Modeling relative effects of riparian cover and groundwater inflow on stream temperature in lowland Whatcom County, Washington

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MODELING RELATIVE EFFECTS OF RIPARIAN COVER AND GROUNDWATER INFLOW ON STREAM TEMPERATURE IN LOWLAND WHATCOM COUNTY, WASHINGTON

By

Sarah Harper-Smith

Accepted in Partial Completion
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MASTER'S THESIS

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ABSTRACT

Many Pacific Northwest streams have water temperatures that exceed thermal thresholds for salmonids. Supporting and maintaining streams with temperatures below these thermal thresholds requires an understanding of the relationships between the main factors influencing stream temperatures. This study examined the relative effects of two of these factors, riparian canopy cover and groundwater inflow, on stream temperatures at the reach scale. I measured stream temperature, net groundwater exchange, and riparian canopy cover levels in 10 different study reaches designed to comprise a factorial combination of reaches with vegetated and unvegetated riparian buffers, as well as gaining and not-gaining groundwater. I then modeled stream temperatures in each reach with the SSTEMP stream temperature model, and compared model-predicted temperatures to measured stream temperatures during the warmest part of the summer. Finally, I manipulated the model to examine the relative impacts of riparian canopy cover (0-100%) and groundwater inflow (0-50%) on predicted stream temperatures. SSTEMP predicted daily mean reach temperatures well across the range of conditions studied here, although it overpredicted daily maximum temperatures. Model manipulations of groundwater inflow and canopy cover levels showed consistent trends in affecting stream temperatures. Under peak summer conditions and "base" groundwater (0%) and canopy cover (0%) conditions, predicted mean stream temperatures warmed by an average of ~ 4°C across all streams. Full canopy cover and 50% groundwater inflow each reduced this predicted warming by ~ 2.5°C when manipulated independently. However, only the combination of both high canopy cover and groundwater inflow actually reduced predicted mean stream temperatures within the study reaches. In contrast, canopy cover had much stronger effects on modeled maximum stream temperatures than did groundwater inflow. Under peak summer conditions, 100% canopy cover reduced predicted downstream warming of daily maxima by ~ 10°C, while 50% groundwater inflow did so by only ~ 2°C compared to base conditions. The results of this study affirm that both canopy cover and groundwater inflow play significant roles in minimizing stream temperatures in summer, and both should be considered when making restoration, land use, and other management decisions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SUPPLEMENTARY DATA

INTRODUCTION

Overview

Changes in stream temperature have contributed significantly to the decline of Pacific Northwest salmonid stocks (EPA 2003, NMFS 1996, 1998, Richter and Kolmes 2005), and these changes are one of the greatest challenges facing resource managers throughout the region (Gaffield *et al.* 2005, Richter and Kolmes 2005, Tague *et al.* 2007). Increased temperatures can harm salmon populations by increasing juvenile mortality, increasing susceptibility and exposure to disease, reducing spawning success and predator avoidance, changing the timing of migration, and altering fish community structure away from salmonid species (Groot and Margolis 1991, Ice *et al.* 2004, NMFS 1996, 1998, Quinn 2005, Smith 2002). Both riparian canopy cover and groundwater inflow to the stream can have substantial moderating effects on stream temperatures (Gomi *et al.* 2006, Johnson 2004, Moore *et al.* 2005, Poole and Berman 2001, Story *et al.* 2003), however the relative effects of these two factors are less well understood. This study used field and model-derived data to examine the extent to which these two factors moderate stream temperatures at the reach scale, with the goal of providing insight into the effectiveness of riparian restoration as a tool for addressing increased summer stream temperatures.

The small, lowland streams that are the focus of this study provide important habitat for salmonids and are particularly vulnerable to temperature changes. Whatcom County is home to 10 salmonid species, three of which are listed as Threatened under the Endangered Species Act (ESA): Chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*O. mykiss*), and bull trout (*Salvelinus confluentus*) (FWS 2007). The status of these species, as well as their cultural and economic importance, has made support of local salmonid populations an important, and federally mandated, concern. Small, lowland streams provide habitat for two of these species (steelhead and, to a lesser extent, Chinook), in addition to several other salmonids, including chum salmon (*O. keta*), coho salmon (*O. kisutch*, an ESA Species of Concern), and cutthroat trout (*O. clarki*) (Smith 2002, WCPW 2005). These streams are especially at risk of temperature impairment due to their relatively shallow depth, small flow volumes (Budd *et al.* 1987, Neumann *et al.* 2006) and proximity to agricultural, residential, and/or urban development (Booth 2005, Kauffman *et al.* 1997, Roni *et al.* 2002).

Legal definitions of water quality have been tied to key salmonid temperature thresholds. Salmon are temperature sensitive throughout their life cycles; stream temperatures help regulate everything from embryo incubation to juvenile growth and adult migration (Groot and Margolis 1991, Quinn 2005). To monitor local waters more effectively, the state of Washington is divided into Water Resource Inventory Areas (WRIAs), and streams within each WRIA are monitored through a water quality assessment program and associated 303(d) listing (WA DOE 2002). The 303(d) list documents the impairment status of all monitored streams: category 5 streams are impaired, category 2 streams are "waters of concern" bordering on impairment, and category 1 streams are unimpaired; categories 3 and 4 refer to special cases. All category 5 streams are required to have management plans developed, which often include restoration efforts. Streams designated as category 5 for temperature impairment have summer seven-day average daily maximum (7DADM) temperatures exceeding 16°C for core summer salmonid habitat. Additional temperature criteria exist for other salmonid habitat types and life history periods, including a daily maximum temperature threshold of 22°C (a barrier to migration and nearly lethal) (WA DOE 2002, 2005, 2006). I focused on the summer daily maximum and 7DADM temperatures; the 7DADM is used to determine 303(d) impairment because it minimizes influence of any single day, and thus the chance of listing a stream that only exceeds thresholds a few days per year (EPA 2003, WA DOE 2005).

My study seeks to elucidate the effects of riparian canopy cover and groundwater inflow on stream temperatures to better predict and test the effects of restoration efforts. Stream restoration is mandated or strongly encouraged by many laws and monitoring plans designed to protect streams and facilitate salmon preservation and recovery (Clean Water Act 2002, EPA 2003, NPPC 2000, Roni *et al.* 2002, Smith 2002, WA DOE 2005, WCPW 2005), particularly in streams considered impaired by one or more factors (WA DOE 2002). Despite the increasing consensus within the scientific community that restoration should address the natural ecosystem processes within a watershed, most restoration efforts still take place at the site or reach-specific scale (Booth 2005, Roni *et al.* 2002). One of the major challenges to restoration efforts is the lack of information available regarding which restoration techniques are most successful in facilitating salmon population recovery (Roni *et al.* 2002). Identifying the most successful restoration methods has presented many challenges, particularly because post-restoration monitoring and evaluation are rare and, when they occur, often take many years to detect a response (Bernhardt *et al.* 2005, Booth 2005, Palmer *et al.* 2007, Roni *et al.* 2002). Despite these challenges, thorough monitoring and evaluation are necessary to improve the quality and science of ecological restoration (Klein *et al.* 2007). Given that riparian restoration frequently happens over relatively small distances, I sought to match the scale of this study (~500 m) to the typical scale of local riparian restoration efforts (NRT 2004).

Riparian vegetation and stream temperature

One common restoration strategy is to reestablish riparian vegetation for stream shading and other benefits (Bernhardt and Palmer 2007, Bernhardt *et al.* 2005, Kauffman *et al.* 1997). The benefits of a healthy native riparian plant community are numerous, including provision of large woody debris, stream bank stability, and nutrient inputs, among others (Anbumozhi *et al.* 2005, Broadmeadow and Nisbet 2004, Endreny 2002, Watanabe *et al.* 2005). Shade helps to minimize daily fluctuations in stream temperature, limits excess primary production within the stream, supports salmon life cycle timing, and increases the summer carrying capacity of the stream by maximizing available habitat (Gregory *et al.* 1991, Johnson 2004, Malcolm *et al.* 2004, Murphy 1995, Naiman *et al.* 2005). In this study, I examined the role of riparian canopy cover in providing shade to the stream. However, shade is only one of several factors that are modified by human development and that influence stream temperature.

The effects of riparian canopy cover removal on stream temperature are well established in the literature. In upland Pacific Northwest streams, total forest removal (without retaining a riparian buffer) typically results in increases of up to 12°C in maximum stream temperature (reviewed in Moore *et al.* 2005), though the magnitude of the effect varies widely across sites (Gomi *et al.* 2006, Moore *et al.* 2005, Wilkerson *et al.* 2006). In one case, four of seven upland study streams exhibited no significant change in temperature after clear-cutting, although this was likely due to shade provided by slash left covering the stream after forest removal (Jackson *et al.* 2001). In addition, multiple studies report temperature recovery over 10+ years after forest removal and subsequent regrowth, suggesting that decreases in temperature as canopies close are equivalent to the increases seen after clear-cutting (Johnson 2004, Moore *et al.* 2005). However, most of the streams examined in these previous studies are located in upland watersheds that differ substantially from lowland streams in a variety of ways that may influence stream temperature. For example, elevation, gradient, and turbulence are often greater in upland streams and generally minimize increases in stream temperature (Allan 1995). Given that lowland streams typically have the greatest pressures from development, support dwindling salmon populations, and are the focus of many restoration projects in the Pacific Northwest, understanding the potential effects of restoration on their temperature regimes will help maximize the effectiveness of limited restoration resources.

Guidelines for riparian buffers have focused on minimum buffer widths, but buffer lengths have received much less attention (Blinn and Kilgore 2001, Lee *et al.* 2004). For small, fish-bearing streams such as those studied here, Washington State now has condition-specific requirements for riparian buffer widths, such that harvest within 15 m of the stream is never permitted, and, depending on site-specific conditions, harvest is either limited or prohibited within 20 to 45 m of the stream channel (WFPB 2001). In many cases, the maintenance or creation of minimum buffer widths mitigates or eliminates stream temperature changes due to forest removal (Barton *et al.* 1985, Blinn and Kilgore 2001, Budd *et al.* 1987, Frimpong *et al.* 2005, Gomi *et al.* 2006, Lee *et al.* 2004, Wenger 1999, Wilkerson *et al.* 2006). These positive impacts are diminished, however, if the restored or preserved buffer is an isolated patch along an otherwise heavily impacted stream (Booth 2005, Roni *et al.* 2002). In such situations, buffer length can be an equally important component of riparian restoration or protection.

Guidelines similar to those for buffer width are not generally available for buffer length. In Ontario, Canada, Barton *et al*. (1985) investigated the effects of riparian buffer length on small agricultural streams in southern Ontario, Canada, and found that 56% of weekly maximum water temperature variation at a given location was explained by riparian conditions within 2.5 km upstream. Since then, studies focused on decreases in stream temperature over a given distance have found that as little as 150 m of canopy cover may be enough to reduce stream temperatures by 2-3°C (Johnson 2004). Even greater effects have been observed over distances closer to 500 m in a variety of streams (Frimpong *et al.* 2005, Rutherford *et al.* 2004). While streams can decrease in temperature upon moving through a shaded reach, they typically increase again once canopy cover is no longer present (Rutherford *et al.* 2004). Still, the buffer length needed to reduce temperature by a given amount depends on a variety of factors (e.g., air temperature, temperature at the upper limit of the reach, groundwater exchange), all of which can vary from stream to stream and from reach to reach. Finally, a key question for restoration is whether restored riparian canopy cover is likely to substantially cool streams below ambient upstream temperatures as opposed to minimizing further warming. Understanding the interactions of these factors is necessary to make reasonable predictions about the potential effectiveness of a given restoration strategy or project.

Groundwater inflow and stream temperature

While restoration efforts frequently focus on riparian vegetation as a way to decrease stream temperatures, groundwater inflow may also mitigate temperature increases. Groundwater inflow is defined here as any subsurface inputs to streamflow. In areas where virtually all streams are groundwater fed to some degree, the same changes to land cover (e.g., increasing impervious surfaces), and land use (e.g., land conversion to agriculture) that create a need for riparian restoration can dramatically affect the hydrology of local streams (Allan 2004, Boulton and Hancock 2006, Harbor 1994, Scanlon *et al.* 2007). Groundwater inflow moderates stream temperature by entering the stream at a cool and constant temperature, regardless of season; it generally cools the stream in summer, and warms it in winter (Adam and Sullivan 1989, Brosofske *et al.* 1997, Johnson 2004, Moore *et al.* 2005, O'Driscoll and DeWalle 2006, Poole and Berman 2001, Story *et al.* 2003, Younus *et al.* 2000). In lowland Whatcom County, groundwater temperatures tend to be 10-11°C year-round (Cox *et al.* 2005). In summer, the effect of groundwater cooling peaks just after the daily maximum air temperature is reached, when the difference between stream and groundwater temperatures is greatest. Hyporheic exchanges also tend to buffer stream temperature changes because of the delayed subsurface response to air temperature variation; hyporheic flows generally have a cooling effect when stream temperature is rising, and a warming effect when it is cooling (Loheide and Gorelick 2006, Poole and Berman 2001).

While the general effects of groundwater inflow on stream temperature, as described above, are relatively well-established, the magnitude of those effects is not. The effects of groundwater inflow on stream temperature depend upon the relative amount of groundwater entering the stream, the flow volume, the velocity of the stream itself, and the difference in temperature between stream and groundwater (Becker *et al.* 2004, O'Driscoll and DeWalle 2006, Whitledge *et al.* 2006). In one study attempting to quantify the effects of groundwater inflow on small upland streams in British Columbia, Canada, 40% of the cooling that occurred throughout one of the study reaches was attributed to groundwater inflow (Story *et* *al.* 2003). Bed heat conduction and hyporheic exchange were responsible for the remaining cooling. One reason these effects are so difficult to quantify is the challenge of determining the relative amount of groundwater entering the stream. This difficulty is largely due to the dynamic nature of stream-groundwater interactions and the inherent limitations of different measurement methods (Becker *et al.* 2004, Boulton and Hancock 2006, Christensen *et al.* 1998, Keery *et al.* 2007, Moore *et al.* 2005, Story *et al.* 2003). One common and reliable method of estimating net groundwater exchange is to compare total streamflow at the top and bottom of the study reach (Becker *et al.* 2004). However, net exchange can still miss groundwater inputs that may have a significant effect on stream temperature if these inputs are balanced, in whole or in part, by loss of stream water to groundwater. To help account for such effects, groundwater-fed segments of small, lowland streams in Pennsylvania were distinguished from neutral or losing segments by examining stream-air temperature relationships (O'Driscoll and DeWalle 2006). For those relationships, the slopes decreased and the intercepts increased as groundwater inflow increased because rising air temperatures did not increase stream temperatures as rapidly in gaining streams as in non-gaining streams. I used a combination of net flow differences and air-stream temperature relationships to estimate groundwater exchange in this study.

Stream temperature modeling

Given the logistical challenges of manipulating canopy cover and/or groundwater inflow levels in the field, models can help examine how stream temperatures may be affected by these two factors. Several recent stream temperature modeling studies have identified canopy cover and/or groundwater inflow as important factors controlling stream temperature.

In addition to the field measurements of the effects of canopy cover (as described above), modeled canopy cover significantly reduced stream temperatures, even at levels as low as 70%, in small, lowland New Zealand streams (Rutherford *et al.* 1997). In another study modeling stream and river temperatures in the Cascade Mountains in Washington, model-varied buffer widths with full canopy cover revealed that buffer widths greater than 30 m did not result in further significant decreases in stream temperature (Sridhar *et al.* 2004). Solar radiation, a factor heavily influenced by canopy cover, is a main control of stream temperature in many stream temperature models. This was the case in reaches with groundwater inflow, as well as reaches without it, across a variety of different study areas (Sinokrot and Stefan 1993, St-Hilaire *et al.* 2000, Younus *et al.* 2000). Heat exchange with the streambed, a factor heavily influenced by groundwater inflow, is another significant factor in some stream temperature models (Sinokrot and Stefan 1993). Other models identify groundwater inflow as a significant factor, in one case in the form of shallow subsurface flow from tile drains (Younus *et al.* 2000). Solar radiation, groundwater discharge, and stream width were identified as the three most sensitive factors when modeling urban stream temperatures in Ontario, Canada (LeBlanc *et al.* 1997). While it is clear that both canopy cover and groundwater inflow can be important in determining stream temperature, few studies have quantified the relative magnitudes of these effects. While riparian restoration strongly emphasizes canopy cover, a key issue for predicting restoration success is the extent to which changes in groundwater exchange (e.g., decreased inflow because of further upland development) might offset any temperature improvements due to shade from riparian plantings.

This study aimed to quantify the effects of groundwater and canopy cover on daily mean and maximum stream temperatures during peak summer conditions using the Stream Segment Temperature Model (SSTEMP, Bartholow 2002). SSTEMP is an extensive heat budget model incorporating a variety of physical and meteorological parameters (Supplementary Table S1) to predict mean and maximum daily stream temperatures at the end of a reach of specified length. It is not a spatially explicit model, in contrast to others that predict stream temperatures throughout an entire stream network (e.g., Bartholow 1989, Cox and Bolte 2007). Two recent studies have used SSTEMP to ask similar questions focusing on summer daily mean stream temperatures. Whitledge *et al*. (2006) found that groundwater inflow was necessary, even under maximum riparian canopy cover, to decrease mean stream temperatures to a level safe for resident smallmouth bass during peak summer air temperatures in the Midwest. Gaffield *et al*. (2005) modeled the magnitude of change in mean temperature for small streams in southeastern Wisconsin under varied groundwater and canopy cover conditions, and found that the concentration of groundwater inflow was very important. While concentrated groundwater inflow resulted in the greatest decrease in mean temperature over short distances, more diffuse groundwater inflow kept the stream coolest at the end of a 2 km reach. The same modeling experiments showed the effects of maximum riparian canopy cover to be very similar to those of groundwater inflow. In contrast to these studies, which were conducted in Midwestern streams subject to different climatic and geographical constraints, I used SSTEMP to further examine these questions in lowland Pacific Northwest streams.

Study overview

Within the context of riparian restoration and alleviating summer stream temperatures that are too warm for salmon, this study aimed to quantify the relative magnitude of the effects of changes in riparian canopy cover and groundwater inflow on peak summer stream temperatures in lowland Whatcom County, Washington. I measured stream temperature, net groundwater exchange, and riparian canopy cover in ten different study reaches designed to comprise a factorial combination of reaches with vegetated and unvegetated riparian buffers, as well as gaining and not-gaining groundwater. I evaluated stream temperature impairment by examining daily maximum and 7DADM stream temperatures relative to salmonid thermal thresholds. Using a combination of reach-specific and regional conditions as inputs to the SSTEMP model, I compared model-predicted temperatures to measured stream temperatures during the warmest part of the summer. I then manipulated the model to examine the relative impacts of riparian canopy cover and groundwater inflow on predicted stream temperatures. I expected that both riparian canopy cover and groundwater inflow would have measurable and ecologically important effects on stream temperature. I expected that the effect would be similar for both factors, and that the magnitude of effect on daily maximum temperatures would be greater than the effect on daily mean temperatures. However, I also expected that while canopy cover would reduce stream warming, groundwater inflow would be necessary to cool temperatures within the study reaches.

METHODS

Study area and site selection

This study was conducted in the watersheds of lowland Whatcom County, the northwestern-most county in Washington, adjacent to the northern portion of Puget Sound. The area is contained within the greater Nooksack River watershed, formally known as Water Resources Inventory Area 1 (WRIA 1) by the state. The climate is Mediterranean-like with wet, cool winters and dry, warm summers (Bailey 1995). Prior to Euro-American settlement, the lowland area was dominated by red alder (*Alnus rubra*) and western red cedar (*Thuja plicata*), as well as black cottonwood (*Populus trichocarpa*) and Sitka spruce (*Picea sitchensis*) in riparian forests. By 1940, settlers had burned or logged much of the lowland forest and converted the land to agriculture, and many streams and rivers had been ditched or diked (Collins and Sheikh 2003).

This project focused on longitudinal temperature changes in stream reaches that have, or are at risk of, impaired maximum stream temperatures. I defined impaired streams as those meeting the criteria for listing on the state 303(d) list as Category 5 temperature impaired, including a summer seven-day average daily maximum (7DADM) temperature greater than 16°C (WA DOE 2005). My study reaches were chosen based on the 303(d) temperature listing, a survey of aerial photographs and surficial aquifer maps, and *in situ* suitability evaluations at candidate sites. I chose a study reach length of ~500 m because it is a length representative of most local riparian restoration projects (NRT 2004).

My goal was to test SSTEMP across a wide variety of lowland stream conditions. I selected ten reaches, six with high riparian canopy cover (stream channel heavily shaded throughout the reach), and four with low canopy cover (stream channel erratically shaded by patches of riparian vegetation or primarily unshaded). Each study reach was located in a wadeable (1st - 3rd order), perennial stream, with consistent levels of riparian cover (or lack thereof) throughout the reach. Surficial aquifer maps were used to identify sites that were likely gaining groundwater flow, and likely not gaining (neutral or losing) within each canopy cover group. Thus, the study reaches were intended to fit into the following groups:

2 gaining reaches with low canopy cover

2 not gaining reaches with low canopy cover

3 gaining reaches with high canopy cover

3 not gaining reaches with high canopy cover

Field measurements during data collection revealed that not all reaches fit into the category for which they were intended (see Results); most reaches had substantial net gains in flow, indicating groundwater inflow. However, I was successful in finding study reaches that exhibited a wide range of conditions across all categories. Reaches were chosen to represent not only the range of local canopy cover and groundwater exchange conditions, but geographical, physical, and geological conditions as well (Figure 1, Supplementary Figure S1). Reaches were located in primarily agricultural or rural areas (Anderson, Bertrand.P, Bertrand.S, Double Ditch, Terrell), and primarily residential or urban areas (Deer, Fishtrap, Padden, Squalicum, Whatcom) (Supplementary Figure S2). Three reaches flowed from lakes with controlled outlets: Padden, Terrell, and Whatcom. Stream substrate in most reaches was cobbly, although some reaches had substantially more fine sediments (Bertrand.P, Bertrand.S, Double Ditch, Fishtrap, and Terrell).

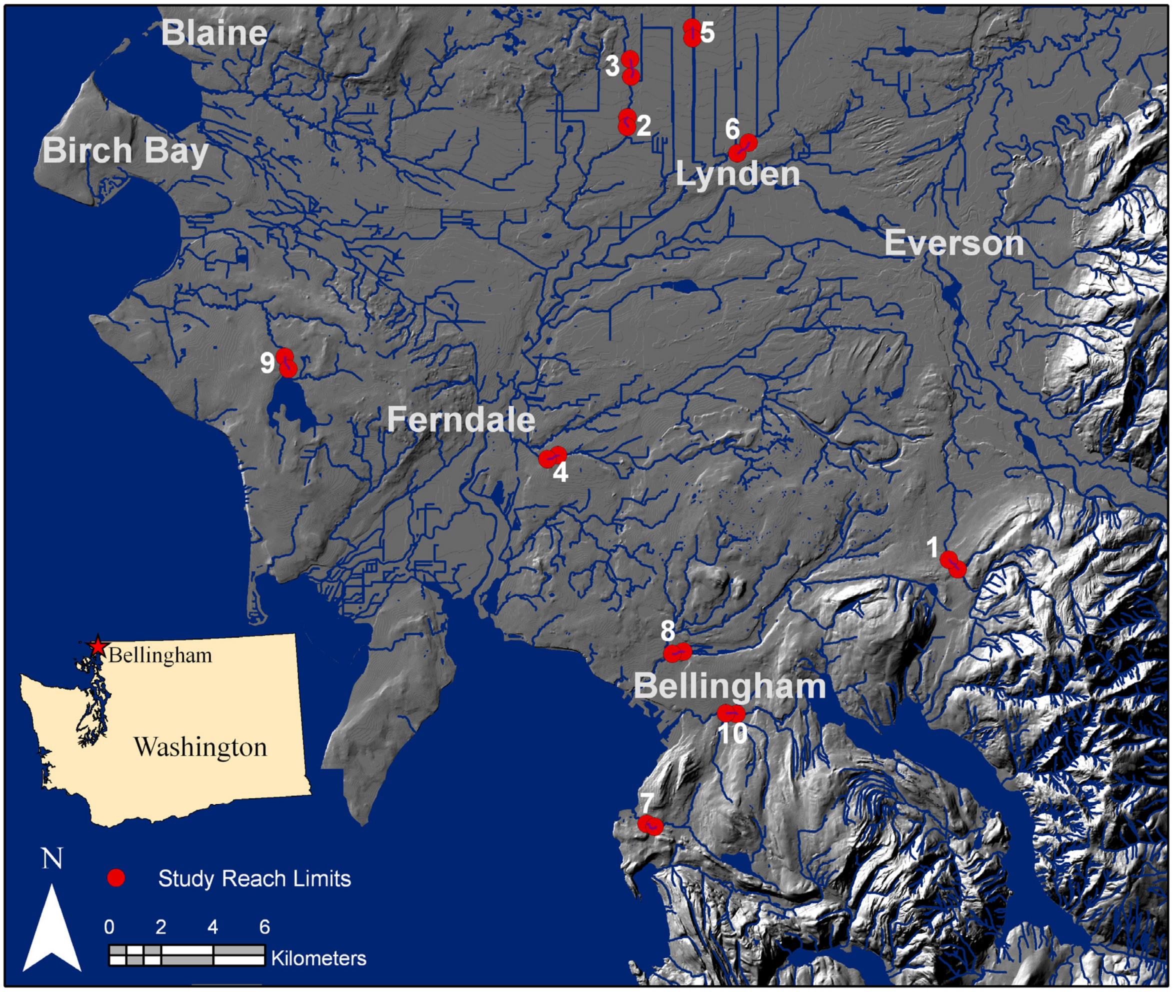

Figure 1. Relief map of the study area in lowland Whatcom County, Washington. Study reach limits are indicated by red dots, water bodies are in blue. Study reaches are numbered as follows: 1) Anderson; 2) Bertrand.P; 3) Bertrand.S; 4) Deer; 5) Double Ditch; 6) Fishtrap; 7) Padden; 8) Squalicum; 9) Terrell; 10) Whatcom. All data accessed from Huxley College at Western Washington University.

Field data collection

To measure temperature over the course of the summer within each study reach, two water-resistant temperature data loggers (iButton DS-1921G®, 60 minute interval recordings, ±0.5ºC accuracy, Maxim Integrated Products Inc., Sunnyvale, CA) were deployed at the top, middle, and bottom of each 500 m reach (approximately every 250 m). Each pair was attached to a piece of rebar (0.5 m long) hammered into the streambed so that the iButtons were submerged mid-way between the stream bottom and the surface in an area of well-mixed flow. In streams where the middle of the reach was inaccessible or highly-trafficked, no middle loggers were placed. I also recorded air temperature hourly with two temperature data loggers placed in the shade, attached to streamside vegetation in the middle of each study reach (or at the top or bottom, if the middle of the reach was not available). Data loggers were deployed for 2.5 months (July through mid-September 2006), recording temperatures hourly through the hottest part of the summer.

At the up- and downstream data logger locations, I measured streamflow three times throughout the summer using the EPA Environmental Monitoring and Assessment Program (EMAP) velocity-area discharge measurement procedure (Lazorchak *et al.* 1998). Flow was measured at the same locations each time, and whenever possible all locations were downstream of gravel bars, to minimize loss to hyporheic flow. Due to dry summer conditions, flow measurements approximated base flow conditions. I interpreted the difference between the up and downstream flow measurements as a proxy for net groundwater exchange. While this technique has limitations (it cannot measure gross groundwater exchange), it is an accepted and reliable method for estimating net exchange between stream and groundwater flows, particularly in the absence of a continuous hydrograph or other monitoring data (Becker *et al.* 2004, Gaffield *et al.* 2005, Kalbus *et al.* 2006). Only one stream (Padden Creek) had a tributary within the study reach, and flow was also measured above and below the tributary, to account for tributary gain in the final calculations of average flow and change in flow. Depending on equipment availability, flow was measured with a Swoffer Model 2100® (Swoffer Instruments Inc., Seattle, WA) or a Marsh-McBirney Flo-Mate® (Marsh-McBirney Inc., Frederick, MD); equipment was consistent within each of the three measurement periods.

In addition to collecting stream temperature and flow data, I conducted riparian vegetation and stream physical habitat assessments with modified EMAP protocols (Lazorchak *et al.* 1998). The vegetation survey included a semi-quantitative assessment of riparian vegetation type and cover, as well as in-stream densiometer measurements, and a summary of anthropogenic disturbances present within 10 m of the stream bank (e.g., buildings, agricultural land use, pavement). The physical assessment included average wetted and bankfull widths and thalweg depth. Both assessments were conducted at each logger location and at the mid-point between each pair of loggers for a total of five equidistant assessment locations in each stream reach.

Data analysis

For all analyses, temperatures recorded by both data loggers at each location were averaged, and calculations were performed on the average values. Daily mean, daily maximum, and 7DADM temperatures were used to compare stream reaches to one another, as well as to identify temperature-stressed reaches. I examined how maximum temperatures changed from upstream to downstream within each reach ($\Delta T_{measured}$), and how those changes varied across reaches with different canopy cover and groundwater flow conditions. To characterize impairment within my reaches, I calculated the percentage of days reaches exceeded two criteria set forth by the state water quality standards (WA DOE 2006): 1) the 22ºC daily maximum temperature threshold (a barrier to adult migration and close to the lethal threshold), and 2) the 16ºC 7DADM temperature threshold (the limit for summer core salmonid habitat, the use designation of the study streams).

Net groundwater exchange estimates were examined for accuracy by assessing two relationships: 1) the slope of the relationship between 7DADM stream temperature and 7DADM air temperature for each reach, and 2) the daily stream temperature variation at the downstream logger location, by estimated percent groundwater flow. Based on results of previous studies, I expected that reaches with higher levels of groundwater inflow would have a shallower slope for the stream – air temperature relationship, as well as lower daily variation in stream temperature (Constantz 1998, O'Driscoll and DeWalle 2006). I assessed these relationships for both raw temperature data and temperature data normalized for flow across reaches by dividing stream temperature by average flow volume.

Temperature modeling

SSTEMP-predicted temperatures were tested for fit with the actual temperatures recorded in the study reaches. SSTEMP incorporates a variety of factors, all measured in the field or acquired from regional data sources, in its prediction of daily mean and maximum temperatures at a specified distance downstream of the head of the reach (Supplementary Tables S1- S3). In calculating the net heat flux as water moves through the specified reach, the model incorporates a variety of heat flux components, including: convection, conduction, evaporation, water's back radiation, atmospheric radiation, friction, solar radiation, and vegetative radiation. Model predictions may be somewhat limited by the assumptions of the model structure (Bartholow 2002). For example, it is assumed that the stream channel is well-mixed at all times, with no vertical stratification in pools. SSTEMP is based on, and derived from, a series of stream temperature models developed by U.S. Fish and Wildlife Service (Theurer *et al.* 1984).

I used regression analyses to test model fit and compare the actual temperature data to the model-predicted temperatures on 13 dates for each reach individually and for all reaches together. For two reaches (Fishtrap and Whatcom Creeks), only 12 dates were used due to the slightly later deployment of loggers in those locations. For the Bertrand.P site I used 12 dates, all occurring within the first three weeks of data collection, due to loss of both downstream loggers. The dates were haphazardly chosen to represent the full range of stream temperature and weather conditions throughout the summer (Supplementary Table S2). The only modeled date to include rain was the final date in September, and precipitation was negligible at < 0.3 mm.

I manipulated SSTEMP to evaluate mean and maximum stream temperatures under varying canopy cover (CC) and groundwater inflow (GW) conditions. These manipulations were conducted for 3 of the 12 sub-sampled dates, representing the range of air temperatures and other meteorological conditions exhibited throughout the study period: 1) a peak temperature date, 2) a mid temperature date, and 3) a cool temperature date (Supplementary Table S2). A factorial combination of groundwater inflow levels (0%, 10%, 20%, 30%, and 50% of upstream flow added from groundwater flow) and riparian canopy cover levels (0%, 25%, 50%, 75%, and 100%) was modeled for each reach. Levels of both canopy cover and groundwater inflow were chosen because they are representative of common regional conditions (Llyn Doremus, personal communication[1]), and I standardized reach length at 500 m for all manipulations. To assess overall trends in the effects of these manipulations, I calculated the change in stream temperature from recorded upstream temperatures to predicted downstream temperatures within each study reach (ΔT_wmean and ΔT_wmax) on each of the three dates under the following treatments: 1) 0% CC and 0% GW; 2) 0% CC and 50% GW; 3) 100% CC and 0% GW; 4) 100% CC and 50% GW. I analyzed the results with an ANOVA, examining changes in both mean and maximum temperatures. The ΔT_wmax values were transformed to fit ANOVA assumptions ($\sqrt{(|\Delta T_w|)}$, negative values were reinstated after transformation). The ANOVA model was: ΔT_w = constant + Date + Stream + CC + GW + Date*GW + Date*CC + CC*GW + Date*CC*GW + error. Date had three levels (Peak, Mid, and Cool), Stream had 10 levels and functioned as a blocking factor, CC had two levels (0% and 100%), and GW had 2 levels (0% and 50%). Contrasts were also performed within each date, comparing each of the 4 treatments to all others (Dunn-Ŝidák corrected alpha = 0.0085).

I performed similar analyses to look for significant effects across modeled reach conditions (ΔT_amean and ΔT_amax) for each study reach when modeled on each of the three dates for two tests: 1) the difference between predicted downstream temperatures in reaches with 0% canopy cover (CC) and reaches with 100% CC; I calculated ΔT_a at two levels of groundwater inflow (GW, 0% and 50%); 2) comparing reaches with 0% GW to reaches with 50% GW at two levels of CC (0% and 100%). ΔT_a values for test 1 (change in temperature between reaches with 0% and 100% CC at two levels of GW) were transformed to fit

[1] Llyn Doremus; Nooksack Natural Resources; 5016 Deming Rd; Deming, WA 98244; June 6 2007.

ANOVA assumptions $((\ln(|\Delta T_a|))+1$, negative values were reinstated after transformation). The ANOVA model was: ΔT_a = constant + Date + Level + Stream + Level*Date + error. Date had three levels (Peak, Mid, and Cool), Stream had ten levels and functioned as a blocking factor, and Level had two levels (0% and 50% GW for test 1, 0% and 100% CC for test 2). Selected contrasts assessed differences between Dates (e.g., comparing Peak to Mid and Cool) as well as levels of one factor within the other (e.g., comparing ΔT_amax for change in CC at 0% GW versus 50% GW). For all contrasts, Dunn-Ŝidák corrected alpha = 0.0085. I used the sensitivity analysis program within SSTEMP to evaluate the sensitivity of all model parameters for a representative reach, Deer Creek, under peak temperature conditions. The SSTEMP sensitivity analysis tool varies each parameter individually, holding all others constant (Bartholow 2002). Each parameter was increased and decreased by 10%, and the changes in predicted temperature reported. The tool also assigned a relative sensitivity score to each parameter, ranging from 0 to 30, indicating how strongly that parameter influenced model results. I conducted sensitivity analyses for both mean and maximum temperature parameters.

RESULTS

Reach data

Study reaches spanned a broad range of conditions typical of lowland streams in this region in terms of canopy cover, overall flow, and groundwater exchange (Table 1). Most reaches exhibited streamflow rates less than 0.11 cms, although the streamflow of the Whatcom Creek reach was more than three times greater. While I achieved a factorial balance of gaining/not gaining and covered/not covered streams overall, in several cases the reaches did not fit into the *a priori* riparian canopy cover or groundwater exchange category. Change in flow from upstream to downstream locations (net groundwater exchange) varied from -34% to +120% and canopy cover ranged from 11% to 92% (Table 1). There was less variation in canopy cover across reaches than was expected based on initial observations at each reach, with 8 reaches exceeding 65% canopy cover.

As expected based on individual reach conditions, summer stream temperatures at the downstream logger locations varied considerably across time (July through September) and space (10 reaches). However, all sites experienced their hottest temperatures in late July 2006 (Figure 2), when maximum air temperatures exceeded 30°C in some locations. Whatcom Creek had consistently higher mean and maximum stream temperatures than all other reaches (due to warm outflow from Lake Whatcom), while Anderson was mid-range and Deer was typically coolest (Figure 2). One reach (Bertrand.P) had less than three weeks (mid-July through early-August) of downstream logger data due to iButton disappearance. In all cases, there was a strong relationship between daily mean and maximum air and stream temperatures at each reach; within a reach, peaks and lows in these temperatures occurred within hours of one another (reach-specific air temperature data not shown). There was a

Table 1. Study reach stream order, gradient, canopy cover, flow, and temperature data. Not all reaches fit into their expected canopy cover (Bertrand.P, Squalicum) or groundwater (Padden, Bertrand.P, Double Ditch, Whatcom) condition categories; however, the full range of categories is represented. Not gaining reaches were identified as having less than 10% groundwater inflow. CC = canopy cover; GW = groundwater exchange, mean ± standard error ; Location = the up or downstream end of the reach; DailyMax = daily maximum stream temperature; 7DADM = seven-day average daily maximum stream temperature. Table 1 continued on following page.

CC Conditions	GW Exchange Conditions	Reach	Location	Stream Order †	Gradient (%)	Avg CC (%)	Avg Streamflow (cms)	GW Exchange (% Δ Flow)	% Days DailyMax > 22°C	% Days 7DADM > 16°C
High Canopy Cover	Gaining	Bertrand.S	Up	--	--	--	0.021 ± 0.003	--	0.0	77.8
			Down	2	0.28	83	0.047 ± 0.005	120.6	0.0	6.5
		Deer	Up	--	--	--	0.033 ± 0.004	--	0.0	1.9
			Down	3	0.22	88	0.039 ± 0.005	18.0	0.0	5.7
		Fishtrap	Up	--	--	--	0.071 ± 0.025	--	0.0	76.0
			Down	2	0.16	89	0.106 ± 0.023	49.9	0.0	78.0
		Padden	Up	--	--	--	0.023 ± 0.004	--	0.0	15.8
			Down	2	0.79	91	0.029 ± 0.011	29.4	0.0	26.3
	Not gaining	Terrell	Up	--	--	--	0.005 ± 0.001	--	1.6	96.4
			Down	1	0.39	89	0.006 ± 0.002	9.2	0.0	83.9
		Anderson	Up	--	--	--	0.029 ± 0.004	--	0.0	20.3
			Down	3	2.05	80	0.025 ± 0.010	-15.5	0.0	50.9

† = Strahler's stream order

Table 1 (continued). Study reach stream order, gradient, canopy cover, flow, and temperature data. Not all reaches fit into their expected canopy cover (Bertrand.P, Squalicum) or groundwater (Padden, Bertrand.P, Double Ditch, Whatcom) condition categories, however, the full range of categories is represented. Not gaining reaches were identified as having less than 10% groundwater inflow. CC = canopy cover; GW = groundwater exchange, mean ± standard error; Location = the up or downstream end of the reach; DailyMax = daily maximum stream temperature; 7DADM = seven-day average daily maximum stream temperature.

CC Conditions	GW Conditions	Reach	Location	Stream Order †	Gradient (%)	Avg CC (%)	Avg Streamflow (cms)	GW Exchange (% Δ Flow)	% Days DailyMax > 22°C	% Days 7DADM > 16°C
Low Canopy Cover	Gaining	Whatcom	Up	--	--	--	0.357 ± 0.009	--	7.1	100.0
			Down	2	0.69	11	0.409 ± 0.006	14.4	37.5	100.0
	Not gaining	Bertrand.P	Up	--	--	--	0.063 ± 0.001	--	0.0	0.0
			Down	2	0.21	74	0.069 ± 0.014	9.8	0.0	27.3
		Double Ditch	Up	--	--	--	0.108 ± 0.026	--	0.0	47.2
			Down	1	0.48	16	0.108 ± 0.028	-0.6	0.0	49.1
		Squalicum	Up	--	--	--	0.022 ± 0.0003	--	0.0	82.1
			Down	3	0.67	66	0.014 ± 0.004	-34.0	0.0	21.4

† = Strahler's stream order

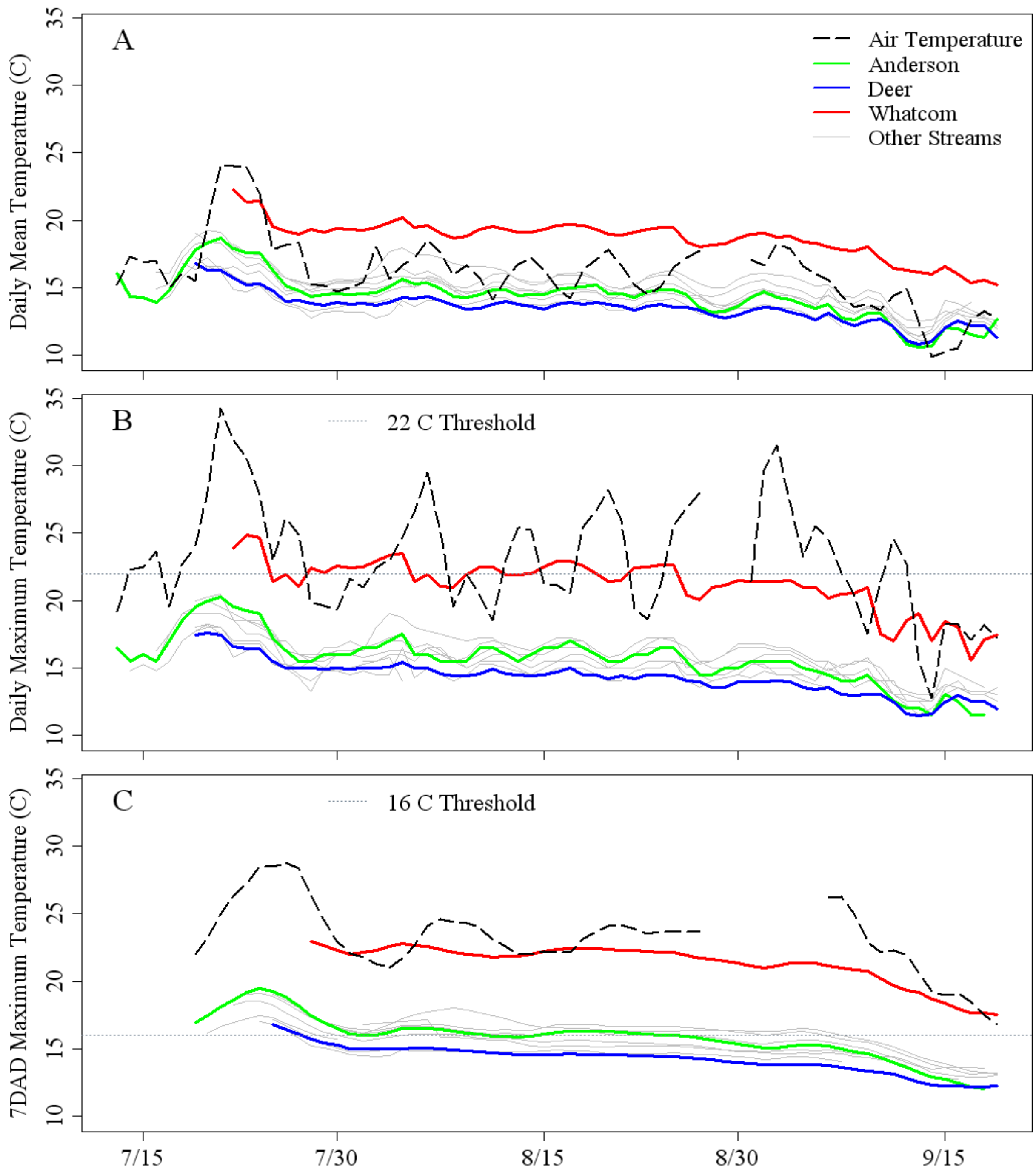

Figure 2. Stream and air temperatures for A) daily mean, B) daily maximum, and C) 7-day average daily (7DAD) maximum. Highlighted reaches show the range of reach temperatures, remaining reaches are plotted in the background; horizontal lines indicate salmonid thermal thresholds (WA DOE 2006). Study period includes the peak summer (May-Sept) temperatures; weeks preceding summer peak have temperature patterns similar to weeks following; air temperatures are regional values with some missing data (AgWeatherNet 2006).

wide range among study reaches in the change in recorded temperature from up to downstream ($\Delta T_{measured}$) during peak study period conditions (Figure 3). Three reaches cooled consistently (Bertrand.S, Terrell, and Squalicum), five reaches exhibited little (< ±1°C) change (Padden, Fishtrap, Deer, Anderson, and Double Ditch), and two reaches warmed consistently (Whatcom and Bertrand.P). $\Delta T_{measured}$ did not follow a consistent pattern across reaches with respect to either canopy cover or groundwater exchange levels (Figure 3).

My measurements confirmed that all study reaches exceeded temperature thresholds indicating impairment. The study period included the hottest summer air and water temperatures. Stream temperatures more frequently exceeded the summer 7DADM threshold than the summer daily maximum (DailyMax) threshold (Figure 2). At downstream logger locations, temperatures exceeded the 22°C DailyMax threshold in one reach, Whatcom, on more than 35% of days. This was largely due to the source of Whatcom Creek: a surficial outflow of Lake Whatcom with very warm summer temperatures (Matthews *et al.* 2008). All 10 reaches exceeded the 16°C 7DADM threshold on 6-100% of days (Figure 2, Table 1). Three reaches (Bertrand.S, Terrell, and Squalicum) had a greater percentage of days exceeding the 7DADM threshold at the upstream logger location than at the downstream location, and the number of days in excess of the threshold decreased by 12-71% at the downstream location in these reaches. These were the same three reaches that experienced the greatest up to downstream cooling throughout the study period (ΔT_{within}, Figure 3). Groundwater inflow may have contributed to this pattern, particularly in the Bertrand.S and Squalicum reaches. Bertrand.S had the highest net groundwater inflow of any reach, and, while Squalicum experienced a net loss of flow (Table 1), it may have had

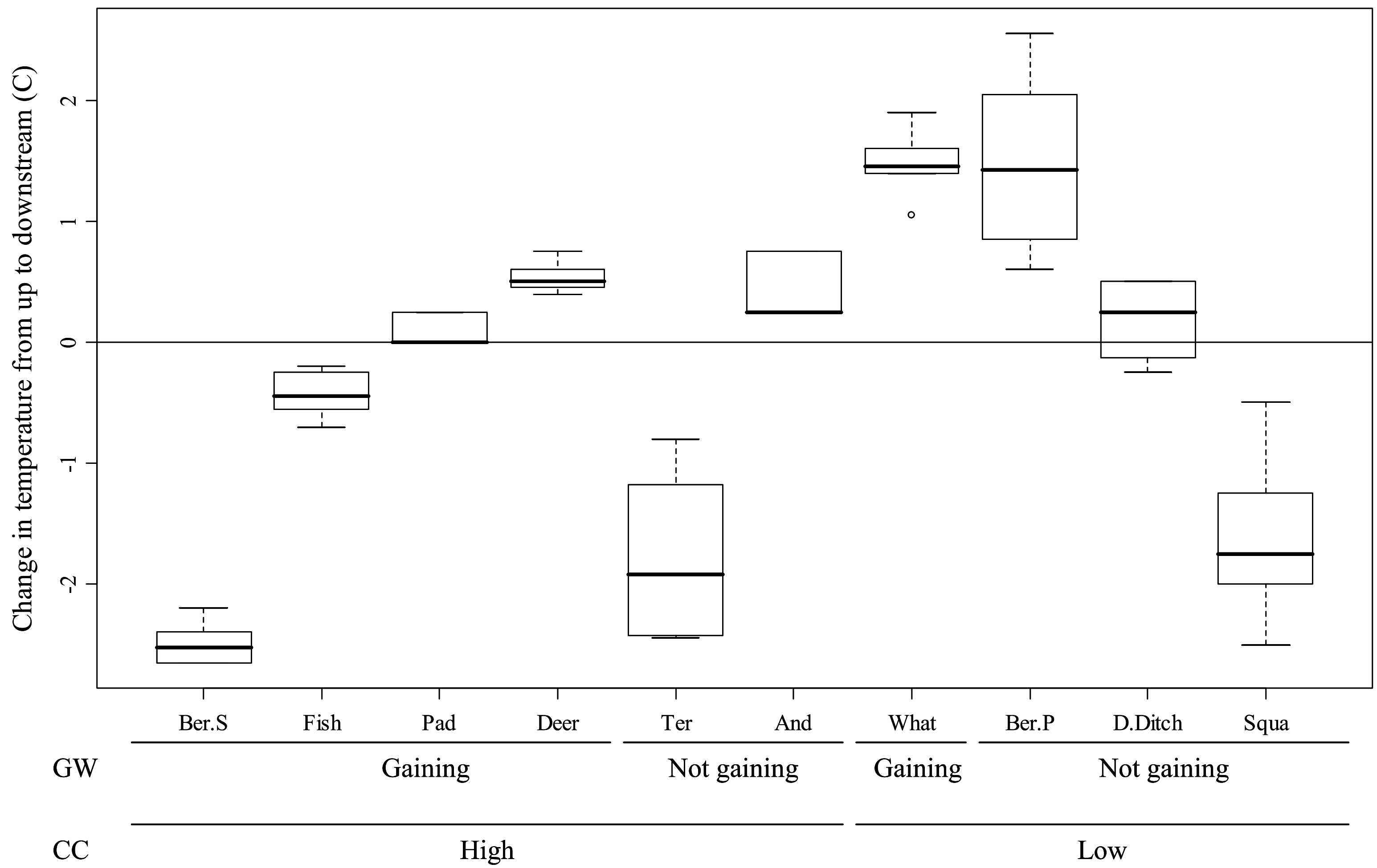

Figure 3. Boxplot of changes in maximum stream temperature from up to downstream ($\Delta T_{measured}$) during the first 8 days of temperature logging at each reach. For all reaches, this period included peak summer temperatures. Patterns were similar for entire study period. Within a canopy cover (CC) level, reaches are arranged from highest to lowest groundwater exchange (GW). The box is the interquartile range (IQR); whiskers represent 1.5xIQR; dots indicate outliers >1.5xIQR. For specific CC and GW values, see Table 1.

substantial inflow as well as outflow (see analysis of groundwater flow estimates below). Canopy cover may also have contributed to cooling. The Squalicum reach was just downstream of an entirely unvegetated reach and Terrell Creek flows out of a warm lake just upstream of the study reach, so the increased canopy cover may have decreased stream temperatures.

Change in flow likely gave a more reliable estimate of groundwater exchange in some reaches than others. A plot of 7DADM air temperatures by 7DADM stream temperatures at the downstream location in each reach revealed that the Bertrand.P, Double Ditch, and Squalicum reaches had best-fit lines with shallower slopes than would be expected based on their groundwater exchange estimates; the relationship between slope and groundwater exchange was significant when these reaches were removed (Figure 4, Supplementary Figure S3). While flow measurements suggested that these reaches were nearly neutral or losing (Table 1), the air-water temperature slope suggested that groundwater inflow likely reduced the sensitivity of daily maximum stream temperatures to variation in air temperature. Attempts to normalize across reaches by examining stream temperatures per unit flow did not help to identify reaches with potentially inaccurate groundwater measurements: a regression of daily temperature variation per unit flow by groundwater exchange (%GW) was non-significant (even with Whatcom, an apparent outlier reach, removed, $p = 0.28$) (Supplementary Figure S4).

SSTEMP model data

SSTEMP generally predicted daily mean (DailyMean) reach temperatures more accurately than DailyMax temperatures, though all relationships between measured and predicted

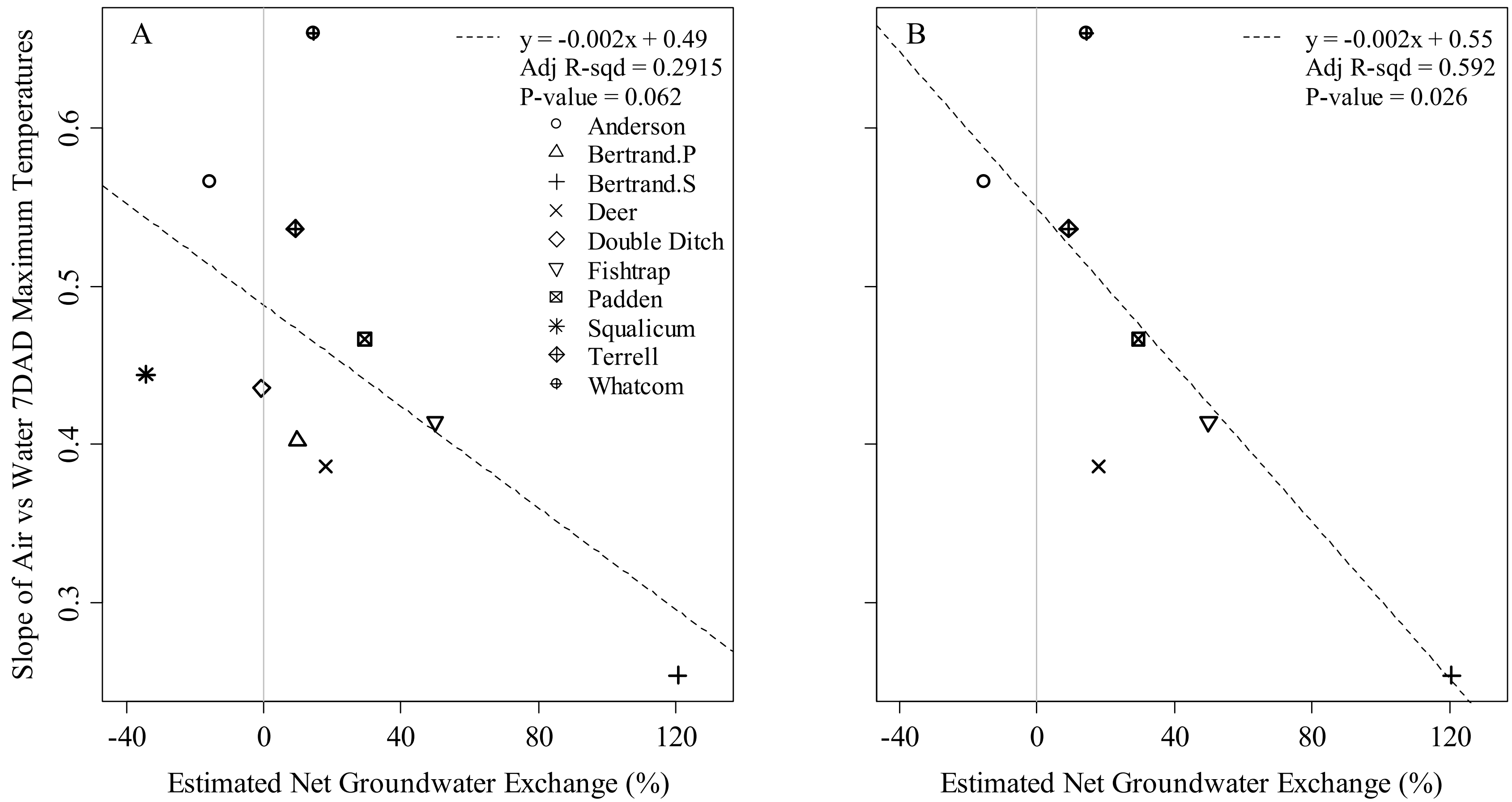

Figure 4. Relationship between groundwater inflow and the slope of the 7DADM air and stream temperature relationship for A) all reaches, and B) 7 reaches, excluding Bertrand.P, Double Ditch, and Squalicum, which have shallower slopes than would be expected based on their estimated groundwater exchange. Reaches with higher groundwater inflow should have a shallower slope (O'Driscoll and DeWalle 2006). See related Supplementary Figure S3.

temperatures were significant (Table 2). For DailyMean, seven reaches showed a nearly 1-to-1 linear relationship between measured and predicted temperatures (e.g., Deer, Squalicum). Three reaches (Fishtrap, Padden, and Whatcom) had strongly linear relationships, but DailyMean was significantly underpredicted by the model within the range of temperatures recorded (Table 2, Figure 5, Supplementary Figures S5-S7). In all three cases, the slope was significantly less than one, and the intercept was significantly greater than zero, indicating that they were underpredicted by a greater margin at higher stream temperatures. In all reaches except one, the DailyMean relationship was quite strong, with an R^2 greater than 0.93 (Table 2). Only the Bertrand.P reach was lower (~0.82). On the other hand, SSTEMP consistently overpredicted DailyMax temperatures by ~3.2°C ± 0.2 (average ± standard error), and the relationships were generally weaker than the corresponding DailyMean (Table 2, Figure 6). Again, seven reaches were not significantly different from a 1-to-1 relationship. Two reaches (Anderson and Squalicum) had slopes significantly greater than one, indicating that they were overpredicted by a greater margin at higher stream temperatures. A single study reach, Padden, had an intercept that was significantly greater than zero (Table 2). For both DailyMean and DailyMax, Bertrand.P did not differ significantly from the 1-to-1 relationship, but had a lower R^2 value than the other reaches, largely due to the limited data available for modeling that reach (Supplementary Table S2).

The model manipulations of canopy cover (CC) and groundwater inflow (GW) looking at temperature change within reaches (ΔT_w), revealed that both CC and GW had significant effects on the difference between measured upstream and predicted downstream

Table 2. Regression data from analysis of predicted versus actual temperatures for: A) daily mean stream temperatures, and B) daily maximum stream temperatures. Data are from 12 or 13 haphazardly chosen dates that cover the full breadth of environmental conditions during the study period. Slopes and intercepts significantly different from 1 and 0, respectively, are indicated in bold. See Supplementary Tables S1-S3 for specific dates and conditions, and Figures 5-6 and S5-S7 for regression graphs

	Mean Temperatures				Maximum Temperatures			
Reach	Slope ± 95% CI	Intercept ± 95% CI	Adj R^2	P-value	Slope ± 95% CI	Intercept ± 95% CI	Adj R^2	P-value
All reaches	**0.88 ± 0.07**	1.54 ± 1.05	0.837	<0.0001	1.05 ± 0.16	2.40 ± 2.55	0.591	<0.0001
Anderson	1.04 ± 0.06	-0.95 ± 0.96	0.991	<0.0001	**1.21 ± 0.20**	-0.68 ± 3.38	0.933	<0.0001
Bertrand.P	0.86 ± 0.27	1.85 ± 3.99	0.816	<0.0001	0.79 ± 0.73	8.24 ± 11.76	0.304	0.037
Bertrand.S	0.99 ± 0.18	0.05 ± 2.55	0.929	<0.0001	1.24 ± 0.53	-0.26 ± 7.99	0.707	0.0004
Deer	1.04 ± 0.10	-1.07 ± 1.27	0.981	<0.0001	1.24 ± 0.41	-0.98 ± 6.04	0.782	<0.0001
Double Ditch	1.02 ± 0.07	0.12 ± 1.00	0.990	<0.0001	1.37 ± 0.41	0.07 ± 6.72	0.815	<0.0001
Fishtrap	**0.75 ± 0.10**	**2.79 ± 1.54**	0.962	<0.0001	1.07 ± 0.21	0.17 ± 3.48	0.919	<0.0001
Padden	**0.71 ± 0.08**	**3.11 ± 1.14**	0.971	<0.0001	0.79 ± 0.25	**3.88 ± 3.85**	0.797	<0.0001
Squalicum	1.13 ± 0.15	-0.84 ± 2.26	0.959	<0.0001	**1.47 ± 0.40**	-1.03 ± 6.20	0.845	<0.0001
Terrell	1.01 ± 0.18	-0.24 ± 2.84	0.929	<0.0001	1.09 ± 0.17	0.44 ± 2.70	0.934	<0.0001
Whatcom	**0.77 ± 0.03**	**2.83 ± 0.70**	0.994	<0.0001	1.15 ± 0.21	-0.30 ± 6.12	0.901	<0.0001

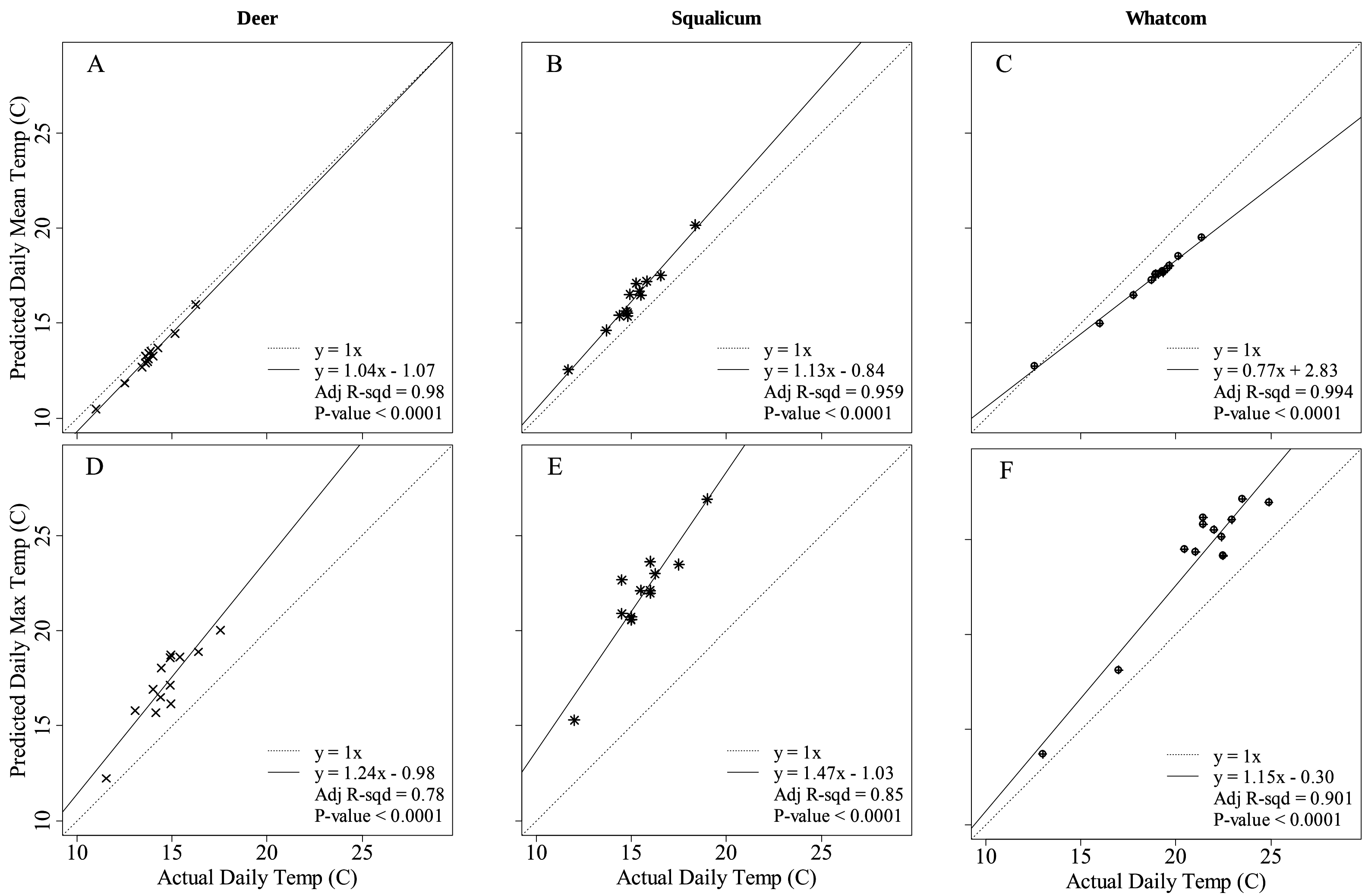

Figure 5. Examples of the range of relationships between SSTEMP predicted and measured reach temperatures for three reaches: Deer, Squalicum, and Whatcom. A – C show Daily Mean relationships; D – F show corresponding Daily Maximum relationships. See Supplementary Figures S5-S7 for other reach regression figures.

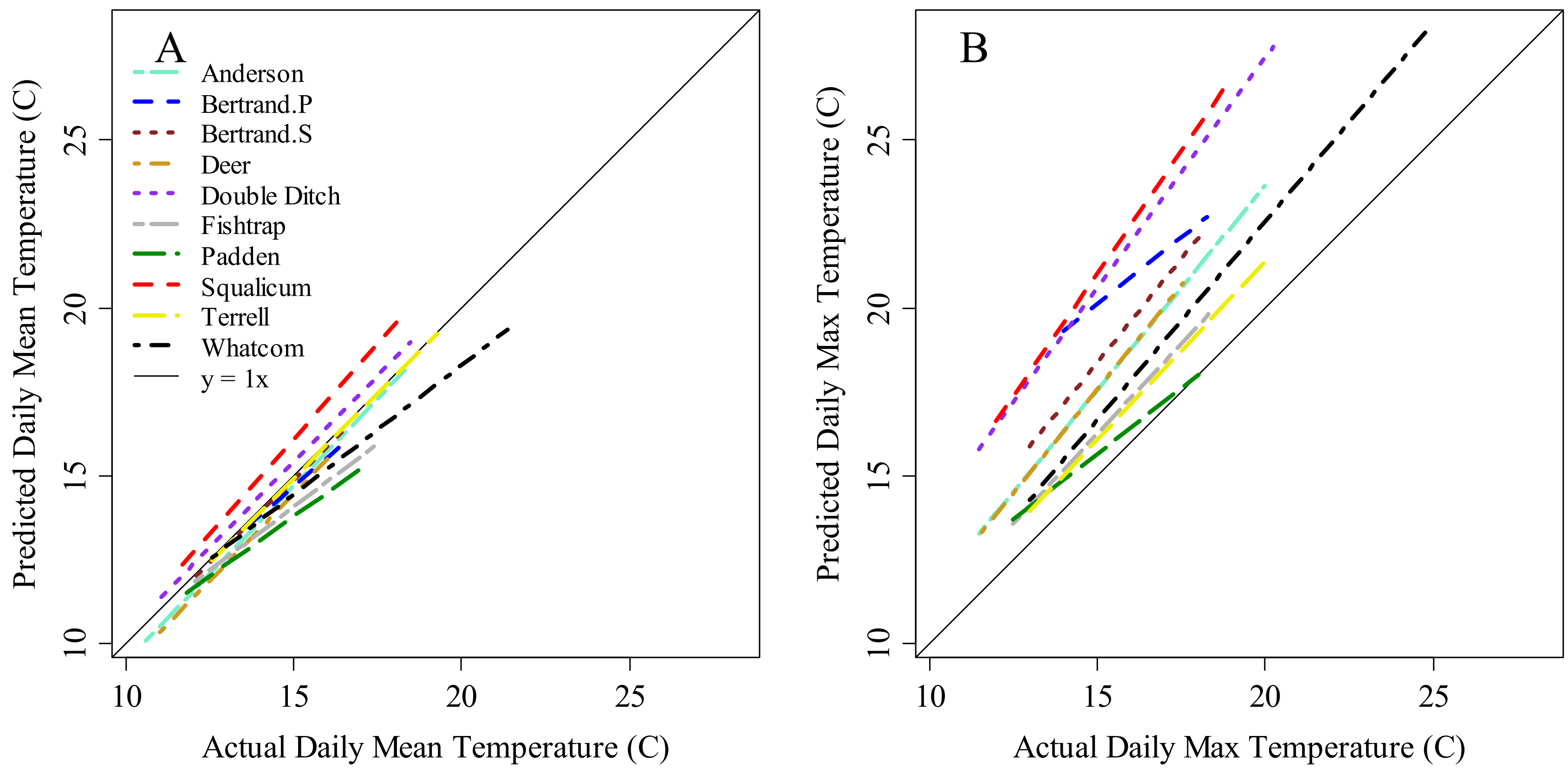

Figure 6. Regressions of predicted versus actual measured stream temperature for A) Daily Mean and B) Daily Maximum temperatures. Predicted values are from SSTEMP modeling. See Table 2 for regression statistics.

mean temperatures (ΔT_wmean) across all three dates (Tables 3-4). In addition, the magnitude of those effects varied depending on Date (significant Date*CC and Date*GW interactions, Table 3). Both CC and GW significantly reduced warming on the Peak date (Table 4). The effect of 100% CC alone reduced ΔT_wmean by over 70%, while 50% GW alone reduced it by over 60%. Significant cooling (ΔT_wmean < 0) was achieved only with a combination of maximum levels of both factors. For the Mid and Cool dates, there was decreased warming across all conditions, resulting from different meteorological conditions later in the summer (including lower air temperatures and decreased solar radiation). On the Mid date, substantial cooling (> 1°C) was only observed with the combination of maximum CC and GW. None of the treatments warmed on the Cool date, and three out of four (all except 0% CC and 0% GW) exhibited significant cooling. This was expected, given that on this date, end of summer conditions included air temperatures that were quite close to both stream and groundwater temperatures.

Similarly, both CC and GW had significant effects on the difference between measured upstream and predicted downstream maximum temperatures (ΔT_wmax) on all three dates (Table 3). The magnitude of effect of CC, however, varied significantly with Date (Date*CC interaction, Table 3). CC significantly reduced warming on the Peak date, and it did so by over 75% (a decrease in predicted downstream temperatures, ΔT_amax, > 10°C, Table 4, Figure 7, Supplementary Tables S5-S6). The magnitude of effect of GW on ΔT_wmax was much smaller (a decrease in predicted downstream temperatures, ΔT_amax, of ~ 2°C, Table 4, Figure 7, Supplementary Tables S5-S6). While no combination of CC and GW resulted in significant cooling for maximum stream temperatures on the Peak date, maximum levels of both factors resulted in warming of less than 2°C. On the Mid and

Table 3. ANOVA table for comparison of change in mean and maximum temperatures (ΔT_w) from recorded upstream to predicted downstream temperatures. The ANOVA model was: ΔT_w = constant + Date + Stream + CC + GW + Date*GW + Date*CC + CC*GW + Date*CC*GW + error. Date had three levels (Peak, Mid, and Cool), Stream had 10 levels and functioned as a blocking factor, CC had two levels (0% and 100%), and GW had 2 levels (0% and 50%). ΔT_wmax values were transformed to fit ANOVA assumptions ($\sqrt{(|\Delta T_w|)}$); negative values were converted back after the transformation. Significant p-values are bold.

		ΔT_wmean		ΔT_wmax	
Treatment	df	F	P	F	P
Date	2	43.63	**<0.001**	159.20	**<0.001**
Stream	9	5.27	**<0.001**	20.69	**<0.001**
CC	1	46.43	**<0.001**	505.72	**<0.001**
GW	1	39.18	**<0.001**	27.40	**<0.001**
Date*CC	2	10.37	**<0.001**	20.35	**<0.001**
Date*GW	2	7.90	**0.001**	1.26	0.290
CC*GW	1	0.39	0.535	1.78	0.185
Date*CC*GW	2	0.04	0.959	1.59	0.209
Error	91				

Table 4. Average change in stream temperature within a study reach (from measured upstream to predicted downstream, ΔT_w) under different canopy cover and groundwater conditions. ΔT_wmean and ΔT_wmax are the differences between recorded upstream temperatures and predicted downstream mean and maximum temperatures within a reach. Table values are means ± 95% confidence interval across all study reaches for the Peak date (n = 10), and all study reaches except Bertrand.P for the Mid and Cool dates (n = 9), respectively, averaged across all reaches with factorial combinations of canopy cover (0 and 100% CC), and groundwater inflow (0 and 50% GW). 95% confidence intervals can be used to identify when ΔT_w was significantly different from zero. ΔT_w values were calculated for three different summer dates varying in air temperature (and other meteorological factors, see Supplementary Table S2): 1) Peak, mean air T = 23.9°C, max air T = 30.5°C; 2) Mid, mean air T = 14.1°C, max air T = 18.5°C; and 3) Cool, mean air T = 9.8°C, max air T = 12.8°C. These correspond to specific dates at the beginning of the study period (Peak: July 23, 2006), the middle of the study period (Mid: August 11, 2006), and the end of the study period (Cool: September 14, 2006). Contrasts within each date and ΔT_w (mean or max) revealed some significant differences, indicated by different letters (Dunn-Ŝidák corrected alpha = 0.0085).

CC (%)	GW (%)	ΔT_wmean (°C)			ΔT_wmax (°C)		
		Peak	Mid	Cool	Peak	Mid	Cool
0	0	3.81 ± 1.56 ^{a}	0.66 ± 0.46 ^{a}	-0.43 ± 0.52 ^{a}	13.38 ± 2.38 ^{a}	4.99 ± 1.32 ^{a}	2.04 ± 0.74 ^{a}
0	50	1.44 ± 1.61 ^{b}	-0.89 ± 0.75 ^{b}	-0.71 ± 0.69 ^{a}	11.90 ± 2.88 ^{a}	3.76 ± 1.73 ^{b}	1.61 ± 1.00 ^{a}
100	0	1.10 ± 0.55 ^{b}	-0.85 ± 0.84 ^{b}	-0.74 ± 0.66 ^{a}	3.37 ± 1.23 ^{b}	-0.52 ± 0.86 ^{c}	-0.10 ± 0.62 ^{b}
100	50	-0.94 ± 0.87 ^{c}	-2.06 ± 0.86 ^{b}	-0.94 ± 0.76 ^{a}	1.65 ± 1.63 ^{c}	-1.62 ± 1.06 ^{d}	-0.36 ± 0.79 ^{b}

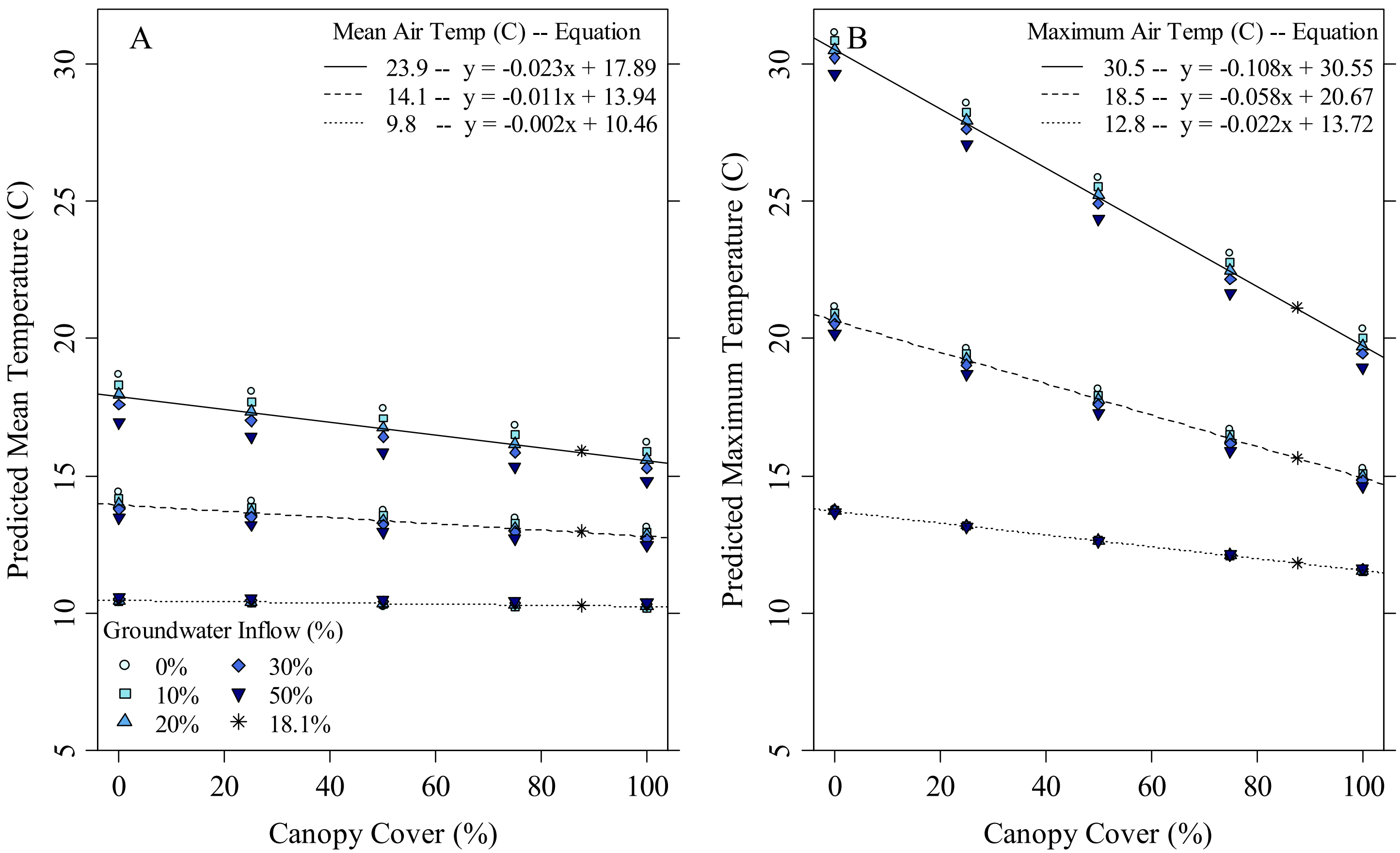

Figure 7. Manipulation of groundwater and canopy cover levels in SSTEMP for a representative reach (Deer Creek) for A) mean stream temperature, and B) maximum stream temperature. Manipulations were run under three different air temperature regimes reflecting Peak, Mid, and Cool summer conditions. Star indicates predicted temperature under actual groundwater and canopy cover conditions. Recorded mean/max upstream temperatures were: Peak, 14.6/16°C; Mid, 13.1/14.5°C; Cool, 10.3/11°C. See Table 4 for summary data of differences between recorded upstream temperatures and predicted downstream temperatures (ΔT_w), and Supplementary Tables S4-S5 for summary data of differences between predicted downstream temperatures (ΔT_a). The model used mean air temperature for all predictions; maximum air temperature was only used to calculate maximum temperature (see Table 5).

Cool dates, patterns were similar to those observed in ΔT_wmean. For the Mid date, significant cooling only occurred under the combination of both 100% CC and 50% GW. For the Cool date, there was slightly significant warming for two treatments (0% of both CC and GW, and 0% CC with 50% GW), and there was no significant change in temperature when 100% CC was present (the other two treatments). Again, this was due to cool, end of summer conditions.

Sensitivity analyses for a representative study reach (Deer Creek) were helpful in exploring why canopy cover and groundwater inflow had similar effects on predicted DailyMean temperatures, but canopy cover had a much greater effect than groundwater inflow on DailyMax. The two parameters manipulated were Segment Outflow (which varied amounts of groundwater inflow), and Shade (canopy cover). When calculating DailyMean under peak temperature conditions, the sensitivity of Segment Outflow was twice that of Shade (Table 5). Their total effects were similar because Shade was increased twice as much (0-100%) as Segment Outflow (0-50%), effectively canceling out the difference in sensitivity. When predicting the DailyMax under peak temperature conditions, however, the sensitivity of Shade was three times that of Segment Outflow (Table 5). Thus, the total effect of changes in canopy cover on DailyMax was approximately six times that of groundwater inflow.

Table 5. SSTEMP parameter sensitivity analyses for an example study reach (Deer Creek) on the Peak date (July 23, 2006), for predicted mean and maximum temperatures. 10% Decrease/Increase indicates the degrees by which stream temperature was predicted to change if the parameter value was decreased or increased by 10%. Relative sensitivity values range from 0 (not at all sensitive) to 30 (maximum sensitivity). Parameters relating to groundwater inflow are Accretion Temperature and Segment Outflow. Manning's n and Maximum Air Temperature were only used to predict maximum stream temperature.

	Effects on Mean Temperature			Effects on Maximum Temperature		
Model Parameter	10% Decrease (°C)	10% Increase (°C)	Relative Sensitivity	10% Decrease (°C)	10% Increase (°C)	Relative Sensitivity
Segment Inflow	-0.27	0.27	8	-0.2	0.2	5
Inflow Temp.	-0.95	0.96	30	-0.67	0.68	16
Segment Outflow	0.28	-0.33	10	0.26	-0.29	7
Accretion Temp.	-0.15	0.15	5	-0.11	0.11	3
Width's A Term	-0.04	0.04	1	-0.09	0.1	2
Width's B Term	0.03	-0.03	1	0.06	-0.06	2
Manning's n	--	--	--	0.08	-0.06	2
Mean Air Temp.	-0.33	0.31	10	0.34	-0.27	8
Relative Humidity	-0.13	0.13	4	-0.23	0.22	5
Wind Speed	0.0	0.0	0	0.01	-0.01	0
Ground Temp.	-0.03	0.03	1	-0.06	0.06	1
Thermal Gradient	-0.01	0.01	0	0.02	-0.02	0
Possible Sun	0.0	0.0	0	0.0	-0.01	0
Solar Radiation	-0.03	0.03	1	-0.13	0.13	3
Total Shade	0.17	-0.17	5	0.83	-0.85	21
Maximum Air Temp.	--	--	--	-1.22	1.24	30

38

DISCUSSION

Overview

This study predicted the magnitude of effects of groundwater inflow and riparian canopy cover across a wide range of lowland stream conditions, establishing an initial baseline of data about local stream conditions to inform future restoration or management decisions. Both factors had substantial effects on stream temperatures over a 500 m reach distance. The effects of canopy cover and groundwater inflow on mean temperature were similar; however, canopy cover had a much greater effect on maximum temperatures than did groundwater inflow. The benefits of canopy cover on stream temperature were expected in this study, as they are well-documented in others (Gomi *et al.* 2006, Moore *et al.* 2005, Wilkerson *et al.* 2006). However, the model results indicated that groundwater inflow to local streams was also an important factor in summer stream temperature moderation: under the warmest summer conditions, stream temperatures decreased only with both full canopy cover and groundwater conditions. Either factor alone reduced warming, but did not actually cool streams. Groundwater inflow, therefore, should be considered when making restoration, land use, and other management decisions (Ebersole *et al.* 2001, Torgersen *et al.* 1999). This is particularly true for streams with intact, closed-canopy riparian buffers that have substantial groundwater inflow and are within a few degrees of thermal thresholds for salmon and other stream organisms. In these instances, managing local hydrology with streams in mind could help prevent temperature impairment.

For each reach, the SSTEMP-predicted temperatures had a strong, but unique, relationship with measured stream temperatures. The model was most accurate when predicting daily mean (DailyMean) temperatures; it consistently overpredicted daily maximum (DailyMax) temperatures. This suggests that SSTEMP could be a useful tool for future temperature modeling in lowland streams, provided reach-specific data are available for input into the model and the relationship between model-predicted and actual temperatures is identified. The overprediction of maximum temperatures does not compromise estimates of change in predicted temperatures caused by canopy cover and groundwater inflow in this study, as the slope of predicted to actual temperatures was close to one for most reaches. However, studies using the model to assess the effects of restoration on actual temperatures (e.g., with respect to particular thermal thresholds) would need to adjust the model-predicted temperatures accordingly.

Relative effects of canopy cover and groundwater inflow

The results of this study support the idea that both canopy cover and groundwater inflow are important in keeping peak summer stream temperatures at, or below, thermal thresholds for sensitive species such as salmon. This study is unique in examining the relative effects of both of these factors on the same streams, at the same time. The magnitude of effect of canopy cover on daily maximum stream temperatures in my model manipulations (~10°C) is at the high end of what has been seen in previous studies assessing the effects of clear-cutting in upland forests (2-12°C) (Gomi *et al.* 2006, Johnson and Jones 2000, Moore *et al.* 2005). This wide range of effects may result from several factors, including differences in stream aspect or gradient, methods of clear-cutting, and extent of clear-cutting (Moore *et al.* 2005). The predicted 10°C decrease in stream warming for peak summer maximum temperatures attributed to canopy cover in my study suggests that the opportunity for thermal recovery in lowland areas may be greater than in many upland areas, likely because of more extreme summer air temperatures in lowland areas. Despite the model's overprediction of daily maximum stream temperatures and occasional underprediction of mean temperatures (Figure 5), the magnitude of effect should be similar in real streams because I focused on the change in model-predicted temperatures under different scenarios. Actual maximum temperatures would be lower, however. Even if the magnitude of effect was slightly smaller, severely impaired streams with little to no canopy cover might be kept below thermal thresholds by increases in canopy cover. The Whatcom Creek reach, for example, was the most severely impaired of the study reaches and was still less than 5°C greater than the daily maximum thermal threshold (Figure 3B). While other local factors at this site (e.g., stream width) might reduce its effects, canopy cover would still facilitate thermal recovery given the magnitude of effects I observed.

Under peak summer conditions, groundwater inflow may mitigate extreme stream temperatures, even though the magnitude of effect may be relatively small (~1.5°C). The effect of groundwater inflow on stream temperature depends on many factors, especially the volume of groundwater inflow relative to streamflow and the differences between the air, stream, and groundwater temperatures (Becker *et al.* 2004, O'Driscoll and DeWalle 2006, Whitledge *et al.* 2006). For example, one of my study reaches, Bertrand.S, exceeded the seven-day average daily maximum (7DADM) threshold on more than 72% of days at the upstream logger location, but only 6% of days at the downstream location. This change was due to a drop in stream temperature of ~ 2°C between the two logger locations (Table 1). Canopy cover was likely not a factor in this temperature change because it was consistently high both above and throughout the reach. There was, however, dramatic groundwater inflow (>120%) to the reach. In addition, previous research on Bertrand and Fishtrap creeks found both to be heavily influenced by groundwater inflow (Cox *et al.* 2005).

Even at lower levels of groundwater inflow, the SSTEMP manipulations indicated that groundwater inflow could decrease warming of mean and maximum stream temperatures by similar amounts with all else being equal (Table 3). For the gaining reaches in this study (10-120% estimated net groundwater inflow), the model sensitivity of Segment Outflow attributed temperature reductions of ~0.3-3°C to groundwater inflow (Table 5). However, this was likely an underestimate of actual effects since change in streamflow measured only net, not total, groundwater exchange. Even "losing" reaches could have some groundwater exchange, as was apparently the case for at least two of my study reaches (Anderson and Squalicum, see discussion of SSTEMP-predicted to actual DailyMax relationships). This magnitude of effect on stream temperature is consistent with other field and modeling studies, even in different regions (Gaffield *et al.* 2005, Torgersen *et al.* 1999). Previous SSTEMP manipulations of groundwater inflows in warm, Midwestern streams resulted in a ~2.5°C decrease in mean temperature over 500 m, with 50% canopy cover and 50% groundwater inflow (Gaffield *et al.* 2005). Even under conditions likely to limit the effect of groundwater inflow (e.g., a short, upland reach), a 1.2°C decrease in maximum stream temperature was attributed to groundwater inflow (Story *et al.* 2003).

Where stream temperatures are close to thermal thresholds, groundwater exchange might make the difference between maintaining unimpaired temperatures and exceeding thermal thresholds. This is particularly important where the thermal benefits of full canopy cover have already been achieved by riparian restoration or protection, yet streams remain close to impairment. I saw such conditions in the SSTEMP model manipulations of peak conditions, where reach temperatures were predicted to remain constant or decrease only under maximum levels of both groundwater inflow and canopy cover. Full canopy cover alone was insufficient to produce cooling during peak temperatures in the middle of the summer. Similarly, longitudinal temperature monitoring of two upland, Pacific Northwest streams revealed abrupt decreases in mean temperature of 2-4°C that were likely due, in large part, to groundwater inflow to those reaches (Torgersen *et al.* 1999). Many reaches in my study, when not exceeding the 7DADM threshold, were close to it. The Deer Creek study reach, for example, only surpassed the 7DADM threshold on ~5% of summer days. If changes to local hydrology deprived this reach of groundwater inflow (~20% of baseflow), it might easily exceed that threshold more frequently, as more than 63% of days were within 2°C of the 7DADM threshold. In addition to the role groundwater inflow may play in maintaining stream temperatures below thermal thresholds, areas of groundwater inflow may also serve as thermal refugia for salmonids (Brunke and Gonser 1997, Ebersole *et al.* 2001, Ebersole *et al.* 2003, Isaak *et al.* 2007, Morley *et al.* 2005, Power *et al.* 1999, Sutton *et al.* 2007, Torgersen *et al.* 1999). The cool segments where groundwater enters the stream can allow salmonid populations to persist even in streams that are otherwise too warm (Ebersole *et al.* 2001, Sutton *et al.* 2007, Torgersen *et al.* 1999). Thus, the SSTEMP-predicted effects of groundwater inflow on DailyMean and DailyMax may not reflect the full magnitude of groundwater's actual importance.

I did not explicitly test the effects of reach or riparian buffer length, but my measurements and modeling results suggest that thermal recovery can occur within 500 m, given appropriate canopy cover and groundwater inflow conditions. I chose this study reach length because it is representative of many local restoration and revegetation projects (NRT

2004). This distance is also similar to those found in previous studies conducted in the Midwest and New Zealand (Frimpong *et al.* 2005, Rutherford *et al.* 2004). In an upland Pacific Northwest stream, Johnson (2004) measured decreases of more than 1°C in the maximum stream temperature over as little as 150 m of artificial shade (black plastic sheeting). Temperature recovery may occur within 500 m, but loss or absence of riparian buffers will generally result in an equivalent increase in temperature over an even shorter distance (Rutherford *et al.* 2004). Thus, while 500 m may be a sufficient distance to mitigate impaired summer stream temperatures within a single reach, it may be necessary to maintain riparian buffers and groundwater exchange throughout the entire stream to keep temperatures below thermal thresholds (Ebersole *et al.* 2003, Watanabe *et al.* 2005, Wissmar 2004).

Reflections on SSTEMP

I found significant, linear relationships between model-predicted and measured mean and maximum stream temperatures across a wide range of lowland stream reaches. DailyMax temperatures, however, were overpredicted in nearly all cases (by ~ 0°C to 9°C). It is unclear why some reaches were so dramatically overpredicted, but the SSTEMP documentation suggests one possible reason: the model was originally developed specifically to calculate mean temperatures, and the tools to calculate maximum temperatures were added secondarily (Bartholow 2000b, 2002). The documentation suggests that tuning some of the standard parameters (e.g., Manning's n, a measure of stream roughness, and Thermal Gradient, a measure of steam-streambed heat exchange) may help adjust model fit. Both of these parameters, however, have very low sensitivity under the conditions studied here. For example, Manning's n has a typical range of 0.02 – 0.05 in small, cobbly streams, similar to my study reaches (I used n = 0.035; Supplementary Table S1) (Arcement Jr. and Schneider 1984, USGS 2008). This parameter would need to be increased by 500% to 1.75 (an impossible value), to achieve a 3°C decrease in DailyMax. Another hypothesis is that inaccuracies in the regional data used across all reaches contributed to the overprediction of DailyMax temperatures. But again, the sensitivity of these factors makes this an unlikely explanation. For example, of the regional values used in the model, Relative Humidity had the greatest sensitivity and it is possible that the relative humidity in each study reach varied from the weather station measurements. To decrease predicted DailyMax temperatures by 3°C, however, the Relative Humidity would have to be more than 130% lower at the study reaches – another impossible value, and a change in the opposite direction for how I would expect actual relative humidity values at the study reaches to differ from weather station values.

Reach-specific conditions provide a possible explanation of why some reaches varied significantly from the 1-to-1 relationship for DailyMean temperatures (Fishtrap, Padden, and Whatcom) and DailyMax temperatures (Anderson, Padden, and Squalicum). For the DailyMean relationships, all three reaches had slopes that were significantly less than one, and intercepts that were significantly greater than zero, suggesting that these reaches were warmer than the model predicted in the range of temperatures measured. However, in all cases, the difference between predicted and measured temperatures was relatively small (a range of 0 ± 2°C). Padden Creek was the only reach that differed significantly for both DailyMean and DailyMax relationships (although in opposite directions), and the difference between predicted and measured was always less than ± 2°C. While both slope and intercept were significantly different for the DailyMean relationship, only the intercept was significantly different for the DailyMax. This may be related to a very small tributary that entered the middle of the reach. This tributary was accounted for in the reach's flow measurements, but it may have had a slightly warmer temperature (a potential problem, given that the model cannot account for two different inflow temperatures). If this were the case, we would expect the model to have underpredicted both the DailyMean and DailyMax temperatures; it only underpredicted DailyMean, however, suggesting that other factors must also be involved.

Two other reaches differed significantly in slope from the 1-to-1 relationship for DailyMax (Anderson and Squalicum) differed only in terms of slope. These reaches had slopes significantly greater than one; they were cooler than the model predicted, particularly at higher temperatures. The Anderson reach's DailyMax temperatures were overpredicted by 1-4°C, while Squalicum was more dramatically overpredicted by 3-8°C. This discrepancy may result from inaccurate groundwater measurements; these were the only losing reaches (net loss of 15-35% of streamflow). While my measurements revealed that these reaches had a net outflow of water from the stream to the ground, they may also have had groundwater inflow that was ultimately masked by a larger volume of outflow. This would result in cooler temperatures than the model predicted. For the Squalicum reach, this hypothesis was also supported by the slope of the 7DADM air by stream temperature relationship, which was shallower than would be expected for a losing reach.

Suspected inaccuracies in groundwater exchange estimates did not render the model unable to predict stream temperatures, but some applications of SSTEMP may benefit from the use of more detailed methods for measuring groundwater exchange. Detailed stream temperature surveys, piezometers installed throughout the study reach, models integrating flow measurements and temperature surveys, and spatial models based on geological databases are examples of alternative methods for identifying areas of groundwater exchange in hydrologically dynamic reaches (Becker *et al.* 2004, Christensen *et al.* 1998, Keery *et al.* 2007, Westhoff *et al.* 2007). The labor intensity of these methods, however, would have prohibited conducting the broad survey of many different reaches in this study.

The results of my manipulations of canopy cover and groundwater inflow could be further refined by adjusting predicted reach temperatures to account for any under or overprediction by the model. In addition, covarying other secondary parameters with canopy cover or groundwater would also improve the reliability of these results. For example, one would expect that air temperature, wind speed, relative humidity, and channel morphology would all vary with changes in canopy cover (Bartholow 2000a). Similarly, changes in flow would also affect stream width and depth (and Width's A Term). The model, however, does not account for these changes. Including empirical data on how these parameters respond to changes in groundwater inflow or canopy cover in the model manipulations of these factors may enhance the fit of predicted to actual stream temperatures (Bartholow 2002). Another important consideration that was not addressed in this study, and is not included in the SSTEMP model, is that stream orientation (i.e., north-south versus east-west) may influence the effectiveness of canopy cover in providing shade to the stream throughout the day (LeBlanc and Brown 2000, LeBlanc *et al.* 1997, Sridhar *et al.* 2004). Canopy cover over north-south oriented streams provides much more shade than equivalent cover on east-west oriented streams in the morning and afternoon, but dramatically less shade at solar noon. This means that while north-south oriented streams may have a higher daily maximum temperature (by ~1°C), east-west oriented streams will have a longer duration of the daily maximum temperature (by ~ 2.5 hrs) (LeBlanc *et al.* 1997). Incorporating this factor could improve predictions of DailyMax temperatures, especially, because it would affect Shade, one of the most sensitive SSTEMP parameters and one of the factors I manipulated. The complexity of stream systems makes accounting for all environmental and physical factors difficult, particularly when modeling experimental manipulations, such as those in this study. Future model predictions may benefit from expanding or refining SSTEMP to account for variation in these potentially important parameters.

Looking forward: Implications for restoration, climate change, and future study

This study indicates that the focus of stream management efforts (both protection and restoration) for temperature-impaired streams should include groundwater exchange as well as canopy cover. If canopy cover restoration alone cannot maintain summer maximum temperatures below thermal thresholds for Pacific Northwest streams, restoration or watershed protection efforts may need to address hydrological changes that have reduced groundwater inflow, as has been observed in other areas of the country (Whitledge *et al.* 2006). In addition, temperature is not generally the only factor addressed by restoration efforts (Bernhardt *et al.* 2005, Booth 2005, Isaak *et al.* 2007, Katz *et al.* 2007, Wissmar and Beschta 1998). Thus, managers must balance all factors when they determine where restoration efforts would be most effective in achieving the desired outcome (e.g., salmon population recovery). This balance is particularly important given that previous research has found that in some cases, even reaches with cool temperatures and other good habitat characteristics may have highly degraded biotic communities if they are located in highly urbanized or agricultural watersheds (Booth 2005, Neils 2007).

While this study did not manipulate canopy cover or groundwater exchange conditions in the field, such studies could help understand and quantify the interactions and effects of these factors in the real world. Intensive, longitudinal stream studies relating detailed field measurements of stream temperature, hydrological, and riparian conditions to one another may validate the model-predicted effects of these factors, and further clarify their relationship. Additional model manipulations may identify ways to prioritize restoration efforts based upon potential for temperature and habitat restoration, test methods for determining minimum buffer lengths, and relate watershed hydrology (and local anthropogenic effects on hydrology) to stream temperatures (Bernhardt and Palmer 2007). Particularly in areas such as the one studied here, where groundwater inflow to streams is pervasive, a better understanding of the role groundwater plays in maintaining stream temperatures is necessary to inform watershed and hydrological management decisions (Becker *et al.* 2004, Boulton and Hancock 2006, Brown *et al.* 2007, Brunke and Gonser 1997, Gaffield *et al.* 2005, Tague *et al.* 2007). In particular, explorations of how different types of groundwater inflow (e.g., continuous inflow along the reach versus isolated springs) affect the relationship of groundwater inflow to summer maximum stream temperatures may help distinguish between different types of reaches: 1) those where groundwater inflow may maintain stream temperatures below thermal thresholds, 2) those where thermal refugia are likely to be present, although reach temperatures in general exceed thermal thresholds, and 3) those where groundwater inflow may be insufficient to buffer thermal loads to protect salmonids.

Climate change will likely enhance the importance of canopy cover and groundwater exchange in buffering stream temperatures (Battin *et al.* 2007, van Roosmalen *et al.* 2007).

In this region, average annual air temperature is predicted to increase by 1.5 – 3.2°C by the middle of this century (Battin *et al.* 2007). Restoration efforts, and especially restoration of riparian canopy cover, may mitigate salmon population decline due to climate change by enhancing livable habitat (Battin *et al.* 2007). My results suggest that restoration of canopy cover in lowland areas should produce substantial decreases in summer maximum stream temperatures, even under higher peak summer temperatures. However, the cooling effect of groundwater on summer stream temperatures will be influenced by several concurrent changes, including potential alteration of rates and volume of groundwater recharge, stream flows, and stream-groundwater exchange (Palmer 2007, van Roosmalen *et al.* 2007), and groundwater temperatures that increase with mean annual air temperature (i.e., 1.5 – 3.2°C). Additional modeling studies that incorporate these changes would help to determine the extent to which riparian restoration efforts and maintenance of stream-groundwater interactions can continue to support local salmon populations under a warming climate (Crozier and Zabel 2006, Nelson and Palmer 2007). As both land use and climate continue to change, supporting healthy streams will become increasingly challenging, and require a greater understanding of the biotic and abiotic factors affecting stream temperatures.

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SUPPLEMENTARY DATA

Tables

Table S1. Parameters and units used in SSTEMP model runs. For regional values, see Table B. Reach specific values are in Table 1 or Table C. Accretion Temperature is equivalent to groundwater temperature; Width's A Term incorporates both width and discharge; Manning's N is a measure of channel roughness; Thermal Gradient refers to the rate of thermal transfer between the streambed and the water; Possible Sun is a reflection of cloudiness (higher values indicate clear skies).

Model Parameter	Parameter Value
Month	Regional - Table B
Day	Regional - Table B
Segment Inflow (cms)	Reach specific - Table 1
Inflow Temperature (°C)	Reach specific - Table C
Downstream Flow (cms)	Reach specific - Table 1
Accretion Temperature (°C)	11
Latitude (°)	48
Dam at Head of Segment	0†
Segment Length (m)	Reach specific - Table C
Upstream Elevation (m)	Reach specific - Table C
Downstream Elevation (m)	Reach specific - Table C
Width's A Term (sec/m^2)	Reach specific - Table C
Width's B Term	0.2‡
Manning's N	0.035‡
Mean Air Temperature (°C)	Reach specific - Table C
Maximum Air Temperature (°C)	Reach specific - Table C
Relative Humidity (%)	Regional - Table B
Wind Speed (mps)	Regional - Table B
Ground Temperature (°C)	Regional - Table B
Thermal Gradient (J/m^2/sec/°C)	1.65‡
Possible Sun (%)	Regional - Table B
Solar Radiation (J/m^2/sec)	Regional - Table B
Total Shade (%)	Reach specific - Table 1

† = 1 for Terrell, where a lake outflow was present just upstream of the study reach.
‡ = Indicates a generally applicable value suggested for use when measured values were not available (Bartholow 2002).

Table S2. Regional weather data used in SSTEMP model calculations for each date modeled (for all reaches except Bertrand.P‡). Data from Lynden, WA (AgWeatherNet 2006). Peak, Mid, and Cool dates are indicated by asterisks.

Month	Day	Ground Temperature (°C)	Relative Humidity (%)	Possible Sun (%)	Solar Radiation (90%†, $J/m^2/s$)	Wind speed (m/s)
7	20	17.08	77.34	95.00	245.58	0.45
7	23*	19.54	74.55	95.00	240.56	0.75
7	27	19.34	83.90	65.00	228.70	1.16
7	31	17.78	80.05	45.63	191.69	0.46
8	4	17.70	76.79	81.20	227.92	0.71
8	11*	17.60	90.49	33.70	128.49	0.97
8	14	17.48	82.30	94.14	219.23	0.69
8	17	17.43	90.65	60.00	175.71	0.74
8	20	17.52	78.13	95.00	217.38	0.50
8	23	17.34	89.79	32.86	136.93	1.21
9	2	16.09	71.42	87.56	191.93	0.27
9	7	16.22	85.76	77.58	175.61	0.57
9	14*	14.59	97.71	16.43	41.68	0.23

† = As recommended by SSTEMP model documentation, I used 90% of reported daily solar radiation values as model input (Bartholow 2002).
‡ = Dates and data for Bertrand.P, where loss of temperature logger limited possible dates:

Month	Day	Ground Temperature (°C)	Relative Humidity (%)	Possible Sun (%)	Solar Radiation (90%†, $J/m^2/s$)	Wind speed (m/s)
7	20	17.08	77.34	95.00	245.58	0.45
7	21	17.97	73.64	95.00	245.67	0.49
7	22	19.02	79.15	95.00	224.54	0.63
7	23*	19.54	74.55	95.00	240.56	0.75
7	24	19.79	75.51	95.00	242.61	0.85
7	25	19.59	86.40	92.00	224.43	1.44
7	27	19.34	83.90	65.00	228.70	1.16
7	31	17.78	80.05	45.63	191.69	0.46
8	1	17.62	79.44	85.83	215.82	1.01
8	2	17.68	74.63	66.15	195.45	0.93
8	3	17.61	82.24	80.17	219.16	0.59
8	4	17.70	76.79	81.20	227.92	0.71

Table S3. Reach specific parameter values for SSTEMP model runs. Channel width was not a model parameter, but was used to calculate the Width's A Term for each reach: A = W/QB, where W = average width, Q = average discharge, and B = 0.2 (Bartholow 2002). Temperature values are the minimum and maximum values measured at each reach for the range of dates modeled.

Reach	Upstream Elevation (m)	Downstream Elevation (m)	Length (m)	Average Channel Width (m)	Width's A Term (sec/m^2)	Inflow Temperature (°C)	Mean Air Temperature (°C)	Maximum Air Temperature (°C)
Anderson	106	95	537	3.75	3.78	10.38 – 17.86	10.01 – 20.83	13.50 – 27.75
Bertrand.P	27	26	469	8.74	7.37	12.79 – 15.63	15.61 – 23.15	19.75 – 30.75
Bertrand.S	33	31	721	6.42	6.18	11.52 – 19.46	12.13 – 21.97	15.75 – 29.75
Deer	40	39	458	3.98	3.79	10.25 – 15.54	11.16 – 22.07	14.36 – 27.19
Double Ditch	16	14	420	2.14	1.64	11.36 – 18.70	12.30 – 23.53	16.80 – 30.20
Fishtrap	27	26	634	6.91	5.50	12.33 – 17.92	12.87 – 19.55	16.95 – 26.40
Padden	26	22	505	3.39	3.38	12.28 – 17.24	12.04 – 20.04	15.25 – 23.50
Squalicum	23	20	446	5.63	6.16	12.92 – 17.73	12.07 – 22.13	16.00 – 29.75
Terrell	65	63	518	2.32	3.23	14.28 – 20.69	12.29 – 21.97	14.81 – 25.61
Whatcom	15	12	435	10.08	5.99	15.69 – 20.56	12.72 – 18.43	18.31 – 26.25

Table S4. ANOVA table for effects across modeled reach conditions for each study reach (difference between predicted downstream temperatures, both ΔT_amean and ΔT_amax) on three dates for two tests: 1) the difference between reaches with 0% canopy cover (CC) and reaches with 100% CC, calculated at two levels of groundwater inflow (GW, 0% and 50%); 2) the difference between reaches with 0% GW and reaches with 50% GW, calculated at two levels of CC (0% and 100%). The ANOVA model was: ΔT_a = constant + Date + Level + Stream + Level*Date + error. Date had three levels (Peak, Mid, and Cool), Stream had ten levels and functioned as a blocking factor, and Level had two levels (0% and 50% GW for condition 1, 0% and 100% CC for condition 2). ΔT_a values for condition 1 (change in temperature between reaches with 0% and 100% CC at two levels of GW) were transformed to fit ANOVA assumptions $((\ln(|\Delta T_a|))+1)$; negative values were reinstated after transformation. Significant p-values are bold.

		1) CC				2) GW			
		ΔT_amean		ΔT_amax		ΔT_amean		ΔT_amax	
Treatment	df	F	P	F	P	F	P	F	P
Date	2	6.14	**0.005**	4017.66	**<0.001**	703.87	**<0.001**	140.37	**<0.001**
Stream	9	0.62	0.770	4.43	**0.041**	54.26	**<0.001**	31.81	**<0.001**
Level	1	0.03	0.873	111.52	**<0.001**	3.57	**0.037**	4.6	**0.016**
Date*Level	2	0.19	0.826	4.89	**0.012**	32.99	**<0.001**	0.08	0.779
Error	41								

Table S5. Temperature differences across modeled reach conditions for each study reach (difference between predicted downstream temperatures, both ΔT_amean and ΔT_amax) on three dates for two tests: 1) the difference between reaches with 0% canopy cover (CC) and reaches with 100% CC, calculated at two levels of groundwater inflow (GW, 0% and 50%); 2) the difference between reaches with 0% GW and reaches with 50% GW, calculated at two levels of CC (0% and 100%). Table values are means ± 95% confidence interval across all study reaches for the Peak date (n = 10), and all study reaches except Bertrand.P for the Mid and Cool dates (n = 9). 95% confidence intervals can be used to determine when ΔT_a was significantly different from 0. Average differences calculated for three study period dates varying in air temperature (and other meteorological factors, see Supplementary Table B): 1) Peak, mean T = 23.9°C, max T = 30.5°C; 2) Mid, mean T = 14.1°C, max T = 18.5°C; and 3) Cool, mean T = 9.8°C, max T = 12.8°C. These correspond to specific dates at the beginning of the study period (Peak: July 23, 2006), the middle of the study period (Mid: August 11, 2006), and the end of the study period (Cool: September 14, 2006). Contrasts assessed differences between Dates (e.g., comparing Peak to Mid and Cool) as well as levels of one factor within the other (e.g., comparing difference between 0% and 100% CC at 0% GW versus 50% GW); significant differences are indicated by different letters. For all contrasts, Dunn-Ŝidák corrected alpha = 0.0085.

		ΔT_amean (°C)			ΔT_amax (°C)		
		Peak [a]	Mid [a b]	Cool [b]	Peak [a]	Mid [b]	Cool [c]
Difference between 0% & 100% CC	at 0% GW	-2.72 ± 1.23 [a]	-1.51 ± 1.34 [a]	-0.31 ± 0.17 [a]	-10.01 ± 1.22 [a]	-5.52 ± 0.98 [a]	-2.14 ± 0.39 [a]
	at 50% GW	-2.38 ± 1.03 [a]	-1.18 ± 0.62 [a]	-0.22 ± 0.13 [a]	-10.26 ± 1.34 [a]	-5.38 ± 0.98 [a]	-1.97 ± 0.39 [b]
Difference between 0% & 50% GW	at 0% CC	-2.37 ± 0.40 [a]	-1.55 ± 0.39 [a]	-0.28 ± 0.39 [a]	-1.48 ± 0.57 [a]	-1.24 ± 0.45 [a]	-0.42 ± 0.37 [a]
	at 100% CC	-2.03 ± 0.41 [b]	-1.21 ± 0.44 [b]	-0.20 ± 0.40 [a]	-1.73 ± 0.44 [a]	-1.10 ± 0.46 [a]	-0.26 ± 0.39 [a]

Figures

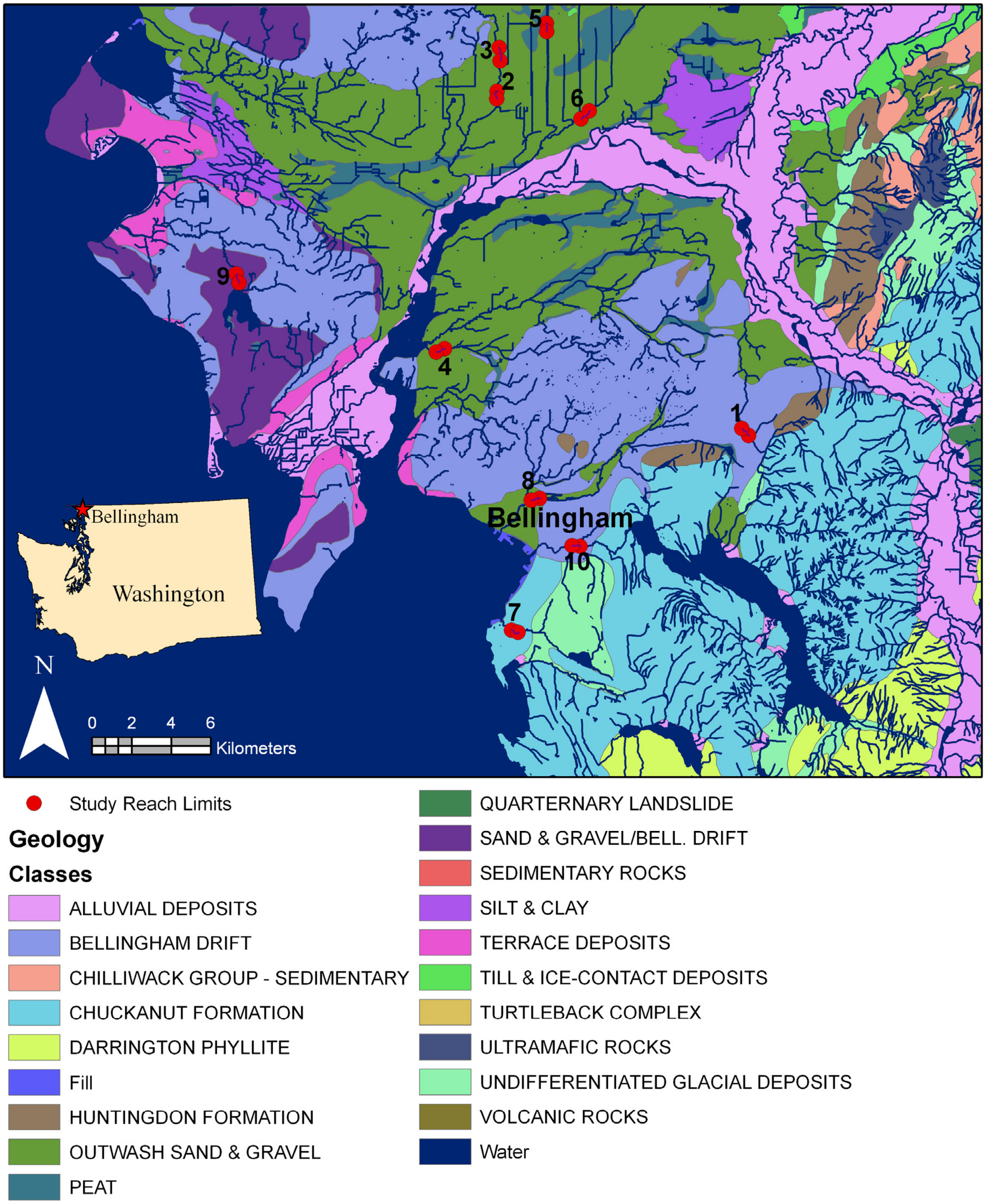

Figure S1. Map of the surficial geology in the study area in lowland Whatcom County, Washington. Study reach limits are indicated by red dots, water bodies are in blue. Study reaches are numbered as follows: 1) Anderson; 2) Bertrand.P; 3) Bertrand.S; 4) Deer; 5) Double Ditch; 6) Fishtrap; 7) Padden; 8) Squalicum; 9) Terrell; 10) Whatcom. All data accessed from Huxley College at Western Washington University.

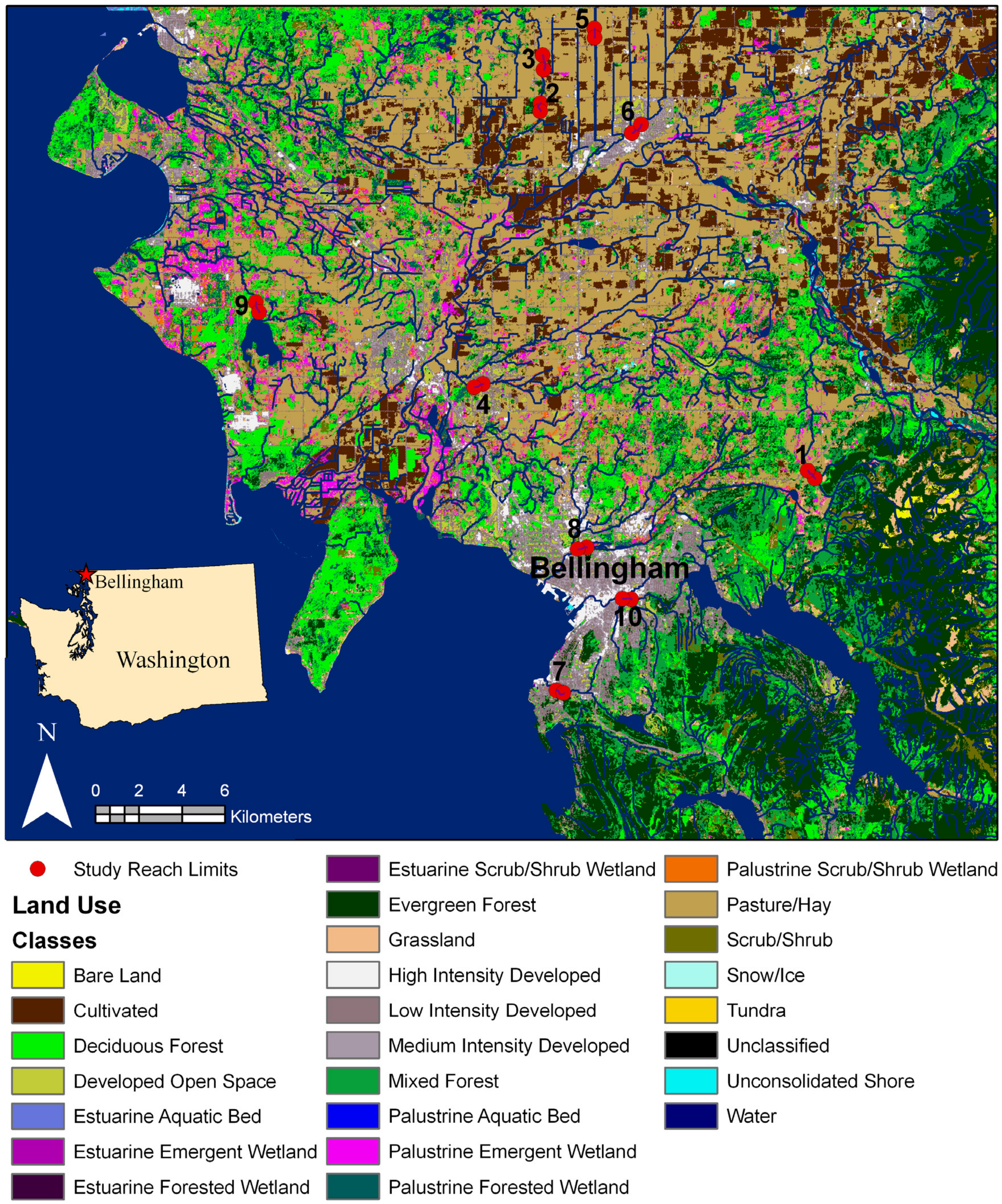

Figure S2. Map of the land cover and land use in the study area in lowland Whatcom County, Washington. Study reach limits are indicated by red dots, water bodies are in blue. Study reaches are numbered as follows: 1) Anderson; 2) Bertrand.P; 3) Bertrand.S; 4) Deer; 5) Double Ditch; 6) Fishtrap; 7) Padden; 8) Squalicum; 9) Terrell; 10) Whatcom. Land cover and land use data from National Oceanic Atmospheric Administration-Coastal Change Analysis Program (NOAA 2008).

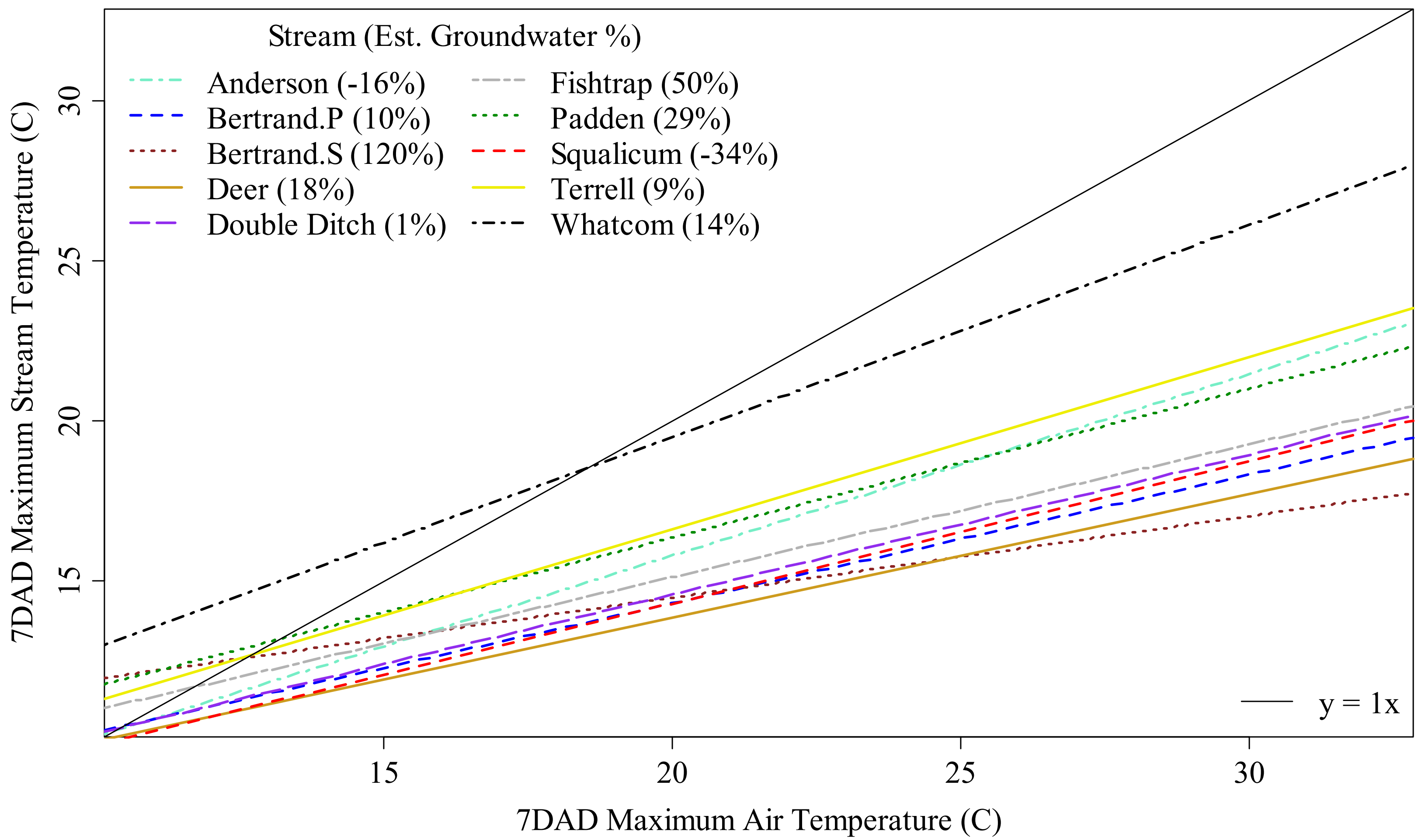

Figure S3. 7 day average daily (7DAD) maximum air by stream temperatures for each reach. Reaches with higher groundwater inflow were expected to have shallower slopes (O'Driscoll and DeWalle 2006). Squalicum, Double Ditch, and Bertrand.P reaches have shallower slopes than would be expected based on their estimated groundwater exchange – they have shallower slopes than streams with higher estimated groundwater inflow. See related Figure 3.

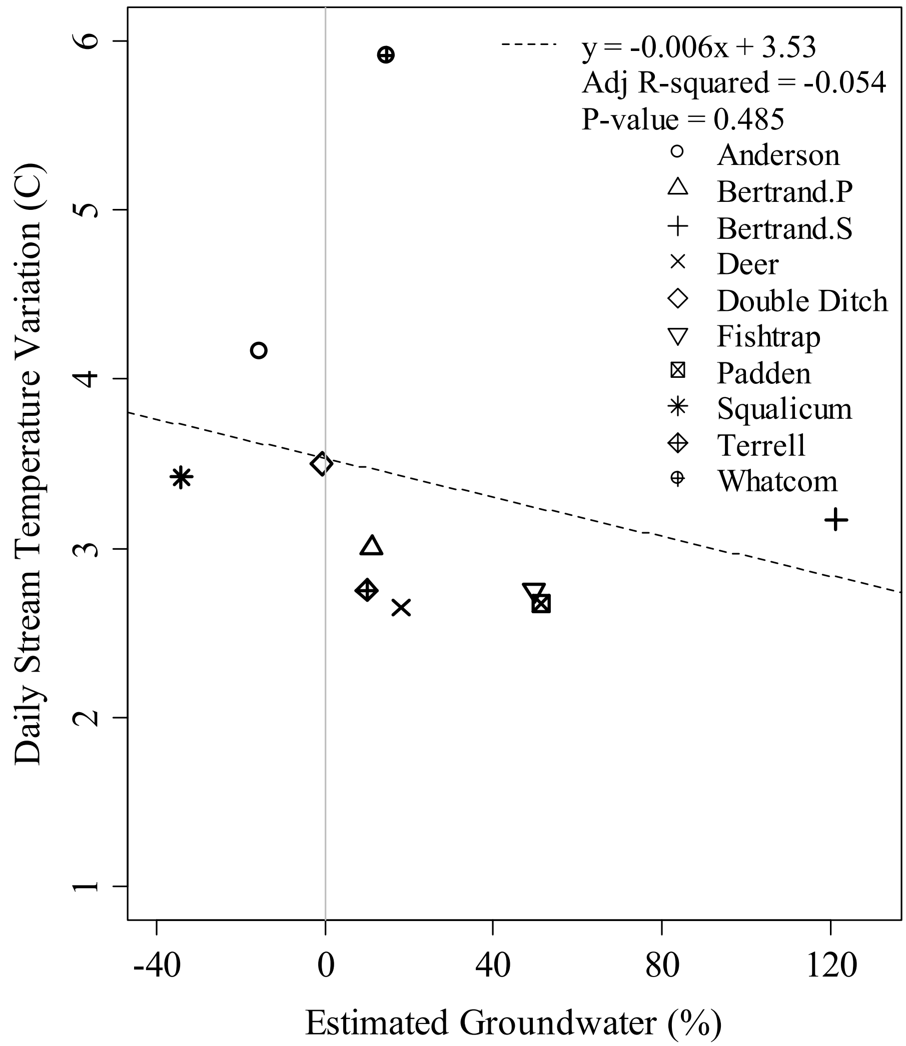

Figure S4. Average daily stream temperature variation by estimated groundwater at the downstream logger location in each reach. Streams with higher levels of groundwater were expected to have smaller daily temperature variation (Constantz 1998).

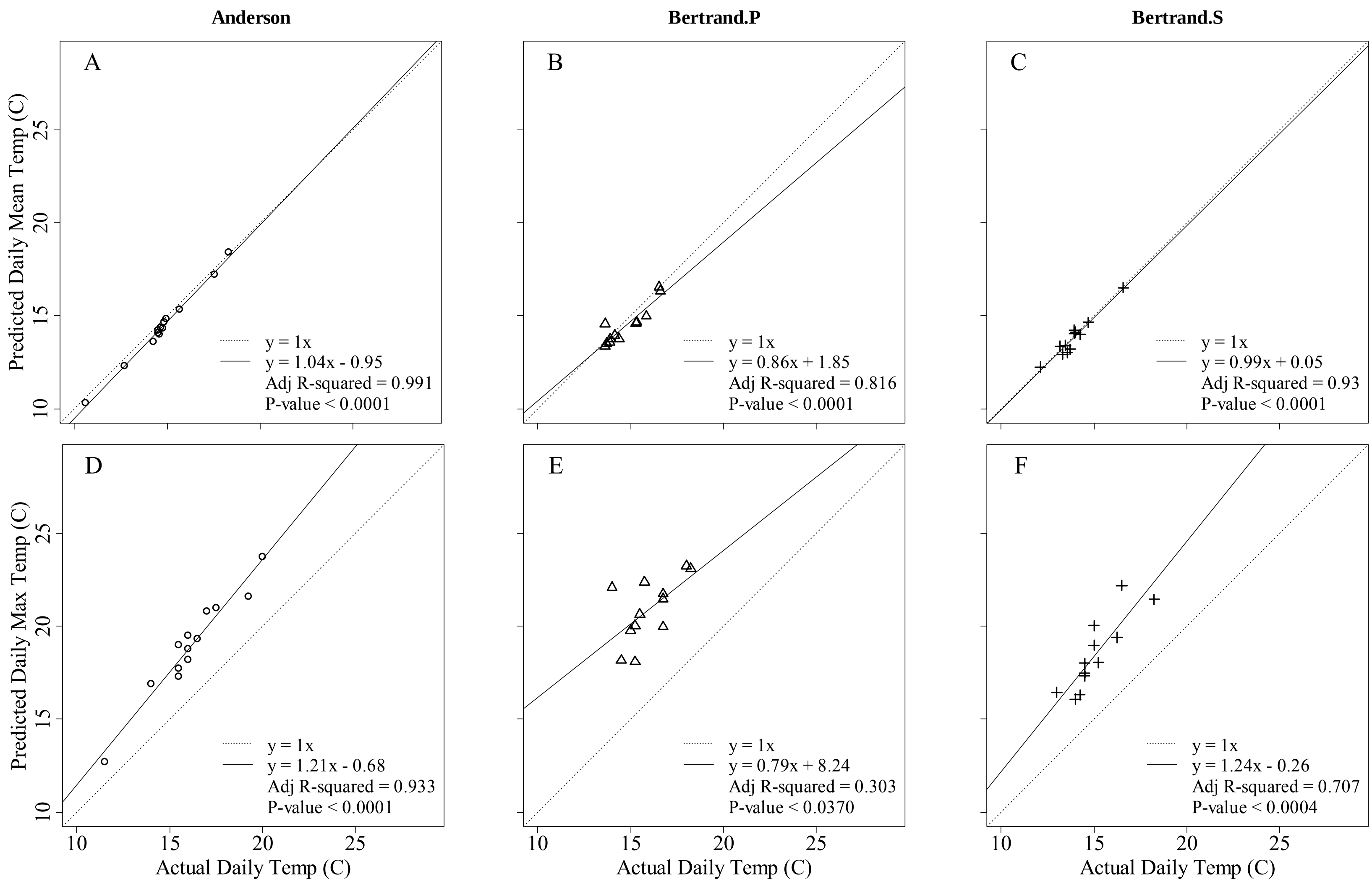

Figure S5. Relationships between SSTEMP predicted and measured reach temperatures for three reaches: Anderson, Bertrand.P, and Bertrand.S. A – C show Daily Mean relationships; D – F show corresponding Daily Maximum relationships.

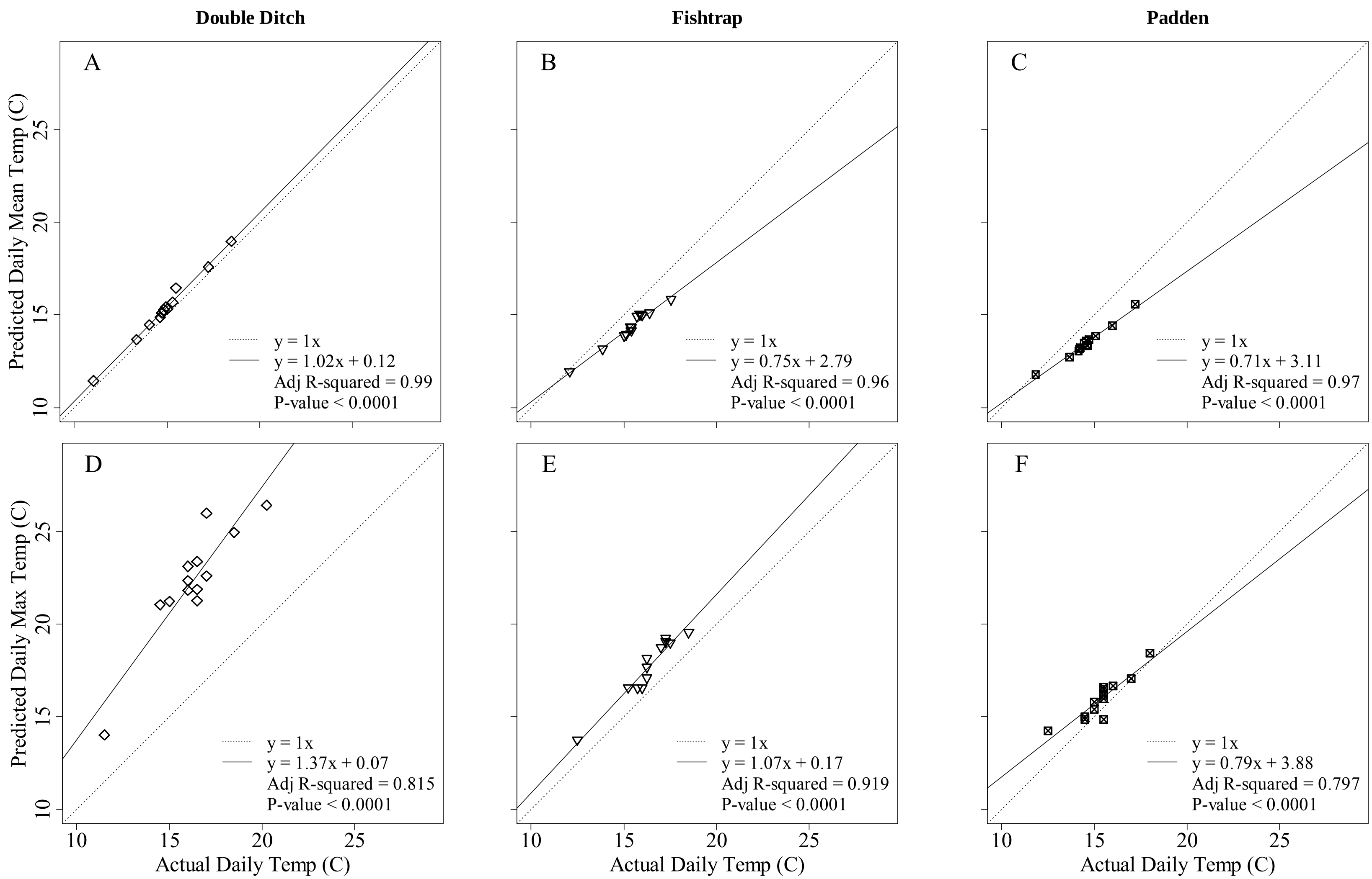

Figure S6. Relationships between SSTEMP predicted and measured reach temperatures for three reaches: Double Ditch, Fishtrap, and Padden. A – C show Daily Mean relationships; D – F show corresponding Daily Maximum relationships.

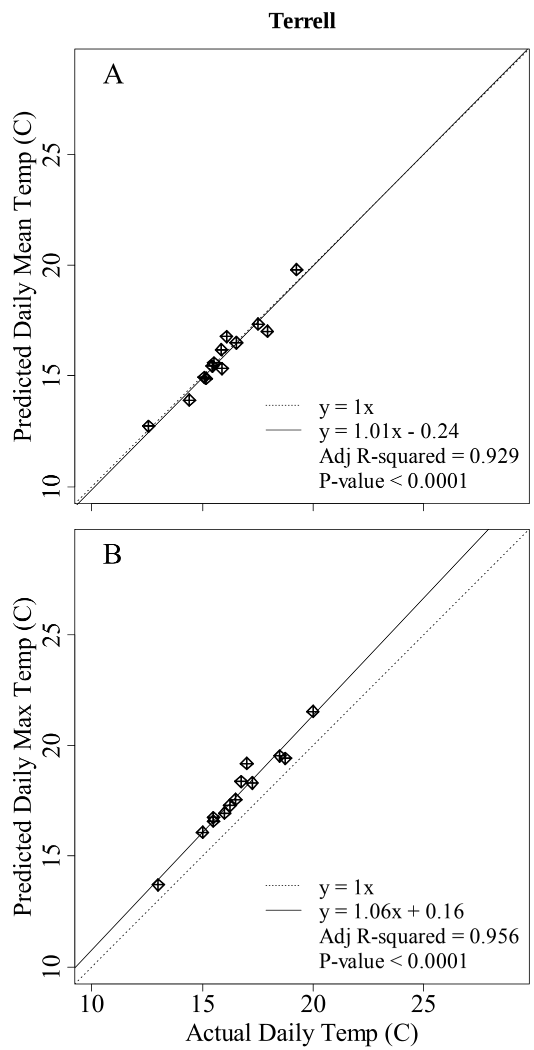

Figure S7. Relationships between SSTEMP predicted and measured reach temperatures for the Terrell reach. A shows Daily Mean relationship; B shows Daily Maximum relationship.