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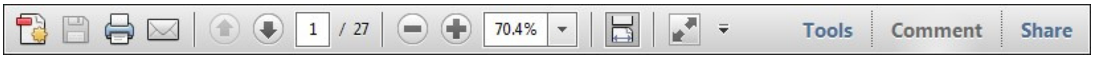

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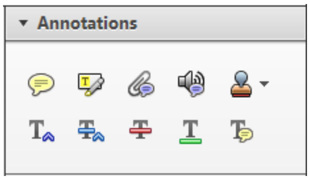

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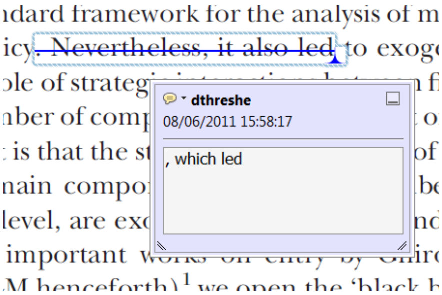

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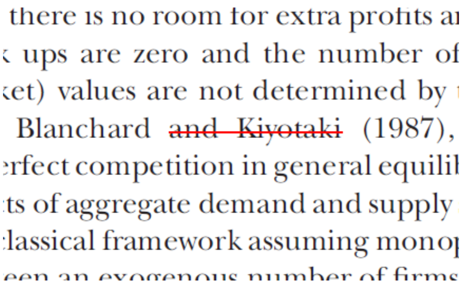

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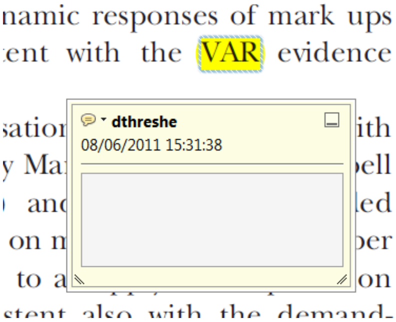

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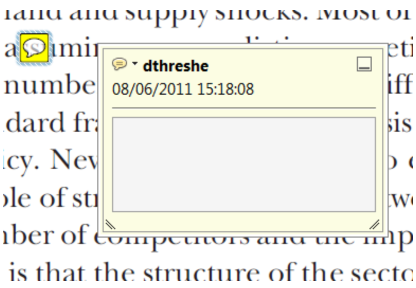

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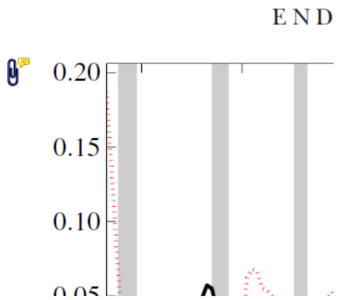

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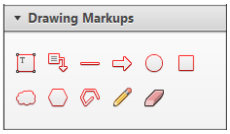

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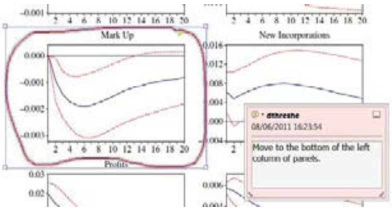

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CONTROLS ON TEMPERATURE IN SALMONID-BEARING HEADWATER STREAMS IN TWO COMMON HYDROGEOLOGIC SETTINGS, KENAI PENINSULA, ALASKA[1]

Michael K. Callahan, Mark C. Rains, Jason C. Bellino, Coowe M. Walker,
Steven J. Baird, Dennis F. Whigham, and Ryan S. King[2]

ABSTRACT: Headwater streams are the most numerous in terms of both number and length in the conterminous United States and play important roles as spawning and rearing grounds for numerous species of anadromous fish. Stream temperature is a controlling variable for many physical, chemical, and biological processes and plays a critical role in the overall health and integrity of a stream. We investigated the controls on stream temperature in salmon-bearing headwater streams in two common hydrogeologic settings on the Kenai Peninsula, Alaska: (1) drainage-ways, which are low-gradient streams that flow through broad valleys; and (2) discharge-slopes, which are high gradient streams that flow through narrow valleys. We hypothesize local geomorphology strongly influences surface-water and groundwater interactions, which control streamflow at the network scale and stream temperatures at the reach scale. The results of this study showed significant differences in stream temperatures between the two hydrogeologic settings. Observed stream temperatures were higher in drainage-way sites than in discharge-slope sites, and showed strong correlations as a continuous function with the calculated topographic metric flow-weighted slope. Additionally, modeling results indicated the potential for groundwater discharge to moderate stream temperature is not equal between the two hydrogeologic settings, with groundwater having a greater moderating effect on stream temperature at the drainage-way sites.

(KEY TERMS: surface water/ground water interactions; surface water hydrology; ground water hydrology; geomorphology; watershed management; anadromous fish.)

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INTRODUCTION

Small headwater streams are critical components of watersheds and river networks (Lowe and Likens, 2005) and successful watershed management requires an integrated approach incorporating hillslopes and headwater streams together with the larger downstream waters (Nadeau and Rains, 2007). Headwater streams comprise a large proportion of stream networks, with estimates indicating that headwater streams make up 50-70% of stream channel length in

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the conterminous United States (Horton, 1945; Leopold *et al.*, 1964; Nadeau and Rains, 2007). Headwater streams act as a critical connection of nutrients, invertebrates, and organic matter between uplands and riparian zones with the downstream river network (Wipfli and Gregovich, 2002; Alexander *et al.*, 2007; Meyer *et al.*, 2007) and are also important refuge and critical rearing habitats for numerous fish species, including salmonids (Bryant *et al.*, 2004; Meyer *et al.*, 2007; King *et al.*, 2012).

Stream temperature is a controlling variable for many physical, chemical, and biological processes, playing a crucial role in the productivity, ecology, and the overall health and integrity of streams (Allan, 1995; Cassie, 2006). For many fish and invertebrate species, stream temperature defines habitat suitability (Coutant, 1976; Beschta *et al.*, 1987; Armour, 1991) and can influence geographic distribution (Ebersole *et al.*, 2001; Mather *et al.*, 2008), growth rates (Bjornn and Reiser, 1991), egg incubation duration and success (Bjornn and Reiser, 1991; Malcolm *et al.*, 2008), and timing of emergence (Nordlie and Arthur, 1981; Beacham and Murray, 1985). In addition, stream temperature can impact critical ecosystem functions and metabolic processes such as nutrient uptake and rates of organic matter breakdown (Cummins, 1974; Webster and Benfield, 1986).

Stream temperature varies on daily and annual cycles (Coutant, 1999; Cassie, 2006), with daily minima and maxima in the morning and afternoon, respectively, and annual minima and maxima in the winter and summer, respectively. The controls on stream temperatures are driven by interactions between atmospheric, hydrologic, and geomorphic factors (Cassie, 2006), with major controlling factors including incoming solar radiation, riparian vegetation cover, topography, discharge, and groundwater inputs (Theurer *et al.*, 1984; Bartholow, 1989; Poole and Berman, 2001; Cassie, 2006). For small streams, direct solar radiation is the dominant mechanism determining summertime stream heating (Allen, 2008), with riparian vegetation cover being the primary control on the amount of direct shortwave radiation reaching the stream surface during the day (Beschta, 1997).

Groundwater inputs have an important moderating and stabilizing effect on stream temperatures, commonly warming water in the winter and cooling water in the summer (Coutant, 1999; Hayashi and Rosenberry, 2002). In headwater streams, groundwater discharge can play an important role in streamflow generation by continuing to provide water to offset losses to evapotranspiration (Winter, 2007). Groundwater discharge, by definition, is the sole component of base flow and has been shown to contribute up to half of total stormflow and >80% of stormflow at a given moment in time, including in some headwater settings (Winter *et al.*, 1998; Burns *et al.*, 2001; Kish *et al.*, 2010). With such extensive contributions to streamflow, groundwater temperature can act as a baseline temperature in headwater streams (Sullivan and Adams, 1991). However, stream temperatures then begin to converge with air temperatures as the water moves downstream. Small, shallow streams are more susceptible to larger swings in temperature, because small volumes of water heat and cool faster than large volumes of water. Therefore, groundwater discharge has potentially greater impacts in small headwater streams than in larger downstream reaches (Sullivan and Adams, 1991).

We conducted a study with the objectives of quantifying differences in stream temperatures in headwater streams and the potential roles played by groundwater discharge in two common geomorphically distinct hydrogeologic settings of the Kenai Lowlands. We hypothesized that local topography and geomorphology strongly influence surface-water and groundwater interactions, which in turn control streamflows at the basin scale and stream temperatures at the reach scale.

Study Location

This study was focused on headwater streams in the southern Kenai Lowlands (Figure 1). The Kenai Lowlands (~9,400 km^2) are located on the Kenai Peninsula in south-central Alaska between Kachemak Bay to the south, Cook Inlet to the west, and the Kenai Mountains to the east. The Kenai Lowlands are a broad, low shelf predominantly less than 120 m above sea level. The four major drainage basins in the southern Kenai Lowlands are: Ninilchik River, Deep Creek, Stariski Creek, and the Anchor River, the latter being the largest of the four drainage basins.

The climate of the Kenai Lowlands transitions from maritime to continental influences from south to north, and is typically characterized by long cool winters from September to May and relatively short warm summers from June to August. Mean annual temperature and precipitation is 3.2°C and 612 mm (Homer Airport, AK US, GHCND:USW00025507, 1933-2011) with the majority of precipitation occurs during the fall (September-November). Mean temperature and precipitation during the study time frame were close to the long-term mean values. Mean annual temperature was 3.1 and 2.5°C with a mean annual precipitation of 606 and 500 mm in for 2007 and 2008 respectively.

The geology of the Kenai Lowlands consists primarily of complex glacial deposits such as till,

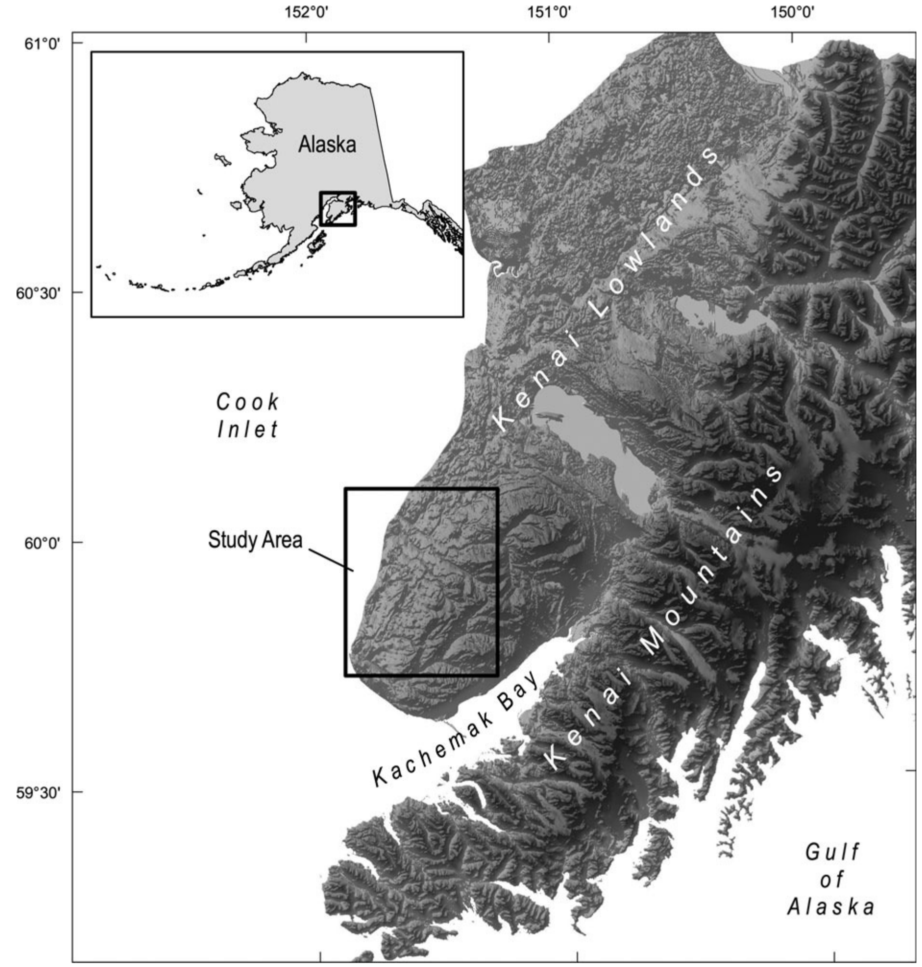

FIGURE 1. Location of the Study Area in the Kenai Peninsula, Alaska.

moraine, and outwash deposits overlying weakly lithified Tertiary bedrock (Karlstrom, 1964). Bedrock consists of poorly to moderately consolidated sandstone, siltstone, claystone, and coal of the Kenai Group (Nelson and Johnson, 1981). Topography of the Kenai Lowlands is primarily the result of five major Pleistocene glaciations and two minor post-Pleistocene glacial advances (Karlstrom, 1964). Multiple ice centers in the surrounding mountains fed glaciers, which left a complex system of moraines and unconsolidated glacial till throughout the area (Karlstrom, 1964; Nelson and Johnson, 1981). The Kenai Lowlands are generally permafrost free (Ford and Bedford, 1983).

Water tables are commonly at or within a few meters of the ground surface and wetlands and water bodies are common, covering approximately 41% of the land surface (Karlstrom, 1964; Gracz *et al.*, 2004). Riparian wetland vegetation associated with headwater streams is dominated by bluejoint (*Calamagrostis canadensis*) (Shaftel *et al.*, 2011; Whigham *et al.*, 2012). Streams flow through mixed forests of lutz spruce (*Picea lutzii*), paper birch (*Betula papyrifera*), and stands of willow (*Salix* spp.) and alder (*Alnus* spp.) (Walker *et al.*, 2012). Riparian wetland vegetation, particularly bluejoint grass litter, supports the majority of the juvenile salmonid production in headwater streams in this region (Dekar *et al.*, 2012).

Streams in the Kenai Lowlands support anadromous salmonid species such as Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and pink (*O. gorbuscha*) salmon as well as Dolly Varden char (*Salvelinus malma*) and steelhead trout (*O. mykiss*) (Walker *et al.*, 2012). These species are important to local and regional economies through recreational and commercial fishing. Recent studies have found juvenile salmonids in Kenai Lowland headwater streams in both spring and summer indicating their importance as rearing and overwintering habitats (Walker *et al.*, 2007, 2009; King *et al.*, 2012). Walker *et al.* (2007) estimated that the headwater streams in our study area support at least ¼ million juvenile salmonids.

METHODS

We investigated two common, geomorphically distinct hydrogeologic settings of the Kenai Lowlands, drainage-way and discharge-slope sites (Reeve and Gracz, 2008). Drainage-way sites (Figure 2) are characterized by relatively low-gradient streams (i.e., mean ± SD valley slopes of 0.04 ± 0.04), which flow through broad valleys dominated by groundwater-fed fens. Headwater streams in discharge-slope sites (Figure 2) are characterized by relatively high-gradient streams (i.e., mean ± SD valley slopes of 0.12 ± 0.09), which flow through narrow valleys. Discharge-slope streams typically have narrow bands of riparian wetland vegetation and there is a sharp break in slope between the streams and the adjacent uplands. Groundwater discharge sites are common where the upland slopes meet wetlands that are adjacent to the streams. Drainage-way sites generally consist of low-permeability substrates composed of peat compared to discharge-slope sites that consist of low-permeability substrates composed of glacial till and other poorly-sorted sediments. A stream will typically flow through multiple geomorphic settings as it flows from the headwaters to the river mouth. For this study we selected eighteen sites. One site was subsequently omitted due to equipment failure, leaving a total of seventeen sites with ten in drainage-way and seven in discharge-slope sites (Figure 3).

Physical Hydrology

Hourly stream temperature was measured for one year at each of the seventeen sites using two model TBI32 StowAway TidbiT temperature sensors with built-in data loggers (Onset Computer Corporation, Cape Cod, Massachusetts). Each sensor was secured to the stream bed using stainless steel wire attached to rebar pounded approximately 1 m into the stream bed. Sensors were located approximately 250 m apart within each stream reach. Stream stage, groundwater temperature, and groundwater hydraulic head in the local groundwater flow systems were also measured for one year at one typical drainage-way (i.e., NANC44) and one typical discharge-slope site (i.e., SANC1203). Piezometers were constructed of 5 cm inside-diameter PVC and screened over 30 cm intervals approximately 1 m below the ground surface. Groundwater temperature and hydraulic head were measured hourly with model 3001 Levelogger Gold pressure transducers and dataloggers (Solinst, Inc., Georgetown, Ontario) either suspended in the piezometers or secured in the streambed. Hydraulic head was corrected with atmospheric pressure measured hourly with Barologgers (Solinst, Inc.) suspended in vegetation at each site. At the drainage-way site, the hydraulic gradient (dh/dl) was calculated from measurements of mean hydraulic heads in a piezometer adjacent to the channel and another piezometer located 50 m directly upgradient; at the discharge-slope site, the hydraulic gradient was calculated from measurements of mean hydraulic head in a piezometer adjacent to the channel and mean stage in a seep located 50 m directly upgradient. Hydraulic conductivity (*K*) values for the local deposits were determined with slug tests. At each site, three slug tests, two falling-head and one rising-head, were performed on a single piezometer. Data were analyzed using the Hvorslev method (Hvorslev, 1951). Effective porosity [1] for the organic deposits at the drainage-way site were taken from Letts *et al.* (2000), while effective porosity for the mixed gravel and sand at the discharge-slope site were taken from Todd (1964). These data were used with the Darcy equation to calculate mean groundwater velocity and related travel times at each site.

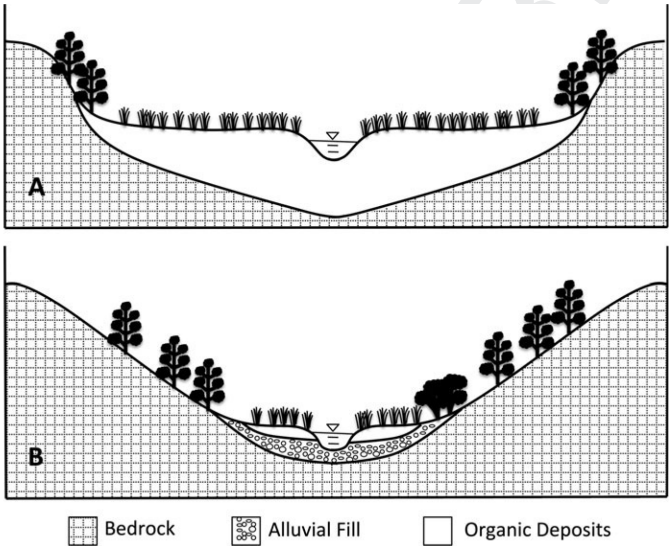

FIGURE 2. Conceptual Cross-Sections of (A) a Drainage-Way Site and (B) a Discharge-Slope Site.

Chemical Hydrology

Water samples were collected from snow and rain collectors opportunistically during spring (March-May) and in streams, piezometers, and seeps during spring (May) and summer (August) sampling efforts. Samples were field filtered with 0.45 μm capsule filters. Samples were collected in acid-washed HDPE bottles and stored at or below 4°C until analyses could be completed. Concentrations of dissolved major (Na, Mg, K, Ca) and trace (Si, Fe, Ba, Sr, B) cations were analyzed with a Perkin-Elmer Elan II

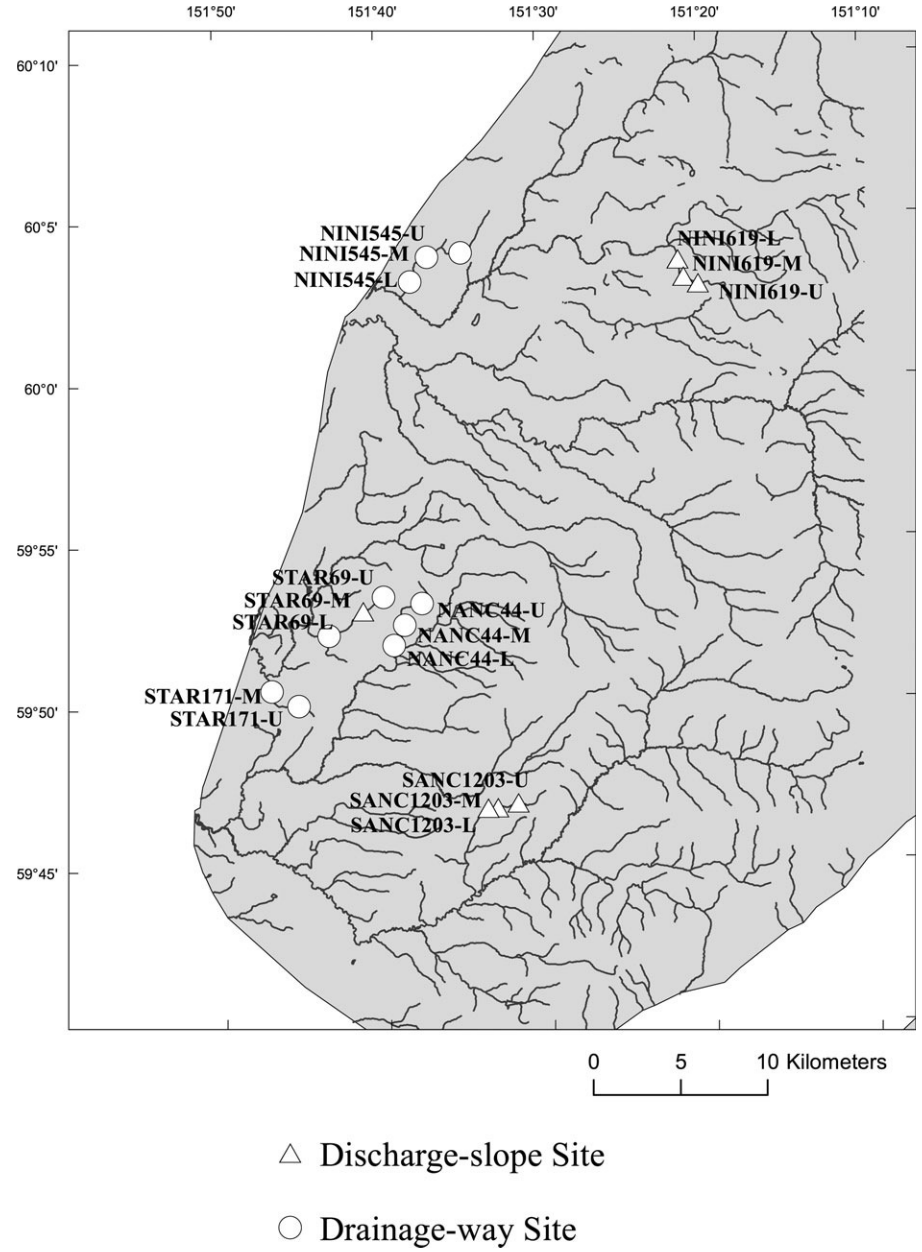

FIGURE 3. Location of the 17 Study Sites in the Kenai Lowlands.

2 DRC Quadrupole ICP-MS in the Mass Spectrometry Lab at the University of South Florida Geology Department. Detection limits were 1.0 μg/l for major elements and 0.1 μg/l for trace elements except B, which was not detected. Each sample concentration was acquired by taking the mean of five separate measurements, and relative standard deviation of the five acquisitions was generally 6% or better. Chloride concentrations were analyzed at Advanced Environmental Laboratories, Inc. of Tampa, Florida, with ion chromatography using EPA method 325.2 and a detection limit of 0.20 mg/l (Clesceri *et al.*, 1998). All concentrations were reported in milligrams per liter.

A two-end-member, mass-balance mixing model was created to calculate the relative contribution of precipitation and groundwater for each sample. Conductivity, Na, Mg, and Ca were used as conservative tracers. Precipitation and groundwater end-member values for each tracer were calculated as the average value for that tracer in all samples of each end-member type. Precipitation values were determined from samples from snow and rain collectors, while groundwater values were determined from samples from seeps and springs or piezometers directly upgradient of the stream channel. The concentration of the theoretical mixtures was calculated using the following equation:

$$f_{\mathrm{qw}} = (C_{\mathrm{mix}} - C_{\mathrm{p}})/(C_{\mathrm{gw}} - C_{\mathrm{p}}), \tag{1}$$

where f_{gw} is the fraction of the mixture contributed by ground water, C_{mix} is the concentration of the mixed solution (i.e., the stream water) in mg/l, C_{p} is the concentration of precipitation in mg/l, and C_{gw} is the concentration of groundwater in mg/l. The final value for the proportional groundwater contribution was expressed as the mean value computed from all tracers combined. Application of the mixing model assumes both that all samples were instantaneous mixtures of the two end members and that evapoconcentration was negligible.

Correlation Analysis

The cross-correlation function in MATLAB (Version R2010A; MathWorks Inc., Natick, Massachusetts) was used to determine the similarity between the groundwater, surface water, and air temperatures at both sites. The cross-correlation function is part of MATLAB's signal processing toolbox and can compute a normalized correlation coefficient (r) between 0 and 1 that reflects the degree of similarity between two time signals of equal length. Cross-correlations were computed for varying lags on one-day intervals for the groundwater, surface water, and air temperatures at both sites. Peak correlations were selected and reported, along with their respective lags or time delays if they occurred.

Flow-Weighted Slope

The flow-weighted slope (FWS) metric was calculated at each site to integrate hillslope basin area and local slope as surrogates for the likelihood of groundwater discharge. FWS accounts for the watershed area contributing to the flow path and the slope of the flow path, as the flow path gets closer to the stream (Walker *et al.*, 2012). The FWS metric is similar to the topographic wetness index (TWI), which is calculated as:

$$\mathrm{TWI} = \ln(A/\mathrm{Tan}\ \beta), \tag{2}$$

where A is the upstream accumulation area and β is the slope (Beven and Kirkby, 1979; Sørensen *et al.*, [3, 4] 2006). ArcGIS™ 10.0 (ESRI®) was used to compute FWS using a 5 m resolution digital elevation model derived from Lidar (vertical accuracy of better than ±2 m) following methods described by Walker *et al.* (2012). FWS is calculated for an individual pixel in the watershed by using the following equation:

$$\mathrm{FWS} = \sum(\beta i \cdot \mathrm{FAC}_i)/\sum(\mathrm{FAC}_i), \tag{3}$$

where βi is the pixel slope, and FAC_i is the flow accumulation value of pixel i (excluding the stream channel), for all pixels in the area draining to an outlet point (King *et al.*, 2012; Walker *et al.*, 2012). The FWS values reported in this study correspond to the outlet of the drainage area directly upstream of each study site. FWS necessarily weights slope values closer to the stream channel, where large accumulation values are most likely to occur along lateral flow paths. A low FWS corresponds to a drainage area with a low gradient, high wetness hydrogeologic setting near the stream (e.g., drainage-way setting), whereas a high FWS corresponds to a high gradient, low wetness hydrogeologic setting along flow paths near the stream. While FWS and the TWI are similar, the FWS is easier to understand and communicate because it is expressed as a percentage and is not dependent on watershed size (King *et al.*, 2012; Walker *et al.*, 2012).

Stream Temperature Modeling

The Stream Segment Temperature model version 2.0 (SSTEMP) (http://www.fort.usgs.gov/Products/Software/SNTEMP; Bartholow, 2004), a process-based mechanistic surface water temperature model, was used to examine the influence of groundwater discharge on summer-time stream temperatures in the drainage-way and discharge-slope sites. SSTEMP is a deterministic model based on a heat/energy flux equation that predicts daily mean and maximum stream temperatures. This equation predicts stream temperatures based on the net heat flux, or the amount of heat entering or leaving a stream. Model input data include stream geometry data, meteorological data, and hydrologic data (Table 1).

SSTEMP input variables were based on local and regional climate data, field measurements, and literature reported values. Local air temperature values were determined using Solinst Barrologger pressure transducers and dataloggers (Solinst, Inc.) installed at the drainage-way and discharge-slope sites. Regional climate data were obtained through the National Oceanic and Atmospheric Administration's National Climate Data Center. Hydrology, stream geometry, and shade data were collected from field measurements. Stream discharge and geometry values for the two hydrogeologic settings were collected with a Sontek FlowTracker handheld discharge meter. [5] Upstream and downstream discharge measurements within a stream reach allowed for the calculation of approximate groundwater discharge rates for the

TABLE 1. Stream Segment Temperature Model (SSTEMP) Input Parameters. SSTEMP input variables were based on local and regional climate data, field measurements, and literature reported values.

SSTEMP Input Variables	Drainage-Way Site (i.e., NANC44)	Discharge-Slope Site (i.e., SANC1203)
Hydrology		
Segment inflow (cfs)[1]	0.543	0.082
Inflow (i.e., stream) temperature (°C)[2]	8.5	6.3
Segment outflow (cfs)[1]	0.603	0.357
Groundwater input (cfs)[1]	0.060	0.275
Accretion (i.e., groundwater) temperture (°C)[2]	2.9	7.0
Geometry		
Latitude[1]	59.88	59.78
Segment length (km)[1]	0.25	0.25
Upstream elevation (m)[1]	115	387
Downstream elevation (m)[1]	114	355
Width's A term[1]	7.74	7.74
B term[1]	0.4	0.4
Mannings *n*[4]	0.035	0.035
Shade		
Total shade[4]	20%	90%
Meteorology		
Air temperature (°C)[2]	12.3	12.3
Relative humidity[5]	71	71
Wind speed[5]	7	7
Ground temperature (°C)[3]	1.83	1.83
Thermal gradient[5]	1.65	1.65
Possible sun[5]	41%	41%
Dust coefficient[5]	5	5
Ground reflectivity[5]	25	10

[1] Single value from field measurement.
[2] Mean monthly from field measurement.
[3] Mean annual from field measurement.
[4] Estimated from field observation.
[5] Estimated from published literature values.

study reaches. Field measurements were collected during the summers (May to August) of 2007, 2008, and 2011. Values for ground reflectivity and the dust coefficient were obtained from published literature (Bartholow, 1989, 2004). For each hydrogeologic setting, a modeled headwater stream was segmented into 17 study reaches measuring 250 m each. The SSTEMP model was used to simulate two different groundwater input scenarios: (1) continuous and diffuse groundwater discharge, and (2) discontinuous and focused groundwater discharge. To simulate continuous groundwater discharge, groundwater was added to each reach throughout the modeled stream; to simulate discontinuous and focused groundwater discharge, groundwater was added only to the first stream reach in the modeled stream. Models were run using mean values for July or August, when conditions are commonly dominated by baseflow.

The SSTEMP model was validated using mean monthly values for all input data and assuming continuous groundwater discharge to the stream along the entire model reach. The drainage-way site was validated using data from August 2007 and the discharge-slope site was validated using data from July 2008. At the drainage-way site, stream-temperature data were available at 0, 2,300, and 3,700 m in the downstream direction; at the discharge slope site, stream-temperature data were available at 0, 1,300, and 1,900 m in the downstream direction. In both cases, stream-temperature data at the upstream location were used as initial conditions and stream-temperature data at the two downstream locations were used for validation purposes.

RESULTS

Groundwater Contributions to Streamflow

Hydrologic characteristics at the drainage-way and discharge-slope sites differed from one another. At the drainage-way site, mean ± SD hydraulic conductivity was $5 \times 10^{-6} \pm 4 \times 10^{-7}$ m/s and the hydraulic gradient of groundwater flowing toward the stream was approximately 0.01. Therefore, specific discharge was 4×10^{-3} m/day and the mean time to travel 2 m (i.e., the approximate distance from the nearest monitoring well to the stream) was ~400 days. At the discharge-slope site, mean ± SD hydraulic conductivity was $1 \times 10^{-5} \pm 4 \times 10^{-7}$ m/s and the hydraulic gradient of groundwater flowing toward the stream was approximately 0.03; resulting in a specific discharge of 3×10^{-2} m/day and a mean time to travel 2 m of ~20 days.

Results from the geochemical analysis and the mixing model indicate overall similar portions of groundwater contribution to the drainage-way and discharge-slope sites (Table 2). Mean ± SD groundwater contribution to streamflow for the spring (i.e., May) was 44 ± 17% for the drainage-way sites and 44 ± 22% for the discharge-slope sites. Mean ± SD groundwater contribution to streamflow for the summer (i.e., August) was 59 ± 25% for the drainage-way sites and 62 ± 15% for discharge-slope sites. Groundwater contribution to streamflow for individual sites was highly variable and ranged from 12% (NINI545 Upper) to 68% (STAR69 Middle) during the spring and 2% (NINI545) to 81% (NANC44 Lower and NINI619) during the summer (Table 2).

Measured Stream Temperature

Mean ± SD annual stream temperatures were 3.6 ± 1.1°C and 2.4 ± 0.2°C at the drainage-way and

TABLE 2. Geochemically Modeled Groundwater Contribution to Streamflow (Equation 1) for Spring (May) and Summer (August) in Drainage-Way (DW) and Discharge-Slope (DS) Sites.

			Proportion of Groundwater	
	Hydrogeologic Setting	**Flow-Weighted Slope**	**Spring**	**Summer**
NINI545 Upper	DW	1.14	0.12	0.02
STAR171 Upper	DW	1.31	0.64	0.75
NINI545 Middle	DW	1.31		0.35
STAR171 Middle	DW	1.41	0.40	0.56
NINI545 Lower	DW	1.78	0.29	0.75
STAR69 Upper	DW	1.93	0.46	0.54
NANC44 Middle	DW	3.09	0.52	0.74
STAR69 Lower	DW	3.53	0.65	0.76
NANC44 Lower	DW	3.59	0.47	0.81
SANC1203 Upper	DS	3.83	0.13	0.57
NANC44 Upper	DW	4.14	0.41	0.66
STAR69 Middle	DS	4.35	0.68	0.79
NINI619 Middle	DS	5.04	0.52	0.65
NINI619 Lower	DS	5.15	0.52	0.81
NINI619 Upper	DS	5.19	0.61	0.64
SANC1203 Middle	DS	8.10	0.20	0.55
SANC1203 Lower	DS	8.36		0.36
Mean (±SD) DW sites			0.44 (±0.17)	0.59 (±0.25)
Mean (±SD) DS sites			0.44 (±0.22)	0.62 (±0.15)

discharge-slope sites, respectively (Table 3). These were significantly different from one another (Mann-Whitney *U* test; $p < 0.01$). Drainage-way sites also had higher instantaneous maximum stream temperature and mean three-, five-, and seven-day maximum temperatures (Table 3). Among the drainage-way sites, NINI545 Upper had the highest mean annual stream temperature (5.7°C) while among the discharge-slope sites, STAR69 Middle and SANC1203 Upper had the highest mean annual stream temperatures (2.5°C each).

At the drainage-way site (i.e., NANC44), groundwater and stream-water temperatures differed throughout the year, with groundwater warmer than the stream water in the winter and cooler in the summer (Figure 4). In the summer, groundwater was approximately 5-7°C cooler. At the discharge-slope site (i.e., SANC1203), groundwater and stream-water temperatures were similar throughout the year (Figure 4). Surface-water temperatures only briefly exceeded groundwater temperatures by 2-4°C during the early summer.

The cross-correlation analysis (Table 4) showed high correlations between air and stream temperatures at both hydrogeologic settings. Cross-correlation coefficients between air and stream temperatures were $r = 0.94$ and $r = 0.93$ at the drainage-way and discharge-slope sites, respectively. At both types of sites, the highest correlations between air and stream temperatures occurred without any time delay or lag between the two signals. Correlation between groundwater and stream temperatures at the drainage-way site was $r = 0.77$ with a zero lag, but increased to $r = 0.82$ at a lag of 27 days (Table 4) (Figure 5). Correlation between groundwater and stream temperatures was higher at the discharge-slope site, with a correlation coefficient of $r = 0.95$ with a zero lag, and was not increased with a longer lag (Figure 5).

TABLE 3. Mean (±SD) Stream-Temperature Metrics (°C) for the Drainage-Way (DW) and Discharge-Slope (DS) Sites. Temperature thresholds (i.e., 0, 13, 15, 20°C) relate to common thresholds at which physical or biological responses may occur. These include: ≤0°C = ice formation, ≥13°C = damage to salmonid egg and fry, ≥15°C = damage to adult salmonids, and ≥20°C approaching upper lethal limit for adult salmonids.

	DW Sites Mean (±SD)	**DS Sites Mean (±SD)**
Flow-weighted slope	2.8 (±1.5)	5.8 (±1.3)
Annual mean daily temperature	3.6 (±1.1)	2.4 (±0.2)
Annual max daily temperature	12.8 (±3.5)	8.0 (±0.5)
Annual min daily temperature	0.0 (±0.3)	−0.9 (±1.6)
Mean daily temperature range	1.0 (±0.5)	1.0 (±0.2)
Max daily temperature range	5.9 (±2.7)	6.8 (±1.9)
Inst. max temperature	14.5 (±4.0)	10.3 (±1.4)
Inst. min temperature	−0.2 (±0.7)	−1.2 (±1.6)
Max seven-day mean temperature	12.1 (±3.1)	7.3 (±0.4)
Max five-day mean temperature	12.2 (±3.2)	7.4 (±0.4)
Max three-day mean temperature	12.5 (±3.3)	7.6 (±0.5)
Min seven-day mean temperature	0.0 (±0.1)	−0.6 (±1.4)
Min five-day mean temperature	0.0 (±0.1)	−0.7 (±1.6)
Min three-day mean temperature	0.0 (±0.2)	−0.8 (±1.6)
No. of days ≥20°C	0.2 (±0.6)	0.0 (±0.0)
No.of days ≥15°C	4.3 (±13.6)	0.0 (±0.0)
No. of days ≥23°C	12.9 (±27.4)	0.0 (±0.0)
No. of days ≤0°C	15.1 (±45.0)	21.7 (±29.8)

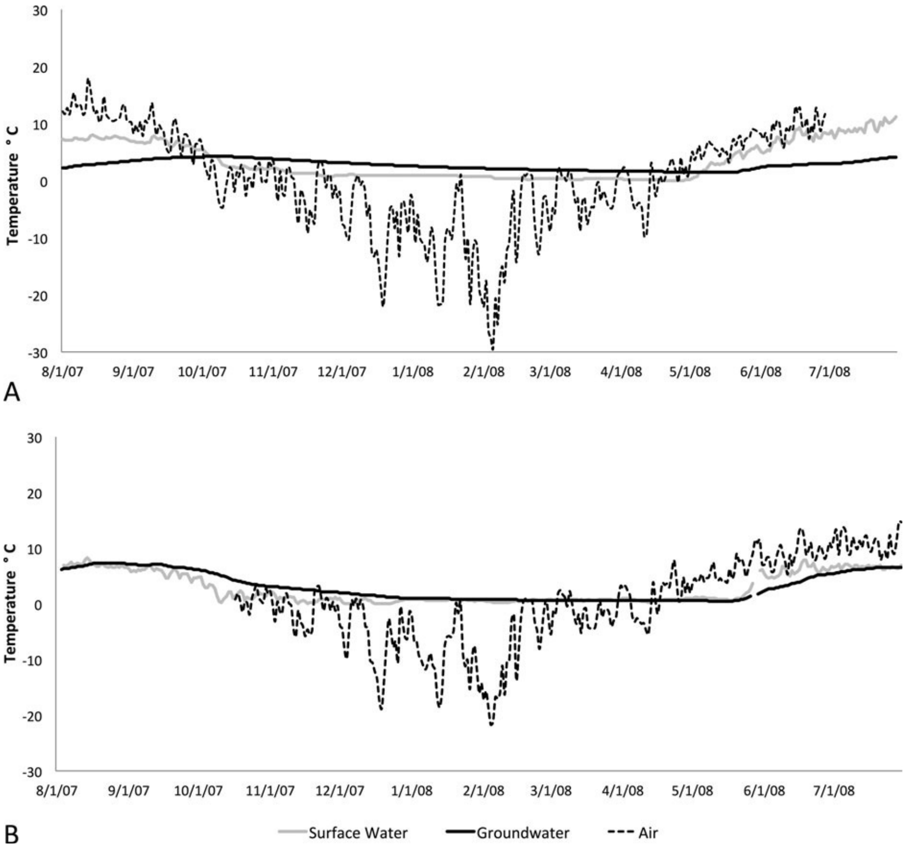

FIGURE 4. Mean Daily Stream-Water, Groundwater, and Air Temperature at (A) the Drainage-Way Site (i.e., NANC44) and (B) the Discharge-Slope Site (i.e., SANC1203).

TABLE 4. Results of the Cross-Correlation Analysis between Air (air), Surface Water (SW), and Groundwater (GW) Temperatures at the Drainage-Way (DW) (i.e., NANC44) and Discharge-Slope (DS) Site (i.e., SANC1203).

DW Site (i.e., NANC44)	**Correlation (*r*)**	**Lag (Days)**	**Signal Length (Days)**
Air *vs.* SW	0.94	0	331
Air *vs.* GW	0.64	0	331
GW *vs.* SW	0.77	0	241
GW *vs.* SW	0.82	28	241
DS Site (i.e., SANC1203)	**Correlation (*r*)**	**Lag (Days)**	**Signal Length (Days)**
Air *vs.* SW	0.93	0	288
Air *vs.* GW	0.82	0	288
GW *vs.* SW	0.95	0	241

Groundwater Contributions to Stream Temperature

The modeled FWS metric for the 17 sites ranged along a continuum, from a low of 1.07 to a high of 8.56 (Table 2). Drainage-way sites had significantly lower (Mann-Whitney *U* test; $p < 0.01$) mean FWS (2.8 ± 1.5) than discharge-slope sites (5.8 ± 1.3) (Table 3). Sites with higher FWS values had lower mean annual stream temperatures ($R^2 = 0.64$) (Figure 6). This trend was also evident in the maximum daily mean stream temperature ($R^2 = 0.78$), maximum seven-day average ($R^2 = 0.80$), and the maximum instantaneous temperature ($R^2 = 0.61$) (Figure 6).

Overall, the SSTEMP modeled and measured stream temperatures were well correlated (Table 5). The SSTEMP model was run for both hydrogeologic settings, once with groundwater discharge to each 250 m reach throughout the model domain (i.e., continuous groundwater discharge) and once with groundwater discharge only in the uppermost 250 m reach within the model domain (i.e., discontinuous groundwater discharge). In both cases, modeled continuous groundwater discharge maintained lower stream temperatures, though the effects were more pronounced at the drainage-way site (Figure 7). At the drainage-way site, modeled stream temperature increased from 8.5 to 9.3°C with continuous groundwater discharge (a difference of 0.8°C), and from 8.5 to 12.3°C with discontinuous groundwater discharge (a difference of 3.8°C). At the discharge-slope site,

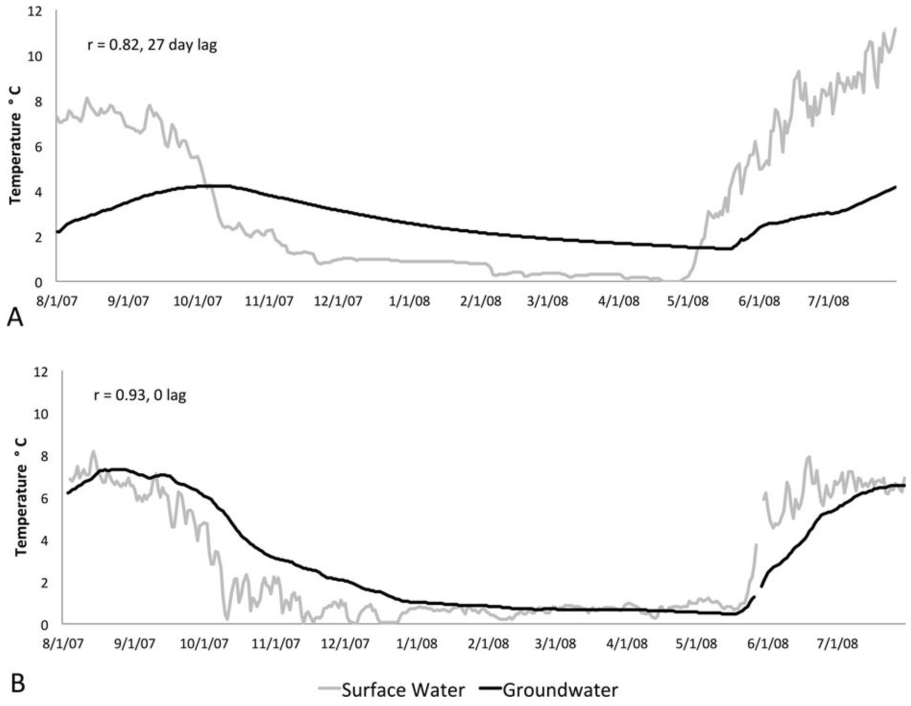

FIGURE 5. Mean Daily Surface Water and Groundwater Temperature with Cross Correlation Coefficient (r) and Lag Time, at (A) the Drainage-Way Site (i.e., NANC44) and (B) the Discharge-Slope Site (i.e., SANC1203).

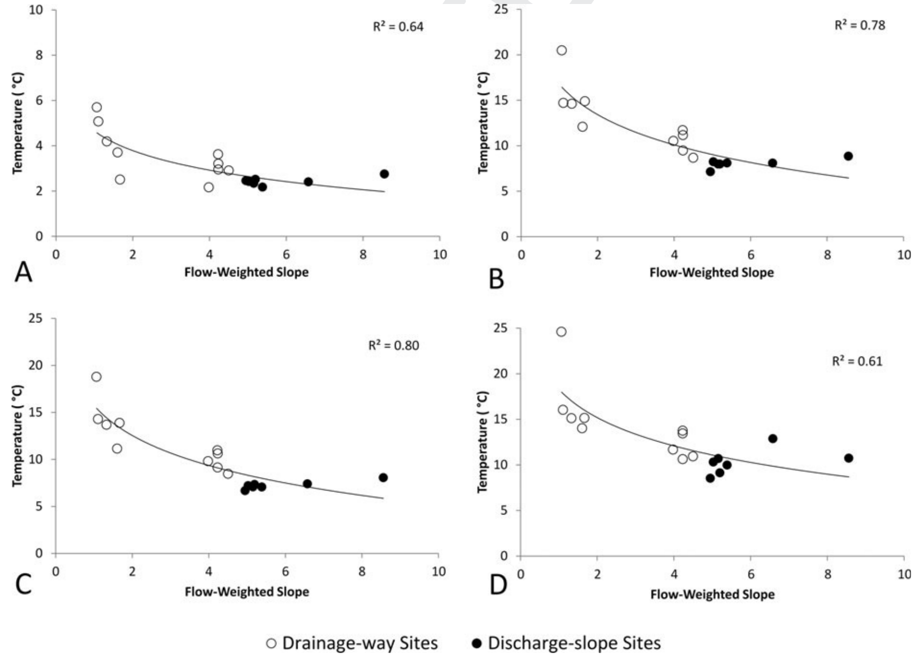

FIGURE 6. Modeled Flow-Weighted Slope (Equation 3) *vs.* (A) Mean Annual Stream Temperature, (B) Maximum Daily Mean Stream Temperature, (C) Maximum Seven-Day Average Stream Temperature, and (D) Maximum Instantaneous Stream Temperature.

modeled stream temperature increased from 6.3 to 7.8°C with continuous groundwater discharge (a difference of 1.5°C), and from 6.3 to 9.4°C with discontinuous groundwater discharge (a difference of 3.1°C).

DISCUSSION

The results of this study show that groundwater discharge plays an important role in streamflow gen-

TABLE 5. Stream Segment Temperature Model (SSTEMP) Validation Table Showing SSTEMP Modeled and Measured Surface Water Temperatures for the Drainage-Way (DW) and Discharge-Slope (DS) Sites. The DW site model was validated using observed temperatures from August 2007 and the discharge-slope site model was validated using observed temperatures from July 2008.

Downstream Distance (m)	Observed *T* (°C)	Predicted *T* (°C)
DW Site (i.e., NANC44)		
0	8.5	8.5
2,300	9.3	9.0
3,700	10.1	9.3
DS Site (i.e., SANC1203)		
0	6.3	6.3
1,300	6.6	6.9
1,900	7.3	7.1

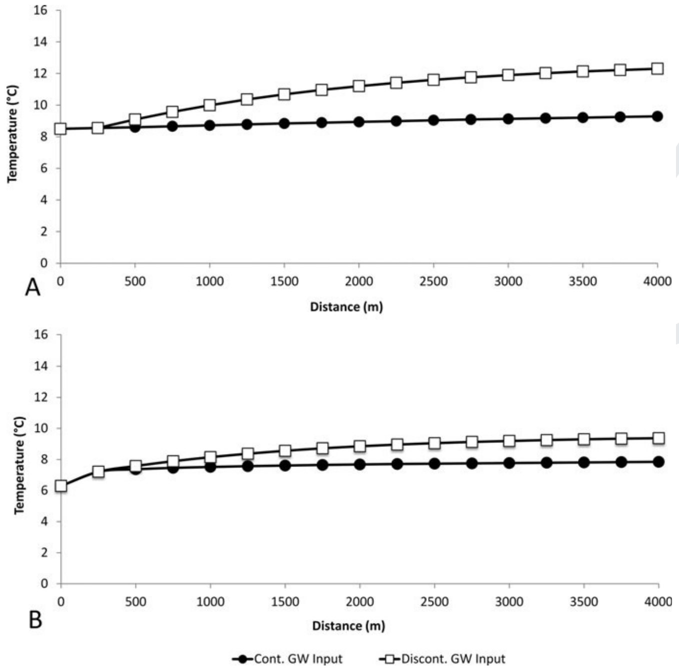

FIGURE 7. SSTEMP Predicted Summer-Time (i.e., August) Mean Stream Temperatures for Continuous (black circles) and Discontinuous (white squares) Groundwater Discharge for (A) the Drainage-Way Site (i.e., NANC44) and (B) the Discharge-Slope Site (i.e., SANC1203).

eration at the basin scale and stream-temperature moderation at the reach scale. As groundwater discharges into a stream, the groundwater retains its chemical signature (i.e., concentrations of cations and anions) for a longer period of time, however the groundwater quickly begins to take on the physical properties of the surface water (i.e., temperature). Because the latter occurs at the reach scale, local hydrogeologic setting plays an important role, with stream temperatures and rates of downstream warming differing between local hydrogeologic settings such as in the drainage-way and discharge-slope sites.

At the basin scale, groundwater discharge plays an important role in streamflow generation in late spring and throughout the summer. In late spring, during peak snowmelt, groundwater discharge accounts for approximately 40% of streamflow; in middle summer, following peak snowmelt, groundwater discharge accounts for approximately 60% of streamflow (Table 2). These values are consistent between drainage-way and discharge-slope sites because both hydrogeologic settings typically occur on the same stream (Figure 3). Our results are comparable to other published results for small streams. For example, Cey *et al.* (1998) found groundwater contributions of 60-80% in small agricultural watersheds and Hinton *et al.* (1994) found groundwater contributions of 29-62% in watersheds composed of glacial till.

Though groundwater discharge contributes to streamflow at the basin scale, the specific amounts of groundwater discharge and the roles they play in moderating stream temperatures vary at the reach scale between hydrogeologic settings. In the drainage-way sites, hydraulic conductivities and gradients are comparatively low so groundwater flow velocities and discharges to the stream are comparatively low, while in the discharge-slope sites, hydraulic conductivities and gradients are comparatively high, so groundwater flow velocities and discharges to the stream are comparatively high. Nevertheless, groundwater discharge plays an important role in controlling stream temperatures in both hydrogeologic settings. This effect appears to be augmented by the presence of numerous groundwater seeps located on the floodplains and hillslopes adjacent to the channels in both hydrogeologic settings, most especially at the discharge-slope sites. Although the rate of groundwater discharge is lower in the drainage-way than in the discharge-slope sites, the mean groundwater temperature is substantially lower in the drainage-way than in the discharge-slope sites during the summer (Table 1). This difference in groundwater temperature provides an important moderating effect on stream temperatures and helps reduce downstream warming as the water flows through the drainage-way sites. Without this cooler groundwater input, stream temperature increases rapidly in the downstream direction at the drainage-way sites (Figure 7). Previous research has also shown the importance of geomorphology on surface-water and groundwater interactions and the resulting effects on stream temperatures, with geomorphology controlling local-scale hyporheic exchange (Baxter and Hauer, 2000; Burkholder *et al.*, 2008; Lisi *et al.*, 2013) to basin-scale spatial variability (Torgersen *et al.*, 1999; Arscott *et al.*, 2001).

The temperature of shallow groundwater is the volumetric weighted average of the temperature of the recharging water (i.e., rain/snowmelt). The difference in groundwater temperatures between the drainage-way and discharge-slope sites comes from the differences in groundwater flow velocities between the two hydrogeologic settings. Because flow velocities are lower in the drainage-way than the discharge-slope sites, groundwater temperatures adjacent to the streams in the late spring and throughout the summer also are lower in the drainage-way than the discharge-slope sites, having been recharged earlier in the year when air temperatures were lower (Figures 4 and 5). Once in the stream, groundwater quickly begins to equilibrate with ambient atmospheric conditions at both the drainage-way and discharge-slope sites. Continuous groundwater discharge moderates the warming during summer in the downstream direction, while the cessation of groundwater discharge results in a more rapid and substantial warming in the downstream direction (Figure 7). Valley slopes and related stream velocities are lower in the drainage-way than the discharge-slope sites, so the warming effect is greater over equal distances in the drainage-way than the discharge-slope sites in the absence of continuous groundwater discharge (Figure 7).

Local geomorphology can affect stream temperatures in ways other than just controlling differences in lateral inflow temperatures and rates of groundwater discharge. Drainage-way sites are in broad, relatively level valleys and have streamside vegetation dominated by one gramminoid, *C. canadensis*. Conversely, discharge-slope sites are in narrow, relatively steep-sided valleys and have streamside vegetation that also is dominated by *C. canadensis* but the riparian zone also often consists of shrubs and small trees, including alder (*Alnus* spp.) and willow (*Salix* spp.). Therefore, differences in topographic and riparian shading and the associated insolation also play important roles (Rutherford *et al.*, 2004; Whitledge *et al.*, 2006), with less shading and more insolation resulting in greater warming over equal distances in the absence of continuous groundwater discharge in the drainage-way than the discharge-slope sites (Figure 7).

Flow-weighted slope correlates with numerous stream-temperature metrics (Figure 6). The FWS metric correlates reasonably well with annual mean stream temperature and shows a strong correlation with annual daily maximum temperature, and annual maximum seven-day temperature. FWS integrates flow path length, which correlates with contributing area and the amount of accumulated water, and flow path slope, which correlates with hydraulic gradient. Therefore, FWS also may serve as a potential indicator of groundwater discharge into a stream as well as water residence time along shallow lateral flow paths (McGuire *et al.*, 2005; Walker *et al.*, 2012). Higher values of FWS would correspond to stream locations that have the potential to receive higher amounts of groundwater discharge, which can greatly affect stream temperatures (Figure 6).

Headwater streams on the Kenai Peninsula provide critical rearing habitat for numerous salmonids, with recent studies showing that these headwater streams in our study area may support up to ¼ million salmonids and that juvenile salmon are present in numerous headwater stream habitat types and in a wide range of size classes (King *et al.*, 2012). The upper lethal temperature limit for anadromous Pacific salmonids generally ranges from about 23 to 29°C, with a preferred upper temperature limit that ranges from 12 to 14°C (Bjornn and Reiser, 1991). Overall, the results of this study show that neither observed nor modeled stream temperatures approach the upper lethal limits for Pacific salmon in either hydrogeologic setting (Table 3; Figures 4-7). Furthermore, only stream temperatures in the low gradient drainage-way sites approach the preferred upper limit range of 12-14°C (Table 3). In winter, salmonids need habitat that stays above freezing and areas free of ice (Cunjak, 1996). Our results show that during winter stream temperatures in both hydrogeologic settings can fall to freezing (Table 3), indicating the importance of microhabitats suitable for overwintering salmonids.

Recent predictive models have shown some degree of habitat segregation by juvenile salmonids, with presmolt (≥10 cm) coho salmon being more prevalent in the deeper, slower, and warmer streams such as the drainage-way sites and larger (≥8 cm) Dolly Varden char being more prevalent in the shallower, faster, and cooler streams such as the discharge-slope sites (King *et al.*, 2012). However, the degree to which stream temperatures play a role in this segregation remains unknown and is the focus of ongoing research, including research into overwintering habitat use. Understanding the temperature dynamics in these headwater streams will be crucial to the understanding of how salmonids are using these different habitats and to the overall management of headwater stream systems. This is particularly critical in light of climate change, in which the region is expected to become both warmer and drier (Klein *et al.*, 2005) and is forecast to experience an increase in the frequency and severity of insect-related tree mortality and wildfires (Wolken *et al.*, 2011). Such changes would be expected to affect groundwater discharge and groundwater temperature and therefore result in changes in streamflow and stream temperature and the related changes in fish and invertebrate habitat suitability (Coutant, 1976; Beschta *et al.*, 1987; Armour, 1991) and geographic distribution (Ebersole *et al.*, 2001; Mather *et al.*, 2008) as well as ecosystem metabolic processes such as nutrient uptake and rates of organic matter breakdown (Cummins, 1974; Webster and Benfield, 1986). This study provides a deeper understanding of the relationships between salmon dynamics and stream temperatures, but there is much that remains to be learned about the overall ecological structure and function of the Kenai Lowland's rivers and streams to aid in the management and protection of this important resource.

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