THE INFLUENCE OF GEOMORPHIC AND LANDSCAPE CHARACTERISTICS ON STREAM TEMPERATURE AND STREAMWATER SENSITIVITY TO AIR TEMPERATURE IN THE COASTAL TEMPERATE RAINFOREST OF SOUTHEAST ALASKA

By

Michael Winfree, B.S.

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

in

Ecohydrology: Interdisciplinary Program

University of Alaska Fairbanks

May 2017

APPROVED:

Dr. Svetlana Stuefer, Committee Chair
Dr. Eran Hood, Committee Co-Chair
Dr. Christopher Arp, Committee Member
Dr. Daniel Schindler, Committee Member
Dr. Leroy Hulsey, Chair
Department of Civil and Environmental Engineering
Dr. Douglas Goering, Dean
College of Engineering and Mines
Dr. Michael Castellini, *Dean of the Graduate School*

ABSTRACT

Climate warming is projected to increase the regional air temperature in southeast Alaska and alter precipitation patterns and storage, with potentially important implications for the region's aquatic resources. Streamwater temperature is controlled by energy inputs from the atmosphere and surrounding environment that are modified by a watershed's geomorphic and landcover characteristics. The climate-landcover relationships that influence stream temperature have not been comprehensively evaluated in southeast Alaskan watersheds. Thus, improving our understanding of current streamwater thermal regimes is critical to better assess how these regimes may be altered by climate change on a regional scale. In this study, seasonal streamwater thermal regimes in forty-seven watersheds across southeast Alaska were evaluated, and the influence of watershed geomorphic and landscape characteristics on stream temperature and streamwater sensitivity to air temperature was assessed. Stream temperatures were measured during the 2015 water year and analyzed for winter and summer seasons. Mean summer stream temperature ranged from 4.0°C to 17.2°C, while mean winter stream temperature were less variable across the region, ranging from 0.5°C to 3.5°C. Maximum weekly average temperatures (MWAT) ranged from 4.3°C to 21.5°C. Regression and time series analyses revealed that lower latitude, low gradient watersheds with higher lake coverage experienced warmer maximum and average summer stream temperatures and were more sensitive to air temperature fluctuations compared to higher latitude watersheds with high gradients during the summer. Winter mean stream temperature was warmer in higher gradient watersheds with greater forest and lake coverage. Moreover, higher latitude watersheds with steep gradients were less sensitive to changes in air temperature relative to low gradient / low latitude watersheds during the winter. Findings from this study demonstrate thermal regimes and air sensitivity are moderated by watershed geomorphology and landcover to create streamwater thermal heterogeneity across the coastal temperate rainforest of southeast Alaska. Results presented herein demonstrate that streamwater sensitivity to air temperature fluctuations are moderated by watershed geomorphology, and should be considered as a framework for predicting thermal regimes to assess relative watershed thermal response to climate change. This information, in turn, is important for quantifying the likely magnitude and spatial extent of climate-driven thermal impacts on Pacific salmon during their freshwater life history stages in southeast Alaska.

TABLE OF CONTENTS

List of Figures

Page

List of Tables

List of Appendices

Page

ACKNOWLEDGMENTS

A study incorporating the entirety of the panhandle in southeast Alaska, like most research projects, can only be successful with the involvement of many people.

I'd first like to thank my co-advisor Eran Hood. I feel quite fortunate to have had many discussions and field days with Eran over the last 30 months, and I am grateful to be able to consider him as a mentor and friend. I'm also grateful to Sveta Stuefer and Chris Arp, both of whom committed significant time to work with me during my first semester at the University of Alaska Fairbanks, and have both offered valuable advice and guidance from a distance now that I'm in Juneau. I'd also like to thank Daniel Schindler for his invaluable statistical guidance and encouragement, often communicating from a remote field camp in Bristol Bay. Overall, I can't imagine having a more supportive and energetic graduate committee.

My home during the majority of my graduate schooling has been the Natural Sciences Research Lab, based at the University of Alaska Southeast. It has been an excellent home for scientific research and collaboration. I'd like to thank Sanjay Pyare for imagining and acquiring funding for this project; and Jason Fellman, Pat Dryer, Kim Homan, and Bruce Simonson for support throughout this project. I'd also like to thank Mike Goldstein, Julianne Thompson, Emil Tucker, and Sheila Jacobson of the U.S Forest Service and Chris Sergeant and Todd Bruno with the National Park Service for helping me muster support for collecting field data in the Tongass National Forest; Scott Harris and Molly Kemp for their willingness to share their work with me; and Timothy Cline and Peter Lisi for guidance and advice with my analysis.

I received logistical help from many, and though this list is likely incomplete, I'd like to thank Jackie DeMontigny, Nate Catterson, Pete Schneider, Cathy Needham, Hetta Creek Weir Crew,

Jessica Davila, Jon Hyde, Steve Heinl, Richard Chappell, Craig Murdoch, Ethan Nichols, Ed Neal, Tony Christianson, Jeff Nichols, Joe Serio, Sara Cleaver, Susan Oehlers, and Bob Lippert. Funding was provided by the Alaska Experimental Program to Stimulate Competitve Research and the U.S. Geological Survey National Institute of Water Resources.

Finally, I'd like to thank Mari, for your encouragement, patience, and love throughout this process, and my family, for always supporting my curiosity in the natural world.

1. Introduction

Water temperature is often considered a master hydrologic variable in freshwater ecosystems (Poole and Berman 2001, Caissie 2006). It is a fundamental driver of physical and biological processes in lotic ecosystems (Webb *et al* 2008), strongly influencing processes such as the solubility of oxygen, nutrient availability, and physiologic and metabolic processes of aquatic organisms (Poole and Berman 2001). Most aquatic organisms, particularly cold-water species such as Pacific salmon, are adapted to the thermal regimes to which they evolved and thus have ideal thermal habitats during different life history stages (Caissie 2006, Hodgson and Quinn 2002). As a result, streamwater temperature influences the spawn timing, incubation, growth, distribution, and abundance of fish species across spatial and temporal scales (Berman and Quinn 1991). As climate becomes warmer and more variable, biological communities in lotic ecosystems will have to adapt to changing thermal regimes. Thus, understanding the implications of climate change for streamwater thermal regimes is a fundamental concern among scientists and land managers (Isaak *et al* 2012, Schindler *et al* 2008).

Streamwater thermal regimes are a product of the geomorphic and hydrological conditions of a watershed and their interactions with its localized climate, primarily air temperature (Caissie 2006, Poole and Berman 2001). The strong relationship between stream temperature and air temperature is well documented (e.g. Caldwell *et al* 2015, Mohseni *et al* 1998). However, air temperature alone is not an accurate predictor of stream temperature because the latter can be modulated by localized watershed attributes. For example, cold-water streams associated with montane ecosystems can experience lower sensitivity to air temperature fluctuations compared to lower elevation watersheds as a result of snowmelt or glacier contributions to streamflow (Fellman *et al* 2014, Lisi *et al* 2015). As a result, quantifying the interaction between watershed landscape characteristics and air temperature can be a powerful tool for predicting stream temperatures (Isaak and Hubert 2001).

Terrestrial and aquatic ecosystems in the Pacific coastal temperate rainforest in Alaska and British Columbia are rapidly being altered by climate change (Bryant 2009, O'Neel *et al* 2015), with unknown implications for keystone species such as Pacific salmon (Willson and Halupka 1995). In southeast Alaska, regional climate models project that mean annual air temperature may increase by 3.7°C, annual precipitation may increase by 480 mm (15% increase), and the snow component of annual precipitation may decline by 400 mm (40% decrease) by 2100 (Shanley *et al* 2015). Over the past 65 years, southeast Alaska's average winter air temperature has warmed at double the rate of the average summer air temperature, and is projected to increase from -4°C to 3.5°C by 2100 (Stewart *et al* 2013, Shanley *et al* 2015).

Warming winter air temperatures and a lower proportion of precipitation falling as snow in southeast Alaska are expected to affect seasonal precipitation storage as snow and the timing of surface water runoff (Shanley *et al* 2015). An increase in runoff from rain-on-snow events and decreased water storage as snowpack will have important implications for hydrological and thermal regimes of watersheds during winter (Leach and Moore 2014). Moreover, small increases in stream temperature and greater daily thermal variation during winter months will alter salmon egg incubation rates and emergence timing (Bryant 2009, Steel *et al* 2012). Anticipated decreases in end of winter snowpack will also impact streamwater thermal regimes in spring and summer by decreasing the snowmelt contribution to streamflow. This in turn both increases the sensitivity of streamwater to air temperature by reducing the thermal buffering effect of snowmelt (Lisi *et al* 2015) and reduces stream discharge during warm summer months (Shanley and Albert 2014). Taken together, effects of diminished snow cover in southeast

Alaska may further alter spawning migration timing of adult salmon as they seek to avoid peak stream temperatures (Kovach *et al* 2013, 2015).

Overall, there remains considerable uncertainty about how projected climate warming will influence streamwater thermal regimes in southeast Alaska (Shanley *et al* 2015). The reasons for this uncertainty are largely that: 1) the influence of geomorphic and landscape conditions on streamwater temperature has not been comprehensively evaluated (Fellman *et al* 2014), and 2) hydrologic regimes are highly variable because of inter-watershed differences in the proportion of streamflow derived from rainfall, snowfall and glacial melt (Edwards *et al* 2013, Fellman *et al* 2014). These knowledge gaps are a barrier to understanding how aquatic ecosystems may be altered by climate change and underscore the need to improve our understanding of the dynamics of watershed thermal regimes at the regional level.

Here, we assess summer and winter streamwater thermal regimes in southeast Alaska by establishing a regional stream temperature monitoring network to quantify spatial and temporal patterns in stream temperature. Regression and multivariate time series techniques are used to determine the influence of landscape characteristics on thermal regimes and streamwater sensitivity to changes in air temperature in both summer and winter seasons. Our findings reveal considerable variability in seasonal thermal regimes in the region's salmon bearing streams and provide insight into how streamwater thermal regimes will respond to climate change.

2. Study Area

The ~81,000 km^2 study area encompasses the northern coastal temperate rainforest spanning the panhandle of southeast Alaska and is bounded to the west by the Pacific Ocean and to the east by the Boundary Range mountains (Figure 1). Southeast Alaska watersheds represent a continuum of geomorphic and landscape conditions that influence surface water hydrology and can be grouped into three broad hydrologic categories based on the dominant sources of streamflow: rain-fed, snowmelt, and glacial melt (Edwards *et al* 2013). Rain-fed catchments occur at lower elevations and have little capacity for seasonal storage of precipitation. Discharge in these streams typically peaks in fall coinciding with high amounts of precipitation, while low flows occur in mid-summer concurrent with peak stream temperature. Snow-dominated catchments extend into higher elevations characterized by alpine/sub-alpine habitat, and experience a bi-modal hydrograph with high discharge during spring snow-melt and again during heavy rainfall events in the fall (Hood and Berner 2009). Low flows in snow-dominated streams occur in late summer and similarly coincide with peak stream temperature (Edwards *et al* 2013, Neal *et al* 2002). Glacial watersheds are characterized by high average elevations. Stream discharge in glacial streams is primarily driven by snow and ice melt and typically peaks in late summer while peak stream temperatures typically occur in late spring before the onset of glacier melt (Edwards *et al* 2013; Fellman *et al* 2014). Overall, the close proximity of the watershed headwaters to the marine environment and steep mountainous terrain results in short water residence times and the rapid transport of nutrients from terrestrial sources to freshwater and marine ecosystems (Fellman *et al* 2009).

The northern coastal temperate rainforest is characterized by glaciers, lush forests, forested wetlands, peat bogs, and 25,000 km of coastlines (Edwards *et al* 2013). The maritime influence of the region's primary climatic control, the Gulf of Alaska, interacts with topographical, latitudinal and longitudinal gradients, leading to highly variable patterns in precipitation and air temperature, which in turn influences landcover and vegetation community structure throughout the region (Shanley *et al* 2015). Elevation within the study area ranges from sea level to over 4700 m on the mainland and up to 1625 m on the larger islands in the Alexander Archipelago. Landcover consists primarily of forest (58% of land area), wetlands (22%), glaciers (16%), with the remainder as snow and bare rock. Elevational gradients in vegetation community structures are characterized by lowland forests giving way to subalpine hemlock forests and subalpine shrub and alpine tundra at high elevations. Glaciers are predominantly located on the mainland and locally influence climate while glacial runoff impacts freshwater and marine processes (Neal *et al* 2010, O'Neel *et al* 2015). Glacial recession also influences vegetation structure, a characteristic most prominent in Glacier Bay (Carstensen *et al* 2007). Vegetation communities located in poorly drained areas of the region are characterized by forested wetlands, small tree forests, ponds, peatlands, fens, and bogs (Edwards *et al* 2013).

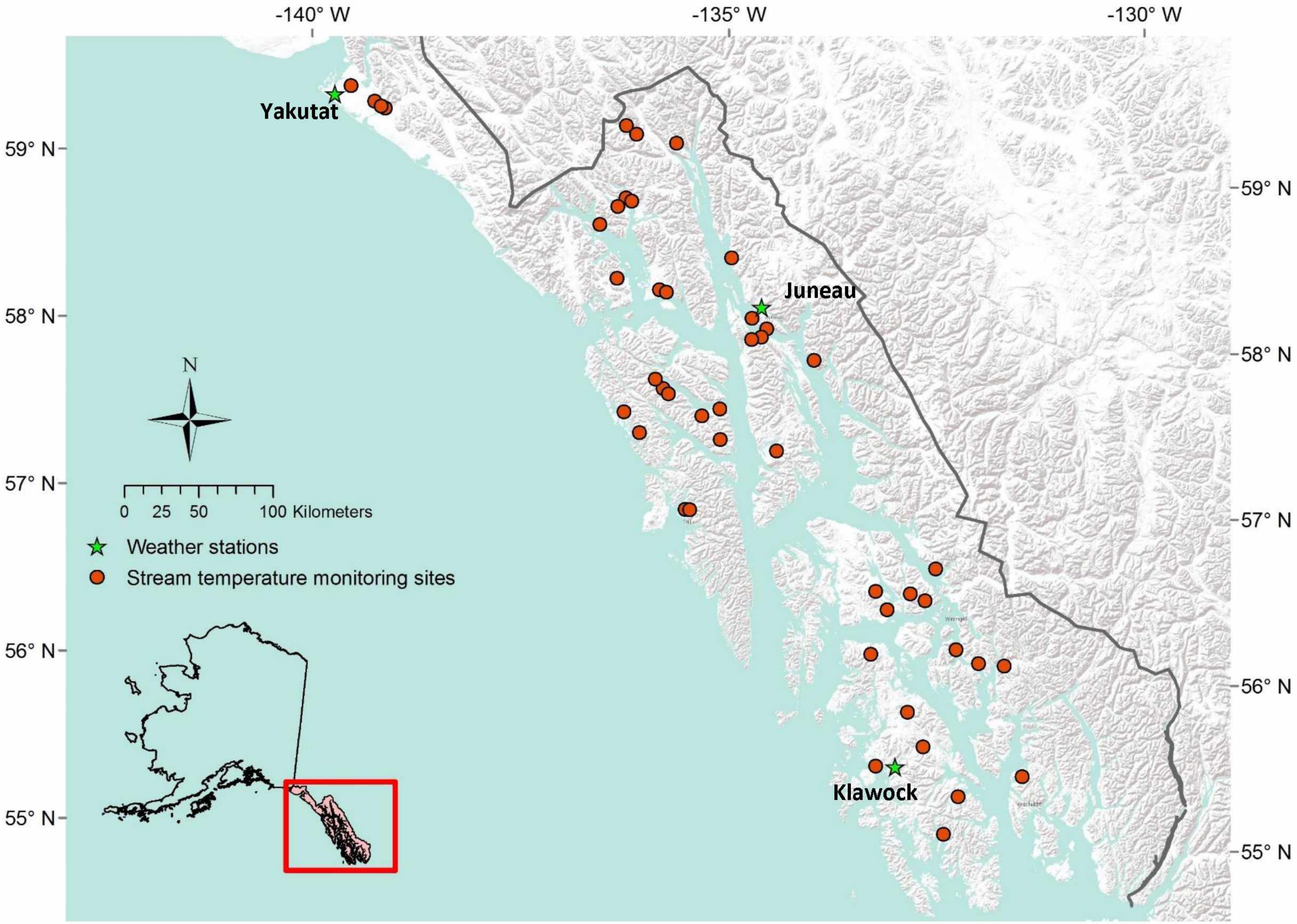


Figure 1. Study site locations and National Weather Service climatological stations in southeast Alaska.

3. Data and Methods

3.1 Stream Temperature Data

Stream temperature sensors were installed in forty-seven watersheds across southeast Alaska for this study (Figure 1). Stream temperature data were collected at hourly to sub hourly temporal resolution from May 2014 through December 2015. The study catchments were chosen to be representative of pristine watersheds in the region and shared the following characteristics: 1) a catchment area of less than 150 km^2, 2) no historical timber harvest in the riparian zone, 3) less than 5% timber harvest in the watershed, 4) all are spawning streams for Pacific salmon. Streams were instrumented with two Hobo Pro-V2 (Onset Computer Inc., Bourne, MA; accuracy ±0.2°C) temperature loggers, (n=45 watersheds), a Solinst level logger (Solinst Canada Ltd, Georgetown, ON; accuracy ±0.05°C) (n=1, Alaska Hydroscience stream gauge), or a Therm-x 44020 probe (Therm-x Southwest; accuracy ±0.1°C, San Diego, CA) (n=1, USGS stream gauge). Hobo Pro-V2 sensors were cross-calibrated prior to deployment and again when or if removed from the stream. Sensors were downloaded two times per year. A field temperature meter was used during site visits to verify accuracy of deployed sensors. Raw stream temperature data were processed following quality control protocols set forth in (Toohey *et al* 2014) and aggregated to mean daily stream temperatures. For the purposes of this study, stream temperature is defined as the average temperature of channel water at the point in the watershed selected for the sampling location. Additionally, streamwater thermal regimes are defined as the variation in stream temperature for a given temporal scale (Caissie 2006).

3.2 Air Temperature and Precipitation Data

The climate of southeast Alaska is high-latitude maritime with cool, wet summers and mild, wet winters. The highest average annual air temperatures and highest annual precipitation for Alaska are found in this part of the state (Shulski and Wendler 2007). The density of existing climate stations that record both air temperature and precipitation is far less than the density of stream temperature network that was established for this project. In southeast Alaska, climate stations that have a historic record of both air temperature and precipitation are generally located at low elevations (Kane and Stuefer 2015). Three climate stations with reliable precipitation and air temperature records, that are readily available for other users and stakeholders, were selected for analysis (Figure 1). The National Weather Service (NWS) climatological data for three regional stations, located in Yakutat, Juneau, and Klawock, were obtained from the Western Regional Climate Center (Neal *et al* 2002). Air temperature during the study period was anomalously warm in both summer and winter compared to long-term averages (Overland *et al* 2015). Mean summer and winter air temperatures across the region ranged from 12.7°C to 13.9°C, and -0.8°C to 4.6°C, respectively (Table 1). Comparatively, thirty-year climate normals (1981-2010) of summer and winter mean air temperatures in the northern, central, and southern areas of the region (Figure 1) ranged from 11.6°C to 13.5°C and -1.4°C to 2.4°C, respectively. Precipitation during the 2015 water year ranged from 1990 mm to 3630 mm, similar to thirty-year climate normals. Snow records were only available for Yakutat and Juneau during the 2015 water year though they likely represent regional patterns, with 1790 mm and 1230 mm, recorded in Juneau and Yakutat, respectively. Snow accumulation at sea level was anomalously low during the study period, with Yakutat and Juneau experiencing 62% and 50% of snow accumulation compared to climate normals. Across the region, strong summer (pearson's r=0.56

- 0.64) and winter (pearson's r=0.77 – 0.80) air temperature correlations between the Juneau NWS station and stations located in Yakutat and Klawock (Figure 1) suggest climatological data from Juneau is sufficient to represent regional air temperature patterns in the multivariate time series model.

3.3 Landcover Data

The Spatial Analyst Tool in ArcGIS (v10.2 Environmental Systems Research Institute, Redlands, CA, USA) was used to process Interferometric Synthetic Aperture Radar (IFSAR) 5 m (http://lta.cr.usgs.gov/IFSAR_Alaska) and Shuttle Radar Topography Mission (SRTM) 20 m (http://www2.jpl.nasa.gov/srtm/) digital elevation models (DEM) to delineate watershed boundaries and estimate watershed area, mean watershed elevation, and mean watershed slope (Appendix A). Landcover characteristics were quantified from multiple data sources in ArcGIS. Lake coverage was derived using the National Hydrography Dataset (http://nhd.usgs.gov), forest cover and alpine area were estimated using The Nature Conservancy Terrestrial Ecosystems of southeast Alaska database (Albert and Schoen 2006). Wetlands were derived from the National Wetlands Inventory (http://www.fws.gov/wetlands/). Glacier coverage was derived from the Randolph Glacier Inventory 3.2 (http://www.glims.org/RGI/). Timber harvest area was informed by the Tongass National Forest Activity Polygon 2013 (http://epscor.glynx.gina.alaska.edu) and The Nature Conservancy Terrestrial Ecosystems of southeast Alaska database (Albert and Schoen 2006).

Table 1. Climatological data from Yakutat, Juneau, and Klawock NWS weather stations. Mean summer and winter air temperature, precipitation, and precipitation as snow from each weather station are presented at the timeframe of thirty-year climate normals (1981 - 2010) and during the 2015 water year (1 October 2014 - 30 September 2015).

	Climate normals				Study period			
	Mean air temperature (°C)		Precipitation (mm)		Mean air temperature (°C)		Precipitation (mm)	
Weather station	Summer	Winter	Total	Snow	Summer	Winter	Total	Snow
Yakutat	11.6	1.7	3940	4700	12.7	1.2	3630	1790
Juneau	13.2	-1.4	1580	2460	13.9	-0.8	1990	1230
Klawock	13.5	2.4	2340	380	13.2	4.6	2200	--

3.4 Stream Temperature Metrics and Predictive Models

Four stream temperature metrics were calculated for each study watershed: 1) summer (June 1- August 31) maximum weekly average temperature (MWAT), 2) mean summer stream temperature, 3) winter (1 Dec – 28 Feb) maximum daily stream temperature, and 4) mean winter stream temperature. Empirical linkages between stream temperature metrics and landscape variables were evaluated utilizing multiple linear regression techniques using R statistical software (R Development Core Team 2016). The multiple regression model used in this analysis is:

$$y = \beta_0 + x\beta_1 + x\beta_2 + x\beta_3 \ldots + x\beta_n + \varepsilon \qquad (1)$$

Here, y = stream temperature, x = the landscape variable coefficient, β_0 = the intercept and $\beta_{1\ldots n}$ = geomorphic and landscape parameters, and ε = residual error. The multiple regression models were parameterized using the following watershed characteristics: watershed area (log transformed km^2), mean watershed elevation (m), alpine area (%), lake coverage (%), mean watershed slope (degree), wetland area (%), forest coverage (%), and latitude (decimal degrees). Data were filtered for significant outliers using Cook's Distance, and watersheds determined to be an outlier were removed from the summer and winter analyses. Recent studies have shown multiple linear regression is an effective modeling approach when using watershed characteristics to predict summer and winter thermal regimes (Fellman *et al* 2014, Lisi *et al* 2013).

3.5 Time Series Analysis

Dynamic Factor Analysis (DFA) was used to evaluate underlying regional scale trends in mean daily stream temperature during summer and winter seasons, following Lisi *et al* (2015).

DFA analyses estimate common trends among stream temperature time series by treating the observed data as linear combinations of one or more unobservable common trends (Zuur *et al* 2003, 2007). Shared trends are the information common to each stream temperature time series that is not explained by air temperature, and temporal correlation among estimated trends is assumed. Because DFA is a state-space model, it can account for spatial and temporal autocorrelation and missing values in the observed data (Zuur *et al* 2003, 2007).

Within the framework of this study, DFA was used to evaluate spatial and temporal trends in stream temperature with air temperature covariates. The Template Model Builder interfaced with R statistical software was used to fit linear multivariate autoregressive state-space models with Gaussian errors to the data (Kristensen *et al* 2016). For the purposes of this study, the analysis focused on three forms of the model structured as data = trend + explanatory variables + noise. Following Zuur *et al* (2003), the model form can be written as follows:

$$\boldsymbol{y_t} = \mathbf{Z}\boldsymbol{x_t} + \mathbf{D}\boldsymbol{g_t}\,\mathbf{D}\boldsymbol{g_{t-1}} \ldots + \mathbf{D}\boldsymbol{g_{t-n}} + \boldsymbol{v_t} \qquad \mathbf{(2)}$$

$$\boldsymbol{x_t} = \mathbf{x_{t-1}} + \boldsymbol{w_t} \qquad \mathbf{(3)}$$

Here, the response variable $\boldsymbol{y_t}$ equals n observed stream temperature observations at time *t*, $\boldsymbol{x_t}$ is the common trend at time *t*, which is multiplied by **Z** stream specific factor loadings. Covariate loadings $\mathbf{D}\boldsymbol{g_t} + \mathbf{D}\boldsymbol{g_{t-1}} \ldots \mathbf{D}\boldsymbol{g_{t-n}}$ are parameterized by air temperature at time t, $t_{-1} \ldots t_{-n}$, $\boldsymbol{v_t}$ equals random observation error with a multivariate normal distribution mean equal to zero and a variance-covariance matrix **R**. Models exploring different daily air temperature time lags and error matrix structures were assessed using AICc .

3.6 Landscape Influence on Stream Sensitivity to Air Temperature

Thermal sensitivity of streamwater to air temperature fluctuations were evaluated, following methods in Lisi *et al* (2015). Covariate loadings **(D)** for the most parsimonious DFA model were transformed to stream specific air sensitivity, a metric indicating the seasonal average change in stream temperature per 1°C change in air temperature (Δ°C T_w/°C T_a), herein referred to as air sensitivity. Geomorphic parameters, consisting of 1) watershed area (log km^2), 2) mean watershed elevation (m), 3) lake coverage (%), and mean slope (deg), were regressed against air sensitivity to evaluate geomorphological controls of stream specific air sensitivity (Lisi *et al* 2015) for both summer and winter models.

4. Results

4.1 Regional Overview

Stream temperature exhibited substantial variation across time and space during the 2015 water year. Air temperature and mean daily stream temperature in the 47 watersheds showed similar seasonal regimes (Figure 2). Air and stream temperatures were lowest in February, followed by a gradual increase, peaking in July and August. Freezing air temperature conditions were prevalent between December and February, however, no streams froze up completely to the channel bottom.

There was considerable stream temperature variability in the magnitude of maximum weekly average temperatures (MWAT) in forty-three streams with complete summer records (Figure 3A). MWAT ranged from a low of 4.3°C in Clear Creek in the northern portion of the study area to a high of 21.5°C in Castle River in the southern portion, with a median of 13.1°C. MWAT was inversely correlated with latitude (R^2_{adj}= 0.44, $p<0.001$). The start date of MWAT ranged from 2 May to 15 August across the study watersheds (Figure 3B). However, the region exhibited considerable temporal coherence in the peak date, with MWAT occurring between 4 July and 7 July in thirty of the forty-three watersheds. Mean summer stream temperature was strongly correlated with MWAT (R^2_{adj}= 0.98, $p<0.001$), and ranged from a low of 4.0°C in Clear Creek to a high of 17.2°C in Hetta Creek in the southern portion of the study area, with a median of 11.6°C (Figure 3C). Mean winter stream temperature ranged from a low of 0.5°C in Echo Creek to a high of 3.5°C in Old Situk, both in the northern portion of the study area, with a median of 2.2°C (Figure 3D). Winter maximum daily stream temperature in the thirty-six streams with complete winter temperature records ranged from 2.3°C in Berg Creek to 5.9°C in Rio Roberts with a median of 3.8°C (data not shown).

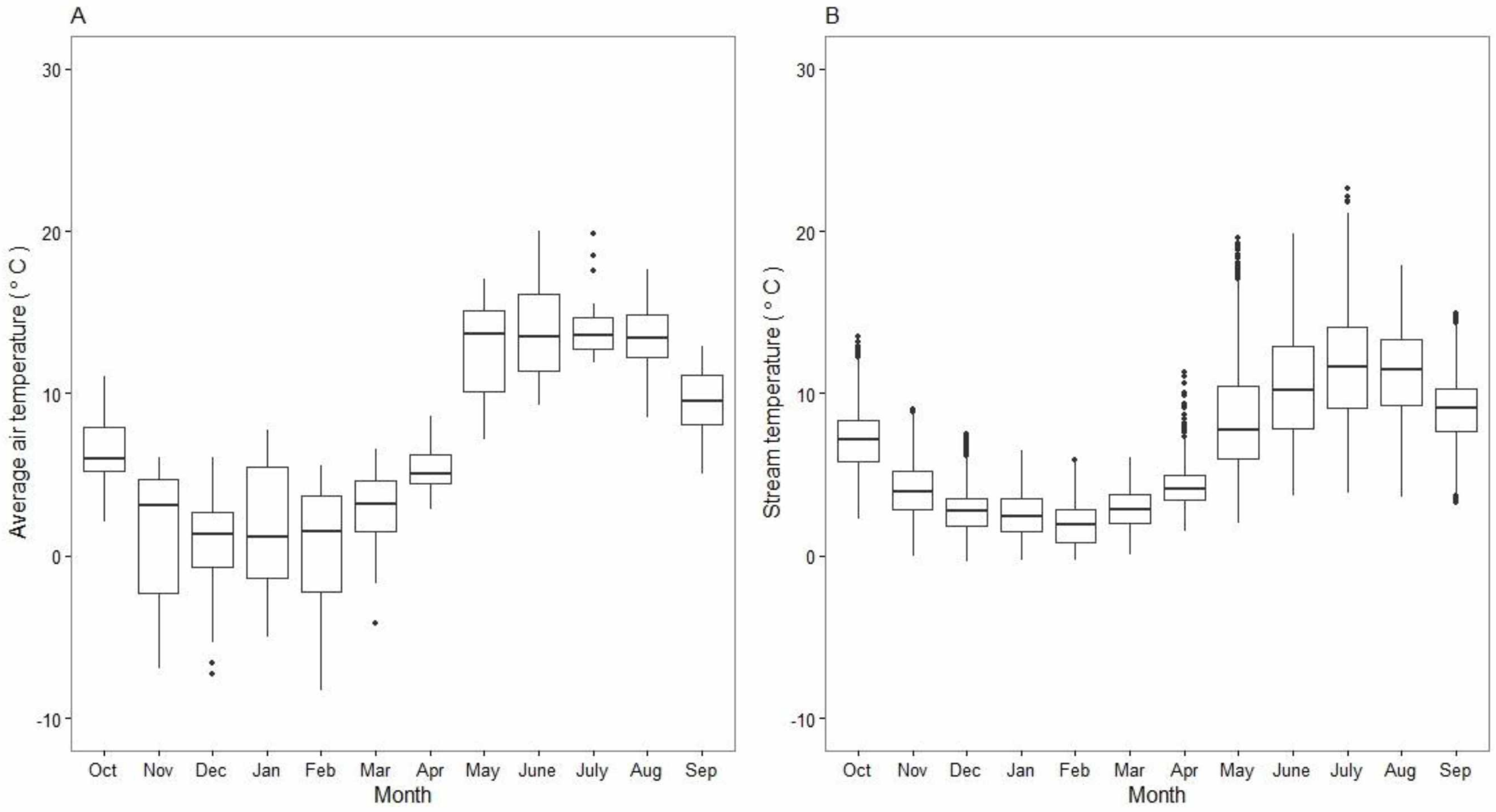


Figure 2. Distribution of mean daily air temperature from a National Weather Service climatological station in Juneau and mean daily stream temperature from 35 to 47 watersheds by month in the 2015 water year. The horizontal lines inside the boxplots indicate the median and the upper and lower lines of the box indicate the 25th and 75th quartiles. The black dots indicate outliers.

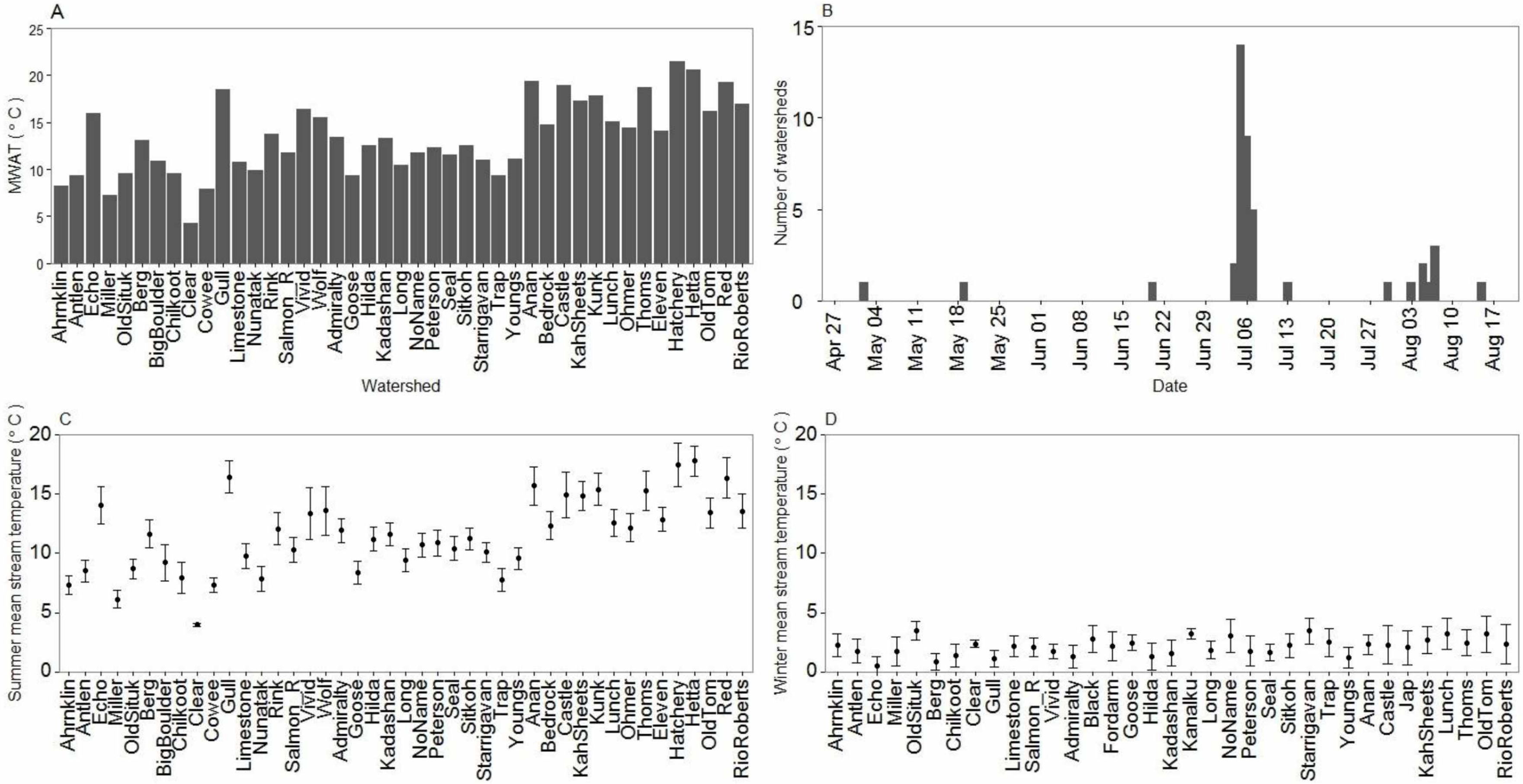


Figure 3. A. Magnitude of maximum weekly average temperature (MWAT) for watersheds monitored in summer 2015. B. MWAT start date occurrence. C. Summer mean stream temperature for watersheds monitored in summer 2015, whiskers represent one standard deviation. D. Winter mean stream temperature from 35 watersheds monitored from December 2014 – February 2015, whiskers represent one standard deviation. Note that the scale in C and D are different. Streams are ordered north to south in A, C, and D.

4.2 Landscape Controls on Thermal Regimes

Mean summer stream temperature in the study watersheds showed a significant positive correlation with lake coverage, wetlands coverage and forest coverage (Figure 4). In contrast, mean watershed elevation, alpine coverage, and watershed latitude were all significantly negatively correlated with mean summer stream temperature. Despite the significant correlations, none of the watershed characteristics explained major portions of the variation in mean summer temperature (Figure 4; R^2 = 0.07 – 0.41). Correlations between MWAT and watershed characteristics were similar in direction and magnitude to those for mean summer temperature (Appendix B). Watershed characteristics were generally less strongly related to mean winter stream temperature compared to summer. Mean winter stream temperature had significant positive correlations with lake coverage and forest cover. In contrast, mean winter stream temperature had significant negative correlation with latitude. The correlations between mean winter stream temperature and watershed characteristics explained thirteen to thirty-two percent of the variance (Figure 5; R^2 = 0.00 – 0.22).

Watershed characteristics were used to develop multiple linear regression models for the following thermal metrics: mean summer stream temperature, MWAT, maximum winter daily stream temperature, mean winter stream temperature. The strongest multiple linear regression (MLR) models for mean summer temperature (R^2_{adj}= 0.64) and MWAT (R^2_{adj}=0.67) included the same series of watershed characteristics and indicated that these thermal metrics were positively correlated with watershed lake coverage and were negatively correlated with slope, forest cover, and latitude (Table 2). In the absence of landcover data, models utilizing solely geomorphic variables (watershed area, mean watershed elevation, mean watershed slope, watershed lake coverage), herein referred to as the geomorphic model, derived from digital elevation models and

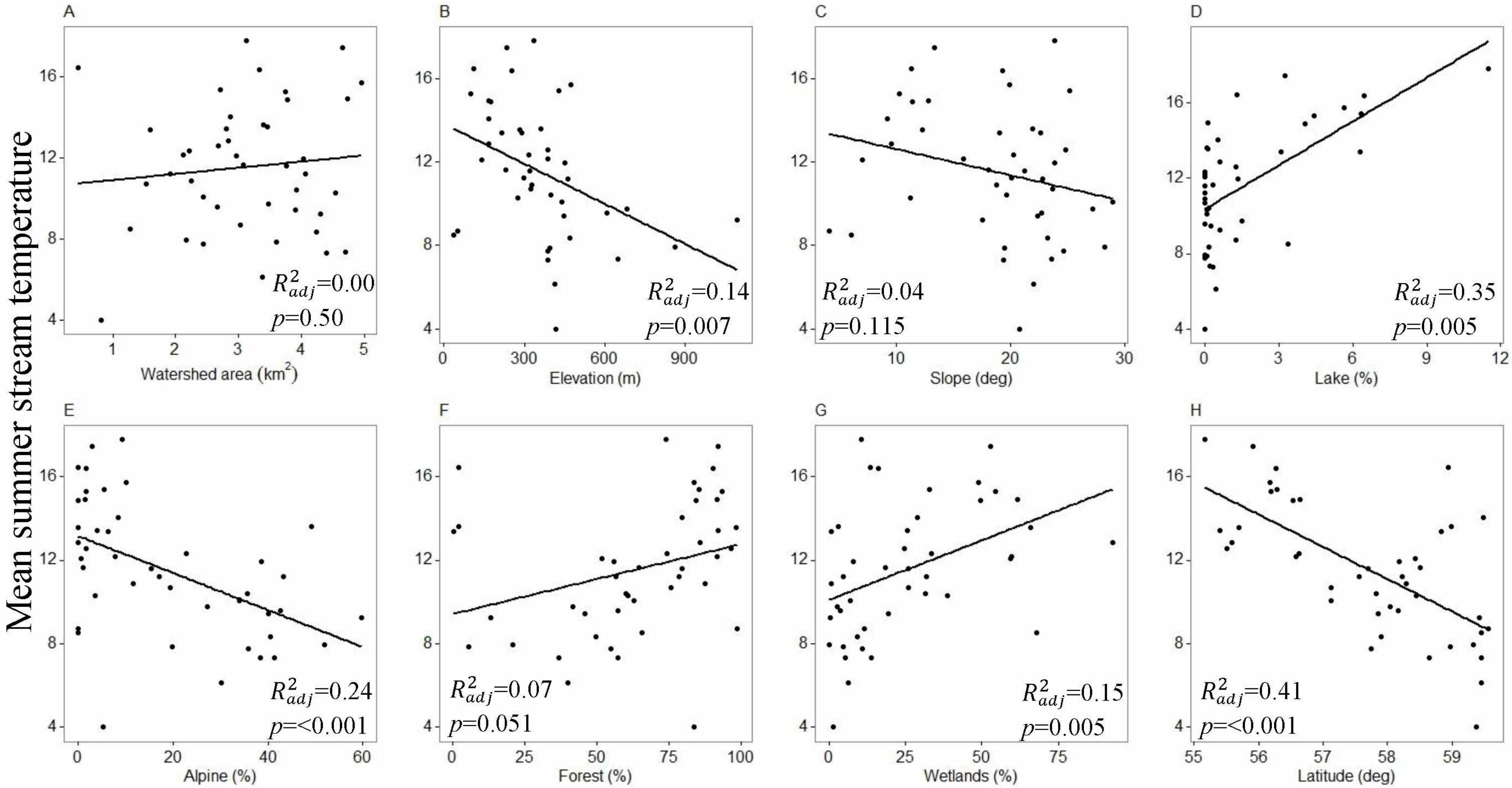


Figure 4. Linear regressions of mean summer stream temperature of 43 watersheds vs catchment landcover characteristics: A) watershed area (log km^2), B) mean watershed elevation (m), C) mean watershed slope (deg), D) lake coverage (%), E) alpine area (%), F) forest cover (%), G), wetlands (%), H) latitude (deg).

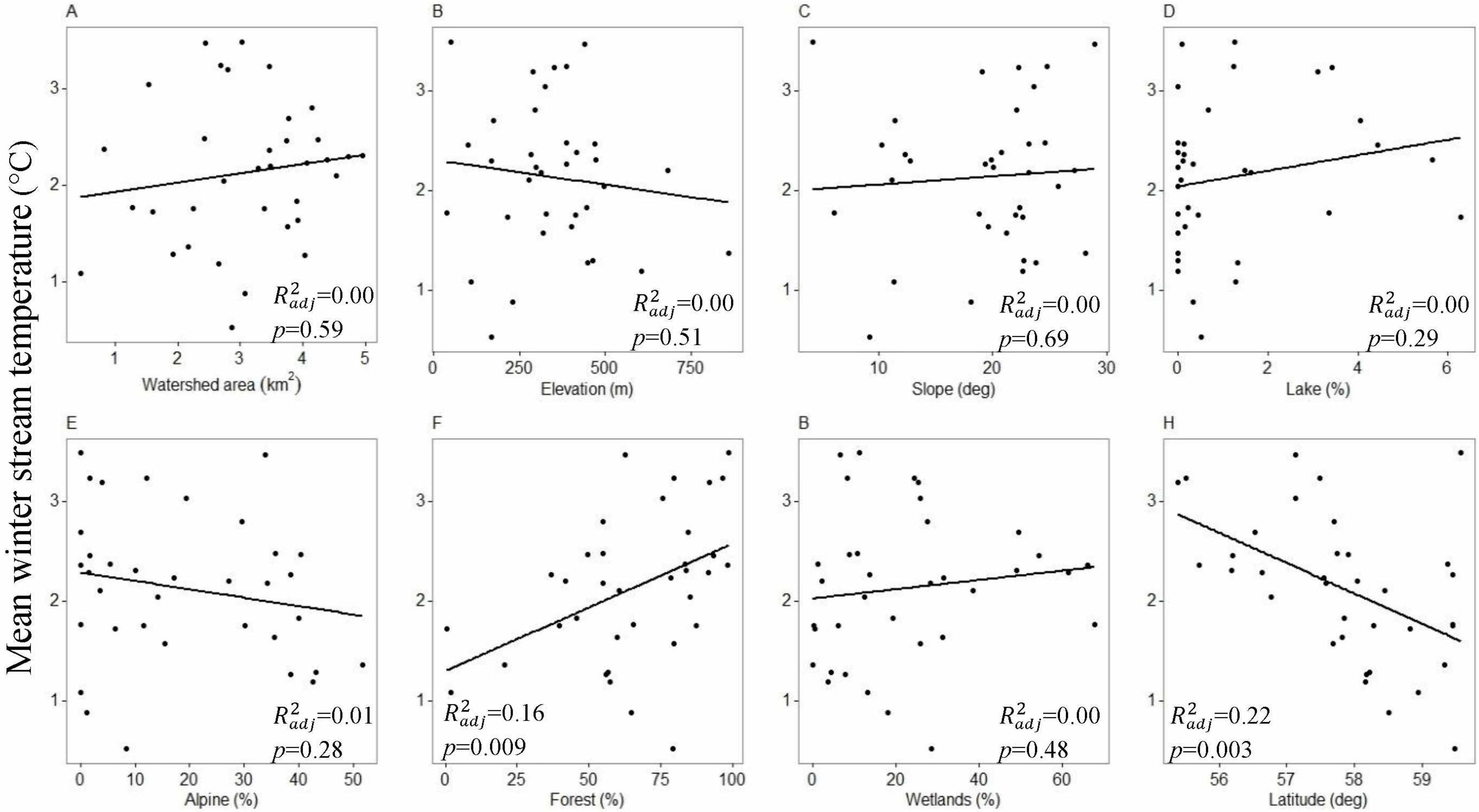


Figure 5. Linear regressions of mean winter stream temperature for 35 watersheds vs catchment landcover characteristics: A) watershed area (log km^2), B) mean watershed elevation (m), C) mean watershed slope (deg), D) lake coverage (%), E) alpine area (%), F) forest cover (%), G), wetlands (%), H) latitude (deg).

the National Hydrography Dataset, were similarly strong predictors of mean summer stream temperature and MWAT ($R^2_{adj} = 0.60, R^2_{adj}$=0.62, respectively, Table 2).

The strongest winter maximum stream temperature model included elevation, lake coverage, and latitude and explained 57% of the variation in maximum winter stream temperatures (Table 2; R^2_{adj}= 0.57). The model for winter mean stream temperature included positive correlations with slope, lake coverage, and forest cover; however the model was not as strong as the winter maximum stream temperature model (R^2_{adj}= 0.23). Geomorphic models for winter maximum and winter mean stream temperature explained similar variation in winter temperature metrics (R^2_{adj}= 0.57, R^2_{adj}= 0.22) compared to the watershed characteristic models (Table 2). Overall, predictive models of winter streamwater thermal regimes explained less of the variability in stream temperature metrics relative to summer models, largely due to less variability in stream temperature during the winter.

4.3 Landscape Controls on Stream Specific Air Sensitivity

Dynamic factor analysis (DFA) was used to model the common stream temperature trend shared among watersheds during the summer and winter seasons and to estimate the stream specific air sensitivity from the model covariance matrix. The strongest summer DFA model included an air temperature lag of one day ($t + t_{-1}$) as covariates. The model fits indicate summer stream temperature variation was captured by the analysis (Appendix C) and allowed me to evaluate seasonal stream specific air sensitivity (Δ°C T_w/°C T_a). The shared summer stream temperature trend not explained by air temperature was characterized by a gradual increase from 1 June, a maximum in mid-August, and a downward trend in late August (Figure 6a). Across all of the study watersheds, stream specific summer air sensitivity ranged from 0.01 C T_w/°C T_a

Table 2. Multiple linear regression predictive models fitting stream temperature metrics with landcover and geomorphic variables during the summer and winter seasons of the 2015 water year. Model metrics with (DEM) represent the geomorphic models.

Season	**Model metric**	**Model and coefficients**	R^2_{adj}	**SE**	**p-value**
Summer	MWAT	148.15*** -0.24(slope)*** + 0.53 (%lake)** -0.05(%forest)* -2.22(lat)***	0.67	2.31	<0.001
	MWAT (DEM)	103.47*** -0.17(slope)** + 0.61(%lake)*** -1.52(lat)***	0.62	2.47	<0.001
	Mean stream temperature	115.34***-0.19(slope)*** + 0.44 (%lake)** -0.04(%forest)* -1.71(lat)***	0.64	1.91	<0.001
	Mean stream temperature (DEM)	80.86*** - 0.14(slope)** + 0.50(%lake)*** -1.17(lat)***	0.60	2.02	<0.001
Winter	Max stream temperature	43.52*** -0.002(elev)* -0.17 (%lake)* - 0.67(lat)*	0.57	0.69	<0.001
	Max stream temperature (DEM)	43.52*** -0.002(elev)* -0.17 (%lake)* - 0.67(lat)*	0.57	0.69	<0.001
	Mean stream temperature	-0.30 + 0.035(slope)* + 0.11 (%lake) +0.016(%forest)	0.23	0.65	0.01
	Mean stream temperature (DEM)	19.74*** -0.30(lat)**	0.22	0.66	<0.003

Significance: '*' = <0.05, '**'=<.01, '***' = <0.001

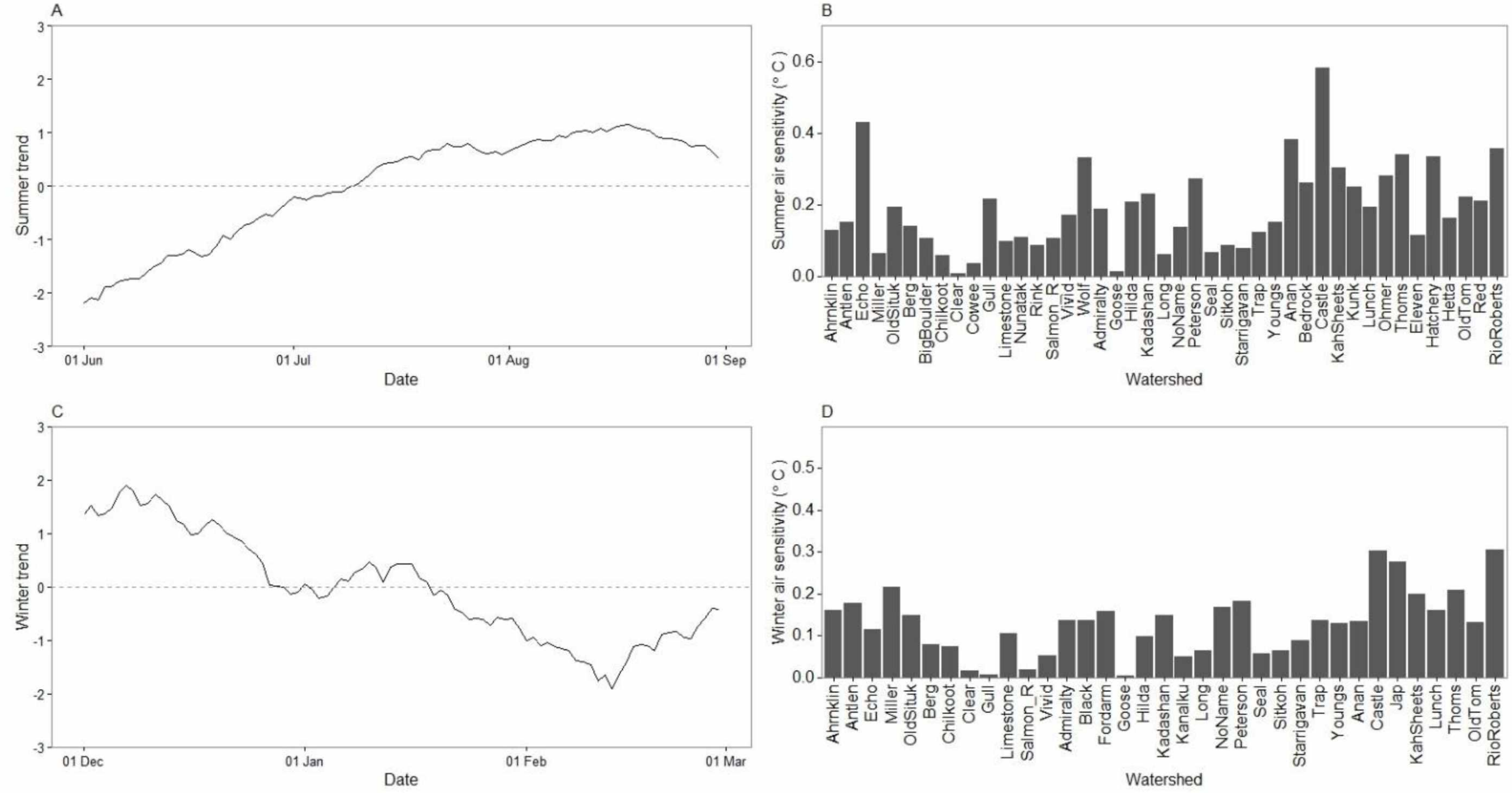


Figure 6. Stream temperature trends and stream specific air sensitivity southeast Alaska. Shown are A) the common trend for 43 watersheds in summer 2015, and B) air sensitivity (Δ°C T_w / Δ°C T_a) for watersheds during summer, C) common trend for 35 watersheds in winter 2014-2015, and D) air sensitivity (Δ°C T_w / Δ°C T_a) for watersheds monitored during winter. Streams are ordered north to south in figures B and D.

in Clear Creek to 0.58°C T_w/°C T_a in Castle River (Figure 6b), reflecting the substantial spatial variability in streamwater sensitivity to changes in air temperature.

The best multiple linear regression model revealed summer stream specific air sensitivity was controlled by geomorphic features along a latitudinal gradient (Table 3). Moreover, air sensitivity decreased as watershed slope increased in conjunction with increasing latitude (R^2_{adj}=0.27). Watershed elevation and area were not significant predictor variables in the final model.

The strongest winter DFA model includes covariates incorporating a one-day air temperature time lag ($t + t_{-1}$). The most parsimonious shared stream temperature trend not explained by air temperature was characterized by a gradual decrease from 1 December, exhibiting minimum in early February, followed by a gradual increase in late February (Figure 6c). The DFA model provided an excellent fit to the variation in winter stream temperatures (Appendix D). Winter stream specific air sensitivity was generally lower in magnitude compared to summer and varied between catchments, with a low of 0.01°C T_w/°C T_a in Goose Creek on Chichagof Island in the central portion of the study area to a high of 0.31°C T_w/°C T_a in Rio Roberts Creek in the southern portion of the study area (Figure 6d). Winter stream specific air sensitivity was negatively correlated with watershed slope, revealing low gradient watersheds are more sensitive to air temperature relative to higher gradient watersheds. Significant negative correlations with latitude indicate the air temperature effect is reduced as latitudes increase (R^2_{adj}=0.19, Table 3).

Watersheds that were most sensitive during the summer tended to be the most sensitive during the winter (Figure 7). Summer air sensitivity explained 27% of the variance in the winter air sensitivity, thus indicating the influence of watershed gradients on air sensitivity is consistent across seasons. A regression of watersheds with both summer and winter sensitivity metrics revealed seasonal sensitivity increased along a decreasing gradient of average watershed slope. Furthermore, watersheds with lower average slope were more sensitive to changes in air temperature during the summer and winter.

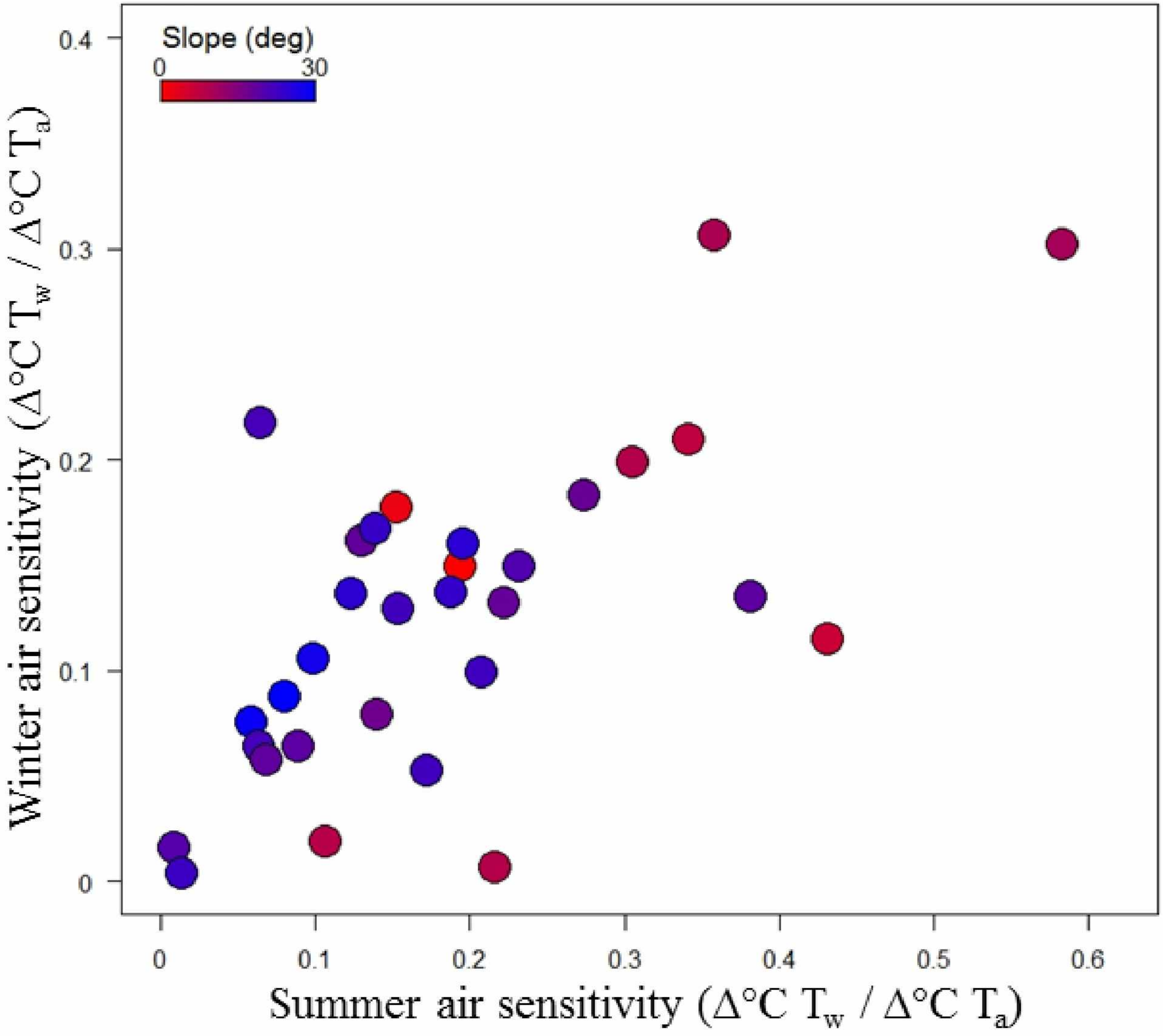


Figure 7. Scatterplot of summer vs winter air sensitivity for 30 watersheds. Least squares regression indicates the relationship (R^2_{adj}= 0.27, p=.0018).

Table 3. Multiple linear regression predictive models fitting stream specific air sensitivity with geomorphic variables during the summer and winter seasons of the 2015 water year.

Season	**Model metric**	**Model and coefficients**	$\mathbf{R^2_{adj}}$	**SE**	**p-value**
Summer	Air sensitivity	2.40** -0.008(slope)** -0.036(lat)**	0.27	0.1	<0.001
Winter	Air sensitivity	1.86** -.003(slope). -0.029(lat)**	0.19	0.07	0.013

Significance: ‘.’<0.10,*' =<0.05,'**'=<.01, '***' = <0.001

5. Discussion

My findings indicate there is considerable variation in seasonal streamwater thermal regimes and sensitivity to air temperatures associated with spatial heterogeneity of landscape and geomorphic characteristics across watersheds in southeast Alaska. I demonstrate that multiple regression models can be used successfully to describe the influence of watershed characteristics on seasonal stream temperature regimes, and that DFA provides a useful tool for assessing seasonal stream specific air sensitivity relative to the regional shared trend in stream temperature. My results reveal variation in streamwater thermal sensitivity at seasonal temporal scales and provide a geomorphic template identifying watersheds that may be more sensitive to climate change.

5.1 Seasonal Thermal Regimes and Air Sensitivity

Study findings reveal that landscape characteristics interact with a latitude to create variation in seasonal thermal regimes and air sensitivity across time and space in the coastal temperate rainforest southeast Alaska. Stream temperature varied along a gradient of slope and elevation that influences underlying physical processes of seasonal thermal regimes (Caissie 2006). Colder summer thermal regimes were associated with watersheds with higher average slope. Slope is highly correlated with elevation (pearson's r=>0.65), implying both slope and elevation influence thermal regimes though their effect is only represented by slope in the models. High gradient/elevation watersheds have a greater proportion of cold source water contributions from seasonal snowpack to surface water relative to low elevation watersheds in the region (Hood and Berner 2009). Average watershed slope also influences water residence time, and thus the duration of streamwater exposure to atmospheric conditions is shorter in high gradient watersheds (Caissie 2006). Topographic shading associated with high gradient watersheds can also suppress streamwater temperature by reducing exposure to solar radiation (Webb and Zhang 1997). Moreover, groundwater aquifers in higher elevation catchments are likely recharged by colder source water, thus moderating stream temperatures through groundwater exchange processes (Lisi *et al* 2015).

Results from this study support findings from other studies in coastal Alaska and British Columbia (Adelfio 2016, Fellman *et al* 2014, Lisi *et al* 2013, 2015, Mauger 2011, Moore 2006, Moore *et al* 2013, Parkinson *et al* 2016), in that slope had significant negative correlations with summer streamwater thermal regimes. Fellman *et al* (2014) found elevation was a key control of MWAT and monthly average stream temperature in six glacial and three non-glacial watersheds in the northern mainland of southeast Alaska. Elevation was also a key control of MWAT in British Columbia (Moore *et al* 2013, Parkinson *et al* 2016), maximum stream temperature in Prince William Sound (Adelfio 2016), and average temperatures in Bristol Bay (Lisi *et al* 2013). Lisi *et al* (2015) also found below normal snow accumulation reduced snow melt contributions to surface water discharge compared to higher snow years. This is consistent with the idea that snowmelt input to surface water discharge following 1 June, the start date of my summer analysis, was likely below normal in my study watersheds making it more difficult to detect the meltwater signal, and influence of watershed elevation, at a regional scale. Moreover, the strong influence of watershed slope during an anomalously warm year suggests that slope may become an increasingly important landscape control as air temperature rises and snow accumulation decreases in the future (Shanley *et al* 2015)

Winter thermal regimes in streams draining higher elevation watersheds reflect the influence of colder air temperature gradients. In contrast, steeper gradients were associated with warmer winter stream temperature. Similar thermal response occurred in high gradient streams in Prince William Sound, where slope was correlated with decreased frequency of freezing days (Adelfio 2016). Several factors, including the reduced contribution of cold meltwater from high-elevation reaches of the watershed (Hood and Berner 2009), and the moderating influence of groundwater inputs common in winter base flows (Caissie 2006) may contribute to the observed winter thermal response.

High gradient watersheds were strongly associated with lower summer stream specific air sensitivity ($p<0.01$), reflecting the influence of shorter temporal duration of atmospheric energy flux at the stream surface interface and meltwater contributions to stream flow (Fellman *et al* 2014, Lisi *et al* 2015). Similarly, slope was correlated with reduced thermal sensitivity to air temperature changes during winter months ($p<0.05$). The one-day lag in thermal memory indicates shorter water residence time may be a powerful year-round control of air sensitivity.

Percent lake coverage within a catchment was an important landscape control on stream temperatures, exerting a warming effect on both summer and winter thermal regimes. The warming influence of lakes on summer stream temperature is a function of increased exposure to atmospheric energy flux heating the lake surface, and subsequently the streamwater of the lake outlets (Jones 2010, Mellina *et al* 2002). My findings are consistent with previous research in southeast Alaska which focused on summer streamwater thermal regimes at finer spatial resolution (Fellman *et al* 2014), thus extending the empirical evidence that relative lake coverage is a significant control on thermal regimes across the region. Few regional studies, however, highlight the importance of lake coverage on winter thermal regimes (Moore 2006). My findings demonstrate lake coverage is associated with warmer year-round stream temperatures, a result that is consistent with a study in British Columbia, which similarly demonstrated lake coverage had a warming influence throughout the year and equated to a 3-4 °C increase per 10% increase in freshwater cover during the summer (Moore 2006).

The effect of lake coverage on streamwater thermal sensitivity to air temperature contrasts at seasonal scales, though it was not a significant parameter in air sensitivity models. Streams with higher relative lake coverage within the basin were more sensitive to fluctuations in summer air temperature. Conversely, lake coverage was a correlated with reduced winter stream specific air sensitivity. In southwest Alaska, lakes were associated with increased variation in summer thermal regimes (Lisi and Schindler 2015). I found stream specific air sensitivity was correlated with seasonal stream temperature variance in summer (R^2_{adj}=0.39) and winter (R^2_{adj}=0.65). However, the negative correlation between lake coverage and winter air sensitivity occurred during an anomalously warm winter, and these results contrast with a multiyear study with a smaller sample of watersheds that found increased lake coverage was correlated to increased variation in winter mean stream temperature in Prince William Sound, Alaska (Adelfio 2016). Thus, lakes with seasonal ice cover may play a role in stabilizing winter streamwater by reducing water exposure to air temperature fluctuations. This effect may be less pronounced during mild winters, which may exhibit greater air temperature variability relative to colder winters. The location, elevation, size, and number of lakes within a watershed likely influence the effect that relative lake coverage has on watershed air sensitivity (Jones 2010). It was not within the framework of this study to quantify the location of lakes' influence on thermal regimes, however, future research should quantify these relationships.

My results suggest the influence of forest canopy on seasonal thermal regimes was of year-round importance in the region. Across the region, forest coverage was an important cooling mechanism during summer, consistent with previous work showing that forest cover significantly moderated summer streamwater thermal regimes in Scotland and North Carolina (Hrachowitz *et al* 2010, Scott *et al* 2002). Forest canopy can insolate surface water and shallow groundwater sources (Beschta *et al* 1987, Kurylyk *et al* 2015, Leach and Moore 2011, Moore *et al* 2005), and reduce wind speed at the water surface (Webb and Zhang 1997), thus keeping the stream cooler. The slight, yet significant (<0.05) association of forest cover with warmer winter stream thermal regimes during this study suggests that riparian vegetation reduces net energy loss from the stream (Beschta *et al* 1987). Forest canopy structure also has contrasting influences on snow melt contribution to streams: low density forests accumulate more snow, yet higher canopy density extends the duration of the ablation period through shading from solar radiation (Anderson *et al* 2014), likely moderating stream thermal regimes during spring. Canopy density is considered high throughout southeast Alaska, likely limiting snow accumulation at elevations below the treeline and extending the snowmelt season (Harris and Farr 1974). However, canopy density may not limit snow accumulation in this study area relative to other regions because southeast Alaska experiences high levels of winter precipitation, typically as snow (Shanley *et al* 2015).

Latitude explains much of the variation in thermal regimes and air sensitivity in the study area. Latitude represents macroclimate in the models, serving as a proxy for variation in solar radiation and air temperature across the region (Moore 2006). Latitude was significant in all thermal regime and air sensitivity models except for winter mean stream temperature, although this may be an indication of regional coherence in winter climate conditions during the anomalously warm winter of the 2015 water year. The significance of latitude in stream temperature and air sensitivity models may indicate that topographical shading is an important factor of thermal regimes moving from the south to north within the study area. For example, the sun angle during summer and winter solstice for a northern watershed (Old Situk) is 54° and 7°, respectively. Comparatively, the sun angle at a southern watershed (Hetta Creek) is 58° and 11°, respectively. This difference in sun angle may lead to lower solar radiation inputs to water in higher latitude watersheds leading to cooler streamwater temperature.

Watershed area was not a significant control of seasonal stream temperatures or stream specific air sensitivity. Interestingly, watershed area was found to be a strong influence in thermal regimes in other studies. Lisi *et al* (2013) found watershed area to be an important control of average summer stream temperature in Bristol Bay. In British Columbia, an order of magnitude increase in watershed area was associated with a 1°C increase in MWAT (Moore *et al* 2013). Watershed area can have a warming influence during summer, which is a reflection of increased residence time and exposure to energy inputs at the water surface-atmosphere interface (Caissie 2006). Findings from this study suggest watershed area is not a strong predictor of thermal regimes in southeast Alaska, likely due to relatively small variation in the size of study watersheds, which are generally reflective of the size distribution of watersheds in the region with the exception of large transboundary rivers (Fellman *et al* 2009, Neal *et al* 2010).

5.2 Implications for Pacific Salmon

Streamwater thermal heterogeneity associated with geomorphic variability across the landscape has implications for Pacific salmon at varying spatial scales and across freshwater life history stages. Basin scale geomorphic controls of summer thermal regimes have been shown to influence spatio-temporal variation in spawn timing and location in southwest Alaska (Lisi *et al* 2013). Extending these findings to my results implies similar biological processes occur within salmon populations in southeast Alaska. Indeed, salmon life history strategies in the region are adapted to freshwater thermal heterogeneity and are evolving to adapt to shifts in thermal regimes caused by ongoing climate change. For example, my findings suggest low gradient and low elevation watersheds with higher relative lake coverage are the warmest and most sensitive to the influence of climate change on summer thermal regimes. This is consistent with the finding that warming streamwater temperatures in the Auke Creek watershed, which contains a large, low elevation lake, has driven the timing of adult spawning migration to occur two weeks earlier and compressed the temporal duration of migration by approximately thirty days relative to five decades ago (Kovach *et al* 2012, 2013). Similar adaptations are occurring region-wide, with avoidance of peak stream temperatures and low discharge leading to temporal shifts of migratory patterns among salmon populations: sockeye salmon (*Oncorhynchus nerka*) are migrating later and pink (*O. gorbuscha*), chum (*O. nerka*), and coho (*O. kisutch*) populations are migrating earlier (Kovach *et al* 2015). Phenotypical adaptations to increased duration and magnitude of summer stream temperature caused by climate warming will likely continue within the region's salmon populations. Furthermore, complex interactions of stream temperature with biophysical processes may degrade freshwater habitat quality for salmon in certain watersheds. For example, my results indicate the warmest stream temperatures occurred during early July in most watersheds across the region. Peak stream temperatures are typically correlated with low surface water discharge in non-glacial systems (Edwards *et al* 2013, Fellman *et al* 2014). In southeast Alaska, the timing of peak stream temperature coincides with the adult salmon spawning migration. (Fellman *et al* 2015) found that high abundance of adult salmon combined with salmon carcass decomposition depletes dissolved oxygen concentrations in smaller streams, potentially dropping oxygen concentrations to lethally low levels that can result in pre-spawn mortality (Fukushima and Smoker 1997). My findings indicate the region's geomorphic heterogeneity is related to variability in streamwater sensitivity to changes in air temperature.

This suggests that as air temperature increases with ongoing climate change, lower elevation/gradient watersheds may be more at risk of critically low dissolved oxygen concentrations during the spawning migration, particularly in the southern portions of the study area.

Thermal heterogeneity across basins will have year-round implications for juvenile salmon (Bryant 2009). We found lake coverage is associated with lower winter air sensitivity and warmer stream temperature during the egg incubation life history stage, while higher gradient and elevation watersheds were cooler and more variable. Projections of warmer winter air temperatures, a rising snowline and decreased snowpack (Shanley *et al* 2015) will likely lead to warmer winter thermal regimes with greater variability in high gradient streams (Leach and Moore 2014). Increases in the magnitude and variation in winter stream temperature caused by climate warming could lead to increased incubation rates and earlier hatch times (Beacham and Murray 1990, Steel *et al* 2012). Juvenile salmon migration is shifting to adapt to earlier hatch times (Kovach *et al* 2013), a change that may potentially lead to a phenological mismatch with marine food sources (Holtby 1988, Taylor 2008). In contrast, warming stream temperatures in glacier and snow-dominated watersheds will also benefit juvenile salmon by increasing the availability of ideal thermal habitat (Fellman *et al* 2014). Moreover, juvenile survival and juvenile growth rates are projected to increase with warmer winter stream temperatures (Beer and Anderson 2011, Leppi *et al* 2014).

It is well known that salmon utilize behavioral thermoregulation strategies to exploit thermal heterogeneity occurring in within stream habitats (Armstrong *et al* 2013, Armstrong and Schindler 2013, Berman and Quinn 1991). However, the models presented here do not capture inter-watershed thermal heterogeneity. Though sensors installed at a single location within a stream cannot gather temperature data in all microhabitats utilized by salmon in a lotic system, they do capture thermal variation present within a stream, thus serving as a useful index of potential change as well as an indicator of where more intensive monitoring may be needed, particularly as aquatic ecosystems are likely to be altered by climate change (Mote *et al* 2003).

The persistence of southeast Alaska's diverse, natural, and largely intact ecosystem may be the regions greatest asset in buffering salmon populations against the effects of climatic change (Griffiths *et al* 2014a, Schindler *et al* 2010). Here, I demonstrated considerable thermal heterogeneity in stream temperature associated with the regions diverse physiography and landcover. Energy inputs are filtered through the landscape, inducing a thermal response in aquatic systems that controls biological and physical processes influencing salmon populations at multiple scales (Griffiths *et al* 2014b). In addition to inter-watershed landcover and thermal heterogeneity, the exploitation of intra-watershed thermal heterogeneity for various salmon life-history strategies will maximize adaptive capabilities to shifting thermal regimes. Though populations in sub-basins may experience greater inter-annual variation relative to the overall regional stock, ecosystems retaining their natural integrity, with little influence from habitat alterations (e.g. mineral development, hydropower, timber harvest, fish hatcheries), will maximize the resilience of the regional salmon population to climate change (Griffiths *et al* 2014a, Schindler *et al* 2010).

5.3 Implications for Land Management

With approximately 4000 anadromous streams within the coastal temperate rainforest of southeast Alaska (Halupka *et al* 2003), it is critical for managers to understand existing landscape influences on current and future streamwater thermal regimes. My results demonstrate that watershed characteristics can substantially modify the effect of air temperature on streamwater thermal regimes. Thus, I present a geomorphic template of relative streamwater air sensitivity at sub-basin spatial scales and seasonal temporal scales, providing a framework to improve understanding of streamwater thermal response to climate change and identify streams that may be thermally at risk throughout southeast Alaska. For example, empirical models populated with landcover characteristics of a catchment can be utilized to predict relative streamwater thermal sensitivity of a sub-basin during summer and winter. However, sources of uncertainty within the model may be associated with streamwater temperature heterogeneity at the reach-scale that currently cannot be detected by the regional scale models. For example, the models may not accurately predict thermal regimes or air sensitivity in watersheds with a greater proportion of discharge from groundwater sources or hyporheic exchange (Moore *et al* 2013). Moreover, small-scale landcover alterations not included in landcover data informing the models, such as riparian vegetation removal, may create uncertainty in model predictions.

The approach of the air sensitivity model presented here differs from the hydroclimatic index provided by Shanley and Albert (2014), which derived a relative watershed sensitivity index from surface water discharge projections at HUC-10 spatial resolution. Here, I quantify stream-specific sensitivity of streamwater temperature to air temperature fluctuations relative to a common trend in seasonal thermal regimes. Geomorphic linkages to relative air sensitivity was quantified at sub-HUC-14 spatial resolution, thus serving as a useful modeling framework at the sub-basin scale. This sensitivity framework will inform the assessment of potential implications of management actions by identifying thermally sensitive basins. Moreover, thermal regimes and stream discharge are correlated (Caissie 2006, Poole and Berman 2001), thus the two sensitivity models can potentially be used in conjunction and provide a multi-factor approach to improve the understanding of watershed thermal sensitivity to climate change.

A limitation of multiple linear regression stream temperature predictor models is the assumption of stationarity (Arismendi *et al* 2014). The relationships between explanatory and response variables are constantly in flux and nonstationarity will introduce uncertainty into predictive performance of models (Schindler and Hilborn 2015). Thus, linear models typically have the strongest predictive power during temporal range from which they were developed (Arismendi *et al* 2014). The thermal regimes and relative air sensitivity models presented here were developed using data collected during an anomalously warm year with low snow accumulation. Downscaled climate models for the region project warmer winters with increased precipitation, decreased precipitation as snow, and warmer summer temperature (Shanley *et al* 2015), perhaps suggesting seasonal models developed in this study may be more applicable to projected climatic conditions compared to climate normals.

6. Conclusions

My findings demonstrate the considerable variation in stream thermal regimes and air sensitivity across the coastal temperate rainforest of southeast Alaska. Lake coverage, slope, and forest cover are the primary landscape controls of stream temperature during summer and winter in smaller watersheds, and latitude has year-round importance as a proxy for solar radiation and climate. I also demonstrate that streams are sensitive to air temperature fluctuations as moderated by watershed geomorphology, providing a template for potential watershed sensitivity and potential response to climate change. Results presented here should be considered as a framework for predicting stream thermal regimes and to assess response to climate change based on watershed characteristics, thus providing a tool to prioritize and direct future monitoring and research efforts. Future research should address the continued refinement of regional stream temperature sensitivity models. Furthermore, watersheds were only monitored at one location, and information on finer spatial resolution investigating the intra-watershed thermal heterogeneity in relatively sensitive and insensitive basins is needed in the region. This will help in understanding salmonid utilization of freshwater thermal habitats, and impacts of habitat alteration or improvements, to provide greater insight to potential implications of climate change for the regions lotic systems.

References

Adelfio L A 2016 Geomorphic and Climatic Controls on Water Temperature and Streambed Scour, Copper River Delta, Alaska: Implications for Understanding Climate Change Impacts to the Pacific Salmon Egg Incubation Environment. Masters Thesis, Oregon State University, Corvallis, Oregon.

Albert D and Schoen J 2006 A preliminary classification and conservation assessment of terrestrial ecosystems in Southeast Alaska. The Nature Conservancy. 22pp.

Anderson B T, McNamara J P, Marshall H-P and Flores A N 2014 Insights into the physical processes controlling correlations between snow distribution and terrain properties *Water Resour. Res.* **50** 4545–63

Arismendi I, Safeeq M, Dunham J B and Johnson S L 2014 Can air temperature be used to project influences of climate change on stream temperature? *Environ. Res. Lett.* **9** 1–12

Armstrong J B and Schindler D E 2013 Going with the flow: spatial distributions of juvenile coho salmon track an annually shifting mosaic of water temperature *Ecosystems* **16** 1429–41

Armstrong J B, Schindler D E, Ruff C P, Brooks G T, Bentley K E and Torgersen C E 2013 Diel horizontal migration in streams: Juvenile fish exploit spatial heterogeneity in thermal and trophic resources *Ecology* **94** 2066–75

Beacham T D and Murray C B 1990 Temperature, Egg Size, and Development of Embryos and Alevins of Five Species of Pacific Salmon: A Comparative Analysis *Trans. Am. Fish. Soc.* **119** 927–45

Beer W N and Anderson J J 2011 Sensitivity of juvenile salmonid growth to future climate trends *River Res. Appl.* **27** 663–9

Berman C H and Quinn T P 1991 Behavioural thermoregulation and homing by spring Chinook salmon, Oncorhynchus tshawytscha (Walbaum), in the Yakima River *J. Fish Biol.* **39** 301–312

Beschta R L, Bilby R E, Brown G W, Holtby L B and Hofstra T D 1987 Stream temperature and aquatic habitat: Fisheries and forestry interactions In: Streamside management: forestry and fishery interactions. Eds. E.O. Salo and T.W. Cundy, Institute of Forest Resources, Contribution No. 57. (Seattle, Washington) University of Washington 191–232

Bryant M D 2009 Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska *Clim. Change* **95** 169–93

Caissie D 2006 The thermal regime of rivers: a review *Freshw. Biol.* **51** 1389–1406

Caldwell P, Segura C, Gull Laird S, Sun G, McNulty S G, Sandercock M, Boggs J and Vose J M 2015 Short-term stream water temperature observations permit rapid assessment of potential climate change impacts: Rapid assessment of climate change impacts on stream water temperature. *Hydrol. Process.* **29** 2196–211

Carstensen R, Schoen J and Albert D M 2007 Overview of the Biogeographic Provinces of Southeastern Alaska. In: A Conservation Assessment for the Coastal Forests and Mountains Ecoregion of Southeastern Alaska and the Tongass National Forest. Eds. J. Schoen and E. Dovichin (Anchorage, Alaska), Audubon Alaska and The Nature Conservancy 46

Edwards R T, D'Amore D V, Norberg E and Biles F 2013 Riparian Ecology, Climate Change, and Management in North Pacific Coastal Rainforests. In: North Pacific Temperate rainforests: ecology and conservation. Eds. G. H. Orians and J. Schoen (Seattle, Washington) University of Washington Press 43–72

Fellman J B, Hood E, Dryer W and Pyare S 2015 Stream Physical Characteristics Impact Habitat Quality for Pacific Salmon in Two Temperate Coastal Watersheds *PLOS ONE* **10** 7 e0132652

Fellman J B, Hood E, Edwards R T and Jones J B 2009 Uptake of Allochthonous Dissolved Organic Matter from Soil and Salmon in Coastal Temperate Rainforest Streams *Ecosystems* **12** 747–59

Fellman J B, Nagorski S, Pyare S, Vermilyea A W, Scott D and Hood E 2014 Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska *Hydrol. Process.* **28** 2062–73

Fukushima M and Smoker W W 1997 Determinants of stream life, spawning efficiency, and spawning habitat in pink salmon in the Auke Lake system, Alaska *Can. J. Fish. Aquat. Sci.* **54** 96–104

Griffiths J R, Schindler D E, Armstrong J B, Scheuerell M D, Whited D C, Clark R A, Hilborn R, Holt C A, Lindley S T, Stanford J A and Volk E C 2014a Performance of salmon fishery portfolios across western North America *J. Appl. Ecol.* **51** 1554–63

Griffiths J R, Schindler D E, Ruggerone G T and Bumgarner J D 2014b Climate variation is filtered differently among lakes to influence growth of juvenile sockeye salmon in an Alaskan watershed *Oikos* **123** 687–98

Halupka K C, Willson M F, Bryant M D, Everest F H and Gharrett A J 2003 Conservation of Population Diversity of Pacific Salmon in Southeast Alaska *North Am. J. Fish. Manag.* **23** 1057–86

Harris A S and Farr W A 1974 The forest ecosystem of southeast Alaska USDA Serv Gen Tech Rep PNW-25 www.fs.fed.us/pnw/pubs/pnw_gtr025.pdf 109

Hodgson S and Quinn T P 2002 The timing of adult sockeye salmon migration into fresh water: adaptations by populations to prevailing thermal regimes *Can. J. Zool.* **80** 542–55

Holtby L B 1988 Effects of logging on stream temperatures in Carnation Creek British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch) *Can. J. Fish. Aquat. Sci.* **45** 502–515

Hood E and Berner L 2009 Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska *J. Geophys. Res. Biogeosciences* **114** 2005–2012

Hrachowitz M, Soulsby C, Imholt C, Malcolm I A and Tetzlaff D 2010 Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures *Hydrol. Process.* **24** 3374–91

Isaak D J and Hubert W A 2001 A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes *J of Am. Wat. Res. As.* **37** 351-366

Isaak D J, Wollrab S, Horan D and Chandler G 2012 Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes *Clim. Change* **113** 499–524

Jones N E 2010 Incorporating lakes within the river discontinuum: longitudinal changes in ecological characteristics in stream–lake networks *Can. J. Fish. Aquat. Sci.* **67** 1350–62

Kovach R P, Ellison S C, Pyare S and Tallmon D A 2015 Temporal patterns in adult salmon migration timing across southeast Alaska *Glob. Change Biol.* **21** 1821–33

Kovach R P, Gharrett A J and Tallmon D A 2012 Genetic change for earlier migration timing in a pink salmon population *Proc. R. Soc. B Biol. Sci.* **279** 3870–3878

Kovach R P, Joyce J E, Echave J D, Lindberg M S and Tallmon D A 2013 Earlier Migration Timing, Decreasing Phenotypic Variation, and Biocomplexity in Multiple Salmonid Species ed S M Carlson *PLoS ONE* **8** 1-10

Kristensen K, Nielsen A, Berg C W, Skaug H and Bell B M 2016 TMB: Automatic Differentiation and Laplace Approximation. *J. Stat. Softw.* **70** 627–37

Kurylyk B L, MacQuarrie K T B, Caissie D and McKenzie J M 2015 Shallow groundwater thermal sensitivity to climate change and land cover disturbances: derivation of analytical expressions and implications for stream temperature modeling *Hydrol. Earth Syst. Sci.* **19** 2469–89

Leach J A and Moore R D 2011 Stream temperature dynamics in two hydrogeomorphically distinct reaches *Hydrol. Process.* **25** 679–90

Leach J A and Moore R D 2014 Winter stream temperature in the rain-on-snow zone of the Pacific Northwest: influences of hillslope runoff and transient snow cover *Hydrol. Earth Syst. Sci.* **18** 819–38

Leppi J C, Rinella D J, Wilson R R and Loya W M 2014 Linking climate change projections for an Alaskan watershed to future coho salmon production *Glob. Change Biol.* **20** 1808–20

Lisi P J and Schindler D E 2015 Wind-driven upwelling in lakes destabilizes thermal regimes of downstream rivers: Thermal effects of lakes on river outlets *Limnol. Oceanogr.* **60** 169–80

Lisi P J, Schindler D E, Bentley K T and Pess G R 2013 Association between geomorphic attributes of watersheds, water temperature, and salmon spawn timing in Alaskan streams *Geomorphology* **185** 78–86

Lisi P J, Schindler D E, Cline T J, Scheuerell M D and Walsh P B 2015 Watershed geomorphology and snowmelt control stream thermal sensitivity to air temperature. *Geophys. Res. Lett.* **42** 3380–8

Mauger S 2011 Stream temperature monitoring network for Cook Inlet salmon streams 2008-2010. Cook Inlet Keeper. Clean Water Action Grant 11-001. Online: http://inletkeeper.org/

Mellina E, Moore R D, Hinch S G, Macdonald J S and Pearson G 2002 Stream temperature responses to clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes *Can. J. Fish. Aquat. Sci.* **59** 1886–900

Mohseni O, Stefan H G and Erickson T R 1998 A nonlinear regression model for weekly stream temperatures *Water Resour. Res.* **34** 2685–92

Moore R D 2006 Stream temperature patterns in British Columbia, Canada, based on routine spot measurements *Can. Water Resour. J.* **31** 41–56

Moore R D, Nelitz M and Parkinson E 2013 Empirical modelling of maximum weekly average stream temperature in British Columbia, Canada, to support assessment of fish habitat suitability *Can. Water Resour. J.* **38** 135–47

Moore R, Spittlehouse D L and Story A 2005 Riparian microclimate and stream temperature response to forest harvesting: a review *J of Am. Wat. Res. As.* **41** 813-834

Mote P W, Parson E A, Hamlet A F, Keeton W S, Lettenmaier D, Mantua N, Miles E L, Peterson D W, Peterson D L and Slaughter R 2003 Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest *Clim. Change* **61** 45–88

Neal E G, Hood E and Smikrud K 2010 Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska *Geophys. Res. Lett.* **37** 1-5

Neal E G, Todd Walter M and Coffeen C 2002 Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska *J. Hydrol.* **263** 188–97

O'Neel S, Hood E, Bidlack A L, Fleming S W, Arimitsu M L, Arendt A, Burgess E, Sergeant C J, Beaudreau A H, Timm K, Hayward G D, Reynolds J H and Pyare S 2015 Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem *BioScience* **65** 499-512

Overland J E, Hanna E, Hanssen-Bauer I, Kim S J, Walsh J E, Wang M, Bhatt U S and Thoman R L 2015 Air Temperature. In Arctic Report Card: Update for 2015. Online: http://www.arctic.noaa.gov/reportcard/air_temperature.html

Parkinson E A, Lea E V, Nelitz M A, Knudson J M and Moore R D 2016 Identifying temperature thresholds associated with fish community changes in British Columbia, Canada, to support identification of temperature sensitive streams. *River Res. Appl.* **32** 330–47

Poole G C and Berman C H 2001 An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation *Environ. Manage.* **27** 787–802

R Development Core Team 2016 *R:* A Language and Environment for Statistical Computing Version. 3.3.0. R Foundation for Statistical Computing, Vienna, Austria.

Schindler D E, Augerot X, Fleishman E, Mantua N J, Riddell B, Ruckelshaus M, Seeb J and Webster M 2008 Climate change, ecosystem impacts, and management for Pacific salmon *Fisheries* **33** 502–506

Schindler D E and Hilborn R 2015 Prediction, precaution, and policy under global change *Science* **347** 953–954

Schindler D E, Hilborn R, Chasco B, Boatright C P, Quinn T P, Rogers L A and Webster M S 2010 Population diversity and the portfolio effect in an exploited species *Nature* **465** 609–12

Scott M C, Helfman G S, McTammany M E, Benfield E F and Bolstad P V 2002 Multiscale influences on physical and chemical stream conditions across blue ridge landscapes. *J. Am. Water Resour. Assoc.* **38** 1379–92

Shanley C S and Albert D M 2014 Climate change sensitivity index for Pacific salmon habitat in Southeast Alaska ed I Álvarez *PLoS ONE* **9** 1-13

Shanley C S, Pyare S, Goldstein M I, Alaback P B, Albert D M, Beier C M, Brinkman T J, Edwards R T, Hood E, MacKinnon A, McPhee M V, Patterson T M, Suring L H, Tallmon D A and Wipfli M S 2015 Climate change implications in the northern coastal temperate rainforest of North America *Clim. Change* **130** 155–70

Shulski M and Wendler G 2007 The Climate of Alaska, University of Alaska Press, Fairbanks, Alaska 216

Steel E A, Tillotson A, Larsen D A, Fullerton A H, Denton K P and Beckman B R 2012 Beyond the mean: The role of variability in predicting ecological effects of stream temperature on salmon *Ecosphere* **3** 1-11

Stewart B C, Kunkel K E, Stevens L E, Sun L and Walsh J E 2013 Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 7. 60pp. http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_TECH_Report_142-7-Climate_of_Alaska.pdf

Taylor S G 2008 Climate warming causes phenological shift in Pink Salmon, Oncorhynchus gorbuscha, behavior at Auke Creek, Alaska: Climate warming and pink salmon behavior *Glob. Change Biol.* **14** 229–35

Toohey R C, Neal E G and Solin G L 2014 Guidelines for the collection of continuous streamwater-temperature data in Alaska: U.S. Geological Survey Open-File Report 2014-1182, 34 p., http://dx.doi.org/10.3133/ofr20141182

Webb B W, Hannah D M, Moore R D, Brown L E and Nobilis F 2008 Recent advances in stream and river temperature research *Hydrol. Process.* **22** 902–18

Webb B W and Zhang Y 1997 Spatial and seasonal variability in the components of the river heat budget. *Hydrol. Process.* **11** 79–101

Willson M F and Halupka K C 1995 Anadromous fish as keystone species in vertebrate communities *Conserv. Biol.* **9** 489–497

Zuur A F, Fryer R J, Jolliffe I T, Dekker R and Beukema J J 2003 Estimating common trends in multivariate time series using dynamic factor analysis *Environmetrics* **14** 665–685

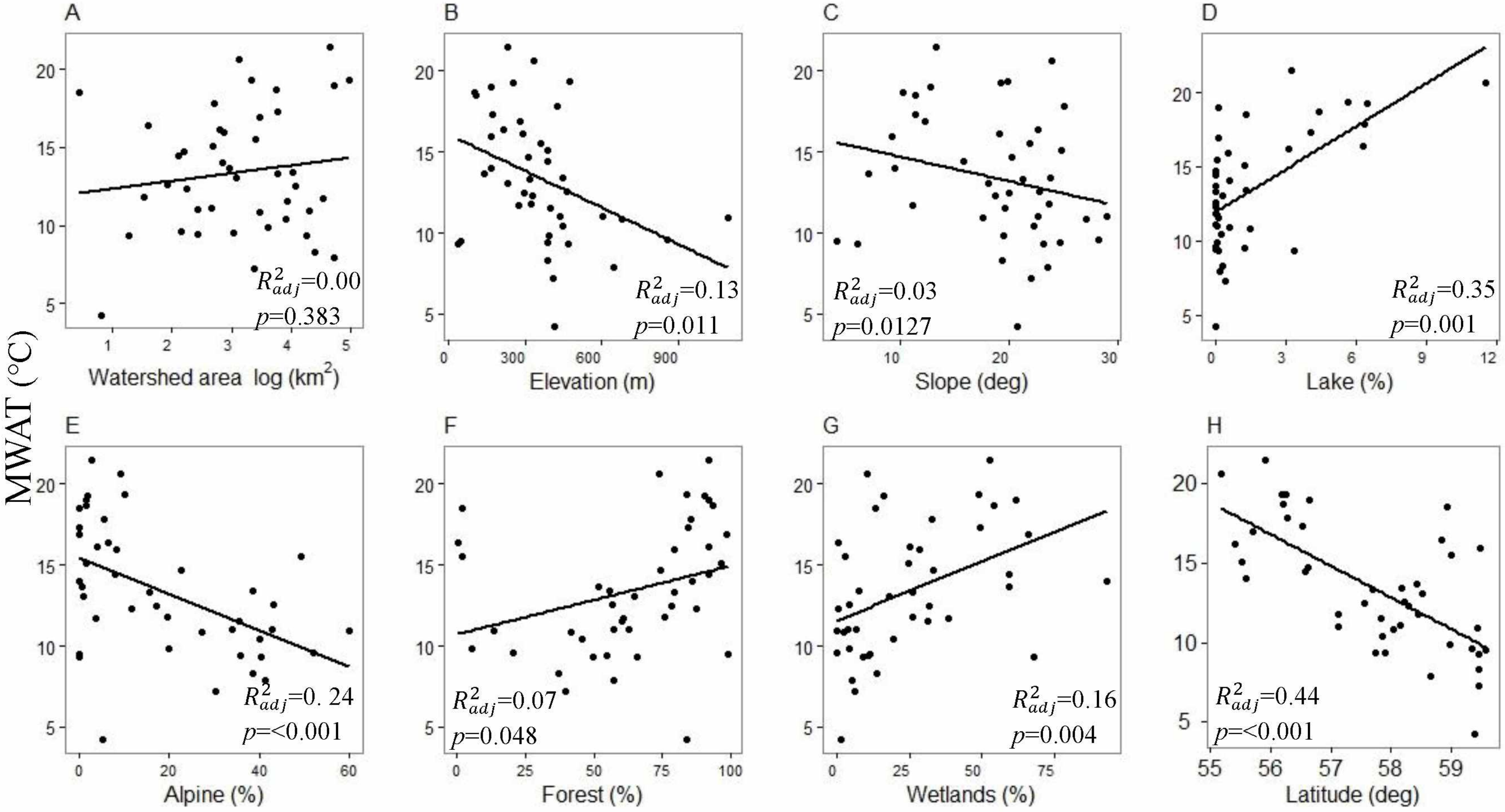
Zuur A F, Ieno E N and Smith G M 2007 Analysing ecological data (New York ; London) Springer 672

Appendix A. Landcover statistics for forty-seven monitored watersheds.

Watershed	Latitude	Longitude	Area (km^2)	Elevation (m)	Slope (deg)	Alpine (%)	Glacier (%)	Lake (%)	Wetland (%)	Forest (%)
Ahrnklin	59.46	-139.10	80.9	387	19	38.46	7.12	0.32	13.70	36.91
Antlen	59.46	-139.11	3.6	38	6	0.00	0.00	3.35	67.88	65.64
Echo	59.49	-139.19	17.6	169	9	8.34	0.00	0.51	28.66	79.40
Miller	59.45	-139.06	29.5	413	22	30.14	9.08	0.44	6.13	39.86
Old Situk	59.57	-139.49	20.6	50	4	0.00	0.00	1.26	11.40	98.79
Berg	58.51	-136.24	21.9	232	18	1.01	0.00	0.32	18.22	64.71
Big Boulder	59.43	-136.19	74.6	1094	18	59.82	1.89	0.59	0.09	13.30
Chilkoot	59.34	-135.59	8.7	859	28	51.83	2.86	0.00	0.00	20.71
Clear	59.38	-136.07	2.3	417	21	5.31	0.00	0.00	1.33	83.63
Cowee	58.65	-134.91	110.5	647	24	41.40	11.06	0.20	5.09	57.18
Gull	58.94	-136.26	1.6	110	11	0.00	0.00	1.27	13.38	1.91
Limestone	58.04	-133.95	32.3	681	27	27.26	0.00	1.49	2.39	41.73
Nunatak	58.98	-136.10	36.6	395	19	19.72	0.00	0.08	4.40	5.49
Rink	58.44	-135.66	19.3	142	7	0.52	0.00	0.00	59.31	51.74
Salmon_R	58.45	-135.74	93.8	277	11	3.56	0.00	0.05	38.69	60.62
Vivid	58.83	-136.46	4.9	214	23	6.28	0.00	6.28	0.61	0.40
Wolf	59.00	-136.17	29.7	360	22	49.12	0.00	0.07	2.96	1.99
Admiralty	58.17	-134.56	56.1	449	24	38.54	0.00	1.32	7.83	55.86
Black	57.71	-136.10	63.1	296	22	29.62	0.00	0.67	27.56	54.84
Ford arm	57.58	-135.92	26.8	313	23	34.24	0.00	1.61	28.37	54.99
Goose	57.91	-135.76	69.7	469	23	40.45	0.00	0.13	8.98	49.50
Hilda	58.23	-134.50	6.8	463	23	43.17	0.00	0.00	4.41	56.68
Kadashan	57.69	-135.22	43.0	319	21	15.46	0.00	0.00	25.99	79.54
Kanalku	57.49	-134.37	31.8	351	22	12.12	0.00	3.42	8.35	79.77
Long	57.85	-135.67	49.9	447	22	40.02	0.00	0.22	19.40	45.67
No Name	57.13	-135.38	4.6	325	24	19.44	0.00	0.00	25.92	75.59
Peterson	58.29	-134.67	9.4	327	19	11.46	0.00	0.00	0.42	87.47
Seal	57.82	-135.60	50.5	400	20	35.58	0.00	0.14	31.42	59.98
Sitkoh	57.55	-135.01	58.7	298	20	17.10	0.00	0.00	31.65	78.47
Starrigavan	57.13	-135.33	11.5	440	29	33.86	0.00	0.09	6.79	62.75
Trap	57.74	-135.02	11.4	388	25	35.76	0.00	0.00	10.87	54.78
Youngs	58.16	-134.67	14.3	607	23	42.68	0.00	0.00	3.64	57.32
Anan	56.18	-131.88	143.2	473	20	10.06	0.00	5.66	49.01	83.74
Bedrock	56.62	-132.89	9.2	315	20	22.73	0.00	0.00	33.33	74.32
Castle	56.64	-133.27	112.9	168	13	1.45	0.00	0.10	61.65	91.65
Jap	56.77	-132.61	15.6	495	26	14.15	0.00	0.00	12.48	85.21
Kah Sheets	56.53	-133.15	43.8	173	11	0.00	0.00	4.04	49.54	84.53
Kunk	56.28	-132.40	15.0	428	25	5.41	0.00	6.35	32.73	85.57
Lunch	55.51	-131.72	14.6	387	25	1.64	0.00	1.23	24.56	96.58
Ohmer	56.58	-132.73	8.3	387	16	7.81	0.00	0.00	59.62	91.71
Thoms	56.20	-132.16	42.0	100	10	1.67	0.00	4.43	54.39	93.50

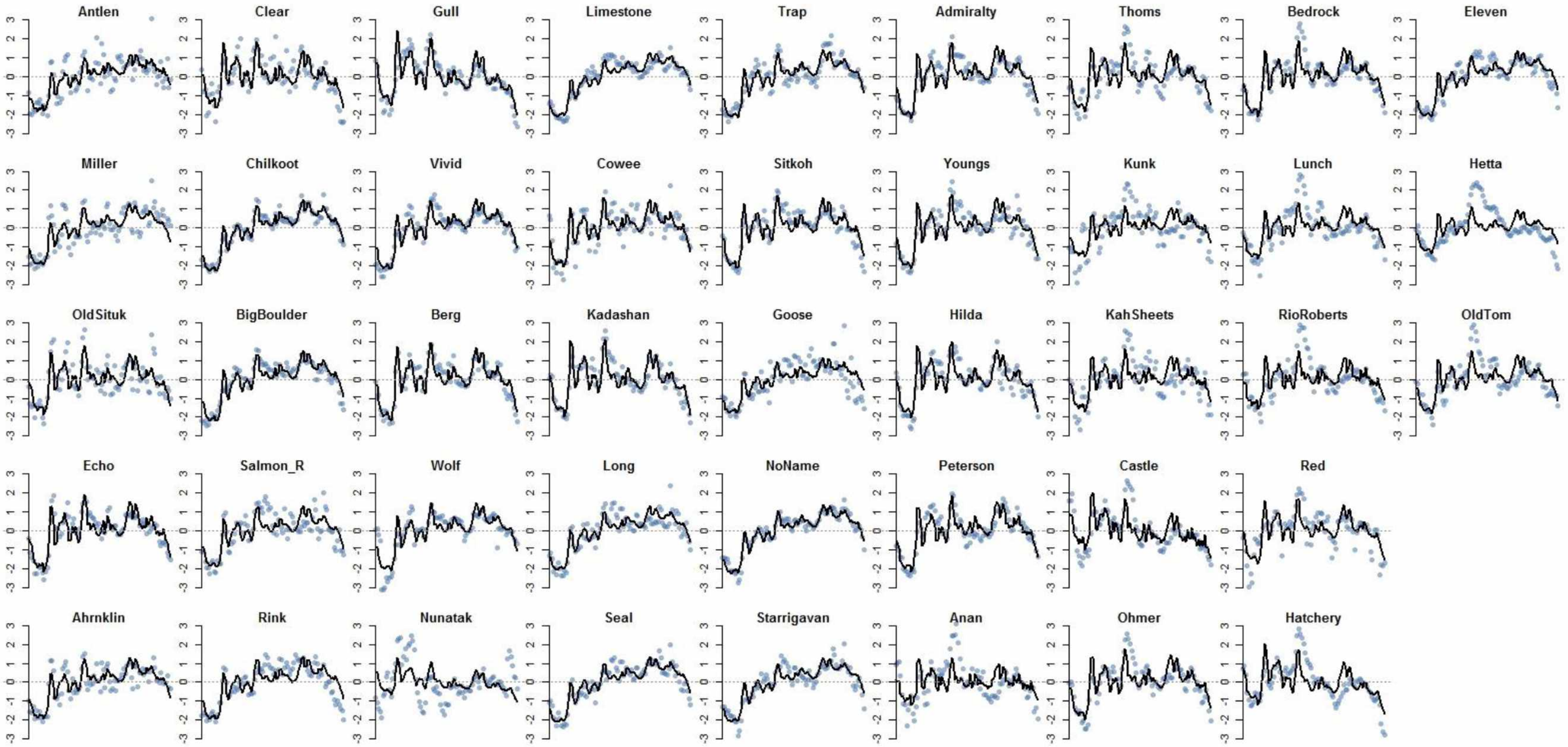
Eleven	55.59	-133.28	17.2	169	10	0.00	0.00	0.58	93.02	85.91
Hatchery	55.91	-132.93	104.8	234	13	2.83	0.00	3.25	52.76	91.94
Hetta	55.17	-132.57	22.8	336	24	9.19	0.00	11.51	10.33	73.86
Old Tom	55.40	-132.41	16.5	290	19	3.89	0.00	3.09	25.39	91.98
Red	56.26	-133.33	27.9	255	19	1.72	0.00	6.44	16.00	90.30
Rio Roberts	55.70	-132.77	32.0	282	12	0.00	0.00	0.12	66.09	98.44

Appendix B.



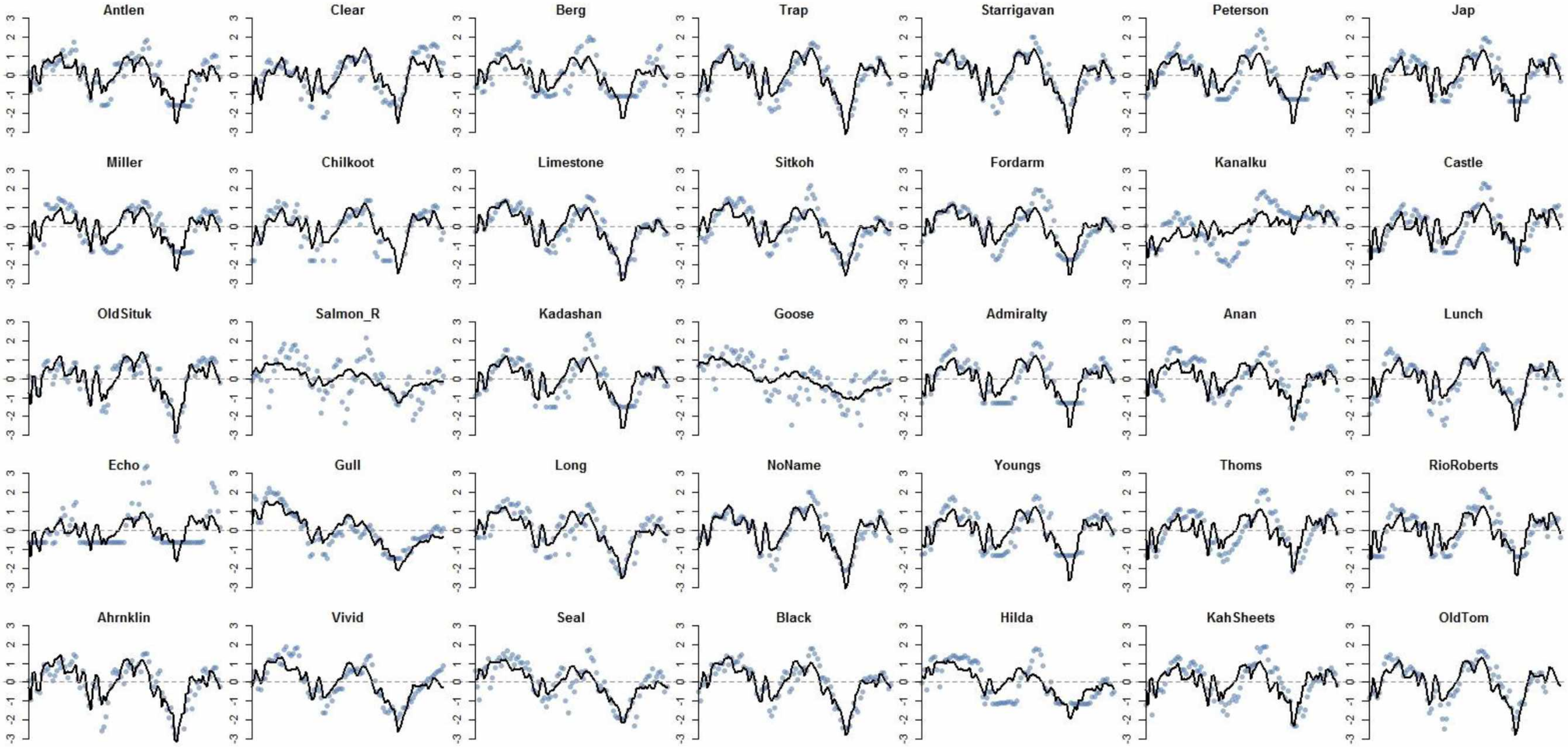
Maximum weekly average temperature (MWAT) of stream temperature for 43 watersheds vs watershed landcover characteristics. A) watershed area (log km^2), B) mean watershed elevation (m), C) mean watershed slope (deg), D) lake coverage (%), E) alpine area (%), F) forest cover (%), G), wetlands (%), H) latitude (deg).

Appendix C.



Summer DFA model fits of 43 watersheds. The y-axis is z-scored stream temperature and the x-axis is the date, 1 June – 31 August of the 2015 water year. Points depict observed stream temperature data and the solid line represents modeled stream temperature. Because the stream temperature is z-scored, zero represents the seasonal mean for each stream.

Appendix D.



Winter DFA model fits of 35 watersheds. The y-axis is z-scored stream temperature and the x-axis is the date, 1 December – 28 February of the 2015 water year. Points depict observed stream temperature data and the solid line represents modeled stream temperature. Because the stream temperature is z-scored, zero represents the seasonal mean for each stream.

Appendix E. Pearson correlation coefficients between watershed landcover and geomorphic characteristics of 43 watersheds monitored during summer 2015.

	Latitude	Area	Elevation	Slope	% Alpine	% Glacier	% Lake	% Wetland	% Forest
Latitude	1.000								
Area	-0.169	1.000							
Elevation	0.203	0.195	1.000						
Slope	-0.050	-0.029	0.652*	1.000					
% Alpine	0.411*	0.188	0.780*	0.607*	1.000				
% Glacier	0.365*	0.270	0.331*	0.191	0.376	1.000			
% Lake	-0.444*	0.019	-0.192	0.013	-0.375*	-0.168	1.000		
% Wetland	-0.514*	0.146*	-0.527*	-0.646*	-0.595*	-0.275	0.074	1.000	
% Forest	-0.631*	0.108	-0.388*	-0.284	-0.568*	-0.295	0.165	0.538*	1.000

Significance: * =<0.05

Appendix F. Pearson correlation coefficients between watershed landcover and geomorphic characteristics of 35 watersheds monitored during winter 2015.

	Latitude	Area	Elevation	Slope	% Alpine	% Glacier	% Lake	% Wetland	% Forest
Latitude	1.000								
Area	-0.322	1.000							
Elevation	0.013	0.070	1.000						
Slope	-0.137	-0.031	0.808*	1.000					
% Alpine	0.240	0.130	0.733*	0.674	1.000				
% Glacier	0.382*	0.127	0.207	0.121	0.306	1.000			
% Lake	-0.227	0.020	-0.317	-0.224	-0.406*	-0.141	1.000		
% Wetland	-0.453*	0.352*	-0.538*	-0.614*	-0.511*	-0.210	0.271	1.000	
% Forest	-0.545*	0.258	-0.289	-0.317	-0.478*	-0.329	-0.025	0.472	1.000

Significance: * =<0.05