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Chum Salmon Life-Cycle Model Description and Results for the Chehalis River Basin

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April 2021

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National Oceanic and Atmospheric Administration
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Chum Salmon Life-Cycle Model Description and Results for the Chehalis River Basin

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1. Introduction

A key element of the Aquatic Species Restoration Plan (ASRP) for the Chehalis Basin is habitat restoration for anadromous salmonids of economic and cultural significance, including spring and fall Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead (*O. mykiss*), and chum salmon (*O. keta*). To assist with development of the Chehalis basin ASRP, the National Oceanic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center developed a suite of analyses and life-cycle models to (1) assess habitat changes from historical (pre-EuroAmerican settlement or natural potential) conditions to present, (2) evaluate which types of habitat changes most limit rebuilding of salmon populations within the Chehalis Basin, and (3) model future restoration scenarios for the ASRP. The identification of habitat restoration potential using diagnostic scenarios is intended to help identify key restoration actions for salmon populations in the basin, and the restoration scenario analysis is intended to estimate potential benefits of proposed restoration actions.

This report describes the chum salmon model structure and parameters, as well as the results for the diagnostic and restoration scenarios. The results are based on Version 14 of the NOAA Model. Model descriptions and model results for spring and fall Chinook salmon, coho salmon, and steelhead were presented in the project report for the Phase 1 modeling using Version 13 (Beechie et al. 2021).

2. Chum Salmon Life-cycle Model

Chum salmon adult spawners enter the Chehalis River in October and November and spawn in November and December (Johnson et al. 1997). Juvenile chum salmon migrate to the estuary within days or weeks of emergence and reach the estuary at a very small size, with peak estuary entry in late April (Johnson et al. 1997). Because chum salmon spend so little time in freshwater as juveniles, they are particularly sensitive to estuary and early marine conditions (Salo 1991, Johnson et al. 1997). However, in this report we do not evaluate effects of changes in delta-bay habitat conditions or effects of delta-bay restoration on chum salmon populations.

In this section of the report, we first describe the model structure (Section 2.1), then our modeling calibration approach (Section 2.2), and finally the model parameters and calculations (Section 2.3).

2.1 Model Description

The chum salmon life-cycle model has five freshwater life stages that are influenced by freshwater habitat conditions (upstream migration, spawning, egg incubation, fry colonization, and fry rearing/outmigration) (Figure 1). Habitat conditions during each life stage influence the abundance of salmon at the end of that stage (spawners, eggs, emergent fry, fry, and fry migrants) (Table 1). Spawners experience density-independent upstream migration mortality, followed by a density-dependent spawning stage. Egg incubation is

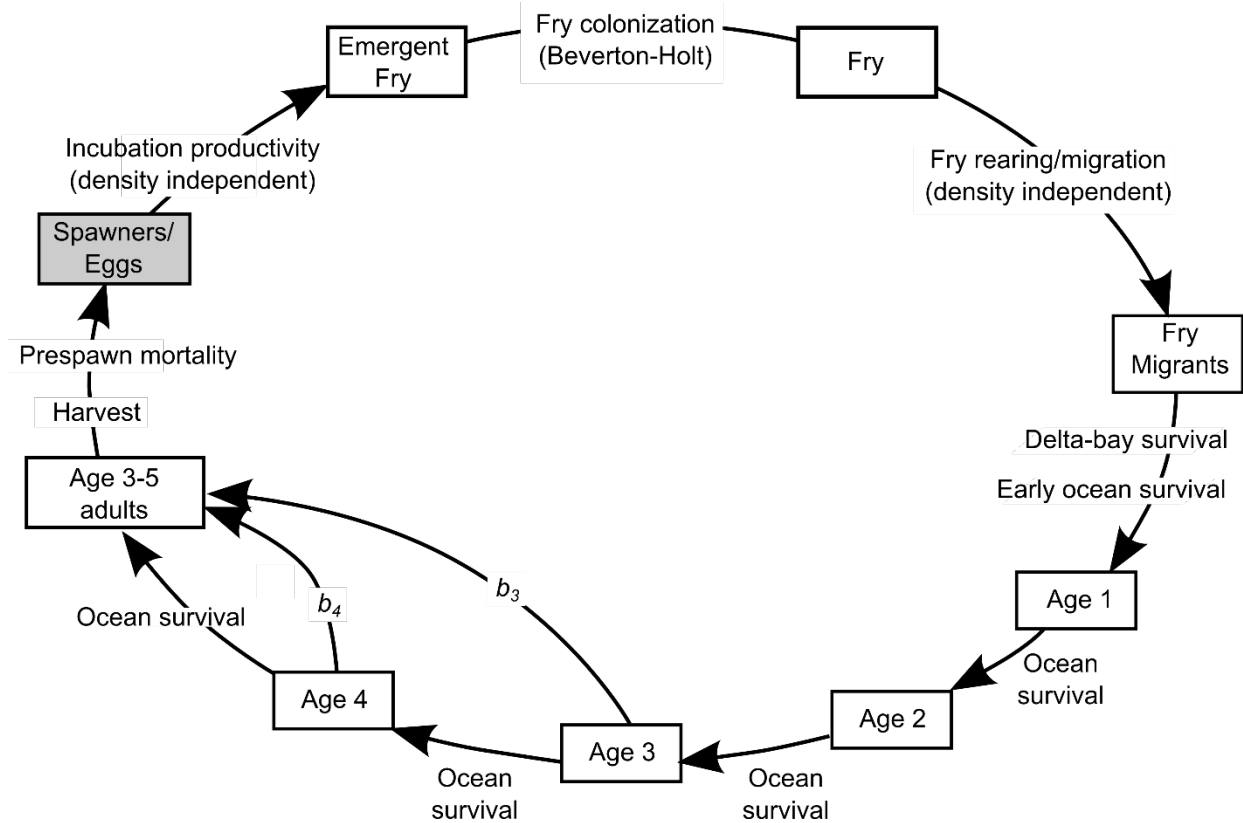


Figure 1. Schematic diagram of the life-cycle model for chum salmon in the Chehalis River basin. Gray box indicates that we report results in number of spawners (or spawners + harvest if harvest is turned on in the model).

Table 1. Definitions of life-stage names (in boxes) in Figure 1.

Term	Definition
Spawners/eggs	Spawners are adult chum that have returned to spawn and survived upstream migration; number of eggs is fecundity \times number of females (females = spawners \times 0.5)
Emergent fry	Fry emerging from the gravel
Fry	Post-colonization fry
Fry migrants	Fry entering the bay after 3 weeks
Age-x adults	Age 2-4 adults in ocean prior to returning to spawn
Age 3-5 adults	Adults returning to Chehalis River to spawn (total run)

density independent, and then emergent fry experience one week of density-dependent colonization followed by two weeks of density-independent rearing as they move to the delta-bay. We refer to chum juveniles as fry migrants when they reach the delta-bay. Fry migrants have a relatively low life-stage productivity in the delta-bay, and thereafter have

annual marine productivity values similar to Chinook salmon in the Phase 1 model (Beechie et al. 2020). Two hatcheries in the Satsop River basin released an average of over 300,000 juvenile chum salmon per year from 2007 to 2018 (Edwards and Zimmerman 2018). However, the model does not account for hatchery effects on chum salmon populations.

The density-dependent life stages (spawning and fry colonization) are modeled with Beverton-Holt functions, and density-independent life stages are modeled as linear survival functions with no capacity limit. The Beverton-Holt function is:

$$N_{stage+1} = \frac{p \cdot N_{stage}}{1 + \left(\frac{p}{c}\right) \cdot N_{stage}} ,$$

where N_{stage} is abundance of eggs or fish at the beginning of the stage, p is the density-independent productivity for the life stage, c is the capacity at the end of the stage, and $N_{stage+1}$ is abundance of fish at the end of the stage (Moussalli and Hilborn 1986). The density-independent survival function is:

$$N_{stage+1} = p \cdot N_{stage} .$$

For the model outputs, we present equilibrium spawner abundance in the absence of harvest (N_{eq}), intrinsic productivity (P_n , also called the cumulative life-cycle productivity), and cumulative life-cycle capacity (C_n) (Moussalli and Hilborn 1986). N_{eq} and P_n are calculated directly from the model outputs, and C_n is calculated from N_{eq} and P_n :

$$C_n = \frac{P_n N_{eq}}{P_n - 1}$$

Results were generated at the basin-wide scale, Ecological Diversity Region (EDR) scale, and subbasin scale. The subbasin results are not presented in this report, but they are available upon request.

2.2 Model Calibration Approach

Because we lacked sufficient data for several life-stage parameters for chum salmon, we took a different modeling approach than in Phase 1 for the other species. In Phase 1, we were able to model coho, Chinook, and steelhead using literature values and local data to estimate parameters for all life stages except the delta-bay productivity. Therefore, we could back-calculate the delta-bay productivity parameter, and we did not need to calibrate any of those models to abundance.

For chum salmon, there are few measurements or estimates of juvenile rearing densities or survival values in streams and rivers, due in part to their small size and rapid night-time migration. This lack of density and survival data results in a model with three unknown or uncertain parameters: juvenile rearing capacity, fry colonization productivity, and fry

rearing productivity. Hence, we set these freshwater life-stage parameters by calibrating the model to a target equilibrium spawner abundance (N_{eq}) and a target intrinsic productivity (P_n). This raises the questions of what values to use as the target equilibrium abundance and intrinsic productivity for calibration, and which parameters to adjust for calibration.

2.2.1 Choosing a Target Equilibrium Abundance (N_{eq}) for Calibration

Recent escapement records show average escapement for the entire Chehalis basin of 28,200 over the 10-year period from 2009 to 2018 (final Grays Harbor spreadsheet from Gary Morishima). The total run size estimate for that period (i.e., adding back harvested fish) was 39,900, and average harvest was 11,600 (harvest rate ~30%). However, recently revised escapement estimates are 1.5 to 1.7 times higher than prior estimates in the Humptulips, Wynoochee, and Satsop River basins (Edwards and Zimmerman 2018, Ronne et al. 2019). This suggests that observed escapement with harvest should probably be in the neighborhood of 45,100 ($28,200 \times 1.6$) and observed total run with harvest should probably be in the neighborhood of 56,700 ($45,100 +$ average harvest of 11,600), assuming that the same multipliers apply to the remaining subbasins with chum spawning and the average 10-year harvest was accurately counted.

There are two reasons we believe the target abundance should be higher than the observed current total run. First, the NOAA model has harvest turned off, so modeled N_{eq} should be higher than the observed value of 56,700 because the intrinsic productivity is higher when harvest is set at zero. Second, the spawning distribution used in the model is larger than the current known spawning distribution, so the model has more spawning area than in the observed current distribution. Both factors would tend to increase modeled abundance above the currently observed values. The current known distribution has no chum spawning above Black River, whereas the distribution agreed upon by the Science Review Team include spawning in Scatter Creek, Skookumchuck River, and Newaukum River (Figure 2). Historically, the distribution may have extended into the South Fork Chehalis, as indicated in unpublished survey notes and in the Washington State stream catalog (Phinney and Bucknell 1975). However, in the current model runs, areas above Black River account for only 5-10% of the total modeled Chehalis basin chum population. Based on all of these considerations, we believe that a modeled N_{eq} without harvest between 70,000 and 90,000 could be a reasonable model outcome under current conditions.

For historical conditions, a recommended target value is 200,000 (L. Lestelle, Biostream Environmental, personal communication), based largely on reported non-Indian gillnet catches of chum in Grays Harbor that averaged over 117,000 fish from 1910 to 1919 (Hiss and Knudsen 1993). However, we expected that the life-cycle model estimate of historical abundance would be less than 200,000 because the model does not have a historical delta-bay productivity increase. We do not have a way of estimating how much higher historical intrinsic productivity might be because we do not have an estimate of the survival difference between current and historical delta-bay conditions.

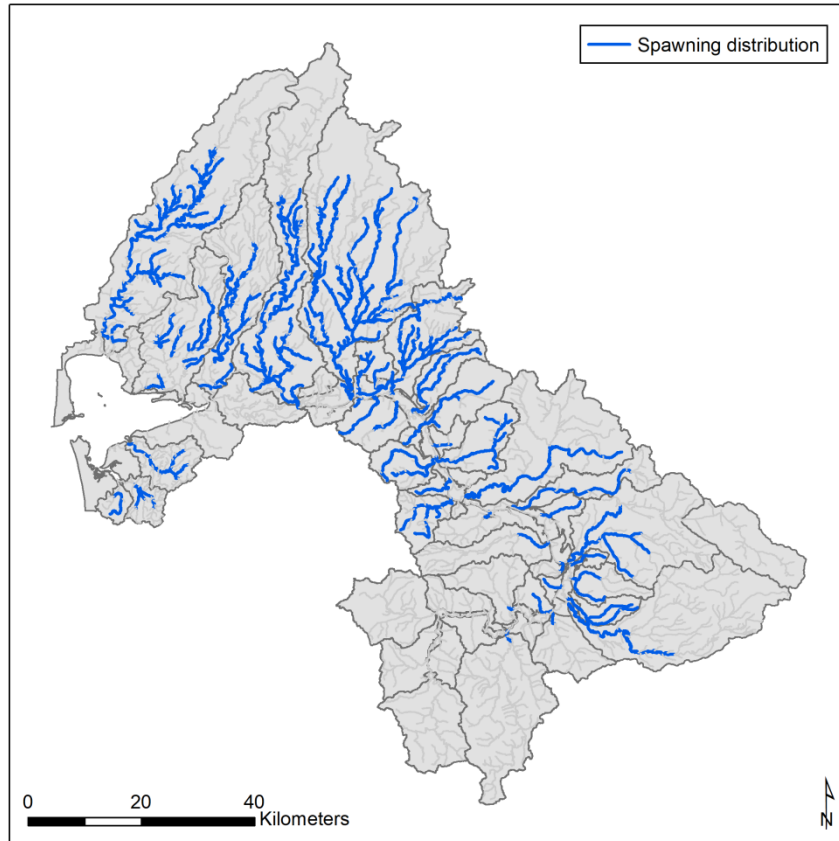


Figure 2. Chum salmon spawning distribution used in the NOAA life-cycle model.

2.2.2 Choosing a Target Intrinsic Productivity (P_n) for Calibration

A summary of adult return data for chum salmon from the Chehalis basin and Grays Harbor from 1969 to 2013 showed that recruits per spawner (R/S) ranged from 0.18 to 8.06, with a median value of 1.64 (Grays Harbor chum salmon data file: FINAL GH Chum Forecast Model2.15.19.xlsx). For comparison, observed R/S in the Fraser River ranged from 0.83 to 3.98 between 1961 and 1974 (Table 4 in Beacham and Starr 1982). There was a notable difference between odd and even years in the Fraser River, as competition with pink salmon outmigrants appeared to reduce early marine survival of chum. In even years, R/S ranged from 1.76 to 3.98 and the median R/S was 2.16 (Beacham and Starr 1982). The Chehalis River basin does not have a significant pink salmon run.

Fitting Beverton-Holt or Ricker curves to the spawner-recruit data provides direct estimates of P_n . However, the Beverton-Holt curve may overestimate P_n , while the Ricker curve reduces over-estimation (Walters and Martell 2004). Fitting a Ricker curve to the Chehalis River basin escapement data produced a P_n of 3.7 (L. Lestelle, personal communication), whereas fitting a Ricker curve to the Fraser River data produced a value of 2.4 in even years (L. Lestelle, personal communication). Eighteen other southern British Columbia stocks have P_n values ranging from 1.39 to 4.65 with a median of 2.5 (Holt et al.

2018). The estimated P_n value for the Chehalis basin is at the high end of the range reported for the southern British Columbia stocks (only one of the 18 stocks had a higher productivity).

While observed R/S and P_n both indicate a number of adults produced by each spawner, they are not synonymous (Moussalli and Hilborn 1986, Walters and Martell 2004). An observed R/S value for a given brood-year reflects density dependent and density independent processes affecting recruitment, which vary from year to year. By contrast, P_n is an indication of density-independent survival at low abundance, and observed P_n is based on a statistical fit to spawner and recruit data for all years. In the disaggregated Beverton-Holt calculation, P_n also represents density-independent survival at low abundance, but it is calculated as the product of all stage-specific productivities with no influence of the life-stage capacities (Moussalli and Hilborn 1986).

Based on these calculations and observations, we chose to calibrate P_n to within the range of 2.1 to 2.5, which is in between the median R/S and P_n estimates for the Chehalis basin data (median R/S = 1.64, P_n = 3.7). It is also similar to the parameter estimates from the British Columbia data sets we examined (median R/S = 2.16, P_n = 2.4 for the Fraser River; median P_n = 2.5 for the 18 southern British Columbia stocks). We discuss data limitations that prohibit targeting a higher intrinsic productivity in Section 5.2.

2.2.3 Calibration Parameters

We were able to constrain most life stage parameters with reliable data, but we were left with poorly constrained parameters for juvenile colonization capacity and productivity, and juvenile rearing productivity. If we assume that the weekly productivity is the same during colonization and rearing (but with different durations), then we can calibrate the model using two parameters, colonization capacity and weekly rearing productivity. We made two estimates of colonization capacity—low and high—to bracket the range of possible capacity values (details of the calculations are in the following section), and calibrated the model to N_{eq} for each case using the weekly productivity. We examined the resulting intrinsic productivity (P_n) values for each case, and then adjusted colonization capacity between the low and high values, keeping N_{eq} within the target range (70,000 – 90,000 spawners) by adjusting the weekly rearing productivity until the P_n value was also within the target range (2.1-2.5). When both N_{eq} and P_n were within the target ranges for current conditions, we proceeded to use the model for the diagnostic and restoration scenarios.

2.3 Model Parameters

For chum salmon adult upstream migration and holding, we modeled the life stage as density independent (Table 2). For the spawning life stage (Beverton-Holt form), the spawning capacity is expressed as egg capacity (c), which is the estimated maximum number of redds multiplied by the fecundity (Table 3). We used a density-independent fecundity (F) of 3200 eggs per female, which is the average of late spawners (Koski 1975) (Table 4). In large rivers (>20 m bankfull width), redd capacity is a function of spawning gravel area digitized from aerial photography (Beechie et al. 2021) and redd area (2.3 m²)

(Burner 1951). In small streams, we estimated redd capacity based on estimated spawning area divided by redd area (Beechie et al. 2021). When the number of returning spawners is below capacity, the number of eggs is number of spawners \times 0.5 \times fecundity. Spawning capacity is influenced by migration barriers, wood abundance, and side-channel connectivity in the habitat scenarios (Beechie et al. 2020, Appendix I). The spatial distribution of chum spawning used in the model is shown in Figure 2.

The incubation stage was modeled using density-independent incubation productivity. We assumed that density dependence occurs in the spawning stage (i.e., the number of eggs in the gravel is limited by the egg capacity), and that there is no additional density-dependent mortality in the incubation stage. We estimated that density-independent incubation productivity is 0.04 where the slope-area index is <0.05 due to very low sediment transport capacity and average percent fines of 28% (see Appendices C and I in Beechie et al. 2020 for more details). Where slope-area index is >0.05 , we modeled incubation productivity as a function of percent fine sediment <0.85 mm (Appendix I in Beechie et al. 2020), which was a function of current road density (Appendix C in Beechie et al. 2020).

Table 2. Overview of life stages, parameters, and functions used in the chum salmon life-cycle model in the Chehalis River. Additional details are included in Appendices H and I in Beechie et al. (2020). DI = density independent, DD = density dependent. Gray shading indicates freshwater life stages.

Life Stage	Function	Capacity	Productivity
Upstream migration and holding	DI	No capacity limit	Fixed productivity.
Spawning	DD (Beverton-Holt)	Varies with wood abundance, side channel area and barriers.	Constant among scenarios.
Incubation	DI	No capacity limit	Varies with average percent fines and slope-area index.
Fry colonization	DD (Beverton-Holt)	Varies with side channel area and barriers	Constant among scenarios.
Fry rearing and outmigration	DI	No capacity limit	Constant among scenarios.
Delta-bay	DI	No capacity limit	Constant among scenarios.
Annual ocean	DI	No capacity limit	Constant among scenarios.

Table 3. Chum salmon data used to estimate freshwater life-stage capacities in the chum life-cycle model for the Chehalis River.

Life Stage (Equation Form)	Data Used to Estimate Life-stage Capacities (current condition)
Upstream migration and holding (density independent)	NA (we found no data to estimate holding capacity)
Spawning (Beverton-Holt)	Egg capacity = number of redds multiplied by fecundity (3200 eggs/female) (Koski 1975) <i>Number of redds in large rivers (>20 m bankfull width):</i> Digitized riffle area divided by redd area (2.3 m ²) (Burner 1951) <i>Number of redds in small streams (<20 m bankfull width):</i> Estimated riffle area divided by redd area (2.3m ²) (Burner 1951)
Incubation (density independent)	NA
Fry colonization (Beverton-Holt)	<i>Density (fish/m²):</i> Bank (natural) = 1.33 (95 th percentile) (Beamer and Henderson 1998) Bank (modified) = 1.33 (95 th percentile) (Beamer and Henderson 1998) Bar (boulder) = 1.7 (95 th percentile) (Beamer and Henderson 1998) Bar (gravel) = 1.7 (95 th percentile) (Beamer and Henderson 1998) Bar (sand) = 0.67 (95 th percentile) (Beamer and Henderson 1998) Backwater = 3.0 (95 th percentile) (Beamer and Henderson 1998) Pool (sm. stream) = 3.0 (assumed similar to backwater) Riffle (sm. stream) = 3.0 (assumed similar to backwater) Pond (sm. stream) = 3.0 (assumed similar to backwater) Lake (>5 ha) = 0 (assume no rearing) Side-channel pool = 3.0 (assumed similar to small stream) Side channel riffle = 3.0 (assumed similar to small stream) Slough = 0 (assume no floodplain rearing) Floodplain pond = 0 (assume no floodplain rearing) Marsh = 0 (assume no floodplain rearing)

The fry colonization stage was modeled with a density-dependent Beverton-Holt function. We used the 95th percentile of rearing densities calculated from Skagit River data for all habitat types except floodplain marshes, ponds, and lakes, which are given a density of 0 (Table 3) (Beamer and Henderson 1998). Each density is multiplied by its respective habitat area to calculate the low estimate of colonization capacity:

$$c = d \cdot A$$

where c is capacity (# of fish), d is maximum daily density (fish/ha), and A is habitat area (ha). These density values represent an instantaneous density of juveniles at the time of the survey. However, chum salmon migrate continually downstream, so each habitat space can be occupied by multiple groups of fish over time. That is, juveniles observed in a habitat one week will move downstream and be replaced by juveniles from different spawning locations or emergence timings in subsequent weeks. Therefore, colonization capacity may

be higher than that estimated from these instantaneous densities. We estimated a maximum colonization capacity using:

$$c = d \cdot A \cdot \frac{t}{r}$$

where t is the total extent of the emergence period (weeks), and r is the mean residence time (weeks). For chum salmon, we use a total emergence period (t) of 7 weeks and mean residence time (r) of one week, so a maximum chum fry colonization capacity estimate is

$$c = d \cdot A \cdot 7$$

Table 4. Chum salmon productivities used in the chum life-cycle model for the Chehalis River. Gray shading indicates freshwater life stages.

Life Stage (Equation Form)	Productivity or fecundity (current condition)
Upstream migration and holding (density independent)	Fixed at 1.0 (similar to Chinook salmon in Phase 1 modeling)
Spawning (Beverton-Holt)	Fecundity = 3200 eggs/female; the average of late spawners (Koski 1975)
Incubation (density independent)	Incubation productivity is a function of modeled percent fine sediment <0.85 mm. Productivity equation is below (Jensen et al. 2009). $p = \frac{1}{1 + e^{(-1.989 + 0.185 \cdot sed)}}$
Fry colonization (Beverton-Holt)	$p_b = 0.76$ (calibrated).
Fry rearing and outmigration natal (density independent)	Current condition $p = 0.58$ (p_b^2).
Delta-bay productivity	$p = 0.033$ (produces SAR of 1.1%)
Ocean productivity	Age 1: $p = 0.6$ (same as Chinook) (Greene and Beechie 2004) Age 2: $p = 0.7$ (same as Chinook) (Greene and Beechie 2004) Age 3: $p = 0.8$ (same as Chinook) (Greene and Beechie 2004) Age 4: $p = 0.9$ (same as Chinook) (Greene and Beechie 2004)
Maturation rate	$b_3 = 0.15$ (set by trial and error to match age structure) $b_4 = 0.85$ (set by trial and error to match age structure) $b_5 = 1.0$ (set by trial and error to match age structure) Age structure: 34% age 3, 56% age 4, and 10% age 5 (Ashcraft et al. 2017, Edwards and Zimmerman 2018, Ronne et al. 2019)
Harvest (optional)	Modeled without harvest

After calibration, the equation that gave a reasonable result relative to the target N_{eq} and P_n was

$$c = d \cdot A \cdot 1.1$$

This suggests that a modeled capacity nearer the instantaneous capacity produced a more realistic result than a high capacity.

For juvenile rearing productivity, we varied the weekly productivity value for the colonization stage (one week) and for the rearing and outmigration stage (two weeks). We vary the weekly productivity value as the calibration parameter. After calibration, the weekly rearing productivity was set at 0.8. The vast majority of fry migrants in Grays Harbor are <50 mm in length, supporting the assumption of very short freshwater residence (Sandell et al. 2015).

Once in the delta-bay, fry migrants experience density-independent productivity. We back-calculated the delta-bay productivity from a smolt-to-adult return rate (SAR) of 1.1% (Bradford 1995) and the age-weighted average of annual marine productivities (Table 4), which produced a delta-bay productivity of 3.3%. For reference, the SAR value is within the literature range of 0.5 to 2.6% for chum salmon (Salo 1991).

In the ocean, all fish receive the same fixed density-independent productivity rates, followed by harvest (optional, currently modeled with no harvest) (Table 4). Each age class of fish in the ocean also has a maturation rate (b), so some proportion of each age class matures and leaves the ocean population each year. We modified the b parameters by trial and error until the model approximately reproduced the average age structure of spawning populations in the Satsop River basin from 2015 to 2018 (age 3 = 34%, age 4 = 56%, and age 5 = 10%) (Ashcraft et al. 2017, Edwards and Zimmerman 2018, Ronne et al. 2019).

3. Diagnostic and Restoration Scenarios

A brief description of the diagnostic and restoration scenarios modeled for the Chehalis Basin ASRP is presented here. Additional details of the scenarios are presented in the Phase 1 modeling report (Beechie et al. 2021).

3.1 Diagnostic Scenarios

The diagnostic scenarios are used to model effects of past habitat changes on chum salmon populations, given specific assumptions of how each change in habitat quantity or quality affects life-stage capacities or productivities. Each scenario examines how a change in a single habitat factor might affect potential improvement of chum salmon population performance in each subbasin. The diagnostic scenarios are summarized in Table 5.

3.2 Restoration Scenarios

We also ran a series of restoration scenarios agreed upon by the Science Review Team. These scenarios are listed as the No-action alternative and Scenarios 1, 2, and 3 by the SRT (Table 6). Each scenario includes estimated decline or improvement in capacities and density-independent productivities for each life-stage for mid-century and late-century. The No-action alternative includes future development and climate change, as well as growth of existing trees. For climate change, changes in spring wetted widths (from ICF International) reduce colonization area for chum salmon in future scenarios. Winter widths did not change in the future, so there is no future change in spawning capacity. We did not include the stochastic effect of peak flows in the model because the LCM Workgroup recommended not including stochasticity at this time. Future stream temperature and future development do not affect chum salmon in the LCM because neither adults nor juveniles are in freshwater when temperatures are high or when urban runoff effects adult prespawn survival.

The three restoration scenarios represent low, moderate, and high levels of restoration effort. The primary restoration actions proposed in Scenarios 1, 2 and 3 are barrier removal, wood addition, riparian restoration, and floodplain reconnection. In all scenarios, riparian and floodplain restoration are applied only in Geospatial Units (GSUs) outside managed forest lands. Barrier removal and wood placement are applied in GSUs both inside and outside managed forest lands. In GSUs inside managed forest lands, we also modeled passive recovery of riparian conditions as forested buffer zones mature. Each restoration scenario includes improvement in life-stage capacities and productivities, based on a percentage improvement from the current to the historical condition within a treated reach.

Table 5. Description of the current and historical conditions scenarios, and the nine diagnostic habitat scenarios evaluated with the life-cycle models.

Scenario	Description
Current	Current conditions for all habitat variables.
No barriers	Current conditions for all habitats, but without migration barriers. Barriers reduce prespawn productivity and spawning capacity.
Historical fine sediment	Current conditions with historical fine sediment. Fine sediment reduces incubation survival.
Historical wood abundance	Current conditions with historical wood abundance in small streams and large rivers. Wood abundance influences spawning capacity in small streams and large rivers, but not colonization or rearing capacity or productivity (we found no consistent correlation between fish density and wood abundance in juvenile data from Beamer and Henderson 1998).
Historical shade	Current conditions with historical shade and temperature in small streams and large rivers. Stream temperature does not influence chum salmon adult prespawn productivity because they enter the river after high summer temperatures, nor does it influence fry rearing and outmigration because fry leave the river prior to high summer temperatures.
Historical large river bank conditions	Current conditions with no rip-rap in large rivers. Density data from indicate that fry densities do not differ between natural and modified banks (Beamer and Henderson 1998), so there is no effect on fry colonization capacity.
Historical large river length	Current conditions with historical large river length. Large river channel straightening reduces both spawning and fry colonization habitat areas, and therefore chum spawning and fry colonization capacities.
Historical beaver ponds	Current conditions with historical beaver pond areas in small streams. We assumed a fry colonization density of zero, and no effect on chum fry productivity.
Historical floodplain habitat	Current conditions with historical side channel, marsh, and pond habitats in floodplains. Studies of chum migration indicate that they migrate high in the water column in mid-channel (Salo 1991). Therefore, we assumed that chum fry do not use floodplain marsh or pond habitats during the colonization or rearing stages. However, chum salmon spawn in side channels—especially groundwater fed channels—so we assumed that increased side channel area increases spawning and colonization capacities.
Historical wood and floodplain habitat	Current conditions with historical wood abundance and side channel, marsh, and pond habitats in floodplains. Wood and floodplain effects modeled as described above.
Historical	Historical conditions for all habitat variables.

Table 6. Summary of restoration and climate change scenarios identified by the Science Review Team. Recovery of stream shading via tree growth is also included in all managed forest scenarios, regardless of other treatments. GSU refers to Geospatial Units.

Scenario	Mid Century	Late Century
No action	Tree growth: increases shade Climate change: increases stream temperature 1°C Development: increases impervious area	Tree growth: increases shade Climate change: increases stream temperature 2°C Development: increases impervious area
Scenario 1	Restoration + tree growth, climate change, and development Restoration focused in 39 GSUs, 226 miles of stream restored and 356 barrier culverts removed (out of 1790)	Restoration + tree growth, climate change, and development Riparian recovery continues in restored areas and managed forests, increasing shade and reducing stream temperature
Scenario 2	Restoration + tree growth, climate change, and development Restoration focused in 48 GSUs, 315 miles of stream restored and 605 barrier culverts removed (out of 1790)	Restoration + tree growth, climate change, and development Riparian recovery continues in restored areas and managed forests, increasing shade and reducing stream temperature
Scenario 3	Restoration + tree growth, climate change, and development Restoration focused in 67 GSUs, 449 miles of stream restored and 668 barrier culverts removed (out of 1790)	Restoration + tree growth, climate change, and development Riparian recovery continues in restored areas and managed forests, increasing shade and reducing stream temperature

4. Chum Salmon Model Results

After calibration under current conditions, the chum model produced a basin-wide equilibrium abundance without harvest (N_{eq}) of 82,442, and intrinsic productivity (P_n) of 2.49. Under historical conditions, the model produced a basin-wide N_{eq} of 126,259 and a P_n of 3.87. The calibrated parameters producing these numbers were a capacity multiplier of 1.1 and a weekly rearing productivity of 0.8. Calibrating the model to a similar current abundance and higher historical abundance requires a larger capacity multiplier, but then intrinsic productivity must be below 2.0 to keep current abundance within the target range of 70,000 - 90,000. However, the model does not include an increase in delta-bay productivity under historical conditions due a lack of data on habitat effects on productivity for that life stage. Including a delta-bay survival increase between current and historical conditions would yield a higher historical abundance with the current parameters.

4.1 Diagnostic Scenario Results

Modeled chum salmon spawner abundance (N_{eq} , without harvest) was most sensitive to changes in fine sediment, increasing 36% in the historical fine sediment scenario (Figure 3). In general, chum salmon are relatively insensitive to the other freshwater habitat conditions because they spend so little time in freshwater as juveniles. Modeled spawner abundance increased by 13% in the historical wood scenario, 4% in the historical floodplain scenario, and 17% in the historical wood + floodplain habitat scenario. Removing all migration barriers increased N_{eq} without harvest by 4%, and all other scenarios produced a change in spawner abundance of +1% to -10%. The negative change is in the historical beaver pond scenario because there is little rearing habitat potential for chum salmon in beaver ponds, and ponds reduce spawning habitat capacity. Intrinsic productivity (P_n) increased substantially only in the historical fine sediment scenario, and capacity (C_n) did not increase by more than 16% in any scenario except all historical conditions (Table 7).

The fine sediment scenario produced the largest change in abundance and intrinsic productivity, suggesting that reducing fine sediments in spawning gravels could be beneficial for chum salmon. Moreover, abundance and productivity increased by 25% or more in the fine sediment scenario in all EDRs with chum salmon spawning except the Black River EDR (Table 10). While fine sediment reduction has the largest potential benefit to chum salmon, locations and sources of high fine sediment must be confirmed prior to developing a fine sediment reduction plan.

The results also suggest that increasing wood abundance and floodplain connectivity may increase chum salmon spawner abundance by ~17% by increasing spawning and rearing capacity. Increased floodplain connectivity increases side channel area through reconnection of side channels, whereas increased wood abundance can increase the number of pools and spawning riffles. Both changes increase spawning and rearing capacities.

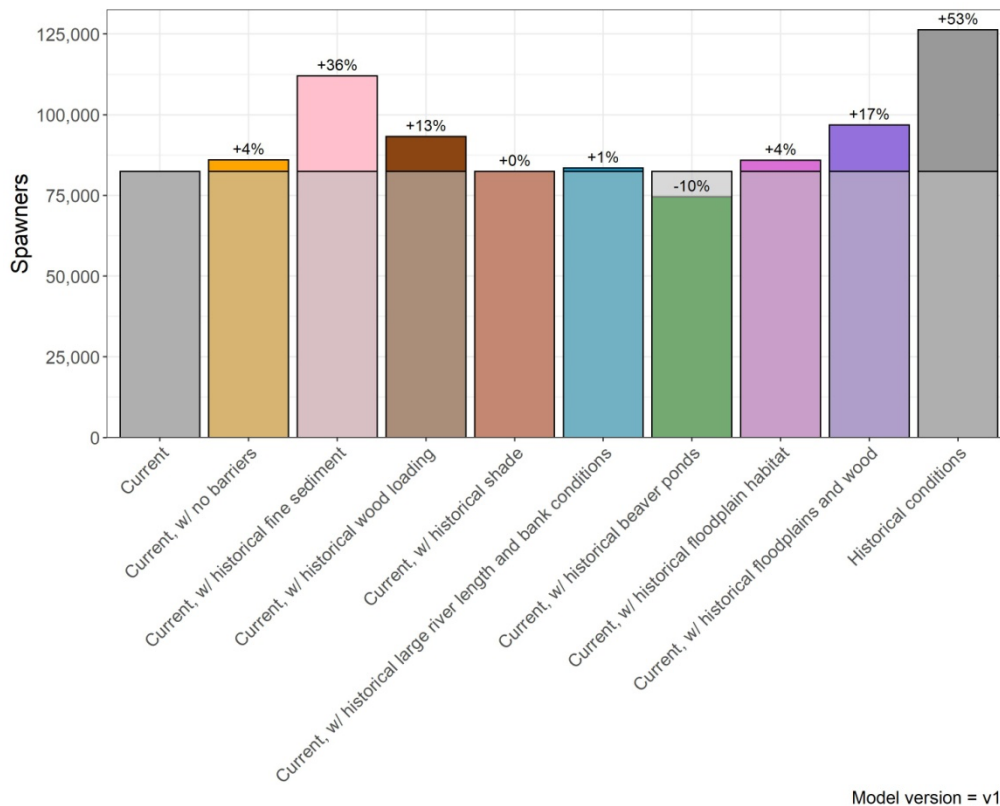


Figure 3. Modeled difference in spawner abundance (N_{eq} , without harvest) among diagnostic scenarios for chum salmon.

Table 7. Modeled chum salmon spawner abundance (N_{eq} , without harvest) in The Chehalis Basin for all diagnostic scenarios, along with life-cycle productivity (P_n) and capacity (C_n). Light blue shaded cells indicate increases 10-25%, medium blue indicates increases 25-50%, and dark blue indicates increases >50%.

Scenario	Spawners (N_{eq})	P_n	C_n
Current conditions	82,442	2.49	137,834
No Barriers	86,001 (+4%)	2.48 (0)	144,004 (+4%)
Historical fine sediment	112,091 (+36%)	3.71 (+49%)	153,431 (+11%)
Historical wood	93,340 (+13%)	2.53 (+2%)	154,383 (+12%)
Historical shade	82,442 (0%)	2.49 (0)	137,834 (0%)
Historical large river habitat	83,492 (+1%)	2.49 (0)	139,560 (+1%)
Historical beaver ponds	74,596 (-10%)	2.50 (0)	124,400 (-10%)
Historical floodplain habitat	85,860 (+4%)	2.49 (0)	143,569 (+4%)
Historical wood + floodplain	96,836 (+17%)	2.53 (+2%)	160,238 (+16%)
Historical conditions	126,259 (+53%)	3.87 (+55%)	170,293 (+24%)

Table 8. Modeled chum salmon spawner abundance (N_{eq} , without harvest), life-cycle productivity (P_n) and capacity (C_n) by EDR for current conditions and the fine sediment scenario. Light blue shaded cells indicate changes 10-25%, medium blue indicates changes 25-50%, and dark blue indicates changes >50%.

Ecological Diversity Region	Current conditions			Historical fine sediment scenario		
	N_{eq}	P_n	C_n	N_{eq}	P_n	C_n
Black Hills	12,687	2.44	21,493	18,448	4.03	24,545
Black River	4,193	2.38	7,223	4,849	2.83	7,504
Cascade Mts	6,174	2.20	11,323	7,941	3.08	11,759
Central Lowlands	3,434	2.17	6,365	5,718	3.09	8,459
Grays Harbor	18,363	2.40	31,435	27,010	3.05	40,199
Lower Chehalis	2,485	3.76	3,385	3,540	6.53	4,180
Middle Chehalis	0	NA	NA	0	NA	NA
Upper Chehalis	0	NA	NA	0	NA	NA
Olympic Mts	35,063	2.55	57,619	44,513	4.05	59,104
Willapa Hills	43	1.76	100	72	2.74	113

4.2 Restoration Scenario Results

Modeled future chum salmon spawner abundance increased in all future restoration scenarios, and there was no decrease due to future temperature changes because juveniles have already migrated to marine areas before summer (Figure 4, Table 9). Wetted widths during the spawning period do not change in future scenarios, but wetted width during the colonization period declines by 5%, reducing colonization capacity (wetted width data from ICF International). However, small colonization capacity changes have relatively little influence on chum salmon populations, so the No-action alternative does not show a significant change due to climate change. Chum salmon are likely very sensitive to increasing peak flow scouring of redds, which would decrease chum salmon abundance and productivity in the No-action alternative. However, the stochastic peak flow effect is currently turned off in the model at the recommendation of the LCM Workgroup.

Modeled spawner abundance increased by 8% in Scenario 1, 11% in Scenario 2, and 12% in Scenario 3 in mid- and late-century. Because all actions are taken prior to mid-century and no actions are modeled between mid- and late-century, there are no substantive changes in modeled abundances between the two time periods. Changes in P_n were $\leq 1\%$ in all three restoration scenarios in both mid- and late-century.

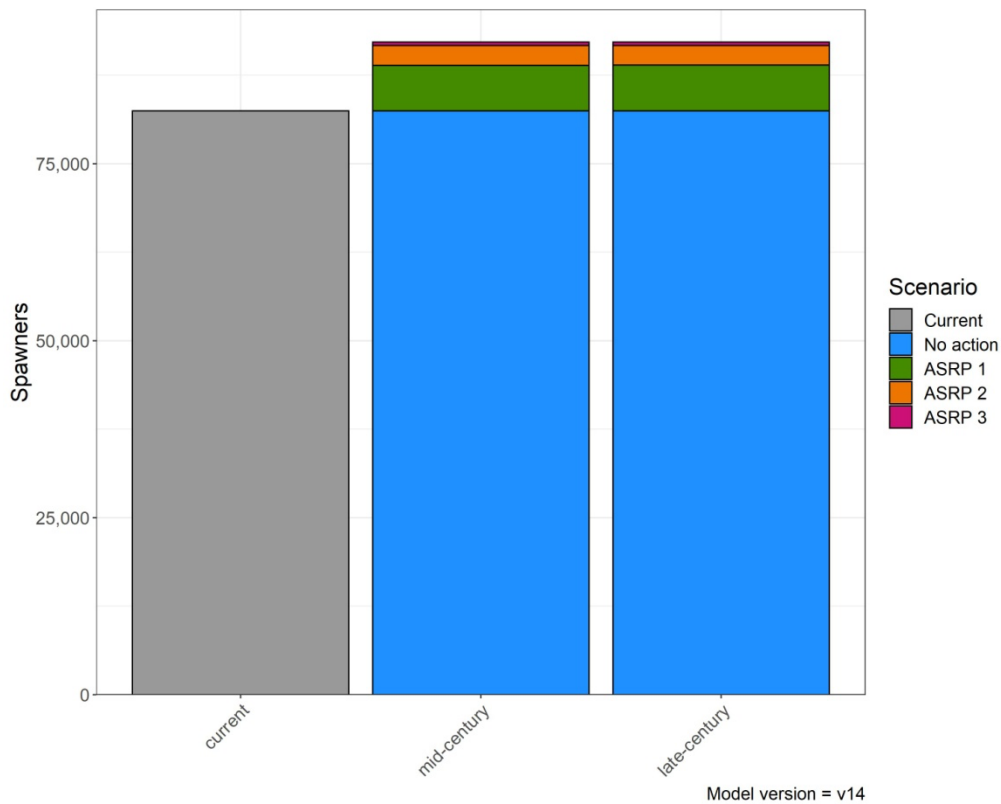


Figure 4. Projected chum salmon spawner abundance (N_{eq} , without harvest) in the Chehalis River basin for the No-action alternative and three future restoration scenarios

Table 9. Modeled number of chum salmon spawners (N_{eq} , without harvest) for the Chehalis Basin for each restoration scenario compared to current conditions, along with life-cycle productivity (P_n) and capacity (C_n) estimated from the life stage parameters. Light blue shaded cells indicate increases $\geq 10\%$.

Scenario	Spawners (N_{eq})		P_n		C_n	
Current	82,442		2.49		137,834	
	Mid-century	Late-century	Mid-century	Late-century	Mid-century	Late-century
No Action	82,448 (0%)	82,456 (0%)	2.49 (0%)	2.49 (0%)	137,844 (0%)	137,857 (0%)
Scenario 1	88,918 (+8%)	88,928 (+8%)	2.47 (-1%)	2.47 (-1%)	149,402 (+8%)	149,418 (+8%)
Scenario 2	91,700 (+11%)	91,710 (+11%)	2.50 (0%)	2.50 (0%)	152,834 (+11%)	152,850 (+11%)
Scenario 3	92,171 (+12%)	92,180 (+12%)	2.50 (+1%)	2.50 (+1%)	152,443 (+11%)	153,457 (+11%)

5. Discussion

The chum salmon LCM is designed to evaluate effects of freshwater environmental conditions (above tidal influence) on salmon populations originating in the Chehalis River basin. An important outcome of the chum model is that egg incubation is the life stage most affected by freshwater habitat conditions (fine sediment). All of the other modeled freshwater habitat attributes have little influence on abundance relative to current conditions. These results are consistent with our knowledge of the life history of chum salmon (Johnson et al. 1997). That is, chum spend so little time in freshwater as adults or juveniles that freshwater habitat conditions affecting colonization and rearing life-stage productivities have little influence on population size.

5.1 Potential Restoration Options

The chum salmon life-cycle model suggests that fine sediment reduction could benefit chum salmon populations in the Chehalis River basin, although the fine sediment values are modeled based on road density and only represent a hypothesis about where fine sediment levels may be high and reduce incubation survival. A restoration plan for reducing fine sediment in spawning gravels should begin by measuring fine sediment levels in areas predicted to have high fine sediment to confirm if and where fine sediment levels are high. These measurements should also include observations of sources of fine sediment, so that restoration actions accurately address the causes of high fine sediment. For example, fine sediments may be high in a reach with livestock access and eroding banks, and restoration actions must target livestock exclusion and control of bank erosion in order to be successful.

Restoring wood abundance may improve chum salmon abundance or productivity via changes in spawning capacity or colonization and rearing productivity. However, this option is likely to have a relatively small effect on chum salmon based on the model results (<15% change in abundance or capacity, <5% change in productivity).

Although the chum salmon life-cycle model does not include habitat changes in the estuary, the life history of chum salmon and local information on the Chehalis estuary suggest that degradation of habitats in the delta and/or bay may reduce survival of chum salmon in those habitat areas. While we cannot estimate the potential effect of estuarine habitat degradation on chum salmon with the life-cycle model, it is logical to explore estuary restoration options that may benefit survival of juvenile chum salmon.

5.2 Model Uncertainties

Uncertainties in the chum LCM include parameter uncertainty and model form uncertainty. Parameter uncertainty is the uncertainty in parameter values from measurement error, extrapolation error, lack of Chehalis Basin-specific observational data, and other sources. Model form uncertainties are most commonly introduced by missing model components or inaccurate functions for components that are included.

5.2.1 Parameter Uncertainty

In the chum salmon LCM we have three unknown or poorly known life stage parameters: colonization capacity, colonization productivity, and rearing productivity. Without reliable data to set these parameters, we chose to calibrate the model to accepted ranges of spawner abundance and life-cycle productivity. We chose to use the same baseline weekly productivity value to estimate colonization productivity (p_b) and rearing productivity (p_b^2), which reduced the unknowns to two parameters: colonization capacity and weekly colonization/rearing productivity. We then estimated a colonization capacity using observed densities and habitat areas. In the calibration process, we calculated a weekly p_b value that produced a life cycle productivity of nearly 2.5, and then adjusted the colonization capacity multiplier to 1.1. (theoretically accounting for more than one cohort using each habitat) to produce an abundance within the target range. While the final parameter values produced realistic abundance and productivity estimates, we do not know if the life-stage parameter values themselves are accurate.

The fit of the spawner-recruit data for the Chehalis basin suggested that the intrinsic productivity (P_n) could be as high as 3.7, while our modeled P_n is only 2.5. However, the current condition productivity parameters in the chum salmon LCM are all constrained by data or models as follows:

- Fecundity = 1,600 (3,200 eggs per female, assuming a sex ratio of 0.5)
- Incubation productivity = 0.28 (basin-wide average based on the fine sediment model)
- Colonization productivity = 0.8 (one week, calibrated value, p_b)
- Rearing productivity = 0.64 (two weeks of the calibrated productivity, p_b^2)
- Smolt to adult return = 0.011 (Bradford 1995)
- Harvest = 1 (harvest turned off)
- Prespawn productivity = 1 (no prespawn mortality)

If we assume that these values are correct, a calculated P_n value for the Chehalis basin would be 2.52 under current conditions. For the P_n value to be higher (i.e., above 3 as estimated from the escapement and run size data for the Chehalis basin), at least one of these p values must be too low. However, we have no information to suggest which, if any, parameters should be modified. The parameters with perhaps the most uncertainty are the incubation and colonization productivities, as well as the SAR value. Any of those parameters could be increased, but the colonization productivity is already at the benchmark value (Lestelle et al. 2005), suggesting that either the incubation productivity or SAR may be low. However, increasing one of those values to increase the P_n value requires a decrease in capacity to stay within the target abundance range, and we also have no basis for reducing either spawning or colonization capacity (the only two capacity terms in the model). Colonization capacity is near its lowest possible value in this model configuration, so it seems unlikely that it is too high. Spawning capacity could be too high, but we do not have an alternative method of estimating spawning gravel area or egg capacity.

5.2.2 Model Form Uncertainty

All models include some form of model uncertainty, and the life-cycle model described here has three aspects of model form uncertainty worth noting. First the model does not address whether scour of redds during floods is a significant effect. As with Chinook salmon, scour of redds during large floods appears to cause very low egg-to-fry survival of chum salmon (Weinheimer et al. 2017). We currently have an optional function relating flood magnitude to incubation productivity in the model, but it is currently turned off at the recommendation of the Life-Cycle Model Work Group. If we turn this function on, we modeled abundance and life-cycle productivity to decline from levels reported here.

Second, the model does not address whether delta-bay habitats are degraded and reduce early marine survival of chum salmon. The literature indicates that estuary residence is a critical life history stage for chum salmon (Johnson et al. 1997), and declines in survival during that stage may substantially impact equilibrium spawner abundance. Therefore, it is possible that estuary restoration actions to improve survival might also increase chum salmon spawner abundance in the Chehalis River basin.

Finally, the model also does not address variation in marine survival, and potential correlations in chum salmon run sizes with climate variability indices such as the Pacific Decadal Oscillation (PDO) (Lestelle et al. 2018). Such climate cycles can be modeled as time series with stochasticity, or as separate scenarios for warm and cool phases of the PDO. Currently these effects are not included in the chum salmon life-cycle model.

6. Conclusions

Despite significant uncertainty in the model, the diagnostic scenarios suggest that fine sediment reduction is most likely to significantly increase chum salmon abundance. This conclusion did not change throughout the calibration process, regardless of changes to the calibration parameters. It is not surprising then that the currently proposed restoration scenarios do not result in significant modeled increases in chum salmon spawner abundance because they do not address fine sediment sources. While chum salmon are very sensitive to fine sediment, we are uncertain where fine sediment levels are high and which sediment sources are most important to address. A plan to increase chum salmon spawner abundance could focus on identifying where fine sediment levels are high, pinpointing sediment sources, and identifying restoration actions to reduce fine sediment from those sources. The plan may also consider restoration in the estuary, although the potential effects of estuary restoration on chum salmon populations cannot be estimated with the current chum salmon life-cycle model.

References

- Ashcraft, S., A. Edwards, M. Zimmerman, and M. Scharpf. 2017. Grays Harbor fall chum abundance and distribution 2015 - 2016. Final Report, Washington Department of Fish and Wildlife, Olympia, WA.
- Beacham, T. D., and P. Starr. 1982. Population biology of chum salmon, *Oncorhynchus keta*, from the Fraser River, British Columbia. *Fishery Bulletin* 80:813–826.
- Beamer, E., and R. Henderson. 1998. Juvenile salmonid use of natural and hydromodified stream bank habitat in the mainstem Skagit River, northwest Washington. Skagit River System Cooperative, La Conner, WA.
- Beechie, T. J., C. Nicol, C. Fogel, J. Jorgensen, J. Thompson, G. Seixas, J. Chamberlin, J. Hall, B. Timpane-Padgham, P. Kiffney, S. Kubo, and J. Keaton. 2021. Modeling effects of habitat change and restoration alternatives on salmon in the Chehalis River basin using a salmonid life-cycle model. NOAA Contract Report NMFS-NWFSC-CR-2021-01, Seattle, WA.
- Bradford, M. J. 1995. Comparative review of Pacific salmon survival rates. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1327–1338.
- Burner, C. J. 1951. Characteristics of spawning nests of Columbia River salmon. *Fishery Bulletin* 61, U.S. Fish and Wildlife Service, Washington, D. C.
- Edwards, A., and M. Zimmerman. 2018. Grays Harbor fall chum abundance and distribution, 2017. FPA 18-09, Washington Department of Fish and Wildlife, Olympia, WA.
- Greene, C. M., and T. J. Beechie. 2004. Consequences of potential density-dependent mechanisms on recovery of ocean-type Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 61:590–602.
- Hiss, J. M., and E. E. Knudsen. 1993. Chehalis River basin fishery resources: status, trends, and restoration. Washington Department of Fish and Wildlife, Olympia, WA.
- Holt, C., B. Davis, D. Dobson, J. Tadey, P. Van Will, L. Godbout, and W. Luedke. 2018. Adapting benchmarks of biological status for persistent changes in productivity and variability in exploitation history with a focus on data limited populations (Conservation Units) of Chum Salmon in southern BC. Unpublished report, Canada Department of Fisheries and Oceans, Nanaimo, BC.
- Jensen, D. W., E. A. Steel, A. H. Fullerton, and G. R. Pess. 2009. Impact of fine sediment on egg-to-fry survival of Pacific salmon: A meta-analysis of published studies. *Reviews in Fisheries Science* 17:348–359.
- Johnson, O. W., W. S. Grant, R. G. Kope, K. G. Neely, F. W. Waknitz, and R. S. Waples. 1997. Status review of chum salmon from Washington, Oregon, and California. Technical Memorandum NMFS-NWFSC-32, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA.

- Koski, K. V. 1975. The survival and fitness of two stocks of chum salmon (*Oncorhynchus keta*) from egg deposition to emergence in a controlled-stream environment at Big Beef Creek. Ph.D. Dissertation, University of Washington, Seattle, WA.
- Lestelle, L. L., G. R. Blair, L. E. Mobernd, and Todd. 2005. Rules and concepts for modeling estuarine and marine habitat effects: summer and fall chum salmon in Hood Canal and the Strait of Juan de Fuca. Mobernd Biometrics, Inc., Vashon, WA.
- Lestelle, L., N. Sands, T. Johnson, and M. Downen. 2018. Recovery goal review and updated guidance for the Hood Canal summer chum salmon ESU. Hood Canal Coordinating Council, Poulsbo, WA.
- Moussalli, E., and R. Hilborn. 1986. Optimal stock size and harvest rate in multistage life history models. *Canadian Journal of Fisheries and Aquatic Sciences* 43:135–141.
- Phinney, L. A., and P. Bucknell. 1975. A catalog of Washington streams and salmon utilization, Volume 2: Coastal Region. Washington Department of Fish and Wildlife, Olympia, WA.
- Ronne, L., A. Edwards, and M. Zimmerman. 2019. Grays Harbor fall chum abundance and distribution, 2018. FPT 19-05, Washington Department of Fish and Wildlife, Olympia, WA.
- Salo, E. O. 1991. Life history of chum salmon (*Oncorhynchus keta*). Pages 231–310 *in* C. Groot and L. Margolis, editors. *Pacific Salmon Life Histories*. University of British Columbia Press, Vancouver, B. C.
- Sandell, T., J. Fletcher, A. McAninch, and M. Wait. 2015. Grays Harbor juvenile fish use assessment: 2013 Annual Report. Wild Fish Conservancy, Duvall, WA.
- Walters, C. J., and S. J. D. Martell. 2004. *Fisheries Ecology and Management*. Princeton University Press, Princeton, NJ.
- Weinheimer, J., J. H. Anderson, M. Downen, M. Zimmerman, and T. Johnson. 2017. Monitoring climate impacts: survival and migration timing of summer chum salmon in Salmon Creek, Washington. *Transactions of the American Fisheries Society* 146:983–995.



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