Application of the Out-Migrant Survival Simulator using the SWARM modeling environment to study smolt-predator interactions

Modeling Support to Army Corps of Engineers Columbia River Fisheries Programs

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Project: CRiSP juvenile passage model development and calibration for alternative analysis of the Lower Snake River Juvenile Salmon Migration Feasibility Study (LSRFS)

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Project goals

The goal of this modeling exercise is to understand the sensitivity of certain assumptions regarding the behavior and interaction of smolts and their predators. We are interested to know whether fundamental behavioral attributes of predators and prey can be used to explain population level survival is observed in the field. When the key elements have been identified, we will apply the principles to an unknown and unstudied river condition (drawdown) in order to anticipate predator prey relationships.

Results of this exercise will include:

1. qualitative and quantitative descriptions of anticipated changes in smolt-predator interactions as a result of major changes in the hydrology of the Snake River (i.e. drawdown versus full pool)
2. sensitivity of changes in predator density, predator distribution and smolt mortality to a set of assumptions regarding predator behavior and environmental preferences
3. recommendations for incorporating these changes into CRiSP passage model
4. anticipation of the effects of drawdown on survival due to predation.

Process

1. Install both SWARM and the Out-Migrant Survival Simulator (OMSS) software at Columbia Basin Research. OMSS was prepared by a sub-contractor: Lang, Railsback and Associates (Steve Railsback and Steve Jackson).
2. Select sample reach in which to perform initial analyses and obtain hydrology data for this reach in both full-pool and drawdown states.
3. Analyze modeling assumptions regarding the distribution of predators, smolts and changes in predation as a function of changes in the environment or as a result of changes in the behavior of the fish. For example, this might include predator preferences for depth, distance from shore, velocity, temperature, etc.
4. Modify OMSS (mostly through model developers: Lang, Railsback and Assoc.) to accommodate these variables and changes in model operation.
5. Map the parameter space of these two models to facilitate translation of results from one model to the other. This is necessary because CRiSP is a population-based model and OMSS is an individual-based model.
6. Use currently available version of the CRiSP downstream survival model as a baseline and adjust OMSS parameters to replicate the survival and travel time seen in CRiSP for current full-pool scenarios, and minimize differences with data.
7. Explore sensitivity of smolt survival to predator behavior and distribution assumptions for full-pool scenarios.
8. Model smolt survival under drawdown scenarios using OMSS.
9. Map OMSS parameters to their CRiSP equivalents under drawdown.
10. Analyze survival results in terms of uncertainties regarding modeling assumptions.
11. Extend analysis to entire Snake River.

Background information pertinent to predation modeling

Predation modeling in CRiSP

The survival rate in CRiSP is applied per time step or per reservoir zone, according to the zone and model utilized. In general it is modeled as follows:

$$S = e^{-r}. \qquad \text{Eqn. (1)}$$

Predation occurs in three zones: main reservoir or river reach, forebay and tailrace. Each zone has its own predator abundances (which vary from project to project) and predator activity coefficients (which do not vary by project). In addition, two models are available for main reservoir predation: version 1.5, which assumes that predation mortality is a function of exposure time, and version 1.6, which assumes that predation mortality is a function of both exposure time and distance travelled (Anderson et al. 1999).

CRiSP predation (r) is a function of predator behavior, predator density and temperature. Generally this has the form:

$$r(t, X, T, P_{ij}) = \Phi(t, X) \cdot P_{ij} \cdot f(T) \qquad \text{Eqn. (2)}$$

where

t is time (days),
X is distance,
T is temperature (^0C),
P_{ij} is the predator density in the ith zone (forebay, tailrace, or reservoir) for the jth project.
$\Phi(t, X)$ is the predator behavior function (or term), and
$f(T)$ is the temperature response function.

The temperature response function is selectable with two forms currently available. The first form is an exponential and has traditionally been used in CRiSP:

$$f(T) = ae^{bT}. \qquad \text{Eqn. (3)}$$

Default parameter values are $a = 0.0818$, and $b = 0.2066$. This form is reasonable for the spring migration period where higher temperatures are not encountered.

The second form is a sigmoidal form (reparameterized from Vigg and Burley 1991):

$$f(T) = \frac{C_{MAX}}{1 + e^{(-s_T(T - T_{INF}))}}, \qquad \text{Eqn. (4)}$$

C_{MAX} is the maximum consumption rate,
s_T is a slope parameter,
T_{INF} is the inflection point of the curve.

With this equation predation rate reaches a maximal rate at higher temperatures. An example of equation (4) fit to data from Vigg and Burley (1991) is shown in Figure 1. The parameter values for this plot are $C_{MAX} = 8.0$, $\alpha_T = 0.40$, and $T_{INF} = 16.7$.

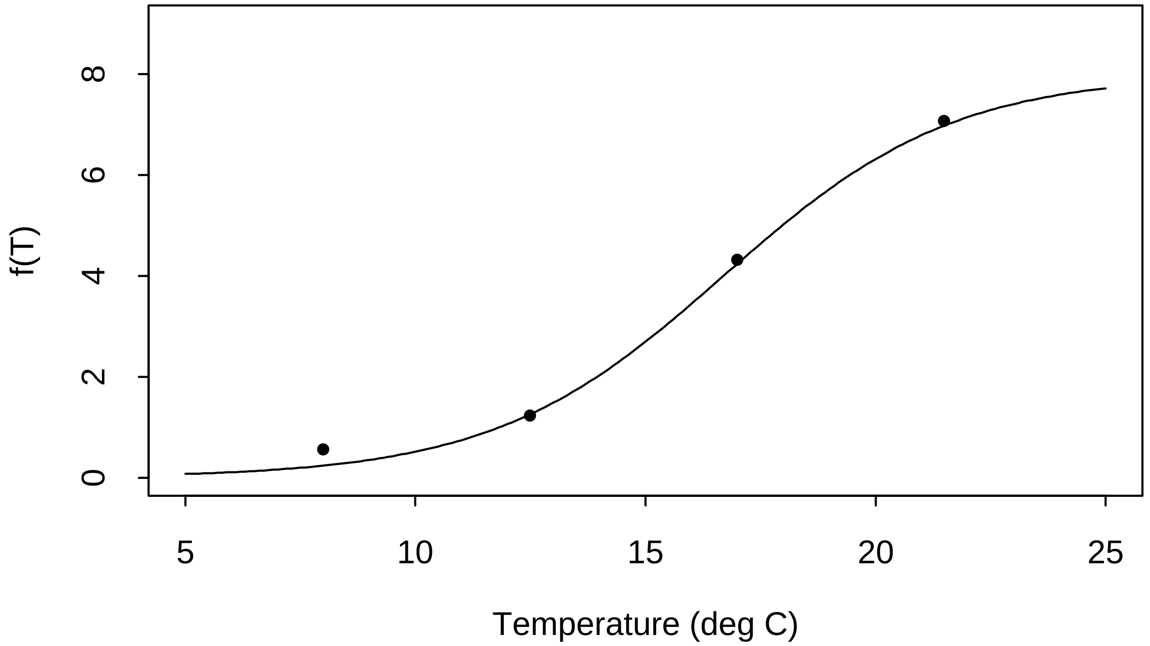


Figure 1: Eqn. (4) fit to data from Vigg and Burley (1991). Note that each point represents the mean from 11 to 22 replicates.

Predation rate is dependent on predator abundance but not on smolt abundance. Thus with a given predator density and temperature, mean predator consumption rate is linearly related to smolt abundance. This is consistent with data provided by Vigg (1988) except at extremely high smolt abundances (which represent only a few points out of hundreds). Also, the Vigg (1988) study was conducted in the tailrace. The CRiSP predation algorithm with the v1.5 reservoir model is very similar to the RESPRED model as described by Beamesderfer et al. (1990). The differences are that RESPRED has a type III functional response of predators on prey; i.e., consumption rate tails off at high prey abundances. Also, RESPRED uses a gamma distribution for the temperature response function instead of the sigmoidal one utilized by CRiSP.

Zone specific formulations of the predation model.

The specific form of Eqn. (1) varies according to reservoir zone (forebay, tailrace, main reservoir or river reach) and version of the model (v1.5 and v1.6). The major difference among the models is type of behavior exhibited by the predators. If predators roam over broad territories and are efficient at locating prey, this leads to a model where survival decreases with exposure time. This is the case with the v1.5 reservoir model and the forebay predation model. On the other hand, if predators are less mobile and exhibit “lie and wait” behavior where prey must enter their territory to be consumed, then the number of predators encountered (which is related to distance travelled) is important to survival rates. The tailrace predation model postulates this type of behavior. The v1.6 reservoir model allows for both types of behavior.

forebay and v1.5 reservoir

In both these cases, predation mortality is applied for each time step a fish is in one of these zones. The specific form of the predation is:

$$\Phi(t, X) = \alpha_i . \qquad \text{Eqn. (5)}$$

Here α_i is a constant that is specified for forebay or reservoir and does not vary per project.

tailrace

The equation that generates predation mortality in the tailrace is the same as the one presented above with an α_i specific to the tailrace. The difference is that for the tailrace, Eqn. (5) is applied only once as a cohort of fish moves through the tailrace.

v1.6 reservoir

There is both theoretical and empirical evidence for predation to be tied to both the exposure time and the distance traveled (Anderson et al. 1999 and Smith et al. 1998) so the activity of both the smolts and predators plays a role in the predation rate. This is a new method to be used in CRiSP v.1.6 on a "per reservoir" basis since it incorporates the time explicitly as:

$$\Phi(t, X) = \sqrt{\alpha_t t^2 + \alpha_X X^2} \qquad \text{Eqn. (6)}$$

Table 1: . Summary of the forms of the predation mortality rate equation

Reservoir zone	$\Phi(t, X)$	applied
forebay, reservoir v1.5	α_f, α_r	per time step
reservoir v1.6	$\sqrt{\alpha_t t^2 + \alpha_X X^2}$	per reach
tail race	α_t	per tailrace

Predation modeling in OMSS

Included here is a brief summary of predation modeling in OMSS version available mid-April, 1999. Details are provided in "Out-Migrant Survival Simulator Formulation" available from Lang, Railsback and Associates. The following rules apply to determine, during each time step whether a migrant is killed:

1. A migrant is killed if its path brings it within a predator's capture radius in three dimensions. There is one exception: if the predator is within the capture radius downstream of the migrant during that time step, the migrant is not killed.
2. Predator distribution is based on the density of the predators as specified in an input file and these are randomly placed in the simulation space with the correct number per square meter.
3. The depth of each predator is selected from a uniform random distribution between the minimum depth and the maximum depth specified in the input file.
4. Predators currently do not move.

Survival, as for the CRiSP model is then:

$$S = e^{-rt} \qquad \text{Eqn. (7)}$$

where

S is the proportion of the fish released that survive through the reach
t is the mean travel time required to pass through the reach
r is the survival rate parameter estimated by the model

This can be recast as:

$$r = -\frac{\ln(S)}{t} \qquad \text{Eqn. (8)}$$

if the parameter r stays constant throughout the simulation. Otherwise r_t is used and compared to r from CRiSP runs by using this formulation:

$$S = e^{-\left(\sum_{1}^{n} r_t \cdot \Delta t\right)} \qquad \text{Eqn. (9)}$$

thus the models are compared by noting:

$$\begin{aligned} r &= r_{CRiSP} \\ r &= \Phi(t, X) \cdot P_{ij} \cdot f(\hat{T}) \qquad \text{Eqn. (10)} \\ r_1 \cdot P_{ij} &= \Phi(t, X) \cdot P_{ij} \cdot f(\hat{T}) \end{aligned}$$

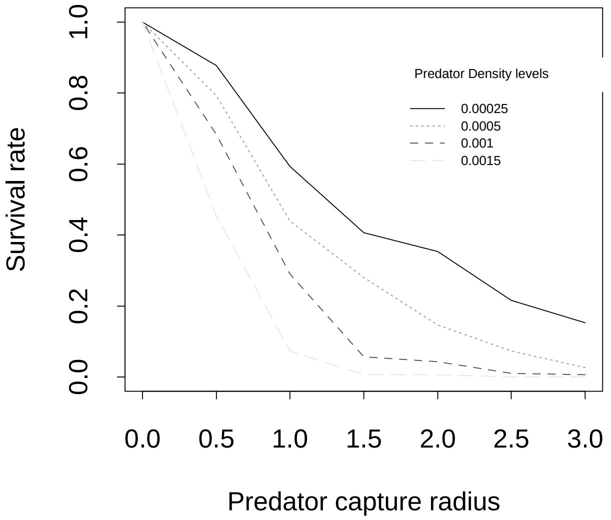
Since CRiSP allows for separate predator densities in the forebay, tailrace and interior of the reservoirs, then allowing $P_{ij} = P_{ijCrisp}$ gives $r_1 = \Phi(t, X)\ f(\hat{T})$. This is the essential relationship that must be explored.

Modeling $\Phi(t, X)$ ➔ $\alpha(t)$ with OMSS

The OMSS predation rate will have to be proportional to the CRiSP temperature response. Comparisons between OMSS and CRiSP runs will be made in single reaches at an assumed constant temperature $\hat{T}$ applied to each time step. Predation is then a function of the exposure time as in CRiSP v.1.5. The capture radius parameter of the individual predators will be allowed to vary, and the predation compared to CRiSP as a means to directly relate the capture radius to temperature. The magnitude of random movements of the prey (dispersion in CRiSP) will affect predation in OMSS but the true sensitivity of predation to this parameter will be assessed only after accounting for the extra time that individuals are exposed. Example output from OMSS showing the sensitivity of predation rate to predator capture radius at four different predator densities is shown in Figure 2.

Figure 1: Simulated survival of migrants as a function of the predator

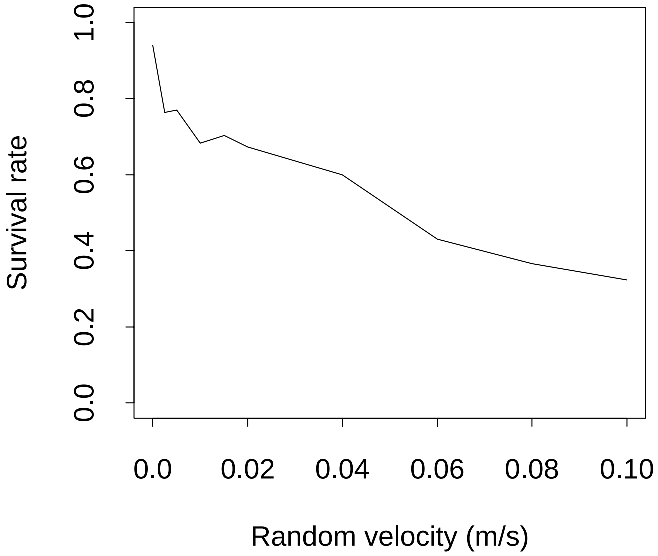
capture radius (m) at four different predator densities.



Modeling $\Phi(t, X)$ with OMSS

The more general model allows predation activity to vary with time and distance of exposure to predators. In OMSS, three key variables drive the predation rate: 1) random velocity of smolts, 2) random velocity of predators and 3) effective predation radius. The simplest approach is to allow the predator capture radius to be mapped to the temperature and then map α_t and α_X to the movements of the predators and prey. According to the theory, the time-exposure increases with predator movements (α_t) and the predator-exposure risk increases with prey movements (α_X). These assumptions will have to be tested and may not be independent. Shown in Figure 2 is example output from OMSS illustrating the sensitivity of predation rate to random smolt velocity.

Figure 2: Simulated survival of migrants (prey) as a function of their random velocity magnitude. The curve is not smooth because the model is based on a discrete number of fish and random chances of their individual survival.



Predator distribution

There is a considerable evidence that the distribution of the predators is not a uniform function of their density and the local section of the reach (i.e. tailrace, forebay and reservoir). Within-area differences were sought from a review of available literature and summarized in Table 2. The following abbreviations are used: NP = Northern Pikeminnow (Squawfish); W = Walleye; SB = Smallmouth Bass; TR=tailrace; FB=forebay; RT = radio-tagged.

Table 2: Resident fish studies on the Columbia River (John Day reservoir mostly) and conclusions regarding depth and/or velocity preferences in piscivorous fishes

Researcher	year of work	Method	Depths (m)	Results	Conclusions
Gray 1985	1983	bottom trawls	1- 15	NA	
Willis 1983	1982	gill nets low flow	>2		NP abundant in littoral and backwater areas. Offshore not sampled NP move to spillways after spill stops. Large numbers in tailraces in July and August. W abundant in backwater and littoral but move out during summer. W and NP respond to H20 temperature and velocity.
		surface and bottom nets in low flow	.3 - 30		
		surface nets in high flow	2 - m		
		electrofishing near shore	<3		
		electrofishing near dams	< 50		
		trap nets near shore	2 - 5		
		beach seine	< 4	ineffective	
		angling	< 15	NP near dams, No W	
Nigro 1985a	1983	based on Willis above			
		drift gill nets in flow	6 - 6.5	not effective	
Nigro 1985b	1984	based on Nigro 1983			
		vertical gill nets used offshore in lower reservoir late in season	? offshore	“did not catch large numbers”	NP are in pelagic areas but not in abundance.
Nigro 1985c	1985	based on Nigro 1984			50% RT Walleye <50 m from shore. ~100% RT NP <50m from shore in lower reservoir and 50-100% RT NP <50m from shore in upper reservoir W and NP are very mobile, SB are not.
Hjort 1981	1981				flow velocity affects residents
Uremovitch 1982	1982				CPUE of NP in FB and T highest in July and August.
Faler 1985	1984/5	radio-telemetry		NP avoid 5.6K m3/sec and high flows	1) NP move close to dam when rates drop below 5.6K m3/s or spill drops off suddenly. 2) NP liked 0-70 cm/sec water w/ mean 24.5. Not ever found in tailrace over 100 cm/s
Poe	1992	lab. swimming test		NP fatigue faster at 12C than 18C	max performance at 107-112 cm/s for medium fish and for large fish max performance at 118-135 cm/s

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Researcher	year of work	Method	Depths (m)	Results	Conclusions
Martinelli, 1993	1993	radio-tracking but local water depth recorded with sonar when a fish detected. Dist. to shore estimated by eye.	NA	accuracy to 3 -5 m if fish were not moving	mean water depth of 279 fish between May and Nov = 4.4 m (1.6 to 45.7 range) and mean dist. to shore for 271 fish = 24.8 m (1.5 to 213 range) average total movement during season was 11 km
Beamsderfer, 1991	1991	gill nets	all near shore	velocity, depth, apparent low densities and other problems made offshore trapping unproductive	W are outside of upstream areas and favor <15 m. SB prefer <15 cm/s as per literature (Edwards 1983; Hjort 1981 and Palmer 1982)
		trap ents			
		electrofishing			
		angling			

Results and ongoing work

Step 1 of the 11 process steps has been completed and steps 2-7 are ongoing. Steps 2, 3 and 4 are important.

- Obtain flow and depth files from PNL researchers and perform initial model runs on a simulation of the Lower Monumental Dam’s reservoir and equivalent in the case of a drawndown river. These are expected the week of May 4, 1999.
- Obtain a batch mode version of OMSS which LRA has agreed to provide.
- Incorporate changes to the OMSS algorithms as described below.

Extending the predation model in OMSS

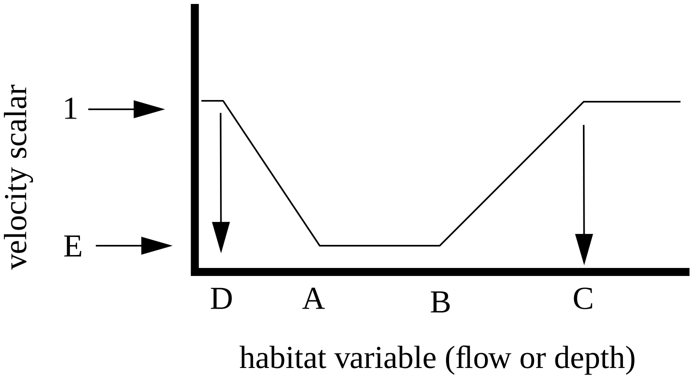
LRA will be asked to modify OMSS in other ways to extend the predation modeling to:

1. Implement random predator movements analogous to prey movements. This would add the following constraint on predators:
    - predator maximum velocity (random).
    - predator direction
2. Give predators habitat preferences. This may result in variable densities in the reservoir which then alters predation and provides a functional response to changes in the hydrology of the river under a drawdown scenario. This should allow predators to congregate in preferred habitat areas and leave less desirable habitat areas. Specifically we will need several parameters read in at the time of implementation:
    - predator preferred flow minimum (A letters refer to use in Figure 3 below)
    - predator preferred flow maximum (B)
    - predator preferred depth minimum
    - predator preferred depth maximum
3. Make predators respond to the habitat by altering their movements depending on the habitat quality. This will be done by modifying the random behavior of the predators

according to their habitat and will be implemented according to the illustration in Figure 3 It will have to include the following parameters:

- flow more than which predator velocity scalar is one (C). The predators maximize their movement if the flow is greater than this amount.
- flow less than which predator velocity scalar is one (D)
- minimum flow velocity scalar (E). If set greater than zero, this ensures that the predators are always moving (slightly) even in ideal habitat.
- depth more than which predator velocity scalar is one
- depth less than which predator velocity scalar is one
- minimum depth velocity scalar

Figure 3: Example showing how the random velocity scaler (VS) is a function of a habitat variable (flow or depth).



Note that this is a very flexible method for controlling predator behavior. For example, no random movement at any depth of water can be set by having A = 0, B = maximum depth in river and E = 0. To have very sharply defined suitable habitat criteria, move D close to A and A close to B while decreasing C closer to B. Since this method will be applied to both flow and depth criteria, the least favorable habitat characteristic should drive the motion of the fish.

For modeling purposes, the velocity scalar (VS) would be expressed as a function of the habitat variables:

$$VS = max\begin{cases} VS_{depth} \\ VS_{flow} \end{cases} \qquad \text{where:}$$

$$VS_{depth} = \begin{cases} E & \text{for A <= depth <=B} \\ 1 & \text{for depth <= D} \\ 1 & \text{for depth >= C} \\ \left(\dfrac{E-1}{A-D}\right)\text{depth} + \dfrac{A-ED}{A-D} & \text{for D < depth < A} \\ \left(\dfrac{1-E}{C-B}\right)\text{depth} + \dfrac{B-EC}{B-C} & \text{for B < depth < C} \end{cases} \qquad \text{Eqn. (11)}$$

$$VS_{flow} = \{\text{analogous to depth criteria}$$

4. Give prey habitat preferences. Yearling and sub-yearling behavior may be quite different in the reaches of the Snake River and we wish to capture the essential differences. Prey will have controls analogous to the Predators. See steps 2, 3, and 4 above.
5. Give prey directed velocity downstream (in flow direction) that is a function (linear) of the flow. This is a direct result of the utility of flow for explaining travel times (Zabel et al. 1998). This would necessitate a term such as:
    - prey downstream velocity scalar.

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