonneville in transportation and in-river migration routes experience different additional mortalities. We must also account for the offset created when we required that the alpha series each sum to zero. As we will show, this offset survival will change as we explore alternative hypotheses about the productivity of the stocks. The equation for alpha is

$$\exp(-\alpha) = (P\lambda_t + (1-P)\lambda_n)S_{offset} \tag{10}$$

where the following terms are region and year specific unless otherwise noted.

λ_n = survival factor for fish not transported as affected by the additional mortality factor

λ_t = survival factor fish transported as affected by the additional mortality factor.

P = fraction of the fish in Bonneville tailrace that were transported. Note the remaining fish in the tailrace arrived through the river passage route.

S_{offset} = survival offset resulting from setting sum of alpha to zero. log(S.offset) represents the decrease in average productivity of a stock due to the increase in delayed mortality caused by the development of the hydrosystem from 1952 to present. See eq(4) for its relations to the delta model.

Now taking the log of eq(10) we have

$$\alpha = -\ln(DP + 1 - P) + \alpha_n + a' \tag{11}$$

where

α_n = additional mortality of nontransported fish -ln(λ_n)

a' = mortality rate for the offset survival

$$a' = \ln(S_{offset}) \tag{12}$$

D = ratio of post-Bonneville survival of transported and nontransported fish is

$$D = \frac{\lambda_t}{\lambda_n} = \exp(\alpha_n - \alpha_t) \tag{13}$$

where

α_t = additional mortality of transported fish.

Because the sum of the αs is zero, we can calculate the offset mortality rate by summing eq(11):

$$a' = \overline{-\ln(DP + 1 - P)} + \overline{\alpha_n} \tag{14}$$

The intrinsic productivity is the productivity of a stock with the average effects of the post-1952 hydrosystem development and climate change removed. It is defined as

$$a_{\text{intrinsic}} = a + a' \tag{15}$$

Note that the $a_{\text{intrinsic}}$ is a measure of the Ricker *a* parameter without the influence of the average systematic change that occurred over the 39 years of observations. Also note that *a* is the average Ricker a over the 39 year period (with the effects of direct passage mortality removed) and *a*' is the average affect of the changes in productivity that occurred due to delayed mortality. The value of *a*' depends on how *D* and α_n are defined and how well they capture the effects on stock productivity of the changes in the dams, trends in climate and any other factors that do not have a cyclic nature on stock productivity over the period of observation. It follows then that *a*' is a measure of the actual productivity decrease that has occurred over the period of observations due to an increase in delayed mortality.

The complete equation defining the relationship between the additional mortality terms can be expressed as

$$\alpha = -\ln(DP + 1 - P) + \alpha_n + \overline{\ln(DP + 1 - P)} - \overline{\alpha_n} \tag{16}$$

or in alternative form,

$$\alpha = -\ln(\exp(\alpha_n - \alpha_t)P + 1 - P) + \alpha_n + \overline{\ln(\exp(\alpha_n - \alpha_t)P + 1 - P)} - \overline{\alpha_n} \tag{17}$$

Hypotheses on the impacts of the hydrosystem, transportation, and climate are contained within the definitions of α_n and D or α_t. Hypotheses on the alpha terms are discussed below. Unfortunately, the equations are nonlinear except when $\alpha_T = \alpha_n$, or $P = 1$, or $P = 0$. Also note that the equation for alpha can be used in the stock-recruitment equation (eq(1)) as long as the α_n and α_t terms are themselves defined by hypotheses with reduced parameters.

Before exploring hypotheses on the alpha terms we briefly discuss how we can weigh alternative hypotheses. One approach is to determine AIC and BIC measures from eq(1) with eq(17) included. A second test is to define transport-to-control ratios and compare the predicted ratios to observed. For this second test we require definitions of the TCR ratio. This is detailed next.

TCR definition

An important test measure is the transport-to-control ratio (TCR). Its definition is somewhat complex because some control fish (used to measure the effectiveness of transportation) were collected and transported at down river dams. To develop the relationship note the definition

$$\Phi = \frac{\lambda_t}{\lambda_c}\frac{R_t}{R_c} \tag{18}$$

where

R_c = survival of control fish from release point to Bonneville trailrace.

R_t = survival of transported fish from collection to release in Bonneville trailrace.

λ_t = survival for transported fish affected by the transport additional mortality factor

λ_c = survival for control fish affected by an mixture of transport and in-river additional mortality factors.

Φ = transport-to-control ratio of for a specific year from a transport experiment

The term λ_c is further defined in terms of the fraction of control fish that were transported. The equation is

$$\lambda_c = \lambda_t f + \lambda_n(1 - f) \tag{19}$$

where

f = fraction of control fish in Bonneville tailrace that were transported there and is obtained from passage model results of the transportation experiments.

Now noting the definition D in eq(13) the Φ ratio can be expressed

$$\Phi = \frac{R_t}{R_c} \cdot \frac{D}{1 - f(1-D)} \tag{20}$$

To a first approximation, we can assume that $f = 0$, so that Φ can be expressed

$$\Phi = \frac{R_t}{R_c} D \ . \tag{21}$$

Stating Hypotheses on α_n and α_t

To define hypotheses on factors controlling the additional mortality, we can partition the transport and nontransport alpha series into components. Since ultimately decisions will be made on processes over which we have some control, we need to distinguish mortality factors that can potentially be controlled from factors that are affected by environmental variations and are uncontrolled. In this way we can formulate hypotheses on each category of factors and systematically proceed to test differing combinations of hypotheses. These hypotheses are the Level 3 hypotheses as originally conceptualized in the PATH structure.

We identify environmental and anthropogenic hypotheses and express the combinations through the equations

$$\begin{aligned} \alpha_n &= \alpha_A + \alpha_E \\ \alpha_t &= \alpha_B + \alpha_E \end{aligned} \tag{22}$$

where

α_A = additional mortality associated with in-river passage

α_B = additional mortality associated with barging

α_E = additional mortality associated with environmental factors

This partition of factors may become partially mixed under some hypotheses but in general, we can partition mortality factors into these categories. Hypotheses testing then involves testing different combinations of each. Note also that by expressing hypotheses for the above components we define equations for α_n and α_t which then go into our system of equations defined by eq(17). In general we can define independent of hypotheses for river and barge passage effects and environmental effects.

Hydrosystem hypotheses

Individual hypotheses on the effects of the hydrosystem are expressed in terms of regression equations on α_A and α_B in eq(22). A number of hypotheses can be stated which have either an obvious ecological basis or are factors that exhibit a strong trend associated with the decline in stock productivity. Many possible factors affecting salmon production occurred coincidentally including: completion of the hydrosystem, development of storage reservoirs, the transportation system, and increased hatchery production. We need to explore each hypothesis alone and in combination with others. The basic hypotheses with either strong correlative or ecological bases are described in Table 1. A distinguishing characteristic of these hypotheses is that all have anthropogenic causes and, to some degree, can be altered to affect fish recovery.

Table 1 Level 3 Hypotheses on post hydrosystem mortality of transported and nontransported fish. VAR designates the covariate in equation. # designates specific hydrosystem (A) and barge (#) hypotheses numbers. Hypotheses on environmental factors which act on both passage routes are designated E.

	#	VAR	Description
Nontransported Fish Hypotheses	A1	X_n	nontransport mortality proportional to the number of dams passed
	A2	J_n	nontransport dependent on arrival timing of non-transported fish to the estuary
	A3	H	nontransport mortality proportional to hatchery fish population in region
	A4	W	nontransport mortality proportional to water travel time
	A5	R_n	nontransport mortality proportional to direct hydro-system nontransport mortality
Transported Fish Hypotheses	B1	X_t	transport mortality proportional to the number of dams passed
	B2	J_t	transport mortality related to arrival timing of trans-ported fish to estuary
	B3	H	transport mortality proportional to hatchery fish population in region
	B4	W	transport mortality proportional to water travel time
	B5	R_n	transport mortality proportional to direct hydrosys-tem nontransport mortality

Environmental hypotheses

We envision three general environmental hypotheses that can be paired with hydrosystem hypotheses. As outlined in Table 2, E1 assumes a common environmental factor characterized by the lower river stocks. This is essentially the delta hypotheses developed in Deriso et al. (1996). E2 is a new hypotheses in which environmental fluctuations for each region are different. E3 states that each region has an independent random environmental variation characterized by a standard deviation and mean. The environmental factors are largely uncontrollable, but long term trends may be partially predicted. Details for each are discussed below.

Table 2 Level 3 Hypotheses on environmental variations acting on both transport and non transport passage routes. VAR designates a covariate in the regression equation. The symbol # designates specific hydrosystem hypothesis numbers.

	#	VAR	Description
Environment Hypotheses	E1	α_2	Regions have common environmental factor characterized by variation in lower Columbia region
	E2	E, F, G	Regions have independent environmental factors characterized by ocean, flow and climate variables
	E3	0	Random environmental factor

E1: ***Lower river environmental hypotheses.*** The assumption of a common environmental effect developed by Deriso et al. (1996) can be stated as an alternative hypothesis. This year effect can be estimated using information from two or three regions. From the analysis of the equivalences of the alpha and delta models, the common climate factor in the Deriso model, δ, is closely related to the lower river α in the alpha model. From the section on Model Equivalence we can then express the climate effect as the lower river climate factor which becomes

$$\alpha_E = \alpha_2 \tag{23}$$

An important result from this analysis is that the Deriso model does not express a pure common climate effect. In fact, because of the changing length of data streams and hydrosystem conditions over the 39 years is difficult to extract a representation of a environmental affect. It is not clear that we would gain any significant knowledge by developing a mathematically correct estimation of the actual common climate factors even if it could be done without strong assumptions. The hypotheses E1 serves to characterize a situation in which the upper river region experiences that same low variation to climate that was evident in the lower river region. This assumption was made in early analysis and is worth carrying forward to provide a lower bound on the impacts of climate.

E2: ***Flow ocean environmental hypotheses.*** The second environmental hypothesis assumes that the effects of climate are specific to each region but that they can be characterized by reduced water availability which is expressed by flow and an ocean/climate factor. In this hypothesis, the impact of river flow is expressed as an inverse function of flow. This can result when the estuary/nearshore habitat mortality rate decreases with the increasing size of the freshwater plume, which is proportional to river flow. The hypothesis also assumes that ocean processes affect the plume predator-prey dynamics may also be scaled by the inverse of river flow. The affect of the environmental index is assumed to be nonlinear to a second order. This is based on the observations that the response of salmon productivity to climate indicators is a nonlinear function of latitude of the spawning stream. In general, Alaska and the West Coast stocks vary inversely to each other in response to shifts in climate A number of ocean/climate indicators can characterize the climate since many if all of them have a significant degree of correlation. For our analysis we choose a pure ocean index the terminal latitude of the drift of a water parcel released from ocean station Papa on January 1. This has been computed for a hundred year record using the OSCURS ocean circulation model (Ingraham, Ebbesmeyer, and Hinrichsen, 1997). An index may be included to characterize effects of droughts on egg to smolt survival. A suggested equation characterizing these environmental relationships is

$$\alpha_E = c_1 \frac{1}{F} + c_2 \frac{E}{F} + c_3 \frac{E^2}{F} + c_4 G \tag{24}$$

where all parameters have inferred year index and are defined

c_i = coefficients characterizing the contribution flow and climate indices on post hydrosystem additional mortality

E = ocean/climate index taken as a 5 year running average of PAPA ocean drift

F = river flow during estuary entrance of fish

G = drought index for each region

E3: *Random environmental hypotheses*. A third environmental hypothesis assumes that the effects of climate are random with no discernible systematic pattern. Under this hypotheses we set

$$\alpha_E = 0 \tag{25}$$

and the random variations in environmental effects are expressed through ε which is characterized by a zero mean and a standard deviation.

Aggregate hypotheses

From the individual hypotheses we can create a matrix that expresses aggregate hypotheses (Table 3). Possible combinations of hydrosystem hypotheses are given in terms of α_A and α_B. These, in turn, are combined with hypotheses on environmental factors E1, E2 or E3. In this way, a given aggregate hypotheses contains anthropogenic and environmental components. Essentially redundant, confounded, or mutually exclusive combinations of hypotheses can be ignored when evaluating the possible compound hypotheses. We believe that simple hydrosystem and ocean-based hypotheses will be inadequate to explain the changes that have occurred in productivity in the Snake/Columbia system. But to illustrate the approach and extremes, hypotheses representing ocean and hydrosystem causes of stock decline are illustrated as H1 and H2 in Table 3. To investigate the best hypotheses for a prospective analysis, plausible alternative compound hypotheses that reflect all possible factors must be described and evaluated. An approach for retrospectively evaluating hypotheses is discussed below.

Table 3 A matrix categorizing possible compound hypotheses on barge and river transport post hydrosystem mortalities. See Table 1 for hypothesis definitions. Heavy shaded cells are redundant, confounded or excluded combinations. Light shaded cells represent asymmetrical responses between passage routes. Hypotheses H1 and H2 illustrate the approach for extreme points of view.

			River Passage Hypotheses				
	VAR		X_n	J_n	H	W	R_n
		#	A1	A2	A3	A4	A5
Barge Passage Hypotheses	X_t	B1					
	J_t	B2		H2			
	H	B3					
	W	B4					
	R_n	B5					H1

Applying the symmetrical passage hypotheses(i.e. barge and in-river passage fish experience the same types of mortality processes) combinations of hydrosystem and environmental hypotheses are illustrated in Table 4.

Table 4 A matrix categorizing possible aggregate hypotheses on hydrosystem and environmental post hydrosystem mortalities. See Table 1 for hypothesis definitions. Hypotheses H1 and H2 illustrate the approach for the extreme points of view.

			Hydrosystem Hypotheses				
	VAR		X	J	H	W	R
		#	A1/B1	A2/B2	A3/B3	A4/B4	A5/B5
Environmental Hypotheses	α_2	E1					H1
	E,F,G	E2		H2			
	0	E3					

H1: *Hydrosystem hypothesis*. Assuming that post-Bonneville mortality is a function of the direct passage mortality passed during juvenile migration we have a pure hydrosystem response based on hypotheses A1 and B1

$$\begin{aligned} \alpha_n &= -a_1 \log(R_n) + \alpha_E \\ \alpha_t &= -b_1 \log(R_n) + \alpha_E \end{aligned} \tag{26}$$

and an environmental response based on E1

$$\alpha_E = \alpha_2 \tag{27}$$

where

a_1 = delayed mortality factor induced by passing a dam

b_1 = delayed mortality factor from transportation

R= number of dams fish pass

α_E = environmental variations as stipulated by hypotheses E1, E2 or E3

This equation assumes that hydrosystem effects can be related to the survival of fish that have passed through the hydrosystem. This hypotheses is similar to the one proposed by Wilson et al. (1997). The rationale for the hypotheses assumes that the hydrosystem affects the ability of both in-river and transport fish to survive salt water entry. Possible mechanisms include saltwater entry timing poorly synchronized with smoltification, stress induced by holding, handling, and release of transport fish, and dam passage of in-river migrants, disease and additional exposure to predators. A common environmental factor is assumed to affect fish and this is characterized by the environmental response of the lower stock.

H2: *Ocean-Arrival time hypothesis*. A second illustrative hypotheses characterizes the additional post Bonneville mortality in terms arrival time of fish to the estuary and ocean variations that are region specific fish. The equation has a hydrosystem response based on A2 and B2 giving

$$\begin{aligned} \alpha_n &= a_2 J_n + \alpha_E \\ \alpha_t &= b_2 J_n + \alpha_E \end{aligned} \tag{28}$$

and environmental variation based on E2 is

$$\alpha_E = c_1 \frac{1}{F} + c_2 \frac{E}{F} + c_3 \frac{E^2}{F} \tag{29}$$

where all parameters have inferred year and region indices and are defined as

a_i = coefficients for contribution to additional mortality in non transported fish

b_i = coefficients for contribution to additional mortality in transported fish

c_i = coefficients for environmental contribution to additional mortality

J_n = Julian day of arrival of in-river to estuary

J_t = Julian day of arrival of transport fish to estuary

F = flow at Bonneville or Astoria

E = Climate indicator such as the Station Papa drift

α_E = environmental variations as stipulated by hypotheses E1, E2 or E3

This equation is based on the work of Hinrichsen et al. (1997) which has demonstrated from a survival index of transported fish that the survival changes over the transport season and in general the later fish are transported to into the estuary the greater their survival. The underlying mechanism proposed is that higher survival in the estuary and freshwater plume requires the onset of the spring upwelling on the coast. This hypotheses assumes no additional or delayed stress in-transportation or in- river passage as is expressed in hypothesis H1. The environmental hypotheses assumes that each region experiences its own environmental response as noted above.

Evaluating Aggregate Hypotheses on α_n and α_t

Testing the hypotheses involves first estimating the hypothesis equations (a_i, b_i, c_i) and then evaluating the resulting models in terms of multiple criteria: (1) the residuals ε of eq(1) or eq(13) and the number of parameters to give AIC and BIC scores, (2) a comparison of predicted transport-to-control ratios Φ, (3) a comparison of predicted to observed smolt-to-adult ratios, (4) agreement or differences of hypotheses applied to the three regions in accordance to the similarities and differences in the regions and finally 5) the ranking of hypotheses on their ecological foundation. At least two hypotheses will be carried in the prospective analysis representing the best formulations of the competing belief systems. The statistical basis of the evaluation is expressed

$$\ln R_{y,i} = (1+p)\ln S_{y,i} + a_i - b_i S_{y,i} - M_{y,i} - \alpha_{y,j} + \varepsilon_{y,i} \tag{1}$$

$$\alpha = -\ln(DP + 1 - P) + \alpha_n + a' \tag{11}$$

$$D = \exp(\alpha_n - \alpha_t) \tag{13}$$

$$a_{\text{intrinsic}} = a + a' \tag{15}$$

$$\Phi = \frac{R_t}{R_c} \cdot \frac{D}{1 - f(1-D)} \approx \frac{R_t}{R_c} \cdot D \tag{20}$$

$$\begin{aligned} \alpha_n &= \alpha_A + \alpha_E \\ \alpha_t &= \alpha_B + \alpha_E \end{aligned} \tag{22}$$

where hypotheses equations are expressed for α_A, α_B and α_E.

The system can be expressed as a nonlinear regression based on eq(1) or we can extract out the α series for each region using eq(1) and express a nonlinear regression of the alpha streams based on eq(11). In the second approach an error term is added to eq(11). We will consider for the moment the second approach where α stream are determined for each region conditioned on the passage model parameters *M* but otherwise the streams independent of any other hypotheses on the system. In this framework we investigate hypotheses on the causes of the additional mortality terms as expressed by α streams.

The nonlinear regression equation to consider is

$$\alpha = -\ln(DP + 1 - P) + \alpha_n + a' + \varepsilon \tag{30}$$

In this approach we fit equation coefficients a_i, b_i and c_i to the α using information on *P*. We can calculate AIC and BIC for each hypotheses using the number of parameters in the hypotheses and the residuals ε. As additional tests of hypotheses, the model predicts a transport-to-control ratio Φ which can be compared to observed Φ through a χ^2 test and using eq(1) smolt-to-adult ratios (SAR) predictions can be compared to observed SARs.

Confounded variables

Because the analysis can be conducted independently for each region (the lower- and mid-Columbia and the Snake), we seek hypotheses that reflect the similarities and differences across the three regions. In particular, hypotheses that are valid for the mid-Columbia and Snake regions will be of particular value since the hydrosystem has not changed appreciably in the mid-Columbia while it did in the Snake and both regions experienced similar declines in productivity. In general, a comparison of the three regions will help to resolve the effects of confounding variables. That is, variables that experienced coincident changes over the stock recruitment record in one region did not necessary experience the same pattern in another region. Changes in variables over years and over regions are illustrated in Table 5. A comparison of the hypotheses between regions may help resolve hypotheses that are confounded because changes in variables are similar over years. The problem of variable confounding may be significant in the Snake Region since all major variables on which hypotheses have been proposed experienced significant changes over the 39 year record. By comparison of the Snake region hypotheses to the Columbia region hypotheses it may be possible to resolves dominant from subordinate processes.

Table 5 Changes of variables over years and regions can help resolve confounded variables within a region. The ranking of the relative change over time of variables over regions is illustrated below where 0 = no change, 1 = smaller change, 2 = larger change in a variable.

Variable	Variable affected	Lower Columbia	Mid Columbia	Snake
Number of dams	*X*	0	1	2
Hatchery Production	*H*	1	2	2

Table 5 Changes of variables over years and regions can help resolve confounded variables within a region. The ranking of the relative change over time of variables over regions is illustrated below where 0 = no change, 1 = smaller change, 2 = larger change in a variable.

Variable	Variable affected	Lower Columbia	Mid Columbia	Snake
Storage Reservoirs	*F*	1	2	2
Fish Transportation	*P*	0	1	2
Climate	*E, F, G*	1	2	2

Specific sub-hypotheses about what has affected salmon productivity might be addressed in terms of the statistical properties of the hypotheses regression coefficients estimates of the regression coefficients α_n, $\alpha_t$and $\alpha_E$equations as in eqs (28) and (29). A number of specific hypotheses addressing differences between regions are expressed below for H2.

H2-1: Snake (1), lower (2) and mid (3) Columbia regions have common climate effects

$$c_{i,1} = c_{i,2} = c_{i,3}$$

H2-2: Flow variations are not significant in lower river stocks

$$c_{1,2} = 0$$

H2-3: Estuary arrival timing has no impact on lower river stock survival

$$a_2 = 0$$

<u>Ecological Rationale</u>

Ranking hypotheses on their ecological foundations is difficult if not impossible to do in a suitable quantitative manner. Such an approach can be of most use for distinguishing hypotheses that have similar statistical properties. Furthermore, stating the ecological bases of hypotheses will help identify studies that can distinguish competing hypotheses, and guide the design of future studies.

The hypotheses H1 and H2 presented as examples in this document have both have plausible ecological basis. H1 suggests that stress in all passage routes impacts survival post the hydrosystem. H2 suggests that with transportation fish have been released too early in the estuary and that there is also a larger response of the up-river stocks to climate variation. All mechanisms may in fact be operating and the real issue then is which ones dominate and which ones can be corrected. In our full analysis we need to explore further hypotheses such as the impacts of hatcheries and combined effects such as H1 and H2.

Prospective Analysis

Prospective analysis will be conducted on suitable hypotheses identified through Table 4. For the prospective analysis the important task is to identify quantitatively the impacts of anthropogenic alterations of the system and project, in probabilistic terms, the uncontrollable environmental factors and the uncertainty in the controllable recovery actions. The hypotheses A and B relating to the hydrosystem will be formulated in probabilistic terms based on the uncertainties of the regression coefficients developed in the retrospective analysis. The same approach can be used to characterize the environmental hypotheses E except that in this case we have uncertainty in the coefficients themselves expressed by c_i, plus the variation in the covariates such as *E* and *F*. The environmental variables under hypotheses E1 and E2 are expected to have an autocorrelation structure that may have spectral peaks at several periods. A number of studies suggest dominate cycles exist at 5, 18, and perhaps 60 years. Of these the decadal-scale cycle associated with a period of about 20 years is particularly important since any recover action horizon will cover a full cycle such as that associated with the climate regime shifts that occurred in 1977. Since the climate has cycles the degree to which the stocks are affected by the climate will affect probabilities of recovery. These factors have not been fully considered yet and will important in the full prospective analyses. Also important is how the climate cycles affect water availability to the hydrosystem and how this affects direct and indirect passage survivals. These issues are discussed below.

Models

The prospective analysis integrates three model systems as follows:

1. The hydroregulation model receives as input the unregulated flow time series (*U*) for each year designated as a "water year". Hydro operations scenario are also input to the hydroregulation. The hydroregulation model outputs hydrosystem flows, *F*.
2. The passage models, CRiSP and FLUSH, receive hydrosystem flows *F*, spill, and fish transportation operations and output total juvenile passage mortality *M* and the transport fraction *P*.
3. The alpha model eq(1) receives as input the passage survival *M*, alpha generated from eq(17).
4. Alpha generated from eq(17) receives the transport fraction *P* from the passage model and the α_t and α_n generated from hypotheses Hi.
5. The α_t and α_n depending on the hypotheses receive information from passage models, flow, *F* and climate indices *E* and *G*.

Correlation structure

Our proposed approach is to drive the correlation structure of the prospective analyses from the water years data used to generate the hydrosystem flows. This involves determining autocorrelation and correlations structures of a number of variables and using these structures to drive the outputs from the modeling system. The structure is described below.

Correlation structure of the variables can be determined independently as follows.

1. Determine autocorrelation structure for U with goal of expressing decadal scale variations.
2. From historical data correlate hydrosystem unregulated flows (U) with climate index E.
2. From an autocorrelation of the unregulated flows U, select the same correlation of hydroregulation flows F and the corresponding environmental index E. Use these series in the prospective analyses to generate M, α_t and α_n.

A list of the statistical information required for a prospective analysis is listed below means and standard errors of the parameter estimates for a_i, b_i, c_i autocorrelation properties over several decades for covariates E, F and α_2.

Final comments

The alpha model in its present form has the flexibility to investigate most if not all hypotheses put forward by PATH. The framework is a mathematical expression of life history pathways for stocks that experience a complex smolt passage history. The equations are a realistic description of the system and are free of strong assumptions. In a sense, the equations are the bookkeeping structure for tracking fish over their life history. To apply the alpha model, we must deal with a number of levels of hypotheses and data.

The primary hypothesis (model) is used to estimate stock and recruitment numbers from redd counts, which are the primary data. In general, the primary level data and hypotheses have been accepted without testing and are based on the belief that the existing data are adequate to demonstrate significant declines in the wild salmon stocks over the past four decades.

The second level hypothesis estimates passage mortalities M. These are generated from the passage models which involve a number of independent data sets. The passage model estimates can be tested against independent survival data being developed by the hydro subgroup of PATH.

A third level of hypotheses defines processes controlling the mortality outside the direct hydrosystem mortality. This delayed or additional mortality is expressed in terms of explicit mortality rate equations for transported and nontransported fish passage. All process hypotheses can be expressed by equations on α_N (the additional mortality for nontransported fish) and D (the ratio of the transported fish to nontransported additional survival). Process hypotheses are built from equations with measurable parameters characterizing hydrosystem operations, environmental variations, hatchery production and any other processes that are measurable and that potentially affect salmon survival. These are the third level data and they involve such measures as the number of dams and the number of hatchery releases. We will test third level hypotheses using several approaches. In a pure statistical approach, AIC and BIC measures can be generated for each process model. Criteria are also needed to test for confounding parameters. Finally, the process hypotheses all yield transport-to-control ratios (TCR) which can be compared to observed TCRs to provide one of the strongest tests of process hypotheses.

A fourth level of hypotheses involve testing for the interactions and relative importance of the processes. Here we address the statistical properties of the coefficients in the α_N and *D* equations. By addressing whether parameters are different from each other in the regions or different from zero, we can test, for example, whether there are common year affects between regions and whether transportation of hatchery fish affects survival of wild fish.

Hypotheses testing can proceed in a hierarchal manner. We accept primary hypotheses producing a common set of stock-recruitment data. At the second level we may generate at least two hypotheses on passage mortality. From these we generate two sets of alpha series for the mid and lower Columbia and the Snake regions. One series will be based on CRiSP, another on FLUSH. Once we have these time series we need not run the stock-recruitment model eq(1). We then can develop equations on α_N and *D* to explore alternative process hypotheses and test for significance and interactions of the processes through the statistical properties of the coefficients in the α_N and *D* equations.

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