AIR - WATER TEMPERATURE RELATIONSHIPS IN THE TROUT STREAMS OF SOUTHEASTERN MINNESOTA'S CARBONATE - SANDSTONE LANDSCAPE: IMPLICATIONS FOR CLIMATE CHANGE, BROWN TROUT BIOLOGICAL PROCESSES, AND LAND MANAGEMENT

by

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A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Water Resources Science

at

The University of Minnesota

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June 2012

ACKNOWLEDGMENTS

I would like to thank Legislative - Citizen Commission on Minnesota Resources for administering Minnesota Environment and Natural Resource Trust Funds used for this project and to Mark Ebbers and Vaughn Snook (Minnesota Department of Natural Resources), Toby Dogwiler (Southeastern Minnesota Water Resource Science Center at Winona State University), and David Huff, formerly with the University of Minnesota Conservation Biology Program, for generously supplying data for this study. I would also like to extend my gratitude to the co - authors of the resulting manuscript which comprises chapter 1 of this thesis: Dr. Joe Magner, Research Professor with the Department of Bioproducts and Biosystems Engineering, University of Minnesota; Dr. Jim Perry, Professor with the Department of Fisheries, Wildlife and Conservation Biology, University of Minnesota; Dr. Bruce Vondracek, Assistant Unit Leader with the U. S. Geological Survey and Minnesota Cooperative Fish and Wildlife Research Unit; Dr. Leonard C. Ferrington Jr., Professor with the Department of Entomology, University of Minnesota. I would also thank graduate students Petra Kranzfelder, William French, Jane Mazack and Patrick Sherman with the University of Minnesota's Stenotherm Research Group for feedback throughout the duration of this project.

ABSTRACT

Carbonate - sandstone geology in southeastern Minnesota creates a heterogeneous landscape of springs, seeps, and sinkholes that supply groundwater into streams. Air temperatures have been shown to be effective predictors of water temperature in surface - water dominated streams. However, no published work investigates the relationship between air and water temperatures in groundwater - fed streams across watersheds. We used simple linear regression models to examine air - water temperature relationships for 40 groundwater - fed streams in Southeastern Minnesota. A 40 - stream, weekly time scale, composite linear regression model has an R^2 of 0.83, a slope of 0.38, and an intercept of 6.63. Regression models were also combined by common intercept and slope and split into winter and non - winter air temperature regimes to allow approximation of winter water temperature regimes based on non - winter data. The air - water temperature relationships for groundwater - fed streams are different in slope and intercept compared to surface - water dominated streams. The high R^2 values demonstrate that air - water temperature regression models for groundwater - fed streams may be useful in predicting the thermal regimes for these systems under future climate scenarios. Climate change is expected to alter the thermal regime of groundwater - fed systems but will most strongly affect streams that are more vulnerable to climate change and will do so at a slower rate than surface - water dominated systems. A regression model of intercept *vs.* slope can be used to identify streams for which water temperatures are more meteorologically controlled than hydrologically controlled, and thus more vulnerable to climate change, with evidence provided by an investigation into the resulting mean summer water temperature under a moderate climate change scenario for various types of linear regression models. Modeling the possible increases in mean summer water temperature provides insight into the potential effects of climate change on the amount of suitable brown trout habitat as well as the possible effects on brown trout biological processes and behavior. Information on possible future thermal conditions and can be used to guide restoration versus management strategies to protect the thermal integrity of trout streams and ensure the persistence of their stenothermic communities.

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Introduction

Groundwater - fed streams (GWFS) support trout and other members of coldwater ecosystems, known as cold and ultra - cold stenotherms, that have biological temperature preferences below 20^{o} C (Lessard and Hayes, 2003). These streams are economically, aesthetically, and recreationally valuable resources. The Explore Minnesota State Tourism Office reported in 2009 that they "received requests from all 50 states regarding fishing opportunities in our state," (http://www.prestonmn.org/NTLC_Magazine_330.pdf). Further, "spending by trout anglers in the four - state Driftless Area [Minnesota, Iowa, Wisconsin, and Illinois] totals nearly $647 million, a conservative estimate," (Trout Unlimited, 2008).

Many stakeholders could benefit from knowledge of the relationship between air and water temperatures in GWFS. Researchers studying the effects of climate change on GWFS could benefit from knowing when and how climate change may affect these systems. Also, researchers interested in the thermal dynamics of such streams could use such information for its predictive potential. State and local agencies that manage natural resources (e.g., the Minnesota Pollution Control Agency and the Minnesota Department of Natural Resources) could use such information to prioritize streams for management activity and restoration. Trout anglers, as well as landowners adjacent to trout streams, would also be interested in knowing how and what may cause temperature changes in these streams.

Two different methods are typically employed to estimate stream water temperature. Energy budget equations that govern heat transfer and flow are one of the most accurate methods for predicting water temperature (Gu *et al*., 1998). However, energy budget equations have numerous parameters, which require very specific measurements that are time consuming to obtain. In lieu of such equations, ambient air temperatures have been shown to have an important influence on stream water temperature (Gu *et al*., 1998; Pilgrim *et al*., 1998). This influence can be detected in surface - water fed streams (SWFS) and GWFS. Air - water temperature relationships are a useful, less involved method for understanding these complex systems. The R^2 values from such regression models help deduce the relationship that a stream has with local groundwater (O'Driscoll and DeWalle, 2004). There have been many studies on air - water temperature relationships in stream and river systems but have included few GWFS; for examples, see Pilgrim *et al.* (1998), Erickson *et al.* (2000), Stefan and Preud'homme (1993) and Morrill *et al.* (2005). A study by O'Driscoll and DeWalle (2004) specifically evaluated air - water temperature relationships in groundwater - fed systems, but studied only one watershed and did not discuss the influences that affect GWFS.

Morrill *et al.* (2005) and Pilgrim *et al.* (1998) found that climate change is expected to affect surface water temperatures. However, less is known about the likely influence on groundwater temperatures. Meisner (1988) suggests that groundwater temperatures may increase by the same magnitude as mean annual air temperatures. Climate change could imperil our coldwater environments; mitigation through riparian land management may be the most promising action to limit the negative effects of climate change and adverse impacts to stenotherms.

The purpose of this study was to investigate the relationship between air and water temperatures in groundwater - fed systems in a carbonate - sandstone landscape and to identify the implications of that relationship for land management and climate change. Carbonate - sandstone landscapes are unique yet highly vulnerable systems that require intensive attention, understanding, and management. We investigated how regression models depict the thermal regime for GWFS, how this relationship varies from stream to stream and differs from SWFS. We describe how linear regression models of air - water temperatures relate to groundwater inflow and how air temperature affects groundwater temperature. We show how a regression model of intercept *vs.* slope can depict mechanisms of water temperature control, suggest which streams are more susceptible to climate change, and how this susceptibility can inform stream management decisions for prioritization of restorative or protective measures. We compare our study to similar ones and describe the necessary considerations for the context of our study. We discuss the relationship between the regression models and other characteristics of the data. We describe the possible causes of residual variation and which environmental features have the most influence on water temperature in GWFS. Lastly, we comment on how these regression models can be used to predict water temperatures under various future climate scenarios with a conclusion about how climate change may affect our study streams.

Study Area

The study area is 7,210 km^2 and includes seven counties in the southeastern Minnesota Driftless Region (FIGURE 1). Streams in this area of Minnesota generally range from first to fifth order. Our study area is comprised of sedimentary bedrock with sequences of limestone, dolostone, shale and sandstone (MNDNR Waters, 2001). The bedrock is capped with varying thickness of loess, colluvium and alluvium in the riparian corridors. In the Pleistocene Epoch, glacial melt water defined the landscape terrain of the Driftless Area when large volumes of runoff scoured through the bedrock to form the streams of southeastern Minnesota. Carbonate rocks comprised of calcite, dolomite and smaller amounts of other minerals were readily eroded to create a heterogeneous set of hydrogeological features. Although selected areas in southeastern Minnesota are classified as karst geology with well - developed surface features such as springs and sinkholes, the majority of southeastern Minnesota is classified as incipient karst, in which groundwater recharge primarily occurs via soil infiltration as water passes beyond the root zone through fractures in the bedrock. Groundwater flowing through these features discharges into streams, creating essential habitat for coldwater species.

Thermal patterns of groundwater at spring sources are generally considered highly dampened relative to ambient air temperatures. However, in areas such as southeastern Minnesota where the bedrock composition can be complex and variable over fine spatial scales, groundwater temperatures have the potential to be more variable (Luhmann *et al.,* 2011), which can add complexity to the pattern of stream temperatures in areas with focused groundwater input. In this study, we selected trout streams that remain cool during summer and usually do not completely freeze over during winter, making it was possible to measure water temperature year - round. Year - round temperature records provide more of an opportunity for understanding compared to more limited datasets from SWFS, which are frozen part of the year, such as those studied by Pilgrim *et al.* (1998). Consequently, we assume that the thermal regime of groundwater influencing the surface water - ambient air temperature relationships of our models is similar to Luhmann *et al.*'s (2011) effective heat - exchange pattern 3 (seasonal temperature variation out of phase with air temperature) or pattern 4 (long - term temperature stability) models for karst aquifers in southeastern Minnesota.

Methods

Linear regression models of air - water temperature relationships were created using Microsoft Excel™ for 40 study streams using water temperature data obtained from the U.S Environmental Protection Agency's STORET Database (2 datasets), the Minnesota Department of Natural Resources (DNR) (33 datasets), the Southeastern Minnesota Water Resource Science Center at Winona State University (2 datasets), and Huff (2010) (11 datasets). Twenty datasets include water temperature measurements throughout an annual cycle, the rest contained four to eleven months of either winter intensive (November - March) or non - winter intensive (April - October) data. The STORET data were non - continuous (not measured at fixed intervals), whereas the rest of the data were continuous. Continuous data were acquired from temperature loggers that recorded water temperatures in 15 minute, 30 minute, or 1 hour intervals; non - continuous data were discrete, one - time measurements often taken once every several days during non - winter periods of the study (1999 - 2008).

We calculated weekly mean water temperature for all weeks that contained more than one day of temperature measurements, regardless of whether it was from one or multiple in - stream water temperature loggers. This approach was used because of the limited amount of water temperature data available for some streams. Water temperature data were obtained from between one and eight in - stream water temperature loggers per stream for a total of 106 loggers. Each logger used for the study was greater than 25 m from all others to avoid localized influence and to produce spatially representative regression models. Weeks were numbered following ISO 8601: the first week always contains at least four days of the new year and all weeks contain seven days. A total of 3,606 weekly temperature means were calculated, which produced 23 - 215 weekly means per stream.

Air temperatures were obtained online from NOAA's National Climatic Data Center. Daily maximum and minimum air temperatures were averaged on a daily and weekly scale to produce mean weekly air temperatures. Mean monthly air temperature data were also obtained for the purposes of determining the correlation between mean air and water temperatures at weekly and monthly scales. ArcGIS was used to map the study streams, karst features, weather stations, and water temperature loggers within the study area. GIS data were either created in ArcGIS or obtained online from the DNR's Data Deli and the Minnesota Geospatial Information Office (MnGeo). Streams were matched to a corresponding NOAA Weather Station by creating Thiessen polygons in ArcGIS for Goodhue, Olmstead, Wabasha, Winona, Fillmore and Houston counties. If a weather station within the same polygon as the stream did not have air temperature data available for a portion or the entire time period, data were used from the weather station outside the polygon that was nearest to the visually - judged center of the stream. Weather stations were between 7.1 and 53.8 km from the streams to which they were matched. Distances between streams and weather stations were kept at a minimum because Stefan and Preud'homme (1993) found that the correlation between air and water temperature was nearly halved when sites for air and water temperature measurements were greater than 160 km from each other.

Climate appears to have become more variable over the past several decades so producing regression models using all historic air temperature data would not adequately represent current conditions. Mean annual air temperatures from 1985 - 2009 for the Rochester International Airport weather station, which is in the approximate center of the study area, were graphed to identify the time period most representative of current conditions (FIGURE 2). Using a 3 - year, moving window average of annual temperatures, we observed a difference in the slope of the linear regression model, as well as the mean air temperature, between 1985 - 1997 and 1998 - 2009. From 1985 - 1997, the slope of the regression model was - 0.102 and the mean air temperature was 6.47° C, but from 1998 - 2009, the slope was 0.009 and the mean air temperature was 7.50° C (FIGURE 2). A two sample for means z - test shows a one and two tail P - value less than 0.05 so we reject the null hypothesis that the mean air temperatures from 1985 - 1997 and 1998 - 2009 are the same. We chose the 1999 - 2008 time frame for our study because it is most similar to present day conditions and contains continuous water temperature datasets. Many datasets had insufficient water temperature data for the years of 2009 and 2010, hence the lack of more recent data. An exception was made for five streams that had less than twenty - five data points within the 1999 - 2008 time frame but had continuous data available for 2009.

We used a weekly temporal scale to create our regression models. For most of Minnesota's largest rivers, the time lag (the amount of time it takes for water temperature to track air temperature) is less than a week; the Mississippi River averaged 6 days (Stefan and

Preud'homme, 1993). Our study found that weekly, year - round regression models for a sub - set of 12 of our study streams produced higher R^2 values than regression models using monthly data for April through October (monthly composite R^2 = 0.56, weekly composite R^2 = 0.86) (FIGURE 3). The weekly time scale allows sufficient data without introducing day - to - day variation.

Linear regression models were also created to assess the effect of environmental and study related variables on the slope, intercept and R^2 values of the air - water temperature regression models. These variables include the number of temperature loggers on each stream; the cumulative minor watershed area (as described by the DNR's Data Deli) containing each stream; the number of weekly temperature means for each stream; and the number of known, GIS - mapped springs within 50 and 250 m upstream from each water temperature logger. These variables were chosen because Erickson *et al.* (2000) speculated that a large watershed might be necessary to produce high air - water temperature correlations (allowing surface waters to travel across more land area) and because sample size, as well as proximity to spring inflows, may affect the air - water temperature relationship.

Results

The slopes, intercepts, and R^2 values produced by weekly linear regression models varied among streams but all were different from the values for SWFS. In our set of 40 GWFS, slopes range from 0.178 to 0.738, intercepts range from 2.897 to 8.287, and R^2 values range from 0.591 to 0.977 (TABLE 1). The P - values were less than 0.001 for all 40 of the regression models. Morrill *et al.* (2005) reported air - water temperature relationships for a set of 43 U.S. and international streams and found that slopes ranged from 0.35 to 1.09, intercepts from 0.46 to 5.80, and the Nash - Sutcliffe Coefficient of Efficiency (a measurement of variability similar to R^2 where a perfect fit equals 1) ranged from 0.42 to 0.83 for linear regression models created using a weekly time scale.

The composite linear regression model for our 40 streams produced a slope of 0.382, an intercept of 6.626, and an R^2 of 0.829 (SE = 1.981, SD = 11.422, P < 0.001) (FIGURE 4). A composite, weekly, linear regression model depicting air - water temperature relationships for a set of 39 (36 surface - water dominated, 3 groundwater - fed) streams across Minnesota had an intercept of 1.88, a slope of 0.966, and an R^2 of 0.830 at a weekly scale (Pilgrim *et al.*, 1998). Our results differed for streams in common with the Pilgrim *et al.* study (1998). Pilgrim *et al.* (1998) found an intercept of 3.78, the slope of 0.73, and the R^2 of 0.88 at a weekly time scale in the Main Branch of the Whitewater River, whereas we found an intercept of 7.29, a slope of 0.52, and an R^2 of 0.91 at a weekly scale. Pilgrim *et al.* also found an intercept of 5.92, a slope of 0.78, and an R^2 of 0.82 at a weekly scale for the South Fork of the Root River, whereas our regression model had an intercept of 6.23, a slope of 0.40, and an R^2 of 0.92 at a weekly scale.

A linear regression model of all study stream intercepts *vs.* slopes produced an R^2 of 0.389, an SE of 0.755, an SD of 0.127, and a P < 0.001 (FIGURE 5). O'Driscoll and DeWalle (2004) reported an R^2 of 0.894 for the linear regression model of intercepts *vs.* slopes for weekly air - water temperature regression models of 12 study sites within one watershed in Pennsylvania.

We found a significant relationship between cumulative minor watershed area containing each stream (in acres) and the slope of each stream's linear regression model (P < 0.001) (TABLE 2). We also found a significant relationship between cumulative minor watershed area and the intercept of each stream's linear regression model (P = 0.016). Lastly, we found a significant relationship between the number of water temperature loggers on each stream and the slope of each stream's linear regression model (P = 0.042). The remainder of the regression model results were not significant.

Non - linear regression models of best fit were applied to the dataset for each stream to test for improvements in R^2 values. Thirty - three of the best - fit, non - linear models were polynomial functions, three were power functions, and four were exponential functions. The R^2 improvements were between 0.0001 and 0.135, with an average improvement of 0.021. The most improvement occurred when the R^2 value for the linear regression model was in the lower range (0.6 to 0.8) because there was a larger margin for improvement, whereas models in the higher range (0.8 to 1.0) experienced diminishing returns. Linear regression R^2 values were most improved (0.015 - 0.051) by the transformation when the best - fit regressions were either exponential or power regressions. However, power functions could not be applied to the majority of the datasets due to negative air temperature values. The R^2 values for the transformed data declined between 0.204 and < 0.001, when compared to the non - transformed data, for 15 regression models whose best - fit, non - linear regression models were polynomial models.

Discussion

Groundwater inputs significantly affect relationships between stream temperature and the temperature of the surrounding atmosphere. Streams with large amounts of groundwater input respond to changes in air temperature to a lesser degree than streams with little or no groundwater input (O'Driscoll and DeWalle, 2004). Most of our GWFS streams have substantially different temperature regimes than those of nearby SWFS, as seen in the elevated intercepts (> 2.8) and reduced slopes (< 0.74) of air - water temperature regressions models for GWFS (Erickson *et al.,* 2000). Thirty - eight of our study streams have annual temperature fluctuations several degrees less than temperatures characteristic of SWFS, especially during high summer and low winter air temperatures. In contrast, Stevens *et al.* (1975) found that GWFS exhibit water temperature differences of only a few degrees compared to SWFS. This difference is most likely because our study streams have a relatively strong groundwater influence. The overall effect of groundwater is that it provides a stabilizing influence on water temperature and reduces the effects of short - term air temperature variability (Webb, 1992; Sinokrot *et al.*, 1992).

Groundwater input did not reduce the strength of the relationship between water and air temperature at the weekly scale in our study. The range of R^2 values for our GWFS is remarkably similar to the range found by Pilgrim *et al.* (1998) for SWFS. Erickson *et al.* (2000) speculated that a large watershed might be necessary to produce high correlations because that would allow the water adequate time for interaction with the atmosphere while traveling across the landscape before entering the stream. They further suggested that small watersheds and high groundwater inflow might create low correlations between air and water temperature. However, similar to Morrill *et al.* (2005), we found no significant relationship between minor watershed area and a stream's R^2 value. We believe that the air - water temperature relationship is also affected by the interaction of the water with the atmosphere while in the stream, which could help explain this lack of correlation.

Several studies suggest that the amount of groundwater input affects the slope and intercept of air - water temperature regression models (O'Driscoll and DeWalle, 2004; Erickson *et al.,* 2000; Mohensi *et al*., 1998). Generally, streams with significant groundwater discharge have low slopes and high intercepts relative to SWFS because stream temperatures are buffered from extreme high and low air temperatures (O'Driscoll and DeWalle, 2004; Erickson *et al.,* 2000; Mohensi *et al*., 1998). Although we also believe this to be true, we did not find that the discrete, point discharge of groundwater affected the components of the linear regression. We found no significant relationships between the number of springs within 50 and 250 m upstream from a logger and the slope, intercept or R^2 value for each stream (TABLE 2). This is likely due to the incomplete karst inventory in southeastern Minnesota.

Intercept and slope are not directly dependent on air temperature (Stefan and Preud'homme, 1993); rather, they are directly related to groundwater input and in - stream characteristics, such as riparian shading and stream velocity, and are also likely related to watershed land use. Further field studies could be done to investigate the relationship between regression model variables and watershed land use as well as in - stream characteristics and groundwater input. Stefan and Preud'homme (1993) found that groundwater inflow had an effect on temperature in small streams, especially during low summer flow. In contrast, we found that effect to be apparent for all of our study streams, including moderately sized ones, during all times of the year.

Air temperature not only affects surface water temperature but also groundwater temperature (Erickson *et al.,* 2000; Meisner *et al.*, 1988). Data from our streams support the argument that groundwater upwellings are near mean annual air temperature (O'Driscoll and DeWalle, 2004) but this observation only applies to groundwater flowing from the regional water table, which Luhmann *et al.* (2011) termed 'the thermally effective aquifer'. Typical upwellings at Big Springs Creek were 9.0° C, the same temperature as the mean annual air temperature for this part of Minnesota. However, the interflow coming into the stream from the hillside at Rock Creek where the water table intersects the ravine was 12.0° C. Water temperature can change relatively quickly in short distances downstream from the groundwater upwelling site because numerous other factors (e.g., stream shade and water velocity) simultaneously affect in - stream water temperatures. Thus, groundwater may not always conform to the pattern 3 and pattern 4 models of Luhmann *et al.* (2011).

Models of intercept *vs.* slope for air - water temperature regression models offer insight into the mechanisms that control stream temperature when groundwater thermal patterns conform to pattern 3 or pattern 4 models of Luhmann *et al.* (2011). Streams that have elevated slopes and reduced intercepts fall on the lower right of the regression model and are more meteorologically controlled; whereas streams that have reduced slopes and elevated intercepts fall on the upper left of the regression model and are more hydrologically controlled (FIGURE 5). The R^2 reported by O'Driscoll and DeWalle (2004) is much higher than the R^2 we found for the intercepts *vs.* slopes of our 40 study streams. The difference between the two values may be attributed to the spatial distribution of our streams across southeastern Minnesota, creating much more diversity among streams in terms of the landscape and hydrogeological features than O'Driscoll and DeWalle's (2004) streams. Also, our regression models used water temperature records spanning longer periods of time, thus we have captured more temporal variation.

Our regression models suggest that streams with steeper slopes and lower intercepts are most susceptible to climate change because they are meteorologically controlled. The underlying relationship between the slope of the regression model and air temperature indicates that under steeper slopes, the water temperature rises at a faster rate in relation to air temperature increases. Also, higher intercepts displace the regression line upwards, thus the water temperature at any given point on the regression line is higher. However, given the relationship between these variables, high intercepts might not be able to occur in conjunction with high slopes. We suggest restorative management activities for streams that fall on the meteorological control end of the spectrum and protective management activities for streams that fall on the hydrological control end of the spectrum (FIGURE 5). Streams on the hydrological control portion of the spectrum are most likely fed by relatively large quantities of groundwater and could be targets for protection because they fulfill the basic requirement for producing ideal coldwater habitat.

Slopes, intercepts, and R^2 values of our streams differ from those of several similar studies. Morrill *et al.* (2005) found the lowest slopes were for streams at higher elevations where the coldwater input was from snowmelt, in comparison to our study where the lowest slopes where due to cold, groundwater input. Our values differ in that our slopes are lower, intercepts are higher and R^2 values are higher. Pilgrim *et al.* (1998) evaluated only three GWFS; their intercept was much lower and slope much higher than our composite, weekly regression model, or the models for any of our individual streams.

We found differences when comparing streams common to both the Pilgrim *et al.* (1998) study and our work. These differences could be due to many factors, including temperature logger placement and resurgence (i.e., changes in groundwater discharge to surface waters). The only study similar to ours produced similar values for a stream with strong groundwater - inflow in England (Slapstone Sike Spring), which had an intercept of 3.39, and slope of 0.51 (Erickson *et al.,* 2000). No other studies similar to ours were found in the literature.

Although non - linear regression models produce less error and higher correlations for surface water dominated streams due to their S - shaped curve (dampening of the regression at extreme air temperatures) (Morrill *et al.*, 2005; Mohensi *et al*., 1998), these regressions should not be applied to streams / rivers that do not have an S - shaped relationship between air and water temperatures (Mohensi *et al*., 1998). It was believed that these conditions would be found downstream from a reservoir or areas of extensive groundwater inflow (Mohensi *et al.,* 1998). However, many of our study streams display a slightly dampened S - shape curve and non - linear regression models had not been previously tested on a large set of GWFS. Applying non - linear regression models (e.g., exponential and quadratic) or transforming our stream data (e.g., square root) marginally improved R^2 values (up to 0.14) for our set of 40 streams due to the lack of a strong S - shape. Since only one of the improvements in R^2 values was greater than 0.1 after applying the non - linear model, we deduce that non - linear models are not necessary for GWFS in southeastern Minnesota.

Mohensi *et al*. (1998) found that SWFS regression models asymptote at air temperatures very near 0° C. In contrast, our study shows that GWFS regression models asymptote at water temperatures at or above 0° C due to groundwater inflow. Also, each stream’s thermal regime approaches this asymptote at air temperatures much less than 0° C. This is opposed to the northerly, SWFS depicted by Pilgrim *et al.* (1998) and Mosenhi *et al.* (1998) where the regression models asymptote near 0° C water temperature and at air temperatures slightly below 0° C. The software program R™ could be employed to determine the water temperature at which a stream's thermal regime asymptotes based on its linear regression equation but was not done in this study. Larger groundwater inflows most likely provide a higher base flow temperature for our study streams. Generally, larger groundwater inflows should produce higher thermal regime asymptotes. This also reflects why large sections of GWFS do not freeze over during the winter months.

There are many considerations that need to be recognized to fully understand the context of this study. First, regression models that represent an entire stream do not express within - stream variation. However, there may not be differences in temperature over fine spatial scales within a stream compared to a regression for an entire stream because groundwater input is so common in the southeastern Minnesota carbonate - sandstone landscape. Secondly, the GIS karst feature databases managed by the DNR and MnGeo are incomplete. Numerous springs and seeps are almost surely present in our study streams that are not present in the GIS layers. For example, there were actually 4 - 5 spring inputs in Big Springs Creek, whereas only one spring is mapped in the GIS karst layer. Thirdly, methods employed to calculate the amount of groundwater input from springs are time consuming. Other surrogates can and have been used to approximate groundwater input, such as hydraulic conductivity, hydraulic gradient, and soil permeability, in trout streams tributary to Lake Superior (Black and Johnson, 2009). These surrogates are useful for streams that receive groundwater primarily through seepage, associated with primary porosity, because they account for steady groundwater base flow. However, surrogates are not useful for karst regions that experience preferential water flow along fracture zones, known as secondary porosity.

The only stream's linear regression model that may have an outlying data point because it is greater than 5^{o} C from the regression model trendline was Cold Spring Brook. However, this data point was not removed since it may be attributed to large changes in mean weekly air temperature (-9.65^{o} C) over a short time period (2 weeks). This outlier could be statistically analyzed to determine if it should be removed. Removal of this data point could result in alteration of the slope and intercept of the stream's regression model as well as an R^2 improvement but will likely minimally affect the composite model. Lastly, groundwater thermal regimes and water temperatures at spring sources in these regions could more closely conform to pattern 1 (event - scale temperature fluctuation) and pattern 2 (seasonal temperature variation in phase with air temperature) models of Luhmann *et al*. (2011) and the resulting water - air temperature regression relationships could differ substantially from the regression models produced from our study.

Several regression models created to identify the variables that affected slopes, intercepts, and R^2 values generally found no significant relationship. The lack of relationship between the number of known groundwater - fed springs within 50 or 250 m from the stream reach and the stream's R^2 value, slope, or intercept is likely due to unknown amounts of groundwater inputs. We found a minimal relationship between the watershed area of a stream and the intercept or R^2 value for the linear regression model for that stream, in contrast to the findings of Erickson *et al.* (2000) relating streams with small watersheds to low air - water temperature correlations. Lastly, surface water enters into the streams from across the landscape, which is reflected in the relationship between minor watershed area and the linear regression components. The fact that our R^2 value was higher for the relationship between minor watershed area and slope of the linear regression model (compared to watershed area *vs.* intercept and R^2) may be because slope more closely reflects land - water interactions affecting surface waters prior to entering the stream, whereas intercepts are associated with temperature of the groundwater inflow to the stream. An R^2 value of 0.36 for this regression model demonstrates that surface water input is important to stream temperature but several other factors influence stream temperature as well. The R^2 values were high for both surface water and groundwater - dominated streams, demonstrating that there was no relationship between watershed area and the R^2 value. Lastly, the significant relationship between the number of water temperature loggers and the slope of the regression models may be because more spatially representative data helps to better define the trend line of best fit, therefore increasing models accuracy and altering the slope.

We believe some linear regression models created for GWFS in northerly climates may to used to adequately predict changes in water temperature under future climate change scenarios. Mohensi and Stefan (1999) stated that regression model slopes created for streams in northerly climates remain near the regression trend line when mean weekly air temperature exceeds 20^o C because of the limited evaporative cooling that occurs in colder, wetter climates. However, the behavior of the regression model slopes at temperatures above 20^o C varied among our streams, with some having a slight asymptote, some with more variability, and some following unity (water temperatures continue to track air temperatures). Although our regressions document current conditions, they may not hold true as climate change increases air temperature; stream temperature may eventually asymptote. The usefulness of each regression model should be judged on a stream - by - stream basis, with the streams that currently follow unity above 20^o C and produce high R^2 values offering the most promise for use as predictive tools for future conditions.

Our regression models often demonstrated residual variation. In some regression models, residual variation occurred in September and October of 2006 when there was a dramatic and sudden change in air temperature across all our weather stations but water temperature did not track air temperature in all streams. For example, Cold Spring Brook displayed higher water temperature residual variation (i.e., water temperature did not change with the corresponding change in air temperature) (FIGURE 6). In contrast, Rock Creek displayed less residual variation in water temperature (i.e., water temperature did change with the corresponding change in air temperature) (FIGURE 7). Although we do not know the cause of these responses, differences in the amount or type of groundwater inflow, stream size, or both, may be responsible. There may also be more residual variation in a regression model when a temperature logger is placed closer to a known spring input and other loggers are more distant, as noted for Sugar Loaf Creek where one logger was within 5 m from a known spring and the other was between 165 and 180 m away from the same known spring (FIGURE 8). Overall, only 7 of 106 loggers were within 195 m of a known spring. Therefore, we assume that the majority of loggers recorded temperature in well - mixed waters that generally characterized the entire stream reach.

Several characteristics of groundwater inflow influence stream temperature, including the thermal effectiveness of groundwater / rock heat exchange (*sensu* Luhmann *et al.,* 2011), the volume of groundwater discharge, distance from the spring to the stream, and the source of resurgence. Velocity and volume are vital components of flow, both into and within the stream. A higher volume of groundwater entering a stream is closer to ambient aquifer temperatures because it is less influenced by changes in air temperatures due to its shorter travel time to the surface. For example, there is an artisian, spring - fed, groundwater pool that enters Sugar Loaf Creek at nearly 1,500 l/s at about 9^{o} C. In contrast, other streams have much less groundwater inflow volume, such as Rock Creek, where the inflow was less than 1 l/s at approximately 12^{o} C.

The source of resurgence reveals many important characteristics about the groundwater entering a stream. The source water table or aquifer depends on stream elevation and dictates the temperature of the groundwater. In general, lower elevation streams receive groundwater from cooler, lower elevation aquifers with longer hydraulic residence times. For example, Big Springs Creek is at a low elevation, and the springs enter directly from the regional water table at 9.0° C. Conversely, Rock Creek receives interflow from the hillside where the water table intersects a ravine at a higher elevation and the temperature of the groundwater is 12.0^{o} C. If a stream and spring are nearly at the same elevation, water from the spring does not have to travel far before reaching the stream. Thus, the water will likely remain near the temperature of the spring as it enters the stream.

Many studies have investigated the important environmental variables that influence stream temperature. Solar radiation is one of the most influential factors affecting stream temperature and is directly related to the amount of shading provided by riparian vegetation (Sinokrot and Stefan, 1993). A portion of Big Springs Creek is a remnant stream channel that has filled in with groundwater and formed a pool with a single, half - meter culvert outlet. Temperature in an unshaded portion of the pool was 20.2° C, whereas approximately 4.5 m away the temperature in a shaded portion of the same pool was 16.6° C. The amount of riparian shading is also dependent on the width of the riparian buffer. A riparian buffer 11 - 43 m (36 - 146 ft) wide can provide 60 - 100% of the total potential stream shading based on the size of the stream channel (Cristea and Janisch, 2007). A 30 m buffer can maintain stream temperature to within 1^{o} C of the mean temperature prior to entering the buffered zone for streams less than 3 m wide (Cristea and Janisch, 2007). Such information is essential for modeling stream temperature dynamics and when considering stream restoration activities.

Vegetation also affects groundwater water temperature. Vegetation reduces temperature variation of shallow groundwater aquifers and reduces the mean annual groundwater temperature (Meisner *et al.,* 1988). For example, Pluhowski and Kanitrowitz (1963) found a 1 - 2° C temperature decrease in maximum groundwater temperature 22 m below a mature forest compared to the maximum temperature at a comparable depth beneath a field. Land management practices that capture snow will provide cold groundwater recharge during snowmelt events. Mohensi *et al*. (1998) found variability at moderate temperatures due to snowmelt in colder regions, whereas residual variation could not be linked to snowmelt in our study. Brooks *et al.,* (2003) found that "when strips were cut at a width equal to from one to five times the height of the surrounding trees, snow water equivalents were 15 to 35% higher in the strips than in the adjacent forest.” Practices that promote infiltration and groundwater recharge demonstrate promise for maintaining the thermal integrity of groundwater resources. Intensive extraction of groundwater in highly agricultural areas threatens the thermal integrity of GWFS, thus enforcement and strengthening of water usage regulations may prove pivotal to retaining thermally suitable stream reaches, especially in light of the predicted lengthening of drought periods due to climate change (Coldwater Fish and Fisheries Working Group, 2010).

There is collective agreement that restoration of riparian vegetation is one of the most effective management activities for improving stream temperature (Johnson and Jones, 2000; Blann *et al.*, 2002; Cristea and Janisch, 2007). For small streams in areas where the native vegetation is grassland or savannah, a riparian buffer of similar composition may narrow, deepen and shade the stream channel, thus reducing stream temperatures more effectively than forest (Coldwater Fish and Fisheries Working Group, 2011). For larger streams in forested areas, shading is a prominent force creating thermally suitable trout habitat (Coldwater Fish and Fisheries Working Group, 2010). Restoration of riparian vegetation will likely mitigate coldwater streams against the effects of climate change.

Land use has been shown to have a pronounced effect on stream water temperature at the reach scale and beyond. A comprehensive study of the effect of land use on numerous water quality parameters in southeastern Minnesota found that stream temperature was higher in agricultural areas over the Galena Aquifer than under mixed land use over the Prairie Du Chien Aquifer or under mostly forested land use over the Jordan Aquifer at a watershed scale (Troelstrup and Perry, 1989). Stream temperature was also higher when the adjacent riparian areas where either in pasture or cultivation, in comparison to forested riparian areas at a reach scale. Similarly, rivers in other areas of the United States with different stream characteristics and landscape dynamics show similar patterns between land use and water temperature. For example, mean water temperature increased with the percentage of non - forested land cover within both the immediate riparian corridor (30 m) and the riparian sub - corridor (1000 and 2000 m) in a southern Appalachian headwater stream (Sponseller *et al*., 2001). Thus, land use in the riparian buffer within at least the reach scale may be important when managing for stream temperature.

Under the A1B SRES regional climate change scenario for central North America, which assumes no heavy reliance on a particular energy source, air temperatures are predicted to rise between 2.4 and 6.4^{o} C above 2000 conditions for the summer months (June - August) by the years 2080 - 2099 (IPCC Working Group I, 2007). Applying these air temperature increases using our composite model with a slope of 0.38 suggests a 0.91 to 2.43^{o} C rise in water temperatures for this set of groundwater - fed streams relative to current mean summer water temperatures. This may not be a large enough magnitude of channel to affect brown trout survival via thermal tolerance levels but will likely indirectly affect survival due to increased physical stress in streams with already marginal thermal regimes, such as the North Fork of the Zumbro River and the Main Branch of Burns Valley Creek. For some streams, this magnitude of water temperature increase may decrease the amount of thermally suitable habitat for cold stenotherms. Lyons *et al.,* (2010) predicted that suitable habitat for brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*) would be reduced by 33% and 94%, respectively, for Wisconsin streams under a scenario of a 2.4^{o} C air temperature increase. However, Lyons *et al.* (2010) did not explicitly model groundwater - fed streams so further studies could be done to evaluate increases to the temperature regime of GWFS under climate change scenarios. For other designated trout streams not yet considered marginal, management decisions, particularly those that do not protect thermal integrity, coupled with this magnitude of predicted temperature increases, will likely cause stream segments to become thermally unsuitable in the future. Generally, under such conditions, summer coldwater habitat within these streams will be restricted to headwaters and progressively smaller areas downstream of groundwater - fed springs during the summer. In parallel, warm water thermal refugia in the winter may be expanded (Meisner *et al*., 1988;

Meisner *et al.,* 1990). The significance of that compression of cold summer conditions and expansion of warm winter conditions will vary among ecological communities and those communities have different value to humans.

Tables

TABLE 1. (pg. 7)

Stream Name	Slope	Intercept	R^2
Winnebago Creek (138, 2)	0.342	6.930	0.977
Trout Brook (33, 1)	0.234	6.734	0.977
Cedar Valley Creek (120, 1)	0.474	5.998	0.976
Latsch Creek (36, 1)	0.313	6.308	0.974
Hay Creek (93, 6)	0.388	6.466	0.969
Rush Creek (122, 1)	0.511	5.929	0.968
Klaire Creek (36, 1)	0.282	7.110	0.966
Little Pickwick Creek (49, 1)	0.257	6.342	0.962
Badger Creek (24, 1)	0.354	7.346	0.960
East Indian Creek (104, 2)	0.420	6.486	0.960
Hemmingway Creek (88, 1)	0.411	5.271	0.955
West Indian Creek (110, 2)	0.325	6.272	0.951
Garvin Brook (212, 8)	0.354	6.371	0.940
Clear Creek (50, 3)	0.354	6.102	0.939
Middle Branch of the Whitewater River (215, 5)	0.515	6.135	0.936
Coolridge Creek (49, 1)	0.309	5.723	0.936
Gilbert Creek (33, 3)	0.252	7.576	0.935
Beaver Creek (201, 5)	0.443	6.110	0.933
Duschee Creek (58, 2)	0.306	7.283	0.932
Torkelson Creek (46, 2)	0.322	6.335	0.932
Swede Bottom Creek (47, 1)	0.280	6.720	0.929
South Branch of the Whitewater River (71, 3)	0.499	6.596	0.926
South Fork of the Root River (180, 3)	0.398	6.234	0.921
Ferguson Creek (173, 1)	0.292	6.377	0.917
Main Branch of the Whitewater River (180, 3)	0.521	7.289	0.912
Trout Run Creek (210, 4)	0.306	6.406	0.907
Pickwick Creek (62, 6)	0.611	6.434	0.905
Gribben Creek (165, 6)	0.250	7.037	0.901
North Fork of the Zumbro River (23, 2)	0.739	3.614	0.881
Daley Creek (47, 1)	0.204	7.171	0.849
Rock Creek (57, 1)	0.204	7.062	0.840
Sugar Loaf Creek (23, 2)	0.347	7.183	0.833
North Branch of the Whitewater River (154, 8)	0.557	6.303	0.821
Trout Valley Creek (25, 1)	0.245	6.105	0.816
Big Springs Creek (47, 1)	0.178	7.569	0.793
North Branch Creek (150, 3)	0.205	8.287	0.754
Cold Spring Brook (70, 2)	0.210	6.585	0.697
Gilmore Creek (39, 2)	0.347	6.874	0.651
Main Branch of Burns Valley Creek (41, 2)	0.563	2.897	0.642
Snake Creek (25, 5)	0.322	7.390	0.591

TABLE 2. (pg. 8)

Regression Model Type	**R^2**	**SD**	**SE**	**P - value**
All watershed areas (acres) *vs.* all slopes	0.358	15,594.226	0.103	< 0.001
All watershed areas (acres) *vs.* all intercepts	0.135	15,594.226	0.893	0.016
All watershed areas (acres) *vs.* all R^2 values	0.018	15,594.226	0.099	0.351
Number of water temperature loggers *vs.* all slopes	0.105	1.969	0.122	0.042
Number of water temperature loggers *vs.* all intercepts	0.002	1.969	0.965	0.772
Number of water temperature loggers *vs.* all R^2 values	0.007	1.969	0.100	0.606
All weekly temperature means *vs.* all slopes	0.026	61.987	0.127	0.492
All weekly temperature means *vs.* all intercepts	0.008	61.987	0.962	0.364
All weekly temperature means *vs.* all R^2 values	0.073	61.987	0.097	0.875
Number of known springs within 250 m *vs.* all slopes	0.005	4.001	0.129	0.677
Number of known springs within 250 m vs. all intercepts	0.000	4.001	0.966	0.943
Number of known springs within 250 m *vs.* all R^2 values	0.002	4.001	0.100	0.789
Number of known springs within 50 m *vs.* all slopes	0.031	2.372	0.127	0.281
Number of known springs within 50 m vs. all intercepts	0.066	2.372	0.933	0.109
Number of known springs within 50 m *vs.* all R^2 values	0.019	2.372	0.100	0.401

Figures

FIGURE 1. (pg. 3)

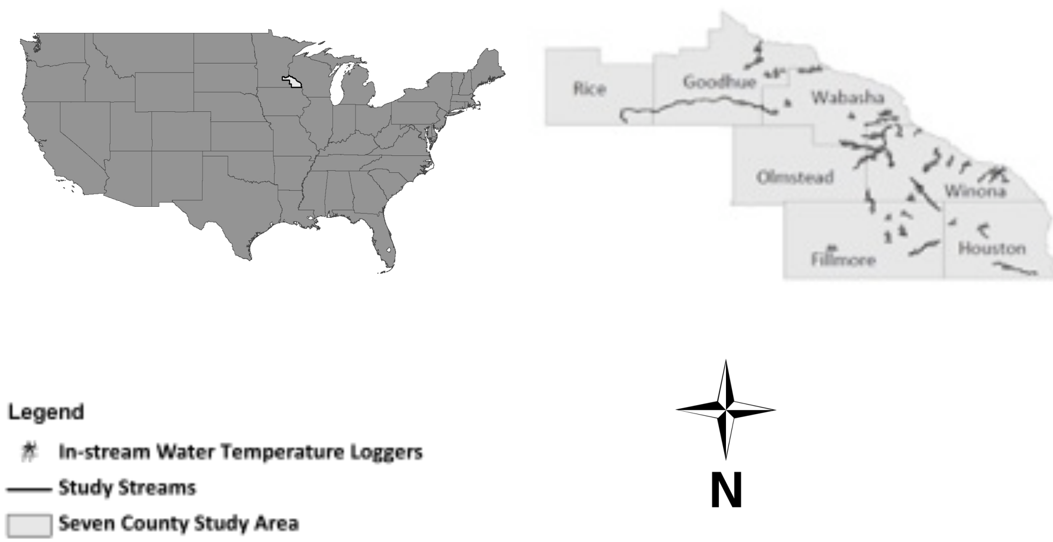


FIGURE 2. (pg. 6)

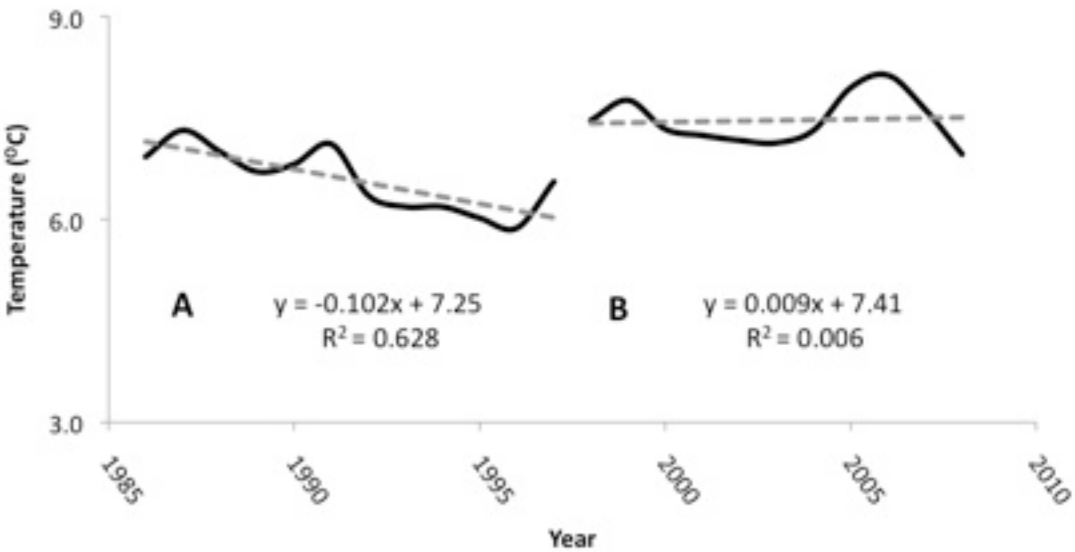
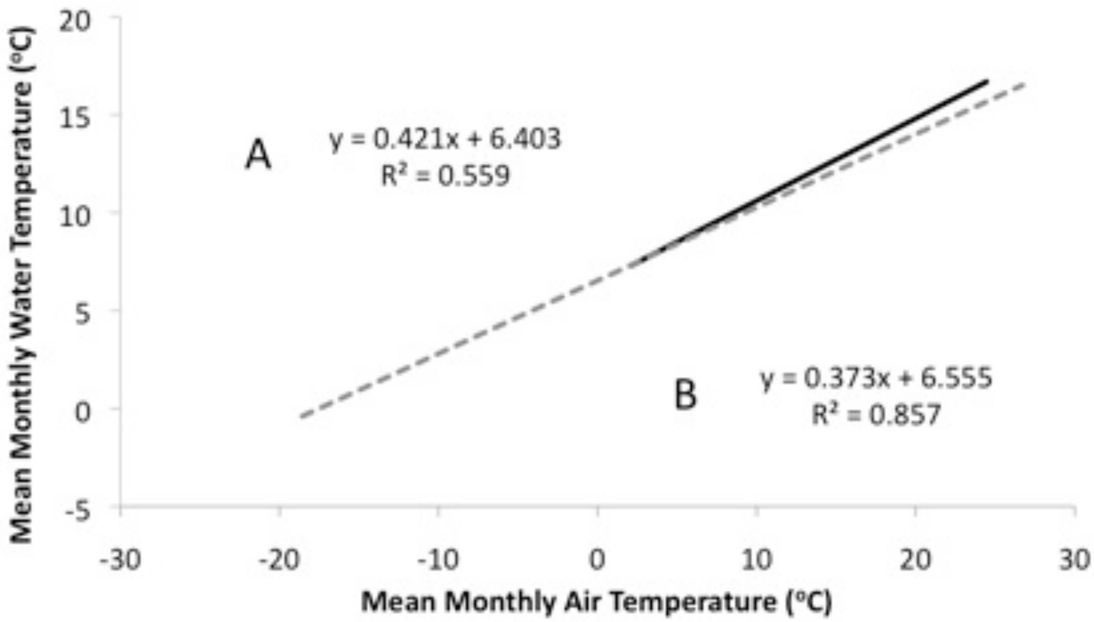
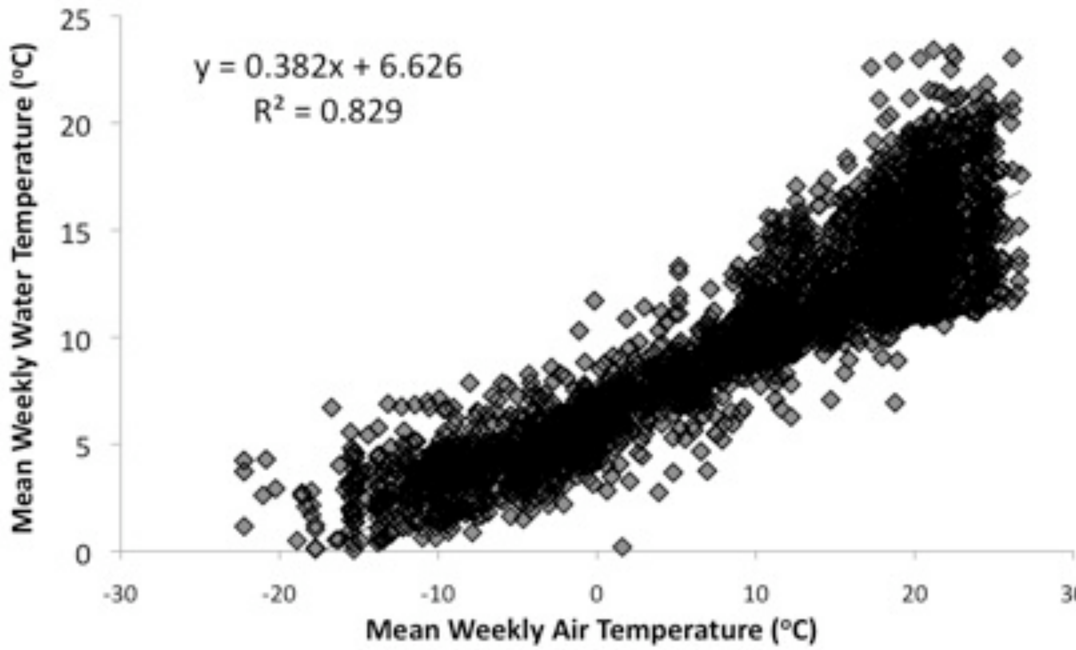

9.0
6.0
3.0
Temperature (°C)
A
y = -0.102x + 7.25
R² = 0.628
B
y = 0.009x + 7.41
R² = 0.006
1985
1990
1995
2000
2005
2010
Year

FIGURE 3. (pg. 7)



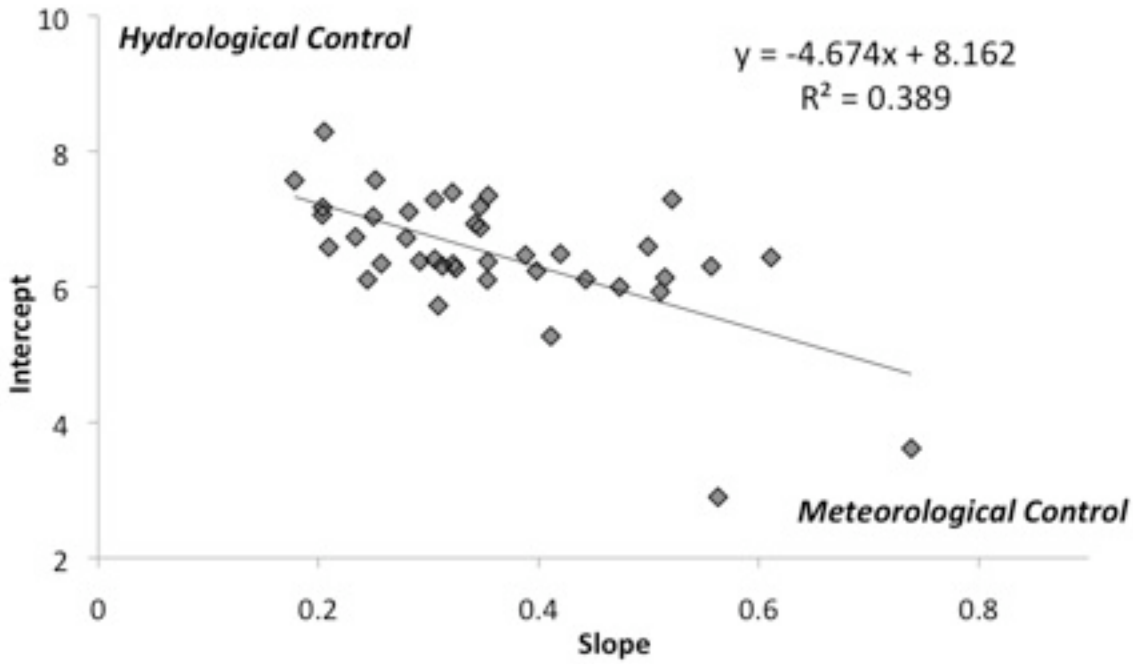
20
15
10
5
0
-5
Mean Monthly Water Temperature (°C)
A
y = 0.421x + 6.403
R² = 0.559
B
y = 0.373x + 6.555
R² = 0.857
-30
-20
-10
0
10
20
30
Mean Monthly Air Temperature (°C)

FIGURE 4. (pg. 7)



y = 0.382x + 6.626
R² = 0.829
Mean Weekly Water Temperature (°C)
25
20
15
10
5
0
-30
-20
-10
0
10
20
30
Mean Weekly Air Temperature (°C)

FIGURE 5. (pg. 8)



Hydrological Control
y = -4.674x + 8.162
R² = 0.389
Meteorological Control
Intercept
Slope
10
8
6
4
2
0
0.2
0.4
0.6
0.8

FIGURE 6. (pg. 15)

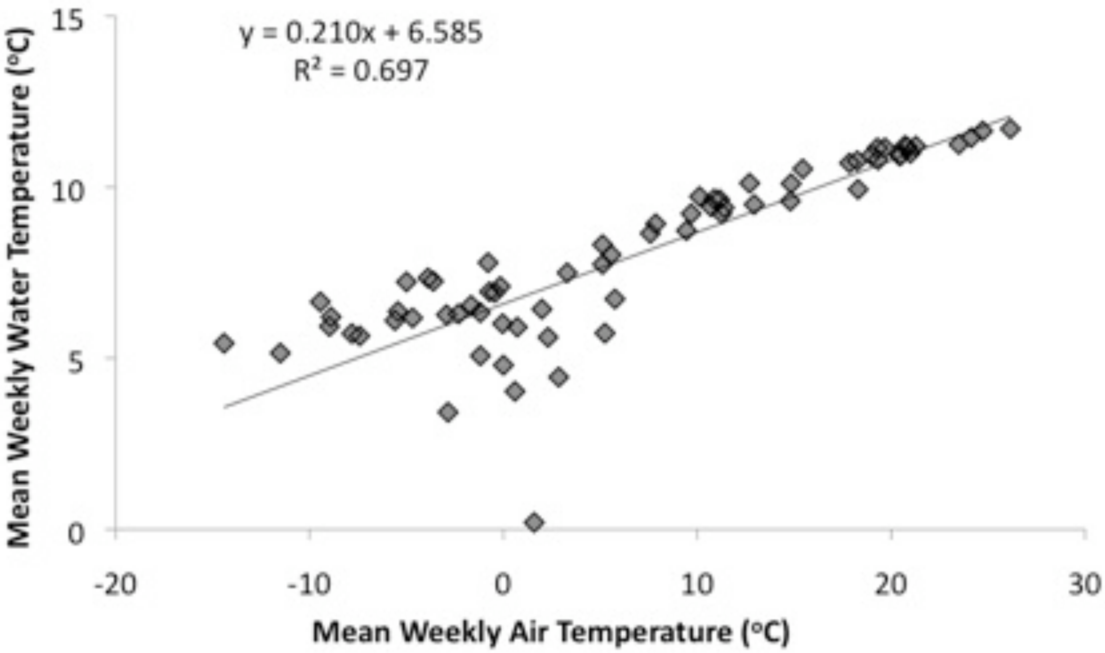


FIGURE 7. (pg. 16)

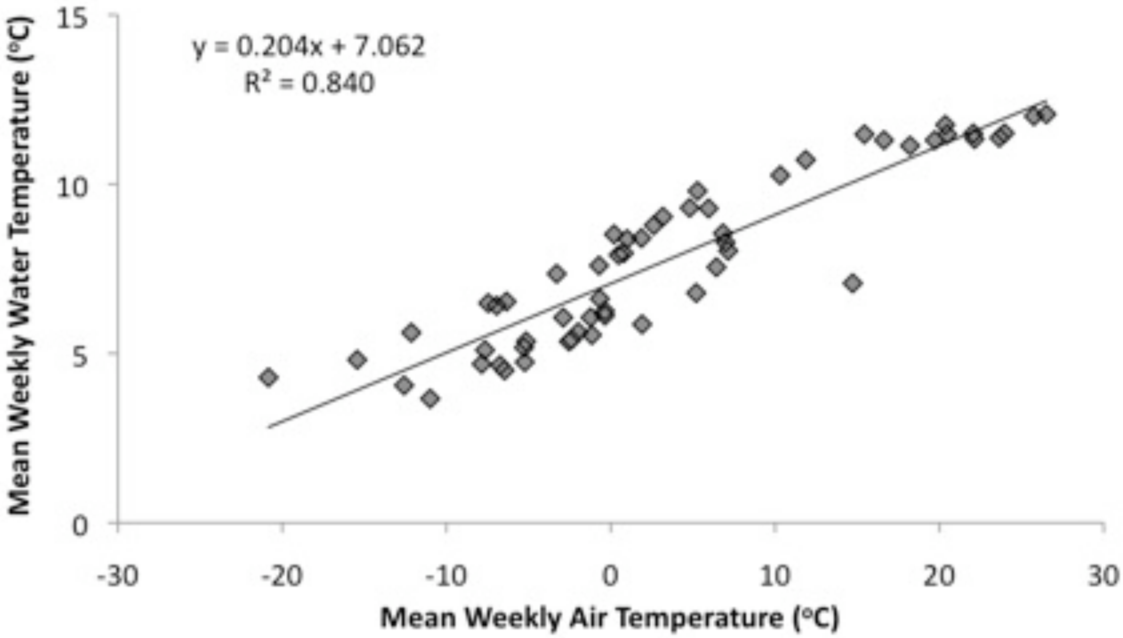
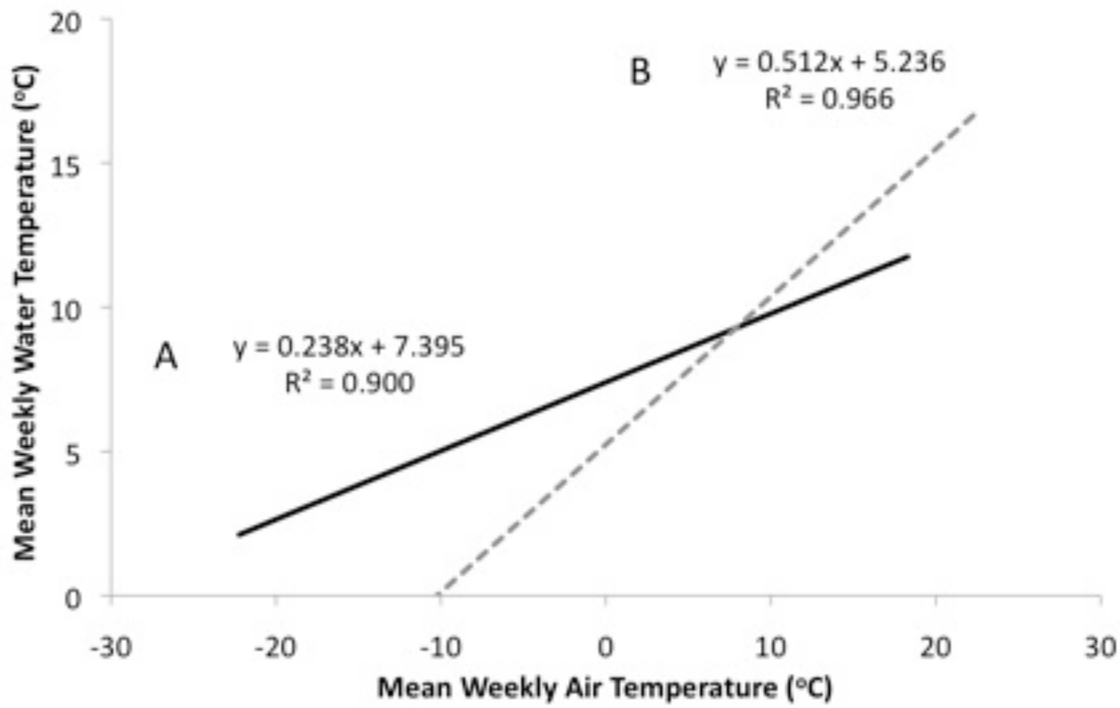


FIGURE 8. (pg. 16)



COMPOSITE LINEAR REGRESSION MODELS OF AIR AND WATER TEMPERATURE BASED ON COMMON SLOPE AND INTERCEPT

Introduction

Carbonate - sandstone geology in southeastern Minnesota creates a heterogeneous landscape of springs, seeps, and sinkholes that supply groundwater into streams, creating coldwater habitat for cold and ultra - cold stenotherms. Air temperatures have been shown to be effective predictors of water temperatures in groundwater-fed systems such as these. However, many datasets contain water temperature information for the non - winter portion of the year and, therefore, our knowledge regarding these thermal regimes is incomplete. Simple linear regression models of air - water temperature relationships were created for 40 groundwater - fed streams in southeastern Minnesota, which were then combined by common intercept and slope to produce a more robust dataset and then split into winter and non - winter air temperature regimes. These composite models allow approximation of winter water temperature regimes based on non - winter data, which can be used to supplement datasets where only non - winter field data were collected. This information can be used in season specific studies or those that require data on year - round temperature regimes and to help researchers refine their experimental design.

Methods

Linear regression models were first combined by common slope and intercept. The first group was split from the rest due to a difference in intercept greater than 2^{o} C. This set consists of two streams with intercepts below 4.0^{o} C (compared to the rest which had intercepts above 5.0^{o} C). The remaining streams were split by intercept first. Dividing the difference between the highest intercept (8.29^{o} C) and the lowest intercept (5.27^{o} C) by 3 gave a split interval of nearly 1 (1.0056). Adding 1.006 to the lowest intercept produced the second group of regression models with intercepts from 5.27^{o} C to 6.28^{o} C. Performing this calculation two more times gave the 3rd

(6.28^{o} C - 7.28^{o} C) and 4th groups (7.28^{o} C - 8.29^{o} C). Groups 2 through 4 were further split by the average slope for each group in order to create two subgroups for each group (TABLE 3). Mean weekly air and water temperature data for each subgroup were combined to create a composite linear regression model for streams with these particular categories of slope and intercept. Since most fieldwork is done in the spring, summer, and fall (above 9° C) and not much in the winter (below 9° C), the data were split to create composite regression models for above 9° C and below 9° C, corresponding to the average annual air temperature for southeastern Minnesota.

Results

Linear regression models were applied to all the groups and subgroups of composite data. The R^2 values ranged from 0.274 to 0.932, slopes from 0.205 to 1.181, and the intercepts from 0.453 to 7.960. Also, SDs ranged from 1.868 to 11.726 and SEs ranged from 0.872 to 2.770 (TABLE 4).

Discussion

All but the first group had higher R^2 values before the data were split into above and below 9° C, which may be associated to the smaller sample size of group 1. All but the second group, subgroup 1, produced higher R^2 values for the composite data below 9° C than for the composite data above 9° C. This is probably be attributed to the very slight asymptote of water temperatures above air temperatures of 20° C. All but group 3, subgroup 1, had the lowest standard errors for water temperatures below 9° C (in comparison to above 9° C or above and below 9° C combined). This can probably be attributed to a larger magnitude of residual variation at higher air temperatures. Although our method appears effective, different methods of combining temperature data (i.e., different methods for calculating the slope and intercept breakage values) would result in R^2 values, slopes and intercepts that are different from the composite regression models shown here. Other methods could be used to adjust sample size of the composite models and to produce datasets that are more desirable in terms of slope and intercept based on a particular researcher's needs.

The ability to extrapolate non - winter data to winter temperature regimes will be more useful for larger data sets. For this set, the most reliable data would be groups with higher R^2 values as well as lower SDs and SEs for the composite sets (groups) as well as above and below 9° C (subgroups). These data can be used to match stream regression models produced using non - winter temperature data to the "above 9° C" set in this study that is most similar in terms of slope and intercept. The corresponding "below 9° C" set can then be used to estimate the stream's complete water temperature regime by providing a close approximation to the missing portions. These data can also be used by researchers studying water temperature related processes, such as fish growth or invertebrate community composition, during only winter or non - winter portions of the year. However, the streams included in this study are dominantly groundwater - fed and, therefore, these results should only be used to complete the temperature regimes for other GWFS. Also, this dataset is based on the air and water temperatures found in southeastern Minnesota and application of this set outside of this range becomes less reliable. Applying this method while adjusting for regional differences is recommended.

Tables

TABLE 3. (pg. 32)

Group and Subgroup Category	**Stream Name**	**Intercept Breakage Value**	**Slope Breakage Value**
Group 1, subgroup 1	Main Branch of Burns Valley Creek		
	North Fork of the Zumbro River		
Group 2, subgroup 1		Below 4^{o} C & above 5^{o} C	
	Trout Valley Creek		
	Coolridge Creek		
	West Indian Creek		
	Clear Creek		
			0.40
Group 2, subgroup 2	South Fork of the Root River		
	Hemmingway Creek		
	Beaver Creek		
	Cedar Valley Creek		
	Rush Creek		
	Middle Branch of the Whitewater		
Group 3, subgroup 1		6.28	
	Rock Creek		
	Daley Creek		
	Cold Spring Brook		
	Trout Brook		
	Gribben Creek		
	Little Pickwick Creek		
	Swede Bottom Creek		
	Klaire Creek		
	Ferguson Creek		
	Trout Run Creek		
	Latsch Creek		
	Torkelson Creek		
Group 3, subgroup 2			0.33
	Winnebago Creek		
	Sugar Loaf Creek		
	Gilmore Creek		
	Garvin Brook		
	Hay Creek		
	East Indian Creek		
	South Branch of the Whitewater		
	North Branch of the Whitewater		

	Pickwick Creek		
Group 4, subgroup 1		7.28	
	Big Springs Creek		
	North Branch Creek		
	Gilbert Creek		
Group 4, subgroup 2			0.31
	Duschee Creek		
	Snake Creek		
	Badger Creek		
	Main Branch of the Whitewater		

TABLE 4. (pg. 33)

Group #	Subgroup #	Split Type	Linear Regression Equation	R^2	SD	SE
1	1	None	$y = 0.594x + 3.671$	0.593	5.397	2.698
1	1	Below 9^o C	$y = 1.181x + 0.453$	0.784	1.868	1.419
1	1	Above 9^o C	$y = 0.507x + 5.417$	0.274	3.299	2.770
2	1	None	$y = 0.322x + 6.152$	0.932	11.214	0.979
2	1	Below 9^o C	$y = 0.251x + 5.862$	0.757	6.077	0.872
2	1	Above 9^o C	$y = 0.348x + 5.851$	0.761	4.925	0.970
2	2	None	$y = 0.462x + 6.021$	0.931	11.327	1.426
2	2	Below 9^o C	$y = 0.346x + 5.480$	0.767	6.265	1.071
2	2	Above 9^o C	$y = 0.490x + 5.654$	0.696	4.850	1.570
3	1	None	$y = 0.270x + 6.589$	0.895	11.726	1.085
3	1	Below 9^o C	$y = 0.229x + 6.363$	0.659	6.842	1.131
3	1	Above 9^o C	$y = 0.252x + 7.030$	0.582	4.640	0.991
3	2	None	$y = 0.426x + 6.774$	0.868	11.231	1.868
3	2	Below 9^o C	$y = 0.329x + 6.436$	0.821	6.517	1.004
3	2	Above 9^o C	$y = 0.484x + 5.833$	0.514	4.688	2.213
4	1	None	$y = 0.205x + 7.960$	0.783	11.217	1.219
4	1	Below 9^o C	$y = 0.214x + 7.671$	0.650	7.248	1.147
4	1	Above 9^o C	$y = 0.275x + 7.498$	0.447	4.470	1.373
4	2	None	$y = 0.437x + 7.469$	0.813	10.201	2.145
4	2	Below 9^o C	$y = 0.361x + 7.011$	0.749	7.996	1.699
4	2	Above 9^o C	$y = 0.446x + 7.354$	0.432	4.348	2.230

THE EFFECTS OF CLIMATE CHANGE ON THE HABITAT AND BIOLOGICAL PROCESSES OF BROWN TROUT IN SOUTHEASTERN MINNESOTA

Introduction

Water temperatures in groundwater - fed streams are closely tied with air temperatures in a carbonate - sandstone landscape (Erickson *et al.*, 2000). The survival of cold and ultra - cold stenotherms, including trout, greatly depends on water temperatures maintained below certain threshold tolerance levels. The amount of suitable habitat for many coldwater fish species, based on water temperature, is predicted to decline due to climate change (Eaton *et al.,* 1996; Lyons *et al.,* 2010). Linear regression models depicting the relationship between air and water temperature have been created for 40 streams in southeastern Minnesota and can be used to predict aquatic thermal regimes under future climate scenarios. Climate change may transform marginal and near marginal trout streams, defined by linear regression models, into unsuitable habitat by the end of the century. Although management actions can be taken to help ensure thermal integrity and summer trout survival, it may not be enough to protect against the range of increased air temperatures predicted by regional circulation models.

Climate change is expected to directly and indirectly affect the survival of coldwater species. Although much of the focus is on thermal tolerance, water temperature is closely tied to the amount of dissolved oxygen in the water and it is unknown which of the two is more constricting (Jonsson and Jonsson, 2009). For example, the 7-day upper tolerance limit (UTL) for brown trout is 25.4^{o} C for the MAXT (maximum daily maximum temperature) (Wehrly *et al.*, 2007). Also, the upper incipient lethal temperature (UILT: the temperature which allows 50% indefinite survival) is 24.7^{o} C and the ultimate lethal temperature (ULT: the temperature at which trout cannot survive more than 10 minutes) is 29.7^{o} C (Jonsson and Jonsson, 2009; Elliott, 1981). It has been found that when the average maximum daily mean water temperature is above 24.6^{o} C for a stream segment, the habitat is considered to be unsuitable for coldwater species of fish, including trout (Lyons *et al.,* 2009). Increasing water temperatures have the potential to limit available habitat for trout, as trout may avoid areas with temperatures near their UILT range. For example, it has been found that brook trout, with a UILT of 24.5^{o} C, tend to avoid water temperatures above 24.0^{o} C, known as the thermal barrier (Meisner, 1990; McCormick *et al.,* 1972). This thermal barrier varies from stream to stream to account for localized population adaptation to consistently slightly higher water temperatures but will likely be similar or slightly higher for brown trout.

Climate change is also expected to affect the distribution of coldwater species across large geographic areas. GIS models created for the state of Wisconsin depicts changes in distribution of brown trout under various climate change scenarios (Lyons *et al.,* 2010). This study predicts that suitable habitat for brown trout may be reduced by 33% for Wisconsin streams under a scenario of a 2.4^{o} C air temperature increase (Lyons *et al.,* 2010). This study also shows that under major climate change scenarios where air temperature increases 5^{o} C by the year 2050 (water temperatures increase by 4^{o} C), there will likely be an 88.2% reduction in brown trout habitat in Wisconsin (Lyons *et al.*, 2010). These estimated reductions might vary slightly in regions where streams are highly groundwater influenced since only a portion of Wisconsin has this type of heavy groundwater influence and the study by Lyons *et al.* (2010) took place across the state.

Climate change is expected to shorten the length of thermal refugia downstream from a spring, drawing the thermal barrier upstream. A study done on brook trout in two groundwater - fed streams of southern Ontario accounted for a projected 4.1^{o} C increase in mean July and August air temperatures as well as the likely increases in groundwater temperatures. This study showed a 42% and 30% reduction in summer thermal refugia for two study streams (Meisner, 1990). The reductions in thermal refugia are dependent on numerous factors, particularly the amount of groundwater input and the amount of riparian shading, thus accounting for inter - stream variation. Reductions in thermal refugia for brown trout will likely be less than that reported above based on the higher thermal tolerances of the brown trout.

Water temperature not only affects survival but also rates of various activities and growth. There are optimal, stressful, and lethal thermal regimes for various lifecycle stages (adult, juvenile and eggs) and activities of coldwater fish species (Elliot, 1994). For juvenile brown trout, maximal growth occurs at 16.87^{o} C, maximum food intake at 17.29^{o} C and maximal activity at 18.31^{o} C (Ojanguren *et al.,* 2001). The temperature necessary for egg development ranges from 0 - 15^{o} C but to achieve 50% hatching rate, temperatures must be between 0 and 13^{o} C (Elliott, 1994). For adult brown trout, growth occurs at optimal levels between 4 and 19.5^{o} C, with piscivorous individuals exhibiting a 3 - 4^{o} C increase in optimal growth temperature, but growth general ceases at approximately 23^{o} C. (Elliott, 1994; Johnsson and Jonhsson, 2009, Johnsson and Jonhsson, 2011). Brown trout will also continue to feed in waters at 25^{o} C (Forseth *et al.,* 2009). Due to the alteration of biochemical processes, the age at first maturity, longevity and fecundity are reduced under increased water temperatures (Jonsson and Jonsson, 2009). Higher water temperatures lead to increased physical stress, decreased performance and, ultimately, decreased rates of survival.

Linear regression models of air - water temperature relationships have been created for numerous streams in the southeastern Minnesota region. The underlying relationship between the slope of the regression model and air temperature indicates that for streams with steeper regression slopes, the water temperature rises faster in relation to air temperature increases. However, higher intercepts displace the regression line upwards so the water temperature at any given point on the regression line is higher. This observation suggests that streams with steeper regression model slopes and higher intercepts would be most susceptible to climate change.

Models of intercept *vs.* slope for air - water temperature regression models offer insight into the mechanisms that control stream temperature. Streams that have elevated slopes and reduced intercepts fall on the lower right of the regression model and are more meteorologically controlled; whereas streams that have reduced slopes and elevated intercepts fall on the upper left of the regression model and are more hydrologically controlled (O'Driscoll and DeWalle, 2004). These models suggest that streams with high slopes and low intercepts will be more susceptible to climate change since they are more meteorologically controlled.

Under the A1B SRES regional climate change scenario for central North America, which assumes no heavy reliance on a particular energy source, air temperatures are predicted to rise between 2.4 and 6.4^{o} C above 2000 conditions for the summer months (June - August) by the years 2080 - 2099 (IPCC Working Group I, 2007). Applying these air temperature increases using a composite model with a slope of 0.38 suggests a 0.91 to 2.43^{o} C rise in the water temperatures of this set of groundwater - fed streams above current mean summer water temperatures. However, the linear regression models vary by stream and some have much higher slopes. To get a more complete picture, the range of regression model intercepts and slopes should also be considered.

The purpose of this study is to investigate how trout biology dictates suitable trout habitat, how the amount of suitable trout habitat may become altered due to climate change, which streams may be more susceptible to climate change based on their linear regression models and how the aquatic thermal regimes of a few, particular southeastern Minnesota streams may change under a future climate scenario. The linear regression models for a subset of streams can be used to predict future water temperature instead of just an estimated increase. For some streams, the resulting water temperature under climate change may decrease the amount of thermally suitable habitat and reduce rates of activity and growth of cold stenotherms.

Methods

To capture inter - stream variability and assess which slope and intercept combinations create higher climate change susceptibility, a subset of stream linear regression models that represent a range of slopes and intercepts from the 40 stream study set in chapter 1 were used to calculate the predicted rise in mean summer water temperature. This subset includes three stream linear regression models, each with one of the following characteristics: high slope and low intercept (meteorological control); low slope and high intercept (hydrological control); moderate slope and moderate intercept. Also, to represent streams believed to be most vulnerable to climate change, a fourth stream with a high, moderate slope and high intercept was included because none of the streams in the original set had both a high slope and high intercept as described herein.

High, moderate, and low slope and intercept categories were calculated by subtracting the lowest value from the highest value, dividing the result by three and sequential adding that value to the lower value. Intercept categories are as follows: low (2.9 - 4.7), moderate (4.7 - 6.5) and, high (6.5 - 8.3). Slope categories are as follows: low (0.18 - 0.37), moderate (0.37 - 0.55), and high (0.55 - 0.74). Since several streams fit these criteria, streams with more data points and higher R^2 values were selected.

Mean summer (June - August) air temperature was calculated from weekly air temperature means for the 22nd to the 36th weeks from the composite regression model for all 40 study streams from 1999 - 2009. Adding 2.4 and 6.4^{o} C to the current mean summer air temperature produced the predicted future range of mean summer air temperatures. The resulting value was substituted as T_a in the linear regression models for this subset of streams and a resulting water temperature was calculated.

Results

Mean summer air temperature for weeks 22 to 36 of the composite regression model for the years of 1999 - 2009 was 20.57^{o} C. Under the A1B SRES regional climate change scenario, a predicted 2.4 - 6.4^{o} C rise in summer air temperature would result in air temperatures between 22.97 and 26.97^{o} C. The linear regression model for Gribben Creek has an R^2 of 0.90, 165 weekly means, and a linear regression equation of $y = 0.25x + 7.0$, which is defined by hydrological control. The resulting water temperature for this stream under this climate change scenario is 12.74 - 13.74^{o} C. The linear regression model for Hemmingway Creek has an R^2 of 0.96, 88 weekly means, and a linear regression equation of $y = 0.41x + 5.3$, which is neither dominantly meteorological nor hydrological control. The resulting water temperature for this stream under this climate change scenario is 14.72 - 16.36^{o} C. The linear regression model for the Main Branch of the Whitewater River has an R^2 of 0.91, 180 weekly means, and a linear regression equation of $y = 0.52x + 7.3$, which is suspected to be the type of regression model characterizing the most susceptible streams. The resulting water temperature for this stream under this climate change scenario is 19.24 - 21.32^{o} C. The linear regression model for the North Fork of the Zumbro River has an R^2 of 0.88, 23 weekly means, and a linear regression equation of $y = 0.74x + 3.6$, which is defined by meteorological control. The resulting water temperature for this stream under this climate change scenario is 20.60 - 23.56^{o} C.

Discussion

These results support the argument that streams with low intercepts and high slopes are most susceptible to climate change because the resulting water temperature is highest among the four selected streams based on air - water temperature linear regression models. This suggests that streams that are more meteorologically controlled are more susceptible to climate change as opposed to streams with higher slopes and higher intercepts. Calculating predicted increases in water temperature based on a larger subset of streams could help to provide evidence for or against this claim. Of the 40 streams studied herein, 2 streams exhibit this type of linear regression model, the North Fork of the Zumbro River and the Main Branch of Burns Valley Creek. This demonstrates that slope is more influential on water temperature than intercept, given that even a low intercept produces the highest predicted water temperatures. However, if the slopes were equally high, a regression model with a higher intercept would result in the highest water temperature. Although it is unknown how high intercept and slope can occur simultaneously for a given stream, the fact that groundwater input seasonally dampens water temperature against extreme highs and lows, resulting in warm winter and cool summer waters, suggests that the two variables can not be high simultaneously.

The magnitude of temperature increases predicted by this regional climate change model to streams with lesser amounts of groundwater inflow may have a negative effect on the biological processes, as well as the activities of brown trout. Rates of growth, fecundity and longevity as well as activities such as swimming and feeding, could be reduced under such water temperature increases and will mostly affect trout in streams which consistently maintain summer water temperatures above approximately 20^{o} C. This includes streams with regression models that currently have both a high intercept and high, moderate slope but particularly those with a high slope and low intercept. This may not be enough of an increase in water temperature to directly affect brown trout survival via thermal tolerance levels but will likely indirectly affect survival due to increased physical stress. Seven and one - day mean and maximum air temperatures not only for the study area but for individual streams and 95% confidence intervals around the predicted water temperature could be calculated throughout the summer months to assess whether thermal tolerance levels may be exceeded under a future climate scenario. Brown trout may avoid reaches with inadequate groundwater buffering during the summer months, while favoring reaches with thermal refugia provided by areas of localized groundwater inflow. This thermal preference may influence competition dynamics and shift the localized population structure to favor mature parr up to two years of age and later life stages in warmer reaches since the youngest life stages are most susceptible to high water temperatures (Jonsson and Jonsson, 2009). Additionally, movement into reaches with suitable summer thermal regimes may result in localized overcrowding and reduced overall carrying capacity of brown trout within a stream.

This study could be repeated for other climate change scenarios, particularly those that estimate an even higher increase in air temperature, such as the A2 SRES model. Trout survival may be directly affected through exceedence of thermal tolerance levels under scenarios of further increased air temperatures. New data that is not readily available online regarding the predicted increase in mean summer air temperature specific to central North America under the A2 scenario would be required. Also, a larger subset of streams could be investigated to get a better idea of inter - stream variation. It is unknown how many streams in southeastern Minnesota may have linear regression models similar to those that are more susceptible and further research would be necessary to discover this. Lastly, these linear regression models do not take into account changes in precipitation that are likely to accompany changes in air temperature. This would require the use of more sophisticated models.

This information could be used to guide restorative vs. protective management actions. Restorative actions can help mitigate near marginal streams against the effects of climate change while protective actions can help prevent suitable streams from becoming marginal or near marginal habitat. Such activities include establishing or maintaining riparian buffers, altering adjacent vegetation to increase snow trapping thereby increasing groundwater recharge, and using grassland vegetation to deepen and narrow stream channels. Also, researchers can better choose field sites in which to study the effects of climate change based on knowledge of predicted changes in water temperature regimes and the biological communities that inhabit those streams.

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