MEMORANDUM

Date: October 1, 2019

To: Chehalis Aquatic Species Restoration Plan Development Team

From: Tim Beechie and Jeff Jorgensen, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Fish Ecology Division

Colin Nicol and Caleb Fogel, Ocean Associates, Inc, under contract to U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Fish Ecology Division

Re: Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon and Steelhead Model Descriptions and Draft Diagnostic Scenario Results for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon

Introduction

Given the broad scope and importance of the *Aquatic Species Restoration Plan* (ASRP) to the Chehalis Basin Strategy, the Washington Department of Fish and Wildlife (WDFW) felt the National Oceanic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center salmonid life-cycle model (NOAA model) was needed as a complement to information generated by the Ecosystem Diagnosis and Treatment (EDT) model. WDFW believes an additional, empirically based model was needed to do the following:

- Provide quantitative assessments of habitat change (e.g., measurements of historical and current floodplain habitat or riparian conditions) that can be linked to empirically based parameters of a life-cycle model.
- Incorporate stochastic or episodic habitat conditions into a life-cycle model when developing alternative restoration strategies.
- Evaluate changes in extinction risk under various habitat restoration scenarios and when incorporating annually varying habitat conditions.
- Assess specific ASRP restoration actions (e.g., wood addition) as compared to EDT's broader categories of habitat change (e.g., habitat complexity).
- Incorporate specific assessments of changes in habitat-forming processes when evaluating restoration needs, consistent with Beechie et al. (2013a, 2013b).
- Incorporate NOAA's extensive experience with life-cycle models into the ASRP.

To meet these needs, the NOAA Northwest Fisheries Science Center developed a suite of analyses and models to assess habitat changes from historical (pre-Euro-American settlement or natural potential) conditions to present. The results of those assessments were then used in a salmonid life-cycle model with nine diagnostic scenarios to determine which types of habitat changes have had the greatest impacts on salmon populations within the Chehalis Basin and how those impacts vary by sub-basin.

Three restoration scenarios that were developed through collaboration of the ASRP Science and Technical Review Team (SRT) and Steering Committee were also modeled to evaluate potential improvements in salmon and steelhead populations in the future. The results of the restoration scenario modeling are not presented in this memorandum as they are still in review; results will be available for future phases of the ASRP. These analyses are intended to help inform development of the ASRP for the Chehalis Basin, and further modeling will occur in future phases. A key element of the ASRP is habitat restoration for anadromous salmonids of economic and cultural significance, including spring-run and fall-run Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead (*O. mykiss*), and chum salmon (*O. keta*). The results are intended to diagnose physical constraints on salmonid populations and help prioritize restoration actions.

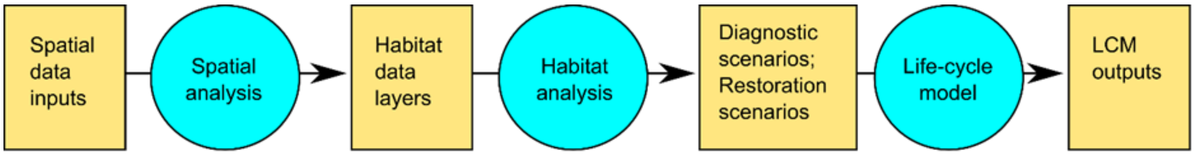
Model Overview

The NOAA analysis uses three separate models to take raw GIS data and ultimately produce results for each salmonid species under each diagnostic or restoration scenario (Figure 1). The three components of the model are the spatial analysis, the habitat analysis, and the life-cycle model (blue circles in Figure 1). This suite of models is referred to hereafter as the NOAA model. The spatial analysis processes the raw data files and produces five habitat data layers that contain current habitat areas and conditions, which are the inputs to the habitat analysis. In the habitat analysis, the five habitat data layers are used to estimate both historical and current life-stage capacities and productivities for each species and sub-basin[1] in each diagnostic or restoration scenario. That is, the outputs of the habitat analysis are individual data files for each diagnostic or habitat restoration scenario, with each file containing the life-stage and species-specific capacities and productivities used as the inputs to the life-cycle model.

The life-cycle model is then run with each diagnostic scenario for each species to diagnose the relative influences of past habitat changes on each species, as well as with each restoration scenario to assess potential improvements in each species in the future (including climate change and future development). The model outputs include estimates of the equilibrium spawner abundance (N_{eq}), as well as cumulative life-cycle productivity (P_n) and cumulative life-cycle capacity (C_n). The species currently modeled are fall-run Chinook salmon, spring-run Chinook salmon, coho salmon, and steelhead. The steelhead model diagnostic results are currently in review and are not presented here.

[1] There are 63 sub-basins, 51 tributaries, and 12 mainstem units used in the NOAA model (Figure 6).

Figure 1
Illustration of the Analysis Steps, Proceeding from the Raw Data Layers, to Habitat Data Layers, to Diagnostic and Restoration Scenarios, and Finally to the Life-Cycle Model Outputs



Raw data layers:
USGS 10-m DEM
C-CAP land cover raster
PRISM mean annual precip
Washington roads
Ecological Diversity Regions
SWIFD streamlines
WDFW Migration barriers
Summer water temperature
Riparian files
Floodplain habitat polygons
Large river edge habitat
Large river backwaters
Spawning riffles

Final habitat layers:
Large river edge habitat
Large river backwaters
Large river spawning riffles
Floodplain habitats
Attributed streamline

Diagnosis:
Migration barriers
Fine sediment
Wood loading
Shade (temperature)
Bank armor
Channel straightening
Beaver ponds
Floodplain habitats

Restoration:
Restoration actions
Climate change effects

LCM results
-Coho
-Spring Chinook
-Fall Chinook
-Steelhead

Notes:
C-CAP: NOAA's Coastal Change Analysis Program
DEM: digital elevation model
PRISM: Parameter-elevation Regressions on Independent Slopes Model
SWIFD: WDFW's Statewide Integrated Fish Distribution
USGS: U.S. Geological Survey

Diagnostic Scenarios

The diagnostic scenarios include scenarios for historical and current habitat conditions, as well as nine scenarios (listed here) in which each habitat factor is set to historical conditions independently (keeping all other factors in current conditions). This allows a comparison of which habitat factors have the most effect on abundance, productivity, and capacity of each species. The current conditions scenario sets all habitats to current conditions and therefore uses all of the current life-stage capacities and productivities for each species. The historical scenario sets all habitats to historical conditions and therefore uses all of the historical life-stage capacities and productivities for each species. The scenarios that use all current conditions except for one habitat component at a time set to historical conditions are used to help determine which types of habitat losses have most influenced salmon and steelhead populations originating in each sub-basin or ecological region. In these scenarios, the separate influences of changes in the following processes and habitat factors are each evaluated:

1. Migration barriers
2. Fine sediment in spawning gravels

3. Wood abundance change in small streams and large rivers[2]
4. Shade (temperature) changes in small streams and large rivers
5. Bank armor in large rivers
6. Large river channel straightening
7. Beaver pond changes in small streams
8. Floodplain habitat change (including all off-channel marshes, ponds, and lakes mapped in historical surveys or the most recent National Hydrography Dataset, and the influence of hyporheic exchange on stream temperature)
9. Wood abundance and floodplain habitat change combined

Tables 1 and 2 indicate which life-stage capacities and productivities are affected by each factor; details of how each habitat factor influences capacities and productivities will be included in the full report documenting the modeling that will be complete in December 2019.

Table 1
Checklist of Life-Stage Capacities (C) and Productivities (P) Affected by Each Habitat Factor in the Habitat Model and Life-Cycle Models for Coho Salmon and Steelhead

HABITAT FACTOR	C_{EGG}	P_{INCUB}	C_{SR}	P_{SR}	C_{WR}	P_{WR}
Barriers	X		X[1]	X	X[1]	X
Fine sediment		X				
Wood loading	X		X	X	X	X
Shade			X	X		
Channel length	X		X	X	X	X
Bank condition			X	X	X	X
Beaver pond area	X(neg)		X	X	X	X
Floodplain			X	X	X	X
Wood + floodplain	X		X	X	X	X

Notes:
1. Effect expressed only when barrier is 100% blocking.
C_{egg}: egg capacity
C_{sr} is summer rearing capacity
C_{wr} is winter rearing capacity
(neg): negative
P_{incub}: incubation productivity
P_{sr} is summer rearing productivity
P_{wr} is winter rearing productivity

[2] Small streams are less than 20 meters bankfull width, and large rivers are greater than 20 meters bankfull width. Bank armor on large rivers was inventoried from aerial photography, but armored segments are not visible on small streams.

Table 2

Checklist of Life-Stage Capacities (C) and Productivities (P) Affected by Each Habitat Factor in the Habitat Model and Life-Cycle Models for Spring-Run and Fall-Run Chinook Salmon

HABITAT FACTOR	$P_{PRESPAWN}$	C_{EGG}	P_{INCUB}	C_{SUB}	P_{SUB}
Barriers		X		X[1]	X
Fine sediment			X		
Wood loading		X		X	X
Shade	X[2]			X	X
Channel length		X		X	X
Bank condition				X	X
Beaver pond area		X(neg)		X	X
Floodplain				X	X
Wood + floodplain		X		X	X

Notes:
1. Effect expressed only when barrier is 100% blocking.
2. Spring-run Chinook salmon only.
C_{egg}: egg capacity
C_{sub}: subyearling rearing capacity
(neg): negative
P_{incub}: incubation productivity
$P_{prespawn}$: prespawn productivity
P_{sub}: subyearling rearing productivity

Habitat Restoration Scenarios

A No Action future scenario and three restoration scenarios developed and agreed upon by the SRT were also run, which are intended to help evaluate the potential biological benefits of habitat restoration for each species modeled. The results of this analysis are not presented in this memorandum as they are currently under review and subject to change. Results will be available for future phases of the ASRP.

These scenarios are identified as the No Action scenario and restoration Scenarios 1, 2, and 3 by the SRT, and each scenario includes estimated changes in life-stage capacities and density-independent productivities for mid-century and late century. The No Action scenario includes riparian tree growth, removal of certain barriers, future development, and climate change. The three restoration scenarios represent low, moderate, and high levels of restoration effort, described as follows (more detail on the scenarios is provided in Section 4 of the ASRP Phase 1 document):

- Scenario 1 focuses restoration effort in 38 geospatial units (GSUs)[3]; within each GSU, barriers are removed and 20% to 50% of the stream length is treated.
- Scenario 2 adds on to Scenario 1 by restoring segments in 10 additional GSUs (48 GSUs total); within each GSU, barriers are removed and 20% to 50% of the stream length is treated.
- Scenario 3 adds on to Scenario 2 by restoration segments in 19 additional GSUs (67 GSUs total); within each GSU, barriers are removed and 20% to 75% of the stream length is treated.

The primary restoration actions proposed are barrier removal, wood addition, riparian planting, and floodplain reconnection. In all scenarios, riparian and floodplain restoration are applied only in 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, passive recovery of riparian conditions is modeled as the maturation of forested buffer zones required by the Forest Practices Act (Revised Code of Washington Chapter 76.09) mature. Each restoration scenario results in improvement in life-stage capacities and productivities, based on the percentage of improvement that the scenario creates from the current to the historical conditions.

Current water temperatures in the NOAA model are from the WDFW Thermalscape model and the Portland State University mainstem temperature model. Future water temperature scenarios are modeled using estimated temperature increases due to climate change, along with riparian and floodplain restoration scenarios to estimate future temperature reduction due to increased shade or increased hyporheic exchange due to floodplain reconnection. For the climate change increases, the U.S. Forest Service NorWeST stream temperature database (Isaak et al. 2017) was used, adjusted for a change in the baseline year from 2002 to 2015, resulting in final estimated changes of +1.0°C for mid-century and +2.0°C for late century. Climate change is also expected to increase peak flows in the Chehalis Basin, but while this effect is included in the model as a stochastic effect, it is currently under review and not included in future climate change scenarios.

Future urban development is included in the scenarios as a projected change in impervious area. In the NOAA model, future development is linked to a reduction in prespawn productivity for coho salmon (Feist et al. 2011, 2017).

[3] GSUs are smaller units within a sub-basin and were used for the EDT modeling. The NOAA model results are presented by sub-basin and ecological region.

Life-Cycle Models

The NOAA Chehalis salmonid life-cycle models are population dynamics models driven by demographic rates, productivities, and capacities, where cohorts are tracked through life stages and space in an age-structured, stage-based approach. Through a series of computational loops, cohorts are moved through the life stages and ages with corresponding life-stage capacity and productivity parameters for each spatial unit. Each loop iteration represents a 1-year time step, transitioning fish from one age class to the next and applying as many intermediate life stages as necessary within a time step. That is, each time step in the model represents 1 year, and that year may include multiple life stages (e.g., fry colonization, summer rearing, and winter rearing).

The freshwater life stages are modeled in a sequence of either density-dependent or density-independent stages. Density-dependent stages use either the Beverton-Holt function or a hockey stick function, applying the life-stage capacities and productivities produced in the habitat analysis. The number and structure of life stages varies among species, but all of the salmon and steelhead modeled for the Chehalis Basin share certain stages or parameters in common (Table 3). Key differences among the species models include the following:

- The life-cycle model for coho salmon has six freshwater life stages that are influenced by freshwater habitat conditions: adult upstream migration, adult spawning, egg incubation, fry colonization, juvenile summer rearing, and juvenile winter rearing. A small percentage of fry move downstream to the mainstem Chehalis River after fry colonization, and another percentage move downstream after summer rearing. Smolts then leave the basin and experience emigration, delta-bay, and marine productivity. Most adults return to spawn at age 3, with a small percentage of jacks returning at age 2.
- The spring- and fall-run Chinook salmon models have five freshwater life stages that are influenced by freshwater habitat conditions: adult upstream migration, adult spawning, egg incubation, fry colonization, and subyearling rearing. Upstream migration productivity is a function of stream temperature for spring-run Chinook salmon but not for fall-run Chinook salmon. The remaining stages are modeled the same for both species. In the models, fry colonize natal sub-basin rearing habitats first, and fry exceeding the natal sub-basin rearing capacity move downstream through the mainstem to the bay as fry migrants. Fry migrants are assumed to be in freshwater for 2 to 4 weeks as they move to the delta-bay, and subyearling migrants are in freshwater for 12 weeks. Fry and subyearlings are assigned different productivity rates in the delta-bay and thereafter have similar ocean productivities. Most adults returning to spawn are ages 3 through 6 (a very small percentage return at age 2).
- The life-cycle model for steelhead has seven freshwater life stages that are influenced by freshwater habitat conditions: adult upstream migration, adult spawning, egg incubation, age 0+ summer rearing, age 0+ winter rearing, age 1+ summer rearing, and age 1+ winter rearing. A percentage of age-1 parr move downstream to the mainstem Chehalis River at the end of age 0+

winter rearing, and some age-1 smolts leave the basin. Some age-2 smolts leave the basin at the end of the second winter and experience emigration, delta-bay, and marine productivity, and the remaining age-3 smolts leave the basin at the end of the third winter and experience emigration, delta-bay, and marine productivity. Steelhead is the only species that has repeat spawners, with spawner ages ranging from 3 to 7.

Table 3

Overview of Common Life Stages and Calculations Used in the Life-Cycle Models of Chehalis River Spring- and Fall-Run Chinook Salmon and Coho Salmon

LIFE STAGE	MODEL CALCULATION	SPECIES
Spawning/eggs	Modeled with a hockey stick function using empirically estimated spawning capacities and fecundity values from literature. Varies with wood abundance.	All species
Incubation	Modeled using density-independent incubation productivity values. Varies with peak flow, fine sediment.	All species
Fry colonization	Density independent for coho salmon and steelhead. Modeled with a Beverton-Holt function for Chinook salmon using estimated fry-rearing capacity and density-independent productivity. For coho salmon, fry-rearing densities are not adequate to produce a density-dependent function. Varies with wood abundance.	All species
Juvenile rearing: fry-parr	Modeled with a Beverton-Holt function using empirically estimated rearing capacities and productivities. Varies with wood abundance, floodplain connectivity, temperature, beaver pond abundance, and other factors.	All species
Juvenile rearing: parr-smolt	Modeled with a Beverton-Holt function using empirically estimated rearing capacities and productivities. Varies with wood abundance, floodplain connectivity, beaver pond abundance, and other factors.	Coho salmon, steelhead
Delta-bay rearing	Density independent. Varies by species and by estuary-entry age.	All species
Ocean rearing	Density independent. Can vary by age and can be stochastic or fixed.	All species
Maturation	Adults in the ocean have age-specific maturation rates (i.e., a specified proportion of adults at each age return to spawn).	All species
Harvest	Optional. Harvest rates are currently not included.	All species
Upstream migration/holding	Density independent; empirical pre-spawn productivities based on literature values/functions for each species. Affected by temperature for spring-run Chinook salmon and impervious area for coho salmon.	All species

Note:
Additional stages and/or fish movement steps are included as needed for each species (e.g., steelhead repeat spawners or density-dependent movement of Chinook salmon fry migrants).

Diagnostic Results

The diagnostic results indicate that restoration of shade, wood, beaver ponds, and floodplain habitat provide the greatest opportunities to increase spawner abundances for coho, spring-run Chinook, and fall-run Chinook salmon in the Chehalis Basin (Table 4). Removal of migration barriers provide only a modest increase in coho salmon in the Chehalis Basin. The largest modeled restoration potentials for coho salmon are in overwinter habitats such as beaver ponds and floodplain habitats, whereas the largest modeled restoration potentials for spring-run Chinook salmon are restoring wood abundance, shade, and floodplain habitats. The largest modeled restoration potentials for fall-run Chinook salmon are restoring wood abundance and floodplain habitats. Reduction of fine sediment may also be important, but there is uncertainty in fine sediment levels and sources of fine sediment at this time, making it difficult to identify high-priority restoration actions and locations. The other factors all have explicit spatial data that help identify where restoration actions may provide significant benefits (i.e., riparian conditions, barriers, etc. have specific locations indicating where and what type of restoration should occur). The following subsections of this report describe the spatial distribution of restoration opportunities for each type of restoration activity.

Table 4

Modeled Estimates of Spawners in Each Diagnostic Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon for the Chehalis Basin

SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Current conditions	71,609	793	23,990
Historical shade	84,904 (19%)	1,111 (40%)	24,429
Historical beaver ponds	151,166 (111%)	820	26,178
Historical floodplain habitat	113,278 (58%)	1,112 (40%)	28,503 (19%)
Historical wood	88,814 (24%)	1,054 (33%)	30,879 (29%)
Historical wood and floodplain	132,791 (85%)	1,439 (81%)	36,491 (52%)
No barriers	78,116	793	24,501
Historical fine sediment	83,903 (17%)	1,223 (54%)	31,868 (33%)
Historical large riverbank condition	71,652	822	24,602
Historical large river length	71,717	852	24,907

Notes:
Estimates of spawners do not account for harvest.
Percent change in parentheses for all changes ≥10%; no color indicates changes <10%
Dark blue indicates changes >25%
Light blue indicates changes of 10% to 25%
Dark gray indicates changes >25% with high uncertainty
Light gray indicates changes of 10% to 25% with high uncertainty

Coho Salmon

The modeled estimates indicate coho salmon spawner abundance is most affected by beaver ponds and floodplains (Figure 2). The historical wood scenario increased modeled spawner abundance by only 24%, whereas the historical wood and floodplain scenario increased modeled spawner abundance by more than 80%. Historical shade, migration barriers, and fine sediment only increased spawner abundance by 8% to 19%, and all other scenarios produced less than 1% change. The diagnostic scenario with all historical conditions had a modeled spawner abundance more than 300% higher than the modeled current abundance.

Spring-Run Chinook Salmon

The modeled estimates indicate spring-run Chinook salmon spawner abundance is most affected by shade, floodplains, and fine sediment and moderately by wood abundance (Figure 3). The historical wood and floodplain combination scenario produced a 81% increase in spawner abundance. All other scenarios produced less than a 15% change in spawner abundance (no barriers, historical beaver ponds, historical large riverbank conditions, and historical large river length). The diagnostic scenario with all historical conditions had a spawner abundance of about 2,900 compared to modeled abundance under current conditions of about 800 (an increase of 259%).

Fall-Run Chinook Salmon

The modeled estimates indicate fall-run Chinook salmon spawner abundance is most affected by the wood and floodplain combination, but most of that increase was apparently from wood abundance (29% in the wood abundance scenario alone) (Figure 4). Modeled spawner abundance increased 33% in the historical fine sediment scenario, suggesting that fine sediment may be a significant issue, particularly for the fry migrant component of the population. All other scenarios produced a change in spawner abundance of 19% or less (no barriers, historical beaver ponds, historical large riverbank conditions, historical large river length, historical shade, and historical floodplain habitat). The diagnostic scenario with all historical conditions had a spawner abundance of about 56,000 compared to modeled abundance under current conditions of about 24,000 (an increase of 134%).

Figure 2
Results of the Coho Salmon Life-Cycle Model for All Diagnostic Scenarios, Without Harvest

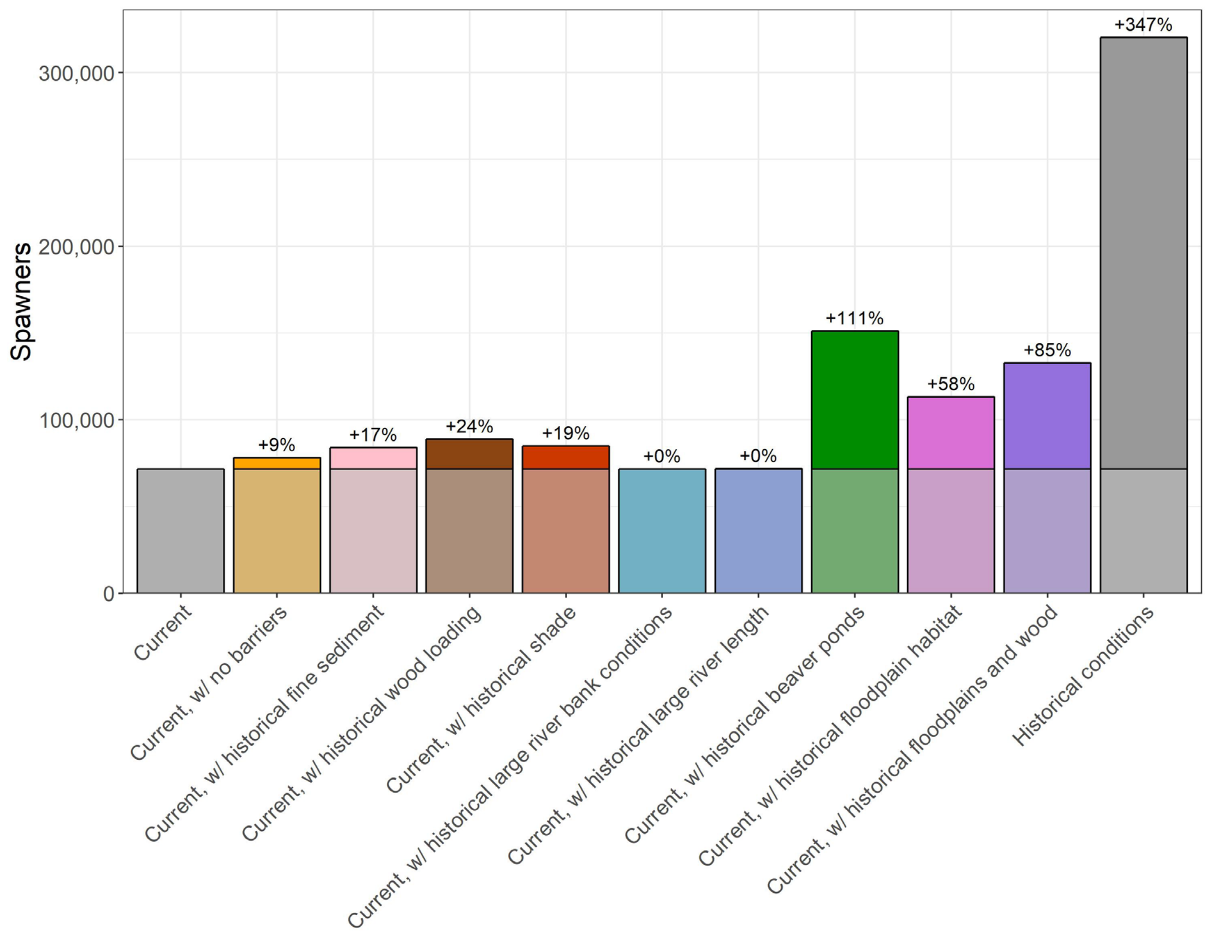


Figure 3
Results of the Spring-Run Chinook Salmon Life-Cycle Model for All Diagnostic Scenarios, Without Harvest

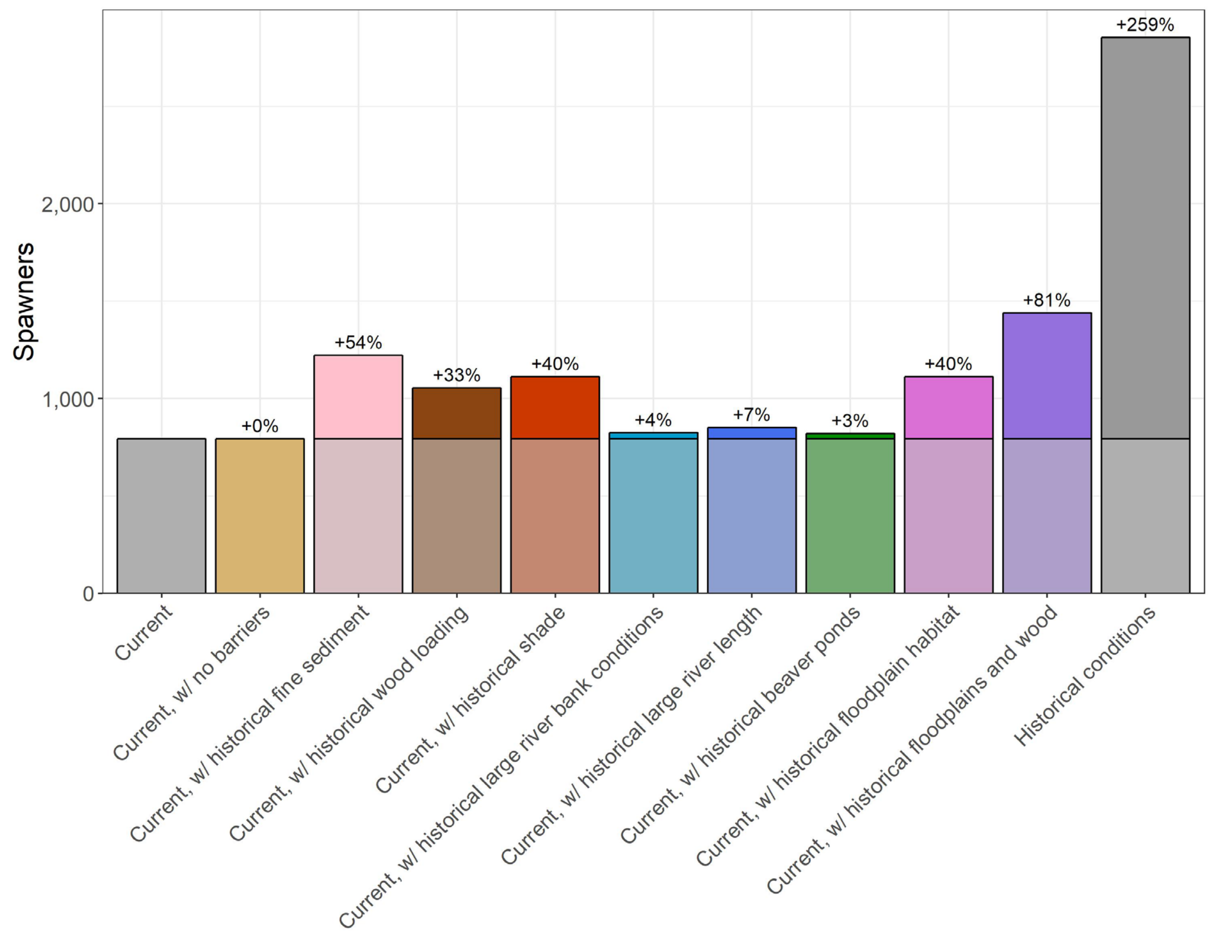
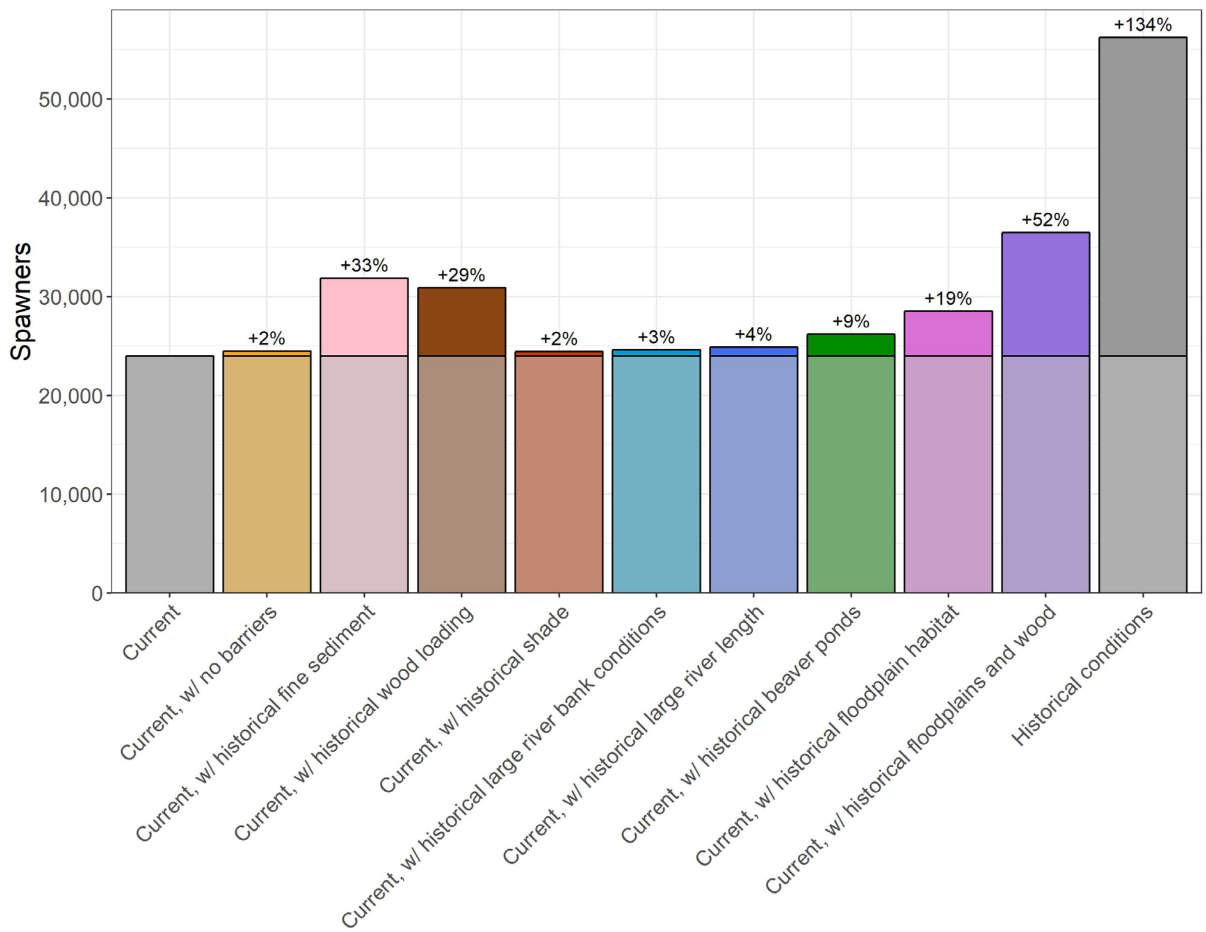


Figure 4
Results of the Fall-Run Chinook Salmon Life-Cycle Model for All Diagnostic Scenarios, Without Harvest



Diagnostic Results by Scenario and Ecological Region

The basin-level results indicate which types of habitat losses have most influenced the decline of salmon populations at the scale of Chehalis Basin, but the magnitude of each habitat loss varies spatially, as do the distributions of species within the basin. Hence, the relative importance of each factor varies among species and ecological regions. This section describes the spatial variation in modeled effects of each diagnostic scenario for each species (excluding diagnostic scenarios that produced little change for any species).

Historical Wood Abundance Scenario

The historical wood abundance scenario produced a moderate increase in modeled spawner abundance for all four species (Table 5). For coho salmon and fall-run Chinook salmon, modeled percent increases in spawner abundance relative to current conditions were similar across ecological regions (generally 20% to 40%). For spring-run Chinook salmon, the percent increase in spawner abundance was highest in the Mainstem: Upper Chehalis Ecological Region (70%), but the absolute abundance increase in that ecological region was very low (seven spawners). Most of the modeled increase in spring-run Chinook salmon spawner abundance in the historical wood scenario was in the Cascade Mountains Ecological Region (Skookumchuck and Newaukum rivers, 196 spawners).

Table 5

Modeled Increase in Spawner Abundance in the Historical Wood Abundance Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

ECOLOGICAL REGION	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	1,749 (28%)	51 (29%)	296 (25%)
Mainstem: Upper Chehalis	0	7 (70%)	64 (30%)
Cascade Mountains	1,895 (30%)	196 (33%)	505 (30%)
Mainstem: Middle Chehalis	0	--	150 (37%)
Central Lowlands	1,494 (50%)	--	27 (57%)
Mainstem: Lower Chehalis	12	--	1,120 (21%)
Black River	977 (21%)	--	289 (27%)
Black Hills	2,137 (23%)	--	254 (42%)
Olympic Mountains	4,392 (21%)	--	2,404 (26%)
Grays Harbor Tributaries	4,549 (22%)	--	1,780 (43%)

Notes:
--: not applicable (spring-run Chinook salmon do not spawn in these ecological regions)
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Historical Floodplain Habitat Scenario

Percent change in spawner abundance under the historical floodplain habitat scenario was high across all ecological regions for coho salmon, except for the mainstem Chehalis River ecological regions (Table 6). However, increases in abundance from historical mainstem floodplain habitat show as zero because there are no spawners in those reaches; increased survival of juveniles from historical mainstem habitat are included in the tributary ecological region spawner abundance totals because all spawner abundance increases are reflected in the natal ecological region spawner abundance regardless of which life stage or location increases productivity. For coho salmon, floodplain habitat is important for the overwinter life stage, while for spring-run Chinook salmon, floodplains are most important for temperature reductions during the prespawn life stage. Because fall-run Chinook salmon are less dependent on floodplain habitats, percent increases in spawner abundance are generally low for those species, although modest increases may be gained in the Grays Harbor Tributaries and Olympic Mountains ecological regions.

Table 6

Modeled Increase in Spawner Abundance in the Historical Floodplain Habitat Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook by Ecological Region

SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	2,986 (48%)	65 (38%)	88
Mainstem: Upper Chehalis	0	10 (100%)	7
Cascade Mountains	8,119 (128%)	253 (39%)	194 (11%)
Mainstem: Middle Chehalis	66	--	118 (29%)
Central Lowlands	2,084 (70%)	--	6 (13%)
Mainstem: Lower Chehalis	692 (315%)	--	329
Black River	5,659 (121%)	--	91
Black Hills	2,466 (27%)	--	91 (15%)
Olympic Mountains	11,199 (52%)	--	2,556 (28%)
Grays Harbor Tributaries	8,398 (41%)	--	1,033 (25%)

Notes:
--: not applicable (spring-run Chinook salmon do not spawn in these ecological regions)
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Historical Wood Abundance and Floodplain Habitat Scenario

The scenario that evaluates the combined effect of wood and floodplain habitat losses shows significant potential spawner abundance increases in all but the middle and upper mainstem ecological regions (Table 7). Based on effects of the individual wood and floodplain scenarios on each species, it is assumed that most of the change in coho salmon abundance is due to loss of floodplain habitat, whereas most of the change in spring- and fall-run Chinook salmon abundance is due to loss of wood.

Table 7

Modeled Increase in Spawner Abundance in the Historical Wood Abundance and Floodplain Habitat Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

ECOLOGICAL DIVERSITY REGION	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	4,831 (78%)	127 (73%)	394 (33%)
Mainstem: Upper Chehalis	0	19 (190%)	71 (33%)
Cascade Mountains	10,922 (173%)	482 (81%)	733 (43%)
Mainstem: Middle Chehalis	88	--	292 (73%)
Central Lowlands	3,959 (133%)	--	37 (79%)

ECOLOGICAL DIVERSITY REGION	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Mainstem: Lower Chehalis	744 (338%)	--	1,487 (28%)
Black River	6,659 (143%)	--	386 (36%)
Black Hills	4,492 (49%)	--	352 (58%)
Olympic Mountains	16,014 (75%)	--	5,601 (60%)
Grays Harbor Tributaries	13,473 (65%)	--	3,148 (76%)

Notes:
--: not applicable (spring-run Chinook salmon do not spawn in these ecological regions)
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
No color indicates changes <10%

Historical Beaver Pond Scenario

Not surprisingly, the historical beaver pond scenario produces very large spawner abundance increases for coho salmon (Table 8). Beaver ponds are a preferred winter rearing habitat for coho salmon, and estimated juvenile survival through the winter is considerably higher in beaver ponds than in stream channels. The model also produces small increases in spawner abundance for fall-run Chinook salmon, but spring-run Chinook salmon show very little potential response to increased beaver pond habitat area.

Table 8
Modeled Increase in Spawner Abundance in the Historical Beaver Pond Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	10,635 (171%)	10	84
Mainstem: Upper Chehalis	0	0	0
Cascade Mountains	7,872 (124%)	17	395 (23%)
Mainstem: Middle Chehalis	0	--	0
Central Lowlands	4,095 (138%)	--	20 (43%)
Mainstem: Lower Chehalis	0	--	0
Black River	3,997 (86%)	--	0
Black Hills	7,594 (83%)	--	226 (37%)
Olympic Mountains	20,178 (94%)	--	950 (10%)
Grays Harbor Tributaries	25,225 (122%)	--	630 (15%)

Notes:
--: not applicable (spring-run Chinook salmon do not spawn in these ecological regions)
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Historical Shade Scenario

The historical shade scenario produces a relatively small change in coho salmon spawner abundance (19%), despite high summer stream temperatures in the Chehalis Basin. This is because the stream temperature *change* from current to historical shade is near 0°C in most ecological regions and less than 2°C in much of the remaining area (Figure 5). However, a few tributary ecological regions have relatively large percentage changes in modeled coho salmon spawner abundance, because shade conditions are locally very poor, notably the Cascade Mountains, Black River, and Central Lowlands ecological regions (≥38%) (Table 9). While the modeled percent increase in coho salmon spawner abundance was high in the Mainstem: Lower Chehalis Ecological Region, the absolute increase was small because coho salmon are modeled only spawning in side channels, and there are very few spawners there.

By contrast, spring-run Chinook salmon show large percent increases in modeled spawner abundance in the historical shade scenario in the Cascade Mountains, Willapa Hills, and Mainstem: Upper Chehalis ecological regions (Table 9). In these three ecological regions, modeled stream temperatures have increased significantly within holding and spawning reaches for spring-run Chinook salmon, and the historical shade scenario produced at least a 35% increase in each location. It is important to note that the spring-run Chinook salmon population in the entire basin is low and the Mainstem: Upper Chehalis Ecological Region currently has very few spawners.

Table 9

Modeled Increase in Spawner Abundance in the Historical Shade Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

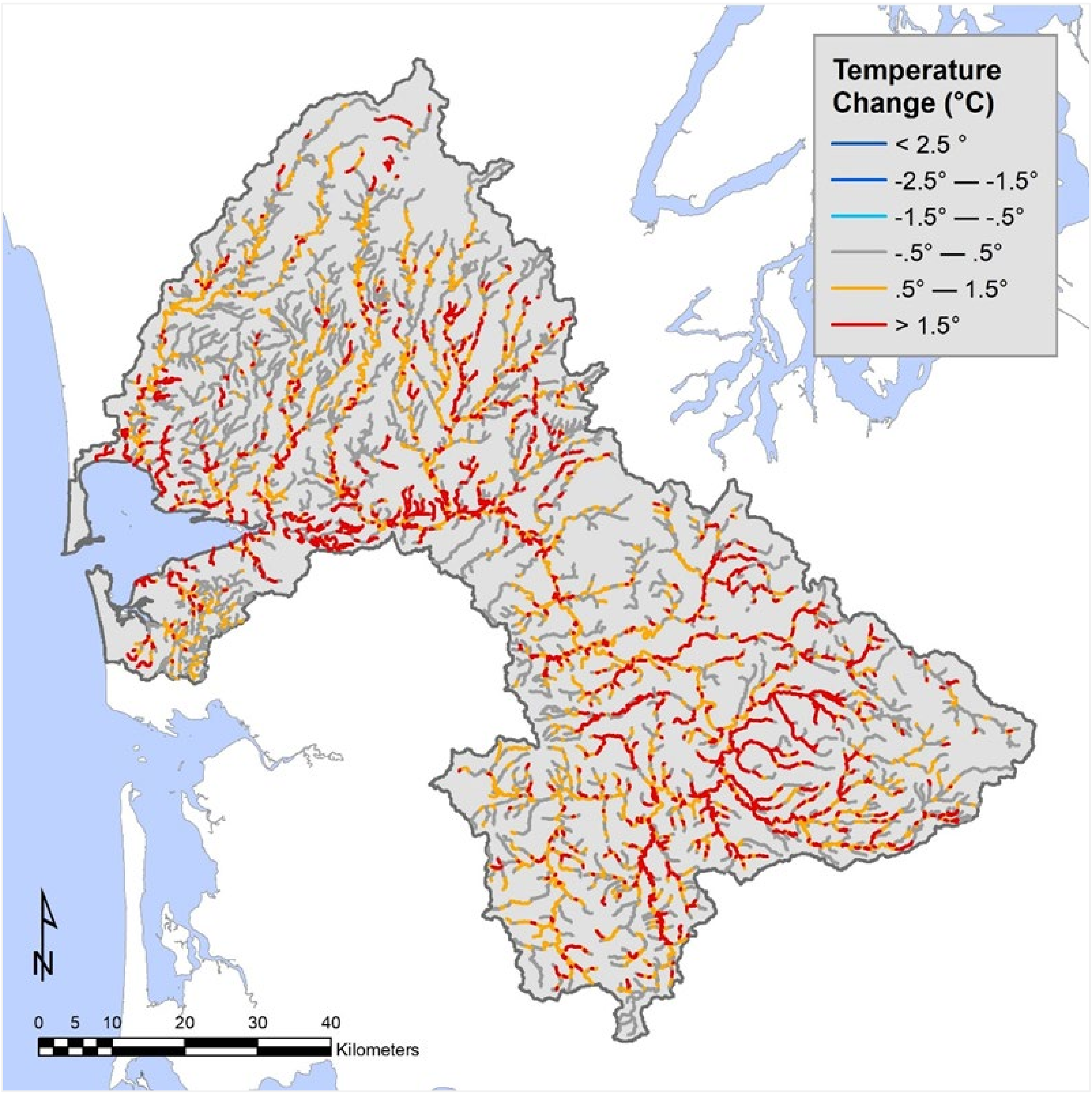
SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	1,267 (20%)	64 (37%)	37
Mainstem: Upper Chehalis	0	8 (80%)	0
Cascade Mountains	4,873 (77%)	237 (40%)	51
Mainstem: Middle Chehalis	0	--	32
Central Lowlands	1,468 (49%)	--	1
Mainstem: Lower Chehalis	134 (61%)	--	176
Black River	1,756 (38%)	--	22
Black Hills	1,257 (14%)	--	13
Olympic Mountains	1,460	--	107
Grays Harbor Tributaries	1,080	--	0

Notes:
--: not applicable (spring-run Chinook salmon do not spawn in these ecological regions)
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Fall-run Chinook salmon are less sensitive to temperature changes because they enter the river after the high summer temperatures, and the historical shade scenario produced modeled increases in abundance of less than 10% in all ecological regions.

The comparison of current to historical shade levels in the Chehalis Basin shows that more than 60% of the basin has riparian shade conditions that are currently near their historical potential, mostly on small streams inside managed forests. Much of that stream length has a modeled temperature difference of <0.5°C, indicating very little potential for continued tree growth to improve temperature conditions in the future (Figure 5). However, most stream reaches in this condition are small streams occupied mainly by coho salmon. Areas with temperature change >2°C are most concentrated in the Cascade Mountains Ecological Region, and to a lesser extent in the Black River, Willapa Hills, Mainstem: Lower Chehalis, and Mainstem: Middle Chehalis ecological regions. This pattern reflects the following two dominant riparian situations in the basin: 1) the current shade condition in many small streams is a closed canopy due to maturing riparian forests; and 2) historical shade conditions in large river channels are relatively open due to wide channels and limited shading, even with tall trees adjacent to them. Areas with the largest modeled temperature changes are in small streams with little or no canopy currently and closed canopy under historical conditions (e.g., in the Skookumchuck River sub-basin).

Figure 5
Modeled Temperature Change due to Loss of Riparian Shade in the Chehalis Basin



No Barriers Scenario

The overall response of coho salmon was small for the diagnostic scenario with barriers removed (9% change), indicating that barriers have a relatively small impact on coho salmon at the scale of the entire Chehalis Basin. However, individual barriers have locally larger impacts when viewed at the ecological region scale (Table 10). This indicates that barriers have locally large effects on coho salmon but that a very small proportion of coho salmon habitat is blocked to adult migration. There is uncertainty associated with the passage rankings assigned to each barrier by WDFW, and because these were incorporated into the NOAA model as reductions in capacity and productivity, this uncertainty carriers over into the NOAA model outputs.

No migration barriers exist in the range of spring-run Chinook salmon spawning in the barrier database, so there is no response of spring-run Chinook salmon in the diagnostic scenario with barriers removed. However, one barrier on the West Fork Chehalis River was not included in the barrier database (West Fork Falls), and that will be added in future model runs. Fall-run Chinook salmon are exposed to a few barriers, but no significant impacts on abundance exist at the ecological region scale (overall response is a 2% spawner increase).

Table 10
Modeled Increase in Spawner Abundance in the No Barriers Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	355	0	0
Mainstem: Upper Chehalis	0	0	0
Cascade Mountains	707 (11%)	0	7
Mainstem: Middle Chehalis	0	--	0
Central Lowlands	1,345 (45%)	--	59 (126%)
Mainstem: Lower Chehalis	0	--	0
Black River	438	--	0
Black Hills	776	--	0
Olympic Mountains	1,619	--	412
Grays Harbor Tributaries	1,276	--	43

Notes:
--: not applicable
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Historical Fine Sediment Scenario

For fine sediment in spawning gravels, modeled changes in fine sediment are based on forest road density, resulting in relatively large declines in incubation productivity parameters for each species. Percent change in spawner abundance under the historical fine sediment scenario was most pronounced for spring- and fall-run Chinook salmon and was somewhat lower for coho salmon (Table 11). Little spatial variation exists in modeled abundance change for all species across the Chehalis Basin. Relatively high uncertainty exists in both the predicted fine sediment levels in the

NOAA model as well as in identification of sediment sources, because no data is available relating other fine sediment sources to fine sediment levels in streams.

Table 11
Modeled Increase in Spawner Abundance in the Historical Fine Sediment Scenario for Coho, Spring-Run Chinook, and Fall-Run Chinook Salmon by Ecological Region

SCENARIO	COHO	SPRING-RUN CHINOOK	FALL-RUN CHINOOK
Willapa Hills	1,691 (27%)	167 (97%)	779 (65%)
Mainstem: Upper Chehalis	0	29 (290%)	173 (80%)
Cascade Mountains	1,770 (28%)	214 (36%)	447 (26%)
Mainstem: Middle Chehalis	0	--	370 (92%)
Central Lowlands	973 (33%)	--	14 (30%)
Mainstem: Lower Chehalis	173 (79%)	--	1,599 (30%)
Black River	534 (11%)	--	218 (20%)
Black Hills	1,770 (19%)	--	201 (33%)
Olympic Mountains	2,691 (13%)	--	3,013 (32%)
Grays Harbor Tributaries	2,692 (13%)	--	1,064 (26%)

Notes:
--: not applicable
Percent change in parentheses for all changes ≥10%
Dark orange indicates changes >50%
Medium orange indicates changes of 25% to 50%
Light orange indicates changes of 10% to 25%
No color indicates changes <10%

Potential Restoration Actions

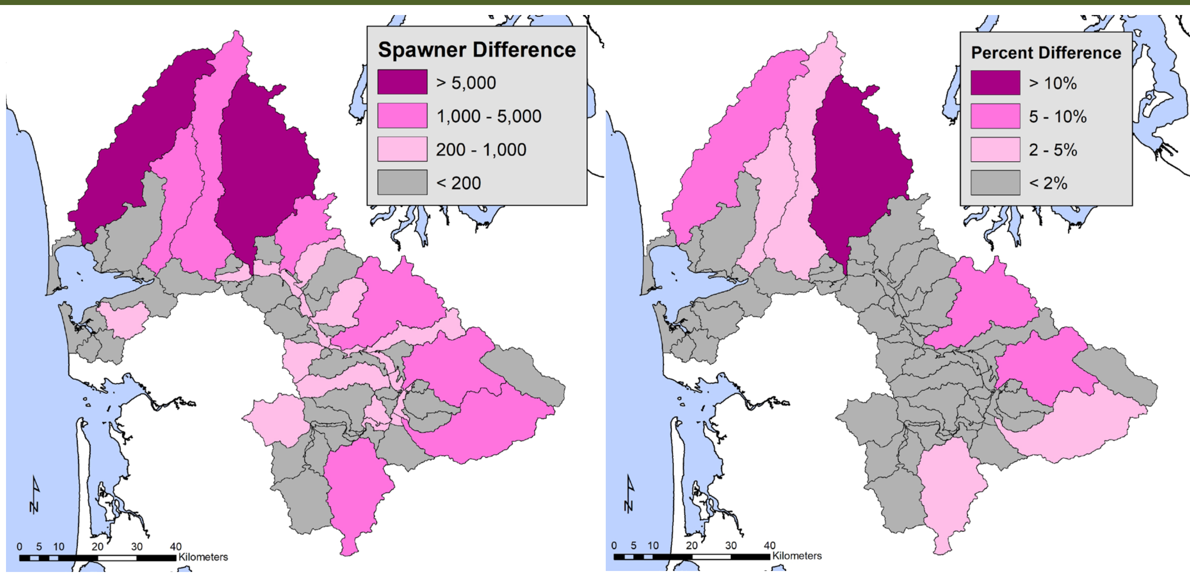
The diagnostic scenarios suggest that five types of habitat changes have had significant effects on salmon populations: loss of floodplain habitat, loss of wood from streams and rivers, loss of beaver ponds, loss or reduction of riparian forests, and, in some locations, migration barriers. Therefore, restoration of these habitats (or habitat attributes) and, to a lesser extent, removal of migration barriers have the potential to significantly improve salmon populations. A sixth potentially important habitat change—increased fine sediment and reduced incubation survival—has high uncertainty in the analysis, and it is currently not considered an important restoration action until its significance and causes are confirmed.

Floodplain and Wood Restoration

The diagnostic scenarios indicate that the combination of restoring floodplain habitat and wood abundance is likely to significantly benefit all three species, with reconnection of floodplain habitats most benefiting coho salmon and wood restoration most benefitting spring- and fall-run Chinook salmon. Importantly, diagnostic runs that separately track the benefit of restoring mainstem habitats at the sub-basin scale for each species indicate that floodplain habitat restoration in the lower mainstem (from the Skookumchuck River to the Wynoochee River) will increase multiple subpopulations of coho salmon upstream of the Wynoochee River, as well as improve spring- and fall-run Chinook salmon populations to a lesser degree. Among the tributary sub-basins, the Skookumchuck, Black, Humptulips, and Satsop rivers have large floodplain restoration potential, both when ranked by absolute abundance and percent increase (Figure 6). Each of those areas had significant historical marsh habitat that has been lost or degraded, likely due to channel incision resulting from channelization and wood removal. Only the Black River sub-basin has an appreciable portion of its historical marsh remaining today. Other sub-basins with relatively large potential absolute increases in coho salmon spawner abundance include the Wishkah, Wynoochee, Newaukum, and South Fork Chehalis river sub-basins.

By contrast, the potential benefits of wood restoration are more evenly distributed across the sub-basins, and the analysis does not indicate strong spatial priorities for wood restoration. However, the scientific literature generally indicates that wood restoration in small, moderate-slope reaches has the greatest potential to increase pool area (e.g., Montgomery et al. 1995), which benefits multiple species that occupy those reach types (primarily coho salmon and steelhead).

Figure 6
Map of Potential Coho Spawner Abundance Increase Through Floodplain Habitat Restoration, by Sub-Basin. Left Panel Is Absolute Change in the Total Chehalis Basin Abundance When Floodplain Habitat Is Set to Historical Condition in One Sub-Basin at a Time; Right Panel Is Percent Increase in the Total Chehalis Basin Abundance When Floodplain Habitat Is Set to Historical Condition in One Sub-Basin at a Time.

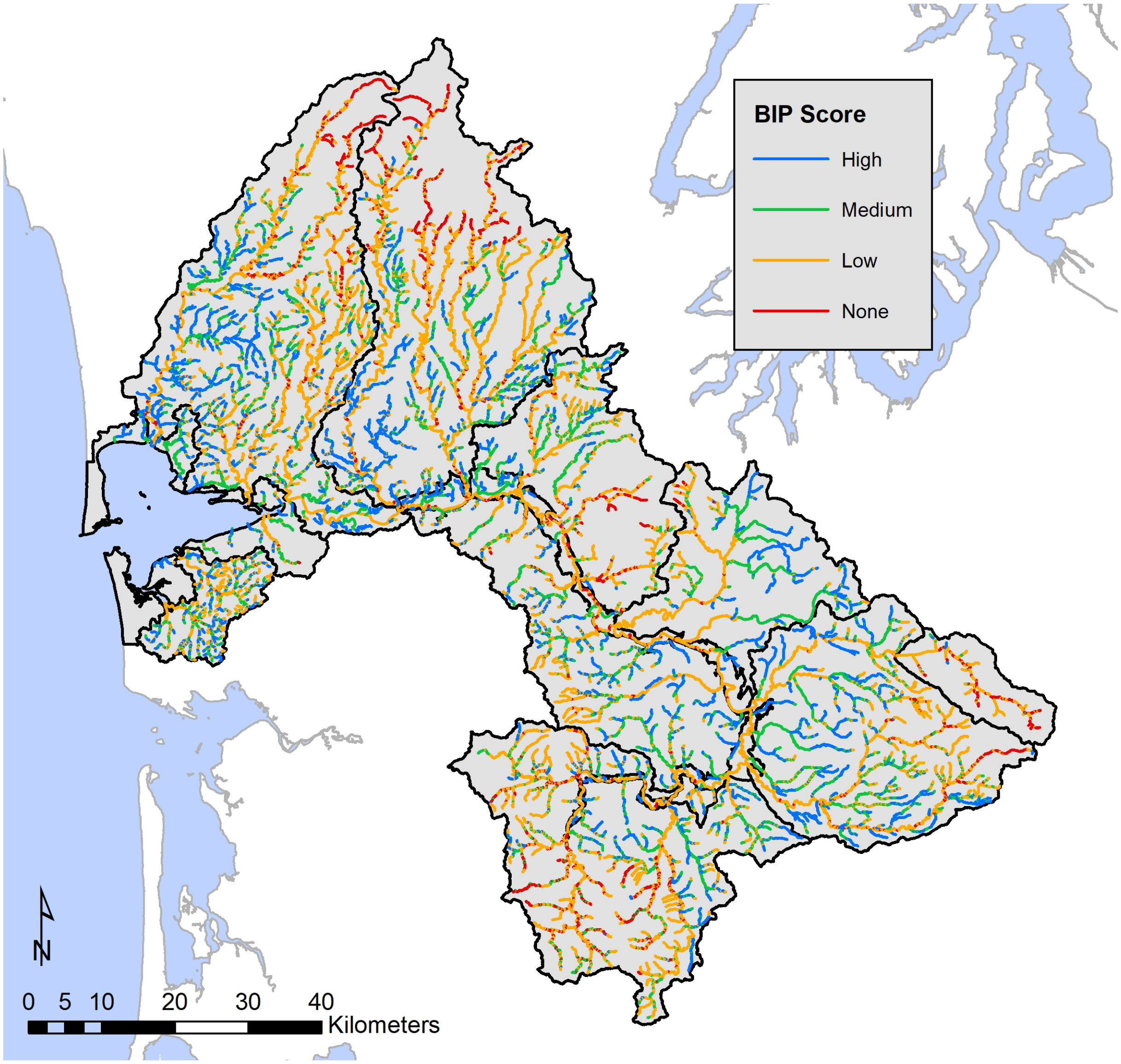


Beaver Pond Restoration

Restoring beaver ponds to small streams is likely to significantly benefit coho salmon (more than doubling the population in the historical beaver pond scenario), with relatively small effects on the other species. The potential for recovery of beaver ponds and beaver populations is greatest in small, low-slope channels with wide valleys[4] (Dittbrenner et al. 2018). A map of beaver restoration potential can help direct beaver restoration to the most suitable locations within the range of coho salmon in the Chehalis Basin (Figure 7). In general, areas with lower potential are in the upper Olympic Mountains, Black Hills, Cascade Mountains, and Willapa Hills, which are the four areas with predominantly volcanic lithology. Areas of alluvium, glacial deposits, and marine sedimentary rocks all contain significant stream length with high or medium beaver intrinsic potential (i.e., lower portions of Olympic Mountains, Grays Harbor Tributaries, Willapa Hills, Black Hills, and Cascade Mountains ecological regions, as well as the Black River and Central Lowlands ecological regions).

[4] Valleys >30 meters wide are considered wide. Channels <7 meters wide are considered small. Slopes <1% are considered low.

Figure 7
Map of Beaver Intrinsic Potential in the Chehalis Basin, Based on a Modified Version of the Beaver Intrinsic Potential Model of Dittbrenner et al. (2018)

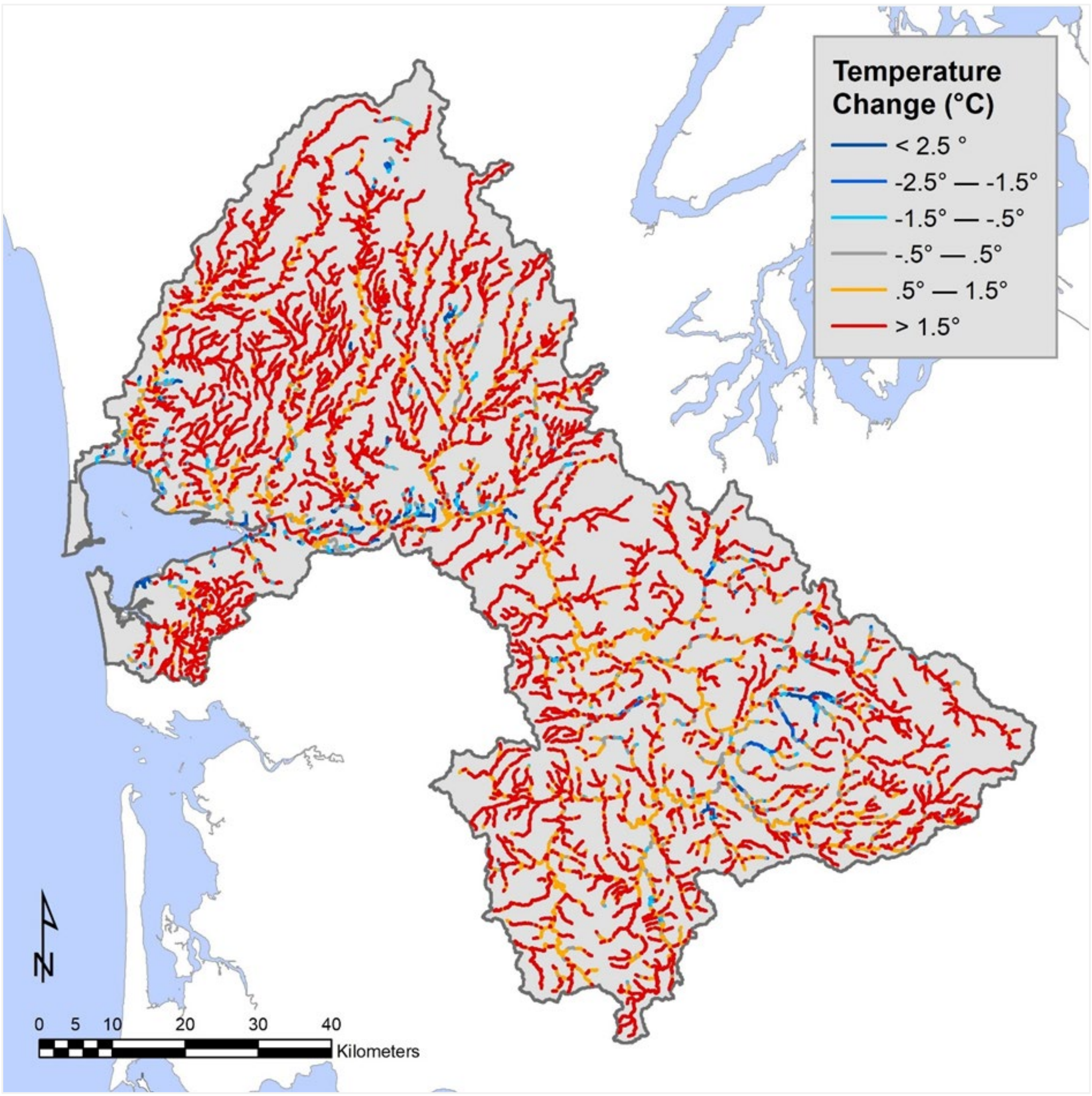


Riparian Restoration

Riparian restoration is both riparian planting and protection, and it is likely to significantly increase shade and reduce stream temperature in a few areas—some of which are very important to spring-run Chinook salmon. Modeling a historical shade scenario indicates that reduction of stream temperature in spring-run Chinook salmon holding and rearing areas can potentially increase the total spring-run Chinook salmon population by 40% under the current climate, as well as slightly increase coho salmon abundance (<10%). However, when projected temperature increases due to climate change are added, the model indicates that stream warming due to climate change will likely exceed cooling due to increased shade, and net warming is likely to occur in most of the stream network by late century. This is a result of the fact that much of the basin has shade levels at or near their historical potential, and continued tree growth does little to reduce stream temperature in the future. Figure 8 highlights areas that the riparian assessment indicates have the greatest potential for increasing shade and reducing stream temperature.

Riparian restoration may also increase wood recruitment in the future, although empirical studies and wood recruitment models both indicate that wood abundance in streams does not begin to increase until riparian forests are more than 60 years old. Currently, many riparian forests in the National Forest areas of the Olympic Mountains and Grays Harbor Tributaries ecological regions are functioning or only moderately impaired for wood recruitment (trees 75+ feet tall and riparian zone width >100 feet or trees 105+ feet tall and riparian zone width >50 feet), but in most other areas of the basin, riparian areas are impaired for the wood recruitment function. Significant increases in natural wood abundance are not expected until late century, and wood placement is recommended as an interim restoration solution, as there is limited stable wood currently in the river channels. However, riparian protection and restoration are important for assuring wood recruitment in the future.

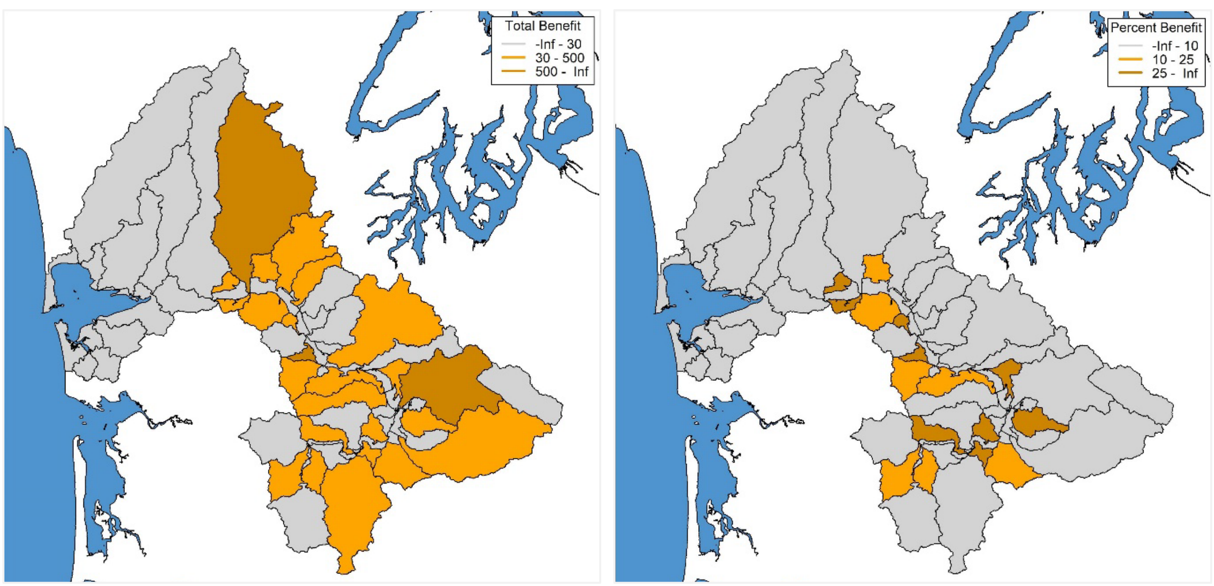
Figure 8
Areas of the Chehalis Basin with High Potential for Increasing Shade and Reducing Summer Stream Temperatures by Late Century. Blue-Colored Reaches Are Reaches in Which Riparian Restoration May Produce a Net Decrease in Stream Temperature by Late Century Despite Projected 2°C Warming due to Climate Change.



Barrier Removal

While the potential for barrier removals to benefit species is small overall (especially for spring-run Chinook salmon, which have no migration barriers within their range), specific sub-basins exist in which barrier removals can significantly improve local subpopulations of coho salmon and modestly improve local subpopulations of fall-run Chinook salmon (Figure 9). The no barriers diagnostic scenario indicates that barrier removals or passage improvements should provide the largest percent increases in coho salmon abundance in the small tributaries to the mainstem Chehalis River from Wynoochee River up to Crim Creek, but the largest potential absolute abundance increases are in the Satsop and Skookumchuck river sub-basins. A number of other large sub-basins may also have significant benefit, including Cloquallum Creek and Black, Newaukum, and South Fork Chehalis rivers. While barrier removals are not likely to provide the largest abundance increases among scenarios for any species, local benefits can be large and cost-effective to achieve.

Figure 9
Map of Sub-Basins with Highest-Potential Coho Salmon Improvement Through Barrier Removals in the Chehalis Basin. Left Panel Is Absolute Abundance Change When All Barriers Are Removed; Right Panel Is Percent Increase in Abundance When All Barriers Are Removed.



Fine Sediment Reduction

The diagnostic scenario for historical fine sediment indicates considerable potential exists to improve Chinook salmon subpopulations by reducing fine sediment levels in spawning gravels, but the model of fine sediment is based on data relating forest roads to fine sediment levels, with no other land uses considered. Moreover, limited data exists on fine sediment in the Chehalis Basin to confirm that fine sediment levels are in fact high relative to natural conditions. A reasonable conclusion from this analysis is that spring- and fall-run Chinook salmon subpopulations are very sensitive to fine sediment levels, but uncertainty exists if, or where, fine sediment levels are high within sub-basins. This suggests that field assessments of fine sediment levels and sources of fine sediment should be conducted to confirm where reducing fine sediment should be a restoration priority and which sediment sources are most important to address through restoration actions.

Summary

The NOAA model was used to evaluate nine diagnostic scenarios along with scenarios for current and historical conditions. The model results for these scenarios indicate that population declines for coho, spring-run Chinook, and fall-run Chinook salmon are most attributable to loss of beaver ponds, loss of floodplain habitats, loss of instream wood, reduced stream shade in some locations, and increased fine sediment. Migration barriers are a significant cause of decline in only a few sub-basins, and primarily for coho salmon. These diagnoses highlight that important restoration actions for salmonids include the following:

1. Reconnect floodplain habitats (side channels, marshes, and ponds) via levee setback and/or re-aggradate channels using instream wood or beaver dam analogs.
2. Restore instream wood to increase spawning and rearing habitat availability (i.e., increase gravel retention and pool formation).
3. Perform riparian restoration to increase stream shading and reduce stream temperature, as well as to provide long-term wood recruitment in the future.
4. Restore beaver populations to increase beaver pond abundance, or potentially use beaver dam analogs to mimic those features.
5. Perform targeted removal of migration barriers that block access to significant amounts of habitat.
6. Confirm areas with high fine sediment levels, identify sediment sources for those areas, and address sediment sources through restoration actions (e.g., by forest road reduction or remediation, or by reducing other sediment inputs such as agricultural or urban sources).

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