Incorporating Spatial Heterogeneity in Temperature into Climate Vulnerability Assessments for Coastal Pacific Streams

Second Progress Report to the North Pacific Landscape Conservation Cooperative
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Purpose and Objectives

Natural resource managers throughout the region encompassed by the North Pacific Landscape Conservation Cooperative (NPLCC) are tasked with complex conservation decisions that address a myriad of existing stressors to rare species (e.g., habitat loss, fragmentation, nonindigenous species). Water temperature, a key driver of ecological processes in aquatic environments, is expected to warm throughout the region as a result of climate change, further stressing stream biota. In addition to consideration of the amount that water temperature will increase as a result of climate change, successful adaptation strategies for freshwater biota will also consider how *spatial patterns* in water temperature (e.g., locations and spacing of cold water patches) may respond.

Our study objectives were to:

1. Characterize the distribution of cold water patches, identify potential hydroclimatic and landscape controls on cold patches, and evaluate how detection of cold patches depends on the spatial resolution of water temperature data;
2. Compare existing and future patterns of thermal heterogeneity to assess the potential influence of climate change; and
3. Illustrate potential vulnerability of salmon to changes in thermal heterogeneity in two case study watersheds.

Summary of Previous Progress

In in last year's report, we described progress towards these three objectives, summarized here.

Objective 1: Thermal heterogeneity, potential drivers, and spatial resolution
Thermal heterogeneity. We used data from existing remotely sensed summertime thermal infrared (TIR) water temperature surveys to characterize the number, length, spacing, and location of cool water (<15 °C) patches in anadromous portions of NPLCC rivers. We found that cool patches were distributed within warmer riverine habitat, increasing in prevalence farther upstream. Thermal heterogeneity metrics suggested that many rivers have cold patches during warm summer afternoons that should be useable by salmonids; however, variation among and within rivers was high. Conservation planners will therefore need to evaluate conditions locally and within the context of management concerns.

Potential drivers. We initiated a collaboration to evaluate this sub-objective. We gathered a team and outlined a conceptual approach, but had not yet performed any analyses.

Spatial resolution. We demonstrated that thermal heterogeneity metrics were sensitive to the spatial resolution of water temperature data and to the exact temperature thresholds used to define "cold". We aggregated the spatially continuous TIR data into a series of increasingly coarser bin sizes to simulate water temperature data collected at lower spatial resolutions, and found that patch size and spacing increased, and patches per kilometer decreased. During preparation of our proposal, we were asked to compare what we could learn from the TIR data with ongoing efforts by another NPLCC-funded project, NorWeST (www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html), which predicted mean August water temperature for rivers throughout the region using a spatial stream network model (SSNM; Isaak et al. 2010; Peterson et al. 2013). Last year, we compared the shapes of longitudinal profiles for rivers where we had data from both sources, and found them to be remarkably similar, although the TIR data showed more spatial variability.

Objective 2: Future thermal heterogeneity
The two approaches we used for simulating future thermal heterogeneity patterns both suggested that substantial within-river patchiness will remain. However, as waters warm, the exact locations, sizes, and spacing of cold patches are likely to change in any given river. We initiated work toward developing process-based models that may be more appropriate for predicting future water temperatures (i.e., they can predict outside the range of historically observed data because they are mechanistic).

Objective 3: Vulnerability of salmon in two case study watersheds
We applied the thermal heterogeneity analyses described in the first two objectives for two case study watersheds: the Snoqualmie River in Washington and the Siletz River in Oregon (Figure 1). We also began parameterizing and calibrating the process-based model for the Snoqualmie. We made some initial contacts with local planning bodies that may be interested in our work in both case study watersheds.

Progress During the Past Year

In this report, we describe efforts conducted during the past year, which focused on our two case study watersheds, the Snoqualmie and Siletz watersheds (Figure 1).

Snoqualmie

The Snoqualmie River drains 1813 km^2 before merging with Skykomish River to form the Snohomish River near Monroe, WA. Streamflow peaks in winter and spring as precipitation falls as both rain and snow (a typical hydrograph of mixed rain and snow dominant watersheds). The three main forks (North Fork, Middle Fork, and South Fork) run through mostly forested public land owned by the United States Forest Service and the Washington Department of Natural Resources before meeting near the city of North Bend and combining to form the mainstem Snoqualmie River. The river flows over Snoqualmie Falls and continues flowing northward where human land use becomes more prevalent. The Snoqualmie River supports wild populations of Chinook, chum, coho and pink salmon, steelhead, rainbow trout, cutthroat trout, and brook trout. Bull trout or Dolly Varden were also present historically; their current distribution is unknown. Chinook, steelhead and bull trout are listed as threatened under the Endangered Species Act (ESA). A Total Maximum Daily Load (TMDL) plan was developed for temperature-impaired reaches in this watershed (Stohr et al. 2011).

Siletz

The Siletz River drains about 970 km^2, and precipitation falls primarily as rain. The two major tributaries (the South and North Forks) meet to form mainstem Siletz River which empties into Siletz Bay, south of Lincoln City, OR. Timber harvest has removed old-growth in riparian zones. As a result, young conifer stands (less than 70 years old) are generally dominant along streams and rivers within the watershed (BLM, 1996). The Siletz River hosts threatened populations of coho salmon and steelhead, coastal cutthroat populations that are candidates for ESA listing, the only native population of summer steelhead in the coast region, and healthy populations of Chinook and chum salmon. The US Environmental Protection Agency and Oregon Department of Environmental Quality staff are currently developing a TMDL plan in this watershed. Sedimentation and high stream temperature are concerns throughout the watershed, especially in the South Fork subwatershed (BLM, 1996).

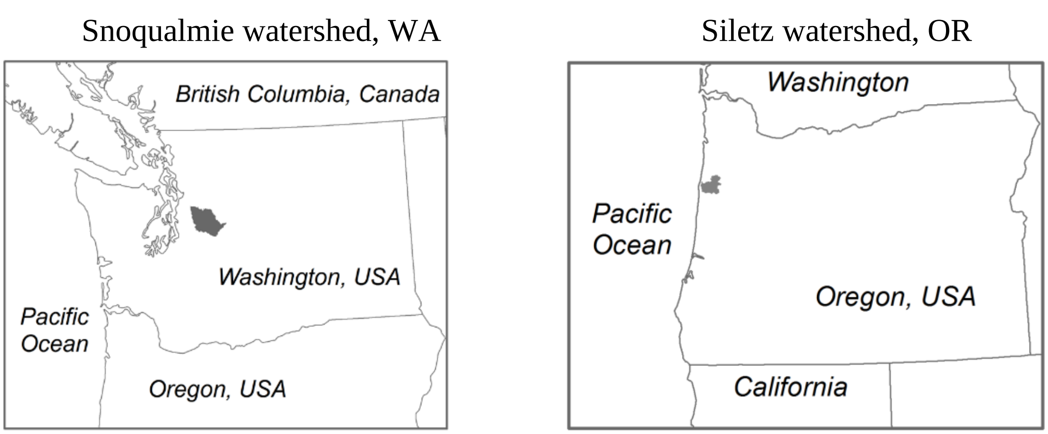


Figure 1. Locations of the two case study watersheds.

Objective 1: Thermal heterogeneity, potential drivers, and spatial resolution

Thermal Heterogeneity & Spatial Resolution
In this report, we compare connectivity among cold patches detectable within remotely sensed TIR data to connectivity among cold patches detectable using water temperatures predicted by the NorWeST project. Because TIR data were available in fewer locations (thick black lines in Figure 2) than were predicted by NorWeST (thin gray lines in Figure 2), we could only make these comparisons for a subset of rivers within each watershed.

The TIR data are essentially spatially continuous; water temperature values were sampled from remotely sensed images approximately every 150 m along the stream thalweg. NorWeST predictions were made at points every 1 km throughout the stream network. These predictions were produced by relating crowd-sourced thermistor data (green circles in Figure 2) to environmental covariates using a spatial stream network model (SSNM; Peterson et al. 2013).

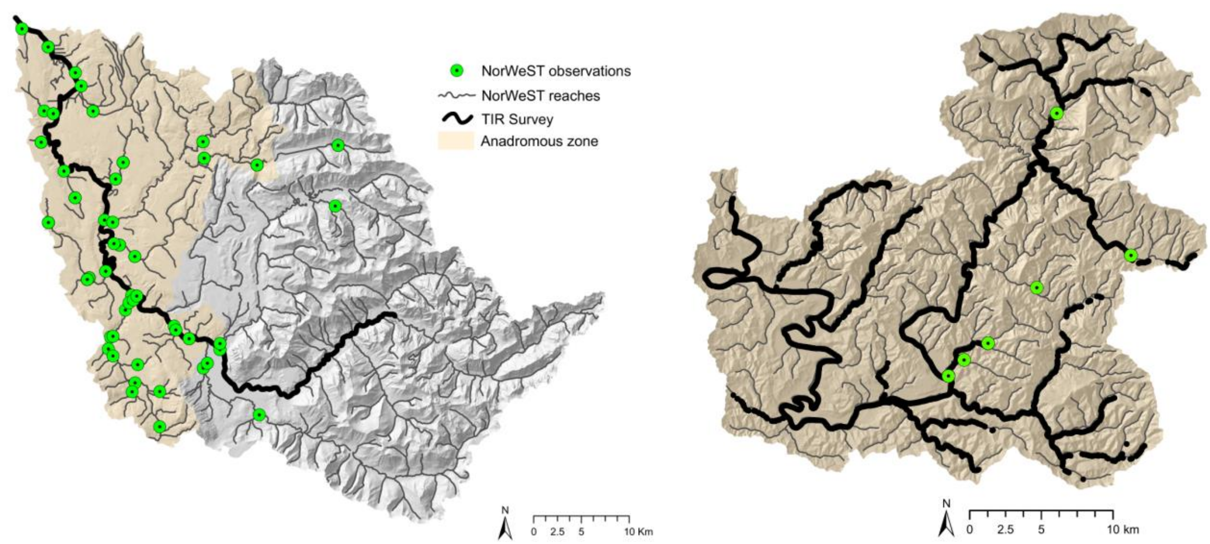


Figure 2. Spatial extent in the Snoqualmie (left) and Siletz (right) watersheds for TIR surveys (thick black lines) and NorWeST predictions (thin gray lines), and locations of observations used in NorWeST models (green circles). Anadromous salmon are restricted to areas below Snoqualmie Falls and occur throughout the Siletz basin.

Another important difference between these datasets is that TIR surveys measured maximum water remperature on one or several days (13 Aug 2006 for the Snoqualmie, and 5-7 Aug 2001 for the Siletz) whereas NorWeST models predicted mean August temperature for a range of years. Therefore, to make comparisons between datasets, we needed a common metric. We scaled the predicted mean August temperature from NorWeST for the appropriate year (2006 for Snoqualmie, 2001 for Siletz) to produce an estimated maximum August temperature using simple linear regression with the TIR data. Maximum August stream temperature from TIR and mean August stream temperature from NorWeST were correlated, but there was a lot of uncertainty in the relationships (Figure 3).

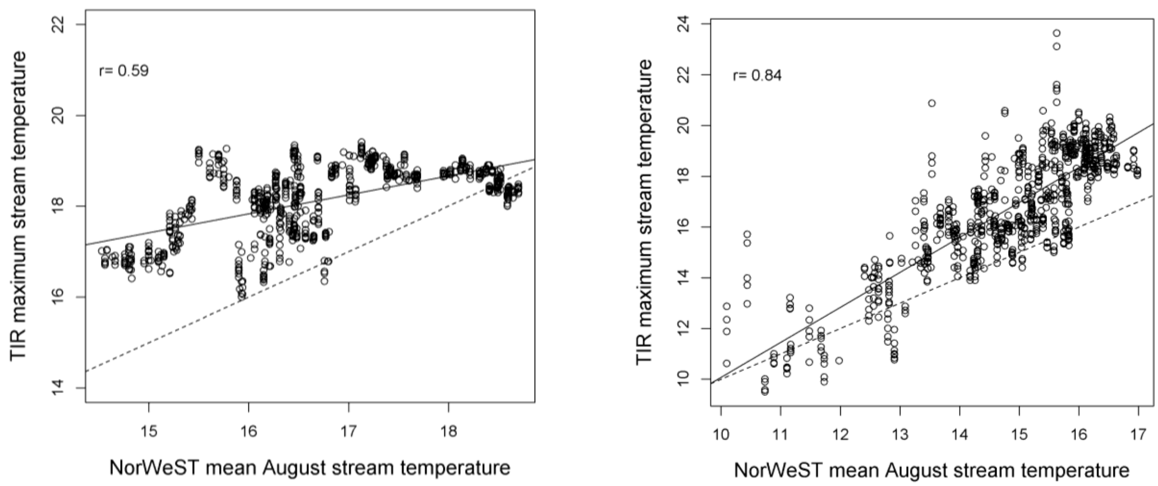


Figure 3. Relationships between observed maximum August stream temperatures (°C) from the TIR survey of Snoqualmie River in Aug 2006 (left) and the survey of Siletz River streams in Aug 2001 (right) and predicted mean August stream temperatures (°C) for corresponding locations from NorWeST during the same year. The solid line is the best fit through the data; the dotted line is the 1:1 line.

Using maximum August temperatures from both datasets (empirical in TIR, estimated in NorWeST), we then identified cold patches in ArcGIS as (1) tributary confluences where the temperature of the tributary at its mouth was <15 °C and the tributary flowed into a warmer stream, and (2) any locations within a stream where temperatures were <15 °C (this included locations surrounded by warmer water both downstream and upstream as well as the downstream-most location of cool headwater areas where water temperature first became cool). We calculated the distance from the mouth of the river to the first cold patch in each dataset, and the distances among subsequent adjacent cold patches.

For reaches common to both datasets, we were able to resolve more cool patches using the TIR data in the Snoqualmie (Figure 4) and Siletz watersheds (Figure 5). In these figures, we also show all cold patches detected in any reach using NorWeST for completeness. In anadromous fish-bearing reaches within the Snoqualmie, very few cold patches were detected using TIR data and none were detected using the NorWeST data (Figure 4). In the Siletz, more reaches common to both datasets were available. There, the TIR data, which had a finer spatial resolution, indicated numerous cold patches throughout the lower migratory corridor that were not seen in the NorWeST predictions (Figure 5). In general, the NorWeST predictions showed a more gradual change in temperature spatially whereas the TIR data indicated more thermal patchiness. SSNMs are useful for characterizing spatial patterns over broad spatial extents (e.g., thermal limits of a species' range). However, the model's smoothing process cannot reproduce observed thermal heterogeneity at very fine resolutions.

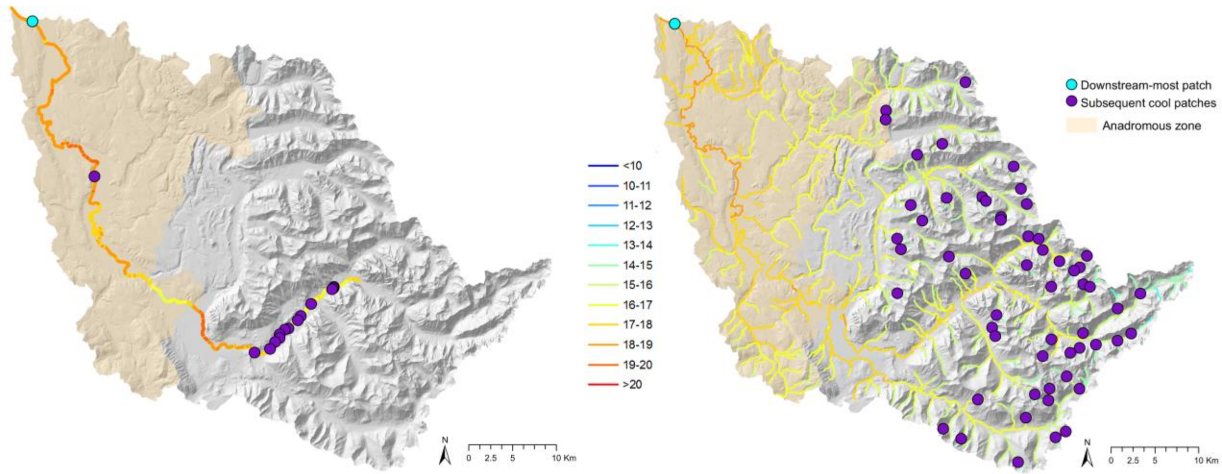
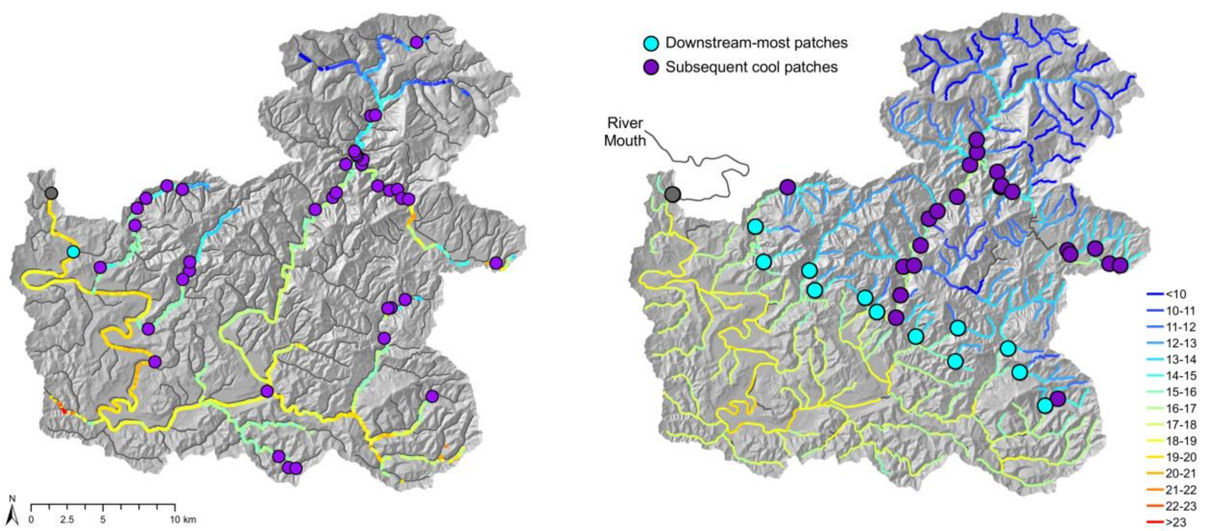


Figure 4. Locations of cold patches (<15 ^{o}C; circles) and maximum August stream temperature (^{o}C) in 2006 (colored lines) for the Snoqualmie River watershed, determined from TIR (left) or NorWeST (right). Anadromous species are limited to reaches below Snoqualmie Falls.



TIR

	Downstream-most cool patch(es)	Subsequent cool patches (< 15 °C)
Minimum		0.2
Mean	5.85	2.7
Median		1.0
Maximum		15.4
Count	1	40

NorWeST

	Downstream-most cool patch(es)	Subsequent cool patches (< 15 °C)
Minimum	23.5	0.1
Mean	55.1	2.2
Median	66.4	2.0
Maximum	74.5	6.7
Count	12	22

Figure 5. Locations of cold patches (<15 ^{o}C; circles) and maximum August stream temperature (^{o}C) in 2001 (colored lines) for the Siletz River watershed, determined from TIR (left) or NorWeST (right). The tables below each map summarize the distances in kilometers from the river mouth to downstream-most patch and the distances between subsequent cold patches encountered in an upstream direction. Anadromous species occur throughout the basin.

<u>Potential Drivers</u>

Collaborating with Dan Miller, TerrainWorks Inc., and Emily Alfred, independent contractor, we have begun work on this sub-objective. Our aim is to predict locations of cold patches using landscape and hydroclimatic variables that likely control the processes forming cold patches (see our conceptual model, Figure 6). Emily and Dan have aligned the TIR data with NetMap stream reaches, and have compiled the locations of known cold patches in the two case study watersheds. They are currently compiling a suite of potential predictor variables from NetMap and other sources, and summarizing them at appropriate spatial scales (e.g., within the reach, some distance upstream, or within the upstream watershed). We will use logistic regression (and potentially also a random forest classification approach) to construct models. We will explore the contribution of covariates and examine goodness of model fits. We will examine predictive accuracy by holding out a subset of data when fitting the model and then assessing how well it predicts known cold patches in other locations. We expect to have initial results soon, and should have some basic working models by the end of this project. We can then use these pilot data to seek additional funding to explore this further and in other watersheds.

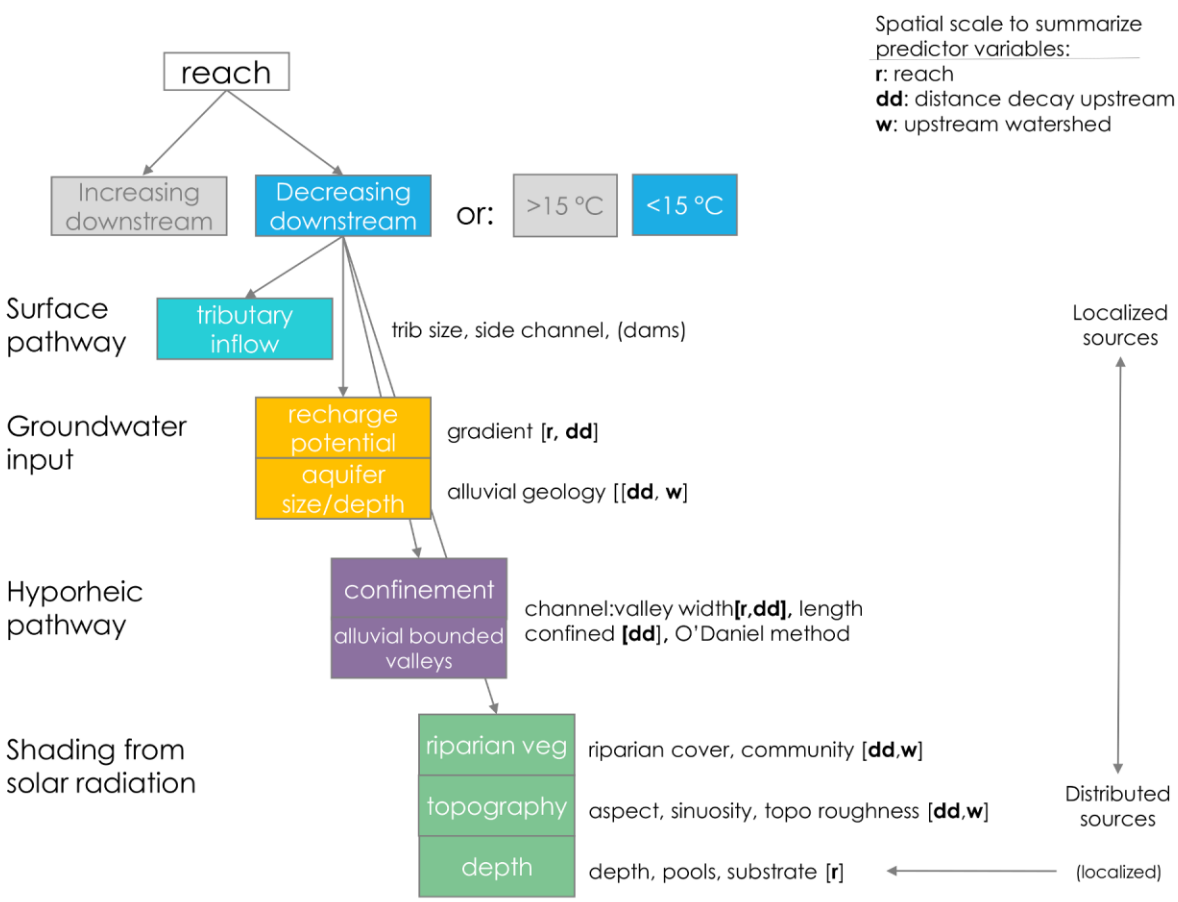


Figure 6. Conceptual model for predicting locations of cool water patches based on environmental covariates.

Objective 2: Future Thermal Heterogeneity
In our two case study basins, we compared potential patterns of thermal heterogeneity expected in a warmer future predicted using two models: an empirical model (random forest regression, described in last year's report) and a process-based model, the Distributed Hydrology Soil Vegetation Model (DHSVM)-RBM.

Model Description and Calibration
DHSVM-RBM is a hydrology and stream temperature model that integrates the spatially distributed hydrologic Model DHSVM (Wigmosta et al. 1994), a vector-based stream temperature model RBM (Yearsley, 2009), and a riparian shading model (Sun et al., 2014). DHSVM-RBM explicitly represents both overland surface and subsurface hydrology related to stream temperature dynamics and simulates streamflow and water temperature throughout a stream network at high spatial (30-150 m) and temporal (typically 3 hours) resolution. DHSVM-RBM has been used to project changes in water temperature in a small urban watershed, Mercer Creek, WA (Sun et al. 2014) and in Puget Sound Rivers, WA (Cao et al. 2016) under changing climate and land use.

The model is forced with meteorological variables such as precipitation, temperature, wind speed, relative humidity, and incoming shortwave and longwave radiation at 3 hour intervals. Geospatial input data such as surface topography, vegetation cover, soil type and depth, and digital elevation data are used to represent spatially distributed land surface characteristics. To explicitly represent riparian shading, the model includes riparian vegetation height, stream width, crown diameter, leaf area index (LAI), and canopy to bank distance (Sun et al. 2014). Stream width was estimated using NetMap (www.terrainworks.com).We obtained riparian tree diameter from the Interagency Vegetation Mapping Project (www.blm.gov/or/gis/data/ivmp.php). We estimated tree height using the relationship between tree diameter and tree height (Nord-Larsen and Nielsen 2015). We estimated crown diameter using the relationship between tree diameter and crown diameter (Gill et al. 2000). Finally, tree height and crown diameter were used as calibration parameters.

The model was calibrated in two steps. First, observed streamflow was used to adjust hydrologic parameters such as precipitation lapse rate, temperature lapse rate, lateral saturated hydraulic conductivity, and exponential decrease in hydraulic conductivity. Once DHSVM was calibrated, the RBM parameters were calibrated by comparing simulated and observed water temperature. Time-series of water temperature at specific locations and a snap shot of spatial distribution (TIR data) were used as historical observations. After the calibration was done, we used the model to simulate streamflow and water temperature for past and future time periods.

Climate Data
We used the daily gridded historical observational dataset developed by Livneh et al. (2015), adjusted to match the monthly time series from PRISM (Daly et al. 2008). The Livneh et al. dataset was created using weather station observations of daily precipitation and daily maximum and minimum temperature, while daily wind speed was based on the NCEP–NCAR reanalysis (Kalnay et al. 1996). For this report, we used one global climate model from the Coupled Model Intercomparion Project (Phase 3) (CMIP3) that was statistically downscaled using the Hybrid Delta approach (Tohver et al. 2014) for a 30-year future time period: 2080s (2070–2099) (Hamlet et al. 2013). We are currently preparing DHSVM forcing data from GCMs from the

Coupled Model Inter-Comparison Project, Phase 5 (CMIP5; Taylor et al. 2012) under representative concentration pathway (RCP) 8.5, a high emissions scenario (Van Vuuren et al. 2011). Daily maximum and minimum air temperature, and precipitation and wind speed from the GCMs will be statistically downscaled to 1/16th degree resolution using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012). For consistency with the corrected Livneh et al. (2015) dataset used for this project, the MACA data will be also bias-adjusted so that monthly MACA data will match PRISM (Mauger et al. 2016). For the final report, we will use 30-year time windows of 1970-1999 (the 1980s) for historical runs and 2070-2099 (the 2080s) under RCP 8.5 to estimate the future change relative to current conditions.

Results

The DHSVM-RBM model is calibrated well with observed streamflow for both the Snoqualmie and Siletz Rivers (Figure 7). For observed time-series water temperature data, multi-year data is available for the Snoqualmie River near Snoqualmie and only one year of data is available for two sites in the Siletz River. We plotted the time series for one site at the Snoqualmie and one year of data for two sites at the Siletz River: South Fork Siletz at the mouth and Warnicke Creek at the mouth (top panels in Figure 8). For longitudinal spatial patterns, we compared TIR data with simulated data from the upper Middle Fork nearly to the mouth of the Snoqualmie River and from the upper North Fork to the lower mainstem of the Siletz River (bottom panels in Figure 8). DHSVM-RBM reproduced spatial patterns of water temperature well in some places and not in others.

The DHSVM simulated future streamflows that were more extreme (i.e. higher winter and lower summer streamflows as shown in Figure 9) and warmer maximum water temperatures (bottom panels in Figure 10) than were observed historically.

Using the approach for quantifying thermal patches from longitudinal stream temperature profiles that was described in the first report, we see that the three cool patches that were present in the Snoqualmie River historically disappear in the future scenario. A number of patches exceeding 20 °C, a stressful temperature for salmon, are predicted in the future (top panels in Figure 11). All of the tolerable patches that were located in downstream reaches of the Siletz historically will become warm patches that are stressful for Pacific salmon and trout in the future. Cold patches will remain in only a small portion of the North Fork Siletz River in the future.

Compared to the random forest model predictions (top panels in Figure 9), future water temperature predicted by the DHSVM was considerably warmer in the Snoqualmie, but less so in the Siletz (bottom panels in Figure 9). Interestingly, the Snoqualmie thermal profile increased rather uniformly whereas this pattern was less pronounced in the Siletz. One difference between these two models was that the median value from the GCMs under RCP 8.5 (CMIP5 data) were used for the random forest model whereas one GCM under the A1B scenario (CMIP3 data) was used for DHSVM-RBM. We will check whether similar patters occur when we use the same data (CMIP5) for DHSVM-RBM.

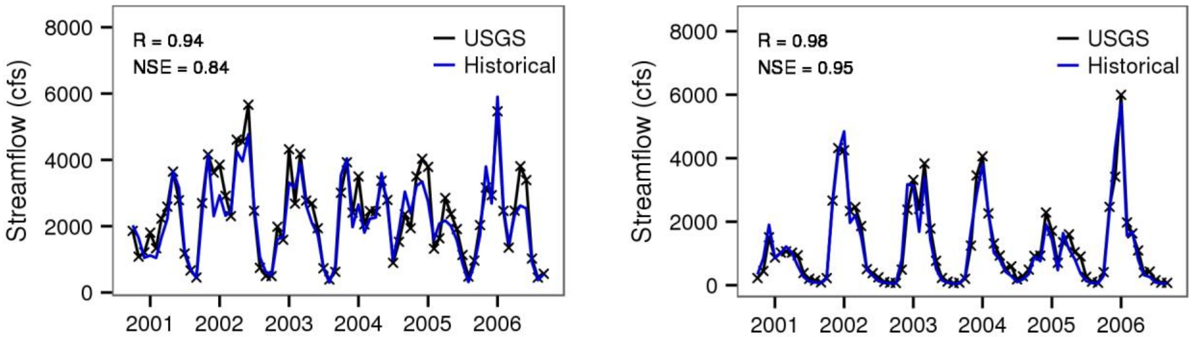


Figure 7. Observed (black) and simulated (blue) monthly streamflow (Water Years 2001-2006) at the Snoqualmie River near Snoqualmie (left) and at the Siletz River at Siletz (right).

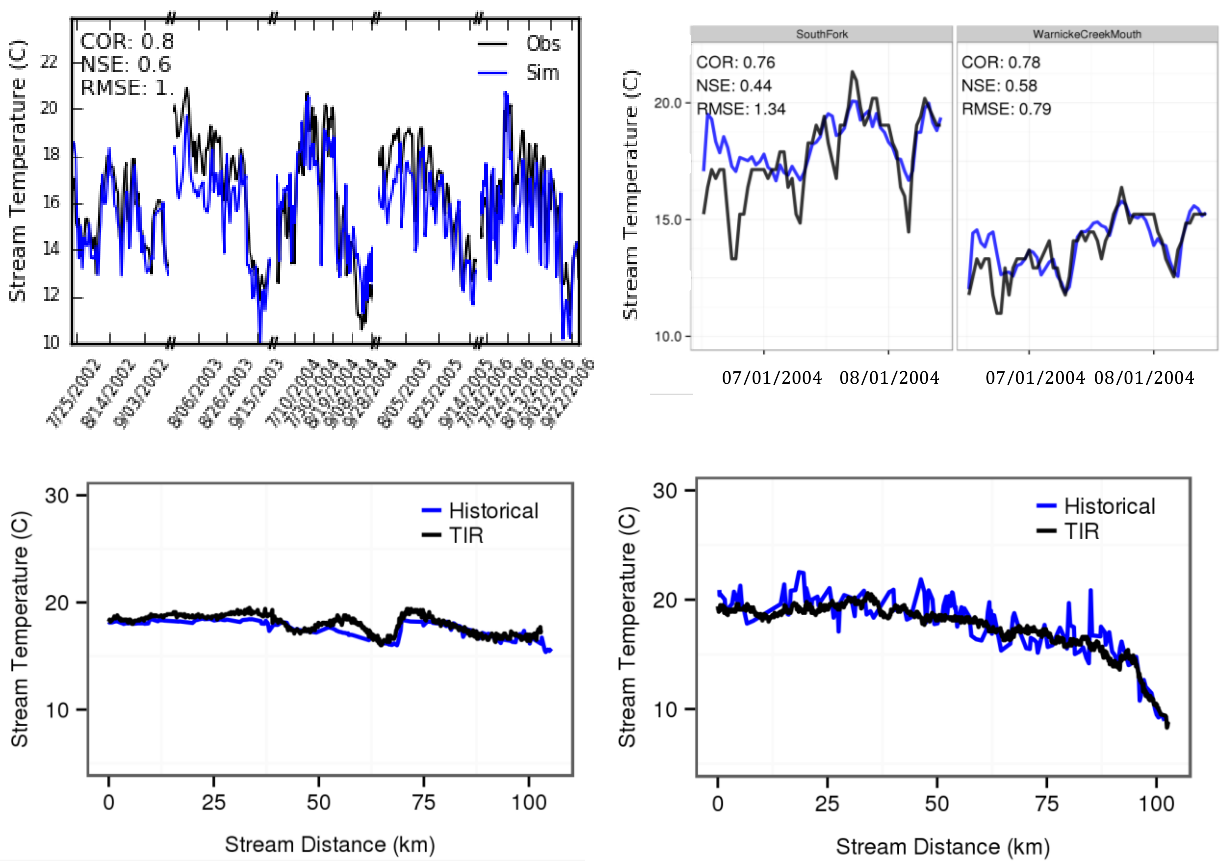


Figure 8. (Top) Observed (blue lines) and simulated (black lines) time-series at the Snoqualmie River near Snoqualmie (2002-2006 summers, left) and at South Fork Siletz at mouth and Warnicke Creek at mouth for the Siletz River (2004 summer, right). (Bottom) Longitudinal spatial patterns of stream temperature from the mouth of the Snoqualmie River to the upper Middle Fork on 13 August 2006 (left) and from the mouth of the Siletz River to the upper North Fork on 05 Aug 2001 (right).

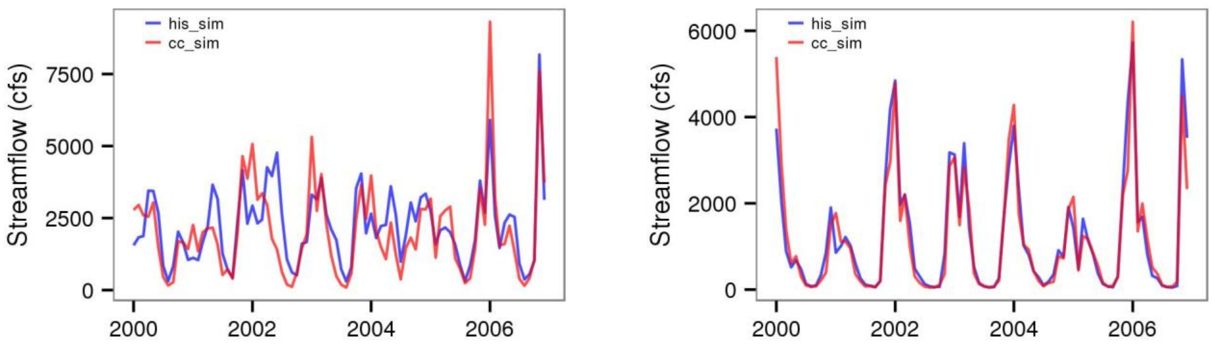


Figure 9. Simulated historical (blue) and future (red) monthly average streamflow in the Snoqualmie River near Snoqualmie (left) and the Siletz River at Siletz (right).

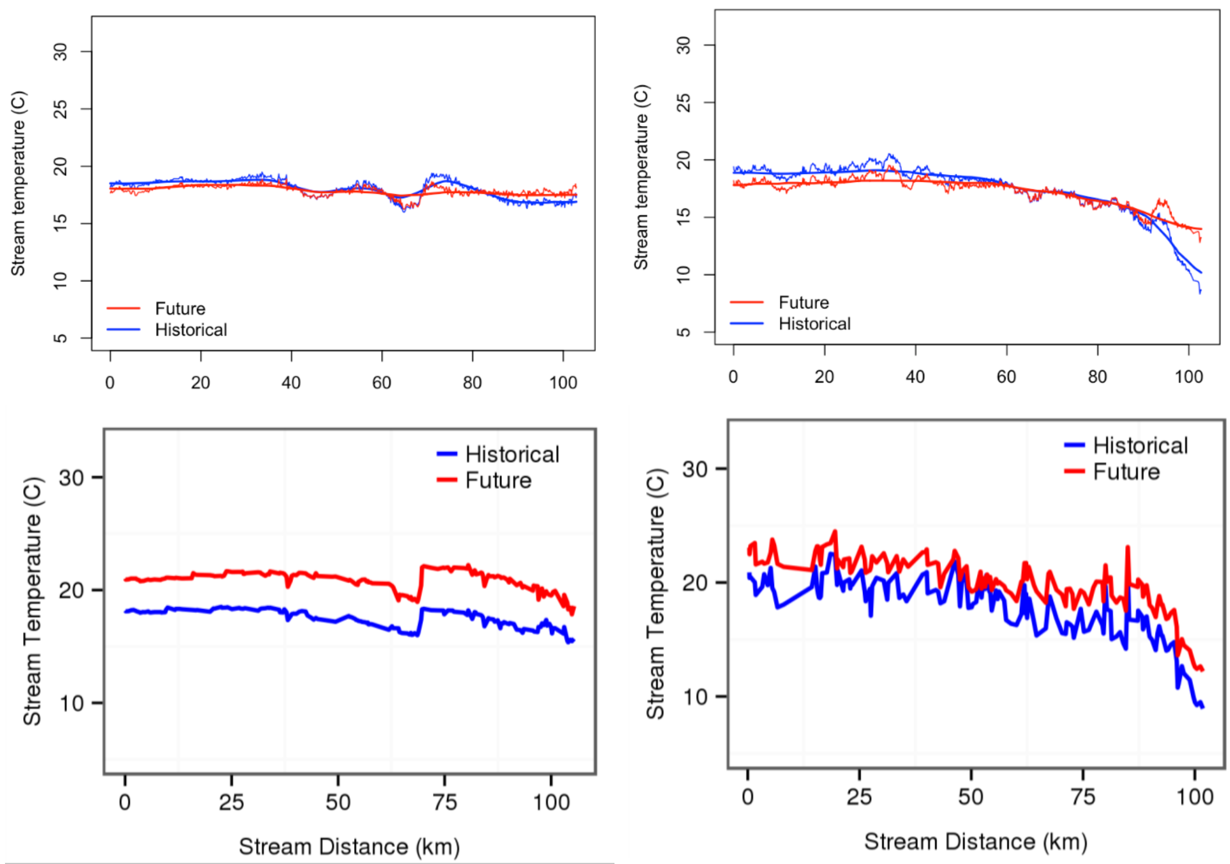


Figure 10. Comparison of longitudinal profiles predicted with random forest using the median from GCMs under RCP 8.5 (a statistical approach described in the previous report; top panels) and longitudinal profiles predicted by DHSVM-RBM using the Echam5 A1B scenario (a process-based model described in this report; bottom panels) in the Snoqualmie (left) and Siletz (right) river mainstems.

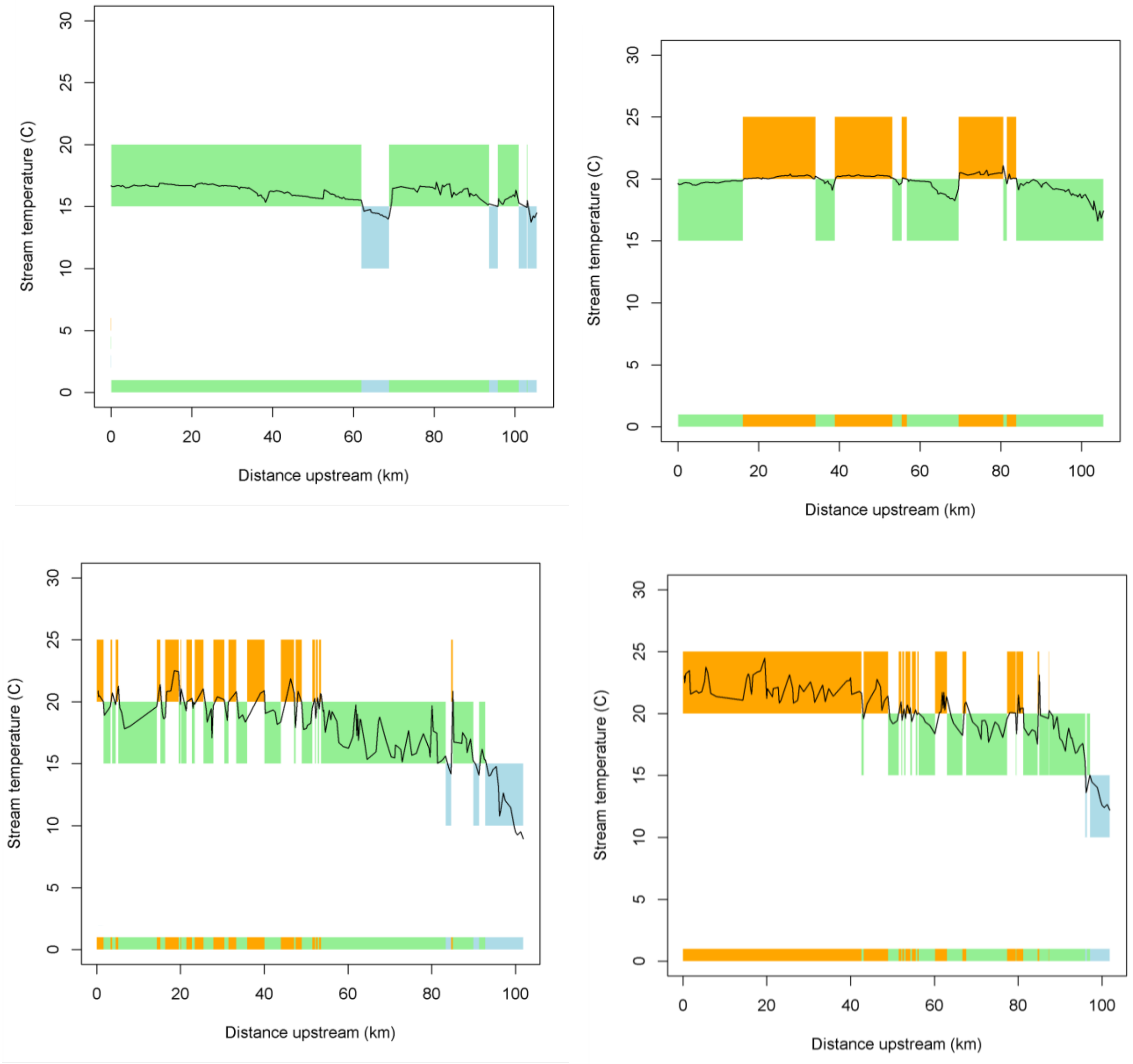


Figure 11. Cool (blue), tolerable (green) and warm (orange) thermal zones in longitudinal stream temperature profiles defined by temperature thresholds of 15 and 20 °C, for the Snoqualmie (top) and Siletz (bottom) river mainstems, predicted by DHSVM for historical (left) and for the 2080s using the Echam5 A1B scenario (right).

Objective 3: Vulnerability of Salmon

Vulnerability assessments typically consist of 3 axes: sensitivity, exposure, and adaptability. It is beyond the scope of this project to address whether or not salmon can adapt to changes in thermal heterogeneity, but see Crozier and Hutchings (2014) for a discussion.

We estimated the sensitivity (S) of adult and juvenile salmonids to warm water, based on values suggested in the literature (e.g., Poole et al. 2001, Burke et al. 2010) and geographic ranges for each species. Each species and life stage was rated as highly sensitive (a score of 3), moderately sensitive (a score of 2), or insensitive (a score of 1). We assumed bull trout to be most sensitive and mainstem spawners like Chinook salmon to be less sensitive. Adult steelhead make use of cold tributaries when migrating upstream when river temperatures exceed 20 °C (Keefer and Caudill 2015) whereas Chinook may be less likely to use cool areas (Keefer et al. 2015).

We estimated exposure (E) to warm water during August (the timeframe for which we had water temperature data). Scores ranged from 0 (no exposure) to 3 (high exposure), calculated as:

$$E = p(u + n + s)$$

where:

p = the binary presence or absence of that life stage during August (present=1, absent=0). Values were derived from maps of range extent and life history timing for each species (Figures 12 and 13). This variable acts as a switch; if the life stage is not present, the exposure (and therefore vulnerability) will default to zero.

u = a habitat use rating representing the proportion of time during August that the life stage is present. We used life history timing in Figures 12 and 13 to estimate habitat use; values ranged from 0 (no use) to 1 (high use).

n = a rating indicating cold water refuge availability ranging from 0 (high cold patch availability) to 3 (no patches available). To calculate this rating, we enumerated the cold water patches (the determination of which were described in Objective 1; see left panels in Figures 4 and 5) per kilometer within the spatial extent used by each species. We normalized densities to a maximum of 0.333 (i.e., 1 cold patch per 3 km on average); we assumed densities higher than this would minimize exposure to warm temperatures. Finally, we subtracted this value from 1 so that high cold patch densities would have low scores (i.e., indicating low exposure to stressful conditions).

s = a rating of the spacing among cold patches, ranging from 0 (low spacing, or high connectivity) to 1 (high spacing, or low connectivity). We used the 75th percentile of distances among all adjacent cold patches within the spatial extent used by the species. We normalized these values to a maximum spacing of 10 km between patches; we assumed that fish would do best when they didn’t have to swim more than 10 km through warm water to access cold patches. Our use of the 75th percentile value captured the majority of conditions; we assumed that fish can occasionally swim longer distances.

We multiplied sensitivity and exposure scores to get vulnerability scores: $V = SE$, ranging from low (scores of 1) to high (scores of 9) for the Snoqualmie (Table 1) and Siletz (Table 2).

We repeated this process to estimate potential future vulnerability. To estimate future cold patches, we assumed a homogeneous increase in water temperature of 2 °C (Figure 14).

Vulnerability ratings ranged from zero (not vulnerable) to nearly 6 (out of 9) in the Snoqualmie watershed. Adult and juvenile chum salmon and juvenile pink salmon are not present during August and therefore had no vulnerability. Whereas steelhead, coho, Chinook, and adult pink salmon had higher vulnerability, especially for adults which are both more sensitive to warm temperatures and more likely to be using warm habitats during August. Expected changes to cold patch abundance and distribution in the future did not increase vulnerability because the current conditions already had very few patches. Note, however, that we could only quantify patches in the mainstem and Middle Fork Snoqualmie; likely, there are numerous other colder areas in tributaries that we did not sample. We did not have range extents for cutthroat or bull trout, so our estimated scores for these species are best guesses and will need to be revisited; this uncertainty is denoted with question marks in Table 1.

We had TIR data for many more streams in the Siletz. There, vulnerability ratings ranged from zero to over 4. Adult and juvenile chum salmon and adult winter steelhead are not present during August and therefore had no vulnerability. Summer steelhead, coho, and Chinook salmon had higher vulnerability, especially for adults which are both more sensitive to warm temperatures and more likely to be using warm habitats during August. Expected changes to cold patch abundance and distribution in the future increased vulnerability for all species. We did not have range extents for cutthroat trout, so our estimated scores for this species are best guesses and will need to be revisited; this uncertainty is denoted with question marks in Table 2.

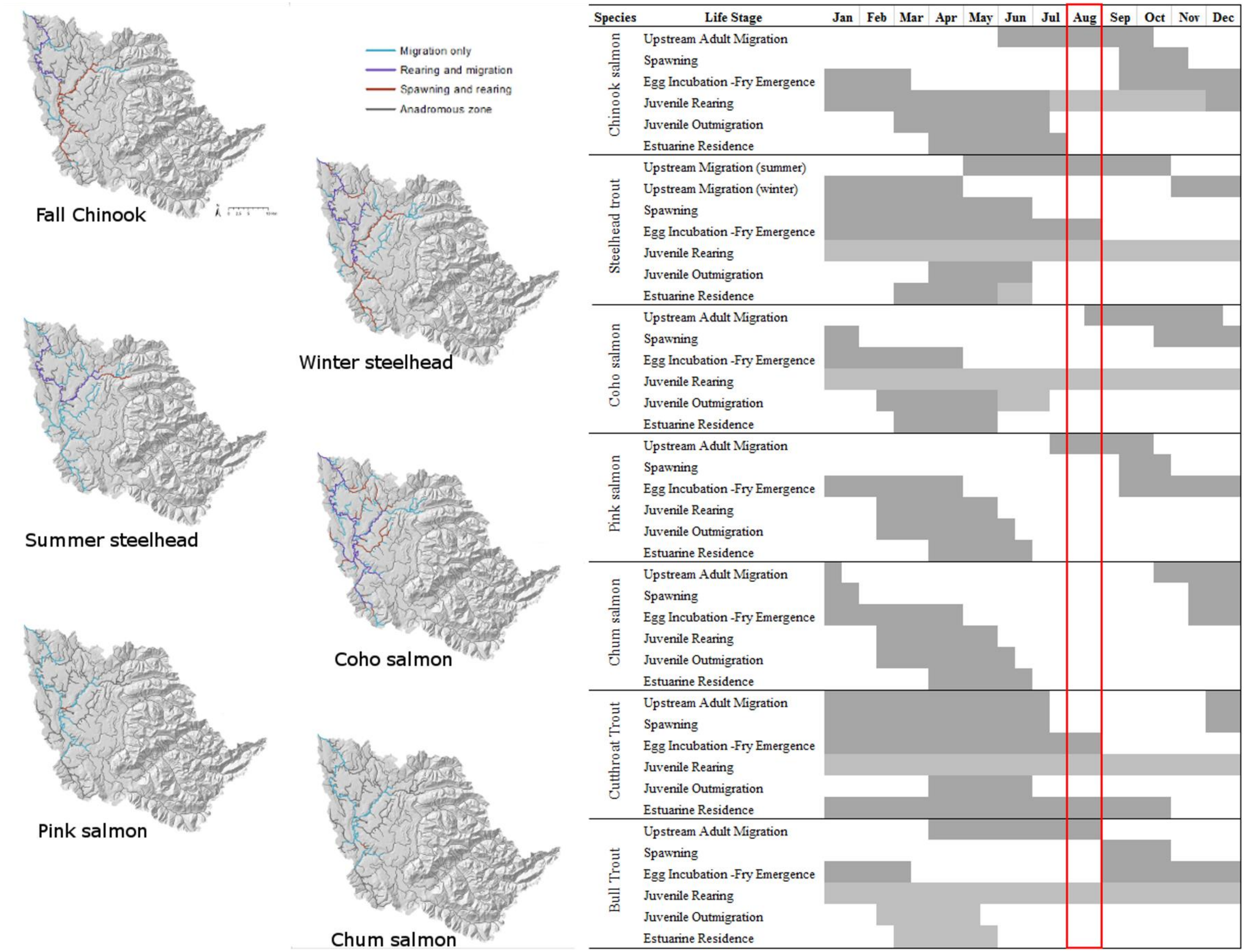


Figure 12. Spatial extent (maps) and timing (right) for salmonids in the Snoqualmie River watershed. Note: we did not have spatial extent information for cutthroat or bull trout. Headwater reaches in the North and Middle Forks and Tolt River are managed for char spawning and rearing (Stohr et al. 2011).

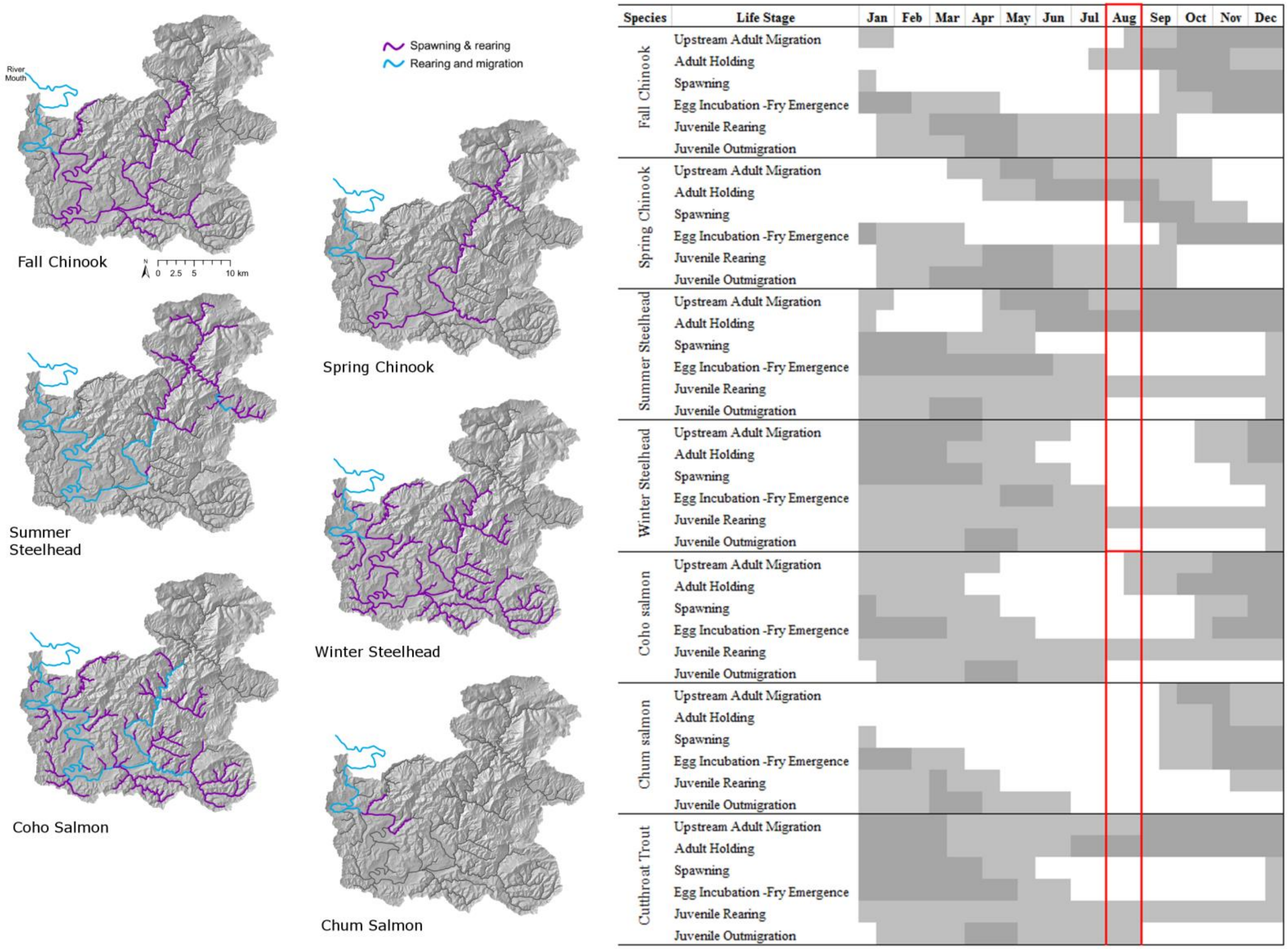


Figure 13. Spatial extent (maps) and timing (right) for salmonids in the Siletz River watershed. Note: we did not have spatial extent information for cutthroat trout.

Historical patterns
(2006 for Snoqualmie, 2001 for Siletz)

Potential future patterns
(if waters warm uniformly by 2 °C)

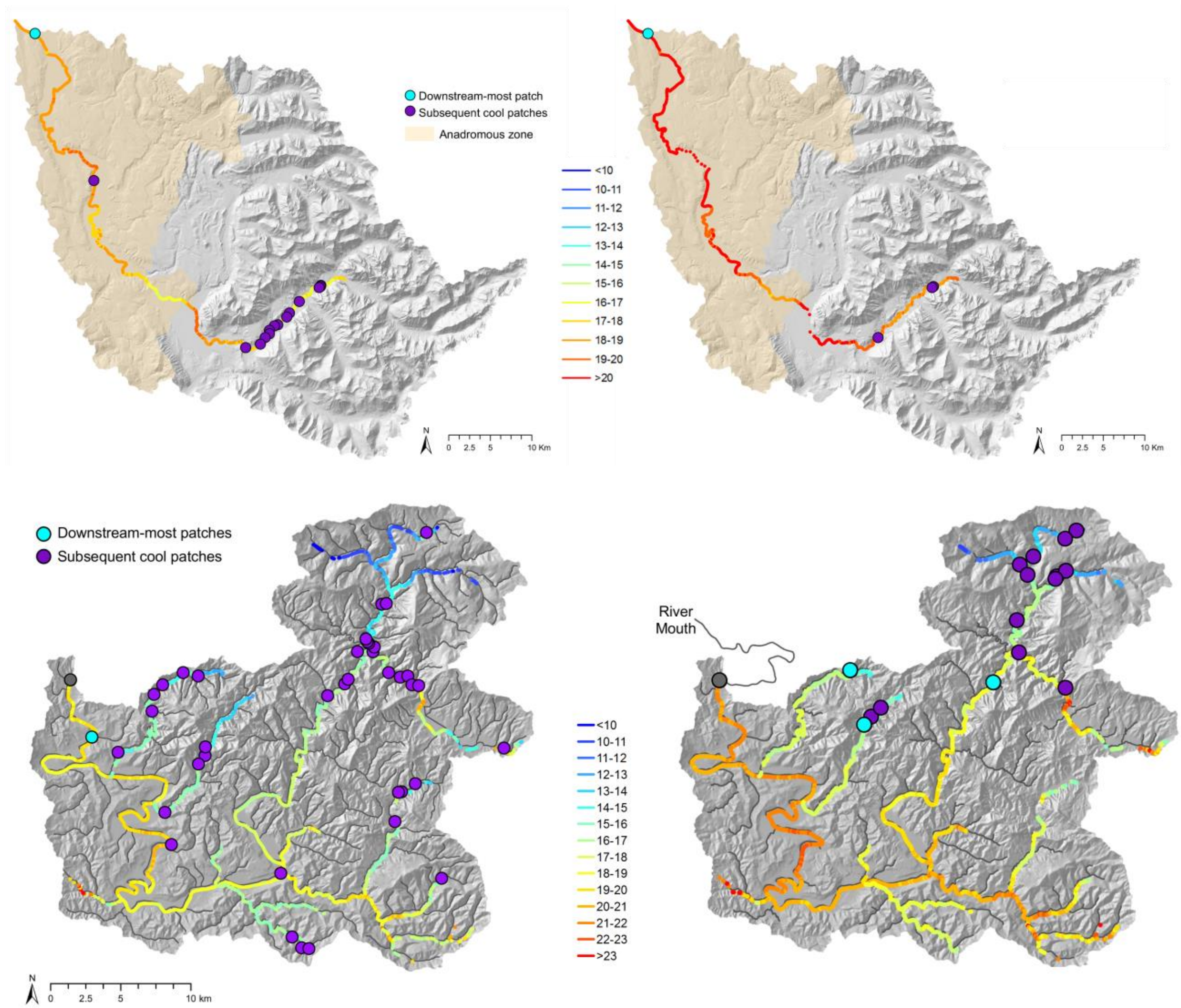


Figure 14. Locations of cold patches (<15 ^{o}C; circles) and maximum August stream temperature (^{o}C) determined from TIR (colored lines) for the Snoqualmie (top) and Siletz (bottom) watersheds for historical (left) and potential future (right) conditions.

Table 1. Vulnerability ratings for Snoqualmie salmonids for reaches where we had estimated maximum temperatures during August.

Species	**Sensitivity**	**Current Exposure**				**Current Vulner-ability**	**Future Exposure**			**Future Vulner-ability**
	Level of impairment at warmer temperatures	Life stage presence during August (*p*)	Use of habitat during August (*u*)	Cold patch abundance score (*n*)	Cold patch spacing score (*s*)		Use of habitat during August (*u*)	Cold patch abundance score (*n*)	Cold patch spacing score (*s*)	
Chinook										
-Adults	1	1	0.75	0.991	1	**2.74**	0.75	0.995	1	**2.75**
-Juveniles	1	1	0.50	0.991	1	**2.49**	0.50	0.995	1	**2.50**
Steelhead										
-Adults	2	1	0.75	0.987	1	**5.47**	0.75	0.993	1	**5.49**
-Juveniles	1	1	1.00	0.987	1	**2.99**	1.00	0.993	1	**2.99**
Coho										
-Adults	2	1	0.25	0.991	1	**4.88**	0.25	0.996	1	**4.49**
-Juveniles	1	1	0.50	0.991	1	**2.49**	0.50	0.996	1	**2.50**
Pink										
-Adults	2	1	0.75	0.994	1	**5.49**	0.75	0.997	1	**5.49**
-Juveniles	1	0	0	0.994	1	**0**	0	0.997	1	**0**
Chum										
-Adults	2	0	0	0.994	1	**0**	0	0.997	1	**0**
-Juveniles	1	0	0	0.994	1	**0**	0	0.997	1	**0**
Cutthroat										
-Adults	2	1	0.50	0.74?	0.10?	**2.67?**	0.50	0.95?	1?	**4.89?**
-Juveniles	2	1	1.00	0.74?	0.10?	**3.67?**	1.00	0.95?	1?	**5.89?**
Bull trout										
-Adults	3	1	0.75	0.10?	0.10?	**2.85?**	0.75	0.50?	0.50?	**5.25?**
-Juveniles	3	1	0.50	0.10?	0.10?	**2.10?**	0.50	0.50?	0.50?	**4.50?**

Table 2. Vulnerability ratings for Siletz salmonids for reaches where we had estimated maximum temperatures during August.

Species	**Sensitivity**	**Current Exposure**				**Current Vulner-ability**	**Future Exposure**			**Future Vulner-ability**
	Level of impairment at warmer temperatures	Life stage presence during August (*p*)	Use of habitat during August (*u*)	Cold patch abundance score (*n*)	Cold patch spacing score (*s*)		Use of habitat during August (*u*)	Cold patch abundance score (*n*)	Cold patch spacing score (*s*)	
Fall Chin										
-Adults	1	1	0.50	0.853	0.585	**2.02**	0.50	0.995	1	**2.50**
-Juveniles	1	1	0.67	0.853	0.585	**2.18**	0.67	0.995	1	**2.66**
Spr Chin										
-Adults	1	1	0.83	0.791	0.141	**1.85**	0.83	0.961	0.499	**2.29**
-Juveniles	1	1	0.67	0.791	0.141	**1.68**	0.67	0.961	0.499	**2.13**
Sum Steel										
-Adults	2	1	0.67	0.827	0.545	**4.22**	0.67	0.956	1	**4.24**
-Juveniles	1	1	0.33	0.827	0.545	**1.78**	0.33	0.956	1	**1.79**
Win Steel										
-Adults	2	0	0	0.895	0.545	**0**	0	0.994	1	**0**
-Juveniles	1	1	0.33	0.895	0.545	**1.81**	0.33	0.994	1	**2.33**
Coho										
-Adults	2	1	0.33	0.897	0.585	**3.74**	0.33	0.994	1	**4.66**
-Juveniles	1	1	0.33	0.897	0.585	**1.87**	0.33	0.994	1	**2.33**
Chum										
-Adults	2	0	0	0.859	0.598	**0**	0	1	1	**0**
-Juveniles	1	0	0	0.859	0.598	**0**	0	1	1	**0**
Cutthroat										
-Adults	2	1	1.00	0.5?	0.5?	**4.00?**	1.00	0.75?	0.75?	**5.00?**
-Juveniles	2	1	0.67	0.5?	0.5?	**3.33?**	0.67	0.75?	0.75?	**4.33?**

Project Timeline

We are on schedule for meeting the goals outlined in the proposal and in the last report.

Communication and Outreach

We have been in communication with parties involved in watershed planning in the Snoqualmie and Siletz watersheds. Specifically, we presented our work and sought feedback from the Tolt River fish group (the Tolt River is a tributary to the Snoqualmie), discussed with members of the Snoqualmie Tribe how our results could inform restoration planning, and have been in conversations with nearby Tribes (Sauk-Suiattle, Nooksack) about related topics. We discussed our project with staff from the Oregon Department of Environmental Quality who are working on the TMDL plans for temperature impairment in the Siletz River basin, as well as colleagues from other groups who are involved in watershed monitoring and planning efforts there.

During the past year, we presented work from this project at the following venues:

Fullerton, A.H. 8 March, 2016. Thermal networks and their relevance to Pacific salmon. Mini-symposium on water temperature and fish health. USGS Western Fisheries Research Center, Seattle, WA.

Fullerton, A.H. 14 June, 2016. Thermal patterns and the Snoqualmie water temperature monitoring network. Tolt River Fish Group, Carnation, WA.

Lee, S.Y. and A.H. Fullerton. Numerous occasions. Informal presentations to get feedback on projects relating to water temperature, salmon, and climate change. Climate Impacts Group and School of Forest and Environmental Sciences, University of Washington, WA.

Fullerton, A.H. 18 October, 2016. Spatiotemporally variable thermal landscapes and implications for Pacific salmon in a changing climate. MtnClim Conference, Leavenworth, WA.

Torgersen, C.E. 20 October, 2016. Spatial patterns in water temperature in Pacific Northwest rivers: substantial diversity at multiple scales and potential influence of climate change. Natural Areas Conference, Davis, CA.

Fullerton, A.H. 29 November, 2016. Informal presentations to federal (NOAA, EPA, USFS, USGS) and state (ODFW) scientists, Corvallis, OR.

Fullerton, A. 30 November, 2016. Managing (cold) water for salmon and people. University of Oregon, Water Science Seminar, Corvallis, OR.

Torgersen, C.E. et al. 14 December, 2016. Spatial patterns in water temperature in Pacific Northwest rivers: diversity at multiple scales and potential influence of climate change. American Geophysical Union conference, San Francisco, CA.

We have drafted two manuscripts resulting from this work. One, on thermal heterogeneity patterns in rivers throughout the Pacific Northwest, has undergone internal review and will soon be submitted for publication in a journal. The other, comparing the DHSVM and random forest modeling approaches, is at an earlier stage.

Signature

Joshua Lawler, Project Manager — Date

Aimee H Fullerton — 12/29/16

Aimee Fullerton, Co-PI — Date

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