Patterns of stream temperature and the influence of groundwater in northern Rocky Mountain watersheds

by

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Abstract

Stream temperature is an important water quality parameter linked to biotic and abiotic processes that influence the abundance and distribution of aquatic organisms. Stream temperatures can be highly variable through space and time and are determined by energy flux processes. Key energy flux processes that influence stream temperature can be categorized into climatic controls (e.g., solar radiation, air temperature, precipitation) and hydrologic controls (e.g., groundwater inputs, tributary inflows). Generally, groundwater inputs into streams have a cooling effect on stream thermal regimes in the summer, and a warming effect in the winter, relative to air temperatures. Fish species that require relatively cold stream temperatures in summer are susceptible to habitat loss due to shifting stream thermal regimes. The objective of this thesis is to explore the importance of groundwater on moderating summer stream thermal regimes in the Canadian Rocky Mountains and foothills. In particular, this work examines the comparative influence of climatic controls versus hydrologic controls and attempts to identify spatial and temporal patterns of summer stream temperature at the watershed scale. A long-term (2005-2018) comparison of climatic versus hydrologic controls in seven headwater sub-catchments identified that groundwater inputs to streamflow explain 1.3-6.9 times more of the variation in stream temperature than climatic controls. Although inputs of groundwater consistently decreased summer stream temperature, there was noteworthy variability in the effects of groundwater inputs across the sub-catchments suggesting there is variability in temperature of different groundwater inputs. Spatiotemporal patterns of stream temperature were identified across a study area (28648 km^2) that included Rocky Mountains and foothills in Alberta. An empirical spatiotemporal model (adjusted r^2=0.93) derived from continuous summer data (2019-2021) from 16 watersheds identified that: 1) groundwater inputs cooled stream temperatures ($p<0.001$), however generalized across a larger, more diverse study area, groundwater inputs were less predictive of stream temperature than climatic controls; 2) an anomalous weather event ("Heat

Dome”) in 2021 elevated mean stream temperatures 0.78 ºC and disrupted patterns of cooling groundwater inputs observed in 2019 and 2020; 3) variability in stream thermal regimes across the different watersheds was highly correlated with terrain complexity metrics ($p<0.001$, r^2=79-81%). These results emphasize the importance of considering both climatic and hydrologic controls (particularly groundwater inputs) on stream temperature in order to understand thermal regimes and their susceptibility to natural and anthropogenic disturbances and changing climates. In addition, the identification of terrain complexity metrics as predictors of thermal regimes may become a useful tool for identifying watersheds with streams that are relatively warmer/cooler and enable resource managers to more effectively prioritize conservation efforts.

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Chapter 1. Introduction

Water temperature is an important water quality parameter that influences instream chemical and biological process and in turn can control the distribution (Torgersen et al. 1999; Hodge et al. 2017) and abundance (Isaak and Hubert 2004; Eby et al. 2014) of many organisms in riverine systems. Water temperatures vary across spatiotemporal scales due to the variability in energy exchange processes driven by climatic (e.g., solar radiation) and hydrologic (e.g., streamflow) conditions and their interactions with static environmental settings (physiography). Natural and anthropogenic changes (e.g., wildfire, forest harvest) to riverine landscapes as well as climate change have the potential to impact aquatic species by changing climatic and hydrologic conditions, and thus riverine thermal regimes (Johnson 2004). The highly variable nature of riverine water temperatures through space and time, unique thermal requirements of different aquatic species and changing climatic and environmental conditions make riverine ecosystem management an important and complex issue.

Climatic controls on stream temperatures include non-advective energy fluxes from solar radiation, longwave radiation, turbulent exchange of sensible and latent heat, and advective mixing of precipitation intercepted by stream channels (Moore et al. 2005, Leach et al. 2022). Climatic controls exhibit strong temporal and spatial variation. Net radiation (shortwave solar radiation and longwave radiation emitted from surrounding environments) is generally considered to be a dominant source of climatic energy flux (Webb and Zhang 1999). Riparian vegetation and topography around stream channels can block shortwave solar radiation (Rutherford et al. 1997), particularly in headwater streams with narrow channel widths. In contrast, longwave radiation reaching streams is typically greater in headwater streams, where a greater portion of a stream is in direct view of vegetation and terrain (Benyahya et al. 2012). Turbulent exchange of sensible and latent heat from air temperature is not a major source of energy flux (Johnson 2003); however, air temperature is often used as a surrogate for net radiation, as the variables are highly correlated, and air temperature data is more widely available than net radiation data. Many studies predicting river temperature focus on radiative controls and often rely on air temperature as a surrogate variable for predicting river water temperature (Caissie 2006). Although some stream temperature thermal regimes may be primarily radiative controlled, a radiative-control focus can overlook the importance of hydrologic controls, particularly groundwater, in regulating stream temperature.

Hydrologic processes that influence stream temperatures include advective energy fluxes primarily related to tributary inflows, hyporheic exchange, groundwater contribution and bed heat conduction (Moore et al. 2005, Leach et al. 2022). Similar to climatic controls, the relative influence of each hydrologic process can vary in magnitude both temporally and spatially and is influenced by interactions with physiographic variables. Hydrologic processes can add or remove heat energy to streams and the overall effect on stream temperature is relative to the difference in temperatures and volumes of waters mixing with streamflow (Kobayashi et al. 1999; Leach et al. 2022).

Increasingly, the importance of the role of groundwater inputs on stream temperatures has been identified (Dugdale et al. 2015; Kaandorp et al. 2019; Somers and McKenzie 2020). Groundwater inputs dampen diurnal and seasonal variation in stream temperature (Ward 1985), moderating temperatures such that they are relatively cooler in the summer and warmer in the winter compared to air temperatures (Anderson 2005; Caissie 2006). The relative influence of groundwater on stream temperature varies with the volume of groundwater inputs and the depth at which the groundwater originates (Kobayashi et al. 1999). The difference in groundwater temperature of deep flow pathways and shallow subsurface flow pathways (typically <5 m beneath land surface) is related to how water infiltrating soil is subject to soil temperatures. The fluctuation in soil temperature decreases with depth until it reaches the "neutral zone" (typically ≥10m below ground surface) where it will remain constant (Taniguchi 1993).

Water temperatures influence the distribution and abundance of aquatic species, particularly cold-water salmonids, by regulating metabolic rates, reproduction, intraspecific competition and mortality (Baxter and McPhail 1999; Bear et al. 2007; Benjamin et al. 2016; Isaak et al. 2010). Many aquatic species have preferred thermal regimes and limit their exposure to temperatures outside optimal ranges. For example, westslope cutthroat trout (*Onchorhynchus clarkia lewisi*) optimum growth occurs in water temperatures of 13.6 ^{o}C, temperatures of above 20 ^{o}C have been shown to lower survival rates, and mortality increases greatly after 7-day exposures to 24 ^{o}C (Bear et al. 2007). Laboratory incubation experiments on Chinook salmon (*Oncorhynchus tshawytscha*) found that fry exposed to warmer thermal regimes emerge earlier and less developed than those from colder water temperatures (Fuhrman et al. 2017). Brook trout (*Salvelinus fontinalis*) invasiveness in current or historical bull trout (*Salvelinus confluentus*) habitat is positively associated with stream temperature in the Canadian Rockies (Warnock and Rasmussen 2013). Summer stream temperatures are particularly important in the Canadian Rocky Mountains where energy inputs from radiation and high air temperatures during periods of low streamflow can lead to increases in water temperatures. In fact, there is evidence that cold-water fish species ranges have contracted (Shepard et al. 2005) with population distributions shifting to cooler, higher elevation areas where cold-water refugia are more abundant (Isaak and Rieman 2013). Cold-water aquatic species face a combined threat of changing climate patterns leading to warmer air temperatures (IPCC 2023) and altered hydrology (Leppi et al, 2011), leading to changing thermal conditions of streams and rivers.

Given the importance of water temperature as a water quality parameter, a wide breadth of research has been conducted to examine spatial and temporal patterns in stream temperatures and the mechanisms contributing to different thermal regimes. Studies have varied in spatial scale – from localized process-based research (e.g., exchanges between rivers and groundwater recharge/discharge zones; Silliman and Booth 1993; Ouellet et al. 2017), to reaches (Leach and Moore 2011), catchments (Wagner et al 2014) and entire basins (Chang and Psaris 2013). Studies have also varied in temporal scale – from single measurements of stream temperature using thermal infrared imagery aimed at capturing yearly maxima (Monk et al. 2013), to continuous datasets of hourly or daily data spanning multiple years. For the purposes of fisheries management, more research on thermal regimes using continuous data at the watershed scale would be beneficial to capture annual and seasonal variability, particularly for sensitive salmonids that can move long distances.

While stream temperatures are regulated by both climatic and hydrologic variables, a comparative influence of these factors on stream thermal regimes is lacking. It is generally understood that advective energy fluxes decrease with catchment area and net radiation energy fluxes increase with catchment area (Leach et al. 2022). However, quantifying the influence of climatic versus hydrologic controls across different watersheds would lend to understanding fundamental differences in thermal regime drivers, and should influence watershed management practices. For example, watersheds that demonstrate more hydrologic control (e.g. groundwater inputs control the thermal regime), are likely to be less sensitive to changes in air temperature, and may be more resilient to disturbance and climate change. Long-term datasets that include temporal variation in climatic and hydrologic conditions across many years (e.g., 10+ years) could assess the comparative influence of climatic and hydrologic controls.

Watershed physiography is an important static factor that determines thermal regimes of streams and rivers due to the physical interaction with both climatic and hydrologic energy flux processes. Thermal regimes are a condition of the aggregate of spatial conditions at a monitoring point and upstream of a monitoring point (Webb et al. 2008). Watershed scale research comparing different thermal regimes has identified a variety of watershed characteristics that predict stream temperature, such as elevation, slope, forest cover (Isaak and Hubert 2001; Chang and Psaris 2013; Imholt et al. 2013; Steel et al. 2016; Johnson et al. 2017). Across many studies, watershed elevation is described as having a strong relationship with stream temperature wherein as elevation decreases, stream temperature increases. For example, Isaak and Hubert (2001) examined a number of spatial variables and identified a negative relationship with mean watershed elevation as the strongest effect, while relationships with tree abundance (riparian shading), watershed slope, valley constraint and grass abundance were less statistically important. While elevational gradients may be an important predictor of thermal regimes across basin scale studies, identifying physiographic conditions that predict thermal regimes across watersheds with similar elevations (e.g. terrain complexity, channel density) could provide insight into other physiographic features that predict stream temperatures.

While both climatic and hydrologic controls can regulate stream temperatures, the comparative influence of these factors is not well understood in the Canadian Rocky Mountains. This thesis includes two studies (Chapter 2 and Chapter 3) that look at temporal and spatial patterns of stream temperature, including the comparative influence of climatic and hydrologic controls on stream temperatures, in the Canadian Rocky Mountains. These works put an emphasis on clarifying the role of groundwater inputs (a hydrologic control) as a regulator of stream temperatures in this region.

The first study (Chapter 2) focuses on examining the influence of climatic and hydrologic controls on stream thermal regimes in the headwaters of two Rocky Mountain catchments near Coleman, Alberta Canada (2005-2018). This study addresses three questions; 1) What are the relationships between stream temperatures and climatic/hydrologic controls? 2)What are the comparative influences of climatic versus hydrologic controls on stream temperatures? 3) Can common watershed physiographic variables be used to predict stream temperature or important climatic/hydrologic predictor variables of stream temperature?

The second study (Chapter 3) looks at spatiotemporal patterns of stream temperature across the Rocky Mountains and foothills of Alberta, Canada (2019-2021). This study addresses three questions; 1) What are the generalized temporal patterns of stream temperature within the Rocky Mountains and foothills of Alberta, in relation to climatic and hydrologic controls? 2) What is the influence of watershed physiology (spatial effect) on stream temperatures? 3) Can common watershed variables be used to predict which watersheds may have relatively cooler/warmer stream temperatures?

Chapter 2. A long-term examination of climatic and hydrologic controls over stream thermal regimes in front-range Rocky Mountain watersheds

2.1. Introduction

Water temperature in streams and rivers is a critical water quality parameter that impacts aquatic ecosystems by influencing the abundance and distribution of aquatic species. Fluxes of heat energy interacting with streams and rivers control water temperatures (stream temperatures) where these energy fluxes are regulated by climate (e.g., short and longwave radiation, air temperatures, precipitation) and hydrologic factors (e.g., streamflow, groundwater upwelling, hyporheic flow). Predictive modelling and past research have often focused on the relationship between stream temperatures and air temperatures (Caissie et al. 2007; Mohsenie et al. 1998; Langan et al. 2001), as they are highly correlated, but many studies have not investigated the contributing controls over stream temperature by hydrologic variables, particularly groundwater inputs. Quantifying and understanding the relative effects of climatic versus hydrometric controls at the watershed scale is important in defining fundamental controls of stream temperatures and informing ecosystem management. This research explores the comparative regulation of stream temperatures by climatic and hydrologic factors using 15 years of continuous stream temperature, air temperature and streamflow data from 7 adjacent sub-catchments in headwaters catchments in Southwest Alberta, Canada.

Energy fluxes originating from atmospheric variables (climatic controls) exert a strong influence on stream temperatures. Climatic control energy sources include; shortwave solar radiation, longwave radiation emitted from surrounding environment, sensible and latent heat turbulent exchange from air temperatures, and channel interception of precipitation (Moore et al. 2005; Leach et al. 2023). Because air temperature is broadly correlated with all of these energy fluxes, it is often used as a proxy for characterizing climatic influences on stream temperature. In some ecosystems, shortwave solar radiation and longwave radiation have been shown to exert the strongest non-advective control over stream thermal regimes (Webb and Zhang 1997; Webb and Zhang 1999), while other climatic controls have less of an effect. Often, research has focused on air temperatures to explain variation in stream temperature, in part due to the simplicity of air temperature data collection as well as broader data availability.

The effects of hydrologic variables (hydrologic controls) on stream temperatures can generally be described as advective energy fluxes wherein variation in streamflow, via inputs/outputs to groundwater, runoff, tributaries, hyporheic flows, can add or remove heat energy to streams (Moore et al. 2005; Story et al. 2003; Leach et al. 2022; Webb et al. 2003). The effect of these advective energy fluxes depend on the relative difference in quality (temperature) and quantity of water mixing with streamflow (Kobayashi et al. 1999; Leach et al. 2022). The temperature of groundwater is strongly buffered against seasonal fluctuation of air temperatures where the temperature of deeper groundwater (e.g., > 6-8 m depth) is often stable over annual seasonal cycles and often approximates the mean annual air temperature of the region (Taniguchi 1993). Thus, groundwater from deeper sources discharging to the surface is typically warm in the winter and cold in the summer compared to air temperatures (Constantz 1998; Kobayashi et al. 1999). Groundwater inputs are particularly important in many lotic systems in their role of regulating effects of seasonal weather fluctuations on thermal regimes of surface waters. Methods for quantifying continuous groundwater contribution to streamflow can be difficult and costly, thus the relative effect of groundwater contributions to streamflow at catchment scales has been understudied. However, application of hydrograph separation analyses offers researchers a continuous approximation of groundwater contribution that can be used to examine relationships with stream temperatures.

In the Canadian Rocky Mountains, atmospheric and streamflow conditions that influence stream temperatures exhibit strong temporal variability. Streamflow shows strong climate driven seasonal trends, characterized by a large seasonal snowmelt peak during the freshet in spring and low flows in winter, late summer and fall. Despite this general annual trend, variation in the magnitude and timing of peak flows and low flows depend on variable snowpack accumulation and melt (Dixon et al. 2014), early spring weather conditions, and interactions with local site conditions (e.g., subsurface storage capacities) (Spencer et al. 2019). Furthermore, anomalous weather events (Jentsch et al. 2007) and large weather patterns like the El Niño/Southern Oscillation (Wang et al. 2021) can introduce significant departures from typical seasonal patterns in stream temperature. In conjunction with streamflow, the amount of groundwater contributing to streamflow is also seasonally and annually variable depending on subsurface flow dynamics (Somers and Mckenzie 2020; Spencer et al. 2021) and temporal variation in groundwater sources (Leach et al. 2023). Varying atmospheric and hydrometric conditions through time create a dynamic of energy flux and stream temperatures. Multi-year, continuous records containing variation in stream temperature, atmospheric conditions and hydrometric conditions are thus key to characterize these fundamental controls on stream temperatures at the catchment/watershed scale.

In the Rocky Mountains in southwest Alberta, Canada, resource managers are challenged with conserving two Species at Risk Act (SARA) listed cold-water fish species; west slope cutthroat trout (*Onchorhynchus clarkia lewisii*) and bull trout (*Salvelinus confluentus*). In this region, these species face threats to their habitat related to changing stream temperatures. With increased summer stream temperatures, these species can be susceptible to limited growth/productivity, lower survival rates (Bear et al. 2007), increased inter-specific competition (Warnock and Rasmussen 2013; Isaak et al. 2010) and increased threat of whirling disease (James et al. 2021). Thus, characterizing the factors regulating stream temperature is likely increasing in importance for conservation of threatened cold-water fish species. Stream thermal regimes under relatively stronger hydrologic control, specifically high inputs of groundwater to regulate radiative and air temperature effects, provide more stable thermal habitats and may be key to future populations of cold-water fish species.

The objective of this study was to characterize the influence of both climate and hydrology in longer-term regulation of stream thermal regimes in seven headwaters sub-catchments located in the headwaters of the Oldman River Watershed, Alberta. Specific objectives were to assess; (1) the relationship between stream temperatures and fundamental hydrologic and climatic controls within each sub-catchment, (2) the relative influence of hydrometric and climatic controls on stream temperatures within each sub-catchment and (3) how stream temperatures and hydrologic/climatic controls vary spatially among the 7 sub-catchments based on differing watershed physiography.

2.2. Materials & Methods

2.2.1. Study area

This study was based on a post-hoc assessment of data collected from 2005-2018 as part of the Southern Rockies Watershed Project (SRWP; Silins et al. 2016). This work focused on a subset of two SRWP catchments (Star Creek and North York Creek) wherein forest harvest and wildfire had not occurred in recent decades and typical forest age was <70 years old. Stream thermal regimes were compared across 7 nested sub-catchments in Star Creek and North York Creek watersheds. Five of the sub-catchments are located within the Star Creek catchment and two of the sub-catchments are located within the North York Creek catchment (Figure 2-1). Star Creek catchment is immediately north of North York Creek catchment and flows into the Crowsnest River approximately 7 km upstream of where North York Creek enters Crowsnest River.

Both Star Creek and North York Creek catchments are typified by similar climatic, ecological, and geological conditions. Mean monthly temperatures range from -7.4 °C (December) to 14.3 °C (July and August) and mean daily annual temperature is 3.6 °C. Annual precipitation (800-1360 mm) is highly variable across elevation gradients and typically falls as snow from October to May and rain from June to September (Silins et al., 2016). The catchments overlap alpine, subalpine and montane natural subregions of the Rocky Mountains (Downing and Pettapiece 2006) ranging from 1487 meters above sea level (m.a.s.l.) to 2643 m.a.s.l. Within the Alpine (>1900 m), the land cover is characterized by steeply inclined to vertical bedrock, talus slopes and alpine meadows. Subalpine and Montane areas are dominated by mixed conifer forests containing subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmanii*) and lodgepole pine (*Pinus contorta*) transitioning into mixed forests containing Douglas fir (*Pseudotsuga menziesii*), trembling aspen (*Populus tremuloides*) and lodgepole pine at lower elevations. Typical forest soils are poorly developed, well to imperfectly drained, Eutric Brunisols. Geologic formations are highly fractured due to folding and faulting (Waterline Resources Inc., 2013) and include sedimentary layers from the Upper Paleozoic, Belly River-St. Mary Succession and the Alberta group (AGS 2004).

Star Creek and North York creek are nival, freestone systems that originate near the Great Continental Divide. Runoff generation in the region is strongly influenced by snowmelt and ground water contributions. Annual hydrographs for both streams are characterized by a large seasonal snowmelt peak during the freshet in spring (April -June). Groundwater contribution to streamflow is variable across time of year and types of subsurface pathways (Spencer et al. 2021).

No provincial records of fish species occurrence exist for North York Creek, however, Cutthroat trout and rainbow trout (*Oncorhynchus mykiss*) have been observed downstream of North York Creek in York Creek. Similarly, no records of fish species occurrence exist in Star Creek within the study area, however, Cutthroat trout have been observed approximately 2 km downstream of the study area (Alberta Environment and Parks 2022). The Westslope Cutthroat Trout Recovery Plan (Alberta Westslope Cutthroat Trout Recovery Team 2013) has identified a stretch of Star Creek, located downstream of the study area between Star Creek Falls and the confluence with Crowsnest River, with a conservation designation of “critical habitat”.

2.2.2. Data Collection

2.2.2.1. Stream Temperature

Stream temperature data were collected for each sub-catchment using instream data loggers located at hydrometric monitoring sites (Figure 2-1). Mean weekly stream temperature (T_s; °C) data were determined from hourly measurements collected with either: (1) HOBO Temperature Data Loggers (Bourne, MA, USA), (2) HOBO Temperature and Water Level Logger (Bourne, MA, USA), or (3) CS547A Water Conductivity and Temperature Probe recorded with a Campbell Scientific CR1000 Data Logger (Logan, UT, USA).

Stream temperature data availability for each sub-catchment were constrained temporally by: (1) varied initiation (2005-2009) of hydrometric monitoring stations, (2) the implementation of forest harvest experimental compartments in 2015 within Star Creek catchment, and (3) completion of data collection in 2018 for North York Creek sub-catchments (Table 2-1). Data were inspected for erroneous stream temperature records by plotting stream temperature and air temperature values and evaluating: (1) rapid increases/decreases in stream temperature values, (2) stream temperature values that coalesce with air temperature values (indicating loggers were no longer submerged in streams), and (3) stream temperature values of -1 °C or lower. Irregular, intermittent data gaps occurred across monitoring sites due to data logger failure, encasement in ice during winter months, or data loggers not being fully submerged during periods of extremely low flows. Gaps in the data record were not filled to avoid unintentional misrepresentation of stream temperatures.

2.2.2.2. Hydrologic Controls

Hydrologic controls represent a class of independent variables, derived from stream discharge data, that focus on sub-catchment streamflow conditions. Stream discharge values were used to create seven independent variables describing instantaneous stream discharge (m^3/s), area weighted stream discharge (mm), the baseflow and quickflow derivatives of instantaneous and area weighted discharges and an index of baseflow relative to total flow. Table 2-2 outlines and defines hydrologic independent variables considered in analyses.

Stream discharge was calculated via standard area-velocity techniques using a current meter (Swoffer Model 2100; Sumner, WA, United States or Sontek Flow Tracker ADV, San Diego, CA, USA). Stage-discharge relationships were developed annually for each sub-catchment to account for potential yearly changes in channel cross sections. Annual hydrographs were created using stage-discharge relationships applied to continuous stage measurements obtained from gas bubblers (Waterlog model H-350; Yellow Spring, OH, USA) or pressure transducers (HOBO Temperature Water Level Logger; Bourne, MA, USA). Continuous streamflow data were available for the entire duration of the stream temperature record, which varied for each sub-catchment. Stream discharge data were summarized into mean weekly instantaneous discharge (Table 2- 2 – "Stream Discharge1", m^3/s). A watershed area weighted mean weekly discharge (Table 2-2 – "Stream Discharge2", mm/week) was calculated from mean weekly instantaneous discharge to allow for standardized comparison of streamflows between sub-catchments.

Additionally, stream discharge data were partitioned into two constituent components, quickflow and baseflow, using a digital recursive filter (baseflow separation technique). Quickflow is considered a proxy measure for the portion of streamflow that is generated by quick runoff (surface runoff dominated) processes while baseflow is considered a proxy for the portion of streamflow that is generated by groundwater entering a stream (slower flow pathways). The baseflow separation technique applies a digital filter to differentiate between low-frequency (baseflow) and high-frequency (quickflow) stream discharge (Nathan and McMahon, 1990). A two-pass filter was applied based on the assumption that the fraction of water yield contributed by baseflow falls between the first and second pass of the digital filter (Arnold and Allen 1999; Arnold et al. 1995). Baseflow separation was completed using the stream discharge record of each stream (hourly time-step data resolution) using the software R (R Core Team, 2019) and packages EcoHydrology (Fuka et al. 2018) and waterData (Ryberg and Vecchia 2017). Streamflow, baseflow and quickflow data outputs from baseflow separations were used to create hydrometric control independent variables such as "Quickflow", "Quickflow2", "Baseflow", "Baseflow2" and "Baseflow Index" that are defined in Table 2.

2.2.2.3. Climatic Controls

Climatic controls represent a class of independent variables, based on air temperature data, that approximate the non-advective energy flux between streams and; (1) shortwave solar radiation, (2) longwave radiation emitted from surrounding environment, (3) sensible and latent heat turbulent exchange from with the air mass. Air temperature data were used to create 4 independent variables including weekly air temperature means, minima, maxima, and ranges.

Air temperature data were collected from data loggers at each meteorological monitoring site in Star Creek and North York Creek watersheds (Figure 2-1, Table 2-3). Air temperature was measured with a Vaisala relative humidity and temperature probe (Vaisala HMP50 or HMP35C or HMP45C model; Vaisala Oyj, Helsinki, Finland) and recorded with a Campbell Scientific data logger (CR10X or CR1000; Logan, UT, USA) every 10 minutes. In some cases, mean values between multiple meteorological stations were calculated to estimate air temperatures representative of a sub-catchment (Table 3). Continuous air temperature data were available for the entire duration of the stream temperature record (See Stream Temperature Data [Section 2.2.2.1]). Air temperature data were used to create the four climatic control independent variables outlined in Table 2-2.

2.2.2.4. Sub-Catchment Physical Characteristics

Six sub-catchment characteristics were identified to examine simple linear regression relationships with stream temperature parameters: Mean elevation, topographic variation relief ratio, terrain ruggedness index (TRI), vector ruggedness measure (VRM), total sub-catchment solar radiation and mean buffered stream solar radiation were calculated using GIS software (ESRI ArcPro 2021, Version 2.92). The sub-catchment physical characteristics were selected based on inferred relation to hydrometric and climatic controls of stream temperature, particularly those that influence groundwater production or air temperatures. Physical characteristics for each study sub-catchment were calculated using a digital elevation model (DEM) with a spatial resolution of 25 m x 25 m (Alberta Environment and Parks 2017). Details on each of the six sub-catchment physical characteristics are outlined in sub-headings below.

2.2.2.4.1. Mean Elevation

Mean sub-catchment elevation was calculated as the average elevation across the entire sub-catchment (m.a.s.l.). Elevation is positively related to precipitation and negatively related to air temperature. Increased snowpack accumulation at higher elevations may influence recharge of shallow subsurface groundwater pathways.

2.2.2.4.2. Topographic Variation Relief Ratio (TVR)

TVR is the sub-catchment elevation variance divided by sub-catchment mean elevation (Wagner 2010). TVR is one of three sub-catchment characteristics used in this study to assess the relationship between topographic variability and stream temperature metrics (the others are TRI and VRM). Higher TVR values are related to relatively steeper slopes within sub-catchments. Sub-catchments with steeper slopes (greater valley entrenchment) are expected to be positively related to steeper subsurface hydraulic gradients driving greater groundwater inputs (upwelling) into streams (Wagner 2010).

2.2.2.4.3. Terrain Ruggedness Index (TRI)

TRI is calculated as the sum of elevation changes from adjacent cells in a DEM, expressed as an index (Riley et al. 1999). Low TRI values reflect flatter areas, while higher TRI values can occur in steep areas or steep and rugged (complex) areas. TRI values were calculated for each raster cell of a DEM in the sub-catchments, and then a mean TRI value was calculated to characterize the entire sub-catchment. Higher values in TRI reflect a greater mean terrain complexity across a sub-catchment. As with TVR, greater terrain complexity may be related to stronger hydraulic gradients driving groundwater movement and increasing the likelihood of groundwater pathways coming to the surface.

2.2.2.4.4. Vector Ruggedness Measure (VRM)

VRM is another allied quantification of terrain complexity measuring variation in three-dimensional orientations of adjacent cells of a DEM (Sappington et al. 2005). In contrast to TRI, VRM values are low in flat and steep areas with minimal complexity, and highest in areas that are both steep and rugged. VRM values were calculated for each raster cell of a DEM in the sub-catchments and expressed as a dimensionless ruggedness value between 0 (flat) and 1(most rugged). Mean VRM values were summarized for each sub-catchment. Sub-catchments with relatively higher mean VRM values will have greater terrain complexity, and similar to TRI, are expected to have greater amounts of groundwater contribution.

2.2.2.4.5. Total Sub-Catchment Solar Radiation

Sub-catchment radiation is an estimation of the annual solar radiation accumulated across each sub-catchment in watt hours per meter squared (WH/m^2). The ArcPro Solar Radiation Tool (ESRI ArcPro 2021, Version 2.9.2) was used to calculate solar radiation for each DEM cell within the sub-catchments, then sub-catchment stream solar radiation was calculated as the sum of solar radiation in all cells within each sub-catchment. Higher values of sub-catchment solar radiation are expected to be related to increased ground or water surface warming which, in turn, can increase and temperatures of shallow subsurface groundwater and surface water (streams).

2.2.2.4.6. Mean Buffered Stream Solar Radiation

Mean buffered stream solar radiation is an estimation of the annual solar radiation accumulated within a 25 m buffer of the stream networks within each sub-catchment (WH/m^2). The ArcPro Solar Radiation Tool (ESRI ArcPro 2021, Version 2.9.2) was used to calculate solar radiation for each DEM cell within a 25 m buffer of the stream networks, then mean buffered stream solar radiation was calculated as the mean of solar radiation all cells within the 25 m buffer for each sub-catchment. Buffered stream solar radiation approximates solar radiant energy directed at stream channels and riparian areas immediately adjacent to stream channels. Spatial conditions that have higher values of buffered stream solar radiation are expected to be related to warmer stream temperatures as greater direct shortwave radiation on and around streambeds should increase stream temperatures.

2.2.3. Statistical Analyses

2.2.3.1. Sub-Catchment Models

To examine the relative effect of differing mechanisms that control stream temperatures, mean weekly stream temperatures were assessed as a function of hydrologic controls (variables derived from streamflow) and climatic controls (variables derived from air temperature data) (Table 2-3). Data analyses were conducted for each sub-catchment by season, which were defined by typical hydrograph fluctuations of study creeks as well as seasonal weather patterns. Winter was defined as January and February (characterized by low stream flows, relatively cold air temperatures), Spring as May and June (characterized by increasing stream flows up to the spring freshet, warming air temperatures), Summer as July and August (characterized by decreasing limb of hydrograph, typically hottest air temperatures of the year) and Autumn as September and October (characterized by a return to low flow conditions, air temperatures cooling into winter).

Multiple linear regression analyses were used to examine mean weekly stream temperature by season for each sub-catchment. Preliminary exploration of stream temperature patterns was conducted across multiple time steps (e.g., hourly, daily, weekly, monthly) and the mean weekly timestep was selected for analyses as it was observed to balance capturing the majority of the temporal variation in stream thermal regimes while constraining excessive fine-scale temporal variability. Additionally, mean weekly stream temperatures are a more suitable metric when considering impacts to aquatic ecology. A multiple regression approach was selected as exploratory data analysis indicated that both climatic and hydrologic variables exerted considerable shared control over stream temperature and thus both groups of these controls needed to be evaluated simultaneously to meaningfully represent their partial and collective regulation of stream thermal regimes. A model was fit for each sub-catchment, for a total of seven models. The analyses generally follow:

$$T_{si} = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \varepsilon_i \quad (2\text{-}1)$$

Where T_{si} represents mean stream temperature of a given week ($_i$) of a sub-catchment, β_0 is the y-intercept, β_1 represents the coefficient for a hydrologic predictor variable (X_{1i}) and β_2 represents the coefficient for a climatic predictor variable (X_{2i}). Due to high collinearity (Pearson correlation coefficients >0.86) between many of the hydrologic control variables, only one hydrologic control variable was considered for each of the final sub-catchment models. In addition, high collinearity (Pearson correlation coefficients < 0.61) was present between many of the climatic control variables (principally mean air temperature and minimum air temperature and mean air temperature and maximum air temperature) across each of the different sub-catchments, and as such, model selection only considered one climatic control variability where high collinearity existed. Final stream temperature models for each sub-catchment were selected based on considering the different combinations of climatic and hydrologic controls and selecting final models based on Akaike's Information Criteria (AIC; Akaike 1973).

Results from the multiple linear regression models were used to: (1) explore how independent variables influence mean weekly stream temperature by examining direction (e.g., positive, negative) and slope of variable coefficients, and (2) examine the relative influence of climatic and hydrologic controls by comparing partial coefficients of determination belonging to variable classes (Table 2-3) in each model. Data analyses and visualization were completed using the software R (R Core Team 2019) and packages lmtest (Zeileis and Hothorn 2002), ggplot2 (Wickham 2016) and ggeffects (Ludecke 2018).

2.2.3.2. Spatial Patterns in Stream Temperature

Stream temperature metrics were explored in relation to spatial variables to understand physical sub-catchment conditions that contribute to relatively greater/lesser hydrometric or climatic controls. Simple least squares regression was used to examine the relationships between sub-catchment physical characteristics and stream temperature metrics: outputs from sub-catchment models (e.g., coefficients of independent variables common across each sub-catchment model), mean seasonal stream temperature and mean baseflow contributions. Data analyses and visualization were completed using ggplot2 package (Wickham 2016) in R Studio (R Core Team 2019).

2.3. Results

Mean seasonal patterns of T_s followed the same general trend across all 7 sub-catchments (Figure 2-2). Stream temperatures were relatively low in winter, increased during the spring, peaked in the summer, and then decreased in the fall (Figure 2-2). Although T_s followed a similar seasonal pattern across the 7 sub-catchments, each sub-catchment varied in overall thermal regime as demonstrated by the ranges of seasonal T_s (Figure 2-2 and Table 2-4). Generally, sub-catchments with T_s closer to 0 °C in the winter months (when air temperatures are relatively cooler) also had warmer stream temperatures in the summer months, suggesting a greater sensitivity to changes in air temperatures in these sub-catchments.

Annual mean weekly streamflows were most variable in spring (Figure 2-3) and typically peaked in late spring (May/early June) for all sub-catchments (Figures 2-3 and 2-4). Baseflow generally comprised a greater portion of total streamflow than quickflow, however, the ratio of baseflow:quickflow varied throughout the year, particularly during the peak flows in the spring and precipitation events in summer (Figure 2-4). As expected due to the immediate proximity of the sub-catchments to one another, maximum, mean and minimum weekly air temperatures were similar across all sub-catchments (Figure 2-5). Seasonal mean weekly air temperatures were coldest and most variable in winter and warmest and least variable in summer across all sub-catchments (Figure 2-5). The distributions of independent and dependent variables did not allow for development of multiple regression models for the annual time step, or for winter, spring and fall seasons. As such, the remainder of the results focus on the assessment and modelling of summer stream temperatures only.

The coldest summer T_s occurred in the headwaters of Star Creek at Star East Upper (3.53 °C) and Star West Upper (4.36 °C). These streams that also had the smallest standard deviation around T_s (0.39 and 0.36, respectively), the lowest mean weekly maximum stream temperatures, the lowest mean weekly minimum stream temperatures, and the lowest mean weekly range in stream temperatures (Table 2-4). The warmest T_s corresponded with the largest standard deviations around the means and occurred at Star Main (7.65 °C, sd = 1.07) and Star West (7.43 °C, sd = 0.98).

2.3.1. Sub-Catchment Models

All sub-catchment models estimated summer T_s as a function of mean weekly baseflow contribution (hydrologic control) and mean weekly air temperature (climatic control) (Table 2-5). Across all models, the addition of mean weekly baseflow contribution improved models more than any of the other hydrometric variables (e.g., total flow, baseflow to total flow ratio, quick flow). Only one hydrologic variable was included in each model, as there were high correlations (>80%) between all hydrologic independent variables. Similarly, only one air temperature metric (mean weekly air temperature) was included in each model to avoid including multiple highly correlated independent variables in the model. The model r^2 values varied across the different sub-catchment models from (0.63-0.82) when analyzing the relationship between stream temperatures and independent variables (Table 2-6). For the individual independent variables, the partitioned r^2 values varied across sub-catchment models for mean weekly baseflow (0.41-0.65) and mean weekly air temperature (0.09-0.36). Across all models, mean weekly baseflow explained 1.3-6.9 times the variability in T_s when compared to mean weekly air temperature (Table 2-6).

Plotted marginal effects were used to visualize relationship between stream temperature and the independent variables in each sub-catchment. Marginal effects are the partial effect of a dependent variable conditional on an independent variable after setting other covariates at their means. Across all sub-catchments, there were strong negative relationships between T_s and mean weekly baseflow contribution ($p<0.001$) (Figure 2-6) and a variable effect of relative magnitude (steepness of slope) of an incremental increase in mean weekly baseflow on T_s (Table 2-5 and Figure 2-6). Figure 2-6 also illustrates the summer thermal regime of each sub-catchment, as denoted by the range of stream temperature values on the y-axis that correspond with plotted marginal effect values. Star East Upper and Star West Upper had a relatively smaller range of mean weekly summer stream temperatures (~1.5 °C) in comparison to all other sub-catchments which showed at minimum a 4 °C range in mean weekly stream temperatures. Additionally, Figure 2-6 shows the variation in mean weekly baseflow (m^3/s) across the different sub-catchments. All sub-catchments included mean weekly baseflow contribution values very near 0 m^3/s, however, the maximum mean weekly baseflow contribution ranged widely from 0.085 to 0.6 m^3/s across sub-catchments.

Across the sub-catchment models, coefficients for mean weekly air temperature indicated a positive relationship with T_s ($p<0.001$; Table 2-5). In previous literature, the coefficient derived from the relationship between stream temperature and air temperature is referred to as the thermal sensitivity

(Kelleher et al. 2012). Plotted marginal effects show the positive relationship between mean weekly air temperature and T_s, as well as the relative variation in thermal sensitivities (steepness of slope) of T_s to increases in mean weekly air temperature among sub-catchments (Figure 2-7). Star East Upper, Star West Upper and North York Upper sub-catchments had the flattest slopes (lowest thermal sensitivity), indicating that T_s in these sub-catchments is less responsive to changes in mean weekly air temperatures. In contrast, North York Main, Star East, Star West, and Star Main sub-catchments exhibited relatively greater sensitivity of T_s to changes in mean weekly air temperatures. The range of mean weekly air temperatures were similar across all the sub-catchments (9 °C +/- 1 °C to 20 °C +/-1 °C), apart from Star East Upper and Star West Upper which had lower maximum mean weekly air temperatures of ~17 °C and ~18 °C, respectively.

2.3.2. Spatial Patterns in Stream Temperature

Four stream temperature metrics derived from the assembly of sub-catchment models were plotted against sub-catchment characteristics to assess spatial patterns of stream temperatures. The four stream temperature metrics include: (1) mean weekly air temperature coefficients (Thermal Sensitivity), (2) mean weekly baseflow contribution coefficients, (3) mean summer stream temperature, and (4) mean weekly baseflow contribution corrected for watershed area. Mean weekly baseflow contribution corrected for watershed area (mm/week) was used instead of mean weekly baseflow contribution (m^3/s), as was used in the sub-catchment models, to allow for a more meaningful comparison across sub-catchments varying in area. Values for stream temperature metrics and sub-catchment characteristics used to explore spatial patterns in stream temperature are summarized in Table 2-7.

In general, mean weekly baseflow contribution coefficients and mean weekly baseflow contribution did not show meaningful relationships with sub-catchment characteristics (Figures 2-8 to 2-10, B and D). Figures 2-8 to 2-10 (A) show negative relationships between air temperature coefficients and mean sub-catchment elevation (Figure 2-8) and terrain ruggedness index (Figure 2-9), and a positive relationship with buffered stream channel solar radiation (Figure 2-10). Similarly, Figures 2-8 to 2-10 (C) show negative relationships between mean summer stream temperature and mean sub-catchment elevation (Figure 2-8), and terrain ruggedness index (Figure 2-9), and a positive relationship with buffered stream channel solar radiation (Figure 2-10). It should be noted that there was a strong positive correlation (r^2=0.97) between the air temperature coefficients and mean summer stream temperatures, which can be observed based on the similar distribution of data points in the plots (e.g., Figure 2-8, A and C).

2.4. Discussion

Summer stream temperatures in seven sub-catchments within two adjacent watersheds in the headwaters of the Southern Rocky Mountains were strongly regulated by hydrologic controls, particularly groundwater contribution to streamflow, from 2005-2018. In contrast to air temperature and associated climatic controls, groundwater contribution to streamflow was the dominant control of summer stream temperatures (1.3-6.9 times greater than the influence of these climatic controls; Table 2-6). Although groundwater contribution was the most important variable predicting summer stream temperatures, we observed varying stream temperatures and responses (regression coefficients) in relation to groundwater contribution (Figure 2-6; Table 2-5), suggesting an important interplay between the quality (temperature) and quantity of groundwater entering streams in each sub-catchment. This is in contrast to the majority of previous studies that have largely focused on air temperature and radiation as dominant controls over stream temperature, or in efforts to model stream thermal regimes based on these climatic controls (e.g. Caissie et al. 2007; Mohsenie et al. 1998; Langan et al. 2001). This research emphasizes the importance of groundwater contribution to stream thermal regimes – groundwater contributions can vary depending on source and across spatial and temporal conditions (Kobayashi et al. 1999; Briggs et al. 2018) and understanding these patterns is critical for managing cold water aquatic ecosystems.

Previous research has identified the varying effect of groundwater contribution on regulating stream temperatures depending on groundwater sources (Kobayashi et al. 1999, Briggs et al. 2018). Shallow groundwater sources exhibit more variation in quantity and quality (temperature) than deep source groundwater, and the increased variation in shallow groundwater temperature is related to ground surface temperatures (Taniguchi 1993). Deep sources of groundwater are often cooler in summer than shallow source groundwater, and more consistent in quality and quantity through time (Kobayashi et al. 1999). Results of this study showed that across all sub-catchments increased groundwater contribution (m^3/s) to streamflow resulted in a decreased summer stream temperature, however, there was no trend across the sub-catchments between average groundwater inputs (mm/week) and summer stream temperatures. This is likely explained by differences in groundwater quality across sub-catchments, where some sub-catchments had greater deep source groundwater contributions, and others had variable temperatures of shallow groundwater inputs based on interactions with different ground surface conditions.

The variation in physiography across the sub-catchments (e.g., forest cover, terrain complexity, ground and shallow subsurface conditions) may be an important factor that explains differences in the temperature of shallow groundwater pathway inputs and thus variable stream thermal regimes. Groundwater inputs into streamflows change thermal conditions of streams through advective mixing and generally buffer stream thermal regimes against climatic energy fluxes. Groundwater inputs can create isolated patches of suitable habitat, as well as at a contiguous reach-scale (Isaak et al. 2015; Ebersole et al. 2003), catchment and watershed scale thermal conditions (this study). Isolated zones of climate refugia may be important for cold-water species to endure short periods of heat stress (Ebersole et al. 2003); however, they need to be accessible to aquatic species and movement of organisms can be constrained by linear networks that are easily fragmented by structural and thermal barriers (Fagan 2002). Thus, conservation efforts need to balance identifying both small-scale point sources of groundwater inputs and large-scale varying control of climatic/hydrometric controls on thermal regimes of watersheds. Managing populations of cold-water fish species would benefit from employing the knowledge from this study on the relative climatic vs hydrometric controls regulating stream thermal regimes at the watershed scale in order to prioritize actions aimed at conservation and restoration of thermally sensitive threatened fish species. These insights are also likely to be important for these same management priorities in the face of changing weather patterns.

Identifying catchments and watersheds with greater deep groundwater pathway contributions may be particularly important in preserving cold water aquatic habitats in the face of climate change. The influence of radiation and air temperature on shallow groundwater pathways is greater than that on deep groundwater pathways. Under changing climatic conditions, deep groundwater pathways will provide a more consistent moderating energy flux source through time. This study did not quantify deep and shallow source groundwater components of streamflow; however, study observations of Star East Upper and Star West Upper thermal regimes suggest greater deep groundwater inputs compared to other sub-catchments. Star East Upper and Star West Upper showed less variation within seasonal averages, less variation across seasonal averages (e.g., winter and summer), had the coolest average summer stream temperatures (3.53 and 4.36 °C, respectively), and the warmest average winter stream temperatures (0.58 and 1.45 °C, respectively; Table 4). Additionally, source water characterization research in the same study area (Spencer et al. 2021) identified deep bedrock groundwater source seep temperatures (2.2-3.5 °C), which are closer to the Star East Upper and Star West Upper mean summer stream temperatures measured in this study, than shallower till source temperatures (4.8-7.1 °C). The thermal regimes of these sub-catchments would likely be better suited to buffer the effects of anthropogenic (e.g., forest harvest) and natural disturbance (e.g., wildfire) as well as climate change. Further research and confirmation of the comparative influence of deep groundwater, shallow groundwater and climatic factors on stream thermal regimes could be useful in identifying and classifying resilience of stream thermal regimes across broader regions.

Examining differences in physiography may be useful in predicting the type and amount of groundwater contribution to stream thermal regimes; however, the close proximity and general physiographic similarity among watersheds in this study did not allow for a meaningful assessment of physical characteristics that could affect stream temperatures, groundwater contribution or air temperatures. A greater range of physiographic conditions and spatial diversity among study watersheds would be needed to explore such relationships. Research in other regions has identified watershed characteristics that predict groundwater inputs at the landscape scale. For example, near the Quebec/New Brunswick border, Dugdale et al. (2015) concluded that a greater density of groundwater thermal refuges at the landscape scale was associated with channel confinement (expressed via an entrenchment ratio). Dugdale et al. (2015) suggest that in semi-confined valley sections there are conditions that increase groundwater upwelling as a result of moderately extensive subsurface flow networks combined with relatively higher water table gradients. Future work should investigate watershed scale spatial patterns of groundwater upwelling and stream temperature controls across the Rocky Mountains of Alberta.

Stream temperature in this study area were shown to be more strongly regulated by in-stream upwelling of groundwater than by climatic energy fluxes. These findings provide valuable insights to help manage cold water species. In particular, information on the factors controlling watershed-scale stream thermal regimes is critical to identifying vulnerability of critical stream habitats to land disturbance and climate change. For example, land disturbances affecting stream shade/radiation inputs (riparian functions) would be expected to have much greater influence in watersheds with comparatively greater regulation of stream thermal regimes by climatic controls than those more strongly regulated by groundwater inputs. Similarly, identifying streams with stronger groundwater controlled thermal regimes will likely be important in identifying potential cold-water refugia for threatened cold water fisheries with climate change. In both cases, additional research on spatial features that predict thermal regimes at the watershed scale would be a valuable tool for understanding habitat suitability resilience of watersheds across the Rocky Mountains of Alberta.

2.5. Conclusions

Across the headwater catchments of this study, groundwater inputs play a greater role in determining thermal regimes than climatic controls, and other hydrologic controls. This result demonstrates the importance of groundwater inputs in defining stream thermal regimes which in turn is important for understanding the resilience of cold-water habitats given pressures from climate change and watershed disturbances. Although groundwater inputs are not the principal control of stream temperatures in all watersheds, demonstrating that it can act in this fashion is important for understanding the dynamic nature of thermal regimes. Continued research in the relative role of groundwater control on stream thermal regimes should investigate how the relative controls change through space and their response to climate change and other watershed perturbations. Detailed understanding of when and where groundwater inputs control stream thermal regimes would an important tool for managing cold-water fish species in the future.

Table 2-1 Summary of stream temperature data recodes by catchment and sub-catchment.

Catchment	Sub-catchment	Year Range	Years	Sample size (number of weeks)
Star Creek	Star Main	2005-2014	10	374
	Star East Upper	2009-2014	6	281
	Star West Upper	2009-2014	6	282
	Star East	2006-2014	9	396
	Star West	2006-2014	9	316
North York Creek	North York Upper	2009-2018	10	424
	North York Main	2005-2018	14	496

Table 2-2: Independent variables considered in estimating mean weekly summer stream temperature for 7 sub-catchments in the headwaters of the Oldman River watershed, AB. Independent variables are categorized into two general classes: hydrologic controls and climatic controls.

Variable Class	**Variable Name**	**Definition**
Hydrologic controls	Stream Discharge1	Mean weekly instantaneous discharge (m^3/s)
	Stream Discharge2	Weekly discharge (mm/week) corrected for watershed area
	Quickflow	Mean weekly instantaneous quickflow (m^3/s) derived from hydrograph separation that partitions stream discharge into quickflow and baseflow components
	Quickflow2	Weekly quickflow (mm/week) corrected for watershed area.
	Baseflow	Mean weekly instantaneous baseflow (m^3/s) derived from hydrograph separation that partitions stream discharge into quickflow and baseflow components
	Baseflow2	Weekly baseflow (mm/week) corrected for watershed area.
	Baseflow Index	Index of baseflow (mm/week) to total flow. Calculated as proportion of Baseflow2: Stream Discharge2.
Climatic controls	Mean air temperature	Mean weekly air temperature (°C)
	Max air temperature	Maximum weekly air temperature (°C)
	Min air temperature	Minimum weekly air temperature (°C)
	Air temperature range	Change in air temperature over a week (°C). Derived from difference between Max air temperature and Min air temperature variables.

Table 2-3: Summary of meteorological stations used to derive sub-catchment air temperature values. For sub-catchments with more than one meteorological station listed, air temperature values were estimated by calculating the mean of the two stations at each timestep.

Catchment	**Sub-Catchment**	**Meteorological Station(s)**
Star Creek	Star Main	Star Main Met station
	Star East Upper	Star East Fork Met station
	Star West Upper	Star West High Met station
	Star West	Star Main Met station Star West High Met station
	Star East	Star Main Met station Star East Fork Met station
North York Creek	North York Upper	North York High Met station North York Main Met station
	North York Main	North York Main Met station

Table 2-4: Summary of weekly mean stream temperatures across different seasons for seven sub-catchments within the headwaters of the Oldman River Watershed, Alberta (2005-2018). Mean minimum and maximum weekly stream temperature values are provided in parentheses.

Sub-Catchment	**Winter Mean Temperature (°C)**	**Spring Mean Temperature (°C)**	**Summer Mean Temperature (°C)**	**Fall Stream Temperature (°C)**
Star East Upper	0.58(0.20,0.95)	2.08(1.66,2.69)	3.53(2.99,4.72)	2.91(2.20,3.70)
Star West Upper	1.45(0.73,1.95)	2.57(1.87,6.07)	4.36(3.38,6.07)	3.20(2.42,4.15)
North York Upper	0.50(-0.13,1.07)	2.75(2.01,4.06)	5.05(3.66,6.98)	3.15(1.89,4.48)
North York Main	0.12(-0.26,0.58)	3.06(1.93,5.15)	6.13(4.20,8.80)	3.65(1.99,5.63)
Star East	0.26(-0.03,0.71)	2.93(1.99,4.70)	6.26(4.69,8.81)	4.22(2.64,6.09)
Star West	0.04(-0.86,1.28)	3.57(2.05,6.03)	7.44(5.32,10.17)	4.49(2.58,6.55)
Star Main	-0.07(-0.41,0.42)	3.64(2.03,6.51)	7.65(5.26,11.17)	4.44(2.32,7.01)

Table 2-5: Model estimates and summary statistics for each sub-catchment stream temperature model

Sub-Catchment	Parameter	Coefficient	Std. error	t value	Pr(>|t|)
Star Main	intercept	5.4598	0.49506	11.029	< 0.001
	Mean weekly baseflow	-11.42847	1.0104	-11.311	< 0.001
	Mean weekly air temperature	0.26385	0.03328	7.927	< 0.001
Star East Upper	intercept	2.90879	0.21341	13.63	< 0.001
	Mean weekly baseflow	-17.74891	2.16239	-8.208	< 0.001
	Mean weekly air temperature	0.08914	0.01731	5.148	0.015
Star West Upper	intercept	3.78229	0.20558	18.398	< 0.001
	Mean weekly baseflow	-7.97436	1.09922	-7.255	< 0.001
	Mean weekly air temperature	0.07252	0.0135	5.373	0.007
Star East	intercept	4.83985	0.39275	12.323	< 0.001
	Mean weekly air temperature	0.18842	0.02792	6.748	< 0.001
	Mean weekly baseflow	-29.28336	2.38574	-12.274	< 0.001
Star West	intercept	5.01562	0.33219	15.1	< 0.001
	Mean weekly air temperature	0.25727	0.02211	11.64	< 0.001
	Mean weekly baseflow	-21.62952	1.47799	-14.63	< 0.001
North York Upper	intercept	4.88113	0.22469	21.72	< 0.001
	Mean weekly air temperature	0.10986	0.01597	6.88	< 0.001
	Mean weekly baseflow	-6.6062	0.52673	-12.54	< 0.001
North York	intercept	4.75934	0.22945	20.74	< 0.001
	Mean weekly air temperature	0.17753	0.01646	10.79	< 0.001
	Mean weekly baseflow	-6.69503	0.38346	-17.46	< 0.001

Table 2-6: Summary of r^2 values for each sub-catchment model output including r^2 values quantifying the amount of variation explained by each independent variable and a ratio showing proportion of independent variable r^2 values relative to one another.

Sub-catchment	**r^2 values for models and model components**			**Ratio of Mean Weekly Baseflow r^2 value: Mean Weekly Air Temperature r^2 value**
	Model r^2 value	**Mean Weekly Baseflow r^2 value**	**Mean Weekly Air Temperature r^2 value**	
Star Main	0.723	0.460	0.264	1.7
Star East Upper	0.634	0.408	0.226	1.8
Star West Upper	0.638	0.443	0.194	2.3
Star East	0.723	0.632	0.091	6.9
Star West	0.824	0.462	0.362	1.3
North York Upper	0.711	0.614	0.098	6.3
North York Main	0.790	0.653	0.137	4.8

Table 2-7: Model coefficients and summer stream temperature metrics and sub-catchment characteristics used to examine spatial patterns of stream temperature across 7 sub-catchments.

	Stream Temperature Metrics				**Sub-Catchment Characteristics**					
Sub-Catchment	**Model Air Temperature Coefficient**	**Model Baseflow Coefficient**	**Mean Stream Temperature**	**Mean Weekly Summer Baseflow Contribution (mm)**	**Mean Elevation (MASL)**	**TVR**	**TRI**	**VRM**	**Total Sub-Catchment Solar Radiation (WH/m^2)**	**Mean Buffered Stream Solar Radiation (WH/m^2)**
Star Main	0.264	-11.428	7.647	8.407	1855	32.63	29.19	0.029	4838143955	309170
Star East Upper	0.089	-17.749	3.532	9.086	1987	13.79	39.13	0.047	839557211	288847
Star West Upper	0.073	-7.974	4.356	7.881	2101	22.02	45.24	0.034	1115488944	280420
Star East	0.188	-29.283	6.262	6.476	1869	21.07	30.47	0.036	1767923481	308737
Star West	0.257	-21.630	7.438	8.339	1933	37.27	34.38	0.029	2126535806	302939
North York Upper	0.110	-6.606	5.047	19.083	2004	25.34	34.59	0.029	2902356605	306379
North York Main	0.178	-6.695	6.127	11.375	1918	29.80	30.20	0.026	4228968053	316360

Figure 2-1: Site map of Star Creek sub-catchments, North York Creek sub-catchments, meteorological monitoring stations and hydrometric monitoring stations.

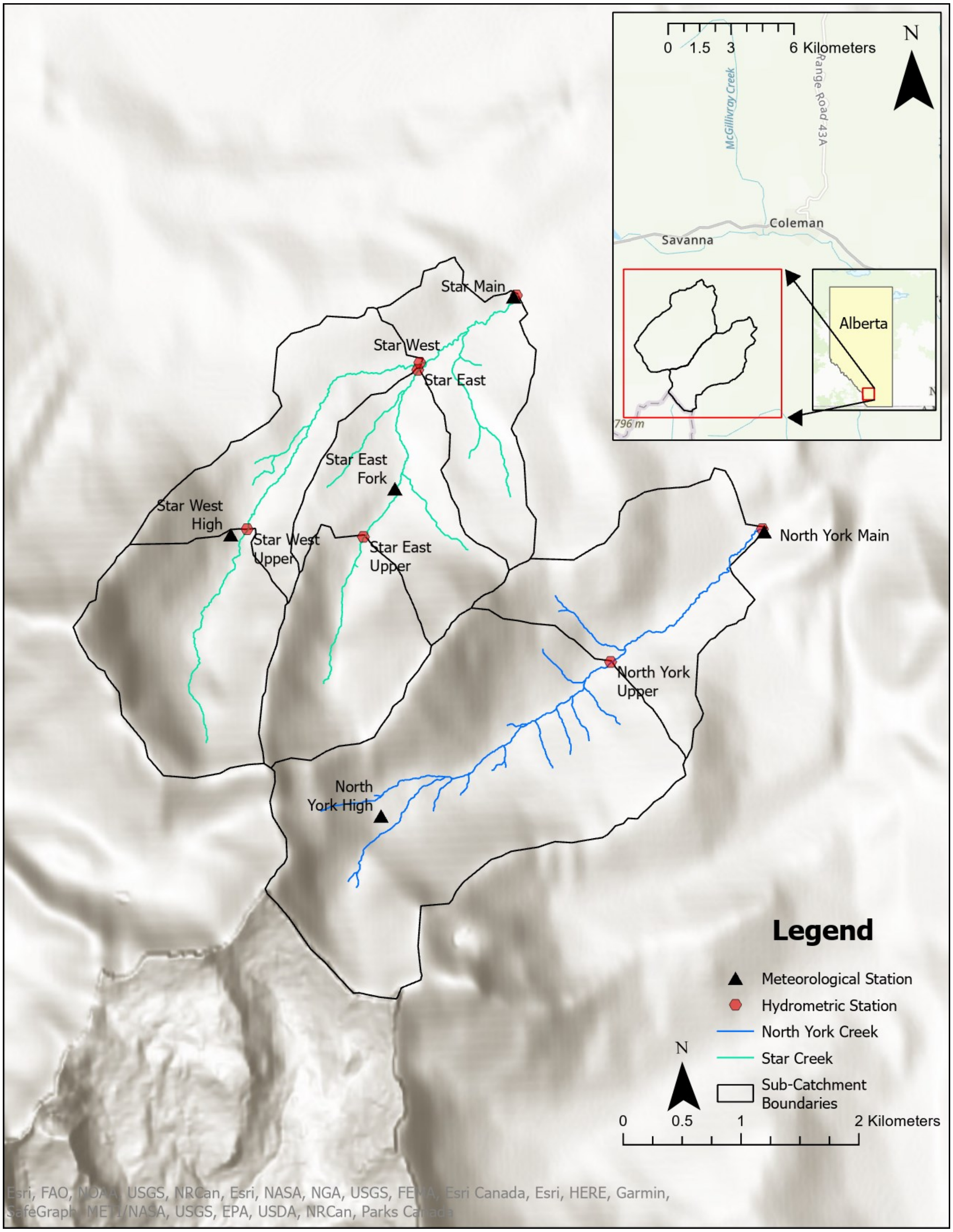


Figure 2-2: Average annual trace of mean weakly stream temperature across 7 sub-catchments within the headwaters of the Oldman River Watershed, Alberta (2005-2018).

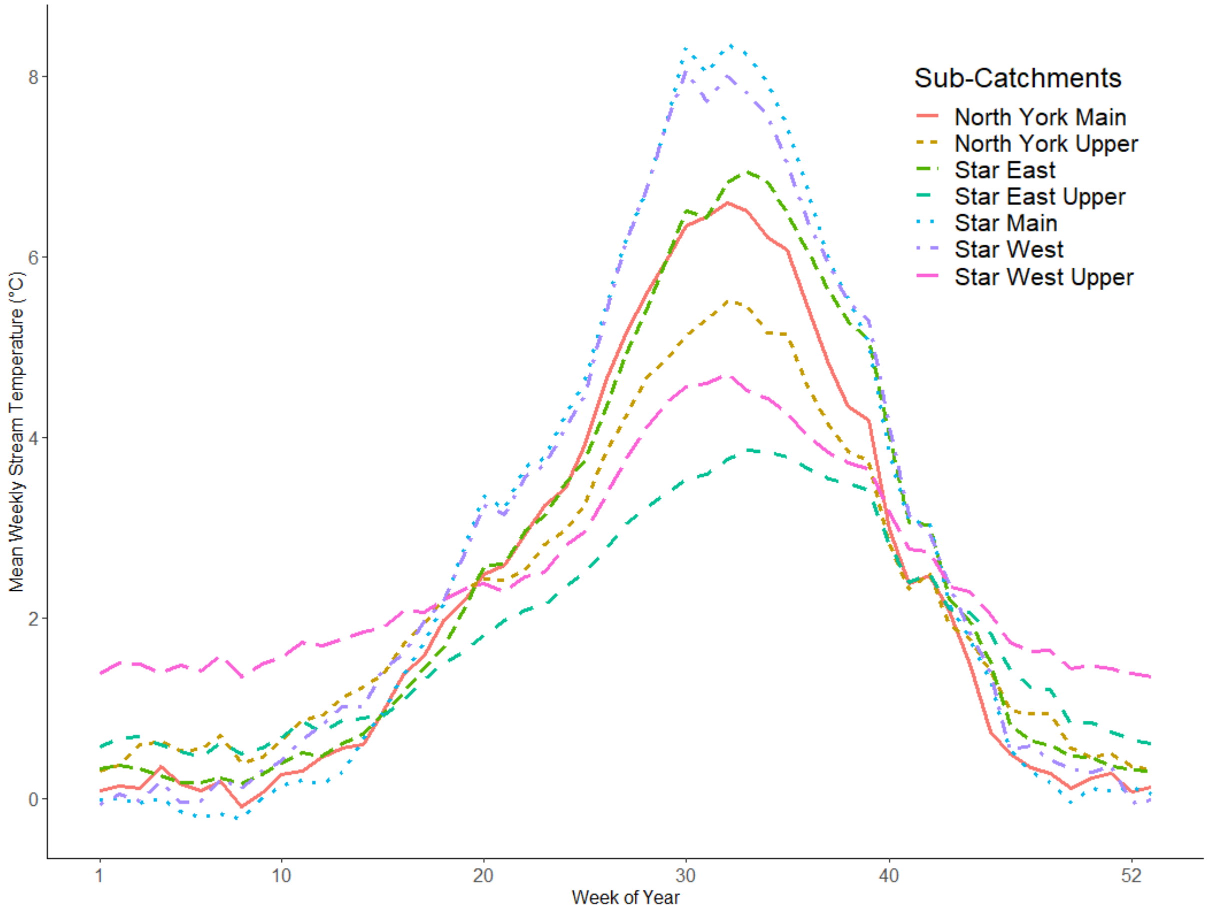


Figure 2-3: Variation in mean weekly streamflow by season for seven sub-catchments (2005-2018). Box indicates upper/lower quartiles, horizontal line=median, vertical lines=upper/lower+/-1.5*IQR (Inter Quartile Range) percentile, dots=outlying points.

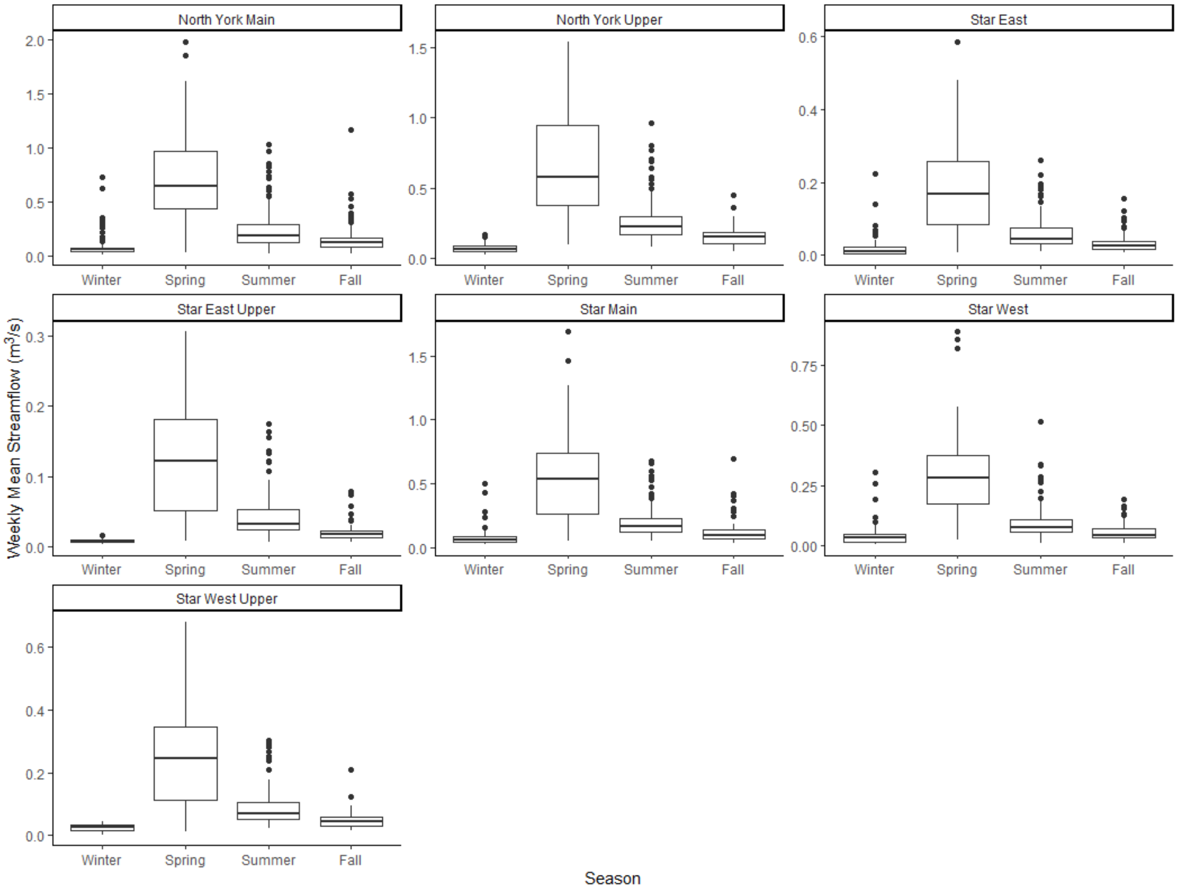


Figure 2-4: Average annual traces of mean weekly baseflow (m^3/s), quickflow (m^3/s) and total streamflow (m^3/s) averaged across study period for each sub-catchment (2005-2018).

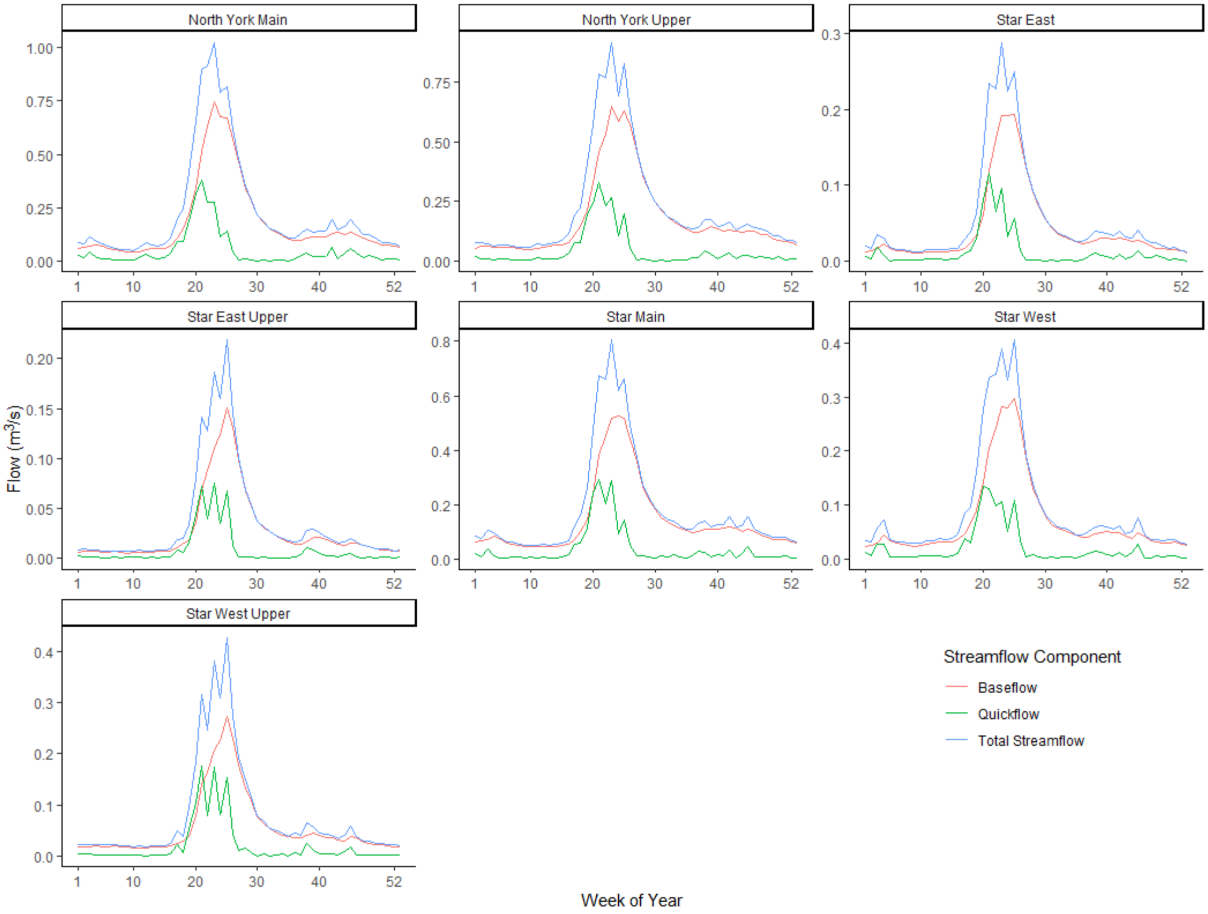


Figure 2-5: Maximum, mean, and minimum weekly air temperatures for each sub-catchment by season. Box indicates upper/lower quartiles, horizontal line=median, vertical line=upper/lower 1.5*IQR (Inter Quartile Range) percentile, dots=outlying points.

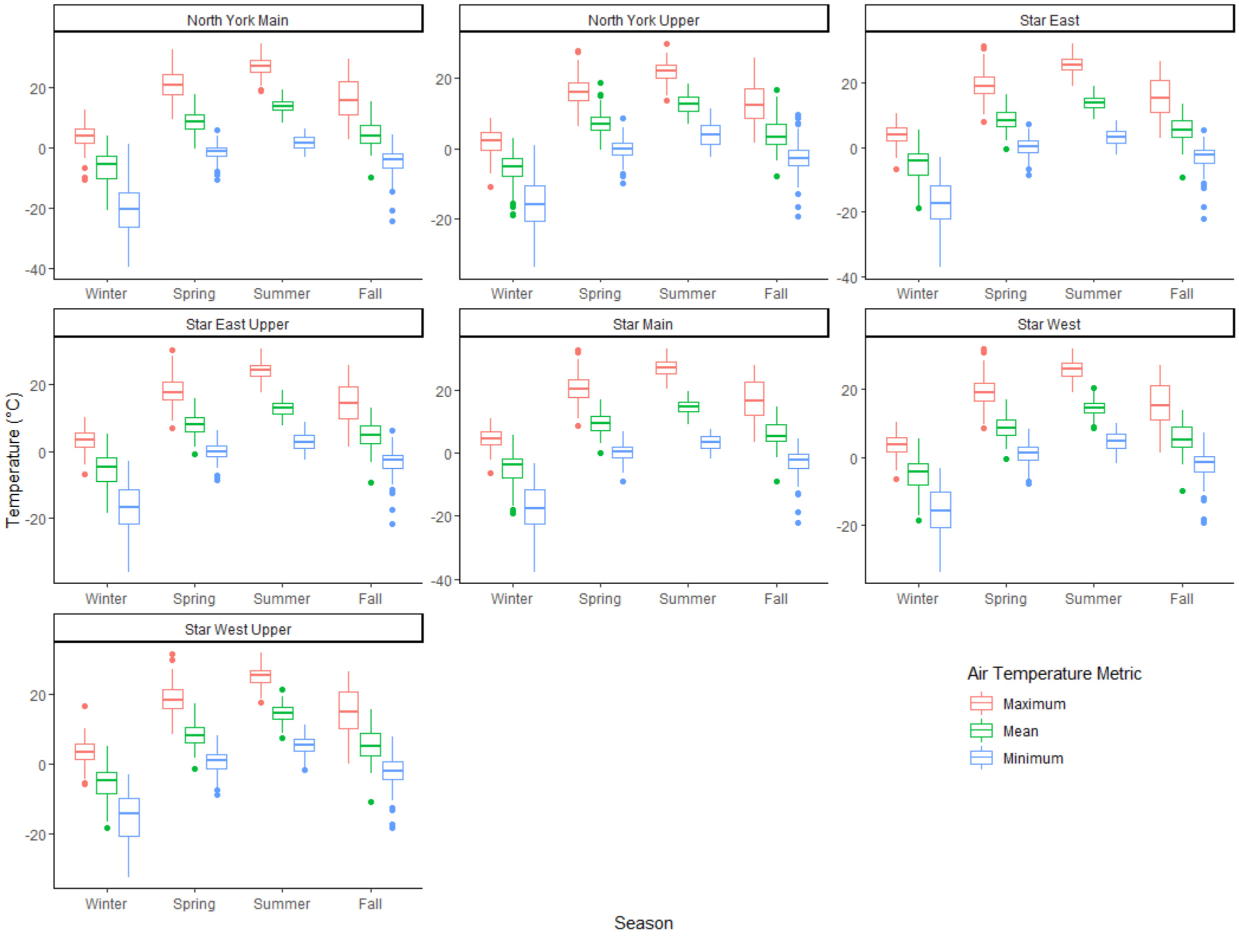


Figure 2-6: Mean marginal effect of mean weekly baseflow contribution (m^3/s) on mean weekly stream temperature (°C) from multiple linear regression models for each sub-catchment. Plotted lines show the predicted mean change in modelled stream temperature as a function of mean weekly baseflow contribution. A 95% confidence interval is depicted as a shaded, grey envelope around the plotted line. Scatterplot is raw data points.

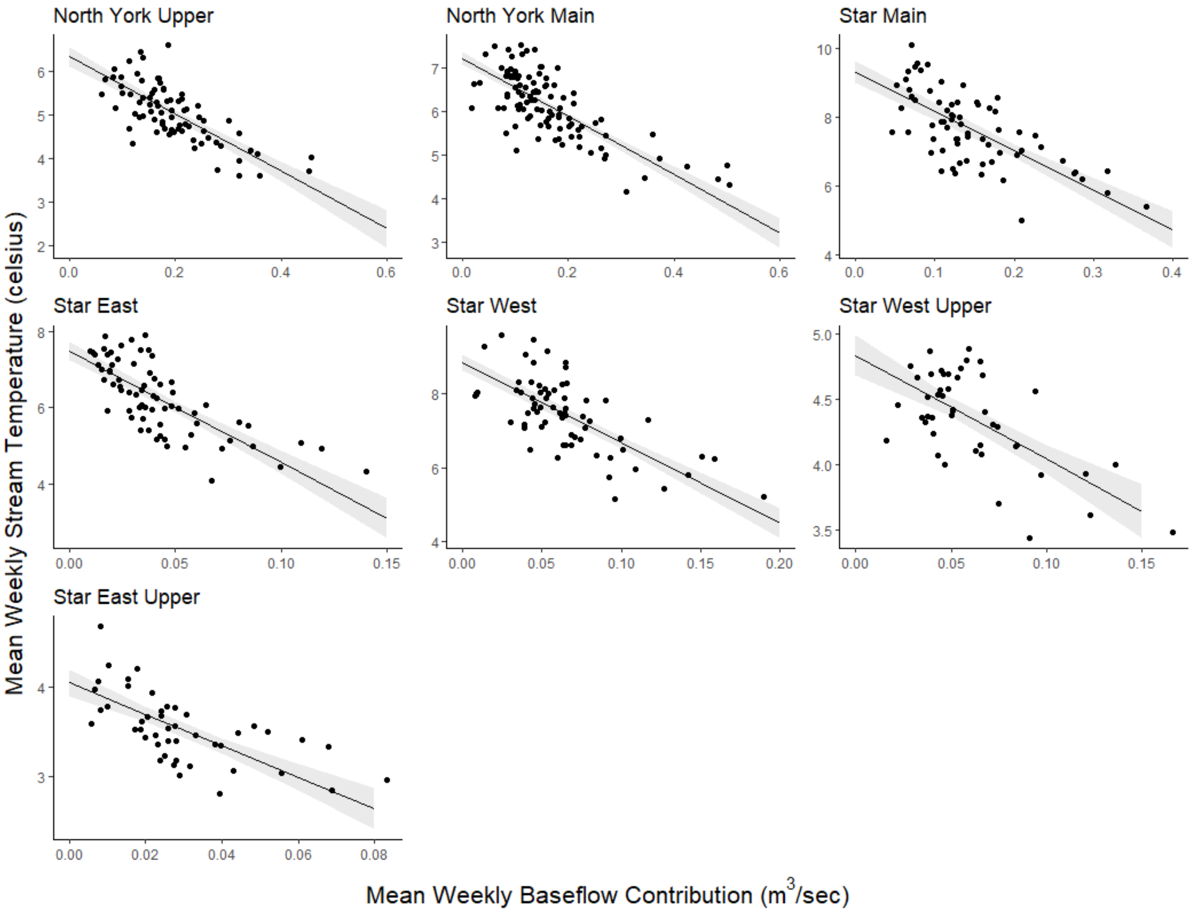


Figure 2-7: Mean marginal effect of mean weekly air temperature (°C) on mean weekly stream temperature (°C) multiple linear regression models for each sub-catchment. Plotted lines show the predicted mean change in modelled stream temperature as a function of mean weekly air temperature. A 95% confidence interval is depicted as a shaded, grey envelope around the plotted line. Scatterplot is raw data points

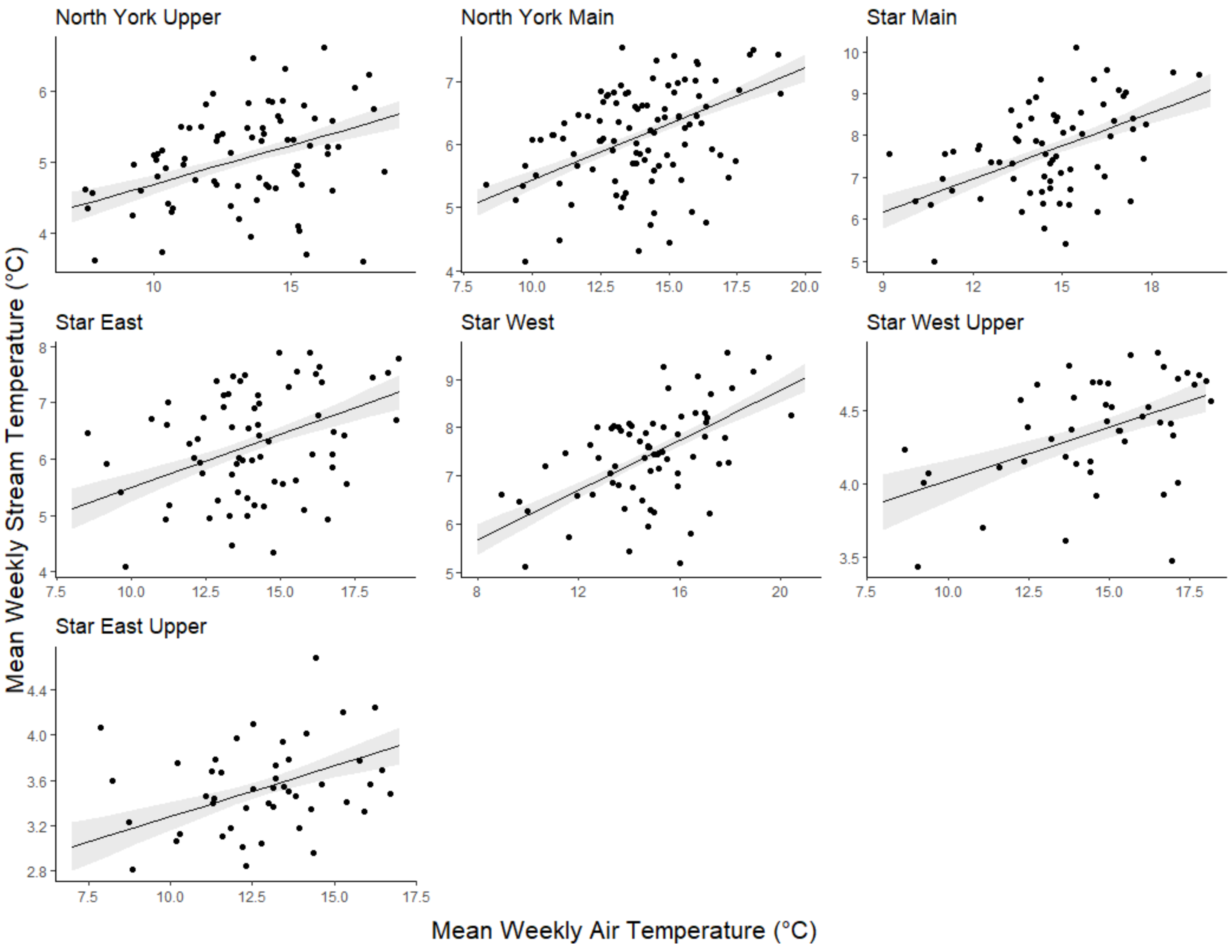


Figure 2-8: Summary of stream temperature metrics and predictors plotted against mean sub-catchment elevation(m): (A) Air temperature coefficients (sensitivity to air temperature) derived from stream temperature models, (B) Baseflow coefficients derived from stream temperature models, (C) Mean weekly summer stream temperature (°C), (D)Mean Weekly Baseflow (mm).

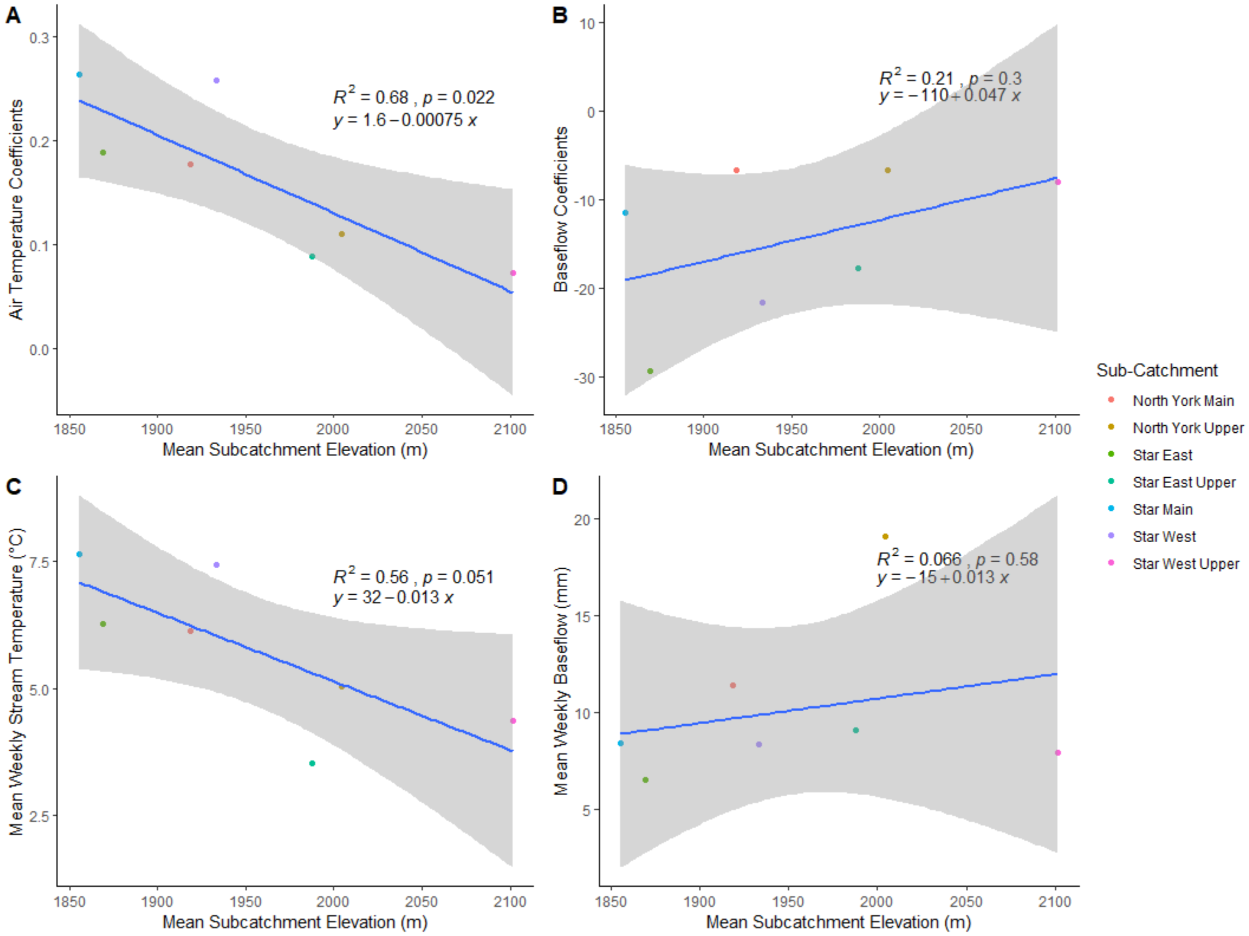


Figure 2-9: Summary of stream temperature metrics and predictors plotted against terrain Ruggedness Index plotted against: (A)Air temperature coefficients (sensitivity to air temperature) derived from stream temperature models, (B) Baseflow coefficients derived from stream temperature models, (C) Mean weekly summer stream temperature (°C), (D) Mean Weekly Baseflow (mm).

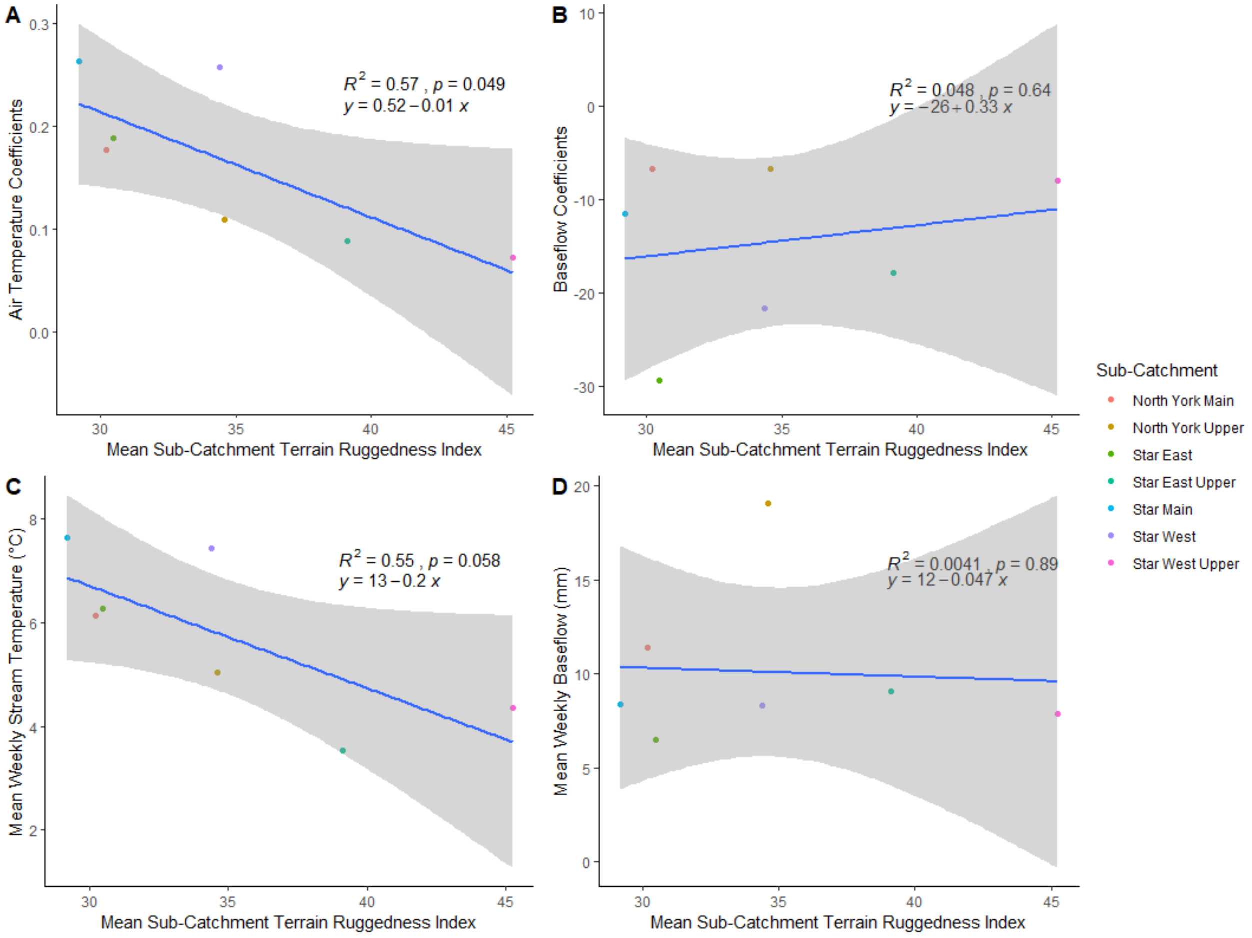
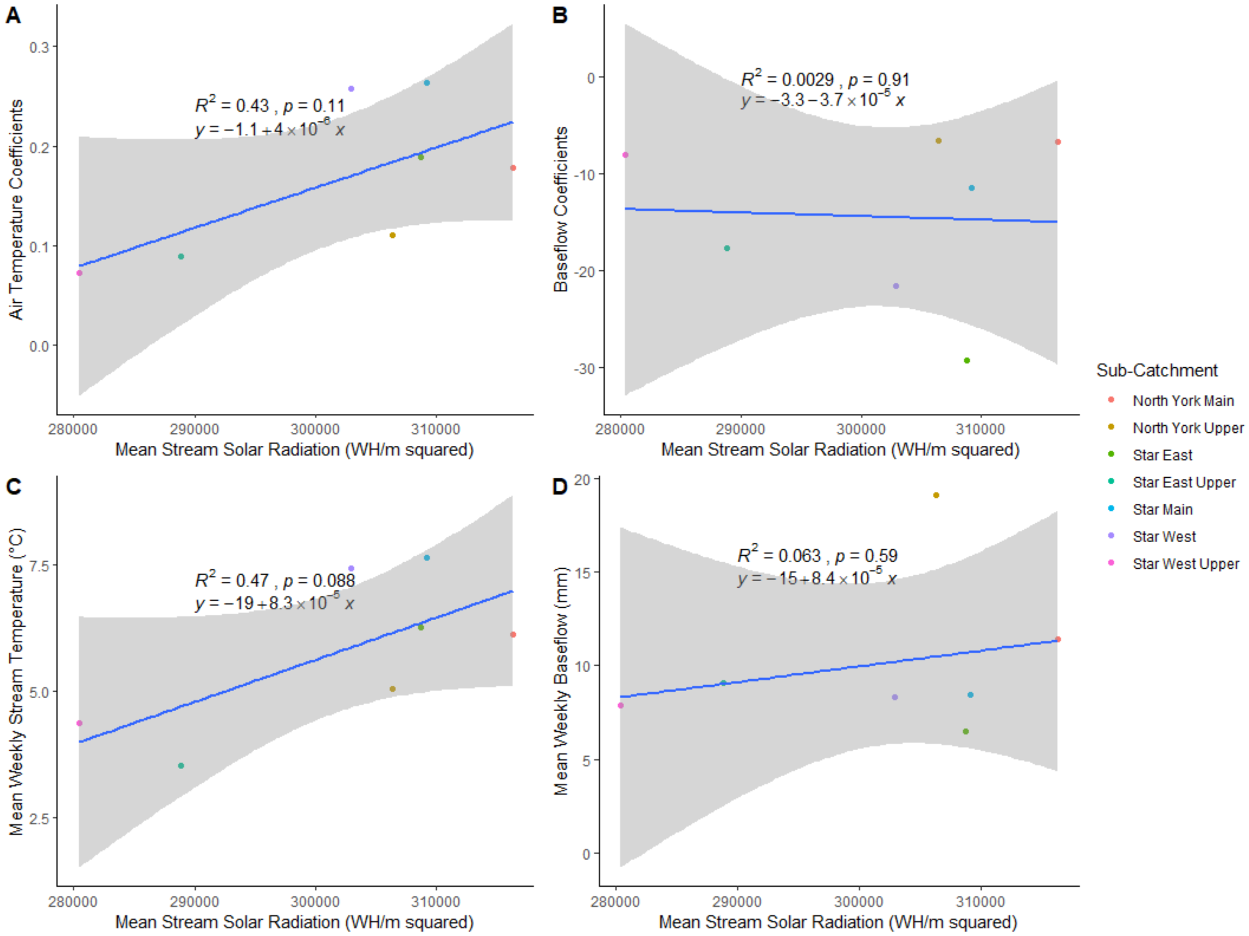


Figure 2-10: Summary of stream temperature metrics and predictors plotted against mean summer Solar radiation accumulating within a 12.5m buffer of the stream network plotted against: (A) Air temperature coefficients (sensitivity to air temperature) derived from stream temperature models, (B) Baseflow coefficients derived from stream temperature models, (C) Mean weekly summer stream temperature (°C), (D) Mean Weekly Baseflow (mm).



Chapter 3. Peering into watershed scale spatiotemporal patterns of stream temperature in the northern Rocky Mountains

3.1. Introduction

Water temperature in streams and rivers is a critical water quality parameter that varies spatially, within and across watersheds, and through time (Webb and Zhang 1997; Webb et al. 2008; Wagner et al. 2013; MacDonald et al. 2014). Water temperatures influence the distribution and abundance of aquatic species by regulating metabolic rates, reproduction, intraspecific competition and mortality (Baxter and McPhail 1999; Bear et al. 2007; Isaak et al. 2010). Spatial and temporal variation of summer stream temperatures is particularly important as many cold-water fishes ranges are contracting (Shepard et al. 2005) and cold-water fish populations are shifting their distribution to cooler, higher elevation areas where cold-water refugia are more abundant (Isaak and Rieman 2013). Range contraction has been linked to interspecific competition (Warnock and Rasmussen 2013), disease (James et al. 2021), reduced productivity and mortality (Bear et al. 2007). In the Rocky Mountains and Foothills of Alberta, summer stream temperatures are particularly important, as inputs of energy from radiation and high air temperatures during periods of typically low streamflows can lead to elevated water temperatures causing deleterious effects to cold-water species. More broadly, changing weather and climate patterns leading to warmer air temperatures (IPCC 2023) and altered hydrology (Leppi et al. 2011) are also changing energy flux processes that control stream temperatures (van Vliet et al. 2013). These pressures collectively heighten the need to better understand the factors controlling stream thermal regimes to support managing aquatic ecosystems, particularly those requiring relatively cooler summer stream temperatures. Identifying cold-water habitats that have thermal resilience to land use pressures and climate change is likely to become increasingly important for conservation of several threatened cold-water fish species in Alberta.

Studies examining patterns of summer stream temperatures have often focused on non-advective energy fluxes (Johnson 2004; Webb and Zhang 2004; Ouellet et al. 2015). Key non-advective energy fluxes influencing stream temperature include short wave solar radiation, long wave radiation emitted from surrounding environment, sensible and latent heat turbulent exchange from air temperatures (Leach et al. 2022). As shown in Chapter 2, the influence of advective energy fluxes from groundwater inputs can exert a strong effect on stream thermal regimes. Additional sources of advective energy fluxes that influence stream temperatures at different scales include inputs from tributaries, hyporheic flow, and channel interception of precipitation (Leach et al. 2022). Both non-advective and advective sources of energy flux vary throughout a season and across years. Complicating things further, interannual climatic variation and antecedent conditions influence watershed storage and precipitation-runoff patterns (Devito et al. 2012), which could influence stream thermal regimes at annual or inter-annual time scales.

Energy fluxes that influence stream temperature can also be directly or indirectly associated with physiographic features of a watershed. The thermal regimes of streams reflect the aggregate of watershed physiographic conditions at and upstream of a monitoring point (Webb et al. 2008). Previous research comparing thermal regimes across watersheds have identified a variety of physiographic characteristics that predict stream temperature (Isaak and Hubert 2001; Chang and Psaris 2013; Imholt et al. 2013; Steel et al. 2016; Johnson et al. 2017). Watershed elevation is a common watershed scale physiographic predictor of stream temperature. For example, Isaak and Hubert (2001) examined a number of spatial variables and identified a negative relationship with mean watershed elevation as the strongest effect, while relationships with tree abundance (riparian shading), watershed slope, valley constraint and grass abundance were less important. While results from Chapter 2 showed regulation of thermal regimes by both climate and hydrologic factors, no single landscape physiographic feature was strongly associated with variation in catchment scale stream thermal regimes across seven nested sub-catchments within two headwaters watersheds. This was likely a reflection of the strong similarity of sub-catchment physiography across this narrowly constrained group of front-range Rocky Mountain watersheds. Thus, the extent to which watershed physiographic features can serve as proxy indicators for climatic and hydrologic controls regulating stream thermal regimes across broader regional of Alberta’s Rocky Mountain eastern slopes remains unclear.

The broad goals of this study were to examine spatiotemporal patterns of summer stream temperatures to evaluate the hydrometric, climatic and physiographic variables governing summer stream temperatures across a large region of the front-range Rocky Mountains, upper foothills and lower foothills of Alberta (2019-2021). Key objectives were; 1) develop an empirical model that generalizes stream temperature as a function of temporal variation (e.g., climatic and hydrologic controls) and quantifies the spatial effects across watersheds, effectively parametrizing and quantifying temporal vs spatial effects, 2) evaluate the relationship between stream temperatures and several watershed physical attributes which may subsequently serve as simpler proxy indicators of stream thermal regimes, at the watershed scale, for use by conservation managers.

3.2. Materials and Methods

3.2.1. Study area

This study examines watershed scale spatiotemporal patterns of water temperature across streams and rivers along the Eastern Slopes of the Rocky Mountains in Alberta, Canada between 2019-2021. The vast study area (28648 km^2; Figure 3-1) includes watersheds within the Rocky Mountains and Foothills Natural subregions of Alberta, located south of Highway 11, and north of the Canada-USA border. Minor portions (<1%) of the study area extend into the Boreal Forest, Parkland and Grassland Natural Regions to accommodate accessibility of monitoring locations. The study area encompasses a wide range of ecological and physiographic conditions with watersheds partially or fully located in the following Natural Subregions: Alpine, Subalpine, Montane, Upper Foothills, Lower Foothills, Foothills Parkland, Foothills Fescue and Dry Mixedwood (Downing and Pettapiece 2006).

The study area has variable physiographic, climatic and hydrologic conditions, that generally correspond to an elevation gradient that decreases west to east (away from the continental divide). Elevation varies from a maximum of 3558 meters above sea level (m.a.s.l.), located at Mt. Assiniboine along the continental divide, to a minimum of 954 m.a.s.l. located on the North Saskatchewan River in the northeast corner of the study area. The mean elevation across the entire study area is 1764 m.a.s.l. Terrain and soils vary across the study area from steep bedrock slopes overlain with thin, poorly developed soils within the alpine, subalpine and montane natural subregions, to rolling topography with broad valleys and more developed soils in the upper and lower foothills (Downing and Pettapiece 2006). A portion of the highest elevations are covered with permanent snow and ice making up less than 1% (162 km^2) of the study area.

Mean annual air temperatures are coolest in high elevation Natural Subregions (Alpine [-2.4 ºC] and Subalpine [-0.1 ºC]) and relatively warmer in the Montane (2.3 ºC), Upper Foothills (1.3 ºC) and Lower Foothills (1.8 ºC). Mean monthly summer air temperatures follow a similar trend where Alpine and Subalpine have the coolest temperatures (8.7 ºC and 11.3 ºC, respectively) and temperatures are relatively warmer in the Montane (13.9 ºC), Upper Foothills (13.4 ºC) and Lower Foothills (14.7 ºC). Mean annual precipitation generally increases with topographic gradients, where the alpine (989 mm) and subalpine (755 mm) have highest amounts of precipitation and montane (589mm), upper foothills (632) and lower foothills (588) see relatively lower precipitation (Downing and Pettapiece 2006). In June 2021 immediately prior to the final summer season of the study period, Western Canada (including the study area) experienced a heat wave commonly referred to as the "Heat Dome". During the "Heat Dome", air temperatures were well above average (up to 20 ºC above average) for a prolonged period of time (approximately June 25-July 1, 2021).

Runoff generation in the study area is strongly influenced by snowmelt and ground water contributions (Paznekas and Hayashi 2015; Pomeroy et al. 2012). Streamflows generally vary along the elevation gradient of the study area, where the highest streamflow production originates in higher elevation areas and decreases into the lower foothills. Annual hydrographs are characterized by large seasonal snowmelt peaks during the freshet in spring (April-June). All watersheds within the study area drain into either the North Saskatchewan or South Saskatchewan River Basins.

The study area overlaps much of the Alberta range of two cold-water fish species of conservation concern; Bull Trout (*Salvenlinus confluentus*) and Westslope Cutthroat Trout (WSCT; *Oncorhynchus clarkia lewisii*). Both Bull Trout and WSCT are listed as Threatened under the Species at Risk Act across Canada and under the Wildlife Act in Alberta. Considerable efforts have been made to improve the status of Bull Trout and WSCT in the region including continued research, monitoring, management and regulation (Fisheries and Oceans Canada 2019; Fisheries and Oceans Canada 2020).

3.2.2. Site Selection

A sample of 16 watersheds from within the study area were selected for monitoring and analyses to meet study objectives (Figure 3-1) based on: (1) varying watershed distribution across the north-south extent of the study area (350 km North-South gradient), (2) varying watershed distribution in distance from the continental divide within study area (7-129 km from divide), (3) sites without regulation of flow (no anthropogenic dams), (4) immediate proximity to Water Survey of Canada monitoring stations (to pair stream temperatures with streamflow data). The watershed selection criteria were designed to allow for a comparison of spatiotemporal variables influencing stream temperatures given the variation in temporal variables (e.g., air temperatures, streamflows) and spatial variables (e.g., mean elevation, watershed size, channel density, terrain complexity) within the Eastern Slopes of the Rocky Mountains of Alberta.

3.2.3. *Data Collection*

3.2.3.1. Stream temperature

Stream temperature data were collected from each watershed at the monitoring point (Figure 3-1) using instream data loggers (Onset Hobo Data Loggers MX Tidbit 400, Bourne, MA, USA) installed near (within 100 m) Water Survey of Canada monitoring sites. Data loggers were fixed into stream water column using rebar pounded into stream bed. Washers welded onto one end of the rebar allowed for data loggers to be securely positioned into the water column. Data loggers were installed in portions of streams where the water column was deep enough to maintain data logger submergence during low flow periods throughout the year.

Stream temperature data loggers were deployed early Spring in 2019, with the exception of two loggers located in Banff National Park (Mistaya River and Bow River loggers), which were deployed in Fall 2019. Delays in deployment were due to delays in receiving a research permit from Parks Canada. Data loggers collected stream temperature (ºC) at 10-minute intervals. Field surveys were conducted bi-annually (during low flows in early spring and fall) to download data from loggers, replace batteries and troubleshoot any issues with data loggers. Finally, data loggers were downloaded and installation hardware were removed in Fall 2022.

3.2.3.2. Hydrologic Variables (Temporal)

Hydrologic controls represent a class of independent variables, derived from stream discharge, that focused on watershed streamflow conditions. Stream discharge values were used to calculate 7 independent variables that measured instantaneous stream discharge (m^3/s), area weighted stream discharge (mm), the baseflow (m^3/s; mm) and quickflow (m^3/s; mm) derivatives of instantaneous and area weighted discharges and an index of baseflow relative to total flow. Table 3-1 outlines and defines hydrometric independent variables considered in analyses.

Streamflow data were compiled from open source data available through Water Survey of Canada (Pers. Comm. Jamison Romano 2021) and AB Rivers (Alberta Environment and Parks 2022). Water Survey of Canada data were used primarily; however, AB Rivers data were used to fill gaps where necessary. Both Water Survey of Canada and AB Rivers datasets summarize streamflow conditions at the same approximate location of study area watersheds. Typically, Water Survey of Canada streamflow datasets were continuous between from April 1 to October 31, however, Summer streamflow data was missing for Bearberry Creek in 2019 and Pincher Creek in 2020 and 2021. As such, both sources of streamflow data were used to complete summer streamflow datasets. Raw streamflow data varied in timestep (5-minute, 10-minute and 15-minute) across sources (WSC and AB Rivers) and locations; however, the data were summarized into mean weekly instantaneous discharge (Table 3-1 – “Stream Discharge1”, m^3/s) across all sites for this analysis. An area weighted mean weekly discharge (Table 3-1 – “Stream Discharge2”, mm/week) was calculated from mean weekly instantaneous discharge to allow for standardized comparison of streamflows between watersheds.

Additionally, stream discharge data were partitioned into two constituent components, quickflow and baseflow, using a digital recursive filter (baseflow separation technique). Quickflow is considered a proxy measure for the portion of streamflow that is generated by quick runoff processes (surface runoff) while baseflow is considered a proxy for the portion of streamflow that is generated by groundwater entering a stream (slower flow pathways). The baseflow separation technique applies a digital filter to differentiate between low-frequency (baseflow) and high-frequency (quickflow) stream discharge (Nathan and McMahon 1990). A two-pass filter was applied based on the assumption that the fraction of water yield contributed by baseflow falls between the first and second pass of the digital filter (Arnold and Allen 1999; Arnold et al. 1995). Baseflow separation was completed using the software package R (R Core Team, 2019) and packages EcoHydrology (Fuka et al. 2018) and waterData (Ryberg and Vecchia, 2017). Streamflow, baseflow and quickflow data outputs from baseflow separations were used to create hydrometric control predictor independent variables such as “Quickflow”, “Quickflow2”, “Baseflow”, “Baseflow2” and “Baseflow Index” that are defined in Table 3-1.

3.2.3.3. Climatic Variables (Temporal)

Climatic controls represent a class of independent variables, based on air temperature and precipitation data, that focus on: (1) shortwave solar radiation and longwave radiation from surrounding environments (net radiation), (2) turbulent exchange of sensible and latent energy between air masses and a stream, and, (3) advective transfer of energy through channel interception of precipitation. Shortwave and longwave radiation data were not available for all watersheds; however, air temperatures are correlated with energy fluxes related to radiative energy inputs. As such, air temperature metrics were utilized to generally describe climatic energy inputs, with the exception of precipitation. Air temperature data were used to create four independent variables including weekly air temperature means, minima, maxima, and ranges. Precipitation data were summarized into weekly sums.

Air temperature and precipitation data were downloaded from opensource resources operated by Meteorological Service of Canada and Environment and Climate Change Canada (Government of Canada 2022). Climatic variables were compiled for each watershed using Meteorological Service of Canada and Environment and Climate Change Canada stations in and around study watersheds. Due to the size, shape and location of study watersheds, climatic variables were often averaged between two or more meteorological stations to estimate watershed-scale climatic control variables as accurately as possible. A summary of study area watersheds and the corresponding meteorological station used to summarize climate variables can be found in Table 3-2.

3.2.3.4. Watershed Characteristics (Spatial)

Nine watershed physiographic characteristics were summarized for each watershed to examine spatial conditions that influence stream thermal regimes. The watershed physiographic characteristics were selected based on inferred relationships with fundamental temperature controls on stream temperature, particularly those that influence groundwater production and air temperature effects. Watershed physiographic characteristics were calculated using a digital elevation model (DEM) with a spatial resolution of 25m x 25m gridded cells (Alberta Environment and Parks 2017). Details on each of the watershed characteristics are outlined in the subheadings below.

3.2.3.4.1. Mean Elevation

Mean watershed elevation was calculated as the average elevation across the entire sub-catchment (m.a.s.l.). Elevation is positively related to precipitation and negatively related to air temperature. Increased snowpack accumulation at higher elevations may influence recharge and discharge of shallow subsurface groundwater pathways. Previous research has identified a negative relationship between stream temperatures and watershed elevation (Isaak and Hubert 2001; Chang and Psaris 2013).

3.2.3.4.2. Terrain Ruggedness Index (TRI)

TRI was calculated as the sum of elevation changes from adjacent cells in a DEM, expressed as an index (Riley et al. 1999). Low TRI values reflect flatter areas, while higher TRI values can occur in steep areas or steep and rugged (complex) areas. TRI values were calculated for each raster cell of a DEM in the watersheds, and then a mean TRI value was summarized to create 5 variables describing different scales of terrain complexity within a watershed: (1) mean watershed TRI, (2) mean TRI summarized within 200 m of stream channels, (3) mean TRI summarized within 100 m of stream channels, (4) mean TRI summarized within 50 m of stream channels, and (5) mean TRI summarized within 25 m of stream channels. TRI variables were quantified across different scales within study watersheds to examine whether watershed scale terrain ruggedness metrics or metrics localized around stream channels were related to patterns of stream temperature. Increased terrain complexity may be related to groundwater production by increasing the likelihood of groundwater pathways coming to the surface (Dugdale et al. 2015).

3.2.3.4.3. Vector Ruggedness Measure (VRM)

VRM is a quantification of terrain complexity measuring variation in three-dimensional orientations of adjacent cells of a DEM (Sappington et al. 2005). In contrast to TRI, VRM values are low in steep/flat areas with minimal complexity, and high in areas that are rugged (greater complexity in terrain) and both steep and rugged. VRM values were calculated for each raster cell of a DEM in the watersheds and expressed as a dimensionless ruggedness value between 0 (flat) and 1(most rugged). VRM value was summarized to create 5 variables describing different scales of terrain complexity within a watershed: (1) mean watershed VRM, (2) mean VRM summarized within 200 m of stream channels, (3) mean VRM summarized within 100 m of stream channels, (4) mean VRM summarized within 50 m of stream channels, and (5) mean VRM summarized within 25 m of stream channels. VRM variables were quantified across different scales within study watersheds to examine whether watershed scale terrain ruggedness metrics or metrics localized around stream channels were related to patterns of stream temperature. Watersheds with relatively higher mean VRM values will have greater terrain complexity, and similar to TRI, are expected to have cooler stream temperatures due to greater amounts of groundwater contribution.

3.2.3.4.4. Solar Radiation

Solar radiation is an estimation of summer solar radiation accumulated across each watershed (WH/m^2). The ArcPro Solar Radiation Tool (ESRI ArcPro 2021, Version 2.9.2) was used to calculate solar radiation for each DEM cell within the watersheds, then was summarized to create 2 variables describing different scales of solar radiation within a watershed: (1) mean watershed solar radiation, and (2) mean solar radiation summarized within 200 m of stream channels. Higher values of solar radiation increase stream temperatures via increased energy inputs from shortwave solar radiation and longwave radiation from surrounding environments. In addition, higher values of watershed solar radiation may be related to increased ground surface warming which in turn, can increase runoff generation and temperatures of shallow subsurface groundwater.

3.2.3.4.5. Topographic Wetness Index (TWI)

TWI is a hydrologic index based on DEMs that indicate how likely an area is to be wet based on slopes and contributing area (Beven and Kirkby 1979). Areas with higher TWI are more likely to be wet relative to areas with low TWI. TWI values were calculated for each raster cell of a DEM in the watersheds. TWI values were summarized to create 6 variables describing different scales of terrain wetness within a watershed: (1) mean watershed TWI, (2) mean TWI summarized within 200 m of stream channels, (3) mean TWI summarized within 100 m of stream channels, (4) mean TWI summarized within 50 m of stream channels, and (6) mean TWI summarized within 25 m of stream channels. Higher watershed TWI values are associated with increased wetlands and lentic water bodies, which have been correlated with warmer stream temperatures (O'Sullivan et al. 2019).

3.2.3.4.6. Watershed Area

Watershed area is the area (km^2) that contributes to streamflow at an outflow point. Watershed area has a positive relationship with stream size and water production. Smaller watersheds are more likely to contain a higher proportion of headwater area, where groundwater production is generally higher.

3.2.3.4.7. Channel Density

Channel density (km/km^2) is the total length of channel divided by the area of the watershed. Channel density is related to groundwater production (Zecharias and Brutsaert 1988). Higher drainage densities are related to highly erodible and impermeable land surfaces, which could influence groundwater contributing to streamflows.

3.2.3.4.8. Channel Slope

Channel slope (%) is the change of elevation (maximum – minimum) of the longest continuous stream channel segment divided by the length of the longest continuous stream channel segment. Greater channel slopes may be related to greater hyporheic flows and shorter streamflow residence times, leading to cooler summer stream temperatures (Garner et al. 2017).

3.2.3.4.9. Distance from Continental Divide

The Continental Divide in Alberta is the height of land that runs Northwest- Southeast along the Alberta British Columbia Border (Figure 1) and separates basins that flow to the Pacific Ocean from basins flowing to the Arctic Ocean and Hudson's Bay. This variable was calculated by measuring the distance (km) from the Continental Divide to the centroid of each study watershed. Distance from the Continental divide represents a change from alpine to subalpine to montane to foothill natural subregions and is negatively related to mean watershed elevation. Previous research has identified a negative relationship between stream temperatures and watershed elevation (Isaak and Hubert 2001; Chang and Psaris 2013)

3.2.4. Analyses

To assess temporal and spatial effects on stream temperature, analyses were conducted in 2 steps;

(1) First, mean weekly stream temperatures were estimated across all 16 watersheds and 3 years of data using a multiple linear regression. The spatiotemporal model was developed using multiple linear regression to estimate mean weekly stream temperature primarily as a function of climatic and hydrologic controls, and variation in time and space. In addition to climatic and hydrologic controls (the main variables of interest), two temporal variables, week of year (continuous) and a factor variable for year, were considered to understand patterns of seasonal and annual variation in stream temperatures. Spatial effects were incorporated into the model by including a categorical variable (factor) called "Watershed", which represented each of the 16 study watersheds. All continuous predictor variables were scaled (standardized) to allow for comparison of effects.

The spatiotemporal model was fit using a stepwise model selection approach using Akaike's Information Criteria (AIC; Akaike 1973). A forward selection process was used where variables were added to the model one at a time. Only using a forward selection process can lead to adding variables that are highly collinear with other important causal covariates. To avoid the addition of spurious variables, after each step of adding a variable, a backwards selection process was used to re-evaluate the model and remove potentially spurious variables as necessary. Interaction terms were considered amongst the temporal variables, but not between temporal and spatial variables. The model selection process was continued until AIC scores no longer changed (decreased) substantially, yielding a final spatiotemporal model. Due to high collinearity across many of the climatic control variables (Pearson correlation coefficients 0.71-0.88) with the exception of precipitation, only precipitation and one other climatic control variable were considered for the final model. Additionally, there was high collinearity (Pearson correlation coefficients >0.75) between many of the hydrologic control variables, and thus, the inclusion of only one hydrologic control variable was considered in the final model. All variables in the final model had a Pearson correlation coefficient less than 0.31.

The spatiotemporal model was evaluated for homoscedasticity visually by plotting standardized model residuals against fitted values and formally by using the Goldfeld-Quandt test. In addition, the normal distribution of model residuals was examined visually using Q-Q plots and by plotting model residuals by watershed location. Finally, normal distribution of residuals was also tested formally using the Shapiro-Wilk normality test. Generally, the spatiotemporal model can be outlined as:

$$Ts_{ij} = \beta_0 + \beta_1 AT_{ij} + \beta_2 BF_{ij} + \beta_3 WeekofYear_j + \beta_4 Year_j + \beta_5 Year_j * Year_j + \beta_6 Watershed_j + \varepsilon_{ij} \qquad (3\text{-}1)$$

Where Ts_{ij} is the mean stream temperature for a given week (i) and location (j), β_0 is the model intercept, $\beta_{1 \ldots 6}$ are coefficients derived from the data, AT_{ij} is mean weekly air temperature, BF_{ij} is mean weekly baseflow (groundwater contribution), $WeekofYear_j$ is a continuous numeric variable describing the passage of time through the Summer season, $Year_j$ is a factor variable for each year of study, $Watershed_j$ represents the spatial effect of each individual watershed's physiographic features, and ε_{ij} is error.

This approach allowed for partitioning and parameterizing of temporal versus spatial effects and led to the second analytical step wherein spatial (watershed characteristics) effects were further explored. The spatiotemporal model produced a coefficient for each individual watershed that parameterized the relative effect (warmer/cooler) of the individual watershed on mean weekly stream temperature, after accounting for the variation attributed to temporal variables. This procedure allowed for a more accurate representation of the relationships between watershed physiography (spatial variation) and stream thermal regimes, as variation attributed to temporal variables (e.g. year) were effectively accounted for, or removed.

(2) Second, simple linear regression analyses were conducted to assess the relationship between the variation in "Watershed" coefficients (the relative effect of each watershed on stream temperature, derived from the spatiotemporal model) and physiographic variables. These analyses identified physiographic conditions that promote cooler summer stream temperatures

across our study watersheds. Relationships were evaluated using p-values and r^2 values and by assessing homogeneity of model residuals.

It is important to note that while many differing approaches to formulation of a general empirical modelling framework were possible, the approach adopted in this study was to develop a model that enabled understanding key influences on stream temperature and partitioned temporal and spatial effects. While the spatiotemporal model was not formulated to specifically enable the generalized prediction of mean weekly stream temperature for any given watershed in the study area, it was does provide insight into how stream thermal regimes vary across space and time and the output of the model can be used to predict which streams and rivers will be relatively cooler on average during the summer.

3.3. Results

3.3.1. Spatiotemporal Stream Temperature Model

The spatiotemporal model included six temporal variables (mean weekly baseflow, mean weekly air temperature, time of year, year, and an interaction between time of year and year) and a spatial variable (Watershed). The spatiotemporal model was notably robust and able to accurately characterize variation in mean weekly stream temperature across this very broad range of front-range alpine to lower foothills watersheds (2019-2021; adjusted r^2=0.93). Model outputs including coefficients and P-values for each variable can be found in Table 3-3. The inclusion of the watershed spatial variable improved the stream temperature model greatly (r^2 improved by 57%). Both spatial and temporal variables were necessary for developing a suitable model to accurately predict patterns of summer stream thermal regimes. Spatial effects (watershed characteristics) were quantified in the final model via the coefficients associated with each "Watershed". The "Watershed" term showed statistically significant variation in the effect of different watersheds on average mean weekly summer stream temperature. "Watershed" coefficients were used in subsequent simple linear regression analyses to explore the physiographic characteristics explaining spatial variation in thermal regimes across watersheds.

Generalized across the monitoring locations and the entire study period, mean weekly summer stream temperatures were positively correlated with variation in air temperature (Figure 3-2) and negatively correlated with the mean weekly baseflow (Figure 3-3). Scaled effects of mean weekly air temperature and mean weekly baseflow contributions showed that mean weekly air temperature had a stronger influence on stream temperature than baseflow contribution (Table 3-3, scaled air temperature and baseflow coefficients). Thermal sensitivity, the relationship between stream temperature and air temperature (Kelleher et al. 2012), was remarkably similar across the 16 watersheds with two watersheds (Bow R. and Mistaya R.) showing lower thermal sensitivity (flatter slopes in relationship between stream temperature and air temperature). In contrast, the relationships between stream temperature and baseflow were more variable (in slope and variability of baseflows) across watersheds (Figure 3). Stream temperatures at two measurement sites (Bow River and Mistaya River) showed no relationship (flat line) with baseflow contribution. Bow River and Mistaya River were unique relative to other monitoring locations in that they were only monitored in 2020 and 2021 and both measurement sites are located in watersheds containing glaciers and permanent snow and ice through the summer months.

Generalizing the relationships between stream temperatures and air temperatures or baseflow contributions across the study period approximates relationships between stream temperature and both climatic and hydrologic variables over the full 3-years, however, a factor variable “Year” was included in the final model and it showed a statistically significant effect (Table 3-3). Average summer stream temperatures were slightly warmer in 2020 (+0.2 ºC) compared to in 2019 (p=0.084), and even warmer in 2021 (+0.78 ºC) compared to 2019 (p<0.001). Interestingly, the positive relationships between stream temperature and air temperature for each watershed was similar for each of the three study years (2019-2021, Figure 3-4). In contrast, the negative relationships between stream temperature and weekly baseflow differed substantially among years (Figure 3-5). Relationships were relatively similar in 2019 and 2020, but changed drastically in 2021 during the unusually hot “Heat Dome” conditions in southern Alberta that summer. In 2019 and 2020, negative relationships between stream temperature and baseflow were observed. However, in 2021, 13 of 16 watersheds displayed positive relationships between stream temperature and groundwater contributions. In 2021, the cooling effect of increased groundwater inputs on stream temperatures was only observed in Pincher Creek, Yarrow Creek and Little Red Deer River watersheds (Figure 3-6). The change in relationships between stream temperature and baseflow contribution across years can be better observed with Bow River and Mistaya River removed from Figure 3-5, as observed in Figure 3-6.

A variable “WOY” (week of year), representing the effect of the passage of time through each year was included in the final model. On average, stream temperatures increased (P<0.001) throughout the summer season (July and August). An interaction term between "WOY" and "Year" was also included in the final model which showed the change in pattern of stream temperatures throughout a season, across the different years. The affect of time of year on mean stream temperature was statistically different between 2019 and 2020 ($p=0.02083$), and 2019 and 2021 ($p<0.001$). In fact, stream temperatures in 2019 and 2020 increased as the summer progressed, however, in 2021, stream temperatures started relatively higher than previous years and decreased throughout the summer (Figure 3-7).

Residuals of the spatiotemporal model were assessed to determine model adequacy. Residuals were found to be normally distributed (Shapiro-Wilk normality test; $p= 0.3558$). In addition, a visual assessment of residual variance structures across the watersheds showed relatively homogenous variance structures (Figure 3-8).

3.3.2. Spatial Analyses

The effects of variable watershed physiography on stream temperatures were captured by coefficients for each watershed location, derived from the spatiotemporal model (Table 3-3). The spatial watershed coefficients reflect the average effect of physiographic features of each watershed on stream temperature after accounting for other model variables (temporal variables). The effect of the "Watershed" variable was responsible for 8.3 °C in variation of mean stream temperatures across the study sites. The watersheds with the warmest and coldest mean stream temperatures (most positive and negative coefficients) were Fish Creek and North Ram River, respectively (Table 3-3).

Watershed coefficients showed statistically significant relationships with stream temperature for 17 watershed physiographic characteristics (Table 3-4), many of which were highly correlated with one another (>80%). After evaluating watershed coefficients as a function of each of the 17 watershed characteristics, the watershed variables that best described the differences in watershed coefficients were: (1) mean terrain ruggedness index buffered within 100 m of stream channel ($p<0.001$, $r^2=81\%$; Figure 3-9), and, (2) mean vector ruggedness measure buffered with 200 m of stream channel ($p<0.001$, $r^2=79\%$; Figure 3-10). Additional watershed characteristics had statistically significant relationships explaining different watershed thermal regimes; (1) mean watershed terrain wetness index ($p<0.001$, $r^2=67\%$), (2) channel density ($p=0.02$, $r^2=28\%$), and, (3) channel slope ($p=0.028$, $r^2=25\%$); however, these variables explained less of the variation than terrain complexity variables. Mean elevation, solar radiation, distance from continental divide and watershed area did not have statistically significant relationships with watershed coefficients ($p>0.05$).

The variables based on TRI were the most strongly associated with spatial variation in mean stream temperature across watersheds as reflected by p-values / r^2 values. Watershed coefficients had a negative relationship with each of the TRI variables, where greater terrain complexity was associated with lower mean watershed summer stream temperatures (Figures 3-9 and 3-10). Relationships between watershed coefficients and each of the TRI variables were statistically significant ($p<0.001$), and r^2 values varied between 0.31-0.81. Across all physiographic variables including other TRI variables, Mean TRI buffered 100 m around stream channels, had the strongest relationship (p=1.20E-06) and explained the most variation in watershed coefficients ($r^2=0.811$). This result suggests that mean terrain complexity, based on TRI, summarized within 100 m of stream channels is a better predictor of thermal regimes than TRI summarized across the entire watershed, or at 200 m, 50 m or 25 m buffers.

Similar to TRI, another terrain complexity variable (VRM), also described trends in watershed effects on stream temperatures. Watershed coefficients were negatively associated with each of the VRM variables, where greater terrain complexity was associated with lower average watershed summer stream temperatures. Relationships between watershed coefficients and each of the VRM variables were statistically significant ($p<0.001$) and had r^2 values between 0.58-0.79. Mean VRM buffered 200 m around stream channels had the strongest relationship (p=2.26E-06), and explained the most variation ($r^2= 0.79$) of all of the VRM based variables. The VRM summarized within 200 m of stream channel had the second lowest p-value and second highest r^2 variable, after TRI summarized within 100 m of stream channels.

3.4. Discussion

A major outcome of this study was the development of a robust empirical stream temperature model that characterized temporal effects (e.g., climatic and hydrologic controls) and allowed for accurate examination of watershed physical features (spatial variation) that promote relatively colder stream temperatures across a broad range of watersheds within the Eastern Slopes of the Alberta Rocky Mountains. This research identified; 1) a strong similarity in the positive and negative influences of air temperature and groundwater controls, respectively, on regulation of stream thermal regimes across a large region in 2019 and 2020, 2) the effect of a major, anomalous weather event (“Heat Dome”) in 2021, wherein the previously negative relationships (2019 & 2020) between stream temperature and groundwater contribution became positive, presumably reflecting excessive ground surface heating in 13 of 16 watersheds, and, (3) patterns of stream thermal regimes based on watershed physiography (particularly terrain complexity within 100-200 m of stream channels) which can be used to identify relatively cooler streams and rivers at watershed scales. These results are particularly important for aquatic resource managers to understand the response of streams to climate anomalies and climate change. Moreover, the identification of a simple, watershed indicator enables natural resource managers to predict the location of cooler stream habitats that may serve as important thermal refugia for several important threatened cold-water fish species.

3.4.1. Climatic and Hydrologic factors regulating the temporal variation in stream temperatures

Generalized across all of the study watersheds, mean weekly air temperature and mean weekly baseflow were the key climatic and hydrologic variables that governed mean weekly stream temperatures. Air temperature, which generally approximates the energy fluxes related to net radiation and turbulent sensible and latent heat exchange, was positively related to mean weekly stream temperatures. Baseflow, an approximation of the groundwater fraction of streamflow, was negatively related to mean weekly stream temperature. Generalized across the study watersheds, air temperature had a greater effect on mean weekly stream temperatures than baseflow as evident by scaled model coefficients associated with each variable (Table 3-3). This finding is contrary to results from Chapter 2, where seven headwater sub-catchments of the Crowsnest River were shown to have stronger groundwater controls compared to air temperature controls. The difference in results between Chapter 2 and this chapter, are likely a reflection of the increased spatial scale of this chapter, where stream temperature relationships were evaluated across a much broader range of watershed physiographic conditions. Each watershed's variable response of stream temperature to the key climatic and hydrometric controls is observed by plotting the spatiotemporal model outputs (fitted values) against air temperature (Figure 3-2) and baseflow (Figure 3-3), however, the comparative effect of climatic versus hydrometric controls within each watershed was not measured. The spatiotemporal model generalized the effects of air temperature and baseflow across all watersheds, however if watersheds were modelled individually, the strength of air temperature versus baseflow control on stream temperature would likely vary with changing watershed conditions (e.g., distance from continental divide) across the study area.

The annual differences, or year effect, in stream temperatures during the study period provide evidence for varying watershed response of stream temperature to an anomalous climate event. On average, stream temperatures were 0.20 ºC warmer in 2020 compared to 2019 ($p=0.084$), and 0.78 ºC warmer in 2021 compared to 2019 (p<0.001), demonstrating a strong year effect in the study period. The major contributing factor to the increased stream temperatures in 2021 was likely the "Heat Dome" that occurred over the 7 days prior to the study period. During this time, elevated air temperatures and solar radiation heated the ground after what is typically a period of shallow pathway groundwater recharge, via snowmelt. The effects of uncharacteristically warm air temperatures and net radiation may have warmed the recharged shallow groundwater, relative to other years. If this is the mechanism behind the altered stream temperature groundwater relationship in 2021, there would have to be a lag in the affect between the elevated air temperatures and net radiation acting on ground surface temperatures leading to increased shallow pathway groundwater temperatures. Such lag effects have been observed, taking 8-19 days, in the Blue Ridge Mountains of northern VA, USA (Briggs et al. 2018). Heating shallow pathway groundwater uncharacteristically, immediately before what are typically the hottest months of the year may have created the conditions observed where instead of groundwater inputs having a cooling effect (2019 and 2020; Figures 3-5 and 3-6), groundwater inputs had no effect or increased stream temperatures (2021; Figures 3-5 and 3-6). If future climate scenarios include prolonged heat waves in advance of the summer season, the cooling effects of shallow pathway groundwater contributions to streams, may not be enough to regulate thermal regimes to support cold water fish species.

3.4.2. Effects of physical watershed characteristics on spatial variability of stream temperature

Conducting a spatiotemporal analysis allowed this study to partition temporal and spatial effects and, in turn, identify watershed characteristics that are correlated with trends in stream temperatures. The variability in physical characteristics of each watershed played a strong role in determining stream thermal conditions. In fact, 57% of the variation in stream temperature across the study area was associated with physiography of the watersheds. This suggests that thermal regimes of individual watersheds differ from one another independent of generalized relationships with air temperature and groundwater, because of their particular physical/topographic characteristics. While previous literature has identified elevation as a key spatial variable that has a negative relationship with summer stream temperatures (Ward 1985; Isaak and Hubert 2001; Chang and Psaris 2013), the results from this study found that mean watershed elevation was not statistically related to mean weekly summer stream temperature (p=0.09). In contrast, results from this study emphasize the relationship between terrain complexity metrics and stream thermal regimes.

Simple linear regression analyses exploring physical watershed conditions that explain variation in thermal regimes across watersheds identified 2 key metrics; (1) mean terrain ruggedness index buffered within 100 m of stream channel ($p<0.001$, $r^2=81\%$); and, (2) mean vector ruggedness measure buffered with 200 m of stream channel ($p<0.001$, $r^2=79\%$). These two variables (terrain complexity metrics) are highly correlated (98%), and functionally describe very similar spatial conditions. The relationship between these terrain complexity metrics and stream temperatures can be explained as watersheds with more terrain complexity (more localized changes in elevation) within 100-200 m of the stream channel had lower summer stream temperatures. Previous literature has identified that terrain complexity can increase groundwater upwelling (Dugdale et al. 2015), riparian area shading (Webb and Zhang 1997; Johnson 2004; Moore et al. 2005), hyporheic exchange (Baxter and Hauer 2000; Harvey and Bencala, 1993), and reduce residency time to gain heat from surrounding environs (Segura et al. 2015). Watersheds with increased terrain complexity are likely cooler because of one or a combination of these factors. Watersheds with greater cross-sectional terrain complexity would be expected to have greater groundwater upwelling and riparian area shading on average, creating relatively cooler thermal regimes. Additionally, watersheds with greater longitudinal terrain complexity would be expected to have increased hyporheic exchange, which can also create cooler stream temperatures, and shorter streamflow residence times. Terrain complexity metrics are simple-to-use GIS tools that can aid future research and conservation efforts by predicting where stream temperatures are cooler at the watershed scale within Canadian Rocky Mountains.

Winter stream temperatures are studied more infrequently than summer stream temperatures, despite exerting important influence on the distribution and abundance of aquatic species (Fuhrman et al. 2018, McDonald et al. 2014). In winter, stream temperatures that are relatively warmer and less sensitive to changes in air temperatures are particularly important for fall-spawning salmonids such as Bull Trout (Baxter and McPhail 1999; McDonald et al. 2014). This work focused solely on summer stream temperatures, partly to limit the research to a reasonable scope, but also due to limited winter streamflow data. As such, spatiotemporal analyses of winter stream temperatures were not completed as part of this research; nevertheless, the relationships between average winter stream temperatures and both of the key terrain complexity metrics were explored. Both mean terrain ruggedness index buffered within 100 m of stream channel ($p=0.00505$, $r^2= 40\%$; Figure 3-11) and mean vector ruggedness measure buffered with 200 m ($p=0.00289$, $r^2=44\%$; Figure 3-12) had positive relationships with mean weekly winter stream temperatures. Previous literature has identified elevation as a principal watershed characteristic that is negatively related to stream temperature (Ward 1985; Beschta et al. 1987; Devine et al. 2021); however, mean watershed elevation was not statistically related to winter stream temperatures (p=0.344) across this study area. Similar to summer stream temperatures, the positive relationship between winter stream temperatures and terrain complexity metrics may be related to increased groundwater upwelling and hyporheic exchange. Although the relationships between the stream temperatures and terrain complexity metrics are not as good of a fit in the winter compared to summer (in part due to not conducting a spatiotemporal analysis to partition spatial and temporal effects), the simplicity of using terrain complexity to identify the relative thermal gradient of watersheds in the winter may be useful for research, monitoring and management across the Rocky Mountains of Alberta. The forgoing suggests terrain complexity may serve as a parsimonious landscape scale indicator of both summer and winter thermal refugia for cold water fish species.

3.5. Conclusions

Examining watershed scale thermal regimes using a spatiotemporal approach provided insight into variation in stream temperatures across the Rocky Mountains in Alberta. Generalized across all of the study watersheds, groundwater inputs were the most important hydrologic variable influencing summer stream temperatures, however, in contrast to Chapter 2, air temperature was a better predictor of stream temperatures than groundwater inputs. Critically, this research showed the importance of watershed characteristics (explaining 57% of variation in stream temperatures) in determining stream thermal regimes and identified terrain complexity as a strong predictor of watershed scale spatial variation in stream temperatures. Future research to test and verify terrain complexity as a predictor of stream temperatures across greater spatial scales, or a greater number of watersheds should be prioritized. Confirmation of a simple predictor such as terrain complexity would be invaluable for allocating management efforts/resources to aid fish conservation.

Table 3-1: Hydrologic and climatic variables used to predict temporal variation in mean weekly summer stream temperature across East Slopes Study Area, Alberta, Canada.

Variable Class	**Variable Name**	**Definition**
Hydrologic controls	Stream Discharge1	Mean weekly instantaneous discharge (m^3/s)
	Stream Discharge2	Weekly discharge (mm/week) corrected for watershed area
	Quickflow	Mean weekly instantaneous quickflow (m^3/s) derived from hydrograph separation that partitions stream discharge into quickflow and baseflow components
	Quickflow2	Weekly quickflow (mm/week) corrected for watershed area.
	Baseflow	Mean weekly instantaneous baseflow (m^3/s) derived from hydrograph separation that partitions stream discharge into quickflow and baseflow components
	Baseflow2	Weekly baseflow (mm/week) corrected for watershed area.
	Baseflow Index	Index of baseflow (mm/week) to total flow. Calculated as proportion of Baseflow2: Stream Discharge2.
Climatic controls	Mean air temperature	Mean weekly air temperature (°C)
	Max air temperature	Maximum weekly air temperature (°C)
	Min air temperature	Minimum weekly air temperature (°C)
	Air temperature range	Change in air temperature over a week (°C). Derived from difference between Max air temperature and Min air temperature variables.
	Precipitation	Sum of weekly precipitation in mm.

Table 3-2: Summary of meteorological stations used to summarize climate data for each study watershed

Stream Temperature Monitoring Location Name	Government of Canada Meteorological Station Name	Meteorological Station Latitude	Meteorological Station Longitude	Meteorological Station Elevation (Meters
Prairie Creek	Rocky Mountain House	52.4166	-114.9167	988
	Clearwater Auto	51.9900	-115.2400	1280
Bearberry Creek	Sundre A	51.7666	-114.6833	1114
	James River Ranger Station	51.8892	-114.9939	1200
Bow River	Lake Louise	51.4333	-116.2167	1524
	Bow Summit (New)	51.7000	-116.4667	2031
Mistaya River	Sask River Crossing 2	51.9666	-116.7167	1392
	Bow Summit (New)	51.7000	-116.4667	2031
Red Deer River	Yaha Tinda Auto	51.6500	-115.3600	1486
	Dogrib Creek	51.6700	-115.5100	1981
	Scalp Creek	51.8000	-115.6500	2042
	Scotch Camp	51.6667	-115.8140	1737
North Ram River	Ram Falls Auto	52.0900	-115.8400	1641
	Kootenay Plains Auto	52.0600	-116.4100	1294
	Nordegg CS	52.4667	-116.0830	1362
Little Red Deer	Water Valley	51.5000	-114.7167	1190
	Fallentimber Creek	51.5333	-115.1000	1555
	North Ghost Auto	51.5700	-114.8600	1477
Waiparous Creek	Ghost Ranger Station	51.3234	-114.9597	1472
	Ghost Diversion	51.3000	-115.1333	1600
Jumpingpound Creek	Cox Hill	51.0013	-114.9366	1675
	Compression Ridge	50.9000	-114.9167	1798
Fish Creek	Priddis Observatory	50.8691	-114.2917	1371
	Forget Me Not Mountain	50.7489	-114.7333	1739
Highwood River	Sullivan Creek	50.5108	-114.4392	1369
	Highwood Auto	50.4100	-114.7300	1576
	Mount Odlum III	50.4833	-114.9000	2060
	Lost Creek South	50.1738	-114.7100	2130
Willow Creek	Willow Creek Auto	50.2400	-114.3500	1446
Castle River	Westcastle	49.2833	-114.3667	1524
	Castle Auto	49.3900	-114.3400	1352
Mill Creek	Beaver Mines	49.4679	-114.1750	1257
	Beauvais Park	49.4166	-114.1000	1524
Pincher Creek	Prairie Bluff	49.3065	-114.0909	1570
Yarrow Creek	Spionkop Creek	49.2166	-114.0833	1861

Table 3-3:Model output for spatiotemporal model.

Variable	**Estimate**	**Standard Error**	**t-value**	**Pr(>|t|)**
Intercept	14.94359	0.19424	76.934	< 0.001
Scale (mean weekly air temp)	1.22967	0.06212	19.795	< 0.001
Scale (mean weekly baseflow_mm)	-0.80914	0.13918	-5.814	< 0.001
locationbowriver	-0.9116	0.51396	-1.774	0.077
locationcastleriver	-4.56652	0.25538	-17.882	< 0.001
locationfishcreek	0.70217	0.24386	2.879	0.004
locationhighwoodriver	-4.42479	0.25633	-17.262	< 0.001
locationjumpingpoundcreek	-6.22426	0.25064	-24.833	< 0.001
locationlittlereddeerriver	-1.20364	0.24432	-4.927	< 0.001
locationmillcreek	-2.00422	0.25003	-8.016	< 0.001
locationmistayariver	-0.48694	0.58312	-0.835	0.404
locationnorthramriver	-7.59651	0.24879	-30.534	< 0.001
locationpinchercreek	-6.76688	0.24885	-27.193	< 0.001
locationprairiecreek	-1.1061	0.24738	-4.471	< 0.001
locationreddeerriver	-4.09943	0.28845	-14.212	< 0.001
locationwaiparouscreek	-2.2325	0.24813	-8.997	< 0.001
locationwillowcreek	-3.40864	0.24377	-13.983	< 0.001
locationyarrowcreek	-4.56266	0.2546	-17.921	< 0.001
scale(woy)	0.43931	0.08238	5.333	< 0.001
factor(year)2020	0.20338	0.11756	1.73	0.084
factor(year)2021	0.78098	0.12471	6.263	< 0.001
scale(woy):factor(year)2020	-0.26452	0.11397	-2.321	0.021
scale(woy):factor(year)2021	-0.88774	0.11591	-7.659	< 0.001

Residual standard error: 0.869 on 372 degrees of freedom

Multiple R-squared: 0.9297, Adjusted R-squared: 0.9255

F-statistic: 223.6 on 22 and 372 DF, p-value: < 2.2e-16

Table 3-4: Results from simple linear regression analyses between watershed coefficients and spatial variables. Spatial variables are sorted by r^2 value.

Spatial Variable	Estimate	Standard Error	t-value	p-value	r^2 value
Mean TRI buffered 100m around Stream Channel	-0.4829	0.0597	-8.089	< 0.001	0.811
Mean VRM buffered 200m around Stream Channel	-1386.34	180.9362	-7.662	< 0.001	0.794
Mean VRM buffered 50m around Stream Channel	-559.07	77.8645	-7.18	< 0.001	0.771
Mean VRM buffered 100m around Stream Channel	-945.689	133.7056	-7.073	< 0.001	0.766
Mean TRI buffered 200m around Stream Channel	-0.4299	0.0609	-7.06	< 0.001	0.765
Mean VRM buffered 25m around Stream Channel	-368.237	52.438	-7.022	< 0.001	0.763
Mean TRI buffered 50m around Stream Channel	-0.4828	0.0697	-6.927	< 0.001	0.758
Mean TRI buffered 25m around Stream Channel	-0.51084	0.07783	-6.564	< 0.001	0.737
Mean Watershed TWI	3.2168	0.5719	5.625	< 0.001	0.671
Mean TWI buffered 25m around Stream Channel	2.1727	0.4346	5	< 0.001	0.615
Mean Watershed VRM	-1042.38	224.3326	-4.647	< 0.001	0.579
Mean TWI buffered 50m around Stream Channel	1.7498	0.4571	3.828	0.002	0.477
Mean TWI buffered 200m around Stream Channel	1.944	0.514	3.782	0.002	0.470
Mean TWI buffered 100m around Stream Channel	1.6768	0.4813	3.484	0.004	0.426
Mean Watershed TRI	-0.17484	0.06259	-2.794	0.014	0.312
Channel Density	21.837	8.383	2.605	0.021	0.279
Channel Slope	-102.147	41.752	-2.446	0.028	0.250
Mean Watershed Elevation	-0.00339	0.001865	-1.815	0.091	0.133
Mean Solar Radiation Buffered 200m around Stream Channel	1.22E-04	7.85E-05	1.552	0.143	0.086
Distance from Continental Divide	2.46E-05	1.88E-05	1.31	0.211	0.046
Mean Watershed Solar Radiation	7.78E-05	7.40E+00	1.052	0.311	0.007
Watershed Area	0.001444	0.002349	0.615	0.548	0.026

Figure 3-1: Site map outlining Study Area and instrumented watersheds in the Rocky Mountains and Foothills of Alberta, Canada

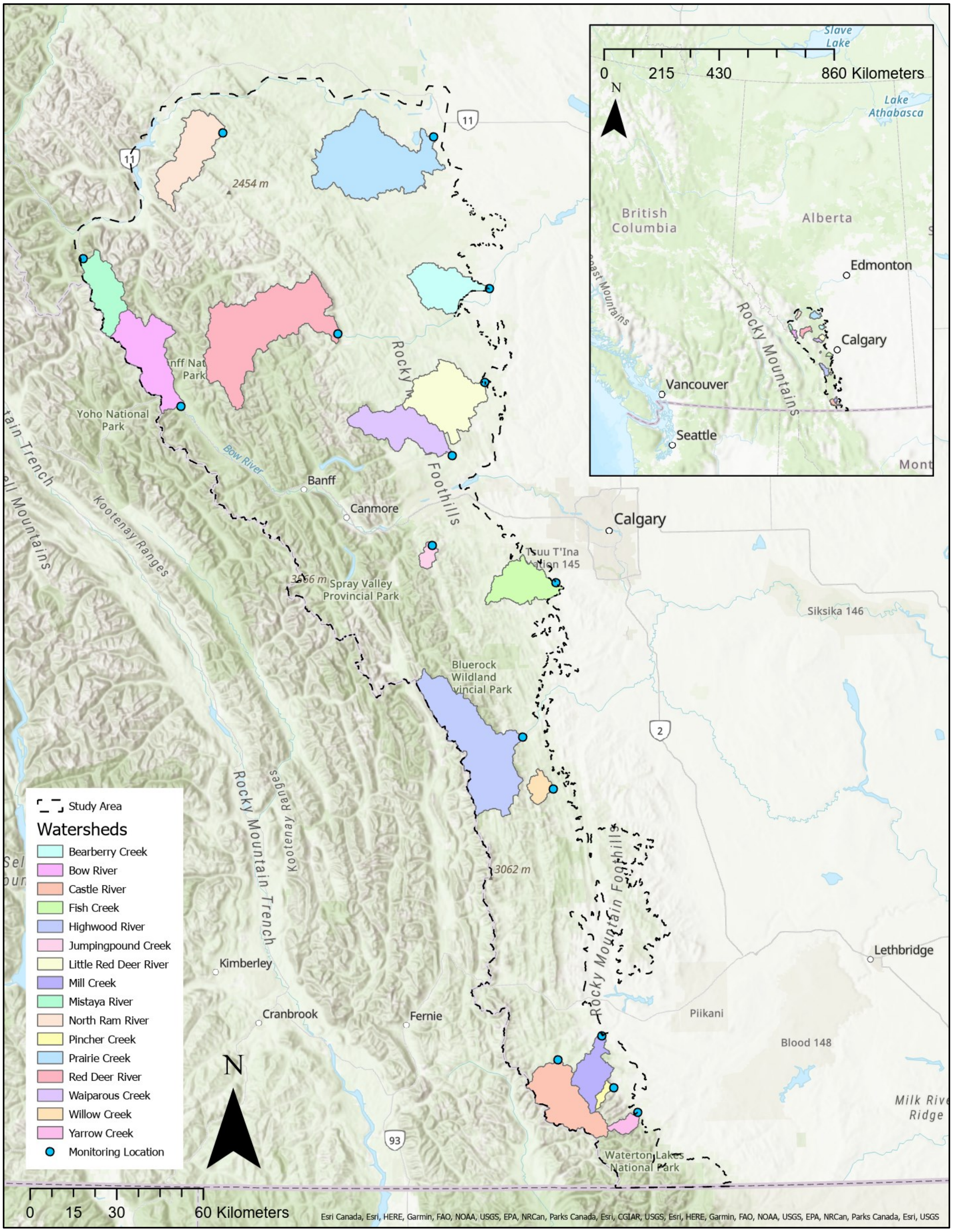


Figure 3-2: Relationship between mean weekly stream temperature (fitted values) and mean weekly air temperature for each study watershed (2019-2021).

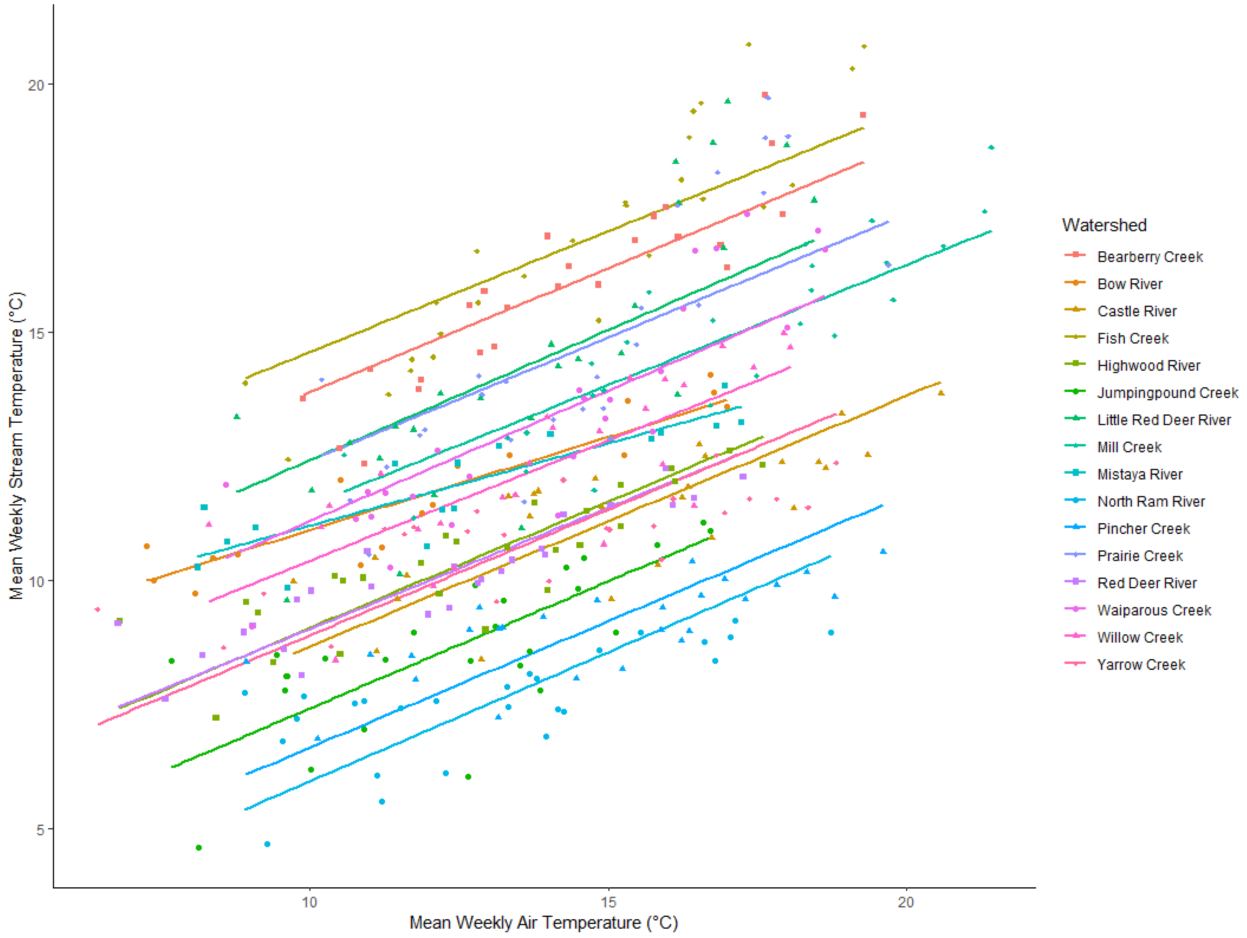


Figure 3-3: Relationship between mean weekly stream temperature (fitted values) and mean weekly baseflow for each study watershed (2019-2021).

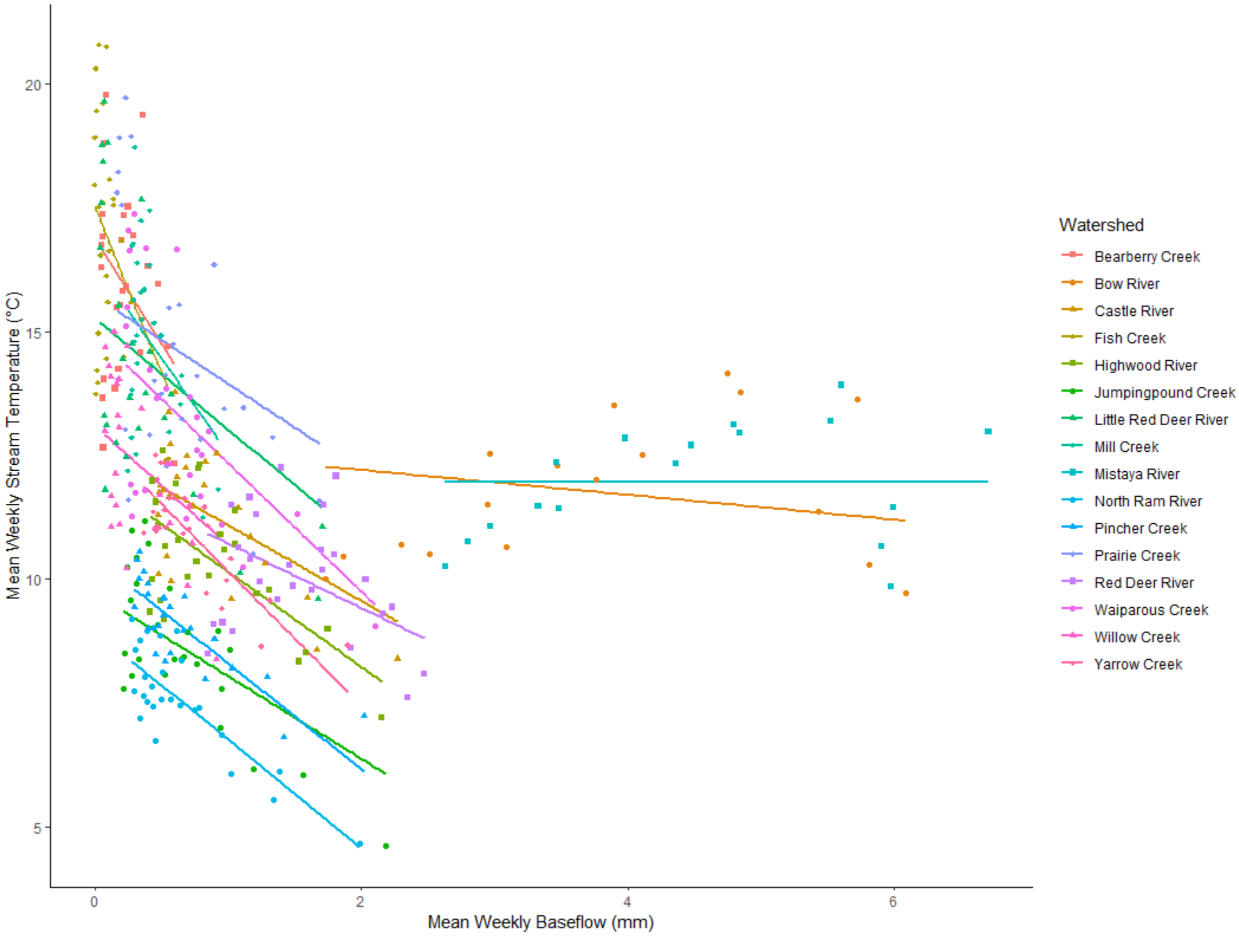


Figure 3-4: Relationship between mean weekly stream temperature (fitted values) and mean weekly air temperature for each study watershed in 2019, 2020, and 2021

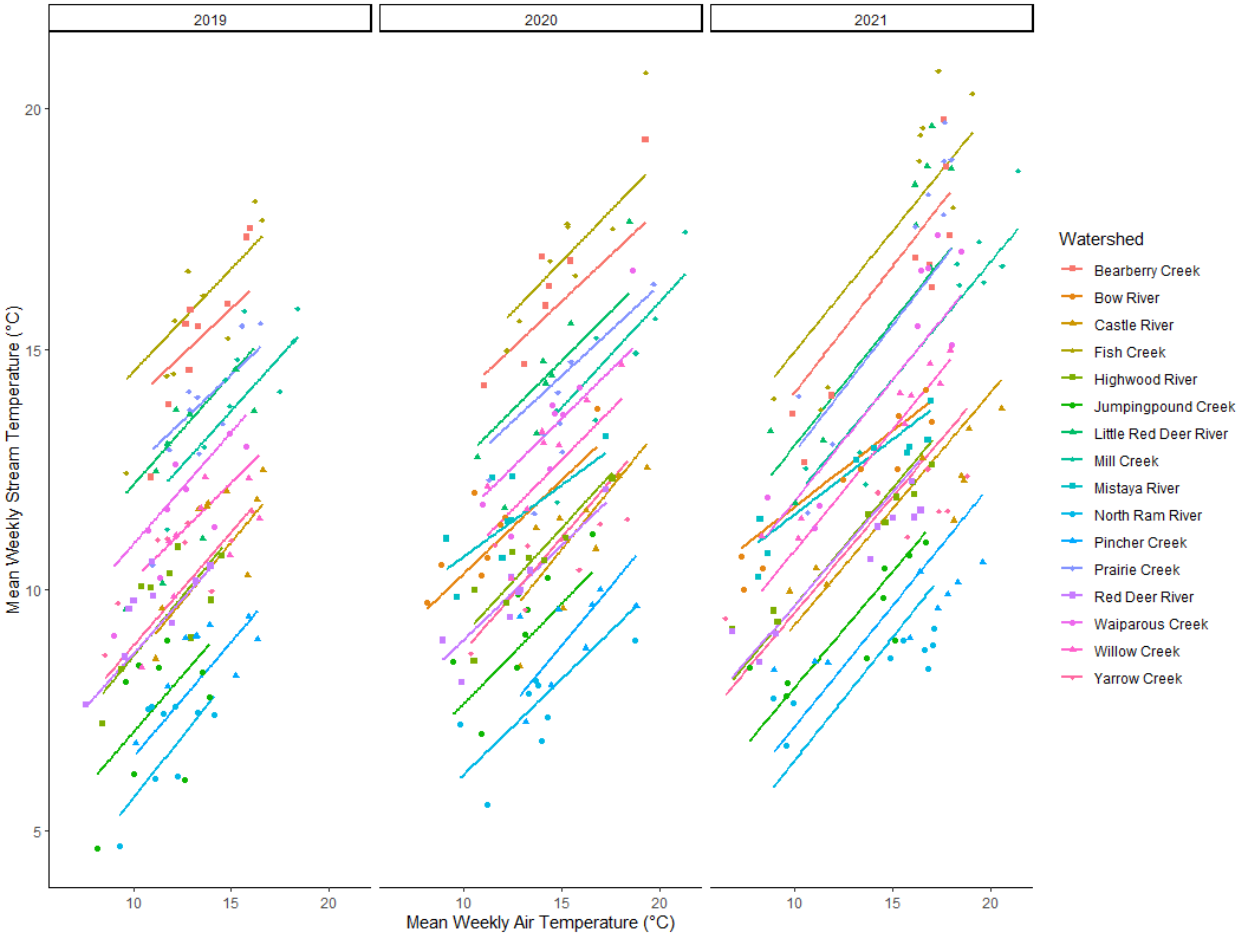


Figure 3-5: Relationship between mean weekly stream temperature (fitted values) and mean weekly baseflow for each study watershed in 2019, 2020, and 2021.

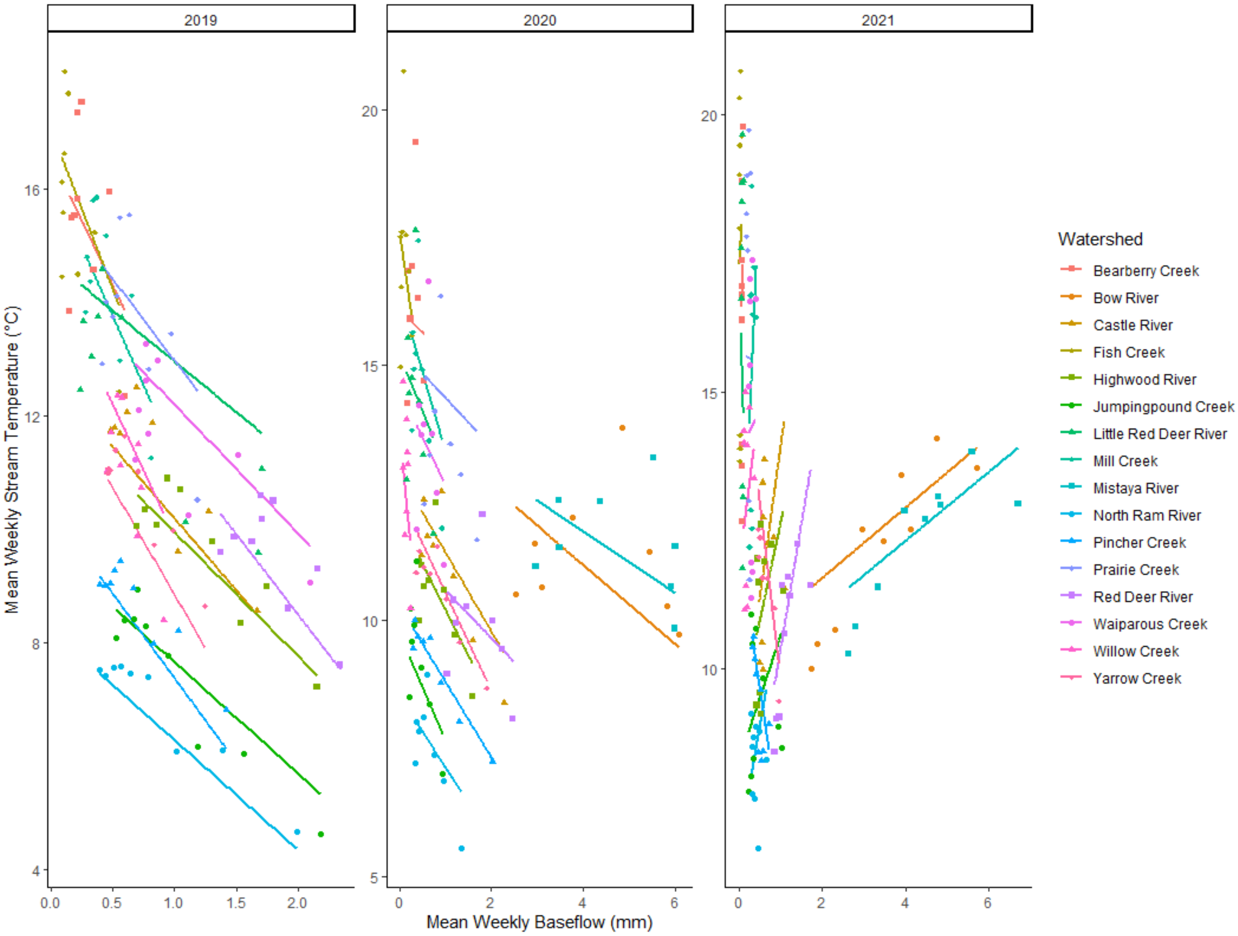


Figure 3-6: Relationship between mean weekly stream temperature (fitted values) and mean weekly baseflow for each study watershed (excluding Bow River and Mistaya Rivers) in 2019, 2020, and 2021.

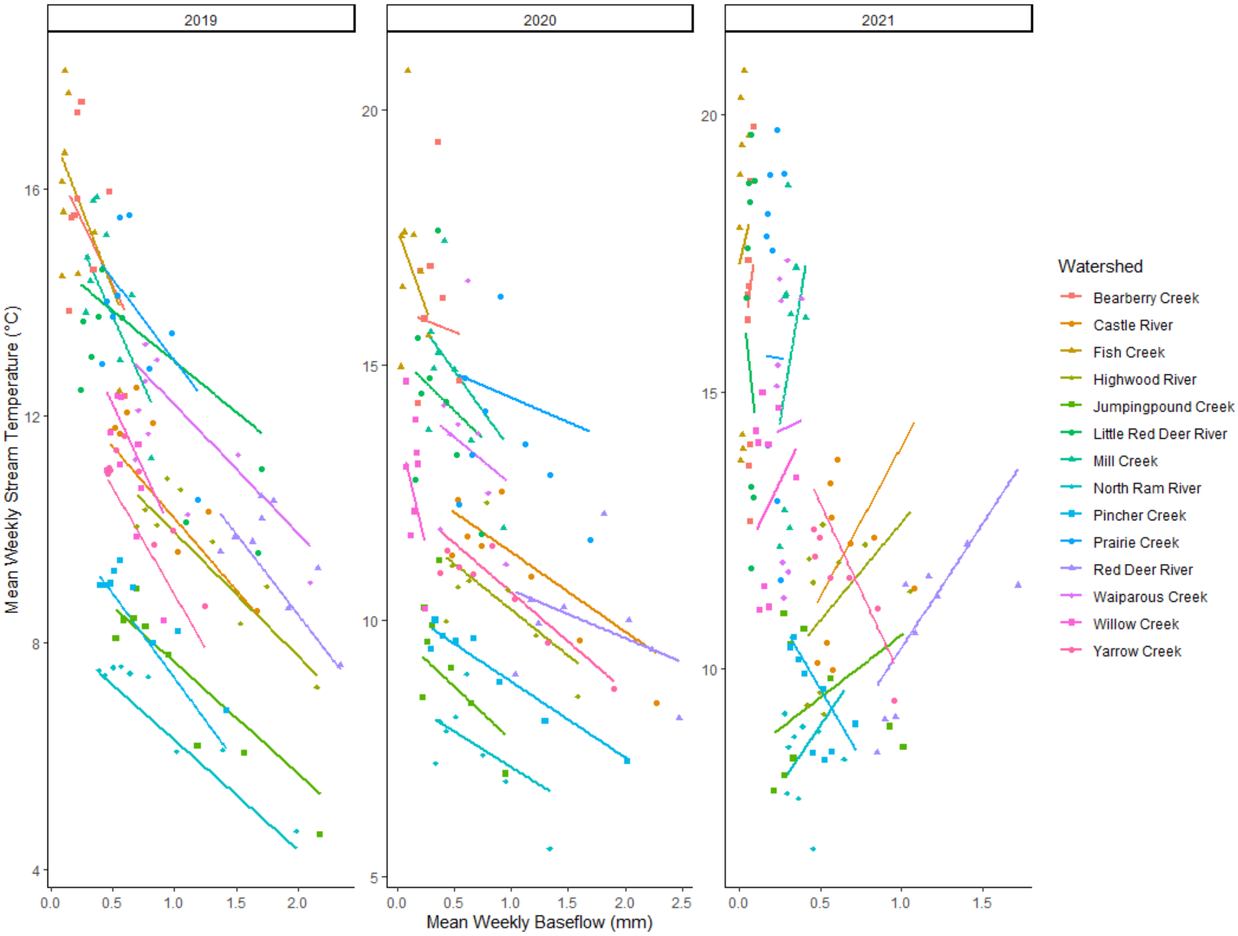


Figure 3-7: Relationship between mean weekly and week of the year (WOY) for each study watershed in 2019, 2020, and 2021.

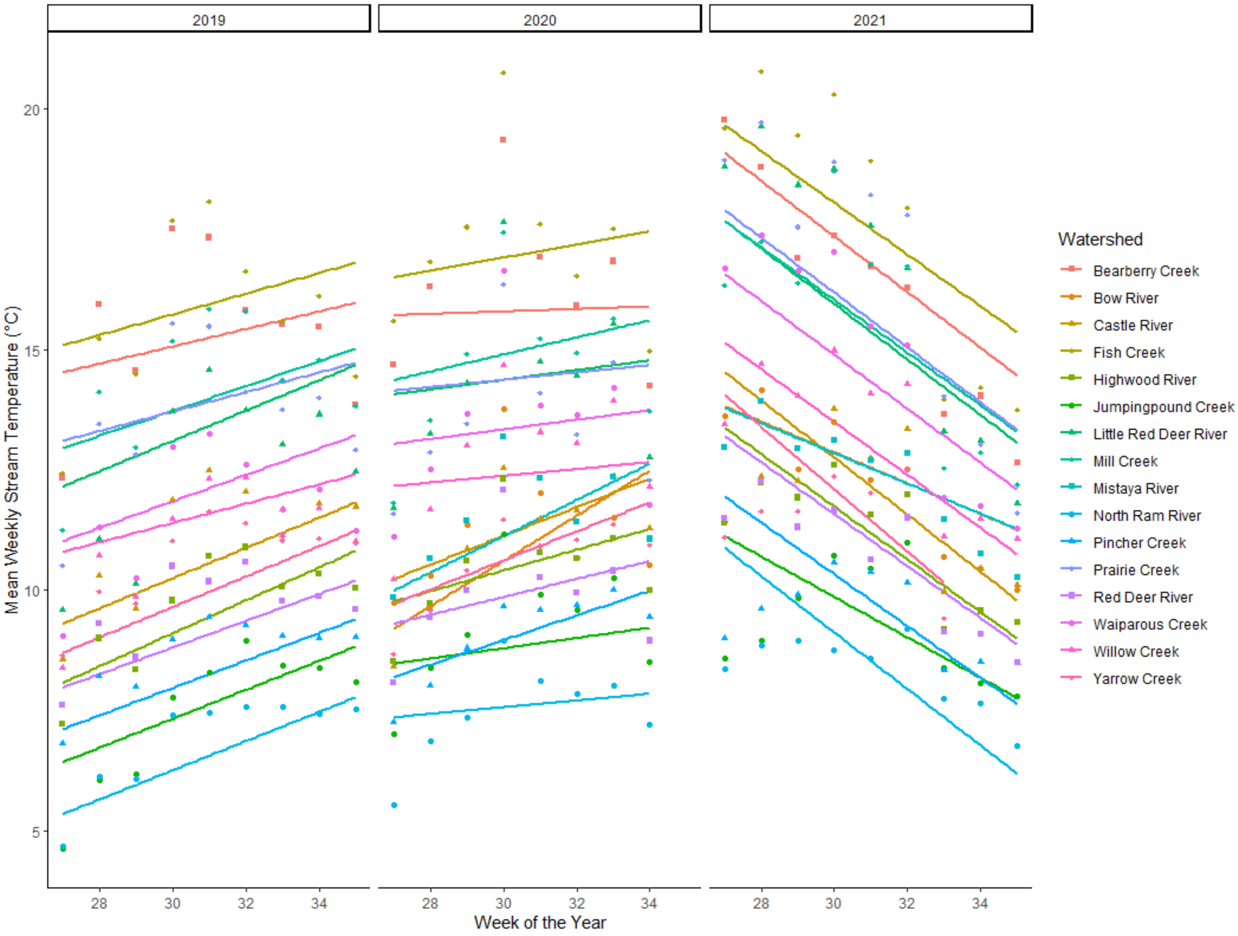


Figure 3-8: Spatiotemporal model residual variance for each study watershed. Box indicates upper/lower quartiles, horizontal line=median, vertical lines=upper/lower+/-1.5*IQR (Inter Quartile Range) percentile, dots=outlying points.

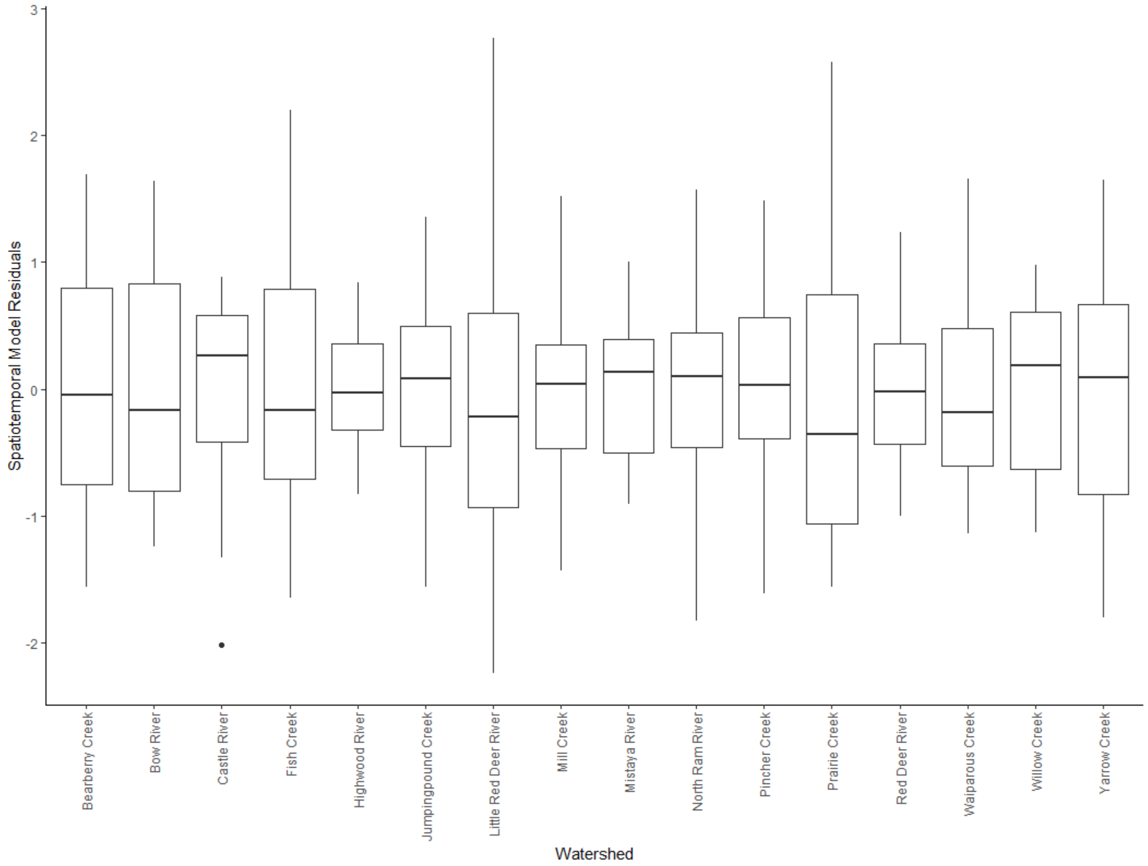


Figure 3-9: Relationship between the mean watershed effect (mean annual stream temperature after standardization (removal) of temporal effects) on summer stream temperature and Terrain Ruggedness Index buffered within 100 m of stream channel. The solid line represents the linear relationship between watershed effects and TRI and can be expressed as y=17.636-0.4829x. Watershed symbols are the spatiotemporal model outputs for each Watershed location and reflect the average summer stream temperature in 2019. The relative difference in mean stream temperature between watersheds would not change year to year, as year effects were accounted for by another variable in the spatiotemporal model

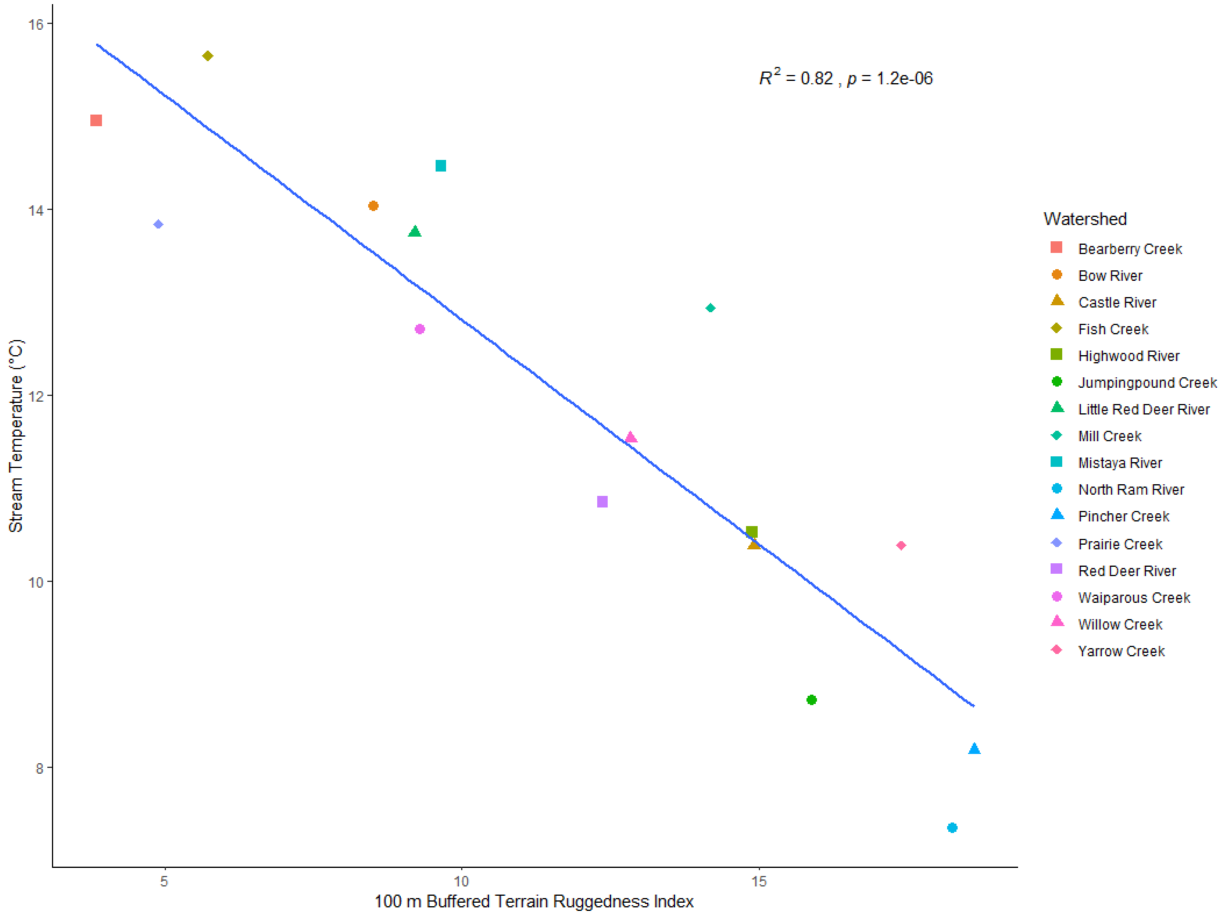


Figure 3-10: Relationship between the mean watershed effect (mean annual stream temperature after standardization (removal) of temporal effects) on summer stream temperature and Vector Ruggedness Measure buffered within 200 m of stream channel. The solid line represents the linear relationship between Watershed effects and VRM and can be expressed as y=16.1953-1386.3407x. Watershed symbols are the spatiotemporal model outputs for each Watershed location and reflect the average summer stream temperature in 2019. The relative difference in mean stream temperature between watersheds would not change year to year, as year effects were accounted for by another variable in the spatiotemporal model.

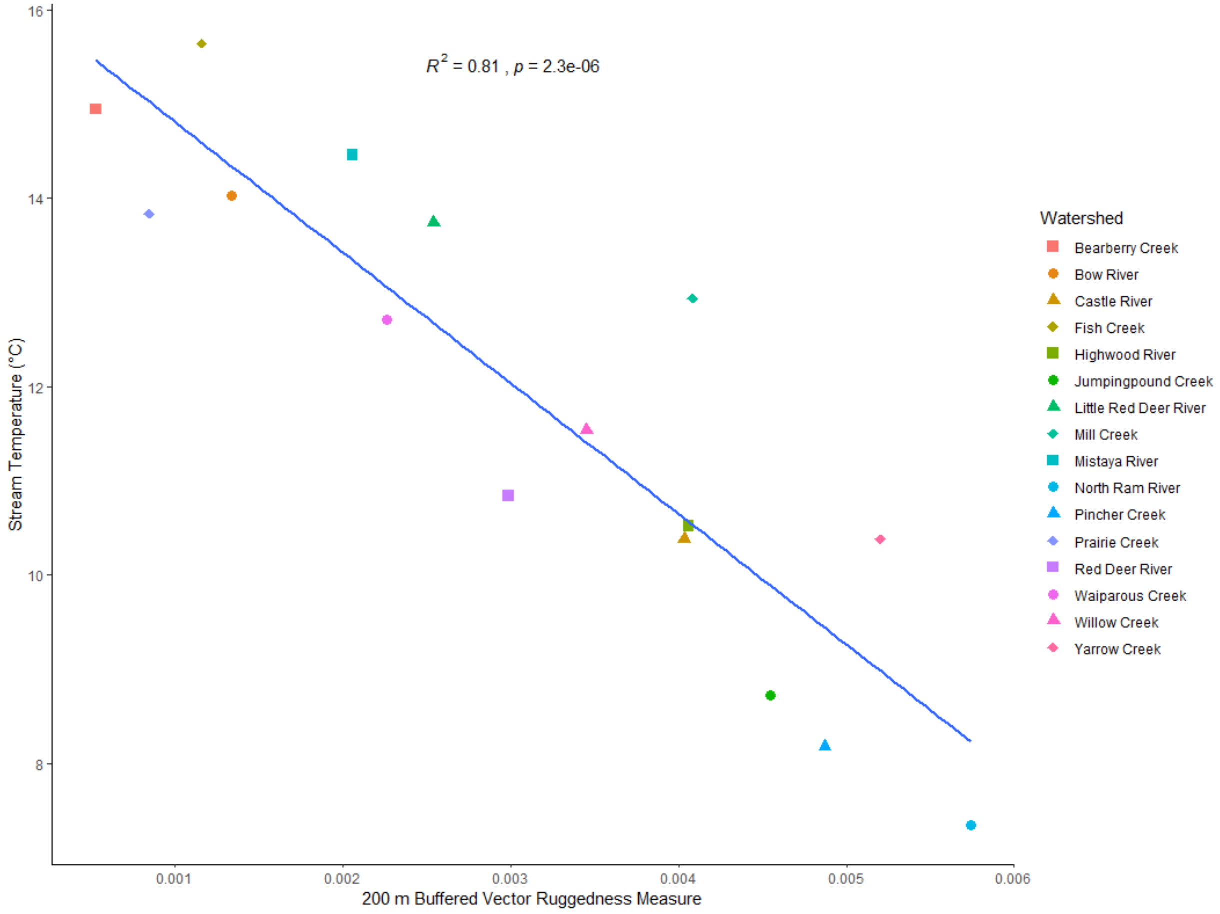


Figure 3-11: Relationship between the winter mean weekly stream temperature and Terrain Ruggedness Index buffered within 100 m of stream channel. The solid line represents the linear relationship between Watershed effects and TRI and can be expressed as y=-0.39918+0.04962x. Watershed symbols are the mean weekly winter stream temperature between 2019-2021. Watershed symbols are the mean weekly winter stream temperatures for 2019-2021.

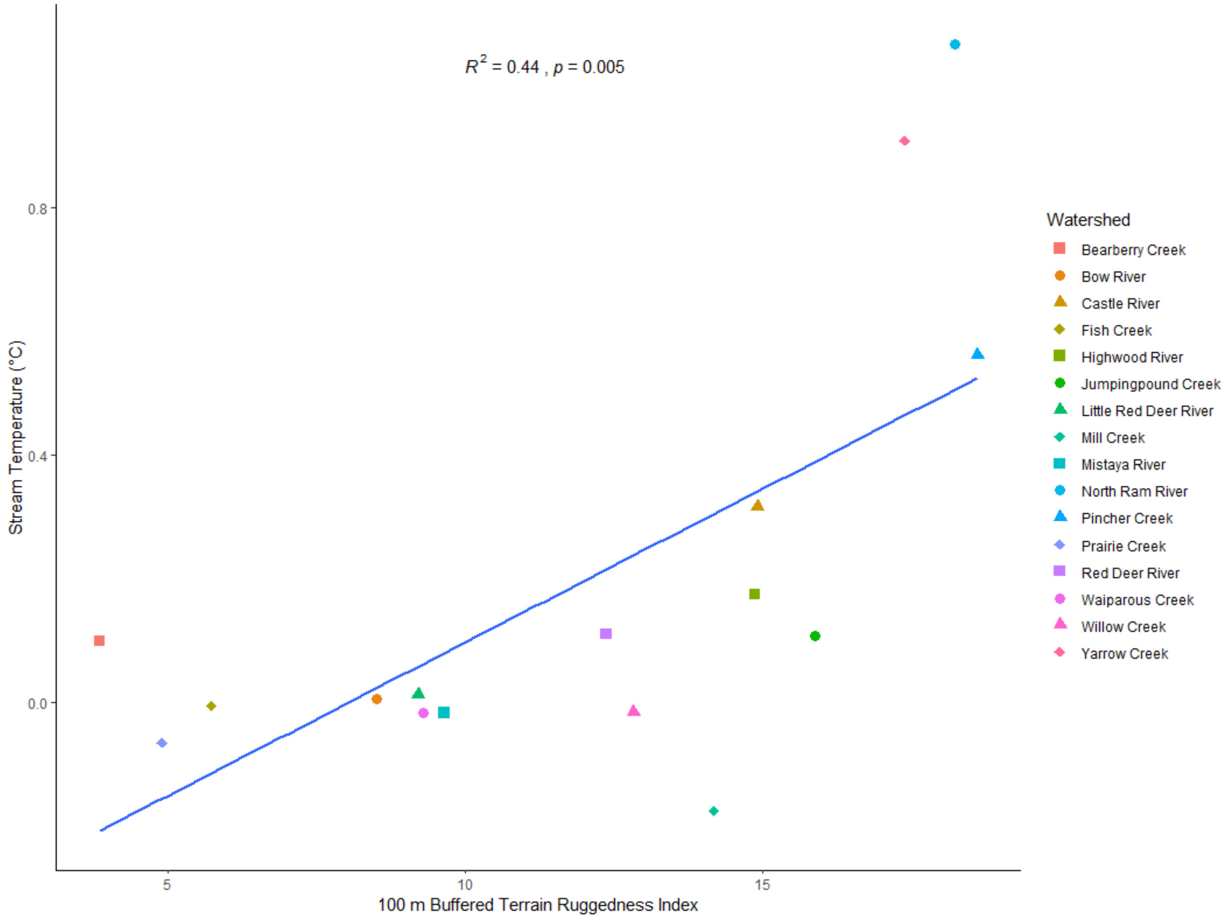
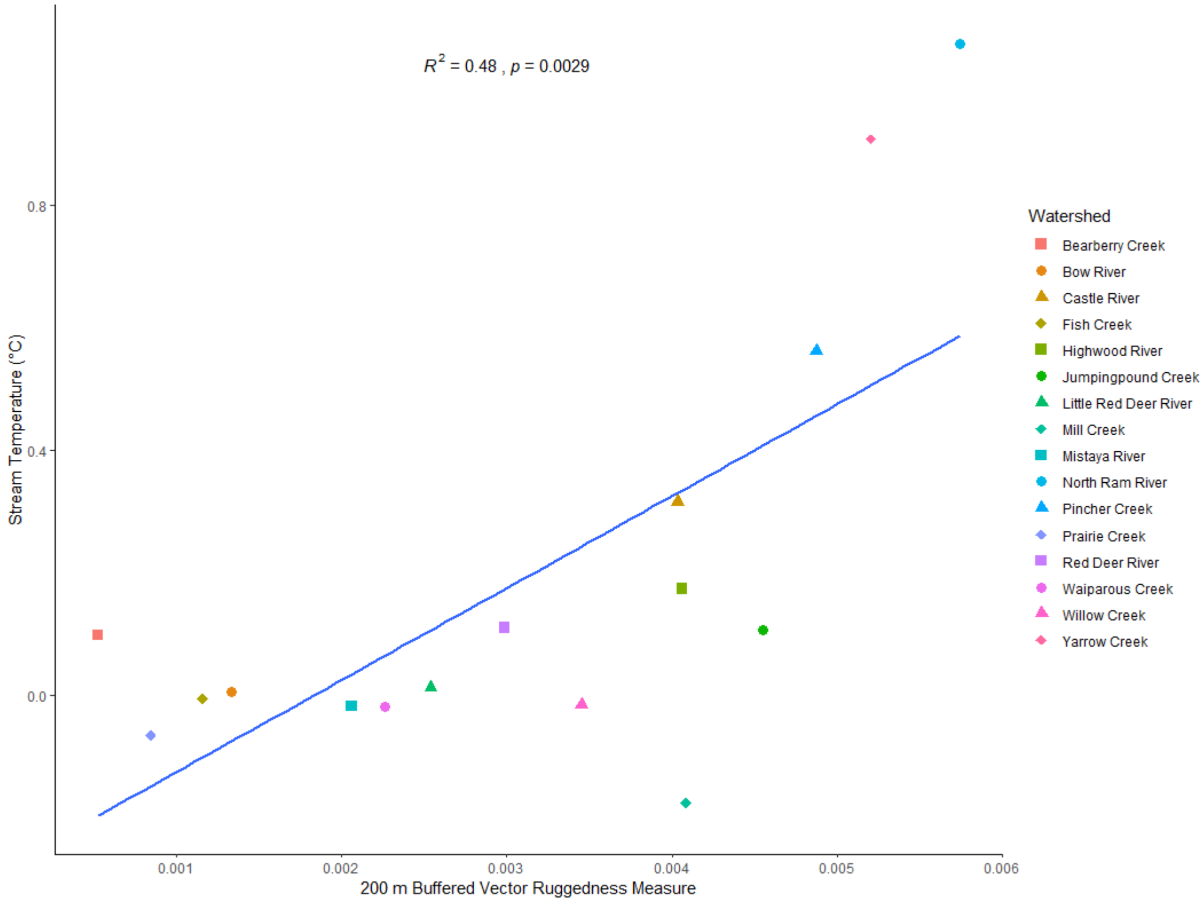


Figure 3-12: Relationship between the winter mean weekly stream temperature and Vector Ruggedness Measure buffered within 200 m of stream channel. The solid line represents the linear relationship between watershed stream temperatures and VRM and can be expressed as y=-0.2756+150.3521x. Watershed symbols are the mean weekly winter stream temperatures for 2019-2021.



Chapter 4. Synthesis

This thesis utilized two datasets to examine spatial and temporal patterns of stream temperature in the Canadian Rocky Mountains: 1) a long-term dataset (2005-2018) covering seven sub-catchments in close proximity that exhibited temporal variability in stream temperatures and the variables that influence stream temperatures (e.g. climatic and hydrologic controls); 2) a spatially diverse dataset that included a variety of watersheds and watershed conditions in a 28648 km^2 area within the Eastern Slopes of the Rocky Mountains in Alberta collected over three years (2019-2021). This chapter summarizes key findings, their potential implications and recommendations for future research.

4.1. Summary of Key Findings

In Chapter 2, a post-hoc assessment of a subset of the SRWP dataset containing continuous stream temperature, air temperature and streamflow data (2005-2018) was conducted to understand temporal variation in stream temperature and the influence of climatic and hydrologic controls. Multiple linear regression was used to model summer mean weekly stream temperature as a function of hydrologic and climatic variables for each of the seven sub-catchments. Across all sub-catchment models, the predictor variables that best explained variation in stream temperatures were mean weekly air temperature (climatic control) and groundwater contribution to streamflow (hydrologic control). Stream temperatures were negatively correlated with groundwater contribution ($p<0.001$) and positively associated with air temperature ($p<0.001$). Multiple regression analyses showed groundwater had a far greater influence on stream thermal regimes compared to air temperature where partitioned r^2 for groundwater contribution variables were 0.41-0.65 compared to 0.09-0.36 for air temperature variables. Across all models, groundwater contribution explained 1.3-6.9 times more variability in stream temperature compared to air temperature. The relationship between stream temperature and groundwater contribution varied across the 7 sub-catchments suggesting that groundwater varied in source (deep source vs shallow source) and quality (temperature).

In Chapter 3, an empirical spatiotemporal stream temperature model was developed using data from 16 watersheds across a geographically diverse study area between 2019-2021. Coefficients from the spatiotemporal model that parameterize the mean effect of each watershed on summer stream temperature were used to identify watershed characteristics that promote watershed-scale cooler mean summer stream temperatures. The spatiotemporal model was particularly robust (adjusted

$r^2=0.93$) and identified; 1) stream temperatures were positively correlated with variation in air temperature ($p<0.001$) negatively correlated with the mean weekly baseflow ($p<0.001$); 2) a year effect ($p<0.001$) due to anomalous weather event ("Heat Dome") where mean summer stream temperatures were elevated and the previously observed (in 2019 and 2020) cooling effect of groundwater contributions were variably altered across the watersheds; 3) a strong spatial effect where inclusion of the factor variable "Watershed" improved the r^2 value by 57%. Finally, watersheds with more terrain complexity (more localized changes in elevation) within 100-200 m of the stream channel had lower summer stream temperatures ($p<0.001$, $r^2=79\text{-}81\%$), and warmer winter temperatures ($p<0.05$, $r^2=40\text{-}44\%$).

Collectively Chapter 2 and Chapter 3 emphasize the importance of considering groundwater as a key control of stream thermal regimes, particularly in the Rocky Mountains of Alberta. In both Chapters, continuous groundwater data, derived from baseflow separation techniques applied to streamflow data, were important components to understanding stream thermal regimes. Across all models in both Chapters, the baseflow component of streamflow (the groundwater contribution variable) was the best hydrologic variable for predicting stream temperatures, when compared to total streamflow, quickflow and an index of baseflow to total streamflow (BFI). The fact that the baseflow component of streamflow improved all models in both Chapters better than the BFI variable lends credibility to the idea discussed in Chapter 2 that there is high variability in groundwater quality (temperatures), particularly shallow source groundwater. While most stream temperature research considers climatic variables, this thesis quantifies and emphasizes the importance of the energy fluxes related to advective mixing of groundwater with streams and rivers.

4.2. Recommendations for Future Research

Chapter 2 identified the importance of groundwater contribution, but also identified that there was likely high variability in quality (temperature) of groundwater entering streams. To date, research has explained how these different groundwater pathways vary mechanistically, but researchers are yet to quantify deep versus shallow pathway groundwater as continuous components of total streamflow. If baseflow components of hydrographs were partitioned into deep source groundwater and shallow source groundwater, analyses could determine their relative control on thermal regimes. An obvious extension of the work done in Chapter 2, would be to conduct research to compare the relative influence of climatic controls versus hydrologic controls, with total streamflow partitioned into quickflow, shallow pathway groundwater and deep pathway groundwater. Combining stream isotope analyses to identify deep groundwater proportion (Peralta-Tapia et al. 2015), in combination with hydrograph separation analyses has potential to be used to estimate continuous deep groundwater contribution to streamflow. This would be invaluable for refining characterization of watershed scale controls on stream temperature, and identifying watersheds with greater deep groundwater control which would likely be more resilient to climate change impacts.

The SRWP dataset used in Chapter 2 could be appended to conduct a Before After Control Impact study testing the effect of a forest harvest on stream thermal regimes and changes to relative climatic and hydrologic controls. In 2015, an experimental forest harvest was applied to Star Creek watershed (Silins et al. 2016), but not the neighboring North York Creek watershed. The dataset and outcomes from Chapter 2 could be used as the "before" conditions, and the effects of the harvest on Star Creek relative to control conditions in North York Creek could be assessed. Changes to thermal regimes (i.e., average summer stream temperature) after harvest could be assessed, but more importantly, the dataset could answer whether the relationships between stream temperature and fundamental controls are altered after the experimental forest harvest. Previous literature has observed increases in stream temperatures after forest harvest (Rishel et al. 1982; Bourque and Pomeroy 2001; Moore et al. 2005) but has not quantified the change in underlying climatic and hydrologic mechanisms that controlling stream temperature. Quantifying changes to relationships between thermal regimes and climatic and hydrologic controls could help explain differences in different thermal regime control sensitives to disturbance.

Chapter 3 identified watershed characteristics (related to terrain complexity) strongly associated with relatively cooler stream temperatures in summer and relatively warmer stream temperatures in winter. The analysis was conducted on a sample of watersheds within a larger study area. An obvious extension of the Chapter 3 results is to apply the relationship between stream temperature and terrain complexity to all watersheds within the study area, or a broader study area, and then test the fit of the relationship using empirical data. Application of the relationship between stream temperature and terrain complexity is relatively simple to complete and would only require computer desktop processing to; 1) convert a DEM into watersheds; 2) delineate and buffer stream networks; 3) calculate and summarize terrain complexity within stream buffers; 4) apply linear relationships from Chapter 3 to summarized terrain complexity values. The output of this process would be an estimation of average relative stream temperature by watershed, which could identify where stream temperatures are relatively cooler in summer and relatively warmer in winter. Since stream temperature data is relatively simple to collect, and there may be existing data available, estimated stream temperatures based on terrain complexity could be compared to empirical data to test the fit of the relationship across larger datasets. Conducting this research could increase confidence in terrain complexity as a proxy indicator of stream thermal regimes and potentially make it a critical resource for fisheries conservation and management.

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