Spatial and seasonal variability of forested headwater stream temperatures in western Oregon, USA

Aquatic Sciences - supplemental material

J.A. Leach (jason.leach@slu.se), D.H. Olson, P.D. Anderson and B.N.I. Eskelson

Introduction

This supplemental material provides details on the spatial statistical analysis that was used to examine spatial variability of stream temperature using all 48 sites in our Keel Mountain, Oregon, USA study area, and its relationship to geomorphic attributes and forest thinning treatments.

Stream temperature metrics

The first step was to determine a suitable response variable that captured the spatial variability of stream thermal regimes at the study area (Arismendi et al., 2013). We calculated eight metrics from both the 2012 and 2013 daily stream temperature data: annual mean, annual maximum, annual minimum, annual standard deviation, annual interquantile range (IQR), number of days above 10 °C, number of days below 5 °C, maximum weekly annual temperature (MWAT) (Figures 1 and 2). Sites were removed from analysis if the records contained data gaps that exceeded 10% of the total annual record. This resulted in data from 48 and 42 sites analyzed for 2012 and 2013, respectively. Many of the metrics were correlated with each other. In this supplement we only show results for standard deviation of mean daily stream temperature and mean annual stream temperature; however, we performed these analyses for all metrics listed above.

Predictor variables

We considered nine predictor variables to be used in the statistical models to predict spatial stream temperature variability (Table 1). These included geomorphic attributes determined from a LiDAR-derived digital elevation model (DEM; resolution 0.91 m) of the study area and used in other studies (Scott et al., 2002; Wehrly et al., 2009; Daigle et al., 2010; Hrachowitz et al., 2010; Mayer, 2012; Moore et al., 2013). We also included two variables based on field measurements (stream width and dominant streambed substrate at datalogger location). The study area has been subject to forest harvesting as part of the Density Management and Riparian Buffer Study (Cissel et al., 2006). Harvesting has consisted of upland thinning treatments with riparian buffers. Therefore, we included two factor variables representing forest thinning treatments associated with the riparian and upland thinning. Each site was assigned a treatment combination based on those treatments found upstream of the sensor location. For more information on the forest harvesting treatments please consult Anderson et al. (2007); Olson and Rugger (2007); Olson and Weaver (2007); Olson et al. (2007, 2014); Olson and Burton (2014).

Spatial statistical modelling

Spatial correlation structure

It was critical to account for spatial correlation in the statistical models due to the spatial distribution of the data loggers. We compared stream network and Euclidean approaches for representing the spatial correlation structure. We used the SSN package (Ver Hoef et al., 2014) for R (R Development Core Team, 2014) to fit models specifically developed for accounting for stream network distances (Peterson and Ver Hoef, 2010). We fit models using different temperature response variables and predictors with: 1) no spatial correlation structure; 2) Euclidean correlation structure; and 3) stream network correlation structure. We compared model performance by evaluating the difference in the second-order Akaike's Information Criterion (AIC_c) for small samples (Hurvich and Tsai, 1989). The comparison supported the use of either a stream network or Euclidean structures over no spatial correlation structure ($\Delta AIC_c > 10$); however, there was not support for favouring the stream network structure (AIC_c = 77.8) over the Euclidean structure (AIC_c = 74.8). This is not surprising since the stream network is not completely nested and the Euclidean distances between sites are similar to the stream network distances. In addition, the model did not appear to be sensitive to changing the Euclidean error structure (exponential, Gaussian, linear, rational quadratics, or spherical). Therefore, we used an exponential spatial correlation structure for all subsequent analyses.

Modelling

None of the predictors were strongly related to the various temperature metrics when examined individually (e.g., Figures 3 and 4 for standard deviation of daily mean stream temperature as the response variable, and Figures 5 and 6 for the annual mean stream temperature as the response variable). We conducted a data exploration exercise where we fit every possible combination of predictor variable set and ranked the models using AIC_c. Conducting this kind of data exploration exercise is not considered appropriate for making statistical inferences since it is likely to select spurious models (Burnham and Anderson, 2002); however, our goal was to exhaustively check if any of the predictors used in our analysis had any relationship to the temperature metrics. We also considered interaction terms in our data exploration exercise, but for brevity, only report the non-interaction results here.

We fit the following global model:

$$Tw = \beta_0 + \beta_1 aspect + \beta_2 elevation + \beta_3 log(catchmentArea) + \beta_4 skyViewFactor + \beta_5 slope + \beta_6 streamWidth + \beta_7 substrate + \beta_8 riparianTreatment \quad (1)$$

where Tw is the response variable (one of the eight stream temperature metrics assessed), and β_i are the coefficients of the predictor variables to be fit by a generalized linear model using maximum likelihood method. We did not include upland treatment in the global model since it created issues in model convergence due to the large number of total factor variables in the model compared to the sample size. It was preferred to include the riparian treatment over the upland treatment because it is presumed to have more influence on stream temperature.

Tables 2 to 5 show subsets of the highest ranked models by AIC_c. We show only the models that had a $\Delta AIC_c < 4$. The results show that there is weak support for the best models and that model uncertainty is high. There is little support that the predictor variables used to represent differences in site characteristics and forest thinning treatments explain the spatial variability in stream temperature at Keel Mountain. These results were consistent when considering the other six stream temperature metrics.

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Table 1: List of predictor variables used in the statistical analyses.

Predictor	Unit	Notes
Elevation	metres	Extracted from DEM
log(CatchmentArea)	m^2	Logarithm of the catchment area determined using the D8 algorithm
Slope	°	Channel slope extracted from DEM
Aspect	°	Aspect extracted from DEM
Sky view factor	-	Terrain sky view factor extracted from DEM
Stream width	metres	Stream width measured in the field at datalogger location
Substrate	factor	Dominant streambed substrate assessed in the field at datalogger location. Three classes include: *coarse*, *medium*, and *fine*.
US Riparian	factor	Upstream riparian thinning treatment: • *con*: control, no treatment • *cc*: clearcut, clearcut upstream outside of study area boundary • *one*: one tree width, approximately 70 m on each side of streams • *two*: two tree width, approximately 145 m on each side of streams • *stream*: streamside retention, 6 m on each side of streams • *var*: variable width buffer, 15 m minimum width on each side of streams • *tt*: thin-through, thinned riparian buffer (reduction in trees per hectare from around 430-600 to around 150)
US Upland	factor	Upstream upland thinning treatment: • *con*: control, no thinning and around 430-600 trees per hectare • *high*: high density retention, thinned upland with around 150 trees per hectare • *mod*: moderate density retention, thinned upland with around 85 trees per hectare • *var*: variable retention, thinned upland with around 100 trees per hectare and 0.4 ha circular clearcuts

Table 2: Model structures and summary statistics for 2012 standard deviation response variable. df is degrees of freedom, AIC_c is the second-order Akaike information criterion, ΔAIC_c is the AIC_c differences, and Weight is the Akaike weight.

Intercept	Aspect	Elevation	Catchment area	Sky view factor	Slope	Stream width	Substrate	US riparian trt	df	AIC_c	ΔAIC_c	Weight
-7.11			0.1258	8.40					5	92.1	0.000	0.1496
-7.76			0.1550	8.93		-0.0916			6	92.8	0.728	0.1040
1.25			0.0809						4	93.0	0.928	0.0941
2.09									3	93.1	0.956	0.0928
1.13			0.1040			-0.0800			5	94.2	2.082	0.0528
2.39					-1.382				4	94.3	2.189	0.0501
-8.99			0.1407	10.08	0.724				6	94.5	2.414	0.0448
-1.67				4.00					4	94.6	2.457	0.0438
-7.16	0.02163		0.1291	8.34					6	94.6	2.549	0.0418
-6.86		-0.000276	0.1240	8.36					6	94.7	2.614	0.0405
4.07		-0.002877							4	94.7	2.648	0.0398
1.57			0.0731		-1.072				5	94.8	2.733	0.0382
-10.98			0.1826	11.79	1.226	-0.1013			7	95.0	2.887	0.0353
2.14						-0.0327			4	95.2	3.100	0.0318
-7.87	0.03532		0.1613	8.83		-0.0948			7	95.4	3.285	0.0290
1.07	0.03103		0.0861						5	95.4	3.288	0.0289
2.10	-0.00465								4	95.4	3.337	0.0282
2.04		-0.001062	0.0749						5	95.4	3.341	0.0282
-7.88		0.000130	0.1559	8.95		-0.0918			7	95.6	3.477	0.0263

Table 3: Model structure and summary statistics for 2013 standard deviation response variable. df is degrees of freedom, AIC_c is the second-order Akaike information criterion, ΔAIC_c is the AIC_c differences, and Weight is the Akaike weight.

Intercept	Aspect	Elevation	Catchment area	Sky view factor	Slope	Stream width	Substrate	US riparian trt	df	AIC_c	ΔAIC_c	Weight
-8.38			0.163	9.64					5	100	0.000	0.2115
-9.19			0.198	10.29		-0.1022			6	101	0.836	0.1392
1.15			0.116						4	102	1.334	0.1085
-12.70			0.193	13.54	1.60				6	102	1.833	0.0846
-14.98			0.243	15.50	2.11	-0.1170			7	102	2.205	0.0702
-8.29		-0.000086	0.162	9.62					6	103	2.620	0.0571
-8.38	9.58e-05		0.163	9.64					6	103	2.620	0.0571
1.00			0.144			-0.0861			5	103	2.696	0.0549
2.36									3	103	3.235	0.0420
1.42			0.110		-0.92				5	104	3.397	0.0387
-9.21	1.24e-02		0.201	10.23		-0.1032			7	104	3.569	0.0355
-9.59		0.000415	0.202	10.38		-0.1031			7	104	3.575	0.0354
2.15		-0.001335	0.109						5	104	3.705	0.0332
1.01	2.37e-02		0.121						5	104	3.771	0.0321

Table 4: Model structure and summary statistics for 2012 mean response variable. df is degrees of freedom, AIC_c is the second-order Akaike information criterion, ΔAIC_c is the AIC_c differences, and Weight is the Akaike weight.

Intercept	Aspect	Elevation	Catchment area	Sky view factor	Slope	Stream width	Substrate	US riparian trt	df	AIC_c	ΔAIC_c	Weight
-6.226			0.1249	13.41	3.78	-0.1949			7	38.5	0.000	0.2253
-4.855			0.1480	11.55	4.24	-0.2380	+		9	39.0	0.546	0.1714
-6.076	-0.0730		0.1084	13.69	3.72	-0.1543			8	39.5	1.057	0.1328
1.115				7.17	2.36	-0.1267			6	40.9	2.461	0.0658
-0.706	-0.1050			9.41	2.66	-0.0828			7	41.4	2.925	0.0522
-5.374	-0.0601		0.1424	12.40	4.32	-0.2138	+		10	41.5	3.064	0.0487
8.419						-0.1565			4	41.6	3.109	0.0476
-5.541		-0.000609	0.1193	13.20	3.74	-0.1934			8	41.7	3.185	0.0458
7.917					1.60	-0.1475	+		7	41.9	3.413	0.0409
2.184	-0.1006	-0.004422		9.55	2.96	-0.1152			8	42.2	3.685	0.0357
8.137					1.23	-0.1547			5	42.2	3.715	0.0352
3.234		-0.003132		7.21	2.41	-0.1331			7	42.3	3.803	0.0336
-2.237	-0.1198			11.11	2.01				6	42.3	3.812	0.0335
7.225			0.0678		1.93	-0.2112	+		8	42.4	3.931	0.0316

Table 5: Model structure and summary statistics for 2013 mean response variable. df is degrees of freedom, AIC_c is the second-order Akaike information criterion, ΔAIC_c is the AIC_c differences, and Weight is the Akaike weight.

Intercept	Aspect	Elevation	Catchment area	Sky view factor	Slope	Stream width	Substrate	US riparian trt	df	AIC_c	ΔAIC_c	Weight
8.35						-0.141	+		6	43.1	0.000	0.2434
8.03					1.32	-0.130	+		7	43.9	0.728	0.1691
8.57						-0.171			4	44.9	1.755	0.1012
8.24					1.33	-0.161			5	45.6	2.452	0.0714
9.81				-1.55		-0.146	+		7	45.9	2.713	0.0627
8.21			0.0149			-0.154	+		7	46.0	2.886	0.0575
8.72		-0.000539				-0.142	+		7	46.1	2.947	0.0558
8.41	-0.0135					-0.142	+		7	46.1	2.961	0.0554
7.86			0.0176		1.33	-0.146	+		8	46.9	3.757	0.0372
6.53				1.51	1.62	-0.123	+		8	46.9	3.758	0.0372
8.60		-0.000846			1.36	-0.132	+		8	46.9	3.760	0.0372
7.68					1.79		+		6	46.9	3.779	0.0368
8.09	-0.0155				1.33	-0.131	+		8	47.0	3.872	0.0351

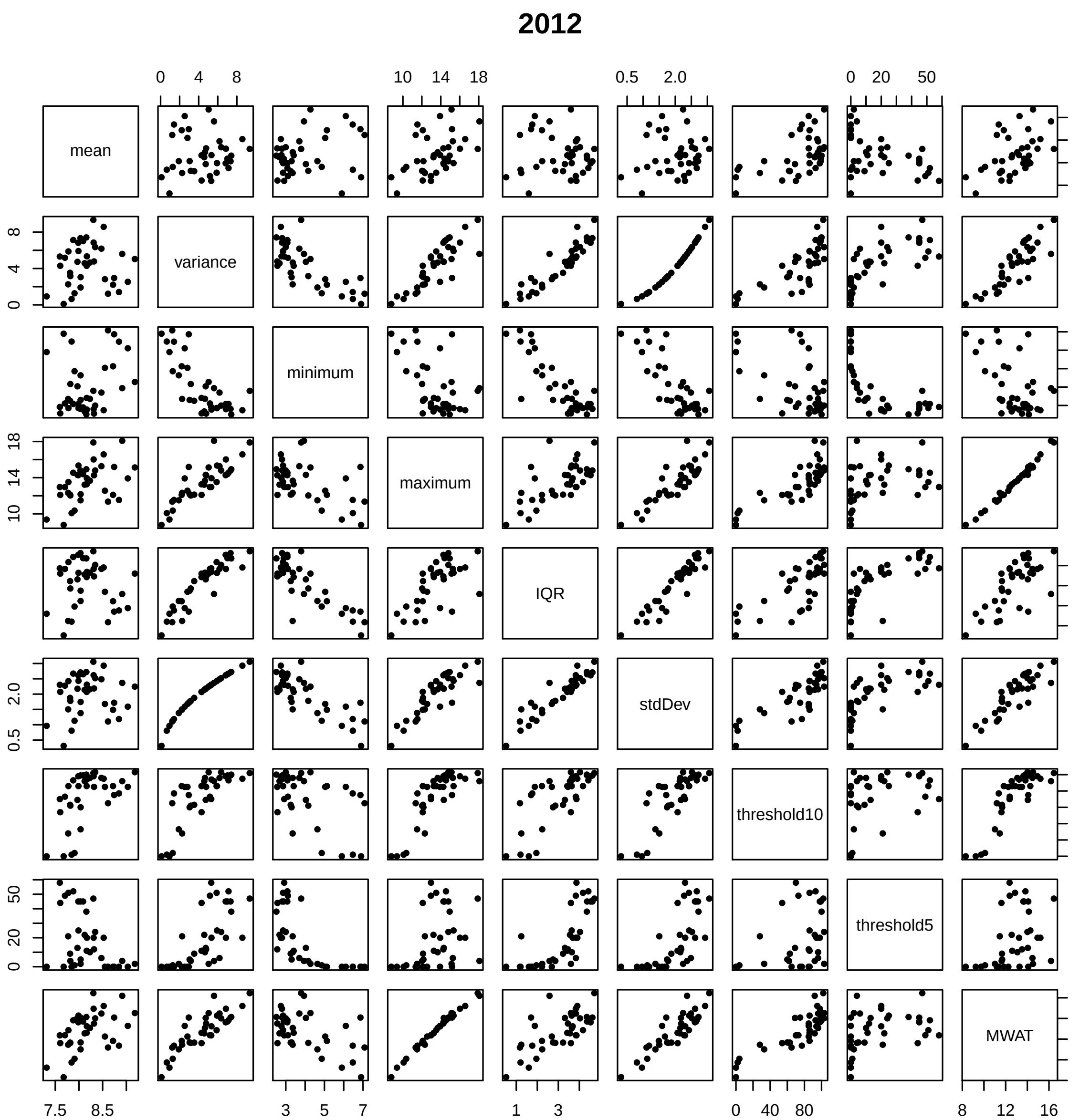

Figure 1: Matrix of scatterplots for the 2012 stream temperature metrics considered. All metrics were calculated using mean daily stream temperature. 'mean' is mean annual stream temperature, 'variance' is annual stream temperature variance, 'minimum' is annual minimum stream temperature, 'maximum', is annual maximum stream temperature, 'IQR' is the interquantile range of annual stream temperature, 'stdDev' is the standard deviation of annual stream temperature, 'threshold10' is the number of days when stream temperature exceeded 10 °C, 'threshold5' is the number of days when stream temperature was below 5 °C, and 'MWAT' is the maximum weekly average temperature.

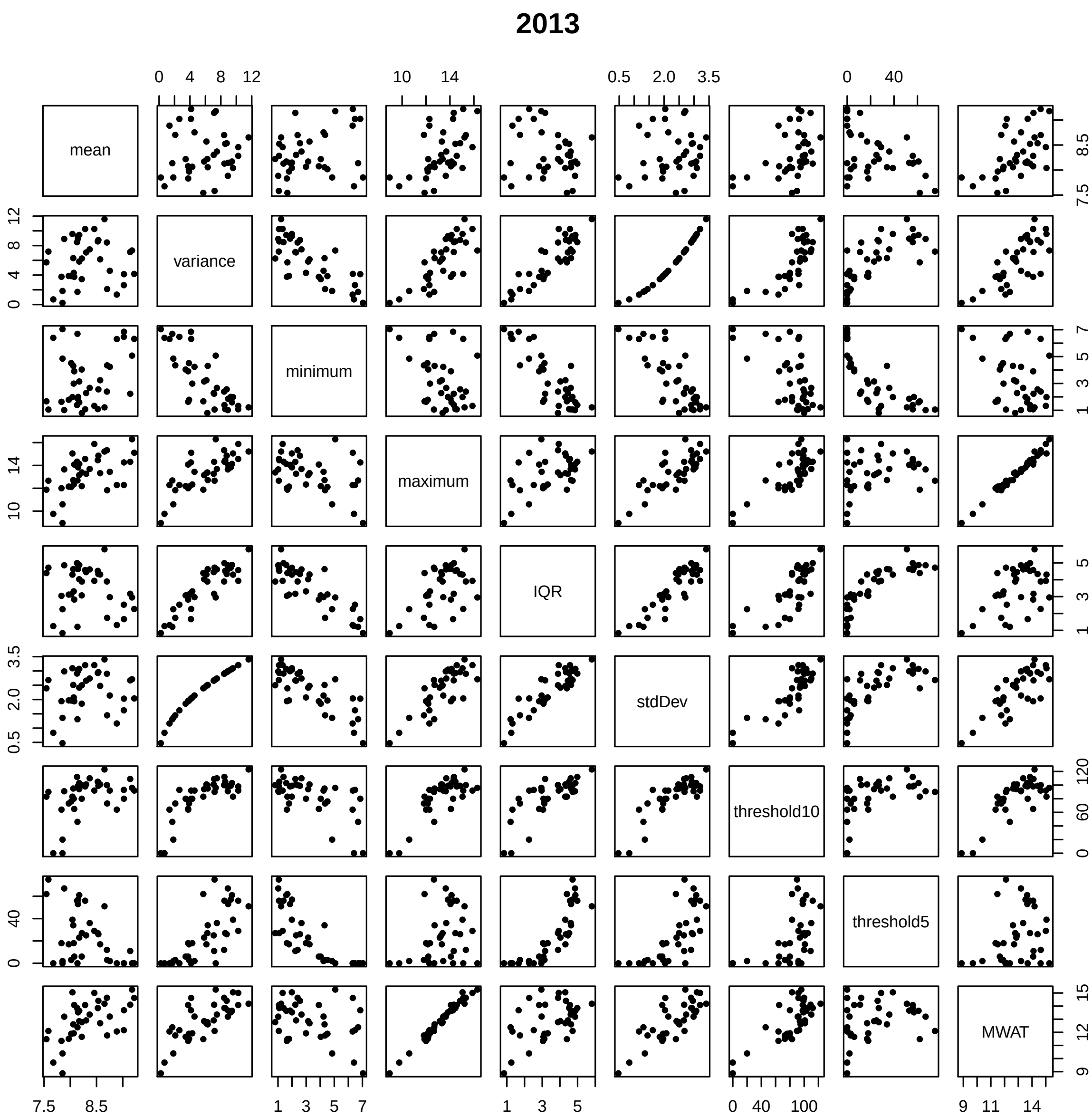

Figure 2: Matrix of scatterplots for the 2013 stream temperature metrics considered. All metrics were calculated using mean daily stream temperature. 'mean' is mean annual stream temperature, 'variance' is annual stream temperature variance, 'minimum' is annual minimum stream temperature, 'maximum', is annual maximum stream temperature, 'IQR' is the interquantile range of annual stream temperature, 'stdDev' is the standard deviation of annual stream temperature, 'threshold10' is the number of days when stream temperature exceeded 10 °C, 'threshold5' is the number of days when stream temperature was below 5 °C, and 'MWAT' is the maximum weekly average temperature.

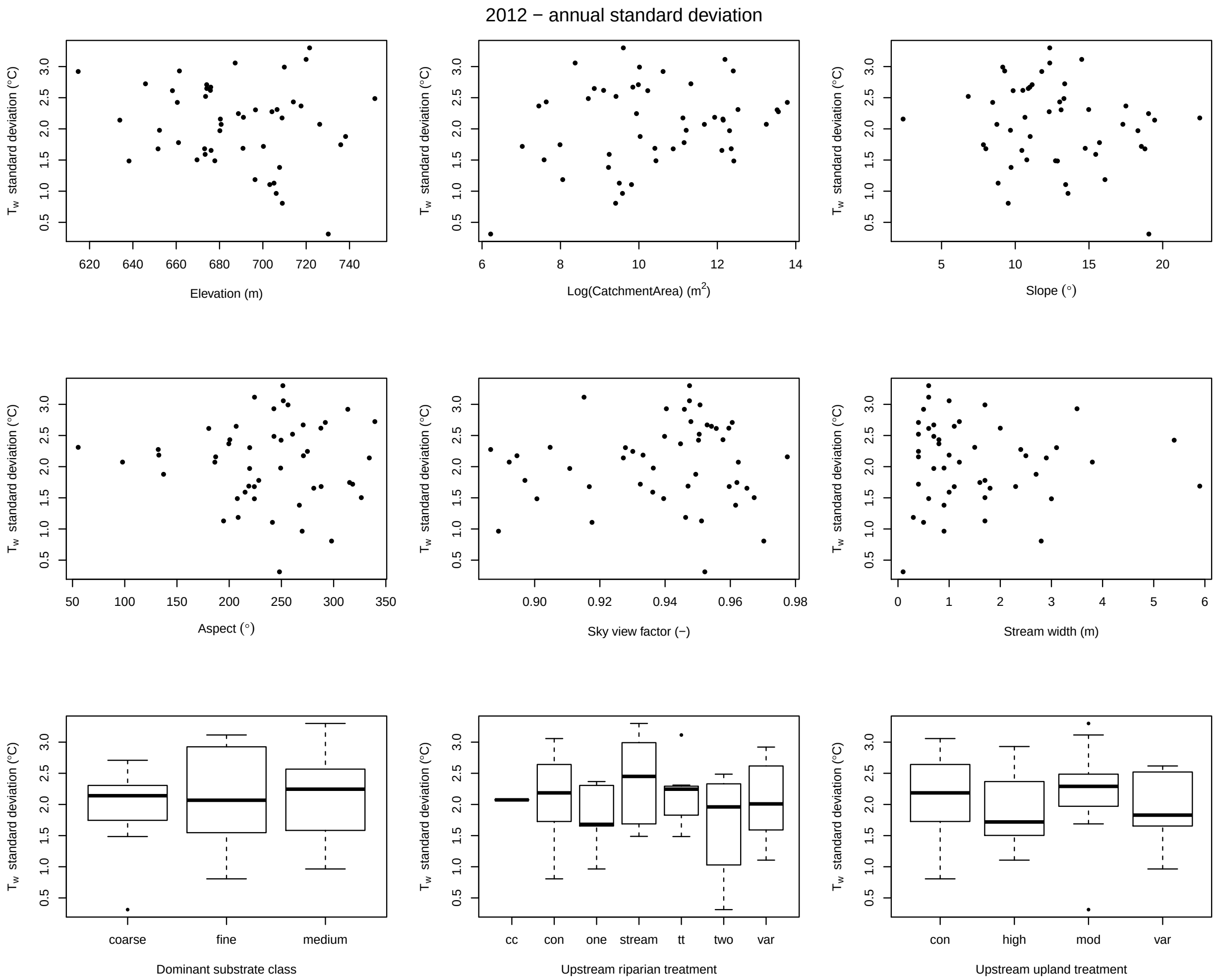

Figure 3: Scatterplots of nine geomorphic/forest attributes and 2012 standard deviation of annual stream temperature for the 48 sites. See Table 1 for more information on the geomorphic/forest attributes.

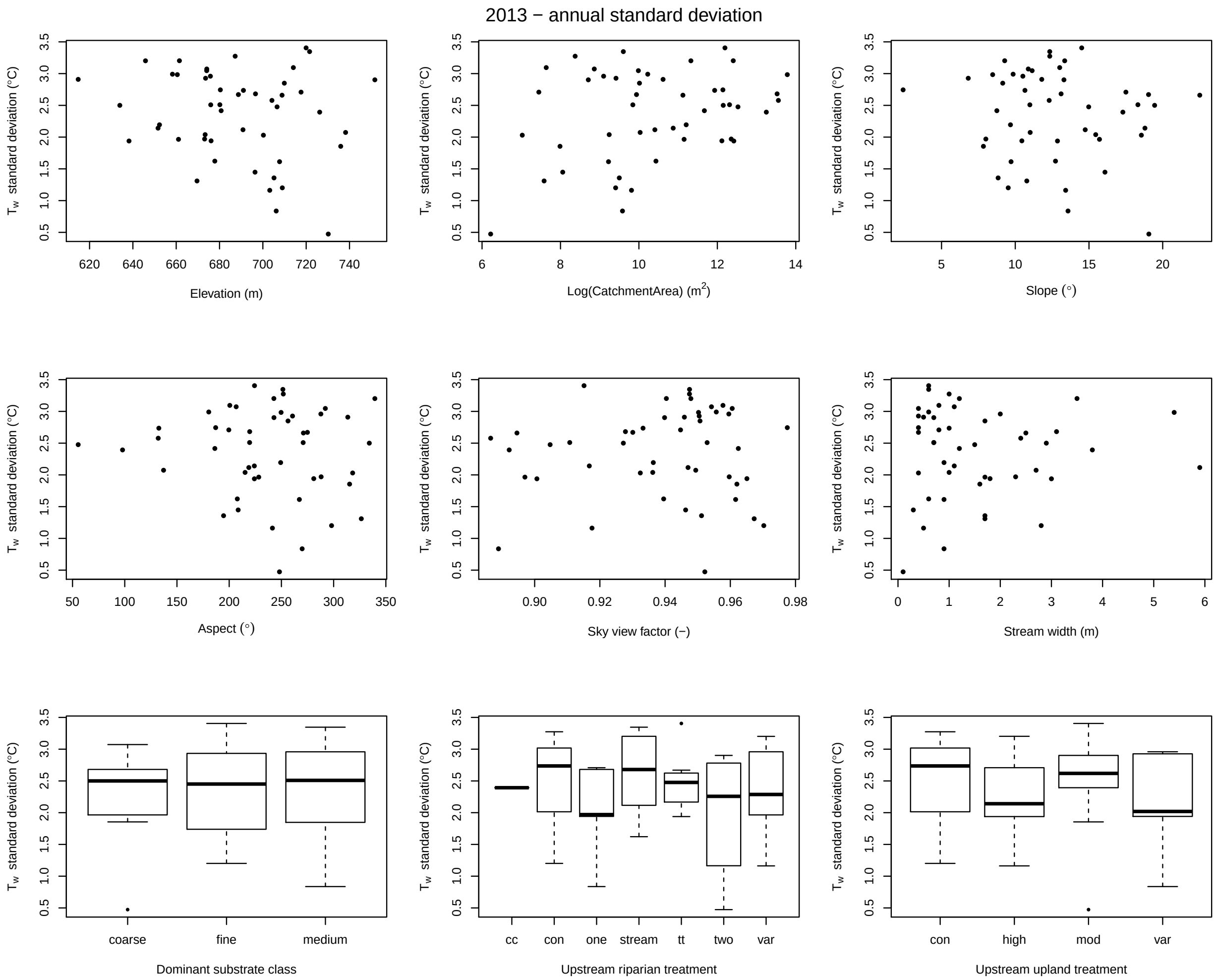

Figure 4: Scatterplots of nine geomorphic/forest attributes and 2013 standard deviation of annual stream temperature for 42 sites. See Table 1 for more information on the geomorphic/forest attributes.

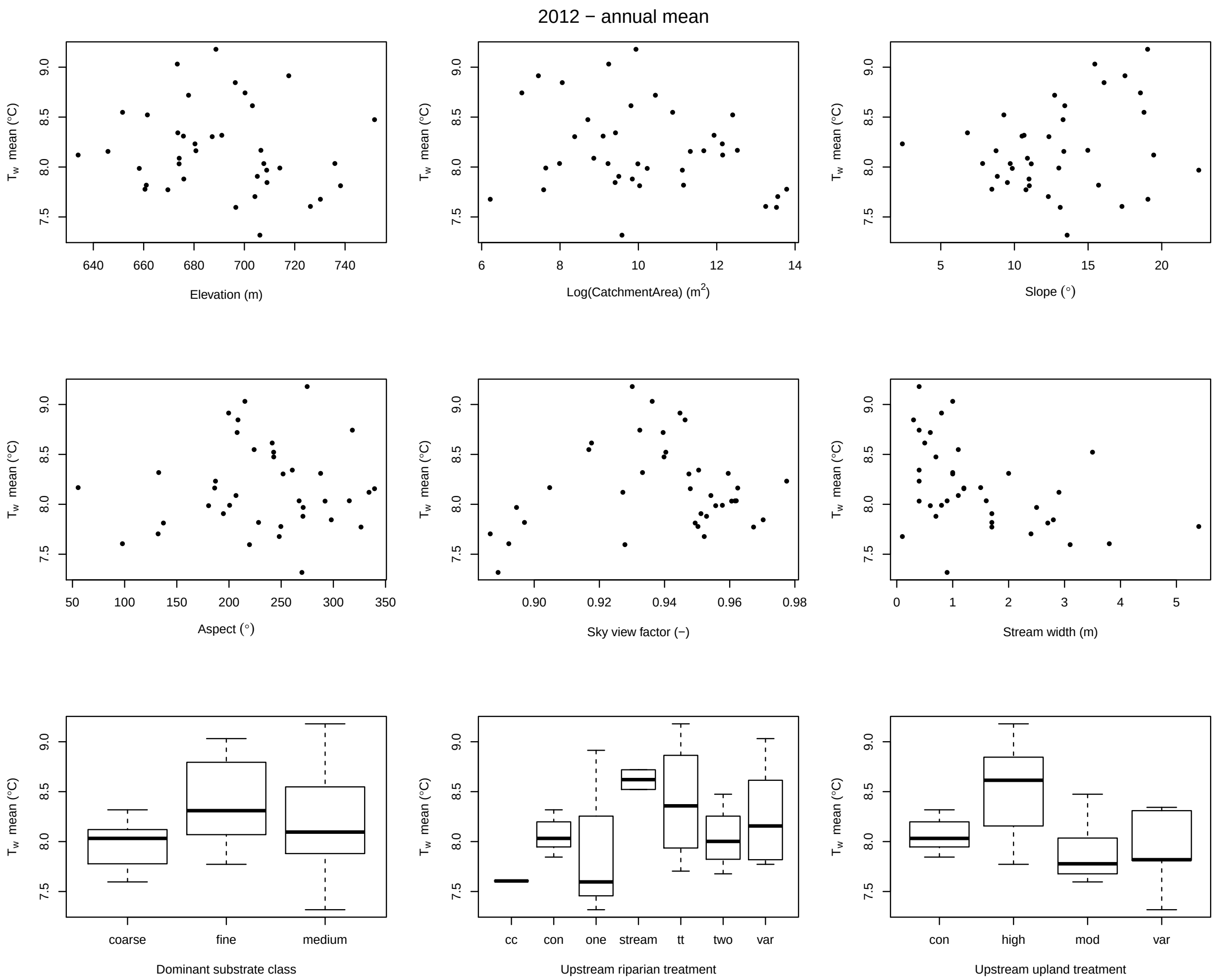

Figure 5: Scatterplots of nine geomorphic/forest attributes and 2012 mean annual stream temperature for the 48 sites. See Table 1 for more information on the geomorphic/forest attributes.

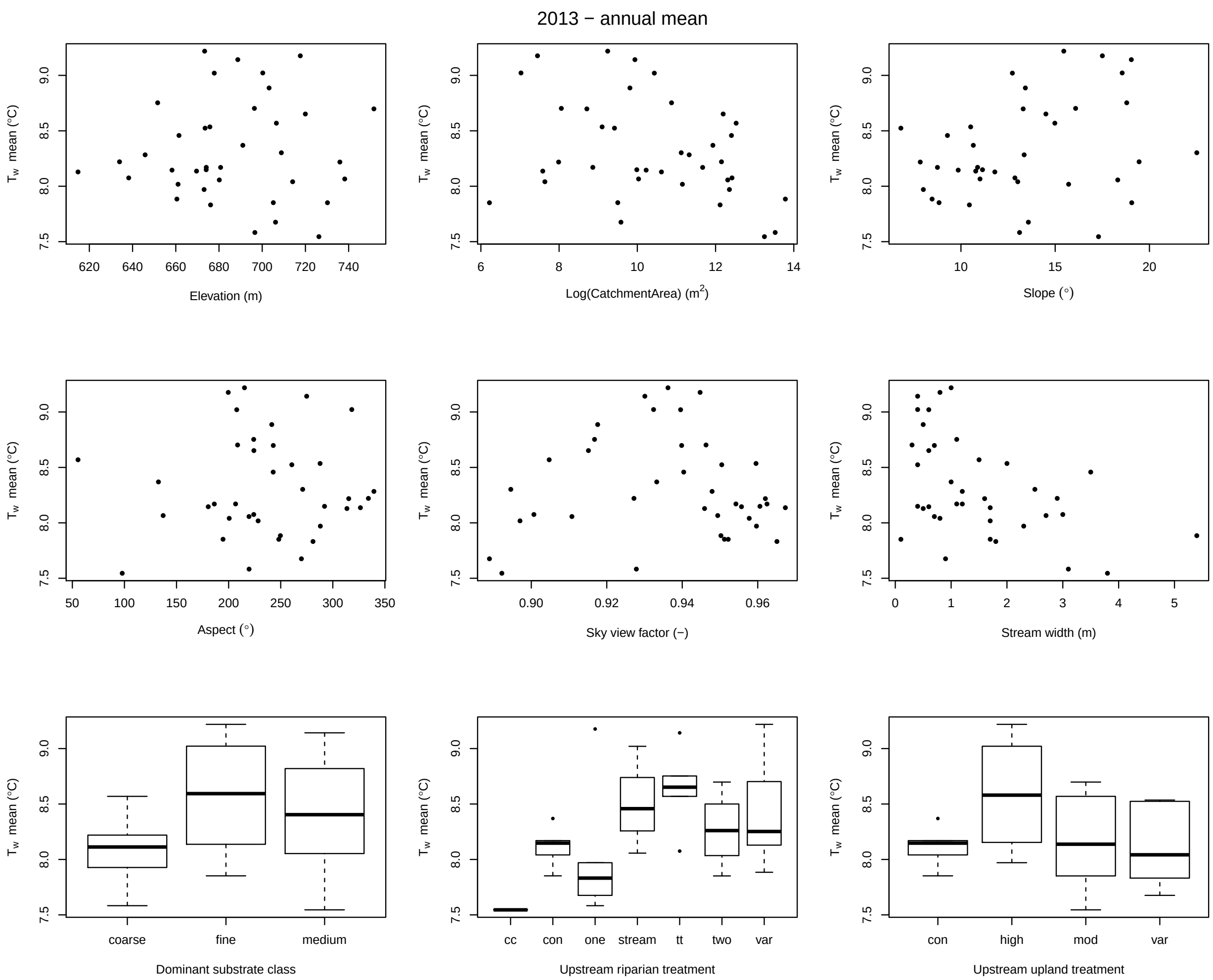

Figure 6: Scatterplots of nine geomorphic/forest attributes and 2013 mean annual stream temperature for 42 sites. See Table 1 for more information on the geomorphic/forest attributes.