Modeling the streamflow and water temperature responses to forest canopy gap treatment scenarios in the Snoqualmie River basin

Technical Report for Snoqualmie Indian Tribe

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1 Executive Summary

Seasonal snow cover dynamics are key to late-season streamflow and river temperature, and consequently, aquatic ecosystem health. While a great number of studies have investigated the snow cover dynamics in the open versus under canopy through field surveys and modeling approaches, snow-forest interactions in canopy gaps are much less explored especially at the watershed scale. Relative to a continuous forest, canopy gaps feature less snow interception and reduced downward longwave radiation emitted by canopy; compared to open areas, canopy gaps receive less incoming solar radiation due to shading and reduced turbulent heat from wind sheltering by the surrounding forest. These characteristics of canopy gaps present unique opportunities to enhance snow retention and snow water storage, and consequently, reduce the stream water temperature in late spring to summer.

Here we used the Distributed Hydrology Soil Vegetation Model and River Basin Model (DHSVM-RBM) version 3.2 to explore the effect of prescribed canopy gap treatments on watershed flow regimes and river thermal regime in the Snoqualmie watershed at a high spatiotemporal resolution (3-hour time step and 150-meter spatial scale). Using the previously calibrated and validated DHSVM-RBM model for the Snoqualmie River basin (Yan et al, *under review*), we first conducted sensitivity experiments over a 2-year historical period (2011/10–2013/09) to explore the response of streamflow and water temperature in both the mainstem and tributaries across the Snoqualmie River Basin (i.e., basin outlet, North Fork, Middle Fork, South Fork, and Tolt) to a suite of prescribed canopy gap treatments that vary in canopy gap size and locations of treatment (e.g. south-facing slopes vs. north-facing slopes; higher elevation vs. lower elevation).

Given that canopy gaps are expected to show the largest impact on snow-dominated regions, we selected two wet years with significant snowfalls for sensitivity analyses. The effectiveness of canopy gap scenarios was evaluated at stream locations of interest using the ratio of summer streamflow increases and summer water temperature decreases to the total gap treatment area upstream of the point of interest. In coordination with the Snoqualmie Tribe, we identified two potential canopy gap scenarios for long-term evaluation of the effectiveness of canopy gap for enhancing late-season streamflow and reducing stream temperature in future climate (2031–2060):

1) **elevation > 932 m & gap diameter = 120m on all slopes;**
2) **elevation > 932 m & gap diameter = 120m on only south-facing slopes.**

Because the eastern Snoqualmie River Basin covers a portion of the Alpine Lakes Wilderness Area that is required to have minimal impacts from human activities, we evaluated two additional canopy gap scenarios which were equivalent to 1) and 2) above except that the Alpine Lakes Wilderness Area was excluded from gap treatment. As a result, a total of four canopy gap scenarios were used in the long-term evaluation (Table 1).

Table 1. The selected four canopy gap treatment scenarios across the Snoqualmie River Basin.

Scenario Number	Elevation (m)	Gap Diameter (m)	Aspect	Including Alpine Lake	Treated Canopy Area (acres)	Treated Canopy Area (%)
S1	≥932	120	-	Y	64,474	15
S2	≥932	120	-	N	27,802	6
S3	≥932	120	south	Y	23,604	5
S4	≥932	120	south	N	10,662	2

In our previous study, we had acquired the top ten Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation models (GCMs) that better reproduced past climate in the Pacific Northwest (PNW) for the Representative Concentration Pathways (RCP) 8.5 scenario. Among the ten GCMs, we further identified three GCMs for long-term evaluations in the Snoqualmie River Basin that represent the best case (MIROC5, larger winter precipitation & lower summer air temperature over the basin), worst case (HadGEM2-ES365, smaller winter precipitation & higher summer air temperature), and median case (bcc-csm1-1-m, median winter precipitation & median summer air temperature) scenarios.

In the long-term evaluation (2031–2060), DHSVM-RBM was driven by combined canopy gap scenarios (four treatment scenarios + one baseline scenario without gap) and climate scenarios (three selected GCMs), resulting in a total of 15 long-term runs. Compared to the baseline simulations, our canopy gap scenario simulations suggest that:

1) In general, all four canopy gap treatments can increase basin outlet summer (June–August) mean streamflow and reduce basin outlet 7-DADMax (highest yearly value of the average of seven consecutive daily maximum temperatures); however, treatment benefits vary by treated locations and climatology.

2) As shown in Table 2, if the Alpine Lakes Wilderness Area is included in the canopy gap treatment area (scenarios S1 and S3), the 30-year average basin outlet summer mean flow increases by between 3% and 11% and the basin outlet 7-DADMax is reduced by between 0.04 and 0.18°C. Note that the smallest canopy gap benefit (shaded red) for both flow and temperature corresponds to the S3 scenario (canopy gaps on only south facing slopes) and the HadGEM2-ES365 climate projection which projects the warmest climate and lowest snowpack over the 30-year simulation period. Conversely, the highest benefit (shaded green) corresponds to the S1 scenario (canopy gaps applied to all slope aspects) and the MIROC5 climate model which projects generally cooler temperatures with more snowpack than the other two models.

3) Table 3 shows 30-year average results for scenarios S2 and S4 (excluding the Alpine Lakes Wilderness Area). This exclusion greatly reduces the area of gap treatment compared to S1 and S3. For these scenarios, the 30-year average increase in basin outlet summer mean flow ranges from 1% to 5%, while the 7-DADMax reduction ranges between 0.01°C to 0.05°C. Similar

to scenarios S1 and S3 discussed above, the smallest canopy gap benefits correspond to the S4 scenario (canopy gaps on only south facing slopes) and the HadGEM2-ES365 climate projections while the largest benefits correspond to the S2 scenario (canopy gaps applied to all slope aspects) and the MIROC5 climate model projections.

4) From 2031 to 2060, the effects of canopy gap treatments from all four scenarios show a declining trend for all three GCMs, despite large inter-annual variability. The gap effects are smaller but still exist in 2060, suggesting that the benefits of canopy gap treatments can at least extend to the middle of the century, even under the high-emission RCP8.5 scenario.

5) Among the four canopy gap scenarios, scenario S3 (elevation > 932 m & gap diameter = 120 m & south-facing & including Alpine Lakes Wilderness Area) showed the highest efficiency (i.e., greatest change per unit canopy treated area) in increasing basin outlet summer flow and reducing basin outlet 7-DADMax.

Table 2. Benefits of canopy gaps for scenarios that include the Alpine Lakes Wilderness Area

	HadGEM2-ES365	bcc_csm1-1-m	MIROC5
	% Change in 30-Yr Avg Summer Flow		
S1- all aspects	7.9	10.2	11.2
S3- south only	3.1	4.0	4.4
	Change in 30-Yr Avg 7-DADMax (°C)		
S1- all aspects	-0.104	-0.148	-0.182
S3- south only	-0.039	-0.056	-0.071

Table 3. Benefits of canopy gaps for scenarios that exclude the Alpine Lakes Wilderness Area

	HadGEM2-ES365	bcc_csm1-1-m	MIROC5
	% Change in 30-Yr Avg Summer Flow		
S2- all aspects	3.0	4.3	4.9
S4- south only	1.1	1.5	1.7
	Change in 30-Yr Avg 7-DADMax (°C)		
S2- all aspects	-0.029	-0.040	-0.048
S4- south only	-0.008	-0.010	-0.016

The rest of the report is organized as follows: Section 2 describes the evaluation framework in detail, which includes the canopy gap implementation, GCM selections, canopy gap treatment sensitivity analysis, and evaluation metrics. Section 3 presents the sensitivity analysis and long-term evaluation results of basin outlet streamflow and water temperature. Additional results for four tributary outlets (North Fork Snoqualmie, Middle Fork Snoqualmie, South Fork Snoqualmie, and Tolt Rivers), are provided in the appendix entitled Supporting Information.

2 Methodology

2.1 Canopy Gap Model Implementation

Figure 1 illustrates the grid representation of a canopy gap in DHSVM. In the DHSVM model structure, any model grid cell with a canopy gap treatment is partitioned into two parts: gap and surrounding forest. The model treats the two parts as independent snowpack governed by separate mass and energy input. The model explicitly accounts for the impact of the surrounding forest (e.g., wind attenuation and shading) on the gap energy balance and generates spatially varied irradiance with an idealized cylindrical gap geometry. For details about the canopy gap model structure, the readers are referred to Sun et al (2018, https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.13150)

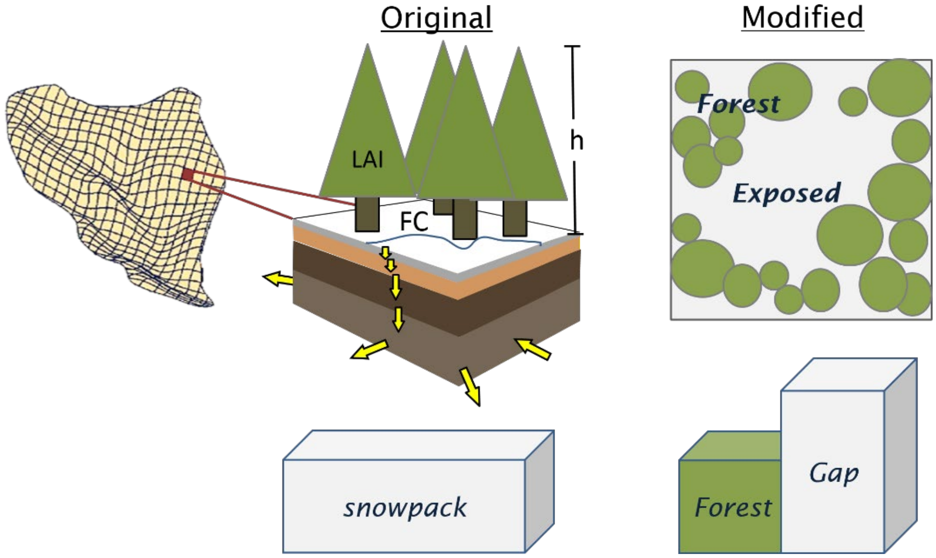

Figure 1. Grid representation of the canopy gap in the original and enhanced DHSVM. Forest canopy is characterized by leaf area index, canopy height, and fractional coverage.

2.2 Data Sources and GCM Selection

For the canopy gap sensitivity analysis over the historical period, we acquired the 1/16° meteorological forcing data consisting of daily precipitation, maximum and minimum temperature, and wind speed from Livneh et al. (2013) with temporal coverage 1950–2013. To project future changes, we used the Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation model (GCM) products (Abatzoglou & Brown, 2012). Among the 20 downscaled GCM products bias corrected to the Livneh historical dataset, we selected the top 10 GCMs that better reproduced past climate in the PNW for the RCP8.5 scenario (Lee et al., 2020; Rupp et al., 2013). The selected 10 GCMs include bcc-csm1-1-m, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-CC365, HadGEM2-ES365, IPSL-CM5A-MR, MIROC5, and NorESM1-M. All downscaled GCM products had the same meteorological variables as the Livneh dataset with temporal coverage 1950–2005 for the historical period and 2006–2099 for the RCP8.5 projection. Figure 2 shows the 10 GCMs' seasonal precipitation and air temperature over the Snoqualmie River Basin in the future period at the end of the century (2087–2099).

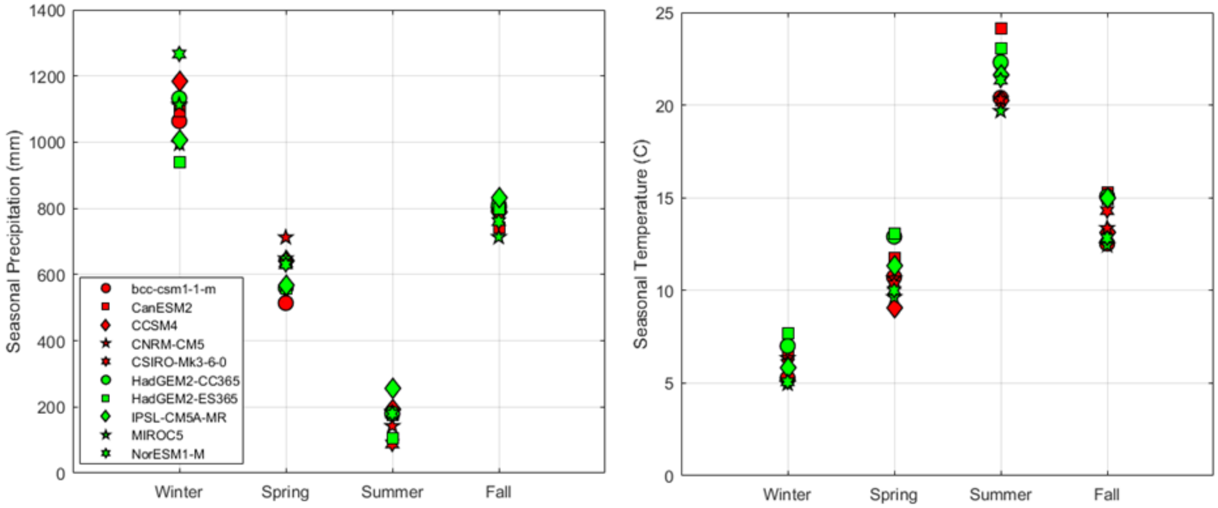

Figure 2. Seasonal precipitation and air temperature over the Snoqualmie River Basin in future period at the end of century (2087–2099) for the 10 GCMs.

Among the 10 GCMs, we further identified three GCMs to represent the best, worst, and median case scenario:

- Best case: larger winter precipitation & lower summer air temperature
- Worst case: smaller winter precipitation & higher summer air temperature
- Median case: median winter precipitation & median summer air temperature

Each GCM was ranked based on the winter precipitation and summer air temperature and then we selected the three representative GCMs based on their combined scores as shown in Tables 4-6. If there is more than one GCM having the same score, we gave the priority to the summer air temperature (e.g., for the best and median cases, we prefer the GCM with the smaller projected summer air temperature).

Table 4. Best case score for the 10 GCMs. The red color indicates the selected GCM.

GCM	Winter P Rank (higher value gets higher rank)	Summer T Rank (lower value gets higher rank)	Best Case Score
bcc-csm1-1-m	4	7	11
CanESM2	5	1	6
CCSM4	9	9	18
CNRM-CM5	2	8	10
CSIRO-Mk3-6-0	7	4	11
HadGEM2-CC365	6	3	9
HadGEM2-ES365	1	2	3
IPSL-CM5A-MR	3	5	8
MIROC5	8	10	18
NorESM1-M	10	6	16

Table 5. Worst case score for the 10 GCMs. The red color indicates the selected GCM.

GCM	Winter P Rank (lower value gets higher rank)	Summer T Rank (higher value gets higher rank)	Worst Case Score
bcc-csm1-1-m	7	4	11
CanESM2	6	10	16
CCSM4	2	2	4
CNRM-CM5	9	3	12
CSIRO-Mk3-6-0	4	7	11
HadGEM2-CC365	5	8	13
HadGEM2-ES365	10	9	19
IPSL-CM5A-MR	8	6	14
MIROC5	3	1	4
NorESM1-M	1	5	6

Table 6. Median case score for the 10 GCMs. The red color indicates the selected GCM.

GCM	Winter P Rank (distance to median rank)	Summer T Rank (distance to median rank)	Median Case Score
bcc-csm1-1-m	1.5	1.5	3
CanESM2	0.5	4.5	5
CCSM4	3.5	3.5	7
CNRM-CM5	3.5	2.5	6
CSIRO-Mk3-6-0	1.5	1.5	3
HadGEM2-CC365	0.5	2.5	3
HadGEM2-ES365	4.5	3.5	8
IPSL-CM5A-MR	2.5	0.5	3
MIROC5	2.5	4.5	7
NorESM1-M	4.5	0.5	5

2.3 Canopy Gap Treatment Sensitivity Analysis

In coordination with the Tribe, we developed a suite of canopy gap treatment scenarios featuring varied gap diameters, treated elevations, and/or treated slopes and aspects. In the sensitivity analysis, we considered three elevation scenarios involving thresholds above which gap treatments were applied (>732m, >932m, and >1106m), which are associated with the highest 40%, 30%, and 20% of the basin respectively; three gap diameters (60m, 90m, and 120m); two aspects (all-facing and south-facing); and three slopes (0°, 13°, and 24°). This resulted in a total of 54 combinations for analysis. Table 7 presents the selected 11 canopy gap scenarios used for sensitivity analysis.

Table 7. The selected eleven canopy gap treatment scenarios across the Snoqualmie River Basin.

Scenario Number	Elevation (m)	Gap Diameter (m)	Aspect	Slope (°)
1	≥728	90	-	-
2	≥932	90	-	-
3	≥1106	90	-	-
4	≥728	60	-	-
5	≥728	120	-	-
6	≥728	90	south	-
7	≥728	90	south	>13°
8	≥728	90	south	>24°
9	≥932	120	-	-
10	≥932	120	south	-
11	≥932	120	south	>13°

2.4 Evaluation Metrics

Four metrics were used to evaluate the performances of canopy gap treatments: summer (JJA) mean flow change; annual average of seven consecutive daily maximum temperatures (7-DADMax) difference; flow efficiency; and 7-DADMax efficiency.

- **Summer mean flow change (%)** is estimated as streamflow relative difference between the canopy gap treatment scenario and baseline without canopy gap: (scenario–baseline)/baseline*100. The summer mean flow (m^3/s) is estimated as the average of the 3-hourly simulated streamflow from June 1st to August 31th.
- **7-DADMax difference (°C)** is estimated as the difference between scenario and baseline. Daily maximum water temperatures are estimated as the maximum 3-hourly water temperature in a day.
- **Flow efficiency (%/%)** is estimated as the ratio of summer mean flow changes (%) to treated canopy area (%). The treated canopy area (%) is estimated as: canopy gap cut area (acres) / associated drainage basin area (acres) *100. Canopy cut area is a function of gap location and gap diameter.
- **7-DADMax efficiency** (°C/%) is estimated as 7-DADMax difference (°C) / Treated canopy area (%).

If flow efficiency = 1, it means 1% treated canopy area will increase 1% summer flow rate; if 7-DADMax efficiency = -1, it means 1% treated canopy area will reduce 1°C 7-DADMax. The higher/lower the values, the higher the efficiencies of canopy gap treatment. Here we estimated the four metrics for both mainstem, and its four tributaries as shown in Figure 3.

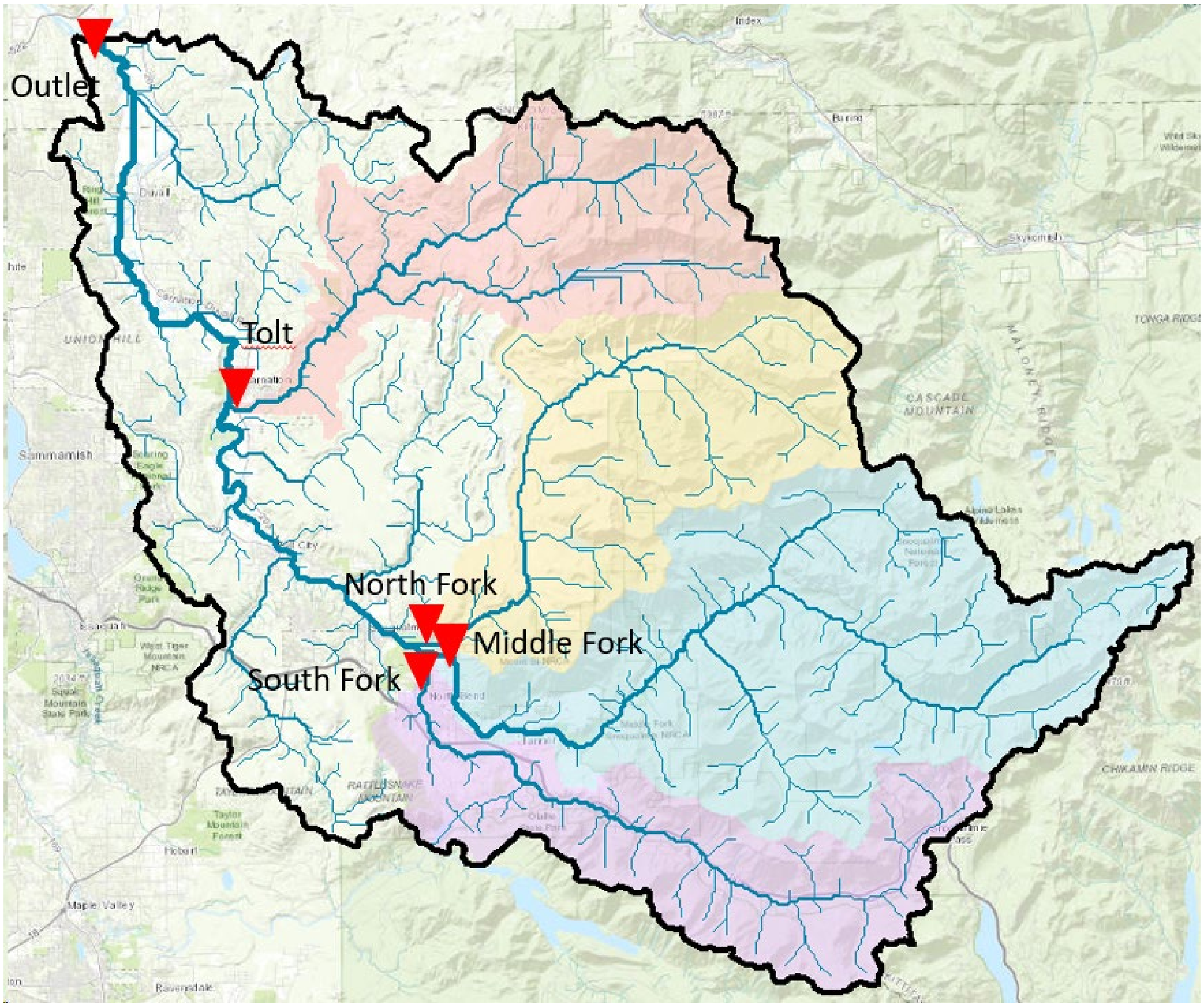

Figure 3. The location of basin outlet and four tributary outlets across the Snoqualmie River Basin. Different color shows the associated drainage basin area.

3 Results

3.1 Sensitivity Analysis of Canopy Gap Scenarios

Two water years (2011-2013) with large snow accumulation were selected for the canopy gap sensitivity analysis. A total of 54 sensitivity analyses have been run and Table 8 summarizes the performance metrics for selected 11 runs that are consistent with Table 7.

Based on Table 8, it is observed that elevation range and gap diameter are the two most important variables in determining the effects of canopy gap treatment. Aspect and slope selection can further increase the canopy gap efficiency: south-facing and steeper slopes are more sensitive than north-facing and mild slope. Scenario 10 has the highest efficiency in summer flow and 7-DADMax and was selected for the long-term run. The associated scenario 9 with its considerably smaller treated area was also selected for purposes of comparison with scenario 10. In light of existing stringent policies that restrict land disturbances in the wilderness areas, we also wanted to examine the impacts of excluding the Alpine Lakes Wilderness Area. As a result, a total of four canopy gap scenarios (Figure 4) was to be used in the following long-term climate projection runs.

Table 8. Impacts of eleven canopy gap treatment scenarios on summer flow and 7-DADMax at the basin outlet. The red color suggests the highest flow/7-DADMax efficiency. Treated canopy area (%) is calculated by dividing the total gap area by total drainage basin area. Summer Flow Efficiency (%/%) = Summer Flow Change (%) / Treated Canopy Area (%). 7-DADMax Efficiency (°C/%) = 7-DADMax Difference (°C) / Treated Canopy Area (%).

Num.	Elev. (m)	Gap Dia. (m)	Aspect	Slope (°)	Treated Canopy Area (acres)	Treated Canopy Area (%)	2-yr Avg. Summer Flow Change (%)	2-yr Avg. Summer Flow Efficiency (%/%)	2-yr Avg. 7DADMax Diff (°C)	2-yr Avg. 7DADMax Efficiency (°C/%)
1	≥728	90	-	-	48581	11.0	11.7	1.06	-0.47	-0.04
2	≥932	90	-	-	36215	8.2	8.4	1.03	-0.55	-0.07
3	≥1106	90	-	-	23849	5.4	3.9	0.72	-0.29	-0.05
4	≥728	60	-	-	21641	4.9	4.1	0.83	-0.22	-0.04
5	≥728	120	-	-	86563	19.6	23.8	1.21	-1.14	-0.06
6	≥728	90	south	-	17666	4.0	5.1	1.28	-0.29	-0.07
7	≥728	90	south	>13°	15458	3.5	4.5	1.28	-0.13	-0.04
8	≥728	90	south	>24°	10600	2.4	3.2	1.33	-0.17	-0.07
9	≥932	120	-	-	64481	14.6	17.5	1.20	-0.75	-0.05
10	≥932	120	south	-	23407	5.3	8.1	1.53	-0.40	-0.08
11	≥932	120	south	>13°	20316	4.6	6.9	1.51	-0.27	-0.06

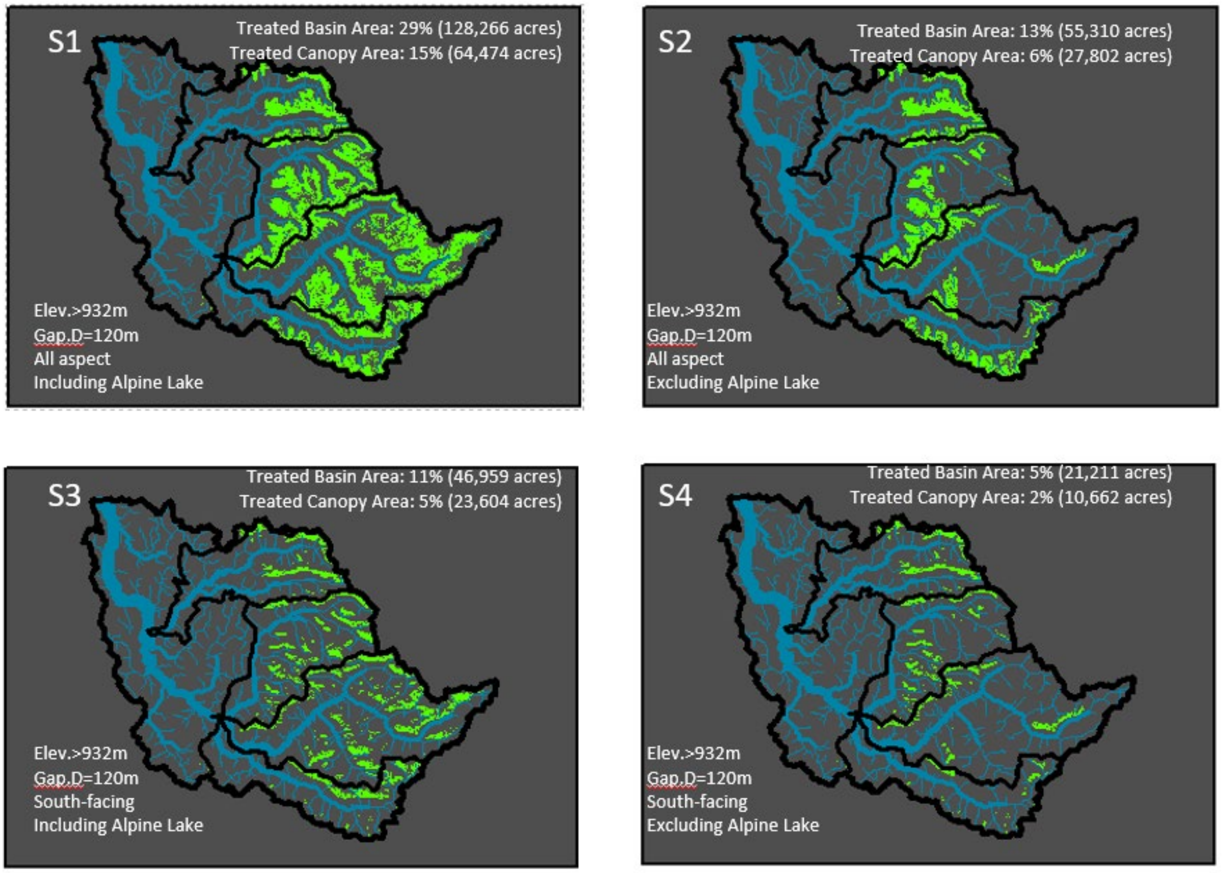

Figure 4. The selected final four canopy treatment scenarios (S1–S4) for long-term climate change projections.

3.2 Canopy Gap Treatment Impacts on Projected Streamflow

We ran the DHSVM-RBM models with canopy gap implementation from 2030/10/01 to 2060/09/30 driven by three GCMs under RCP8.5. The first water year (2030/10/01–2031/09/30) was treated as a spin-up period and not used in the following analysis. In the following, Figures 5 and 6 show the baseline basin mean snow and basin outlet streamflow time series. Figures 7 and 8 present the basin outlet summer flow changes and flow efficiency that is summarized in three 10-year periods. Table 9 summarizes the average flow performance metrics over the 2031–2060 period. Flow performances for four other tributaries are available in the Supporting Information.

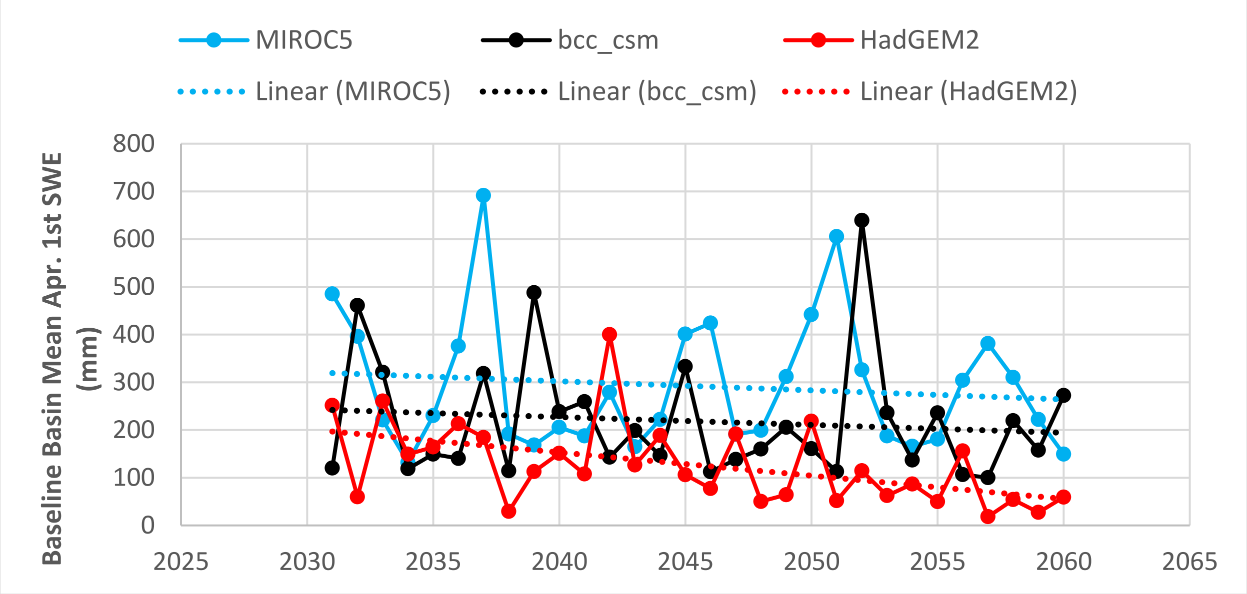

Figure 5. Baseline (no canopy gap) basin mean April 1st snow water equivalent (SWE) from 2031 to 2060 using the three selected GCMs.

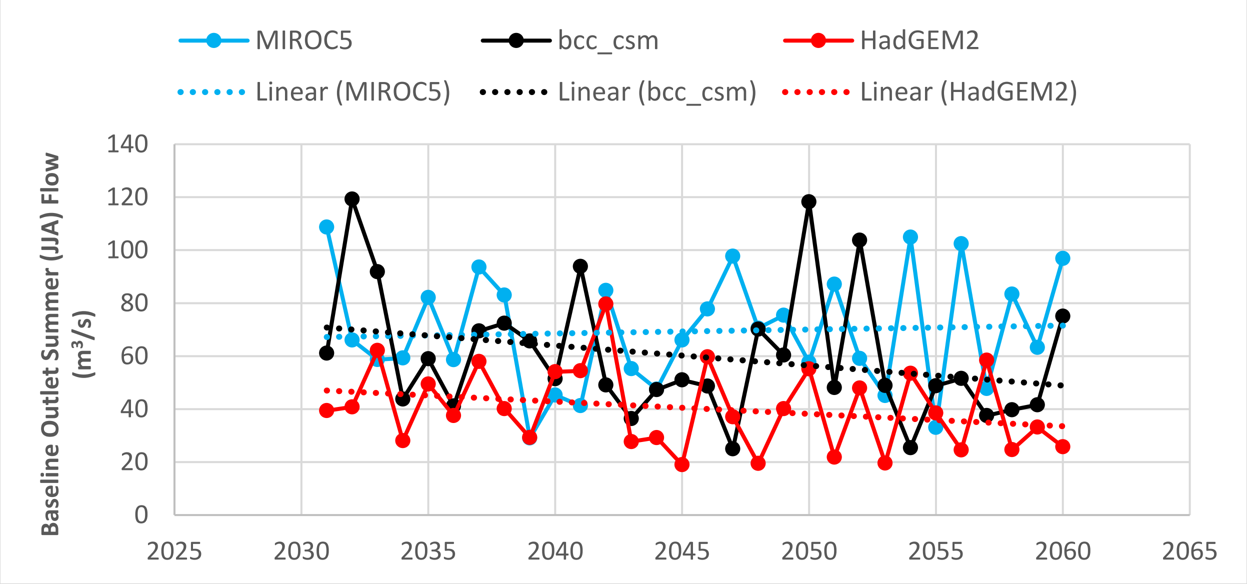

Figure 6. Baseline (no canopy gap) basin outlet summer mean streamflow from 2031 to 2060 using the three selected GCMs.

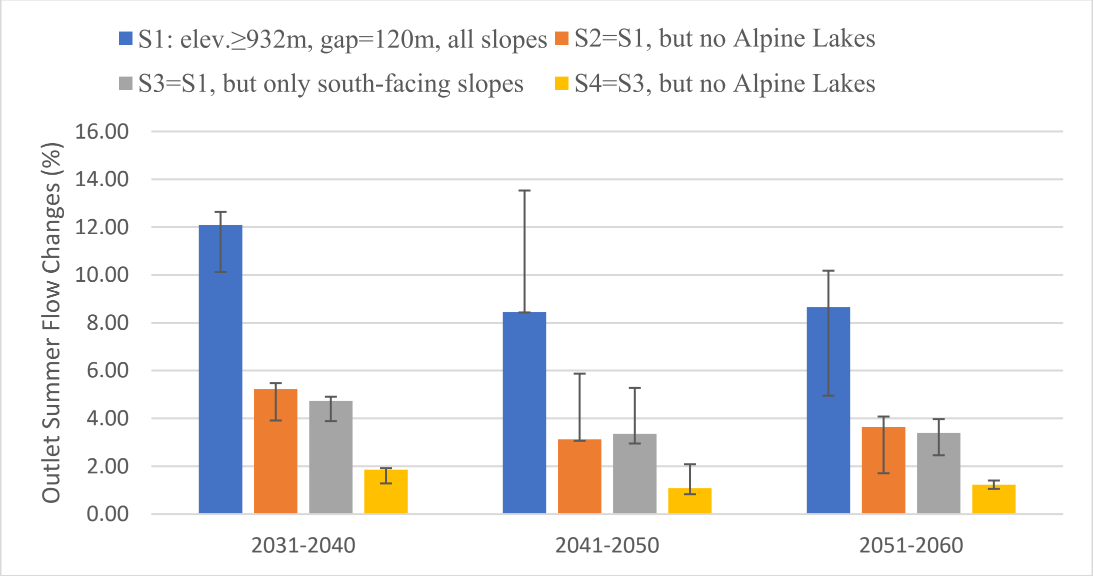

Figure 7. Basin outlet summer flow changes (compared to baseline) averaged over a 10-year period for the four canopy treatment scenarios. The error bars represent the range of three GCM models.

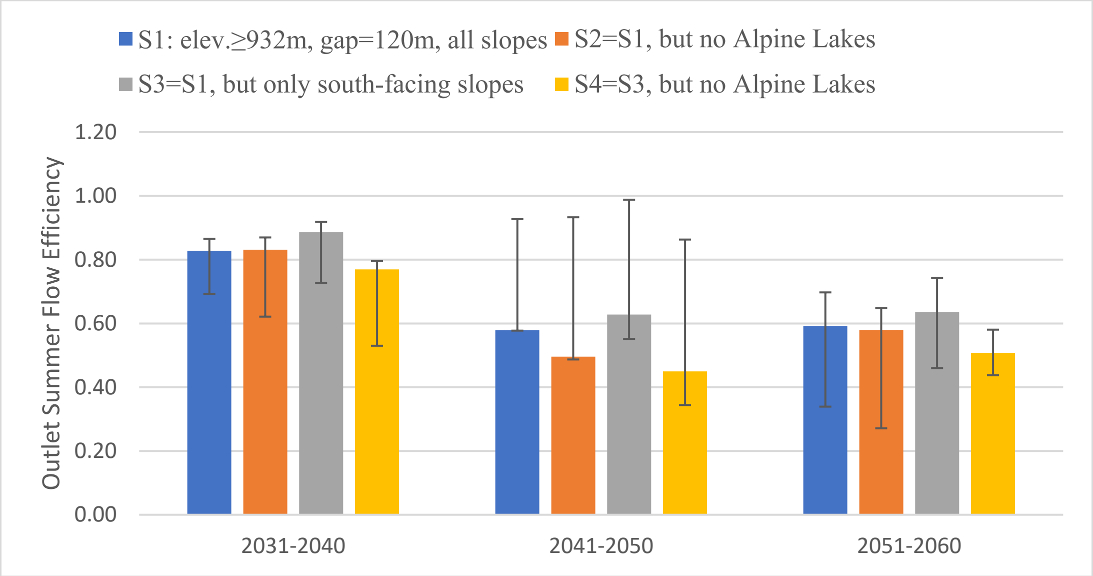

Figure 8. Basin outlet summer flow efficiency (%/%) averaged over a 10-year period for the four canopy treatment scenarios. The error bars represent the range of three GCM models.

Table 9. Impacts of four canopy gap treatment scenarios on summer flow at basin outlet averaged over the period 2031–2060. The red color suggests the highest efficiency among the four scenarios for each GCM.

Num.	GCM	Treated Canopy Area (acres)	Treated Canopy Area (%)	Summer Flow Change (%)	Summer Flow Efficiency (%/%)
S1	HadGEM bcc-csm MIROC5	64,474	14.6	7.9 10.2 11.2	0.54 0.70 0.77
S2	HadGEM bcc-csm MIROC5	27,802	6.3	3.0 4.3 4.9	0.48 0.68 0.78
S3	HadGEM bcc-csm MIROC5	23,604	5.3	3.1 4.0 4.4	0.57 0.75 0.82
S4	HadGEM bcc-csm MIROC5	10,662	2.4	1.1 1.5 1.7	0.44 0.62 0.71

3.3 Canopy Gap Treatment Impacts on Projected River Temperature

In the following, Figure 9 shows the baseline basin outlet 7-DADMax time series. Figures 10 and 11 present the basin outlet 7-DADMax difference and 7-DADMax efficiency that is summarized in three 10-year periods. Table 10 summarizes the average 7-DADMax performance metrics over the 2031–2060 period. 7-DADMax performances for four other tributaries are available in the Supporting Information.

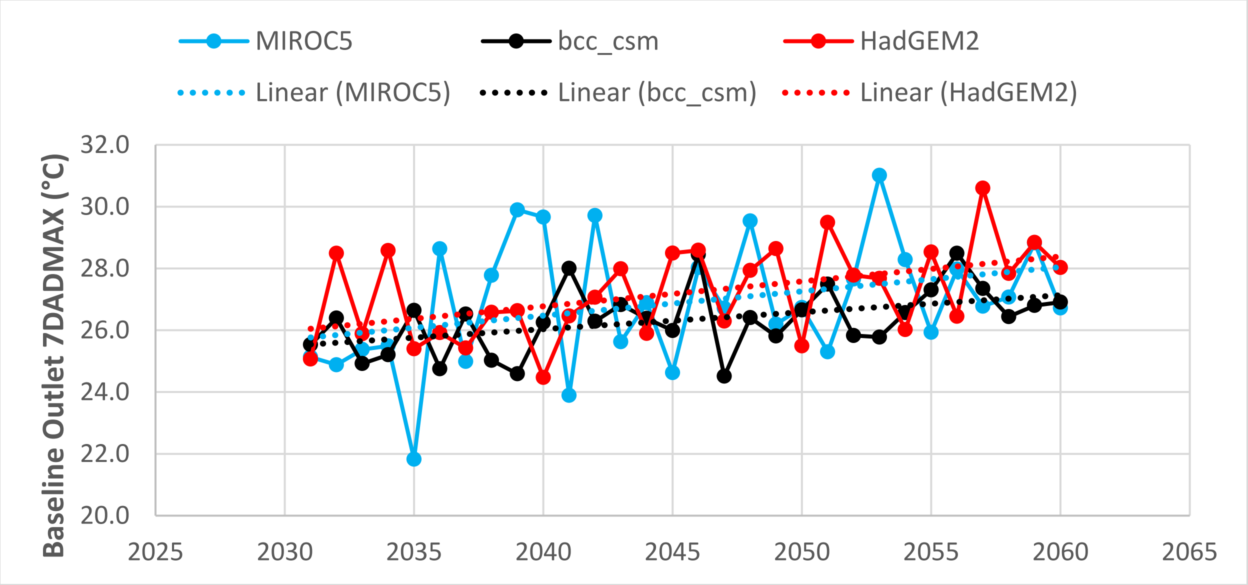

Figure 9. Baseline (no canopy gap) basin outlet 7-DADMax (°C) from 2031 to 2060 using the three selected GCMs. 7-DADMax: the highest yearly value of the average of seven consecutive daily maximum temperatures.

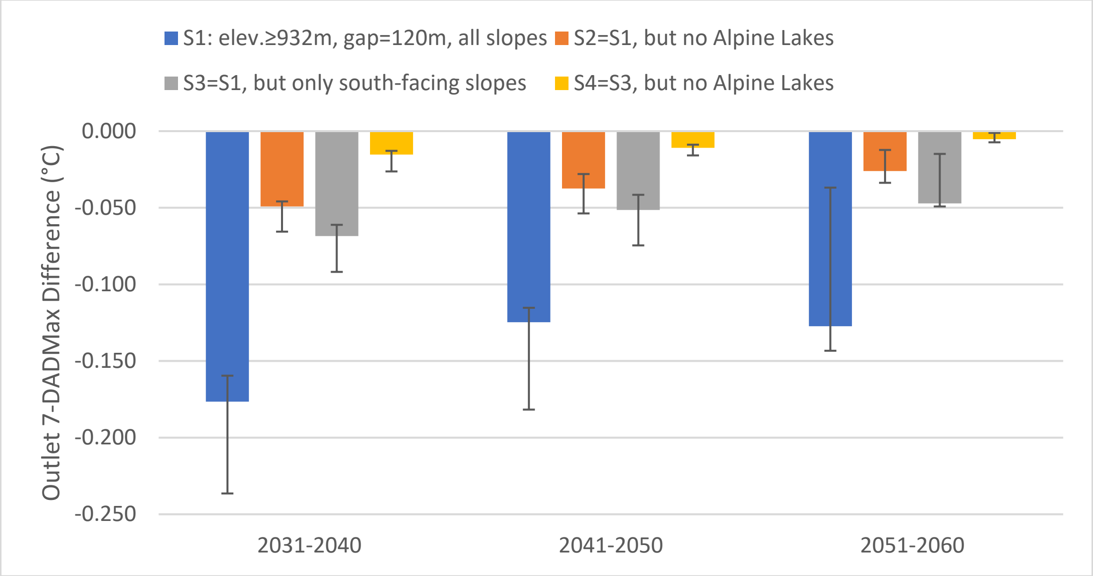

Figure 10. Basin outlet 7-DADMax (°C) difference (scenario minus baseline) averaged over a 10-year period for the four canopy treatment scenarios. The error bars represent the range of three GCM models. 7-DADMax: the highest yearly value of the average of seven consecutive daily maximum temperatures.

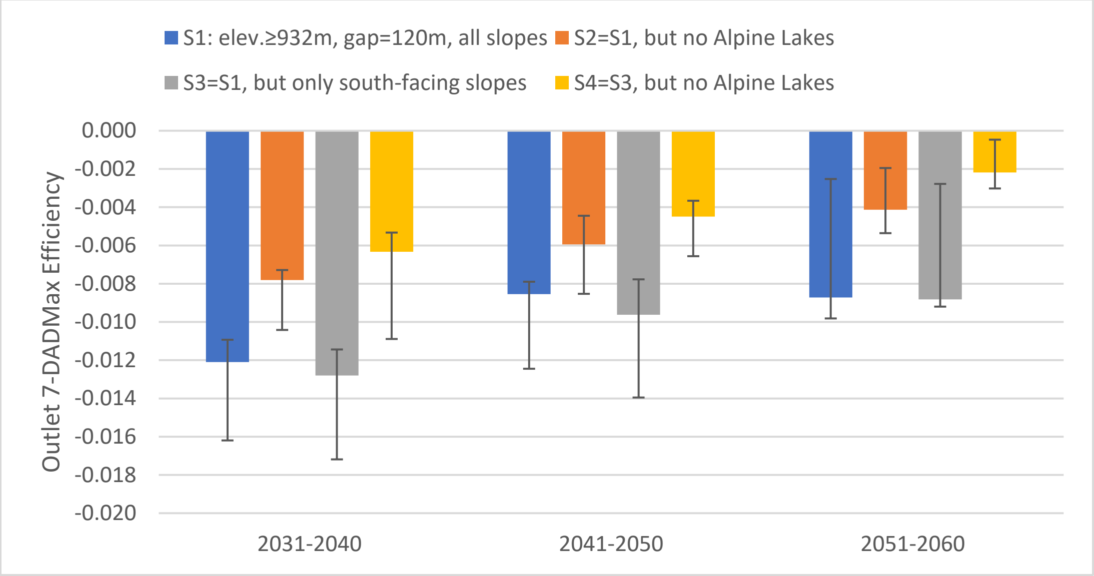

Figure 11. Basin outlet 7-DADMax efficiency (°C/%) averaged over a 10-year period for the four canopy treatment scenarios. The error bars represent the range of three GCM models. 7-DADMax: the highest yearly value of the average of seven consecutive daily maximum temperatures.

Table 10. Impacts of four canopy gap treatment scenarios on 7-DADMax at basin outlet averaged over the period 2031–2060. Red color suggests the highest efficiency among the four scenarios for each GCM.

Num.	GCM	Treated Canopy Area (acres)	Treated Canopy Area (%)	7DADMax Diff (°C)	7DADMax Efficiency (°C/%)
S1	HadGEM bcc-csm MIROC5	64474	14.6	-0.104 -0.148 -0.182	-0.007 -0.010 -0.012
S2	HadGEM bcc-csm MIROC5	27802	6.3	-0.029 -0.040 -0.048	-0.005 -0.006 -0.008
S3	HadGEM bcc-csm MIROC5	23604	5.3	-0.039 -0.056 -0.071	-0.007 -0.011 -0.013
S4	HadGEM bcc-csm MIROC5	10662	2.4	-0.008 -0.010 -0.016	-0.003 -0.004 -0.007

4 Future Study

Besides the canopy gap treatment, previously we explored plausible management scenarios of riparian vegetation and its implications for stream temperature, salmon and their habitats in the future (Fullerton et al, *in prep*), using DHSVM-RBM that was modified to represent the thermal effect of cool snowmelt runoff on river temperatures (Yan et al., *under review*). At the conclusion of this study, riparian restoration can partly offset the adverse impact of warming climate on stream water temperature and juvenile Chinook Salmon. In view of the above works, joint canopy gap treatments (at mid to high elevations) and downstream reparation restoration could potentially offer synergistic benefits for river temperature management.

5 References

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