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Empirical stream thermal sensitivity cluster on the landscape according to geology and climate

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S1. Interannual variability in thermal sensitivity

Our clustering analysis relied on average annual time series of thermal sensitives. However, due to logistical constraints such as differences in recording start dates or physical disturbances and equipment failure resulting in data loss, the annual average is derived from different years of data for different sites. Therefore, an implicit assumption in our analysis is that thermal sensitivity at a set of sites is comparable across different hydrologic years.

We explored the validity of this assumption by conducting an analysis using the annual time series of data from each of seven hydrologic years, each with differing temperature and precipitation patterns (Table S1). Generally, the years spanned by our dataset were warmer than the historical average, with wetter than average winter and fall months and drier spring and summer months (Figure S1). To examine the extent of interannual variability in thermal sensitivity, we employed a two-step approach.

First, we examined interannual variability in thermal sensitivity for seasonal summary metrics. We identified six sites for each basin that possessed consistent data coverage and calculated and plotted seasonal summary metrics of thermal sensitivity through time. Second, to evaluate the sensitivity of clusters to interannual variability, we adopted a "leave-one-out" cross validation sensitivity analysis. We excluded one year of data when calculating the average annual time series and then conducted the clustering analysis on this new annual average time series considering only N-1 years of data. For all clustering analyses, five clusters were specified in the Wenatchee basin and four clusters were specified in the Snoqualmie basin. Two sites in the Wenatchee basin only contain data for the 2020 water year. For these sites, we included all years of data for all clustering results. We compared the similarity of clusters obtained from this approach to our reported results encompassing all years of data using the Rand Index (RI; Rand 1971, Anderson et al. 2010). The RI represents the frequency of occurrence of agreements between clusters over the total pairs, or the probability that two clusters will agree on a randomly chosen pair. The RI value is equal to 0 when points are assigned into clusters randomly and equal to 1 when the two cluster results are identical. This approach allowed us to assess the robustness of our results to the particular years of analysis and whether any specific years have a particularly strong influence on clustering results.

We found that for summary metrics, thermal sensitivities for a site-season combination were generally stable across years, although patterns in thermal sensitivity estimates across years were not identical, highlighting the importance of local influences that may shift year-to-year (Figure S2). Thermal sensitivities for sites with consistent data coverage tended to covary across years. Our results from the sensitivity analysis illustrate that clusters generated from a reduced dataset were comparable to our reported results, as all RI values are relatively large (>0.8), indicating good to excellent similarity between clusters developed from the full and from the reduced datasets. While interannual variability clearly exists, the relatively close correspondence of clustering results using N and N-1 years of data indicates that broad patterns were captured by our analysis and no one year had a particularly strong influence on the results.

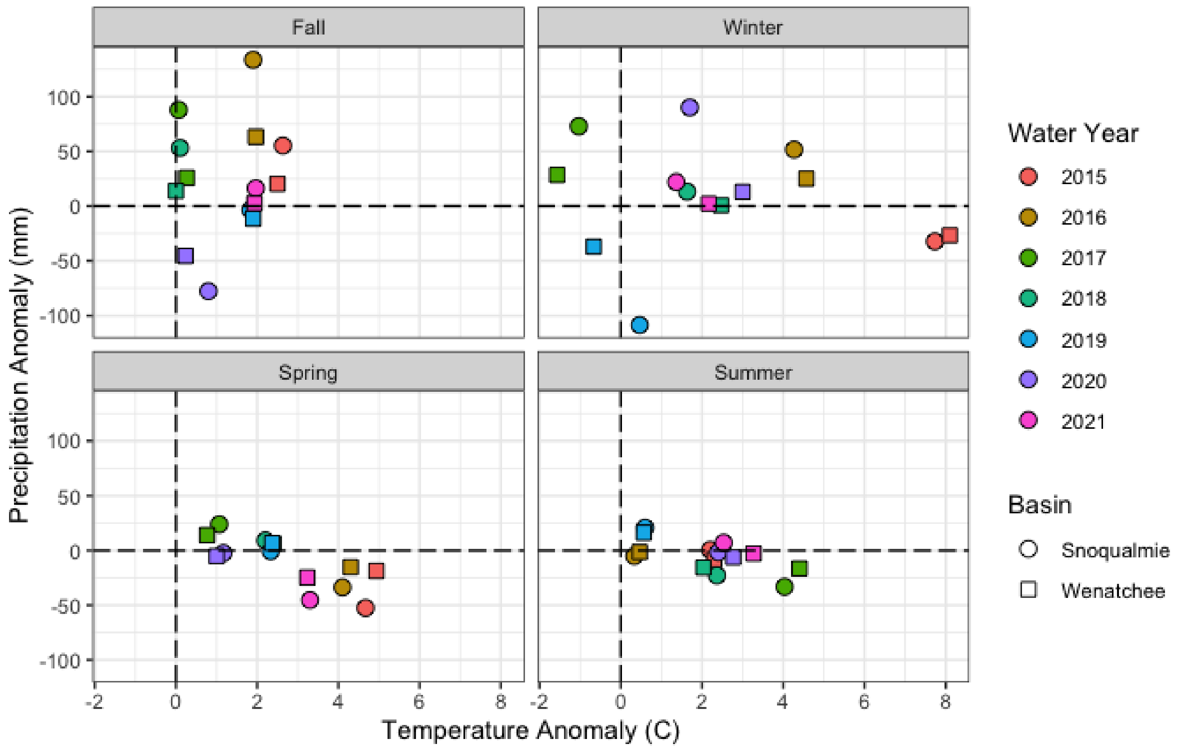

Figure S1. Seasonal temperature anomalies for NOAA National Centers for Environmental Information Washington Climate Division 5 (Western Cascades) and Division 6 (Eastern Cascades) vs seasonal precipitation anomalies. Anomalies are calculated as the departure from the 1901-2000 mean temperature or precipitation by month and subsequently averaged within a season. Positive (negative) anomalies indicate a wetter (drier) season for precipitation and a hotter (cooler) season for temperature.

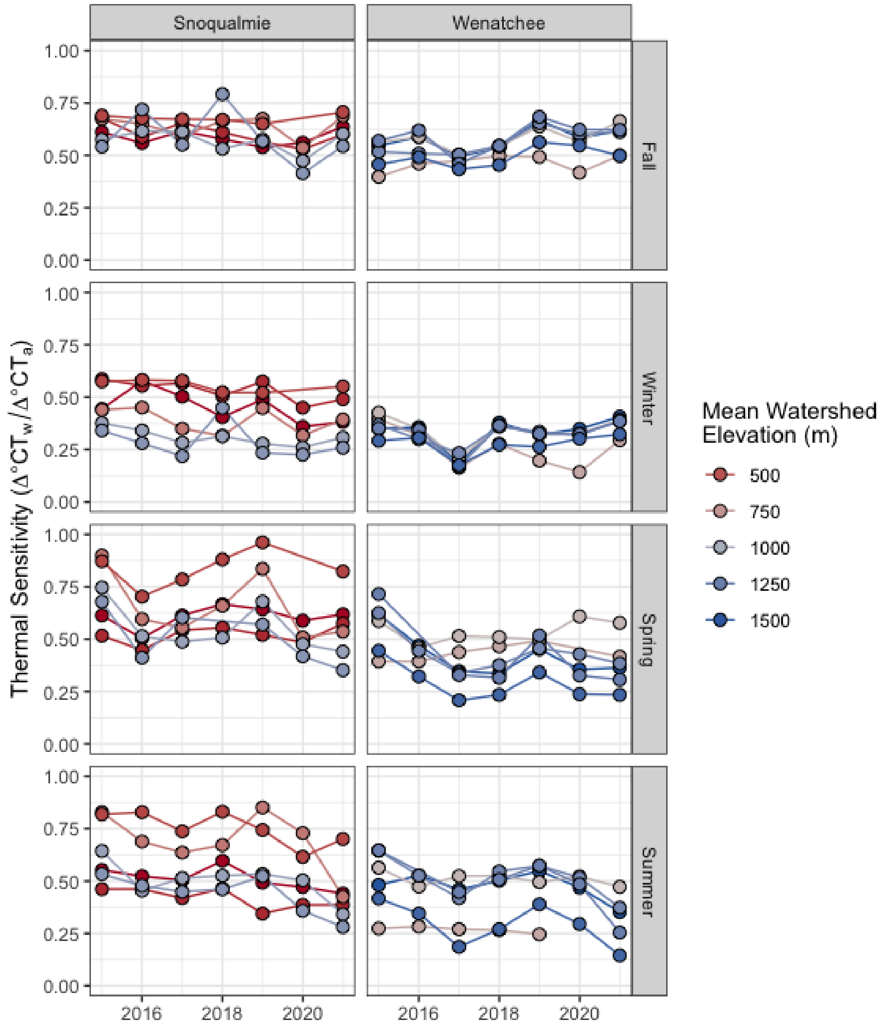

Figure S2. Thermal sensitivity summary metrics for all seasons for sites with relatively long and complete records. Continuous thermal sensitivities for the same sites are visualized in Figure S3. The color of each point corresponds to the MWE.

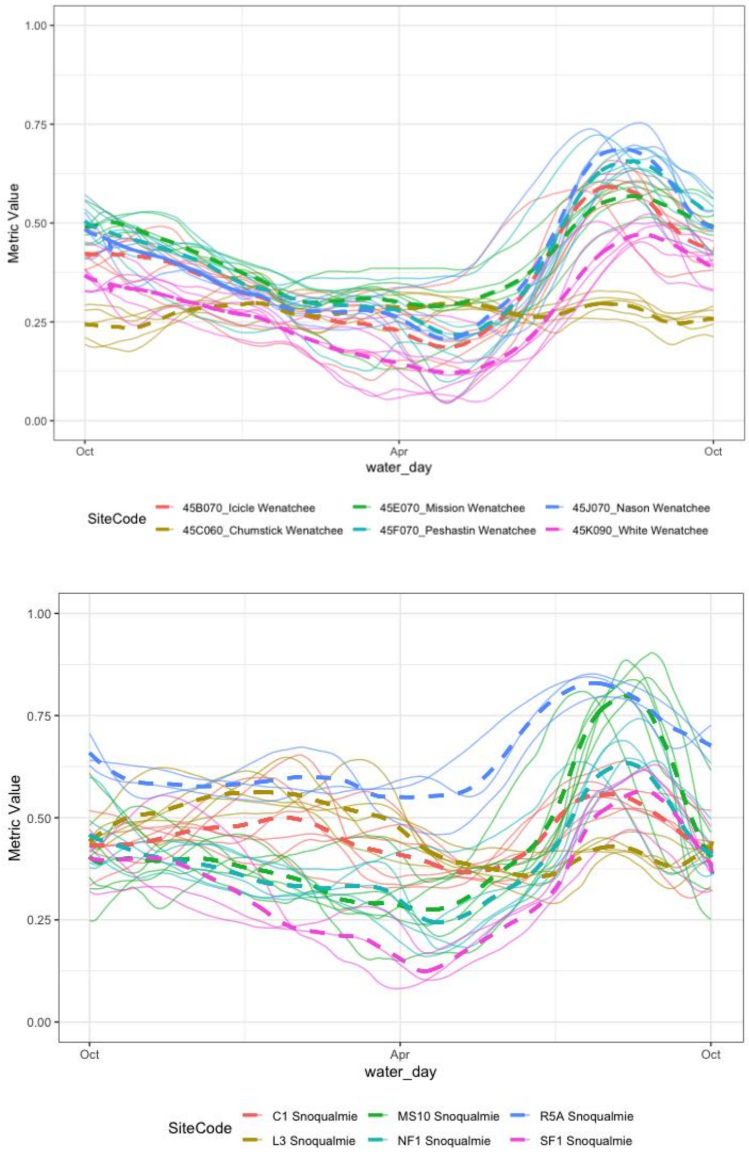

Figure S3. Examples of calculating an average mean time series of thermal sensitivity from individual years. Sites selected have relatively long and complete records. Summary metrics of thermal sensitivity for the same sites are visualized in Figure S2. The mean thermal sensitivity for each site is shown as a dashed line, and each complete year of data is shown as a solid line of the same color.

Table S1. The similarity of clustering results to our reported results for all 7 years when removing data from a given water year. Similarity between clusters is measured by the Rand Index.

		Rand Index	
Water Year Removed	**Water Year Climate Description**	**Snoqualmie**	**Wenatchee**
2015	A hot winter and dry winter and spring led to historically low snowpack, low summer streamflow, and hot summer stream temperatures.	0.93	0.92
2016	This year experienced an anomalously wet fall with periods of very heavy rain. Spring was slightly drier and warmer than average and in the western Cascades, snowpack slightly lower than average due to the warm winter.	0.90	0.97
2017	This year experienced an anomalously wet fall with periods of very heavy rain. Summer was relatively dry, winter relatively cool and wet, and fall relatively wet.	0.95	0.87
2018	A slightly larger than average snowpack.	0.87	0.91
2019	A dry winter led to a smaller than average snowpack that melted off earlier than normal, particularly for the western Cascades.	0.87	0.97
2020	Winter was slightly wetter than average.	0.92	0.91
2021	Higher than average snowpack. A period of extreme heat occurred in early spring. The spring was also relatively dry.	0.93	0.97

S2. Supplemental Figures and Tables

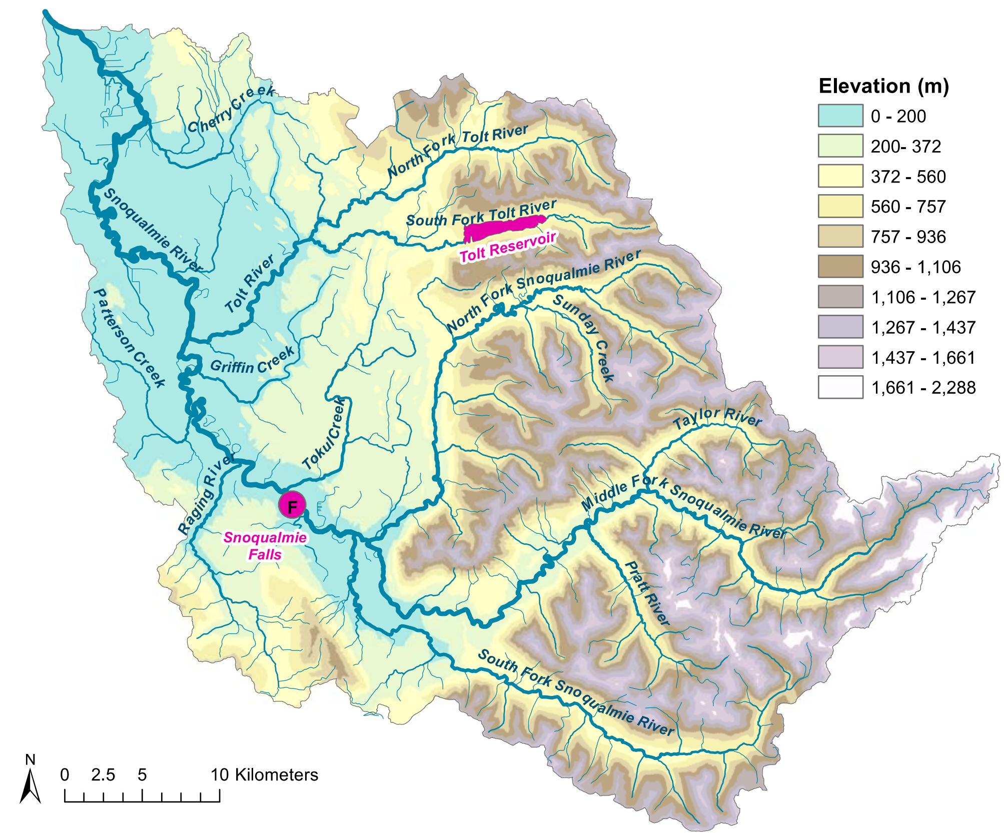

Figure S4. A map of the Snoqualmie basin, showing the locations of all major tributaries, the Tolt Reservoir and dam, and Snoqualmie Falls. Color indicates elevation.

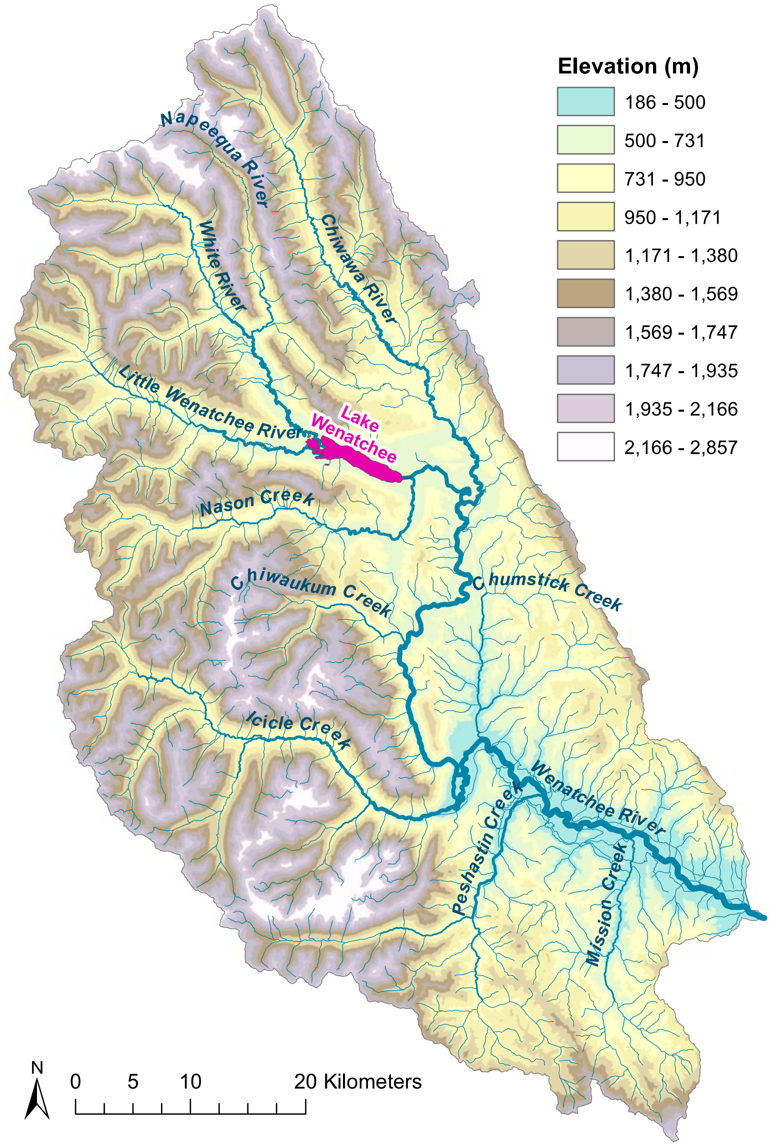

Figure S5. A map of the Wenatchee basin, showing the locations of all major tributaries and Lake Wenatchee. Color indicates elevation.

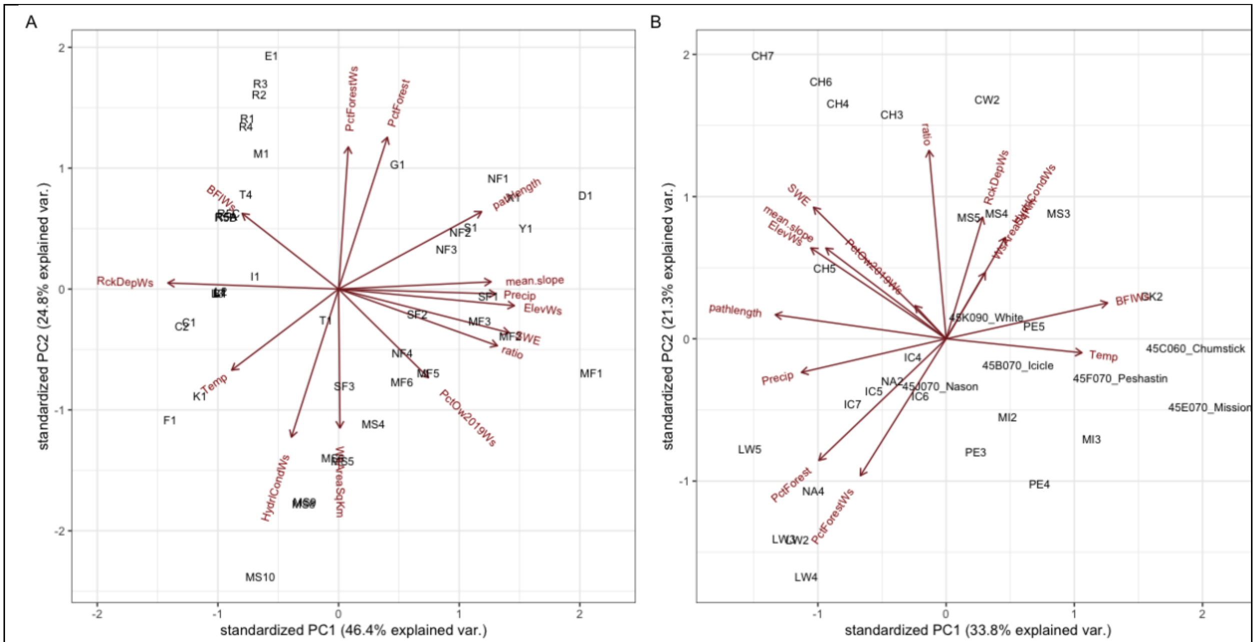

Figure S6. PCA results for the Snoqualmie (A) and Wenatchee (B) covariates. In the Snoqualmie, MWE and slope had high, positive loadings (0.45, 0.41) on PC1 and mean soil depth to bedrock had a high, negative loading (-0.43). In the Wenatchee patterns differed slightly, with MWE, slope, and distance upstream having negative loadings on PC1 (-0.38, -0.40, -0.45) and baseflow index loading positively (0.43). For PC2, both watersheds show percent forest in the watershed and riparian area as the highest loadings (-0.55, -0.52 and -0.43, -0.48), with the Wenatchee also showing percent ice cover loading positively (0.45).

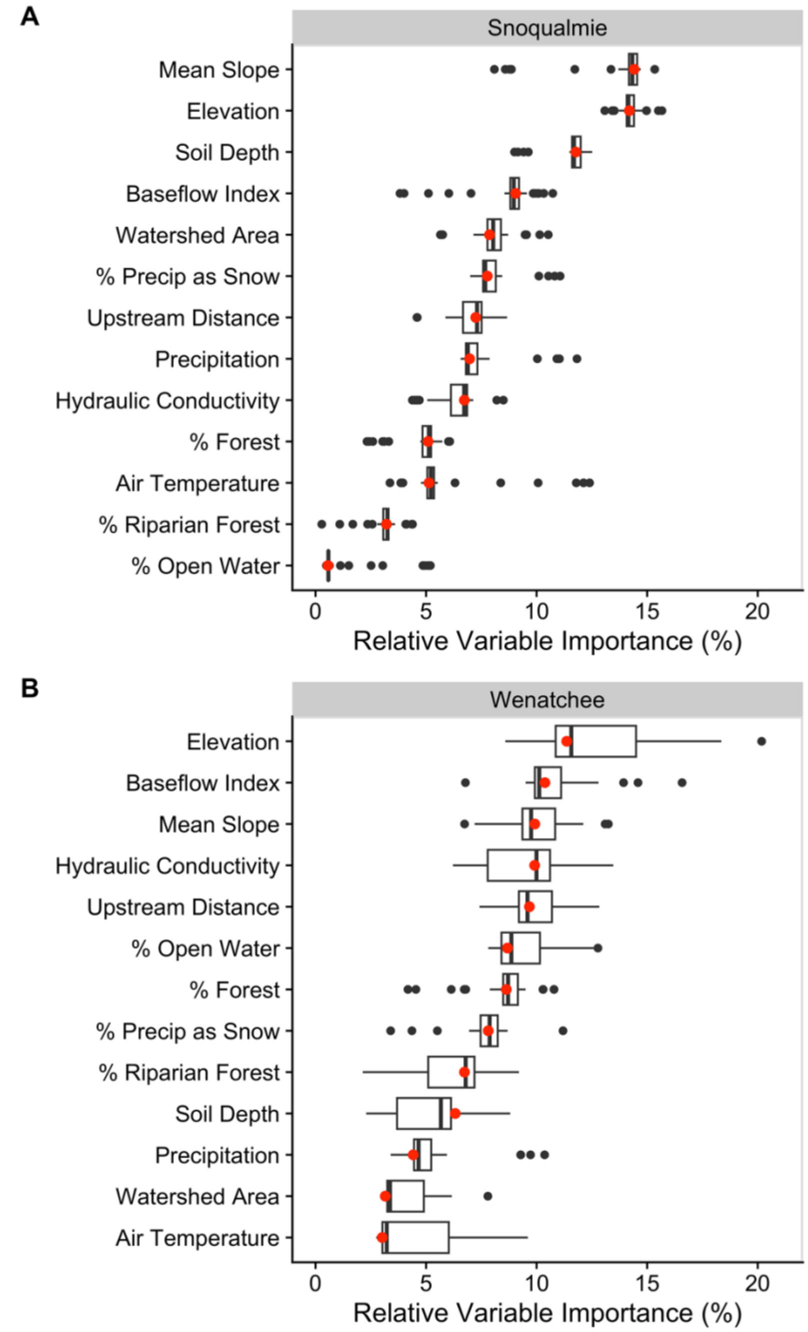

Figure S7. Leave-one-out-cross-validation results for CART modeling. Boxplots indicate the full range of observed relative variable importance values when a single site is excluded from the CART analysis, and red dots indicate the relative variable importance estimate when all sites are considered in the analysis ($N_{Snoqualmie}$=42, $N_{Wenatchee}$=31). Although the inclusion of individual sites can clearly impact relative importance estimates, when all points are considered simultaneously, estimated relative importance estimates closely line up with median values from the cross-validation analysis. This suggests that the CART analysis consistently identifies certain variables as more influential in making predictions, and results are relatively robust to individual data points.

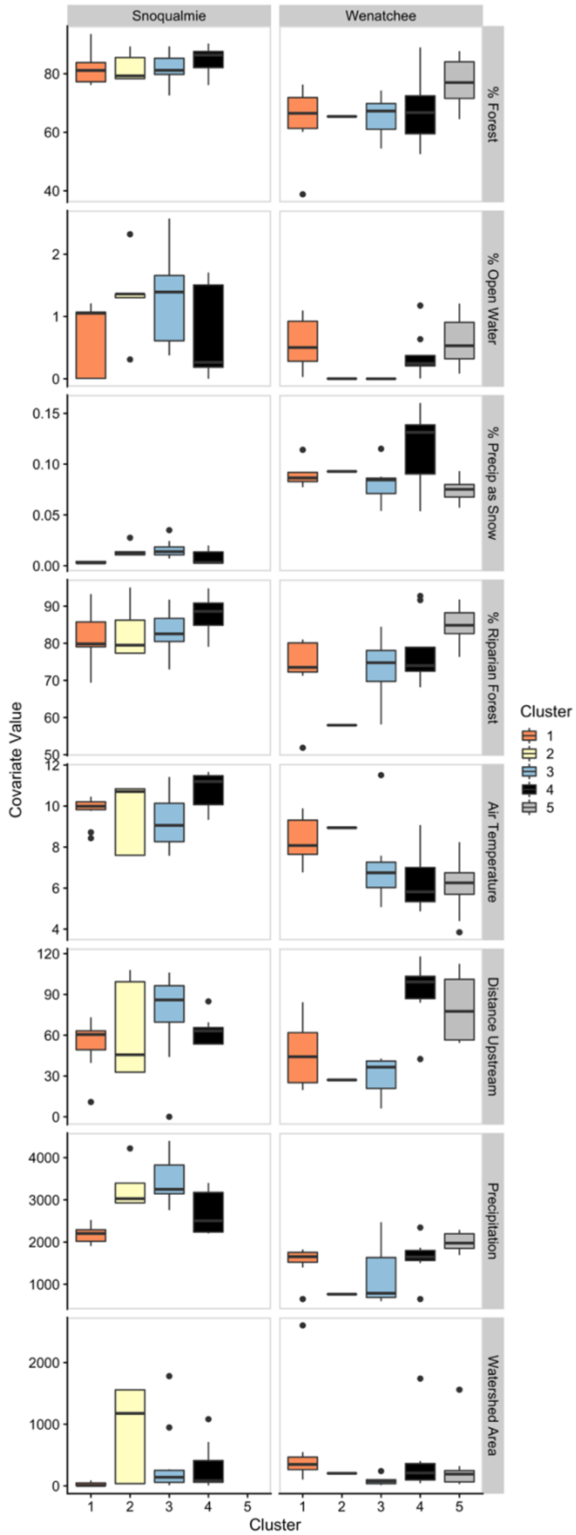

Figure S8. Relative variable importance for all covariates in the Snoqualmie (A) Wenatchee (B) basins, and the distributions of variables for the remaining variables in the Snoqualmie basin and in the Wenatchee basin. Boxes are grouped and colored by cluster membership. See Figure 6 for the four top relative variable importance plots.

Table S2. The optimal number of clusters selected for each metric and cluster validity index (CVI).

Cluster Validity Index	**Wenatchee**			**Snoqualmie**		
	Air Temperature	Water Temperature	Thermal Sensitivity	Air Temperature	Water Temperature	Thermal Sensitivity
Silhouette	**2**	**2**	2	**2**	**2**	2
Gap	**2**	**2**	2	**2**	**2**	2
Davies–Bouldin	**2**	**2**	**5**	**2**	**2**	**4**
Calinski–Harabasz	**2**	**2**	**5**	**2**	**2**	**4**
Generalized Dunn	3	5	**5**	5	4	**4**