

RESEARCH ARTICLE

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Key Points:

- The NorWeST stream temperature database was developed from data contributed by >100 agencies in the western U.S.
- Scenarios created from the database for 343,000 km of streams and rivers indicate a warming trend of 0.17° C/decade occurred during 1976–2015
- The geospatial stream analysis tools developed for the NorWeST project have broad utility for many types of stream data throughout the U.S.

Supporting Information:

- Supporting Information S1

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The NorWeST Summer Stream Temperature Model and Scenarios for the Western U.S.: A Crowd-Sourced Database and New Geospatial Tools Foster a User Community and Predict Broad Climate Warming of Rivers and Streams

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Abstract Thermal regimes are fundamental determinants of aquatic ecosystems, which makes description and prediction of temperatures critical during a period of rapid global change. The advent of inexpensive temperature sensors dramatically increased monitoring in recent decades, and although most monitoring is done by individuals for agency-specific purposes, collectively these efforts constitute a massive distributed sensing array that generates an untapped wealth of data. Using the framework provided by the National Hydrography Dataset, we organized temperature records from dozens of agencies in the western U.S. to create the NorWeST database that hosts >220,000,000 temperature recordings from >22,700 stream and river sites. Spatial-stream-network models were fit to a subset of those data that described mean August water temperatures (AugTw) during 63,641 monitoring site-years to develop accurate temperature models ($r^2 = 0.91$; RMSPE = 1.10°C; MAPE = 0.72°C), assess covariate effects, and make predictions at 1 km intervals to create summer climate scenarios. AugTw averaged 14.2°C (SD = 4.0°C) during the baseline period of 1993–2011 in 343,000 km of western perennial streams but trend reconstructions also indicated warming had occurred at the rate of 0.17°C/decade (SD = 0.067°C/decade) during the 40 year period of 1976–2015. Future scenarios suggest continued warming, although variation will occur within and among river networks due to differences in local climate forcing and stream responsiveness. NorWeST scenarios and data are available online in user-friendly digital formats and are widely used to coordinate monitoring efforts among agencies, for new research, and for conservation planning.

1. Introduction

The importance of temperature in defining aquatic environments is arguably second only to the presence of water. Often referred to as a “master variable,” temperature dictates metabolic rates, physiological processes, and life history events across taxa (Angilletta, 2009; Kingsolver, 2009), constrains the distribution and abundance of ectothermic species that constitute most aquatic communities (Isaak et al., 2017a; Pörtner, 2001), is used to measure habitat impairment (Nusslé et al., 2015; Olden & Naiman, 2010; Rivers-Moore et al., 2013), and serves as the basis for regulatory actions (Todd et al., 2008; U.S. Environmental Protection Agency, 2003). That water temperature varies over time—from day to night, from summer to winter—is obvious, but at landscape to regional extents, temporal covariation among sites is strong, so spatial variation among sites often constitutes the largest proportion of total variation (Hari et al., 2006; Poole et al., 2004). That spatial component, which we refer to as a thermalscape to designate a spatially continuous temperature surface, is inextricably linked to patterns of species’ habitat suitability and conservation strategies based on spatial prioritization of investments (Isaak et al., 2015; Peterson et al., 2013). Thermalscape characterization of river segments has advanced significantly in recent decades through innovations in remote

sensing (Dugdale et al., 2015; Torgersen et al., 2001), but these technologies are best suited to riverine environments where the water surface is exposed to airborne sensors (Fullerton et al., 2015; Handcock et al., 2012). Alternative approaches are needed to characterize thermascapes throughout networks where extents encompass hundreds or thousands of linear kilometers, small streams constitute the bulk of the network, and ungauged basins are common (Bishop et al., 2008; Gallice et al., 2015; Hrachowitz et al., 2013).

Sensor technologies for measuring stream temperatures have proliferated in recent decades (Dugdale, 2016; Ebersole et al., 2003; Quilty & Moore, 2007; Selker et al., 2006; Torgersen et al., 2012; Vaccaro & Maloy, 2006) but the most popular have been inexpensive sensors that record measurements at user-specified intervals and create time series of recordings (Angilletta & Krochmal, 2003; Dunham et al., 2005; Stamp et al., 2014). Inexpensive sensors democratized the collection of temperature data beginning in the early 1990s, which resulted in extensive, albeit largely uncoordinated, monitoring efforts throughout North America and Europe (Daigle et al., 2016; DeWeber & Wagner, 2014; Dunham et al., 2003; Hannah & Garner, 2015; Hilderbrand et al., 2014; Isaak et al., 2010; Isaak & Hubert, 2001; Jackson et al., 2016; Johnson & Wilby, 2015; Mauger et al., 2016; McKenna et al., 2010; Molinero et al., 2016; Moore et al., 2013; Trumbo et al., 2014; Wehrly et al., 2009). Sensors deployed in those efforts sometimes record data only for short periods (e.g., 1–3 months or years) but viewed collectively, constitute a massive distributed monitoring array that provides measurements from thousands of sites. The growth in temperature monitoring is a harbinger of similar trends in monitoring of other water quality constituents (Pellerin et al., 2016; Read et al., 2017), stream discharge (Stamp et al., 2014), and biological sampling using environmental DNA (Goldberg et al., 2015; McKelvey et al., 2016) as new technologies bring the era of big data to aquatic environments (Hampton et al., 2013; Isaak et al., 2017a; Porter et al., 2012).

The rate at which temperature data have been generated has exceeded efforts to organize and curate it in databases, a necessary task for realizing data's current and future potential. Well organized databases, if shared by many agencies and institutions, could also make future data collection efforts more efficient by reducing redundancies and spreading costs among users. Fundamental to organizing stream data sets in the U.S. is the National Hydrography Dataset (NHD), which provides a consistent geospatial framework in which all stream reaches are delineated, assigned unique identifiers within networks, attributed with topological information, and georeferenced in a cartographic projection system (Cooter et al., 2010; Moore & Dewald, 2016). NHD is available in several resolutions but of particular value is the medium-resolution (1:100,000 scale) NHD because of the many reach descriptor variables (e.g., elevation, slope, and watershed area) that have been developed and incorporated to create NHDPlus (McKay et al., 2012; Hill et al., 2016). Once temperature observations are linked to NHD reaches, those descriptors can be used to attribute the observations, serve as covariates in predictive models, visualize results within geographic information systems (GIS), and perform custom queries based on network characteristics.

Many stream data applications are enabled by NHDPlus, but particularly relevant for temperature is the potential to develop network thermascapes that depict historical or future climatic conditions. Those scenarios are rare for lotic environments despite their obvious importance for stream ecology and conservation planning. Because temperature records are collected at discrete sampling locations, however, models are needed to estimate covariate parameters and make predictions at unsampled locations within networks. Many types of models are fit to stream temperature data sets (Benyahya et al., 2007; Webb et al., 2008) including network applications (DeWeber & Wagner, 2014; McKenna et al., 2010; Wehrly et al., 2009) but most are not optimized for broad spatial extents and use with large data sets where spatial autocorrelation is common and may bias parameter estimates (Isaak et al., 2014; Rushworth et al., 2015). Recently developed spatial-stream-network (SSN) models (Peterson & Ver Hoef, 2010; Ver Hoef et al., 2006; Ver Hoef & Peterson, 2010) overcome those limitations by relying on assumptions about the stochastic processes that generate observable data (Schabenberger & Gotway, 2005) and facilitate valid inference from spatially correlated samples (Rushworth et al., 2015; Som et al., 2014). Moreover, SSNs accommodate covariates to describe relationships with response variables and can be implemented with classical geostatistical kriging techniques (Cressie, 1993) to make predictions throughout river networks with spatially explicit uncertainty estimates (Isaak et al., 2017b; Ver Hoef et al., 2006). Like other spatial statistical models (Beale et al., 2010; Temesgen & Ver Hoef, 2015; Ver Hoef, 2002), SSNs also consistently improve predictive performance relative to nonspatial models when applied to correlated data sets (Brennan et al., 2016; Filipe et al., 2017; Isaak et al., 2010; Turschwell et al., 2016).

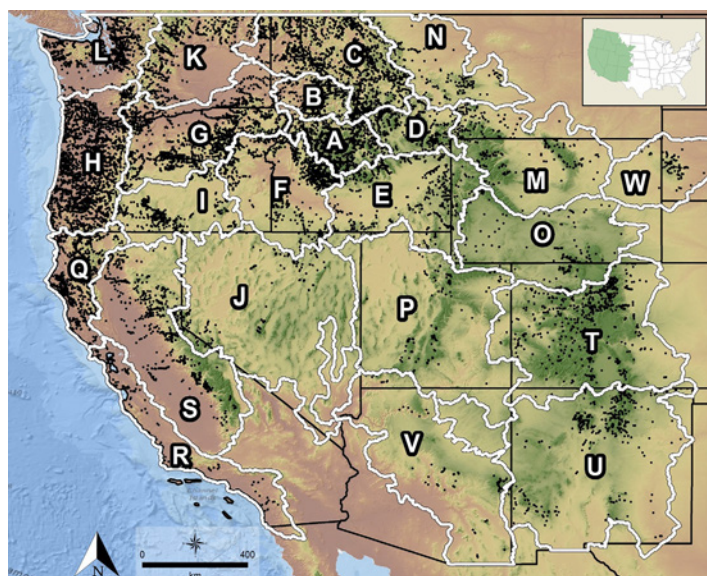


Figure 1. Locations of stream temperature data that were used to develop temperature models and scenarios in the western U.S. Letters and white boundaries denote 23 processing units used to partition the data and fit individual models.

In this paper, we use the NHDPlus framework to organize the comprehensive Northwest Stream Temperature (NorWeST) database that combines existing agency databases with thousands of new records collected by hundreds of professionals from dozens of natural resource agencies across the western U.S. (Figure 1 and supporting information S1). Temperature monitoring within the region has been extensive because of concerns about socioeconomically important cold-water fishes like salmon and trout and other aquatic species that are federally protected under the Endangered Species Act (McClure et al., 2013; Nehlsen et al., 1991). Concerns have grown in recent years as the effects of climate change increasingly manifest through air temperature trends (Barnett et al., 2008; Walsh et al., 2014), seasonal patterns of snow accumulation and stream runoff (Kormos et al., 2016; Luce et al., 2013; Mote et al., 2005; Stewart et al., 2005), and increasing wildfires (Littell et al., 2016; Westerling et al., 2006). We use a subset of the NorWeST database with SSN models and covariates derived from NHD and other national sources to parameterize a series of temperature models for subregions in the western U.S., assess their predictive performance, and then extend predictions to all river and stream reaches to create historical and future summer temperature scenarios. The models are also used to reconstruct historical stream-temperature trends during the 40 year period of 1976–2015 and in attribution analyses to understand the relative importance of covariates for explain-

ing spatial and temporal variation in stream temperatures within and among river networks. Results are discussed with regards to factors affecting thermal heterogeneity in western landscapes, ecological responses to thermal trends, use of NorWeST information for conservation planning, and the broader utility of geospatial analysis tools for many types of stream data.

2. Methods

2.1. Study Site

The western U.S. as circumscribed here encompasses 2,584,000 km², most or all of eleven states from the Pacific Ocean to the Great Plains, and is drained by an extensive network of rivers, streams, and intermittent channels (Benke & Cushing, 2005; Palmer & Vileisis, 2016). The area is topographically complex, with broad basins and multiple mountain ranges, the latter dominated by the Cascade Range and Sierra Nevada near the coast and the Rocky Mountains further inland with peak elevations exceeding 4,400 m. Climate is characterized by seasonally variable temperatures with annual air temperatures that are approximately 10°C warmer at the southern border with Mexico than at the northern Canadian border. Much of the region is arid although coastal areas and higher elevations are relatively mesic. Most precipitation occurs during fall and winter months, except in the southwestern U.S. where summer monsoons are important (Mock, 1996). Precipitation accumulates as snow at high elevations and northern latitudes during cool seasons and melt-water runoff the following spring creates pronounced hydrologic peaks in most streams. The exceptions are lower elevation coastal streams, where peak runoff usually occurs in association with winter rains, and low-elevation southwestern streams where flashy peak flows sometimes occur during monsoons.

Vegetation types are diverse, track local climatic conditions, and include alpine tundra, forests, shrublands, grassland steppe, and deserts. Human populations are large in coastal areas but small throughout most of the interior except for scattered urban centers. Agricultural development occurs primarily in river valleys at the lowest elevations to take advantage of consistent summer water supplies and fertile floodplains. Most mid-elevation to high-elevation lands are publically owned and federally administered by the U.S. Forest Service, U.S. Bureau of Land Management, and National Park Service for a variety of land use, recreational, and conservation purposes. A diverse fauna inhabits western streams and rivers, but cold-water fishes dominate societal interests and conservation investments.

2.2. NorWeST Database

Stream temperature records were downloaded from online agency databases and were solicited from professional biologists and hydrologists employed by state, federal, tribal, private, county, and municipal natural resource groups (supporting information S1). Data sets contributed by individuals consisted of digital records with multiple daily recordings, file formats that became common in the early 1990s with the widespread adoption and use of data logging temperature sensors. Organizing the large amount of data in the western U.S. required geographic and sequential prioritization, so at project initiation in 2011, we divided the area into 23 discrete processing units based on NHD unit boundaries, anticipated data densities, and physiographic similarity (Figure 1). Data within each unit were processed using a standard set of data screening and quality assurance techniques before being summarized into daily minima, maxima, and means that are available from the NorWeST website (www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). Individuals from more than 100 resource groups contributed data to build the NorWeST database, which consisted of >220,000,000 temperature recordings at >22,700 stream and river sites, numbers that continue to increase with periodic database additions. Additional details regarding data processing along with metadata descriptions are provided at the website and in Chandler et al. (2016).

To develop a data set for creating a consistent set of climate scenarios, data were queried from the NorWeST database for all years at sites where August temperatures had been recorded multiple times daily during at least 90% of the month's days and these recordings were averaged to create a mean AugTw metric. We focused on AugTw because the summer is critical for growth and survival of many aquatic species in the western U.S. and this metric is strongly correlated with other commonly used summer temperature metrics (Dunham et al., 2005; Isaak & Hubert, 2001). Data were also available for the largest number of stream sites during the month of August (supporting information S1), which maximized the empirical support for the SSN temperature models and scenarios.

2.3. Stream Network and Model Covariates

Mean AugTw values were linked to reaches in the National Stream Internet (NSI) network (Isaak et al., 2013a; Nagel et al., 2015), which is a derivative of the 1:100,000-scale NHDPlusV2 that has been topologically adjusted to facilitate SSN analysis by applying the Spatial Tools for the Analysis of River Systems (STARS; Peterson & Ver Hoef, 2014) custom ArcGIS toolset (available at the SSN/STARS website: www.fs.fed.us/rm/boise/AWAE/projects/SpatialStreamNetworks.shtml). Adjustments consisted of removing braided stream reaches, which created redundant flow paths for ~3% of the network, shifting the locations of a small proportion of tributary confluences by 50 m to avoid double confluences, and ensuring that network topology was consistent so that hydrologic distances and spatial weights required in SSN analyses could be calculated. Nagel et al. (2015) provide additional details on the technical procedures used to create the NSI network, which has been developed for all streams in the conterminous U.S. and is available for download from the NSI website (www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet.html). Reaches in the NSI are easily matched to their counterparts in NHDPlusV2 so that reach descriptors can be used as covariates in SSN models.

Covariates used in the NorWeST model fits were selected based on a review of the literature, a plausible mechanism that could cause a temperature effect, and whether the covariates could be summarized from nationally available data sets. Table 1 summarizes the rationales for the covariates we chose, supporting studies, and source information for the data sets. The covariates were of two types, spatial and temporal, similar to our previous SSN temperature model for a river network in Idaho (Isaak et al., 2010). Spatial covariates were treated as time-invariant properties of the network, calculated at 1 km intervals, and consisted of elevation (ELE), reach slope (SL), percentage of the upstream watershed area composed of lakes (LK), percentage of the upstream watershed area composed of glaciers (GLA), annual precipitation (AP), northing coordinate (NOR), base-flow index (BFI), cumulative drainage area (DA), and percentage riparian canopy coverage (RC). We did not adjust RC values for wildfires that may alter local canopy conditions and cause stream warming because of the amount of GIS work it requires (Isaak et al., 2010) and because revegetation occurs a few years to decades after fires to ameliorate temperature increases (Dunham et al., 2007; Holsinger et al., 2014; Mahlum et al., 2011). Of greater concern were persistent local temperature anomalies that are created in cold tailwaters (TW) by hypolimnetic water releases from deep reservoirs upstream of dams in some rivers (Dibble et al., 2015). The occurrence and extent of cold TWs was determined by examining temperature records and interviews with local professionals familiar with dam sites. Those reaches

Table 1
Covariates Used in Models to Predict Mean August Temperatures in Rivers and Streams of the Western U.S.

Covariate	Definition and rationale	References	Data source ^a
Elevation (ELE)	Elevation at the AugTw sensor site. Cooler air temperatures and greater snow and precipitation accumulations (cooler ground water inputs) at higher elevations should cool stream temperatures.	Smith and Lavis (1975), Isaak and Hubert (2001), and Sloat et al. (2005)	Digital elevation models (30 m resolution) associated with NHDPlus, downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Slope (SL)	Slope of the stream reach at a sensor site. Steeper slopes should cool stream temperatures by increasing flow velocities and decreasing equilibration with warmer microclimatic conditions at lower elevations.	Sloat et al. (2005), Webb et al. (2008), and Isaak et al. (2010)	NHDPlus Value Added Attribute = SLOPE, downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Lake (LK)	Percentage of watershed upstream of a sensor composed of lake or reservoir surfaces. Lakes absorb heat, slow water transit times through watersheds, and should increase downstream temperatures.	Dripps and Granger (2013) and Maheu et al. (2016)	NHDPlus Value Added Attribute = NLCD11PC, downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Glacier (GLA)	Proportion of watershed upstream of a sensor composed of glacial ice surfaces. Glacial meltwater during the summer should cool streams.	Hari et al. (2006) and Brown et al. (2007)	Data downloaded from Glaciers of the western U.S. website: http://glaciers.research.pdx.edu/Downloads and calculated using flow accumulation script in GIS.
Annual precipitation (AP)	Mean annual precipitation in watershed upstream of sensor site. Wetter landscapes have higher water yields and more groundwater that should cool streams.	Isaak and Hubert (2001)	NHDPlus Value Added Attribute = PrecipV, downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Northing coordinate (NOR)	Albers Equal Area Northing coordinate at the sensor site. Air and groundwater temperatures are cooler further north and should cool streams.	Ward (1985) and Meisner et al. (1988)	Projected coordinates were generated for sensor locations using GIS software.
Base-flow index (BFI)	Base-flow index values at sensor sites calculated as the ratio of base flow to total flow and expressed as a percentage. Sites with larger base flows relative to peak flows have larger groundwater contributions that should cool streams.	Mayer (2012) and Kelleher et al. (2012)	Data developed by Wolock (2003) and downloaded from http://ks.water.usgs.gov/pubs/abstracts/of.03-263.htm
Drainage area (DA)	Drainage area of watershed upstream of sensor that is a surrogate for stream size. Larger streams are isolated over a greater length and are less shaded by riparian vegetation, which should result in warmer temperatures.	Ward (1985), Moore et al. (2005), and Garner et al. (2013)	NHDPlus Value Added Attribute = TotDASqKM, downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Riparian canopy (RC)	Canopy value associated with the 1 km stream reach that encompasses a sensor site. Higher canopy values are associated with more shade and cooler streams.	Moore et al. (2005), Cristea and Burges (2010), Garner et al. (2014), and Nusslé et al. (2015)	Percent canopy derived from the NLCD 2011 USFS Tree Canopy Cartographic layer averaged over 1 km stream reaches. Downloaded from https://www.mrlc.gov/nlcd11_data.php
Air temperature (AT)	Mean August air temperature assigned to AugTw records measured during the same year. Years with warmer air temperatures are associated with warmer stream temperatures.	Webb and Zhang (1997), Mohseni and Stefan (1999), Isaak et al. (2012), and Garner et al. (2013)	Gridded (15 km ² resolution) air temperature data sets from RegCM3 climate model runs for a NCEP historical reanalysis. Data were downloaded from the USGS Regional Climate Downscaling website (http://regclim.coas.oregonstate.edu/index.html ; Hostetler et al., 2011).

Table 1. (continued)

Covariate	Definition and rationale	References	Data source ^a
Discharge (Q)	Mean August stream discharge assigned to AugTw records measured during the same year. Years with higher discharge are associated with cooler stream temperatures.	Hockey et al. (1982), Gu et al. (1998), Isaak et al. (2012), and Elmore et al. (2016)	Discharge records from flow gages without upstream regulation, minimal water abstraction, and the longest records since 1952 were downloaded from NWIS (http://waterdata.usgs.gov/nwis/rt).
Tailwater (TW)	Occurrence of sensor in tailwater downstream from large dam with anomalously cold hypolimnetic water release.	Lehmkuhl (1972), Preece and Jones (2002), and Olden and Naiman (2010)	Examination of temperature records and consultation with local professionals.

^aAdditional details are in metadata documents downloadable from the NorWeST website: <https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>.

were coded “1” in a binary scheme and TW was included as a categorical covariate when SSN models were fit in processing units that contained one or more TWs. In total, 2,352 km of rivers (~0.1% of the full network extent) were coded TW downstream of 58 dams. Cold TW lengths varied depending the size of dams and reservoirs from relatively short 10 km reaches to a long 150 km reach downstream of Lake Powell on the Colorado River. Smaller reservoirs produce minor temperature effects or cause downstream warming similar to natural lakes (Maheu et al., 2016), so they were considered functional equivalents and represented by the LK covariate. Values for each spatial covariate were assigned to all 1 km reaches in the NSI network, and mean AugTw values were referenced to the covariate values within their respective reaches.

Two temporal covariates, mean August air temperature (AT) and stream discharge (Q), were used to represent interannual climate variability that affects AugTw. We focused on an interannual time step because it negates the intraannual mediation of airstream temperature relationships that are caused by changing solar angles (Isaak et al., 2012; Luce et al., 2014) and yields AT and Q parameters useful for creating scenarios of historical and future conditions. For each temporal covariate, processing-unit average values were developed to represent time series of mean August conditions from 1976 through 2015, and these values were assigned to the AugTw samples recorded in the same year. August AT data were obtained from 15 km gridded data sets that were generated for a NCEP RegCM3 reanalysis and were downloaded from the U.S. Geological Survey Regional Climate Downscaling website (<http://regclim.coas.oregonstate.edu/index.html>; Hostetler et al., 2011). August Q data from flow gages in each processing unit were downloaded from the National Water Information System website (<http://waterdata.usgs.gov/nwis/rt>) and screened to extract the longest station records where upstream water abstraction was minimal and storage reservoirs did not occur. August Q from 3 to 17 gages that met those criteria within each processing unit were averaged to create the Q time series (station numbers are listed in S2 and Table S2).

2.4. NorWeST SSN Model

After covariates and AugTw data sets were prepared, the topological, spatial, and attribute information needed to fit SSN models were generated for the data sets using the STARS toolset (Peterson & Ver Hoef, 2014). That information was imported into R (R Development Core Team, 2014) and the SSN package (Ver Hoef et al., 2014; Version 1.1.7) was used to fit the temperature models (processed data sets and R scripts to replicate all analyses are available at the NorWeST website). A SSN model was fit to each processing-unit data set that included all covariates regardless of their final statistical significance (although GLA and TW were not included when absent from a unit). Retention of all covariates was a luxury afforded by our large sample sizes, but it also enabled consistent comparisons among the 23 processing units. The computation time required to fit SSN models (up to 7 days on a 16-core workstation for the largest data sets) also made minimizing the number of model fits a practical necessity. The SSN model was a linear mixed model of the form,

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{L}\boldsymbol{\gamma} + \mathbf{R}\boldsymbol{\eta} + \mathbf{z}_{\text{TU}} + \mathbf{z}_{\text{TD}} + \mathbf{z}_{\text{EUC}} + \boldsymbol{\epsilon}, \quad (1)$$

where \mathbf{y} is a vector of AugTw, \mathbf{X} is a design matrix of covariate values, $\boldsymbol{\beta}$ is a vector of regression coefficients, \mathbf{L} is a random-effects design matrix for location, $\boldsymbol{\gamma}$ is a vector of zero-mean, normally distributed random effects for location, \mathbf{R} is a random-effects design matrix for year, $\boldsymbol{\eta}$ is a vector of zero-mean, normally

distributed random effects for year, and ε is a vector of independent and normally distributed random errors. The model specification included random effects for year and location to account for repeat measurements at sites across years or at many sites within years. Spatial structure in residual errors was modeled using vectors of zero-mean random effects (\mathbf{z}_{TU} , \mathbf{z}_{TD} , and \mathbf{z}_{EUC}) with an autocorrelation structure based on exponential Euclidean (EUC) and exponential tail-down (TD) covariance functions, as well as an exponential tail-up (TU) function with a spatial weighting scheme based on watershed area (Peterson & Ver Hoef, 2010; Ver Hoef & Peterson, 2010). We included a mixture of spatial-autocorrelation functions (TU, TD, and EUC) because each class represents spatial relationships in a different way (e.g., patterns created by passive downstream drift or upstream and downstream movement processes) and previous research suggests that mixed spatial-autocorrelation constructions perform better than single autocorrelation functions to characterize spatial patterns in stream networks (Frieden et al., 2014; Isaak et al., 2017b).

The covariance matrix for $\mathbf{y} \sim N(\mathbf{X}\boldsymbol{\beta}, \Sigma)$ in (1) was

$$\Sigma = \sigma_{\gamma}^2 \mathbf{L}\mathbf{L}' + \sigma_{\eta}^2 \mathbf{R}\mathbf{R}' + \sigma_{TU}^2 \mathbf{C}_{TU} + \sigma_{TD}^2 \mathbf{C}_{TD} + \sigma_{EUC}^2 \mathbf{C}_{EUC} + \sigma_{\varepsilon}^2 \mathbf{I}, \quad (2)$$

where σ_{γ}^2 , σ_{η}^2 , σ_{TU}^2 , σ_{TD}^2 , σ_{EUC}^2 , and σ_{ε}^2 were variances for γ , η , \mathbf{z}_{TU} , \mathbf{z}_{TD} , \mathbf{z}_{EUC} , and ε , respectively, and \mathbf{C}_{TU} , \mathbf{C}_{TD} , and \mathbf{C}_{EUC} were autocorrelation matrices for \mathbf{z}_{TU} , \mathbf{z}_{TD} , and \mathbf{z}_{EUC} , respectively, where each \mathbf{C} -matrix has an additional parameter that controls the spatial range of autocorrelation for that model. For an in-depth discussion of stream covariance functions, readers may wish to consult previous work (Frieden et al., 2014; Peterson & Ver Hoef, 2010; Ver Hoef & Peterson, 2010).

Prior to fitting each SSN model, potential issues with multicollinearity were assessed by calculating variance inflation factors (VIF; Helsel & Hirsch, 1992) using the covariates in a nonspatial multiple linear regression model. Except in rare cases, VIFs were low (i.e., <5) and not at levels problematic to parameter estimation or interpretation. After SSN models were fit, the relative importance of covariates within and among processing units was determined based on the magnitude of raw and standardized parameter estimates and their statistical significance. Predictive performance of the SSN models was described in three ways. First, we calculated the mean absolute prediction error (MAPE) between the observed and leave-one-out cross-validation (LOOCV) predicted AugTw values. Second, we computed a predictive r^2 based on the squared correlation of observations and the LOOCV predictions. Third, we computed the root mean square prediction error as

$$\text{RMSPE} = \sqrt{\frac{\sum_{i=1}^n [\hat{y}(s_i) - y(s_i)]^2}{n}}, \quad (3)$$

where $y(s_i)$ is an observation at a unique location and time, $\hat{y}(s_i)$ is the LOOCV prediction value for s_i , and n is the total number of observed data values.

2.5 Historical Trend Description

Increasing air temperatures and decreasing summer flows associated with climate change are well documented across the western U.S. (Clow, 2010; Luce & Holden, 2009; Mote et al., 2005; Stewart et al., 2005) and these trends are expected to warm streams by increasing long-wave radiation and warming groundwater inputs (Kurylyk et al., 2015a; Webb et al., 2008). Previous stream-temperature trend estimates, however, are available only from a small number of sites with long-term monitoring records that sometimes provide inconsistent results due to variable record lengths (Arismendi et al., 2012; Isaak et al., 2012). To estimate historical trends consistently, we multiplied the AT and Q parameters from each SSN model fit by the amount of change observed in mean AT and Q for 1976–2015 and then summed the stream temperature changes as in previous work (Isaak et al., 2010, 2012). This approach obscured site-level variation in warming rates but yielded accurate estimates at the processing-unit scale while also providing a description of the relative contributions of long-term trends in AT and Q to stream temperature changes. Trend reconstructions were possible for any recent historical period, but 1976–2015 was a useful focus because the start date largely coincides with the globally coherent warming signal that emerged in recent decades (Foster & Rahmstorf, 2011; Intergovernmental Panel on Climate Change [IPCC], 2013). It was also long enough to temper the effects of short-term climate cycles like the El-Niño Southern Oscillation and Pacific Decadal Oscillation that are important in the western U.S. (Easterling & Wehner, 2009; Mote et al., 2003).

2.6. Stream Temperature Scenarios

The SSN model fits and universal kriging (Cressie, 1993) were used to predict stream temperatures at 1 km intervals and create scenarios for the networks within processing units. The kriging equations have two parts, predictions based on the linear regression model and adjustments based on local spatial autocorrelation,

$$\hat{\mathbf{y}}(s_0) = \mathbf{x}(s_0)' \hat{\boldsymbol{\beta}} + \mathbf{c}(s_0)' \boldsymbol{\Sigma}^{-1} (\mathbf{y} - \mathbf{X} \hat{\boldsymbol{\beta}}), \quad (4)$$

where $\mathbf{x}(s_0)$ is a vector containing the covariate values at prediction location s_0 and the vector $\hat{\boldsymbol{\beta}}$ contains the estimated regression coefficients, so that $\mathbf{x}(s_0)' \hat{\boldsymbol{\beta}}$ forms the linear regression prediction. The remaining portion of equation (4) is an adjustment for spatial autocorrelation, where $\mathbf{c}(s_0)$ is a vector of covariances between observed data and the prediction site, and $\boldsymbol{\Sigma}$ is the covariance matrix among observed data (equation (2)). Prediction variances (Ver Hoef, 2008) are given by

$$\text{var}[\hat{\mathbf{y}}(s_0)] = \sigma_0^2 - \mathbf{c}(s_0)' \boldsymbol{\Sigma}^{-1} \mathbf{c}(s_0) + \mathbf{d}' (\mathbf{X}' \boldsymbol{\Sigma}^{-1} \mathbf{X})^{-1} \mathbf{d}, \quad (5)$$

where $\sigma_0^2 = \text{var}[\mathbf{y}(s_0)]$ (including all of the variance components) and $\mathbf{d} = \mathbf{x}(s_0) - \mathbf{X}' \boldsymbol{\Sigma}^{-1} \mathbf{X} \mathbf{c}(s_0)$.

Thirty-six scenarios were created for each processing unit (supporting information S2 and supporting information Table S2). Two baseline scenarios representing composite periods when most of the temperature data were collected (Scenario 1: 1993–2011 and Scenario 2: 2002–2011) were developed based on the average AT and Q values for these periods. Additional historical scenarios were created for each year from 1993 through 2015 (Scenarios 3–21 and 33–36) based on the AT and Q values observed in individual years. Scenario 22 provides local prediction variances from equation (5) at 1 km intervals (e.g., Figure S3 in supporting information S2), which are useful for mapping spatial uncertainty and could be used to direct subsequent temperature monitoring efforts. Ten future scenarios (Scenarios 23–32) were developed by adding stream temperature deltas to the Scenario 1 baseline. Stream delta values were of three types: (1) simple integer values (+1.0, +2.0, and +3.0°C); (2) values obtained by multiplying global climate model (GCM) projected changes in August AT and Q (described below) by the parameters for these covariates in the SSN models, and (3) values based on the integers and GCM projections in 1 and 2, but which were also adjusted to account for differential sensitivity among streams within processing units (i.e., some streams warming more than others in response to the same climate forcing). Differences in stream sensitivity were incorporated into five of the future scenarios (Scenarios 24, 26, 28, 30, and 32) by adjusting projected AugTw increases based on unit-specific sensitivity parameters estimated from observed patterns of interannual variation (calculations and parameters are in supporting information S3). Those patterns usually showed that the coldest streams were less responsive to interannual climate variation than warmer streams as has previously been documented in the western U.S. (Luce et al., 2014; Isaak et al., 2016a) and other mountainous regions (Hari et al., 2006; Lisi et al., 2015). As a result, future scenarios with sensitivity adjustments project that temperature increases in cold streams will be smaller than in warm streams.

The GCM projections of AT changes were the mean values from a ten-climate model ensemble (Hamlet et al., 2013) that was used to simulate the A1B emissions scenario for the 2040s (2030–2059) and 2080s (2070–2099; Intergovernmental Panel on Climate Change, 2007). The same GCM ensemble and A1B scenario were used with the Variable Infiltration Capacity (VIC) hydrologic model to obtain projections of August Q changes at the gaging stations used to develop historical time series for each processing unit (supporting information S2 and supporting information Table S4). The VIC Q deltas were obtained from the Climate Impacts Group Hydrologic Climate Change website (<http://warm.atmos.washington.edu/2860/>) for the gages in Idaho, Oregon, and Washington processing units or were derived using similar techniques for gages in other western states based on the flow routing and accumulation procedures described in Wenger et al. (2010). Although the A1B emissions scenario was originally run for the third phase of the Coupled Model Intercomparison Project (CMIP3) and has been superseded by Representative Concentration Pathways (RCP) in CMIP5, there is a strong similarity between A1B and RCP 6.0 (Wright et al., 2015).

The 36 stream temperature scenarios were developed for the full extent of the NHDPlusV2 network within the 23 processing units that included 1,632,000 km of streams in the western U.S. Scenarios are downloadable as ArcGIS shapefiles (Environmental Systems Research Institute, 2015) from the NorWeST website and Isaak et al. (2016b) provide additional technical details. The full NHDPlus network, however, contains many reaches that are

Table 2

Descriptive Statistics for Covariates Associated With Mean August Stream Temperature Observations in the Data Set Used to Develop Temperature Models and Scenarios for Rivers and Streams in the Western U.S.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	22,751	964	891	723	0	3,576
SL (m/m)	22,751	0.0330	0.0197	0.0393	0	0.485
LK (%)	22,751	0.303	0	1.08	0	50
GLA (km ² /km ²)	22,751	0.000314	0	0.00624	0	0.5
AP (mm)	22,751	990	859	643	21.8	5,710
NOR (m)	22,751	1,566,658	1,622,016	329,347	177,326	2,329,746
BFI (%)	22,751	61.2	65.0	13.3	1	89
DA (km ²)	22,751	3,008	51.0	27,902	0	620,000
RC (%)	22,751	45.6	48.0	29.2	0	97.3
AT (°C)	13–23 ^a	17.1	16.9	2.27	10.9	26.1
Q (m ³ /s)	13–23	8.25	3.50	9.58	0.0354	58.0
AugTw (°C)	63,641	14.5	14.2	3.74	3.69	38.4

Note. Refer to Table 1 for definitions of variable acronyms. Summaries for individual processing units are in supporting information S4.

^aNumber of years varies from 13 to 23 in association with the availability of stream temperature data in the processing units.

unlikely to support aquatic species due to either topographic steepness or flow intermittency that is common in portions of the arid western U.S. Therefore, we filtered the network to represent perennial stream habitats by deleting reaches with slope >15%, with VIC summer flows <0.028 m³/s, and those coded as intermittent (Fcode = 46003) to 343,000 km of streams and rivers that served as the basis of our result summaries.

3. Results

3.1. Temperature Data Set

The database query to extract AugTw records for modeling and scenario development yielded 63,641 years of data from 22,751 sites. Monitoring densities were highest in mesic areas like the Pacific Northwest and Rocky Mountains and lower in drier portions of the region like the Great Basin and Southwest (Figure 1). Descriptive statistics for AugTw and the covariate values at those sites are provided in Table 2 (summaries for individual processing units are in supporting information S4). Spatial variation in the data set was large with temperature monitoring sites spanning more than 2,000 km from north to south, occurring at elevations from 0 to 3,580 m, and in streams that drained headwater basins as small as 0.1 km² to the Columbia River with a basin size of 620,000 km² and mean annual discharge of 7,500 m³/s. Interannual variation in AT and Q during the 13–23 years with AugTw measurements in the processing units was also large, with the

Table 3

Correlations Among Covariates and Mean August Stream Temperature Observations in the Data Set Used to Develop Temperature Models and Scenarios for Rivers and Streams in the Western U.S.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.19	1									
LK	−0.03	−0.11	1								
GLA	−0.02	0.02	0.00	1							
AP	−0.42	0.13	−0.07	0.08	1						
NOR	−0.17	0.03	−0.04	0.05	0.19	1					
BFI	0.55	0.12	0.04	0.02	−0.39	0.40	1				
DA	−0.09	−0.08	0.06	0.00	−0.05	0.02	−0.02	1			
RC	−0.16	0.29	−0.11	0.02	0.46	0.16	−0.10	−0.15	1		
AT	0.01	−0.04	0.06	−0.02	−0.18	−0.64	−0.29	0.02	−0.14	1	
Q	0.22	0.12	−0.04	0.00	−0.08	0.38	0.37	−0.04	0.02	−0.58	1
AugTw	−0.45	−0.38	0.15	−0.06	−0.12	−0.29	−0.44	0.18	−0.37	0.32	−0.32

Note. Summaries for individual processing units are in supporting information S4.

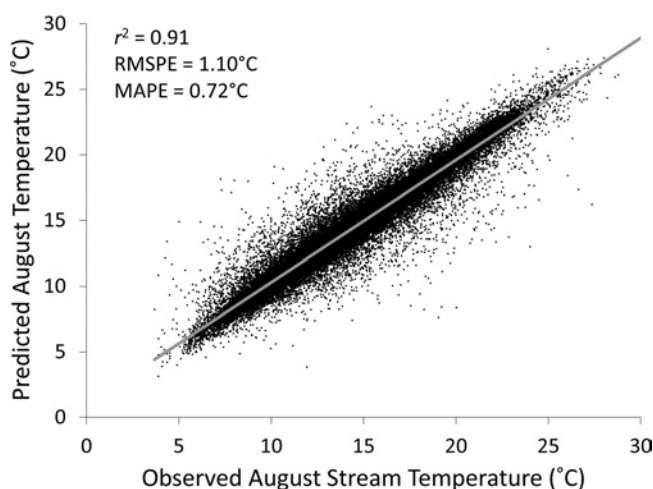


Figure 2. Comparison of 63,641 mean August stream temperature observations and leave-one-out cross-validation predictions from temperature models in the 23 processing units.

range of AT variation spanning 3–6°C and Q varying by threefold to tenfold (supporting information S2 and supporting information Table S1). Observed AugTw values averaged 14.5°C across all site-years of data and ranged from 3.7 to 38.4°C although temperatures <7°C or >21°C were infrequent (Table 2). Correlations among the covariates and AugTw are summarized in Table 3. AugTw was most strongly correlated with ELE (−0.45) followed by BFI (−0.44), SL (−0.38), and RC (−0.37; summaries for individual processing units are in supporting information S4).

3.2. Model Estimates and Historical Trends

The SSN models accurately predicted AugTw within the 23 processing units and had an average predictive r^2 of 0.91, RMSPE of 1.10°C, and MAPE of 0.72°C (Figure 2 and Table 4). The AugTw sample sizes used in the model fits ranged from 143 to 9,521 and model performance was good regardless of sample size. However, there were significant negative relationships between sample size and RMSPE ($r = -0.58$; $p < 0.01$) and MAPE ($r = -0.68$; $p < 0.01$) because predictions in units

with higher sample densities could more often leverage information from neighboring samples through the spatial-autocorrelation function. Covariate relationships with AugTw met a priori expectations described in Table 1. Cooling effects were associated with ELE, SL, GLA, AP, NOR,

Table 4

Summary of Temperature Model Performance and Covariate Relationships With Mean August Stream Temperature for 23 Processing Units in the Western U.S.

NorWeST unit	AugTw <i>n</i>	<i>r</i> ^{2a}	RMSPE ^b	MAPE ^c	Covariates											
					ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q	TW
A. Salmon	4,007	0.89	0.86	0.55	−, 1	−, 5	+, 2	na ^d	−, 4			+, 6	−, 8	+, 3	−, 7	na
B. Clearwater	4,487	0.91	0.96	0.60	−, 1	−, 5	+, 9	na	−, 7	−, 4	−, 6	+, 2	−, 8	+, 3		−
C. SpoKoot	5,482	0.90	0.97	0.62	−, 1	−, 8	+, 2	na	−, 7	−, 3		+, 4	−, 5	+, 6	−, 9	−
D. MissHW	1,145	0.91	1.17	0.75	−, 1	−, 8	+, 2	na	−, 3		−, 5	+, 4	−, 6	+, 7	−, 9	na
E. SnakeBear	1,173	0.86	1.46	0.92	−, 1	−, 2		na					−, 5	+, 3	−, 4	−
F. Mid-Snake	3,384	0.92	1.06	0.62	−, 1	−, 7	+, 3	na	−, 9	−, 2	−, 4		−, 5	+, 6	−, 8	−
G. Mid-Col	9,521	0.94	0.91	0.60	−, 1	−, 8	+, 2	na	−, 3		−, 4	+, 7	−, 5	+, 6		−
H. OR Coast	9,128	0.90	0.92	0.57	−, 1	−, 7	+, 8	−, 9	−, 4	−, 2		+, 6	−, 3	+, 5		−
I. OR South	1,676	0.93	0.95	0.63	−, 1	−, 6		na	−, 3	−, 4	−, 2	+, 5	−, 8	+, 7	−, 9	na
J. Lahontan	576	0.86	1.24	0.88	−, 1	−, 3	+, 8	na	−, 6	−, 5	−, 9	+, 4	−, 2	+, 10	−, 7	na
K. WA East	2,609	0.91	0.97	0.64	−, 1	−, 6	+, 2		−, 4		−, 5		−, 7	+, 8	−, 3	na
L. WA West	3,668	0.88	0.86	0.55	−, 1		+, 2	−, 5					−, 4	+, 3		na
M. Yellowst	513	0.89	1.34	0.91	−, 1	−, 7		na	−, 5		−, 2		−, 4	+, 3	−, 6	na
N. Miss-Marias	300	0.87	1.34	0.89	−, 1		+, 3	na				+, 4	−, 2	+, 5	−, 6	na
O. Wyoming	464	0.92	1.10	0.73	−, 1	−, 2		na		−, 3			−, 4	+, 5		−
P. Utah	248	0.95	1.07	0.74	−, 1			na			−, 2			+, 3		na
Q. CA North	8,118	0.91	0.96	0.60	−, 1	−, 4		na				+, 3	−, 2		−, 5	−
R. CA coastal	447	0.89	1.26	0.87		−, 2		na		−, 1						−
S. CA central	2,865	0.90	1.41	0.92	−, 1	−, 6		na	−, 3			−, 4	−, 2	+, 7	−, 5	−
T. Colorado	2,681	0.95	1.05	0.68	−, 1	−, 8	+, 7	na	−, 2		−, 3	+, 5	−, 4	+, 6	−, 9	−
U. New Mex	755	0.94	1.03	0.75	−, 1	−, 2		na	−, 4		−, 3			+, 5		na
V. Arizona	251	0.93	1.06	0.74	−, 1	−, 3		na			−, 2					na
W. Black Hills	143	0.94	1.41	0.87	−, 1			na						+, 2		−
Tot or ave =	63,641	0.91	1.10	0.72	22/23	19/23	12/23	2/3	14/23	8/23	12/23	12/23	18/23	20/23	13/23	12/12

Note. Significant positive covariate relationships ($\alpha \leq 0.05$) are indicated with +’s, significant negative relationships with −’s, and blank cells indicate nonsignificant relationships. Numbers adjacent to significant relationships indicate the rank importance of the covariate within the model for a processing unit based on standardized parameter estimates (supporting information S4 contains detailed results for each unit).

^aSquared correlation between AugTw observations and leave-one-out cross-validation (LOOCV) predictions.

^bRoot-mean-square prediction error (°C).

^cMean absolute error between AugTw observations and the LOOCV predictions.

^dNot applicable if a covariate did not occur in a processing unit.

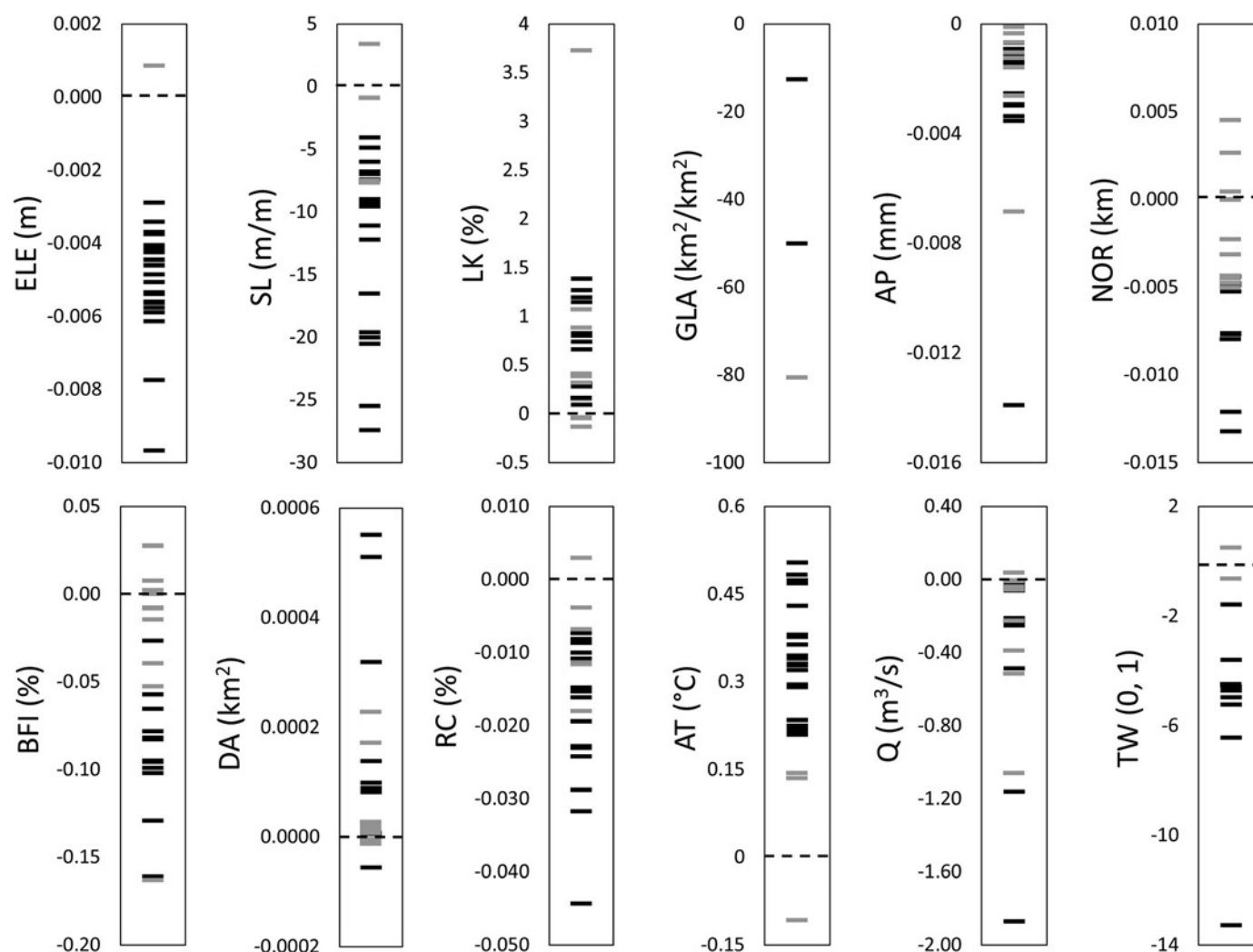


Figure 3. Covariate parameter estimates in original units for temperature model fits to 23 processing units. Black symbols indicate estimates that were statistically significant ($\alpha < 0.05$) in their respective units whereas grey symbols were not significant. Dashed lines indicate the location of zero values. Supporting information S4 provides additional details for individual processing units.

BFI, RC, Q, and TW, and warming effects were associated with LK, DA, and AT (Table 4). Of the 245 covariate significance tests in the SSN model fits, 164 were statistically significant ($\alpha < 0.05$) and only one was counterintuitive (cooling effect of DA in central California unit S; Table 4). ELE was the dominant factor in 22 of 23 models, lacking significance in the coastal California unit where only SL and NOR covariates had significant effects. The covariates SL, RC, and AT also had significant effects in most processing units although their relative importance varied among units as did the size of raw parameter estimates. For example, significant SL (m/m) parameters ranged from -4.03 to -27.4 , RC (%) parameters ranged from -0.0073 to -0.0443 , AT ($^{\circ}\text{C}$) parameters ranged from 0.21 to 0.50 , and ELE (m) parameters ranged from -0.00289 to -0.00967 (Figure 3; additional details regarding model fits for each processing unit are in supporting information S4).

August AT warming trends (average = $0.43^{\circ}\text{C}/\text{decade}$) and Q declines (average = $-6.1\%/ \text{decade}$) were common to most of the processing units during 1976–2015 (Figure 4 and supporting information S2 and supporting information Table S1). The product of those trends and the SSN parameter estimates for AT and Q yielded the estimated AugTw trends for that same period as summarized in Figure 5. Variation occurred among the units, but 22 of 23 showed warming trends and the average trend across all units was $0.17^{\circ}\text{C}/\text{decade}$ ($\text{SD} = 0.067^{\circ}\text{C}/\text{decade}$). Notably, the four coastal units (H, L, Q, and R; Figure 1) showed smaller rates

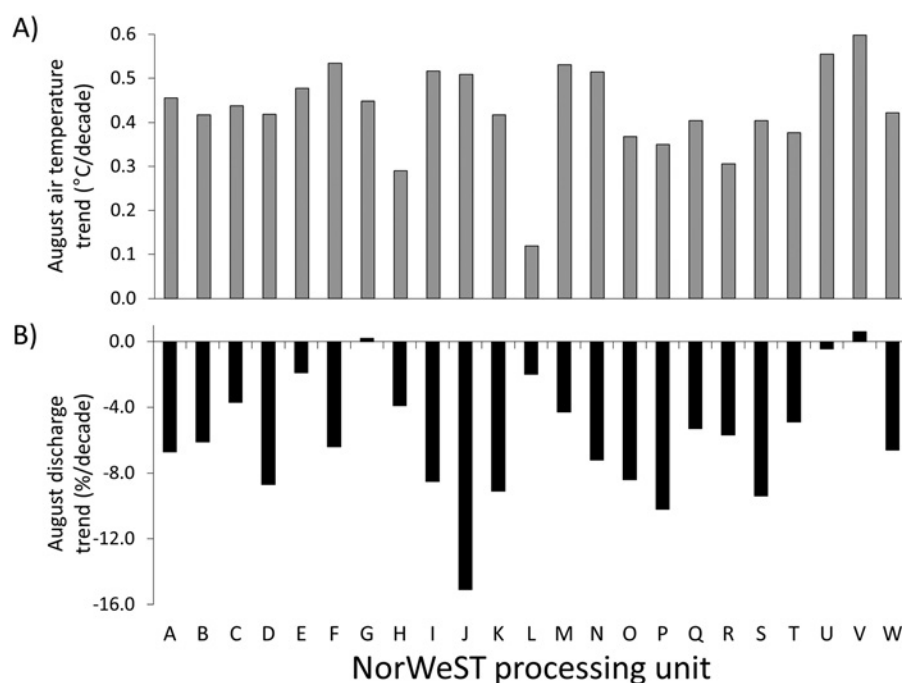


Figure 4. Trends in mean August (a) air temperatures and (b) stream discharge for 1976–2015 in the 23 processing units. Letters correspond to processing units as defined in Figure 1 and Table 5.

of warming (average = $0.07^{\circ}\text{C}/\text{decade}$) due to either weak AT and Q trends (units H and L) or small AT and Q parameters (units Q and R). Most of the AugTw trend for 1976–2015 (83%) was attributable to AT trends although Q declines played important roles in some units (Figure 5b).

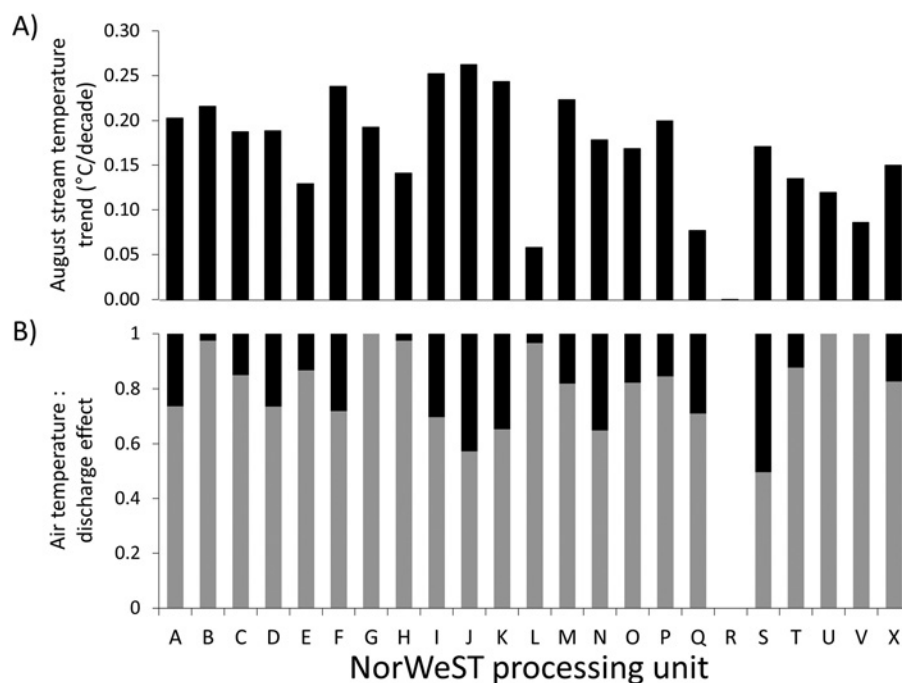


Figure 5. Reconstructed historical trends in mean August (a) stream temperatures for 1976–2015 and the proportional contributions of trends in (b) air temperature (grey bars) and stream discharge (black bars) during the same period. Letters correspond to processing units as defined in Figure 1 and Table 5.

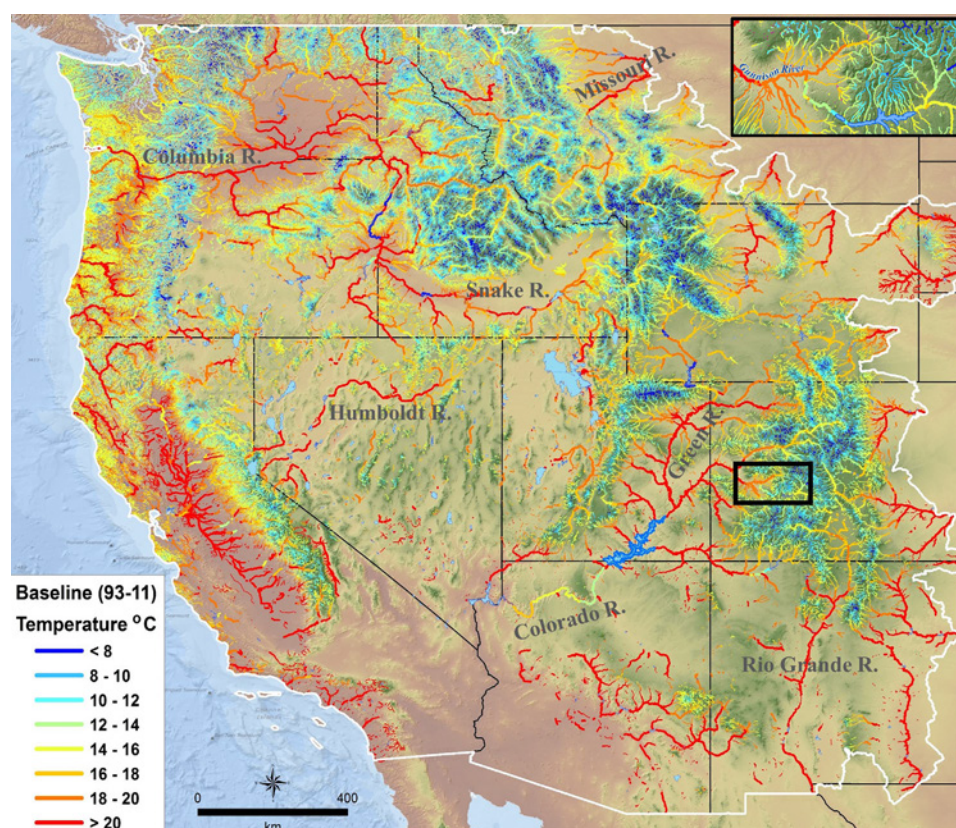


Figure 6. Mean August stream temperature thermalscape for Scenario 1 baseline period of 1993–2011 mapped to the 343,000 km of perennial streams in the western U.S. Map inset shows details within the black box.

3.3. Stream Temperature Scenarios

AugTw in the Scenario 1 baseline period of 1993–2011 averaged 14.2°C (SD = 4.0°C) and this thermalscape is shown in Figure 6 for the 343,000 km perennial stream network (detailed maps for each processing unit are provided in supporting information S4). Significant heterogeneity is apparent across the region with the coldest streams and rivers occurring in mountainous environments and warmer streams flowing through intermountain basins, deserts, and grassland steppes. Also apparent are the large differences in densities of perennial streams between mesic areas and drier subregions. Under the A1B emissions scenario, AugTw was predicted to increase an average of 0.73 and 1.42°C by 2040 and 2080, respectively, relative to the Scenario 1 baseline (Figure 7). As with the historical trends, substantial variation in warming is predicted among

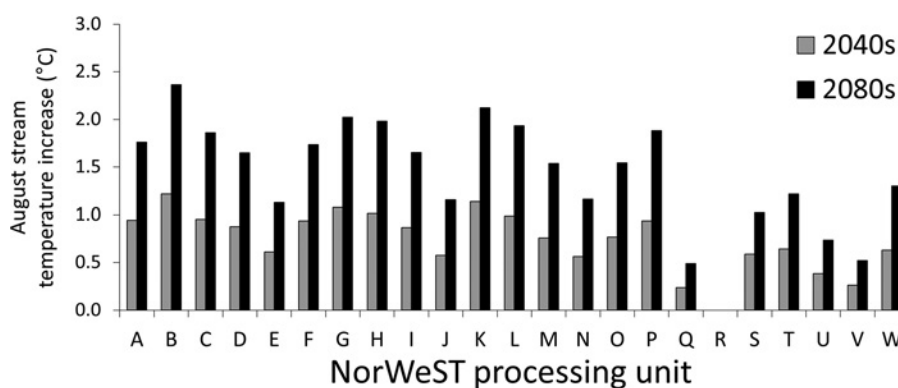


Figure 7. Mean August stream temperature increases predicted for the A1B emissions trajectory by the 2040s and 2080s relative to the Scenario 1 baseline period of 1993–2011.

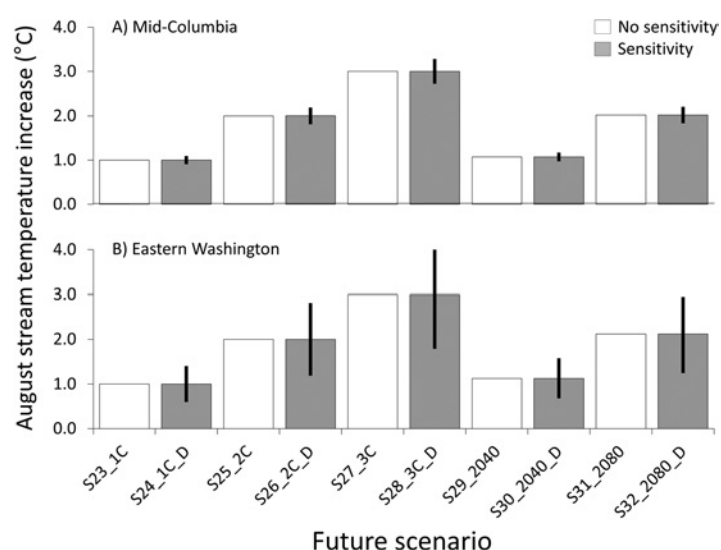


Figure 8. Mean August stream temperature increases relative to the Scenario 1 baseline period of 1993–2011 for two processing units with and without sensitivity adjustments. (a) Scenarios for a processing unit with a small sensitivity parameter, compared to (b) a unit with a large sensitivity parameter. Error bars associated with the sensitivity scenarios are ± 2 standard deviations.

the units although the magnitude of future changes often mimic historical trends (i.e., smaller future changes are predicted where historical trends are small).

The full set of 10 future scenarios, including those based on +1.0, +2.0, and +3.0°C deltas, are summarized for two processing units in Figure 8. In that example, the +1.0 and +2.0°C scenarios are nearly identical to the 2040 and 2080 scenarios but the +3.0°C scenario exceeds the others and generally provides a more aggressive alternative scenario for all the processing units. Figure 8 also highlights differences between scenarios with and without the differential sensitivity adjustment, the latter scenarios denoted by standard deviation error bars that describe variation among predicted changes in the population of 1 km reaches within a processing unit. Also noteworthy is that in scenarios with the sensitivity adjustment, the unit-averaged delta is the same as that of the paired scenario without the adjustment. The practical implications of the sensitivity adjustment are shown in Figure 9, which maps future stream deltas for a small set of streams in the Eastern Washington unit. Temperature increases are a uniform 2°C without the adjustment in Scenario 25 (Figure 9b) but range from 1.6 to 2.6°C with the adjustment in Scenario 26 because cold streams at higher elevations warm less than those at lower elevations (Figure 9c).

4. Discussion

4.1. Stream-Temperature Trends and Projections

Combining a stream temperature database of unprecedented size with new geospatial analysis tools proved useful for describing the thermal heterogeneity of streams and rivers throughout the western U.S. Both observed and predicted AugTw values spanned an order of magnitude, with large differences sometimes occurring in portions of networks that were separated by short geographic distances due to the region's topographic diversity and strong environmental gradients from mountain headwaters to lowland rivers. For that reason, the spatial covariates representing those gradients (ELE, SL, DA, and RC) dominated our temperature models. Other spatial covariates representing more localized effects (LK, GLA, and BFI) were important where specific geologies enhanced groundwater contributions or in landscapes that were glaciated and contain many lakes. Given the amount of variation associated with spatial covariates, the comparatively small effects of temporal covariates, AT and Q, were not unexpected. Combined with multi-decadal trends in AT and Q, however, those effects are noteworthy because they indicate a broad warming trend in rivers and streams during recent decades. To the extent that AT and Q trends are now attributed to anthropogenic climate change (Barnett et al., 2008; National Climate Assessment, 2014), the same attribution appears warranted for warming of the region's lotic environments. Moreover, because historical stream-temperature trends were more strongly associated with trends in AT than Q, the likelihood of continued warming this century is high because nearly all GCMs predict future AT increases (IPCC, 2013). Greater uncertainty exists regarding future precipitation and Q trends but there is a general expectation for lower summer flows as regional snowpacks continue to decline (Barnett et al., 2005; Gergel et al., 2017; Kormos et al., 2016), which may exacerbate stream-temperature trends in many places.

Warming rates will vary within and among streams due to differences in climate forcing and stream responsiveness. At a subregional scale, a distinction appears to exist between interior and coastal areas with the latter showing small or nonexistent warming trends. That pattern could result from a combination of AT trend moderation by the ocean (Jain et al., 1999) and fog persisting in or near ocean areas despite warming (e.g., Dettinger, 2013; Luce et al., 2014). Interior streams may warm more rapidly, but still relatively slowly because their average trend rates are usually less than half that of AT trends. The low responsiveness of streams in the Rocky Mountain region has been noted previously (Mohseni et al., 1999) and broadly attributed to cold mountain environments, winter snow accumulations, and large groundwater reservoirs that

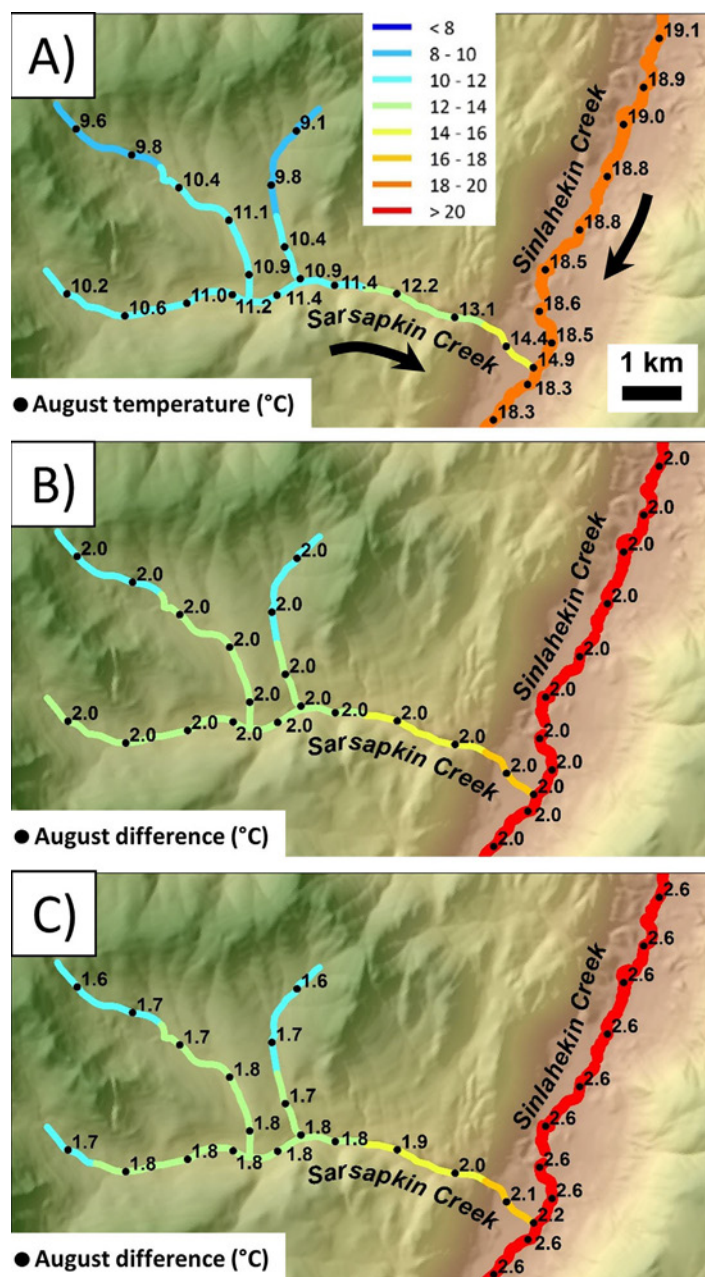


Figure 9. Mean August (a) stream temperatures for the Scenario 1 baseline and future deltas based on (b) Scenario 25 (+2°C) with no sensitivity adjustment and (c) Scenario 26 with a sensitivity adjustment. Note that in Scenario 26, the temperature deltas in the warmest reaches in the low-elevation streams are larger than those in the coldest reaches at higher elevations. In all figures, the line segments are color coded by the August stream temperatures associated with the scenario predictions and the color categories shown in the legend.

provide abundant cold-water influxes during the summer (Luce et al., 2014; Mayer, 2012; Tague et al., 2007). Those buffering sources are unlikely to disappear entirely from the many high-elevation mountain ranges scattered throughout the region and should continue to moderate stream temperature increases for the foreseeable future.

Concerns have been expressed about the stability of statistical models in a changing climate, and consequently, whether model predictions of future conditions are useful for planning (Arismendi et al., 2014; Li et al., 2012; Peel & Blöschl, 2011). However, we think it unlikely that NorWeST projections will be significantly compromised by instability for two primary reasons. First, the representation of the Tw-AT relationship in the NorWeST model has a sounder physical basis for making projections than many previous statistical models. In this regard, the time step of the regression model is important and an interannual basis is preferred over an intraannual basis because AT effects in the latter are confounded with changing sun angles and the amount of daily solar radiation (Luce et al., 2014). Models based on interannual changes, as NorWeST uses, are not similarly confounded and better represent the effect of AT, which is an important determinant of the downwelling long-wave radiation balance that is changing with climate change (IPCC, 2013). Second, the calibration data used to fit the NorWeST model span a large proportion of expected future changes. Interannual variability in AT was 3–6°C and Q varied threefold to tenfold within the processing units and captured high and low flow years, warm and cold years, and many combinations thereof. As a result, projected future deltas in AT and Q generally do not result in conditions outside the range of observed data until the latter half of the century. That far into the future, uncertainties associated with future greenhouse gas emissions and GCM projections (Cox & Stephenson, 2007) are much greater than those associated with the NorWeST model.

However warming of western rivers and streams manifests, it will profoundly affect their ecology. At a fundamental level, net primary productivity, nutrient processing capacity, and food webs will be altered as the region's relatively cold streams become less so (Davis et al., 2013; Woodward et al., 2010). Distributions of macroinvertebrates, stream-dwelling amphibians, and fish species will have to shift in space and time to track thermal niches that strongly constrain ectothermic organisms (Harper & Peckarsky, 2006; Isaak et al., 2017a). Evidence of distribution shifts already exists for headwater trout populations (Al-Chokhachy et al., 2016; Eby et al., 2014) and some salmon species have altered their migration dates to minimize exposure to thermally stressful summer temperatures (Crozier et al., 2008, 2011). For headwater species, local topographic relief and pronounced spatial temperature gradients create slow climate velocities and cold-water refuges are often available upstream (Isaak et al., 2016a; Uno &

Power, 2015). Those factors, however, do not buffer species in larger rivers where warming rates are larger and thermal refuges are sparse (Fullerton et al., 2015; Torgersen et al., 1999). Cold-water fish populations in many western rivers already show evidence of heat-related stress during warm summers that sometimes leads to fishing season closures, migration delays, and mortality events (Cooke et al., 2004; Keefer et al., 2009; Lynch & Risley, 2003). As heat phenomena become more common in the future, their context dependency is also likely to become more apparent. Near warm-edge or cold-edge boundaries of thermal niches, large biological changes may occur with small temperature increases whereas little or no change is

observed across most of the species' range (Isaak et al., 2017a). Similarly, if temperature increases further constrain already small populations, risks of extirpation may increase dramatically whereas that risk may change inconsequentially for populations occupying large habitats (Isaak et al., 2015). The spatial resolution and extent of NorWeST scenarios can be used to assess those risks and discern where critical thermal limitations occur for most aquatic species in the western U.S. with populations that occupy habitat extents >1 km.

Habitat restoration could partially offset future warming and biological effects, especially in small-sized to medium-sized streams and rivers where degradation is severe, if investments are made strategically. Improving minimum flows during the summer where water abstraction is common can help cool streams (Elmore et al., 2016), as would maximizing shade from riparian vegetation because of solar radiation's dominance in stream heat budgets (Diabat et al., 2013; Johnson & Wilby, 2015; Webb & Zhang, 1997). Reconnecting streams to floodplains and facilitating greater lateral and hyporheic flow exchanges have been proposed as cooling strategies (Beechie et al., 2013; Caissie & Luce, 2017; Kurylyk et al., 2015b) although their efficacy at broad spatial scales remains untested. Unfortunately, the NorWeST model in its current form yields few insights about where thermal regimes are impaired by anthropogenic factors because the covariates we used from national data sets do not represent those factors. This limitation has been recognized previously (Moore et al., 2013; Wehrly et al., 2009) and once more detailed covariates are developed, they could be included in temperature model revisions to test for additional effects, identify effect locations through residual sensitivity analysis, and improve predictive accuracy (see Scown et al., 2017 for a relevant SSN example with stream nutrients). Useful covariates might include inventories of channel realignments, water diversions, or detailed measures of riparian canopy conditions. Promising in the latter category are new remote-sensing applications for describing riparian vegetation and site-potential shade (Dauwalter et al., 2015; MacFarlane et al., 2016; Wawrzyniak et al., 2016), although these tasks are made more challenging by the prospect that climate change may also alter future riparian communities (Catford et al., 2013).

4.2. SSN Temperature Model

The rich literature that exists concerning stream temperatures was a valuable guide for choosing covariates and our results largely confirm *a priori* notions about warming or cooling effects and the mechanisms previously described by numerous authors. The magnitude and statistical significance of those effects differed among processing units, but that was expected because each unit is a unique landscape with a slightly different covariance structure that may or may not have been well represented by the nonrandom samples in the NorWeST database. More remarkable we thought, was that the SSN models consistently predicted ~90% of the observed variation in AugTw across diverse landscape and climatic conditions using readily available covariates. That was probably due to the pronounced spatial gradients associated with temperature samples in topographically complex regions but also from the spatial configuration of samples in NorWeST data sets that was conducive to SSN analysis. Data sets built from numerous sources provided samples spread broadly across those gradients that were useful for estimating covariate effects, as well as clustered samples that helped represent local autocorrelation modeled by the spatial correlation function (Ver Hoef et al., 2006). That autocorrelation is associated with environmental variation not represented by the covariates, so developing better or more comprehensive sets of covariates could provide additional resolution.

Regarding the ~10% of variation that the SSN models did not predict, a portion was due to processes occurring at sampling grains less than the 1 km interval at which our covariates were calculated as well as measurement errors associated with sensor imprecision and data screening, but the majority probably resulted from inadequate representation of temporal changes at sensor sites. Most notably, riparian canopy and local solar radiation levels at some sensor sites changed during the course of monitoring due to wild-fires and natural disturbances but our RC covariate values were static. In an earlier SSN model implementation (Isaak et al., 2010), we coupled Thematic Mapper satellite imagery and field hemispherical photography estimates of solar radiation prefire and postfire to document the local importance of riparian canopy changes but the labor intensity of the approach made it intractable at the scale of the western U.S. Additional variation was associated with the use of unit-scale averages based on 15 km resolution AT grids and sparse networks of Q gaging stations to represent interannual changes at sensor sites. Subunit scale variation in interannual cloud cover, weather patterns, and precipitation storm tracks (Nakamura et al., 2002), interacting with processes like topographically influenced cold-air pooling in complex terrain (Daly et al.,

2010; Minder et al., 2010) would expose individual stream temperature sensors to different amounts of AT and Q variation. In the case of Q, the number of gaging stations with long-term records not subject to dam regulation was often limited, and many of the unregulated gages were affected to varying degrees by upstream water withdrawals for agricultural or municipal purposes (Falcone et al., 2010). Imprecise representation of the Q covariate, therefore, could have degraded the temperature model's estimation of this effect, although results here are consistent with a previous analysis of long-term stream temperature records in this region that showed small Q effects at sites colocated with gaging stations (Isaak et al., 2012). Regardless, more precise local representations of both AT and Q covariates would be beneficial and could be derived from high-resolution models parameterized using dense networks of inexpensive AT and Q sensors (Holden et al., 2013; Stamp et al., 2014). Those types of AT microclimate models (Ashcroft & Gollan, 2012; Holden et al., 2016) can provide empirically supported interpolations at subkilometer scales but are not yet broadly available and we are unaware of comparable efforts to develop high-resolution Q models from dense monitoring networks. It may also be possible to reduce unexplained variation in future large-scale stream temperature models by using covariates that are more representative of the mechanistic processes in stream heat budgets. Measurements of those processes are typically costly and limited in spatial extent, but suitable proxies might be found in the increasing array of satellite-based remote sensing data products (Dauwalter et al., 2017), some of which have already been used to accurately predict stream temperatures (McNyset et al., 2015).

4.3. Spatial Analysis Tools for Streams

Achieving NorWeST would have been impossible without the technical and analytical advances provided by NHD and SSN models during the last decade. NHD has long been available at several spatial resolutions but the release of NHDPlus in 2006 with reach descriptors (McKay et al., 2012; Moore & DeWald, 2016) immediately created synergies with the spatially explicit SSN models. The SSNs could then be used with preexisting sets of descriptors to fit models with covariate parameters and make predictions at unsampled locations throughout river networks. This removed a large constraint on our previous SSN temperature model (Isaak et al., 2010), which was implemented using a raster-based synthetic network and required laborious calculation of custom covariates that limited the geographic scope to a single river basin and 2,500 km stream network. Developing custom covariates is now more convenient with ArcGIS toolsets (Peterson et al., 2011; Peterson & Pearce, 2017) and may be essential for some applications but many modeling needs can be met with the dozens of reach descriptors that already exist for NHDPlus (Hill et al., 2016; McKay et al., 2012).

Equally essential to NorWeST were SSNs, which are only one type of recently developed statistical model for stream network data as this field of statistics grows (Cressie et al., 2006; O'Donnell et al., 2014; Skøien et al., 2005). Common to the new generation of models is explicit recognition of an underlying network topology and these models generally offer performance comparable to, or better than, techniques like random forests or neural networks that are frequently applied to network data sets (Jackson et al., 2017; Rizo-Decelis et al., 2017; Turschwell et al., 2016). Of the network models, however, the SSNs possessed several attributes that suited them to the NorWeST project. These included flexible mixed-model spatial-autocorrelation structures, estimation of covariate effects, and prediction using both covariates and spatial autocorrelation so that interpolated scenarios were accurate in regions with sparse data (Peterson & Ver Hoef, 2010; Ver Hoef et al., 2006; Ver Hoef & Peterson, 2010). Moreover, the SSN software enables data simulations on stream networks, can be used to explore sampling design optimization (Falk et al., 2014; Som et al., 2014), and fits not only normally distributed data sets but also Poisson (e.g., count) and binomial (e.g., occurrence) distributions (Ver Hoef et al., 2014). Drawbacks of SSNs relative to other network models are greater technical complexity because data sets require preprocessing with GIS software, minimum sample sizes of 50–100 to support the number of parameters that are estimated, and computational requirements that grow at n^3 (Isaak et al., 2014; Rushworth et al., 2015). When especially large data sets are modeled and computational efficiency is at a premium, therefore, the spline approach employed by O'Donnell et al. (2014) may be a better alternative (Rushworth et al., 2015).

To streamline the application of SSN models, we developed the NSI network by reconditioning the NHDPlusV2 data set for the conterminous U.S. (Nagel et al., 2015). Compatibility among those components now provides a flexible system that can be used broadly for geostatistical analyses of stream data sets. In addition to many local applications, NorWeST-scale efforts could be undertaken with large data sets for

water quality parameters (Olson & Hawkins, 2012; Read et al., 2017; Stoddard et al., 2016), discharge (Falcone et al., 2010), species distribution and abundance (Loftus & Beard, 2009; Wenger et al., 2011), habitat quality (Kershner & Roper, 2010; U.S. Environmental Protection Agency, 2016), or stream temperature data outside the western U.S. (DeWeber & Wagner, 2014; McKenna et al., 2010). Those data sets represent significant investments and contain large amounts of untapped information that could be developed by research teams with technical proficiency in spatial stream analyses. An integrated NSI-SSN-NHDPlus system also incentivizes data aggregation because of its efficiency at creating information from nonrandom samples and could be used to systematically address ungaged basins. For example, as comprehensive databases are developed, inexpensive sensors or biological sampling efforts could be targeted at basins without data and preexisting models simply refit with samples from the new locations, where the predictive accuracy is enhanced by leveraging information about patterns of spatial autocorrelation from the larger database. As computational power increases and database formats are standardized, many analytical steps to perform those calculations could be scripted for automation of model runs and rapid visualization of results (Bush et al., 2017).

4.4. NorWeST User Community

Given the amount of stream temperature data that had been collected at the onset of the NorWeST project in 2011, a robust but informal user community already existed. However, the process of organizing disparate data sets into an openly accessible central database fostered and strengthened that community by increasing communication, facilitating data sharing, and making new monitoring efforts more efficient. Evidence supporting that claim is the amount of traffic through the NorWeST website, which receives ~12,000 annual visits during which time hundreds of temperature data sets, scenarios, and related products are downloaded each year. Database development highlighted important limitations and redundancies within existing data sets, which are now being systematically addressed. Those limitations included the need for more annual and long-term monitoring records rather than those based on summer-only monitoring, so new sensor installation protocols were developed (Isaak et al., 2013b; Stamp et al., 2014) as was an online mapping tool to share information about the locations of annual monitoring sites (https://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/maps.html). In parts of the western U.S. with sparse data sets, we have partnered with Trout Unlimited, National Forests, Bureau of Land Management, and other resource agencies to coordinate new monitoring efforts (Williams et al., 2016) and SSN models will be refit to denser data sets to provide NorWeST scenario revisions in the future. Database summaries have also been instrumental for highlighting the subset of sites with the best long-term monitoring records and communication of that information to local biologists and hydrologists. Most of those sites were established and maintained through grassroots efforts and the long-term perseverance of individuals rather than formalized institutional support, so their recognition may encourage continued monitoring and perhaps help garner that support in the future.

NorWeST scenarios and data sets have been broadly adopted by local decision makers for conservation planning because of their accuracy, ubiquity to all western streams, availability in convenient digital formats, and development from data sets collected by the user community. Planning efforts routinely involve National Environmental Policy Act and Endangered Species Act consultations, National Forest Plan revisions, and climate vulnerability assessments for many species. Several western states are either developing or refining regulatory temperature criteria and NorWeST data sets figure prominently in those discussions. NorWeST scenarios have also been used in a variety of studies to describe realized thermal niches for fish and amphibian species (Al-Chokhachy et al., 2016; Isaak et al., 2017a), delineate climate refuges for trout and char (Isaak et al., 2015, 2016a), describe temperature effects on salmon migrations (Westley et al., 2015), and estimate fish abundance and genetic patterns along temperature gradients (Dauwalter et al., 2015; Isaak et al., 2017b; Young et al., 2016). The data sets used to create the NorWeST scenarios are large but ultimately compose a small portion of the overall database, which makes it a valuable resource to fuel additional temperature research. During this time of rapid global change, particularly important is research on thermal regimes (Maheu et al., 2015; Steel et al., 2017), description of minimally sufficient metric sets for describing those regimes (Olden & Poff, 2003), biological validation of metric relevance (Garcia et al., 2014), and development of climate scenarios for all seasons.

5. Conclusion

Significant concerns exist about climate change and the effects that temperature increases this century may have on the diverse and valuable aquatic ecosystems in the western U.S. Prior to the NorWeST project, the absence of basic information to describe spatial climate patterns and trends throughout the region's stream and river networks created uncertainties that magnified concerns. Addressing those information needs was the ultimate motivation for this work, which began with one small grant to build a temperature database and scenarios from existing data for a portion of the Northern Rocky Mountains. The value unlocked from those first data sets propelled the project's organic growth during the subsequent five years until it encompassed the western U.S. and had generated a database that would require 10–15 million US\$ to replicate. Several factors combined fortuitously to enable the success, including the availability of new spatial tools, large data sets, a favorable funding climate, a scientific team with complementary skillsets, and the advent of digital social media that enabled inexpensive mass communication about the project. The simplest and most essential ingredients, however, were the willingness of people to share their data and a database team that focused exclusively on the social interactions necessary to transfer and organize those data sets while providing responsive customer service whenever questions arose. The human factor is often overlooked with the excitement and efficiencies that new technologies sometimes bring but interpersonal relationships and the trust built between the NorWeST team and hundreds of individuals scattered across a broad geography were ultimately the project's foundation. The resultant database and scenarios, coupled with an efficient analytical framework for stream data, now benefit everyone with a stake in the aquatic resources of the western U.S. as the community moves collectively through a century that will test those resources.

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Supporting information for:

The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user-community and predict broad climate warming of rivers and streams

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Contents of this file: S1, S2, S3, and S4

S1. Supporting information describing temperature database.

To develop the NorWeST database, stream temperature records were solicited and aggregated from professional biologists and hydrologists that were employed by state, federal, tribal, private, county, and municipal natural resource groups throughout the western U.S. Datasets contributed by individuals consisted of digital records with multiple daily recordings, file formats that became common in the early 1990s with the widespread adoption and use of data logging temperature sensors. Several sensor models were used to collect temperature records and these had measurement resolutions of 0.1–0.5 °C and accuracies ≤ 0.5 °C (common sensor models are shown in Dunham et al. 2005 and USEPA 2014). Solicited data were combined with existing databases that were accessible through agency websites as summarized in Table S1. The database team screened each temperature record by visual inspection and using a custom R script to identify anomalous recordings. Anomalies usually consisted of temperature measurements that occurred at the ends of a record or brief periods when sensors were not submerged and these recordings were deleted. Sometimes erroneous or imprecise location information was provided for a temperature record, in which case members of the database team sought clarification from the data contributors. If accurate location information could not be obtained, usually as coordinates from a Global Positioning System receiver or detailed field maps, a temperature record was not integrated into the NorWeST database. In other instances, the R script flagged portions of records where short-term temperature changes exceeded prespecified thresholds (e.g., $>2\text{--}3$ °C/hour) associated with individual processing units and these periods received additional scrutiny and sometimes led to consultations with data contributors to resolve issues. Any duplicate records that were received from more than one source were deleted and all recordings were converted to °C if submitted as °F. Data are periodically added to the NorWeST database

but at the time of this study, the database contained >220,000,000 temperature recordings at >22,700 unique stream and river sites in the western U.S.

Recording intervals in data records varied from a few minutes to 3–4 hours (average interval was 1 hour), so data were summarized into daily minima, maxima, and means, as well as weekly and monthly averages of these summaries. Temperature datasets with the summary metrics for individual processing units are downloadable from the NorWeST website as Excel spreadsheets and ArcGIS shapefiles (<https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>). Additional procedural details and metadata descriptions are given at the website and in Chandler et al. (2016). All data were attributed to the original contributor or source agency in metadata documentation.

Temperature monitoring patterns

Database summaries suggest that the number of sites monitored each year increased from 1993 to 2001, then fluctuated around 4,000 (Figure S2a) before decreasing after 2011. The decrease was an artifact of project timelines because NorWeST started in 2011 in the data-rich Pacific Northwest and data were not solicited for later years until 2014 when the project had moved into parts of the western U.S. that had less data. The majority of sites (70%) were monitored ≤ 2 years although more than 1,200 sites had at least one decade of data (Figure S2b). Most data were recorded during the summer months and were limited during other seasons (Figure S2c).

Dataset for modeling and scenario development

To develop a consistent dataset for modeling and creating summer temperature scenarios, data were queried from the database for all years at sites where August temperatures had been recorded on multiple occasions during at least 90% of the month's days and these recordings were averaged to calculate a mean AugTw metric. This query yielded 63,641 monitoring site-years and represented the month with the largest number of recordings (Figure S2c). To confirm the utility of AugTw for representing summer thermal conditions, we calculated pairwise correlations with several other metrics commonly used to describe summer temperatures in the western U.S. and note that all correlations exceeded 0.79 and averaged 0.92 (Table S3).

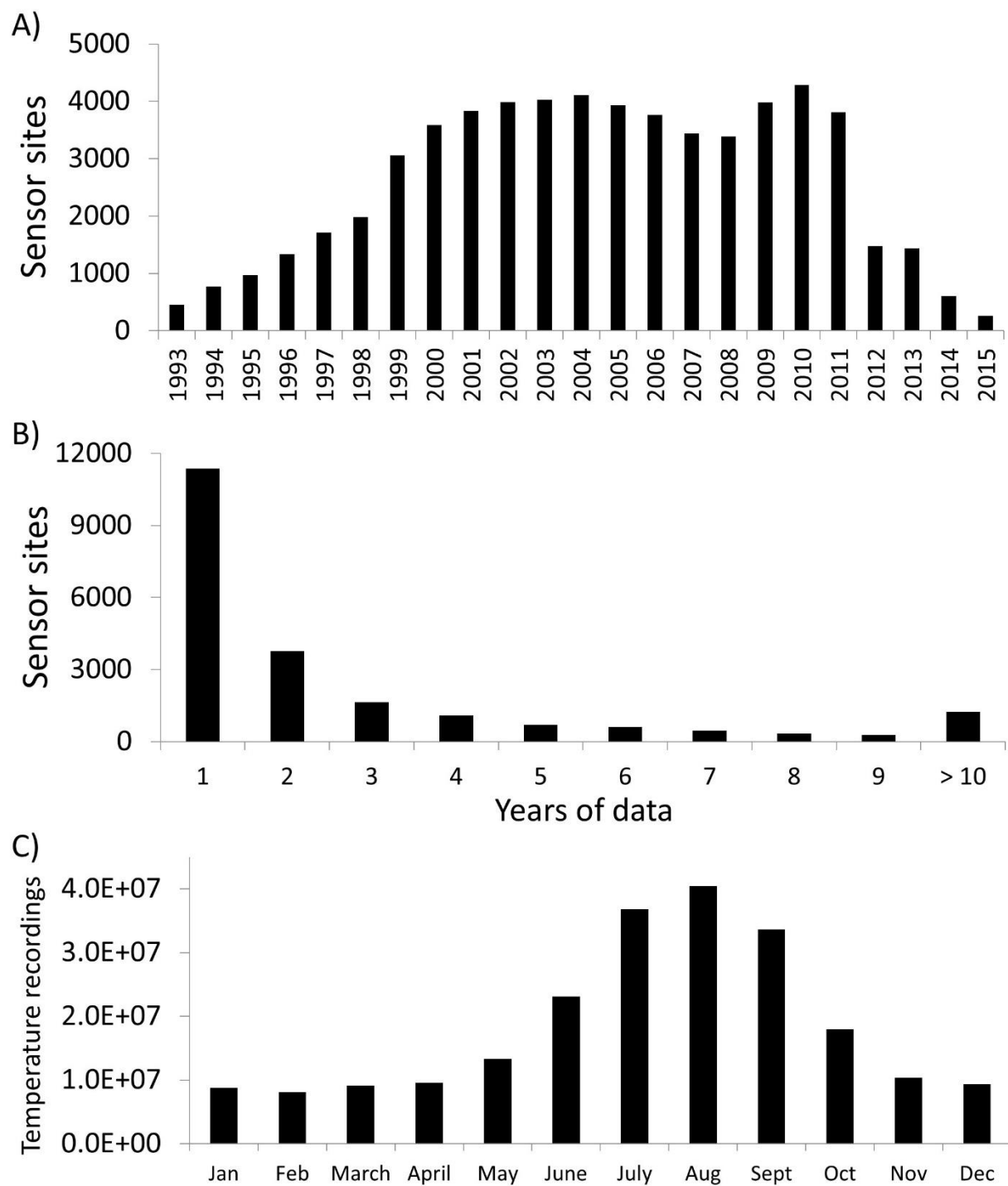
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S1. Table S1. Sources of stream temperature data that were aggregated to create the NorWeST database. Data consisted of digital temperature records that were contributed by professionals or were downloaded from the online databases referenced in the footnote.

Contributing agency ¹	Unique stream sites	AugTw site-years
Bureau of Land Management	790	2,782
County	429	1,532
Non-governmental organization	1,676	5,169
National Oceanic and Atmospheric Administration	421	1,138
National Parks Service	29	71
State	5,575	10,389
Tribe	1,046	4,182
University	1,246	2,327
U.S. Army Corp of Engineers	31	278
U.S. Bureau of Reclamation	196	606
U.S. Environmental Protection Agency	66	160
U.S. Forest Service	9,475	28,419
U.S. Fish and Wildlife Service	152	765
U.S. Geological Survey	1,255	5,143
Miscellaneous	364	680
Totals:	22,751	63,641

¹U.S. Bureau of Reclamation HydroMet: www.usbr.gov/pn/hydromet/, U.S. Geological Survey National Water Information System: waterdata.usgs.gov/nwis, U.S. Environmental Protection Agency STORET www.epa.gov/waterdata/storage-and-retrieval-and-water-quality-exchange, U.S. Forest Service Natural Resource Monitor: <http://fs.fed.us/nrm/>, Columbia River Data Access in Real Time www.cbr.washington.edu/dart/, California Department of Water Resources Water Data Library www.water.ca.gov/waterdatalibrary/docs/Hydstra/, Klamath Resource Information System <http://krisweb.com/index.htm>, Water Information Library and Unified Reference <http://wilbur.gcwin.org/>, U.S. Geological Survey Grand Canyon Monitoring and Research Data Portal www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP, Northern Water Quality Data Retrieval www.northernwater.org/DynData/WQDataMain.aspx, Northwest Fisheries Science Center Integrated Status and Effectiveness Monitoring Program https://www.webapps.nwfsc.noaa.gov/apex_stem/f?p=168:2, U.S. Fish and Wildlife Service Upper Colorado River Basin Data Repository www.fws.gov/mountain-prairie/riverdata/, Confederated Tribes of the Umatilla Indian Reservation Water Quality Data <http://data.umatilla.nsn.us/waterquality/>.



S1. Figure S2. Summaries of NorWeST database that show the number of unique stream sites monitored with sensors each year since 1993 (A), years of monitoring data at stream sites (B), and total number of temperature recordings by month (C).

S1. Table S3. Correlations among metrics commonly used to represent summer mean and maximum temperatures in streams.

Metric ¹	MWMT	MWAT	SummerT	JuneT	JulyT
MWAT	0.91				
SummerT	0.87	0.97			
JuneT	0.79	0.88	0.96		
JulyT	0.89	0.98	0.99	0.93	
AugTw	0.85	0.97	0.97	0.87	0.95

¹MWMT = maximum weekly maximum temperature; MWAT = maximum weekly average temperature; SummerT = mean temperature for June, July, and August; JuneT = mean June temperature; JulyT = mean July temperature; AugTw = mean August temperature.

S2. Supporting information associated with climate scenarios.

1 **S2. Table S1.** Climatic averages, trends, and inter-annual variability associated with mean August AT and Q in the NorWeST processing
2 units during the periods with stream temperature measurements (1993–2015) and used for long-term trend assessments (1976–2015).

NorWeST unit	AT average 1993–2015 (°C) ¹	AT minimum and maximum 1993–2015 (°C)	AT 40-year trend 1976–2015 (°C/decade)	Q average 1993–2015 (m ³ /s) ²	Q minimum and maximum 1993– 2015 (m ³ /s)	Q 40-year trend 1976–2015 (%/decade) ³	Q station numbers
A. Salmon	14.1	11.1, 16.1	0.46	34.8	17.7, 58.0	-6.7	13295000, 13296500, 13302500, 13307000, 13310700, 13313000, 13317000
B. Clearwater	15.6	12.8, 17.2	0.42	20.7	11.2, 31.9	-6.1	13336500, 13337000, 13337500, 13338500, 13339500, 13340000, 13340600
C. SpoKoot	14.7	12.0, 16.4	0.44	14.7	8.43, 25.1	-3.7	12301300, 12302055, 12304500, 12321500, 12330000, 12332000, 12335500, 12340000, 12354500, 12355500, 12358500, 12389500, 12390700, 12411000, 12414500, 12414900
D. MissHW	14.1	10.9, 16.5	0.42	10.6	6.30, 21.4	-8.7	6019500, 6043500, 6025500
E. SnakeBear	17.7	14.6, 19.9	0.48	3.94	2.18, 7.49	-1.9	13073000, 10032000, 10109001, 13082500, 13120000, 10113500, 13011500, 13023000, 13075000
F. Mid-Snake	19.6	16.1, 21.8	0.53	4.47	2.36, 7.23	-6.4	13235000, 13258500, 13185000, 13186000, 13200000, 13168500, 13161500, 13214000, 13216500, 13288200
G. Mid-Col	17.3	14.9, 18.9	0.45	3.32	2.03, 5.30	0.19	13331500, 13345000, 14054500, 14092750, 14113000, 14095500, 14020000, 14020300, 14037500, 14044000, 14042500
H. OR Coast	16.6	14.4, 17.7	0.29	2.83	1.57, 5.42	-3.9	14137000, 14141500, 14154500, 14182500, 14185000, 14219800, 14222500, 14236200, 14301000, 14301500, 14305500, 14306500, 14308000, 14325000
I. OR South	17.5	14.8, 19.7	0.52	0.75	0.41, 1.27	-8.5	10396000, 10393500, 10371500, 10384000, 13214000, 13216500, 14054500, 14037500
J. Lahontan	20.0	17.9, 21.8	0.51	0.36	0.14, 0.93	-15.1	10316500, 10329500, 10343500, 10291500, 10244950, 10243700
K. WA East	16.7	13.5, 18.2	0.42	18.6	8.53, 47.4	-9.1	12401500, 12442500, 12451000, 12452800, 12459000, 12488500
L. WA West	15.4	12.7, 16.8	0.12	9.93	5.65, 21.9	-2.0	12167000, 12209000, 12020000, 12025000, 12035000, 12039500, 12048000, 12054000, 12056500, 12082500, 12097500, 12108500, 12115000, 12115500, 12134500, 12175500, 12186000

M. Yellowst	18.2	15.1, 20.7	0.53	15.7	7.21, 31.4	-4.3	6289000, 6299500, 6311000, 6192500, 6200000, 6205000, 6233000, 6280300, 6218500, 6207500
N. Miss-Marias	16.3	13.1, 18.6	0.51	3.30	1.72, 5.38	-7.2	5014500, 6090500, 6061500, 6115500, 6073500, 6099500, 6088500
O. Wyoming	17.9	14.8, 20.1	0.37	1.49	0.55, 2.98	-8.4	9196500, 9223000, 9203000, 6632400, 9239500, 6623800, 6622700, 9245000
P. Utah	21.6	18.8, 23.6	0.35	0.71	0.28, 1.68	-10.2	9310000, 9310500, 9326500, 9330500, 10146000, 10194200, 10217000, 10237000
Q. CA North	18.4	16.8, 19.9	0.40	1.89	0.99, 3.08	-5.3	11468000, 11468500, 11478500, 11522500, 11532500, 11481200, 11482500, 11523200, 11473900, 11475560, 11475800, 11476600, 11528700
R. CA coastal	23.0	21.1–24.3	0.31	0.13	0.04–0.38	-5.7	11055801, 11058500, 11111500, 11098000, 11138500, 11141280, 11132500, 11120500, 11143000, 11160000, 11151300, 11160500, 11162500
S. CA central	21.1	19.4, 22.9	0.40	1.88	0.75, 5.16	-9.4	11230500, 11315000, 11237500, 11264500, 11379500, 11381500, 11383500, 11413000, 11449500
T. Colorado	18.0	15.5, 20.2	0.38	8.21	2.82, 19.2	-4.9	7083000, 9085000, 9081600, 9112500, 9119000, 9124500, 9146200, 9304500, 9361500, 9165000
U. New Mex	22.6	19.6, 26.1	0.56	1.73	0.51, 6.71	-0.44	7208500, 8267500, 8324000, 8378500, 8380500, 9430500
V. Arizona	23.7	21.2, 26.1	0.60	3.11	0.91, 10.0	0.60	9384000, 9405500, 9406000, 9490500, 9494000, 9497500, 9499000, 9504500, 9512500, 9431500
W. Black Hills	21.4	18.1, 24.5	0.42	0.77	0.30, 1.74	-6.6	6409000, 6431500, 6426500, 6395000, 6404000

¹Based on August averages of gridded air temperatures downloaded from the US Geological Survey Regional Climate Downscaling website (<http://regclim.coas.oregonstate.edu/index.html>).

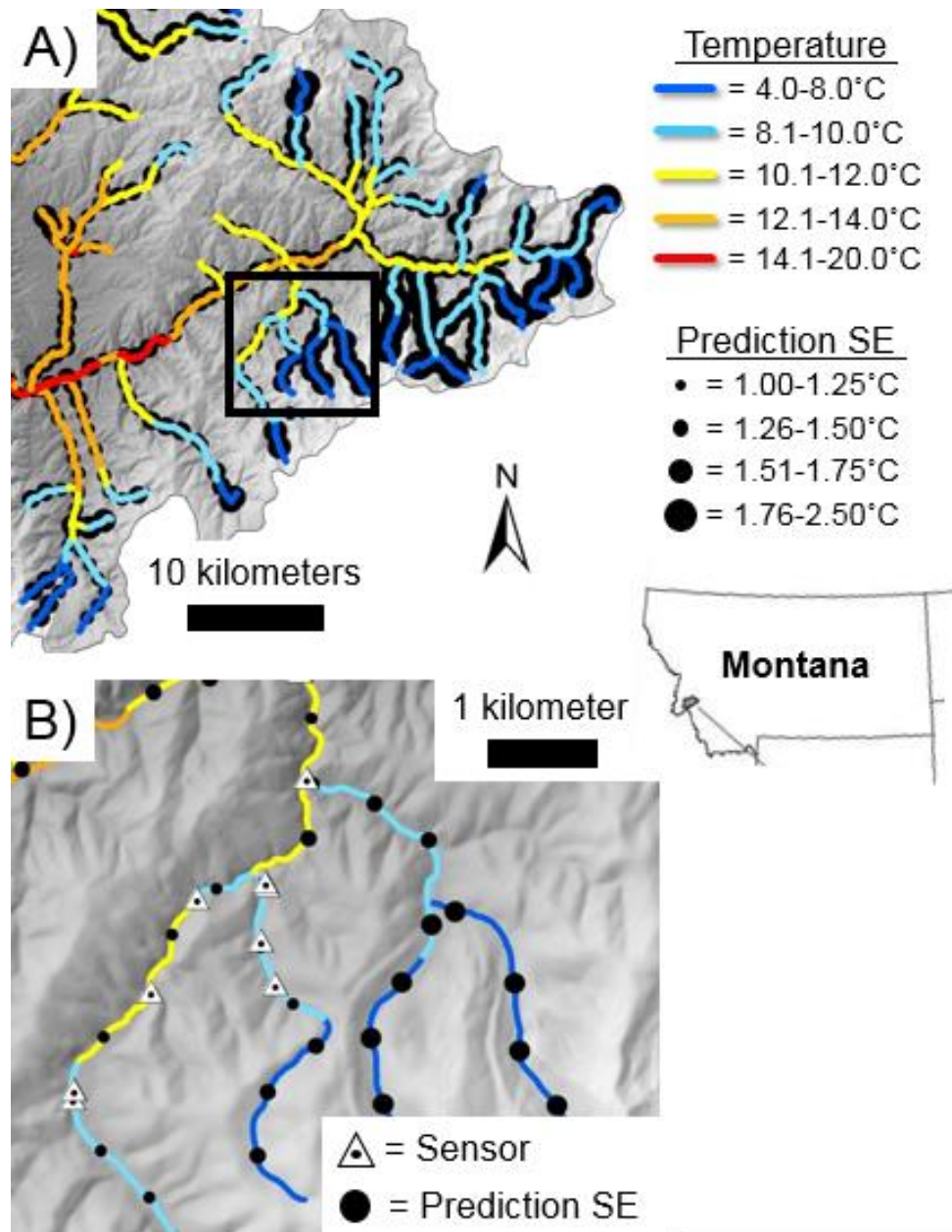
²Based on August averages from Q station gaging data downloaded from the National Water Information System website (<http://waterdata.usgs.gov/nwis/rt>).

³Trends calculated relative to average August Q for the 40-year period of 1976–2015.

S2. Table S2. Descriptions of NorWeST stream temperature scenarios.

Scenario	Description
S1_93_11	Historical composite scenario representing 19 year average August mean stream temperatures for 1993-2011
S2_02_11	Historical composite scenario representing 10 year average August mean stream temperatures for 2002-2011
S3_1993	Historical scenario representing August mean stream temperatures for 1993
S4_1994	Historical scenario representing August mean stream temperatures for 1994
S5_1995	Historical scenario representing August mean stream temperatures for 1995
S6_1996	Historical scenario representing August mean stream temperatures for 1996
S7_1997	Historical scenario representing August mean stream temperatures for 1997
S8_1998	Historical scenario representing August mean stream temperatures for 1998
S9_1999	Historical scenario representing August mean stream temperatures for 1999
S10_2000	Historical scenario representing August mean stream temperatures for 2000
S11_2001	Historical scenario representing August mean stream temperatures for 2001
S12_2002	Historical scenario representing August mean stream temperatures for 2002
S13_2003	Historical scenario representing August mean stream temperatures for 2003
S14_2004	Historical scenario representing August mean stream temperatures for 2004
S15_2005	Historical scenario representing August mean stream temperatures for 2005
S16_2006	Historical scenario representing August mean stream temperatures for 2006
S17_2007	Historical scenario representing August mean stream temperatures for 2007
S18_2008	Historical scenario representing August mean stream temperatures for 2008
S19_2009	Historical scenario representing August mean stream temperatures for 2009
S20_2010	Historical scenario representing August mean stream temperatures for 2010
S21_2011	Historical scenario representing August mean stream temperatures for 2011
S22_PredSE	Standard errors of August stream temperature predictions from the SSN models
S23_100C	Future scenario adds 1.00°C to S1_93-11

S24_100CD	Future scenario adds 1.00°C to S1_93-11 but also accounts for differential warming of streams by using historical temperatures to scale temperature increases so that cold streams warm less than warm streams.
S25_200C	Future scenario adds 2.00°C to S1_93-11
S26_200CD	Future scenario adds 2.00°C to S1_93-11 but also accounts for differential warming of streams by using historical temperatures to scale temperature increases so that cold streams warm less than warm streams.
S27_300C	Future scenario adds 3.00°C to S1_93-11
S28_300CD	Future scenario adds 3.00°C to S1_93-11 but also accounts for differential warming of streams by using historical temperatures to scale temperature increases so that cold streams warm less than warm streams.
S29_2040	Future August mean stream temperature scenario based on global climate model ensemble average projected changes in August air temperature and stream discharge for the A1B warming trajectory in the 2040s (2030-2059). Future stream deltas are identical at all sites within a NorWeST unit.
S30_2040D	Future August mean stream temperature scenario based on global climate model ensemble average projected changes in August air temperature and stream discharge for the A1B warming trajectory in the 2040s (2030-2059). Future stream deltas within a NorWeST unit account for differential sensitivity among streams so that cold streams warm less than warm streams.
S31_2080	Future August mean stream temperature scenario based on global climate model ensemble average projected changes in August air temperature and stream discharge for the A1B warming trajectory in the 2080s (2070-2099). Future stream deltas are identical at all sites within a NorWeST unit.
S32_2080D	Future August mean stream temperature scenario based on global climate model ensemble average projected changes in August air temperature and stream discharge for the A1B warming trajectory in the 2080s (2070-2099). Future stream deltas within a NorWeST unit account for differential sensitivity among streams so that cold streams warm less than warm streams.
S33_2012	Historical scenario representing August mean stream temperatures for 2012
S34_2013	Historical scenario representing August mean stream temperatures for 2013
S35_2014	Historical scenario representing August mean stream temperatures for 2014
S36_2015	Historical scenario representing August mean stream temperatures for 2015



S2. Figure S3. NorWeST Scenario 1 (colored lines) showing mean August stream temperatures for 1993–2011 with Scenario 22 (black circles) that shows prediction standard errors at 1-km intervals in a small portion of a western Montana stream network (a). Standard errors are smaller where predictions occur near sensor measurements because the autocovariance function in the SSN model uses local empirical support with information from covariate relationships (b).

S2. Table S4. Future deltas in August AT and Q based on the A1B emissions scenario for NorWeST processing units from a 10 GCM ensemble relative to a 1980s (1970–1999) baseline period. Additional details about the GCM ensemble and scenario are provided elsewhere (Mote and Salathé 2010; Hamlet et al. 2013). For more information about Q deltas that were derived from the Variable Infiltration Capacity hydrologic model, see the western U.S. flow metrics website (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and the Pacific Northwest Hydroclimate Scenarios Project website (<http://warm.atmos.washington.edu/2860/>). Because the NorWeST S1 baseline scenario was centered on a period fifteen years later (1993–2011) than the GCM baseline, future deltas were reduced proportionally for alignment with the NorWeST baseline period. This reduced future deltas used to create four NorWeST scenarios (29–32) by 25% for the 2040s and 15% for the 2080s (reduced deltas are shown in parentheses).

NorWeST unit	2040s (2030–2059)		2080s (2070–2099)	
	Δ AT (°C)	Δ Q (%)	Δ AT (°C)	Δ Q (%)
A. Salmon	3.26 (2.45)	-22.3 (-16.8)	5.51 (4.68)	-31.4 (-26.7)
B. Clearwater	3.17 (2.38)	-23.9 (-17.9)	5.45 (4.63)	-34.0 (-29.1)
C. SpoKoot	3.05 (2.29)	-20.1 (-15.1)	5.33 (4.53)	-31.5 (-26.8)
D. MissHW	3.25 (2.44)	-14.9 (-11.1)	5.47 (4.65)	-21.3 (-18.1)
E. SnakeBear	3.17 (2.38)	-7.6 (-5.7)	5.26 (4.47)	-9.5 (-8.1)
F. Mid-Snake	3.22 (2.42)	-19.5 (-14.6)	5.45 (4.63)	-26.7 (-22.7)
G. Mid-Col	3.27 (2.45)	-14.4 (-10.8)	5.44 (4.62)	-20.7 (-17.6)
H. OR Coast	2.82 (2.12)	-19.4 (-14.6)	4.86 (4.13)	-29.5 (-25.1)
I. OR South	3.23 (2.42)	-6.0 (-4.5)	5.46 (4.64)	-9.4 (-8.0)
J. Lahontan	2.68 (2.01)	2.6 (2.0)	4.81 (4.09)	6.5 (-5.5)
K. WA East	3.02 (2.27)	-36.3 (-27.2)	5.24 (4.45)	-50.0 (-42.5)
L. WA West	2.73 (2.05)	-32.0 (-24.0)	4.74 (4.03)	-46.4 (-39.4)
M. Yellowst	2.81 (2.11)	-4.1 (-3.1)	5.08 (4.32)	-5.4 (-4.6)
N. Miss-Marias	2.91 (2.18)	-10.0 (-7.5)	5.30 (4.51)	-18.7 (-15.9)
O. Wyoming	2.68 (2.01)	-3.6 (-2.7)	4.76 (4.05)	-4.8 (-4.1)
P. Utah	2.60 (1.95)	2.3 (1.7)	4.67 (3.97)	12.6 (10.7)
Q. CA North	2.22 (1.67)	-2.9 (-2.1)	4.20 (3.57)	-1.4 (-1.2)
R. CA coastal	2.11 (1.58)	5.3 (4.0)	3.76 (3.20)	2.0 (1.7)
S. CA central	2.52 (1.89)	-26.2 (-19.7)	4.58 (3.89)	-25.3 (-21.5)
T. Colorado	2.50 (1.88)	-19.9 (-14.9)	4.30 (3.66)	-22.9 (-19.5)
U. New Mex	2.37 (1.78)	-5.8 (-4.4)	4.02 (3.42)	-5.4 (-4.6)
V. Arizona	2.43 (1.82)	3.1 (2.3)	4.22 (3.59)	11.5 (9.8)
W. Black Hills	2.78 (2.09)	-7.1 (-5.3)	5.10 (4.34)	-10.2 (-8.7)

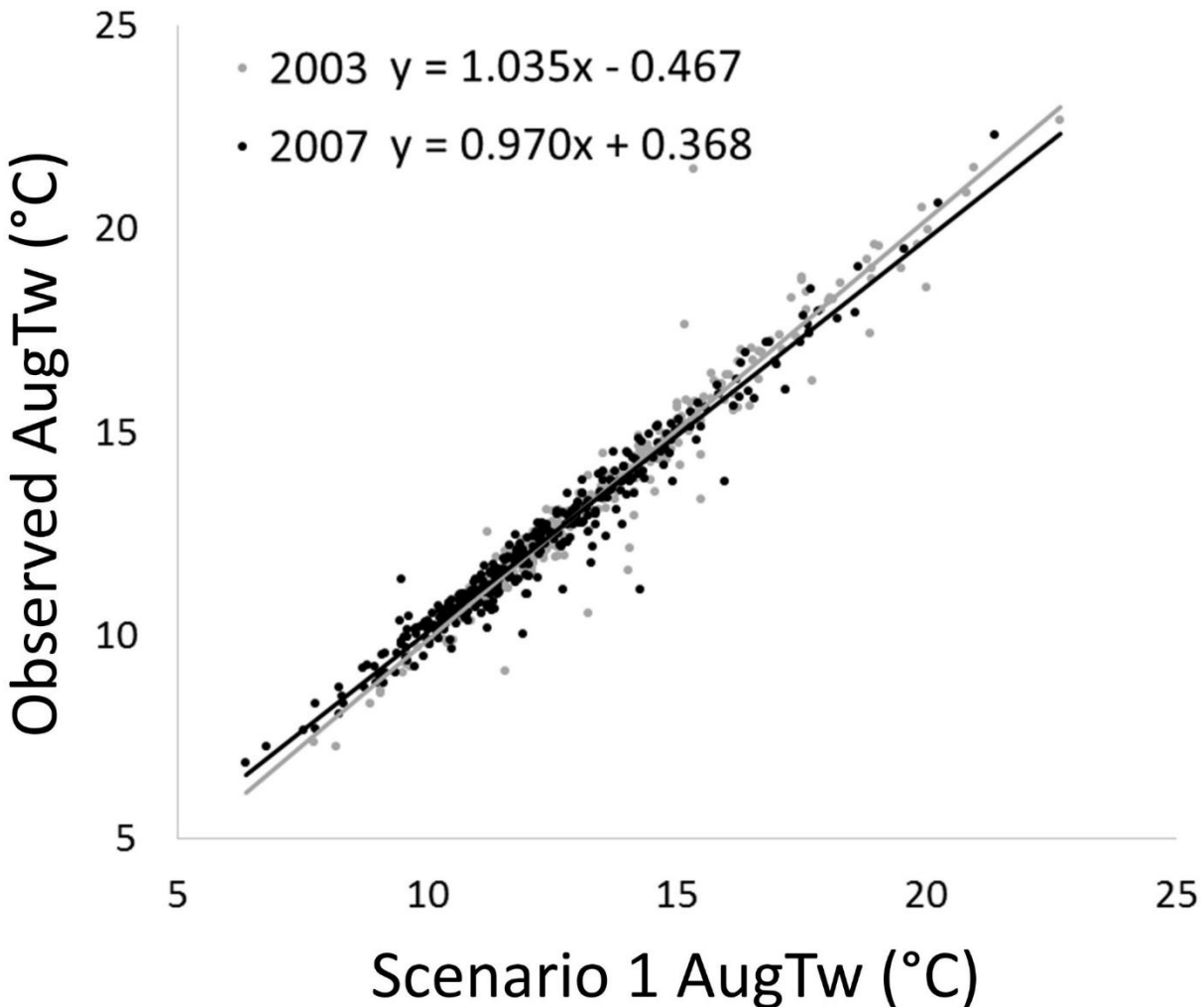
Hamlet, A.F., M.M. Elsner, G.S. Mauger, [et al.], (2013), An overview of the Columbia Basin climate change scenarios project: approach, methods, and summary of key results, *Atmosphere-Ocean*, 51, 392–415.

Mote, P.W., and E.P. Salathé, (2010), Future climate in the Pacific Northwest, *Climatic Change*, 102, 29–50.

S3. Supporting information for stream temperature sensitivity calculations.

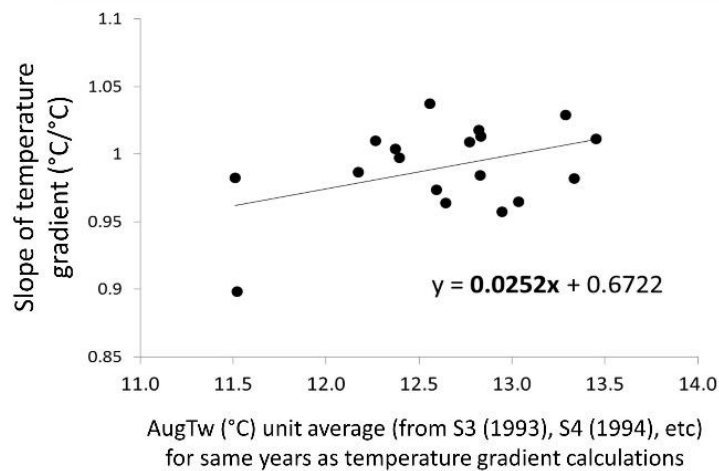
Stream temperature sensitivity is defined as the amount of change in stream temperature relative to air temperature ($\Delta^{\circ}\text{C}_{\text{stream}} / \Delta^{\circ}\text{C}_{\text{air}}$). Numerous studies show that this ratio is usually < 1 and that sensitivity varies among sites and streams (Morrill et al. 2005; Kelleher et al. 2012; Luce et al. 2014; Lisi et al. 2015; Isaak et al. 2016), with cold sites usually being less sensitive than warm sites. Incorporating differential sensitivity into future stream temperature scenarios may be important for some applications, so for a subset of NorWeST scenarios (Scenarios 24, 26, 28, 30, 32), we applied a sensitivity adjustment based on unit-specific sensitivity parameters that were estimated from observed patterns of inter-annual variation in stream temperature among sites.

To estimate the sensitivity parameters, the observed AugTw values at sites during each individual year (1993, 1994, ..., 2015) were regressed on baseline Scenario 1 predictions (representing average AugTw for 1993–2011) at the same sites to describe annual temperature gradients. Plots of those regressions showed that slopes of temperature gradients were steeper in years when observed AugTw values were warmer, as is expected since cold sites are less sensitive than warm sites. The example plot below shows the annual temperature gradients for a cool year and warm year and demonstrates that pattern (Figure S1).



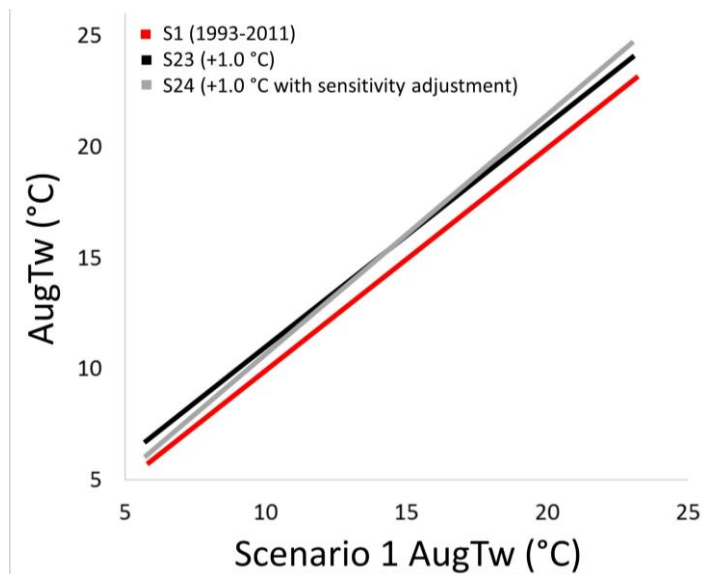
S3. Figure S1. Inter-annual change in temperature gradients between two years in the Clearwater processing unit that was described by regressing observed AugTw values against the baseline Scenario 1 predictions at the same sites. Note that the slope of the temperature gradient was steeper (1.035 versus 0.97) in 2003 when observed AugTw values were warmer on average than in 2007 (13.6°C versus 12.3°C).

Slope values from the annual temperature regressions were then regressed on the network average AugTw value predicted by the NorWeST model for the same historical years (Scenario 3-1993, Scenario 4-1994, etc.), and the slope of that relationship was the sensitivity parameter for a processing unit (Figure S2).



S3. Figure S2. Relationship between slopes representing annual temperature gradients in the Clearwater processing unit relative to the network average AugTw values predicted for the same years. Note that two of the 19 data points in the plot are the regression slope values from the previous Figure S1 (1.035 and 0.97). The positive slope of this second regression relationship (0.0252) was the sensitivity parameter that described how much the temperature gradient increased relative to the change in modeled AugTw for historical scenario years.

Once the sensitivity parameter was calculated for a unit, it was used to scale slope increases in the temperature gradients for the future AugTw delta values used in the unadjusted future scenarios (Scenarios 23, 25, 27, 29, 31) while matching the same overall AugTw delta as in the unadjusted scenarios. Continuing the above example in Figure S3 below, if the future AugTw delta relative to the Scenario 1 baseline was +1°C (Scenario 23), then the slope of the adjusted scenario (Scenario 24) was 1.0252 when plotted against the Scenario 1 baseline.



S3. Figure S3. Comparison of future scenario predictions for 1-km reaches with and without sensitivity adjustment in the Clearwater processing unit. Scenario 1 represents the historical baseline conditions for 1993–2011 whereas Scenarios 23 and 24 show predicted future increases in AugTw values associated with a 1 °C increase. The average predicted delta increase is the same for both future scenarios but Scenario 24 with the sensitivity adjustment shows cold streams warming less than warm streams.

S3. Table S4. Summary of sensitivity parameters used in NorWeST processing units to develop a subset of future stream temperature scenarios.

NorWeST unit	Sensitivity parameter (°C / °C)	Years‡
A. Salmon	0.0217	18
B. Clearwater	0.0252	19
C. SpoKoot	0.0315	16
D. MissHW	0.0245†	7
E. SnakeBear	-0.0005	15
F. Mid-Snake	0.0202	17
G. Mid-Col	0.0127	19
H. OR Coast	0.0289	19
I. OR South	0.0234	13
J. Lahontan	0.0245†	4
K. WA East	0.0523	13
L. WA West	0.0067	17
M. Yellowst	0.0245†	3
N. Miss-Marias	0.0245†	0
O. Wyoming	0.0245†	2
P. Utah	0.0245†	0
Q. CA North	0.0308	18
R. CA coastal	0.0245†	2
S. CA central	0.0644	16
T. Colorado	0.0004	14
U. New Mex	0.0245†	7
V. Arizona	0.0245†	0
W. Black Hills	0.0245†	0
Average:	0.0245	

‡Spatial temperature gradients were calculated only for years with >50 AugTw samples to provide a robust sample.

†Units with <7 years of >50 AugTw samples were assigned the average sensitivity value for all processing units.

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S4. Supporting information describing processing unit datasets and model fits.

A. Salmon

S4. Salmon Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	1,700	1,687	1,792	411	280	2,543
SL (m/m)	1,700	0.0389	0.0261	0.0393	0	0.291
LK (%)	1,700	0.153	0.012	0.499	0	6.79
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	1,700	729	707	256	194	1,472
NOR (m)	1,700	1,633,506	1,640,008	55,575	1,519,969	1,755,574
BFI (%)	1,700	72.5	74	4.57	61	85
DA (km ²)	1,700	483	47.3	3,004	0.085	34,865
RC (%)	1,700	43.1	44.3	25.5	0	93.9
AT (°C)	19	13.8	13.4	1.18	11.1	15.8
Q (m ³ /s)	19	33.1	28.4	11.1	17.7	58.0
TW (0/1)	0	na	na	na	na	na
AugT (°C)	4,007	11.6	11.3	2.67	4.87	26.3

S4. Salmon Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

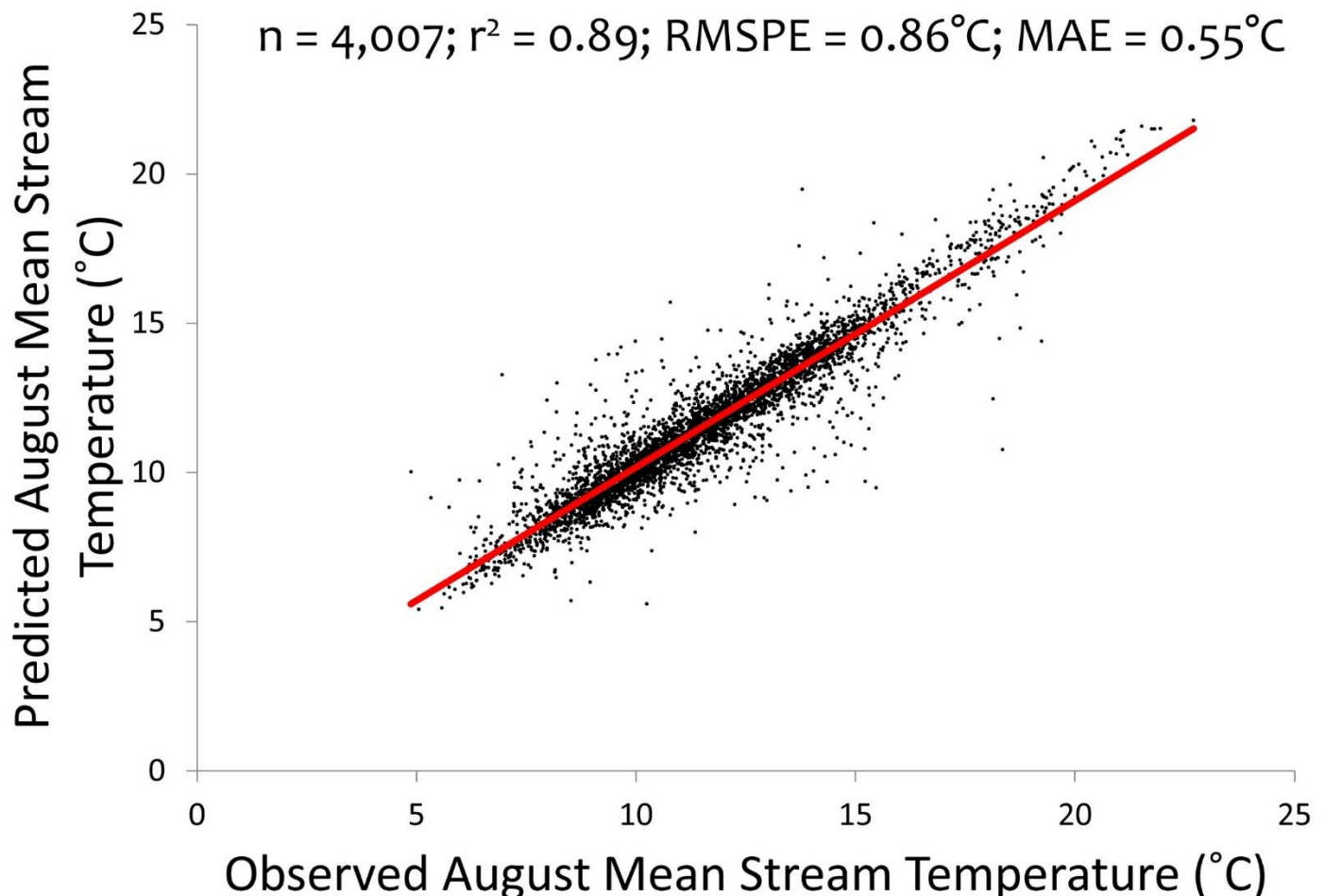
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	-0.16										
LK	0.09	-0.09									
GLA	na	na	na								
AP	0.27	0.03	0.02	na							
NOR	-0.67	0.33	-0.20	na	0.12						
BFI	0.46	-0.09	-0.02	na	-0.52	-0.51					
DA	-0.31	-0.14	0.01	na	-0.16	0.16	-0.01				
RC	-0.07	0.25	0.08	na	0.35	0.40	-0.31	-0.12			
AT	-0.11	0.01	-0.04	na	-0.03	0.07	-0.08	0.02	-0.03		
Q	0.01	0.07	-0.04	na	-0.02	0.06	0.04	0.00	0.02	-0.13	
AugT	-0.57	-0.26	0.18	na	-0.25	0.18	-0.21	0.37	-0.18	0.22	-0.14

S4. Salmon Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

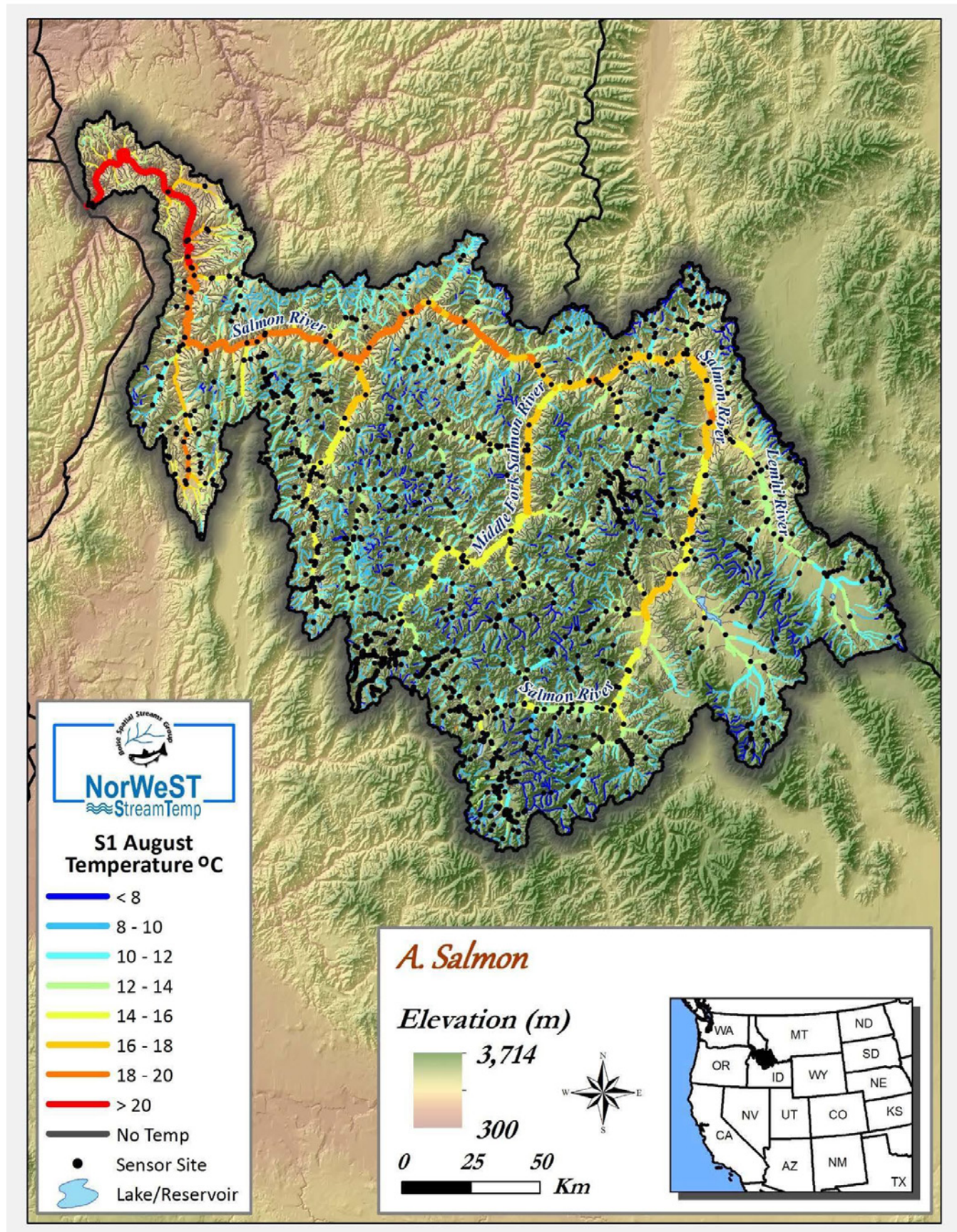
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.12E+01	1.50E-01	11.217	0.150	75.022	0.000	0.893	0.863
ELE (m)	-3.75E-03	2.81E-04	-3.106	0.233	-13.353	0.000		
RC (%)	-7.33E-03	1.84E-03	-0.373	0.093	-3.994	0.000		
SL (m/m)	-7.40E+00	1.23E+00	-0.604	0.101	-6.001	0.000		
AP (mm)	-1.49E-03	3.93E-04	-0.757	0.200	-3.783	0.000		
DA (km ²)	8.95E-05	2.59E-05	0.582	0.168	3.457	0.001		
NOR (m)	4.41E-07	2.92E-06	0.050	0.328	0.151	0.880		
LK (%)	1.20E+00	8.62E-02	1.140	0.082	13.878	0.000		
BFI (%)	2.35E-03	3.22E-02	0.021	0.287	0.073	0.942		
AT (°C)	3.28E-01	4.43E-02	0.779	0.105	7.392	0.000		
Q (m ³ /s)	-2.24E-02	4.56E-03	-0.508	0.104	-4.902	0.000		

S4. Salmon Figure 1. Plot of predicted and observed temperatures.

Salmon River NorWeST Stream Temperature Model



S4. Salmon Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



B. Clearwater

S4. Clearwater Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	746	978	972	316	223	1,873
SL (m/m)	746	0.064	0.045	0.063	0.01	0.335
LK (%)	746	0.044	0	0.150	0	2.25
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	746	1,191	1,169	299	340	2,026
NOR (m)	746	1,816,143	1,818,092	34,239	1,713,334	1,881,121
BFI (%)	746	66.8	68.0	4.44	49.0	74.0
DA (km ²)	746	457	20.3	2,446	1.07	24,212
RC (%)	746	55.7	58.6	24.0	0	96.1
AT (°C)	19	15.4	15.5	1.02	12.8	17.1
Q (m ³ /s)	19	20.3	19.9	5.70	12.6	31.9
TW (0/1)	1 ¹					
AugT (°C)	4,487	12.7	12.3	2.57	5.5	22.7

¹Stream length coded as cold tailwater was 68 km.

S4. Clearwater Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

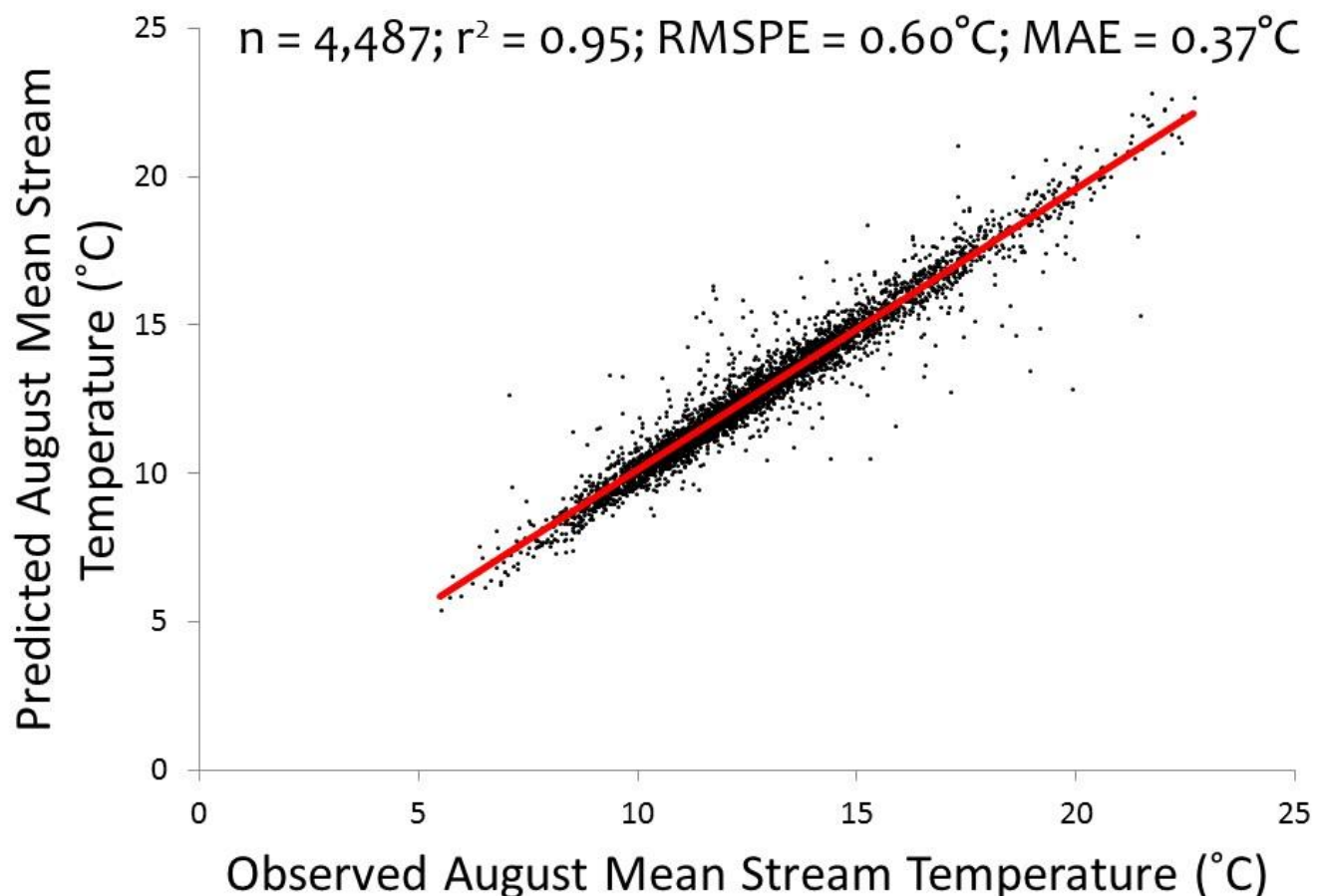
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	-0.16	1.00									
LK	0.09	-0.10	1.00								
GLA	na	na	na	1.00							
AP	0.48	0.22	-0.03	na	1.00						
NOR	-0.08	0.18	0.02	na	0.40	1.00					
BFI	0.32	0.24	-0.01	na	0.25	-0.18	1.00				
DA	-0.33	-0.18	0.24	na	-0.32	-0.03	-0.26	1.00			
RC	0.44	0.11	0.04	na	0.25	-0.11	0.30	-0.30	1.00		
AT	-0.01	0.03	0.00	na	0.01	-0.01	0.02	0.00	-0.01	1.00	
Q	-0.04	0.00	0.00	na	0.02	0.02	-0.04	0.01	-0.01	-0.26	1.00
AugT	-0.60	-0.26	0.01	na	-0.53	-0.22	-0.34	0.21	-0.41	0.21	-0.06

S4. Clearwater Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

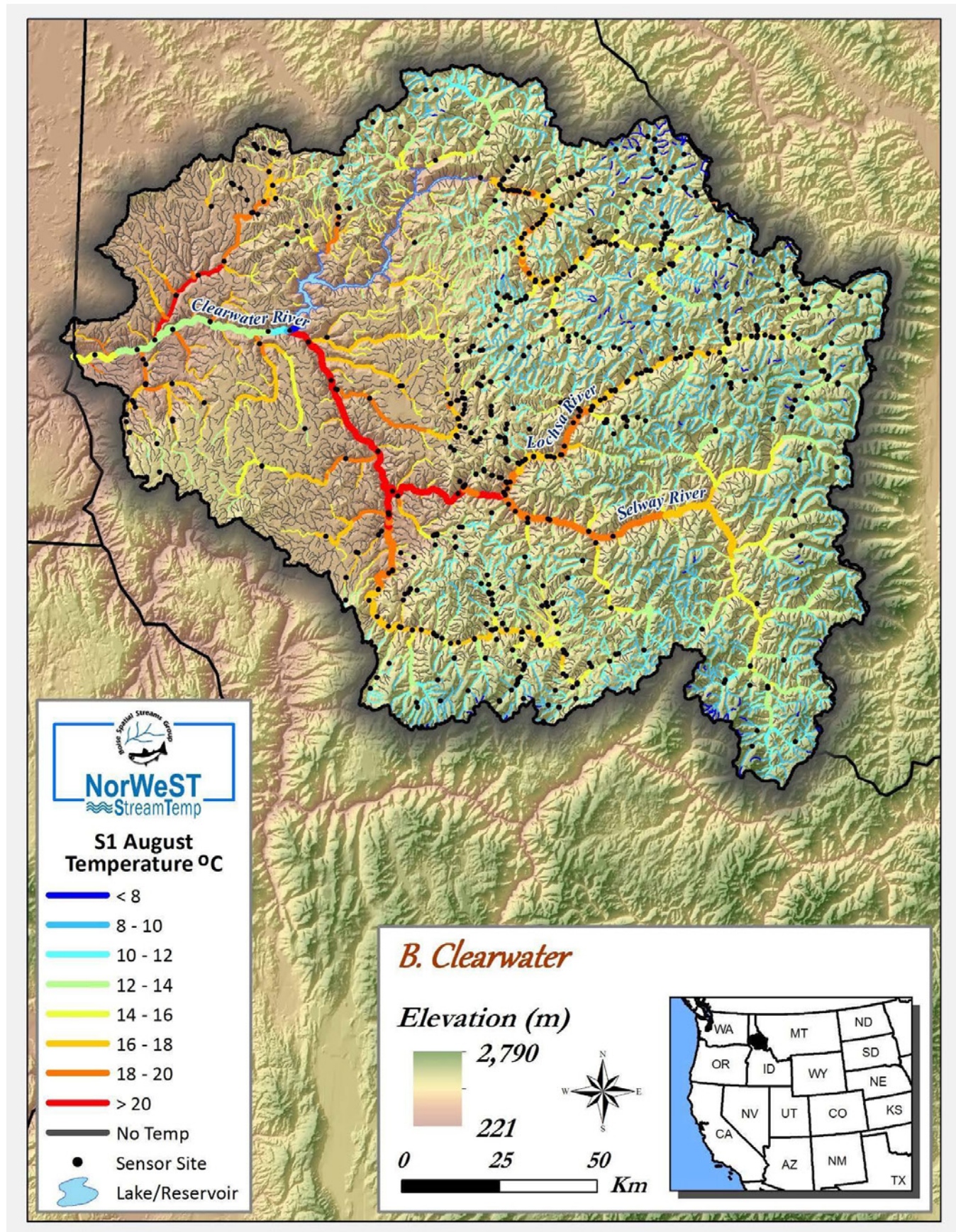
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.28E+01	1.93E-01	12.778	0.193	66.273	0.000	0.946	0.595
ELE (m)	-4.45E-03	3.34E-04	-2.813	0.212	-13.298	0.000		
RC (%)	-8.65E-03	2.06E-03	-0.416	0.099	-4.211	0.000		
SL (m/m)	-5.97E+00	1.03E+00	-0.747	0.128	-5.824	0.000		
AP (mm)	-9.13E-04	3.67E-04	-0.545	0.219	-2.488	0.013		
DA (km ²)	3.19E-04	5.85E-05	1.562	0.286	5.451	0.000		
NOR (m)	-1.21E-05	4.18E-06	-0.829	0.285	-2.907	0.004		
LK (%)	8.84E-01	2.87E-01	0.266	0.086	3.079	0.002		
BFI (%)	-8.16E-02	2.93E-02	-0.725	0.261	-2.781	0.005		
AT (°C)	5.04E-01	7.63E-02	1.025	0.155	6.602	0.000		
Q (m ³ /s)	-4.48E-03	1.44E-02	-0.051	0.165	-0.310	0.757		
TW (0/1)	-1.33E+01	1.12E+00	-13.274	1.118	-11.878	0.000		

S4. Clearwater Figure 1. Plot of predicted and observed temperatures.

Clearwater River NorWeST Stream Temperature Model



S4. Clearwater Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



C. SpoKoot

S4. SpoKoot Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	2,185	1,160	1,144	339	420	2,442
SL (m/m)	2,185	0.0342	0.0225	0.0373	0	0.252
LK (%)	2,185	0.280	0.007	0.730	0	7.86
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	2,185	755	706	288	257	2,217
NOR (m)	2,185	1,903,910	1,900,464	110,683	1,707,146	2,099,328
BFI (%)	2,185	71.6	71	3.81	46	83
DA (km ²)	2,185	1,192	44.7	5,744	0.26	63,753
RC (%)	2,185	48.0	51.4	26.9	0	96.5
AT (°C)	19	14.6	14.7	0.973	11.9	16.3
Q (m ³ /s)	19	14.0	14.2	4.03	8.91	25.1
TW (0/1)	2 ¹					
AugT (°C)	5,482	12.4	12.0	2.99	3.89	24.1

¹Stream length coded as cold tailwater was 236 km.

S4. SpoKoot Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

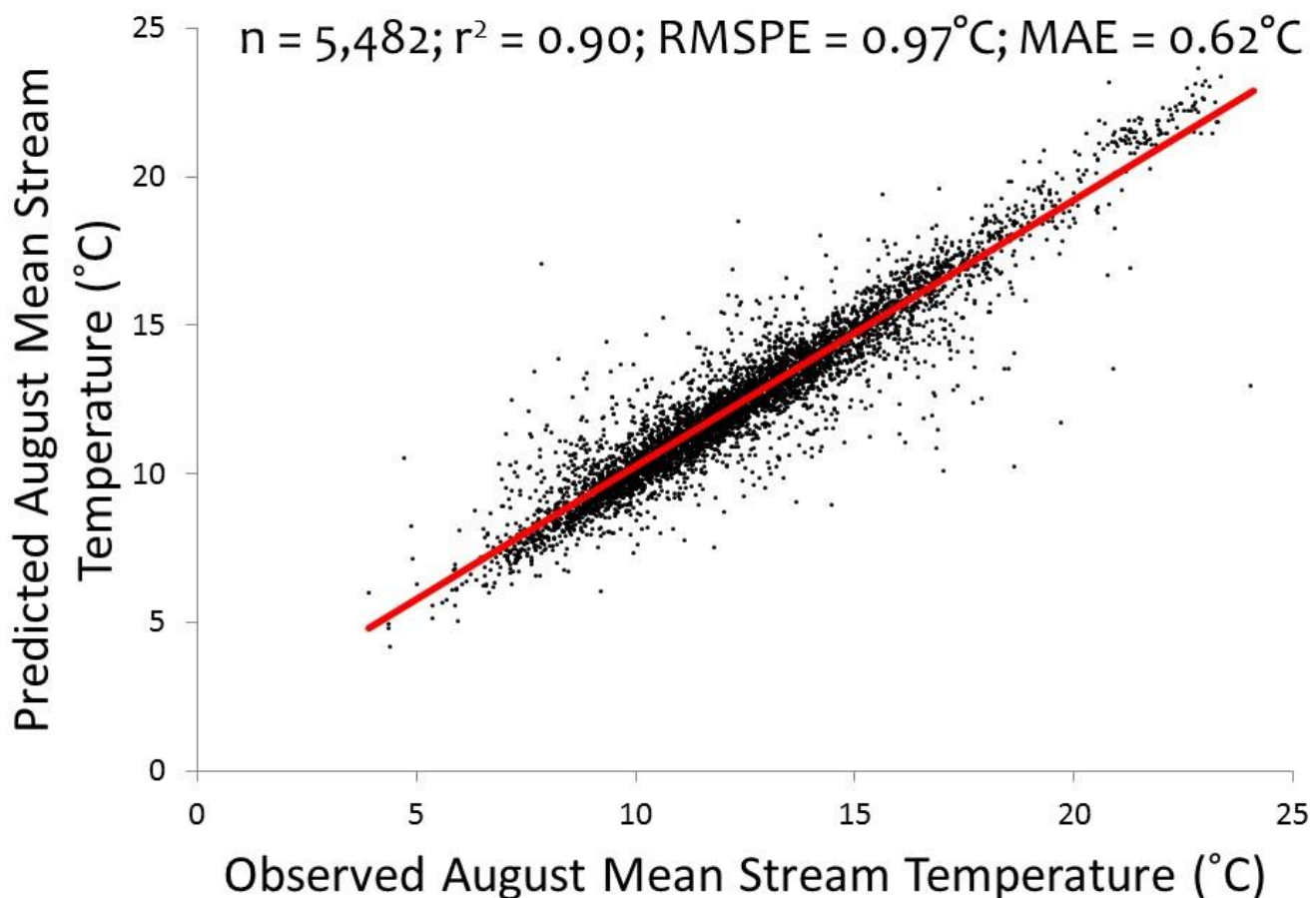
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.26	1.00									
LK	-0.18	-0.20	1.00								
GLA	na	na	na	1.00							
AP	-0.01	0.30	-0.13	na	1.00						
NOR	-0.70	-0.14	0.15	na	0.33	1.00					
BFI	0.16	-0.07	0.23	na	-0.33	-0.06	1.00				
DA	-0.25	-0.12	0.43	na	-0.13	0.15	0.03	1.00			
RC	0.30	0.44	-0.27	na	0.40	-0.10	-0.07	-0.31	1.00		
AT	0.02	0.02	-0.01	na	-0.01	-0.04	-0.02	-0.01	0.01	1.00	
Q	0.01	-0.04	-0.01	na	-0.04	-0.02	0.02	0.00	0.02	-0.21	1.00
AugT	-0.44	-0.39	0.50	na	-0.39	0.12	0.03	0.44	-0.53	0.13	-0.07

S4. SpoKoot Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

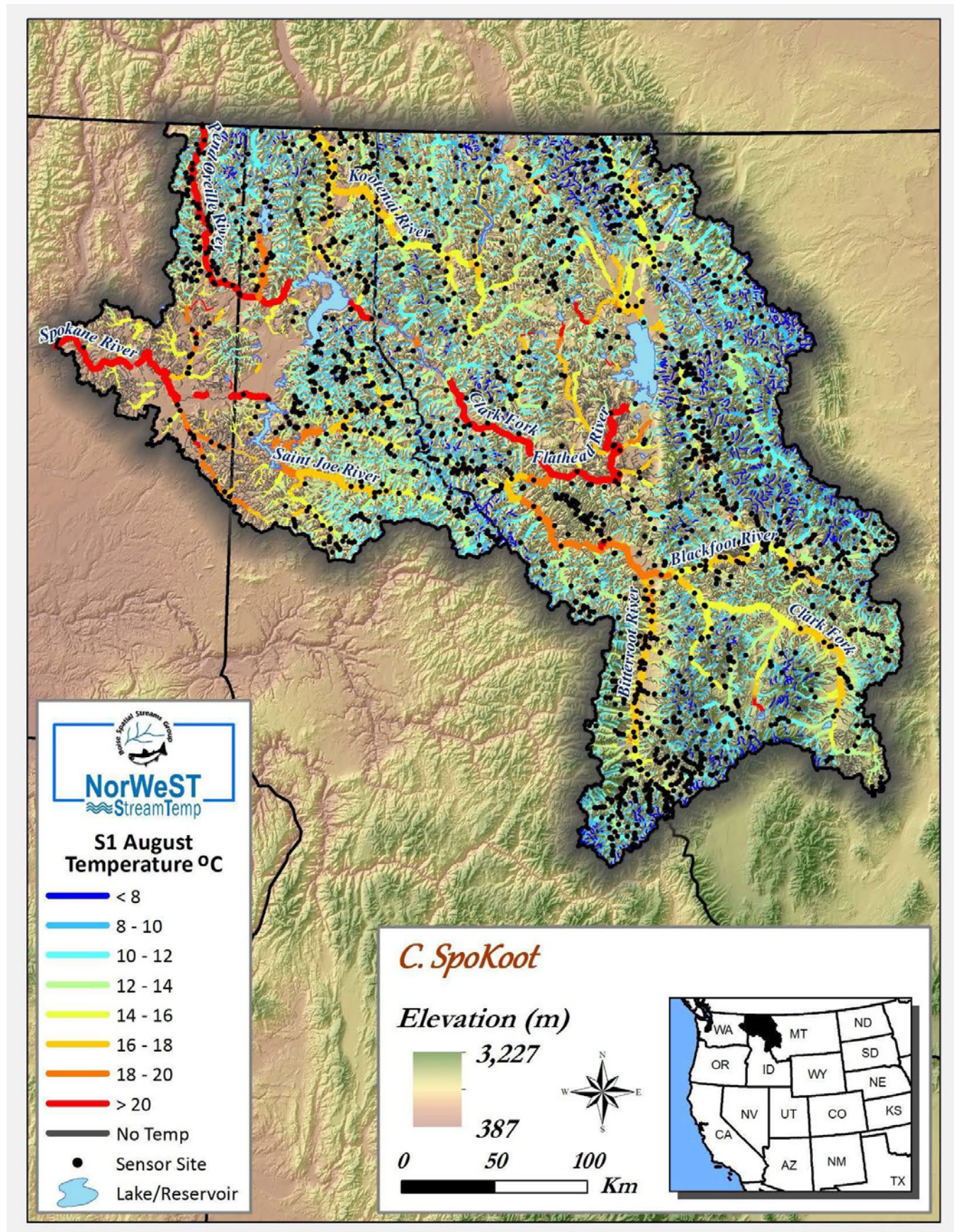
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.22E+01	2.02E-01	12.222	0.202	60.607	0.000	0.895	0.969
ELE (m)	-4.05E-03	3.35E-04	-2.752	0.228	-12.080	0.000		
RC (%)	-1.61E-02	1.83E-03	-0.865	0.098	-8.790	0.000		
SL (m/m)	-6.98E+00	1.29E+00	-0.522	0.096	-5.416	0.000		
AP (mm)	-9.12E-04	2.62E-04	-0.526	0.151	-3.477	0.001		
DA (km ²)	8.17E-05	1.69E-05	0.939	0.194	4.840	0.000		
NOR (m)	-5.23E-06	1.85E-06	-1.158	0.409	-2.831	0.005		
LK (%)	1.27E+00	7.87E-02	1.859	0.115	16.168	0.000		
BFI (%)	2.56E-05	1.13E-04	0.018	0.081	0.227	0.821		
AT (°C)	3.64E-01	6.33E-02	0.708	0.123	5.744	0.000		
Q (m ³ /s)	-5.08E-02	1.64E-02	-0.410	0.133	-3.096	0.002		
TW (0/1)	-1.57E+00	7.76E-01	-1.574	0.776	-2.028	0.043		

S4. SpoKoot Figure 1. Plot of predicted and observed temperatures.

SpoKoot Basin NorWeST Stream Temperature Model



S4. SpoKoot Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



D. MissHW

S4. MissHW Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	578	1,840	1,853	290	1,232	2,754
SL (m/m)	578	0.0226	0.0076	0.0306	0.00003	0.189
LK (%)	578	0.476	0.153	0.707	0	4.6
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	578	515	482	194	234	1,244
NOR (m)	578	1,692,621	1,698,910	47,785	1590595	1,807,226
BFI (%)	578	75.7	76	3.02	66	85
DA (km ²)	578	1,952	151	3,671	0.233	24,000
RC (%)	578	27.2	18.8	24.0	0	91.6
AT (°C)	19	13.8	13.7	1.14	10.9	16.4
Q (m ³ /s)	19	10.7	11.2	3.29	6.26	21.3
TW (0/1)	0					
AugT (°C)	1,145	13.6	14.6	3.84	4.04	22.4

S4. MissHW Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

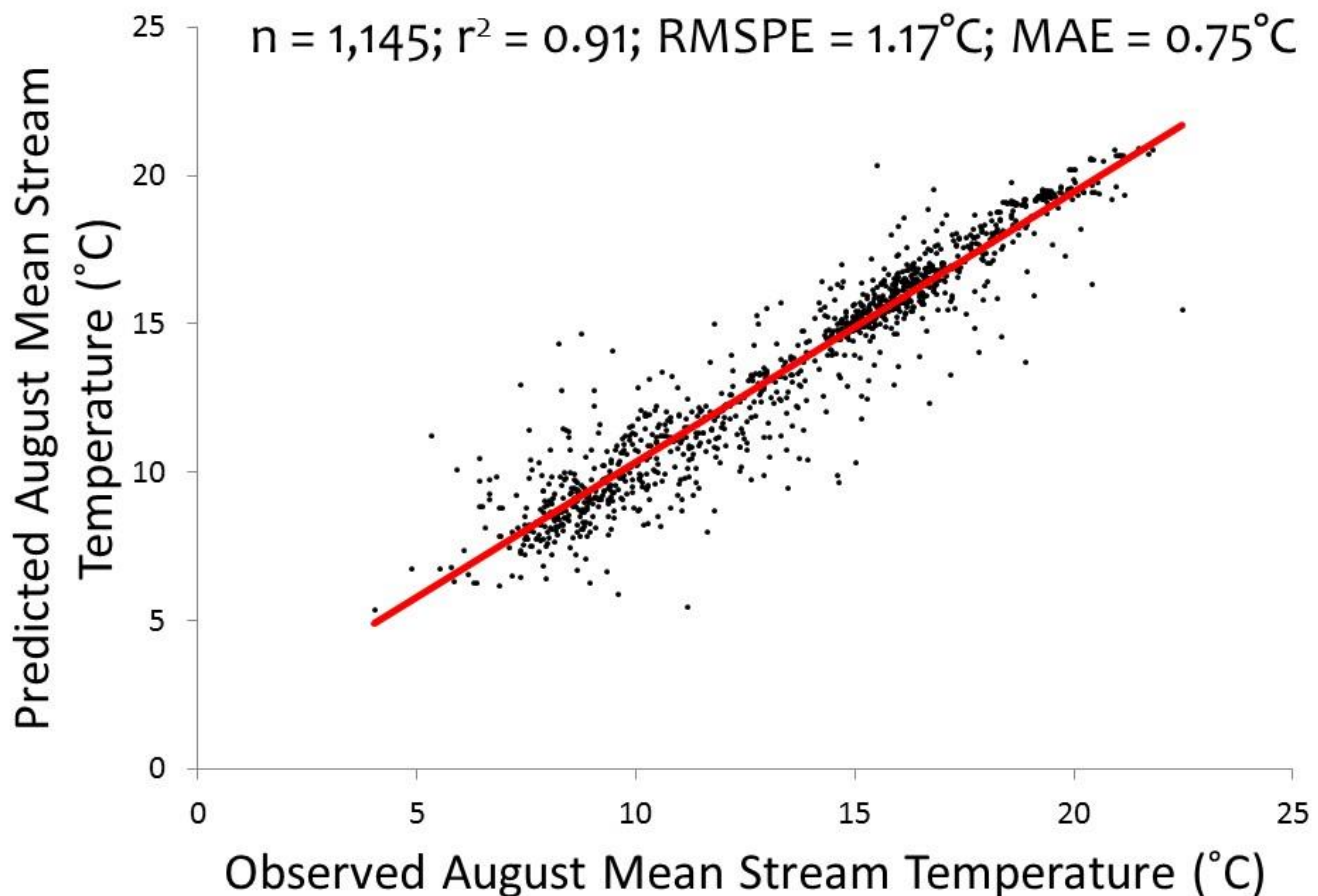
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.52	1.00									
LK	-0.28	-0.28	1.00								
GLA	na	na	na	1.00							
AP	0.68	0.57	0.01	na	1.00						
NOR	-0.47	-0.12	-0.23	na	-0.37	1.00					
BFI	0.33	0.12	0.33	na	0.43	-0.62	1.00				
DA	-0.59	-0.32	0.28	na	-0.36	0.21	-0.07	1.00			
RC	0.40	0.60	-0.28	na	0.48	0.12	0.04	-0.24	1.00		
AT	0.03	0.05	0.06	na	0.10	-0.12	0.11	-0.01	0.03	1.00	
Q	0.02	0.06	0.02	na	0.05	-0.06	0.05	-0.01	0.02	-0.06	1.00
AugT	-0.75	-0.65	0.48	na	-0.62	0.29	-0.20	0.55	-0.56	0.03	-0.09

S4. MissHW Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

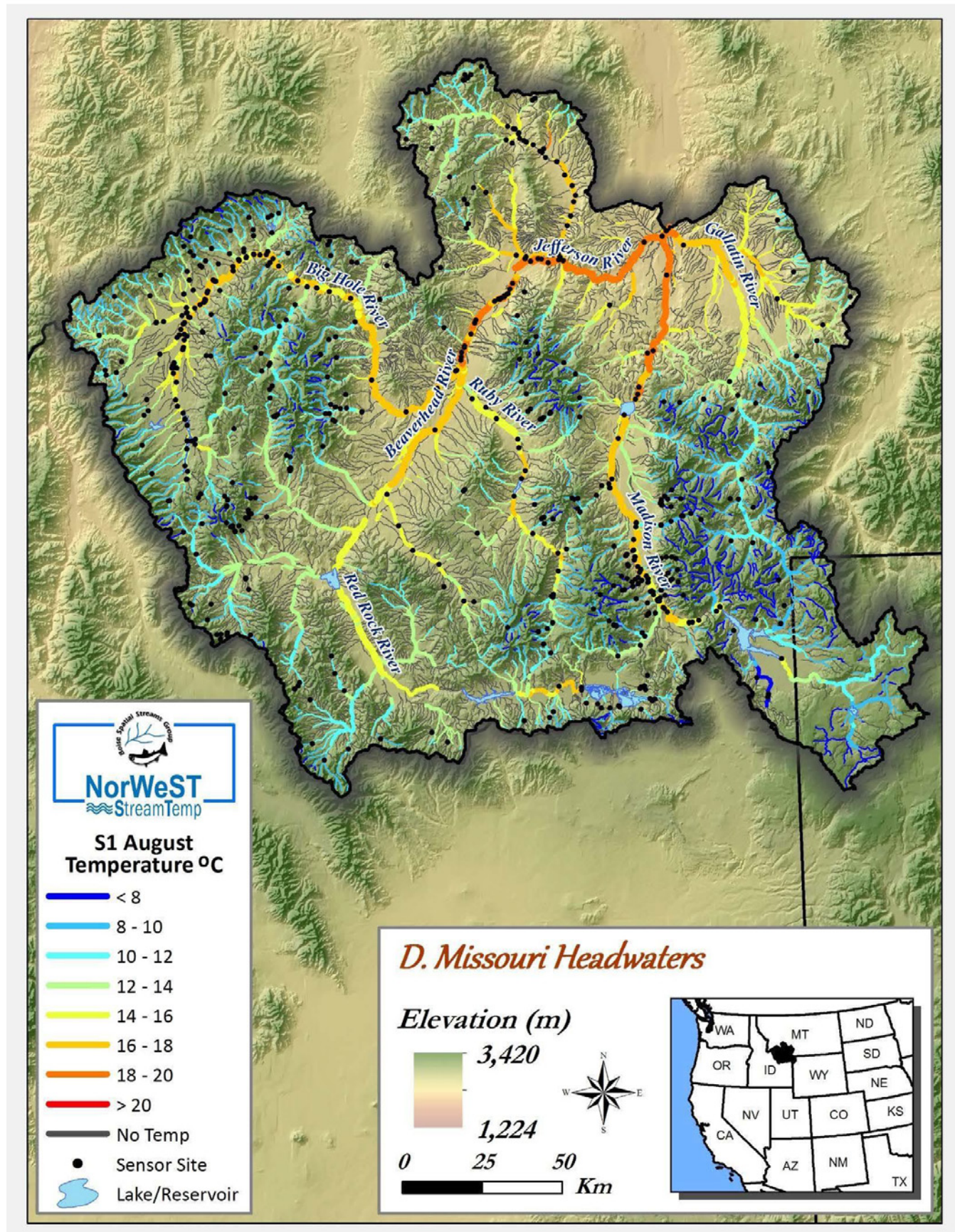
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.26E+01	1.92E-01	12.650	0.192	65.977	0.000	0.907	1.174
ELE (m)	-2.89E-03	5.69E-04	-1.684	0.331	-5.084	0.000		
RC (%)	-1.94E-02	4.02E-03	-0.936	0.194	-4.832	0.000		
SL (m/m)	-6.76E+00	3.35E+00	-0.414	0.205	-2.020	0.044		
AP (mm)	-3.36E-03	7.18E-04	-1.306	0.279	-4.678	0.000		
DA (km ²)	1.39E-04	5.39E-05	1.020	0.396	2.577	0.010		
NOR (m)	2.65E-06	2.87E-06	0.253	0.275	0.921	0.357		
LK (%)	1.15E+00	2.24E-01	1.627	0.317	5.130	0.000		
BFI (%)	-1.61E-01	4.20E-02	-0.973	0.254	-3.835	0.000		
AT (°C)	3.31E-01	5.61E-02	0.755	0.128	5.908	0.000		
Q (m ³ /s)	-5.25E-02	1.89E-02	-0.346	0.125	-2.773	0.006		

S4. MissHW Figure 1. Plot of predicted and observed temperatures.

Missouri Basin NorWeST Stream Temperature Model



S4. MissHW Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



E. SnakeBear

S4. SnakeBear Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	672	1,797	1,842	358	810	2,501
SL (m/m)	672	0.021	0.014	0.024	0.000	0.152
LK (%)	672	0.412	0.010	0.850	0.000	7.56
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	672	502	500	174	225	1,111
NOR (m)	672	1,464,960	1,495,596	95,733	1,211,113	1,609,639
BFI (%)	672	77.5	78.0	5.1	54.0	88.0
DA (km ²)	672	4,972	92	12,977	0	65,496
RC (%)	672	17.7	11.1	18.6	0.0	78.1
AT (°C)	19	17.7	17.3	1.3	14.6	19.8
Q (m ³ /s)	19	4.01	3.88	1.41	2.18	7.49
TW (0/1)	1 ¹					
AugT (°C)	1,173	14.0	13.6	3.9	4.1	24.5

¹Stream length coded as cold tailwater was 102 km.

S4. SnakeBear Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

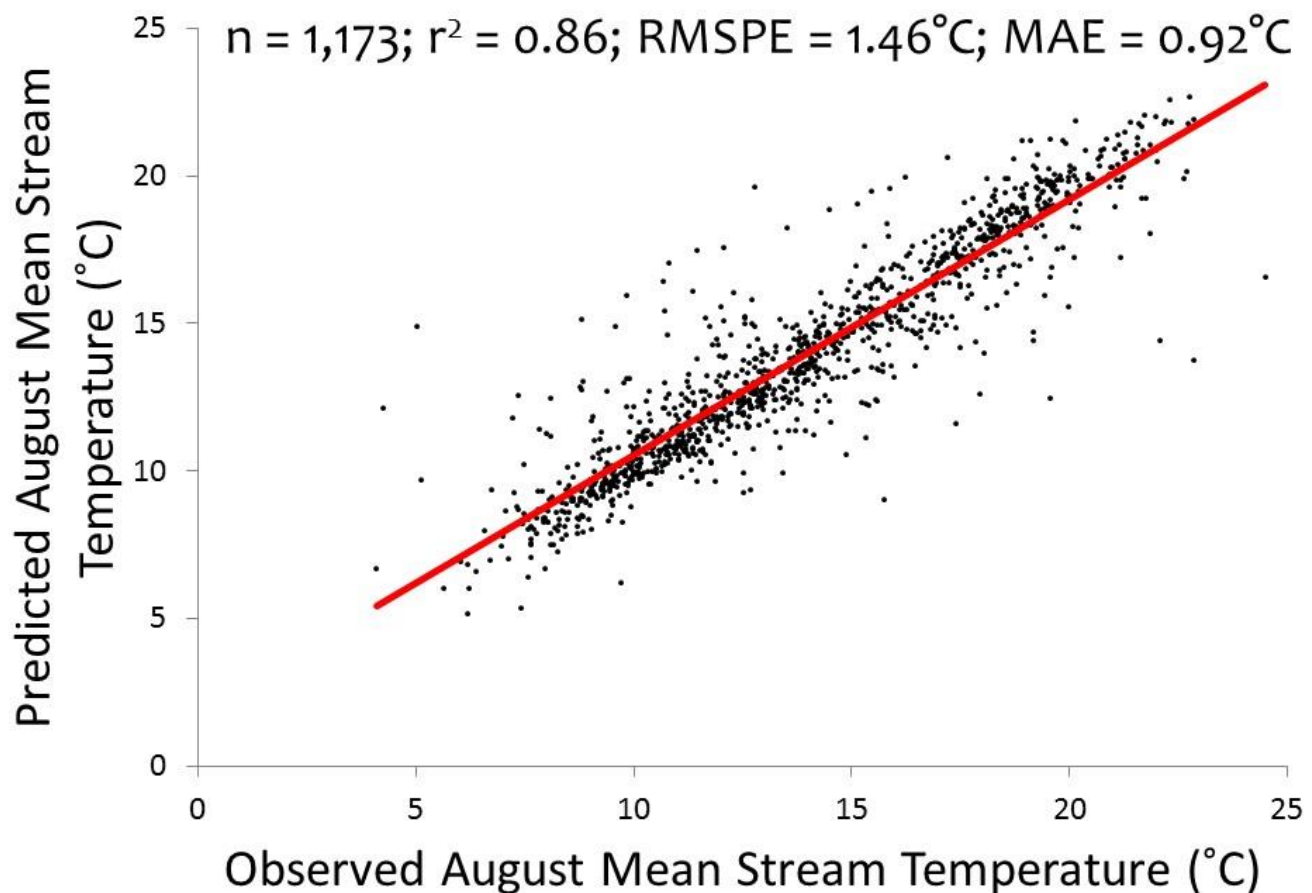
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.41	1.00									
LK	-0.32	-0.31	1.00								
GLA	na	na	na	1.00							
AP	0.66	0.36	-0.18	na	1.00						
NOR	0.44	0.09	-0.02	na	0.13	1.00					
BFI	0.18	0.12	-0.07	na	0.18	0.09	1.00				
DA	-0.68	-0.21	0.44	na	-0.47	-0.20	-0.25	1.00			
RC	0.18	0.24	-0.26	na	0.38	-0.08	0.22	-0.30	1.00		
AT	-0.03	0.06	-0.04	na	-0.07	-0.09	0.00	0.01	-0.02	1.00	
Q	0.02	0.05	-0.04	na	0.00	0.00	0.04	-0.01	0.07	0.00	1.00
AugT	-0.71	-0.56	0.47	na	-0.59	-0.31	-0.16	0.51	-0.30	0.11	-0.13

S4. SnakeBear Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

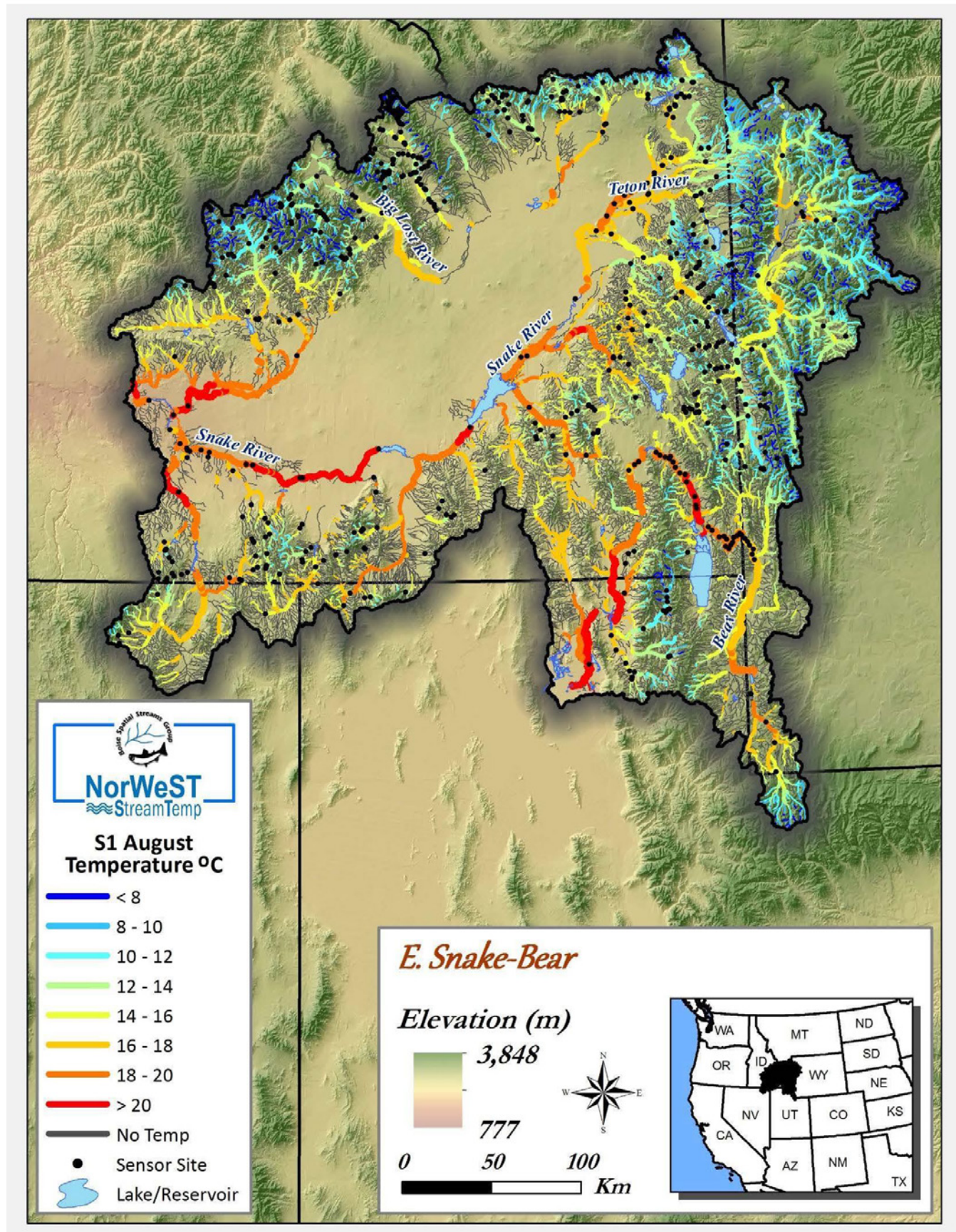
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.38E+01	3.42E-01	13.830	0.342	40.386	0.000	0.859	1.465
ELE (m)	-5.75E-03	8.60E-04	-4.120	0.616	-6.682	0.000		
RC (%)	-1.16E-02	4.83E-03	-0.434	0.180	-2.412	0.016		
SL (m/m)	-2.00E+01	4.46E+00	-0.944	0.210	-4.492	0.000		
AP (mm)	-6.64E-04	1.07E-03	-0.231	0.371	-0.623	0.534		
DA (km ²)	-1.17E-05	2.81E-05	-0.303	0.729	-0.416	0.678		
NOR (m)	-5.02E-06	2.88E-06	-0.960	0.551	-1.742	0.082		
LK (%)	3.06E-01	1.93E-01	0.520	0.328	1.586	0.113		
BFI (%)	-3.94E-02	3.77E-02	-0.405	0.387	-1.046	0.296		
AT (°C)	2.35E-01	4.77E-02	0.628	0.128	4.924	0.000		
Q (m ³ /s)	-2.11E-01	4.74E-02	-0.595	0.134	-4.444	0.000		

S4. SnakeBear Figure 1. Plot of predicted and observed temperatures.

SnakeBear Basin NorWeST Stream Temperature Model



S4. SnakeBear Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



F. Mid-Snake

S4. Mid-Snake Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	1,773	1,472	1,516	323	616	2,407
SL (m/m)	1,773	0.0455	0.0361	0.0395	0	0.254
LK (%)	1,773	0.147	0	0.645	0	7.97
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	1,773	738	763	265	185	1,599
NOR (m)	1,773	1,549,420	1,552,912	77,044	1,253,627	1,671,843
BFI (%)	1,773	68.7	69	5.41	48	80
DA (km ²)	1,773	2,104	29.3	14,010	1.21	149,307
RC (%)	1,773	43.0	46.7	28.5	0	97.2
AT (°C)	19	19.3	19.7	1.24	16.1	21.4
Q (m ³ /s)	19	4.39	3.92	1.34	2.36	7.22
TW (0/1)	4 ¹					
AugT (°C)	3,384	13.1	12.5	3.70	5.20	26.9

¹Stream length coded as cold tailwater was 181 km.

S4. Mid-Snake Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

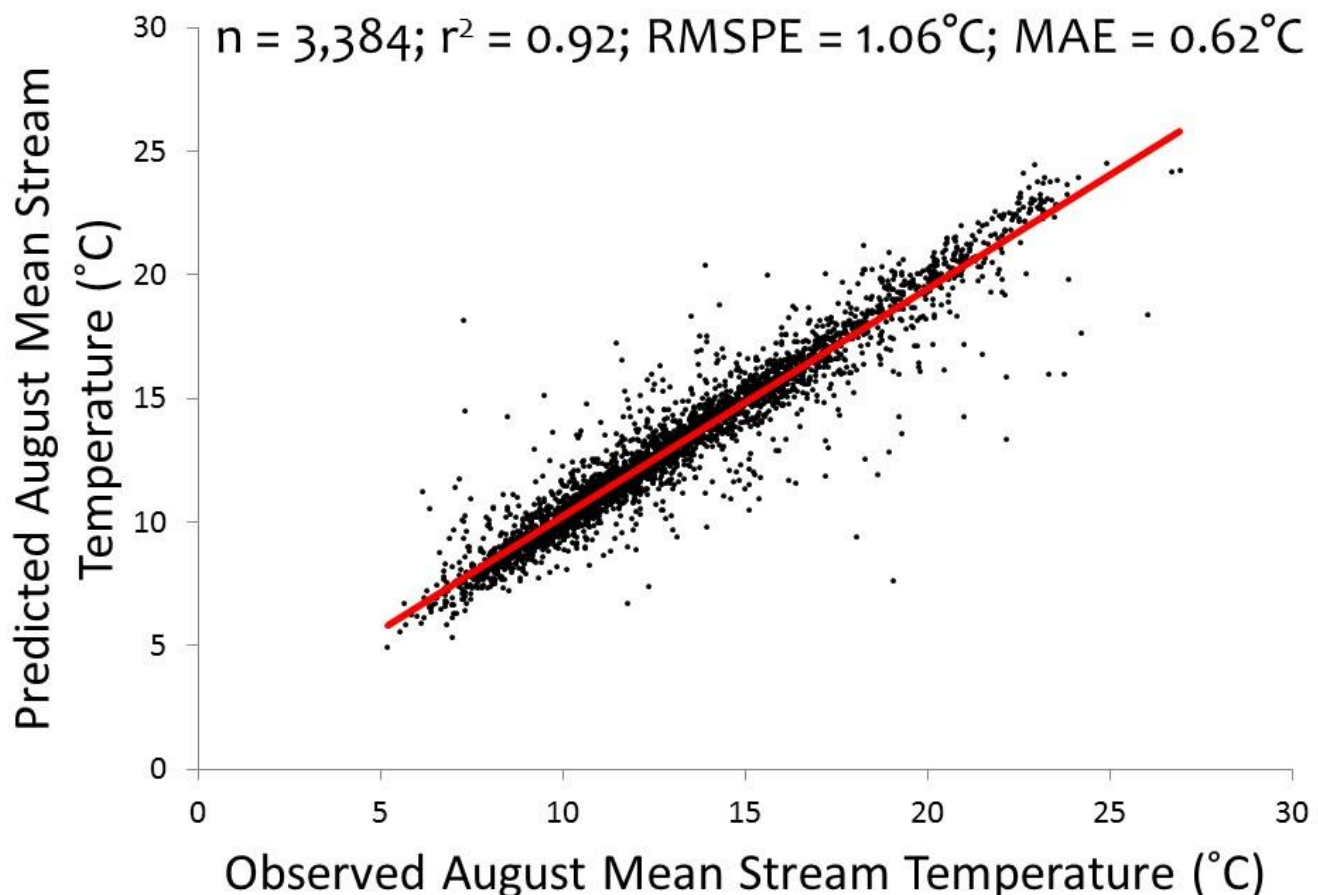
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.27	1.00									
LK	-0.09	-0.09	1.00								
GLA	na	na	na	1.00							
AP	0.59	0.48	-0.07	na	1.00						
NOR	-0.19	0.11	0.05	na	0.38	1.00					
BFI	0.37	0.16	-0.10	na	0.40	0.05	1.00				
DA	-0.34	-0.17	0.16	na	-0.26	-0.08	-0.34	1.00			
RC	0.32	0.20	-0.09	na	0.51	0.50	0.22	-0.21	1.00		
AT	-0.02	-0.09	0.01	na	-0.03	0.07	-0.05	-0.02	0.08	1.00	
Q	0.04	-0.06	0.03	na	0.04	0.05	0.05	0.01	0.08	0.10	1.00
AugT	-0.70	-0.42	0.18	na	-0.71	-0.18	-0.45	0.34	-0.56	0.09	-0.12

S4. Mid-Snake Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

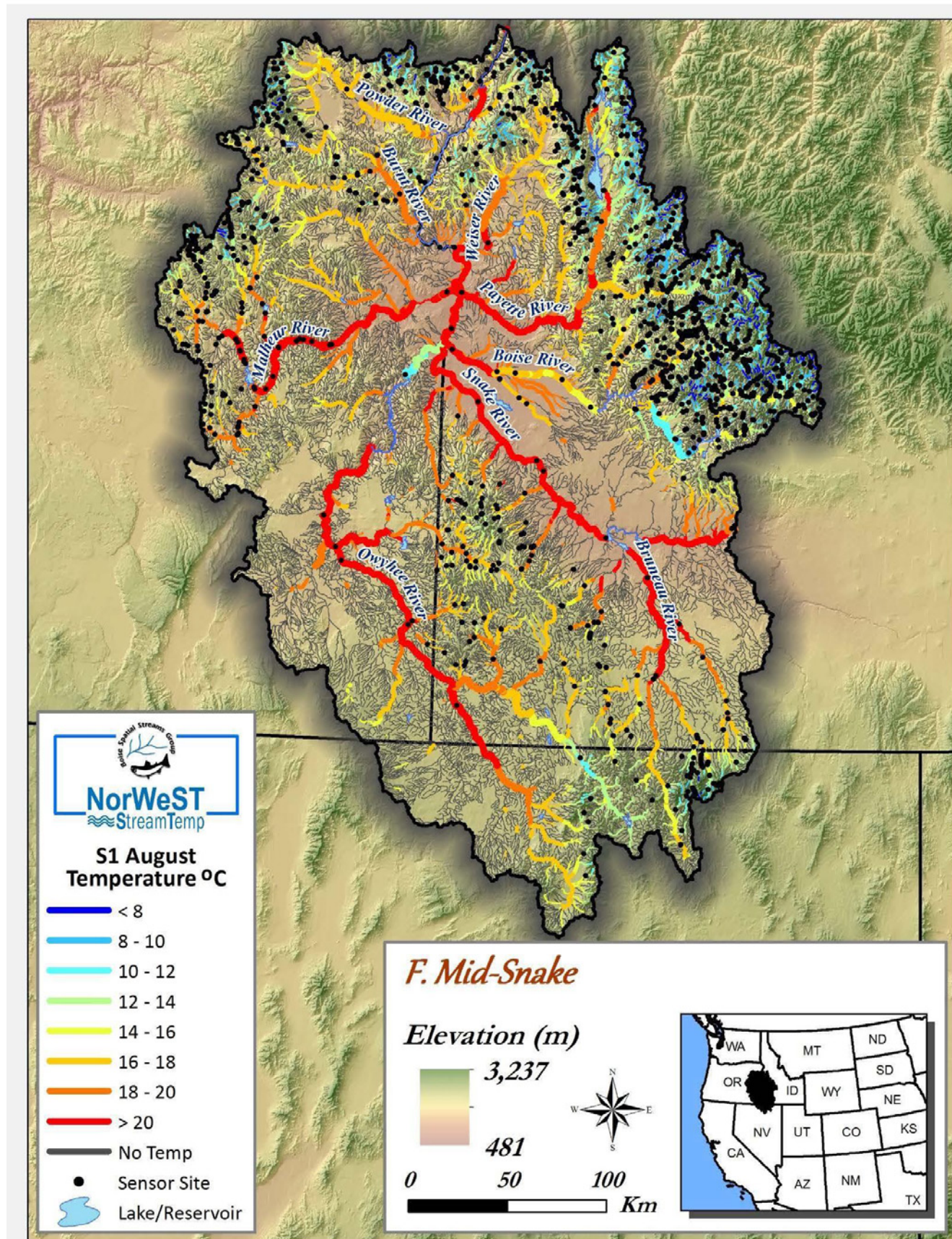
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.32E+01	2.70E-01	13.227	0.270	48.985	0.000	0.918	1.063
ELE (m)	-5.38E-03	3.20E-04	-3.475	0.207	-16.794	0.000		
RC (%)	-1.48E-02	2.28E-03	-0.842	0.130	-6.475	0.000		
SL (m/m)	-8.99E+00	1.42E+00	-0.711	0.112	-6.350	0.000		
AP (mm)	-1.05E-03	4.38E-04	-0.557	0.233	-2.390	0.017		
DA (km ²)	1.56E-05	8.28E-06	0.438	0.232	1.887	0.059		
NOR (m)	-7.68E-06	1.83E-06	-1.184	0.282	-4.202	0.000		
LK (%)	8.01E-01	1.21E-01	1.034	0.156	6.631	0.000		
BFI (%)	-7.80E-02	2.13E-02	-0.844	0.231	-3.661	0.000		
AT (°C)	3.20E-01	5.25E-02	0.793	0.130	6.086	0.000		
Q (m ³ /s)	-2.31E-01	4.60E-02	-0.624	0.124	-5.028	0.000		
TW (0/1)	-6.43E+00	6.12E-01	-6.427	0.612	-10.506	0.000		

S4. Mid-Snake Figure 1. Plot of predicted and observed temperatures.

MidSnake Basin NorWeST Stream Temperature Model



S4. Mid-Snake Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



G. Mid-Columbia

S4. Mid-Col Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	2,760	916	983	442	23.5	2,369
SL (m/m)	2,760	0.0268	0.0191	0.0269	0	0.400
LK (%)	2,760	0.211	0	1.06	0	14.7
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	2,760	724	591	498	207	3,251
NOR (m)	2,760	1,686,394	1,679,203	81,206	1,491,755	1,904,286
BFI (%)	2,760	65.5	65	8.95	39	89
DA (km ²)	2,760	9,155	67.9	56,304	0.84	580,000
RC (%)	2,760	42.5	43.7	29.5	0	96.8
AT (°C)	19	17.3	17.5	0.879	14.8	18.7
Q (m ³ /s)	19	3.31	3.21	0.817	2.02	5.29
TW (0/1)	3 ¹					
AugT (°C)	9,521	14.6	14.5	3.61	3.89	27.5

¹Stream length coded as cold tailwater was 152 km.

S4. Mid-Col Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

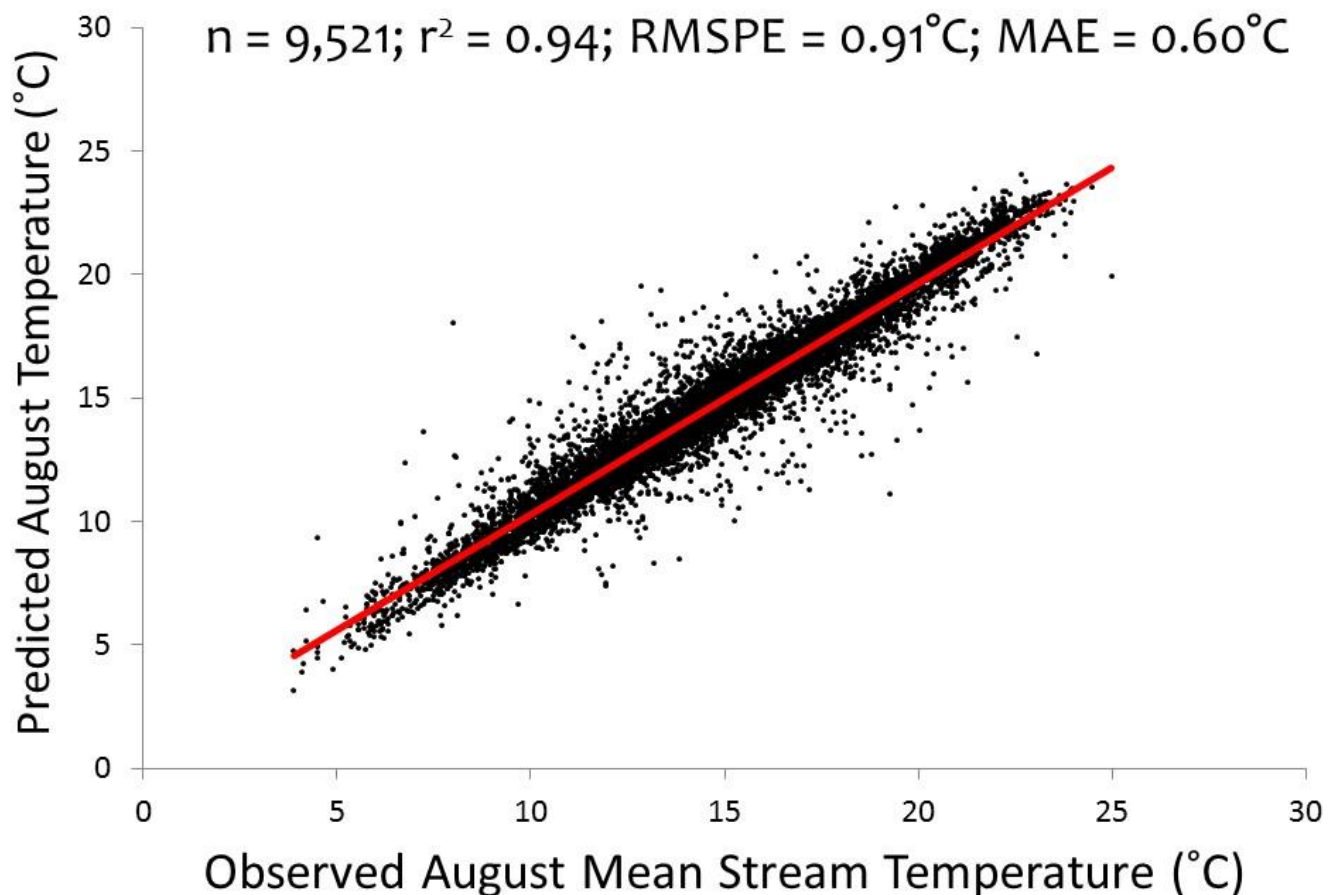
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.25	1.00									
LK	0.09	-0.08	1.00								
GLA	na	na	na	1.00							
AP	-0.05	0.21	-0.01	na	1.00						
NOR	-0.66	-0.10	-0.22	na	0.27	1.00					
BFI	0.03	0.00	0.28	na	0.14	-0.29	1.00				
DA	-0.28	-0.15	0.09	na	-0.07	0.16	-0.06	1.00			
RC	0.44	0.41	-0.06	na	0.46	-0.09	0.09	-0.23	1.00		
AT	0.00	0.00	0.01	na	0.00	-0.02	0.04	-0.01	0.01	1.00	
Q	0.05	0.03	-0.03	na	-0.04	-0.07	-0.04	0.01	0.01	-0.23	1.00
AugT	-0.49	-0.39	0.08	na	-0.42	0.18	-0.26	0.29	-0.64	0.10	-0.03

S4. Mid-Col Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

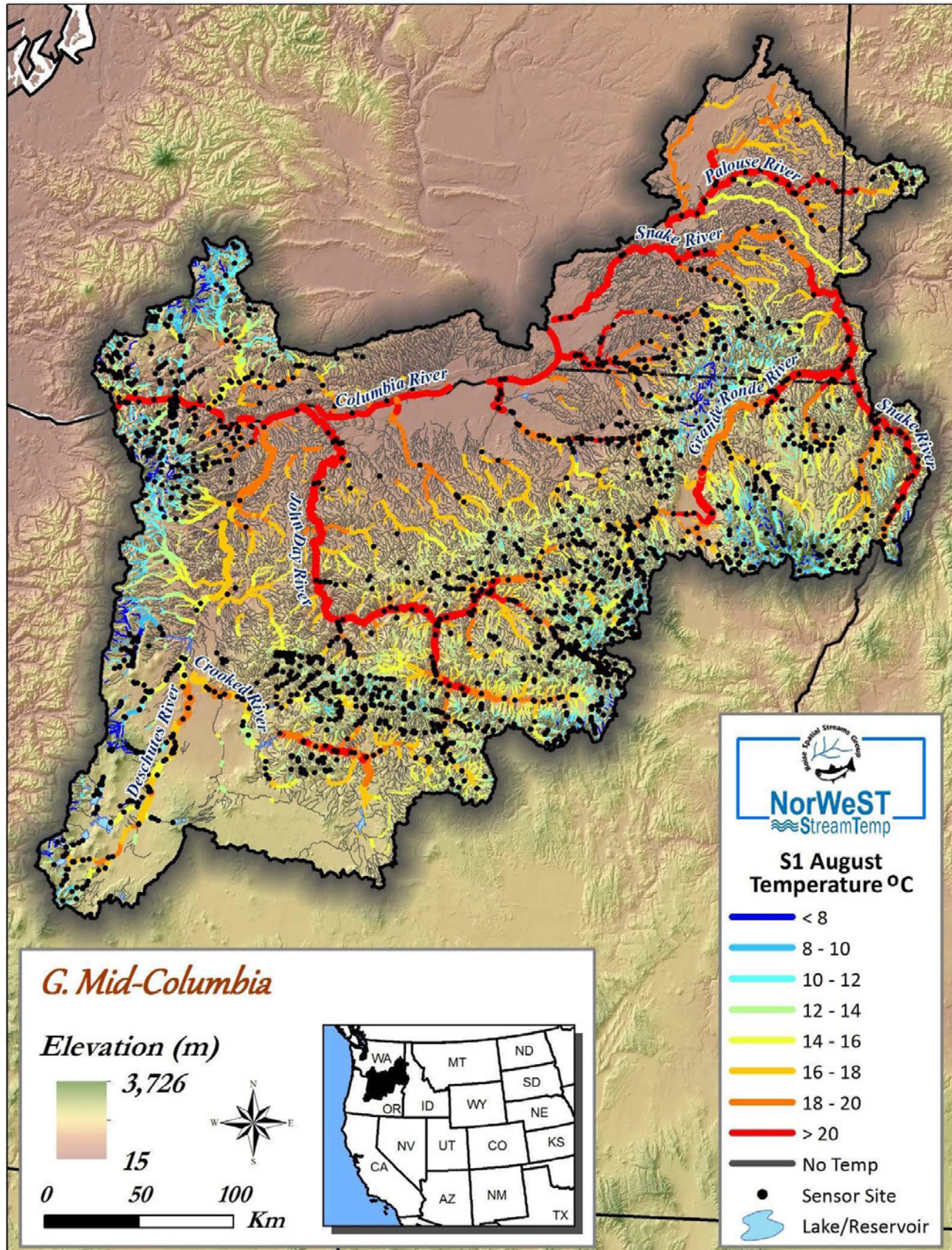
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.41E+01	2.31E-01	14.083	0.231	61.062	0.000	0.936	0.913
ELE (m)	-4.60E-03	3.03E-04	-4.070	0.268	-15.193	0.000		
RC (%)	-1.53E-02	1.78E-03	-0.903	0.105	-8.595	0.000		
SL (m/m)	-9.09E+00	1.64E+00	-0.490	0.089	-5.531	0.000		
AP (mm)	-1.34E-03	2.62E-04	-1.334	0.262	-5.094	0.000		
DA (km ²)	5.41E-06	1.89E-06	0.609	0.213	2.855	0.004		
NOR (m)	-4.77E-06	2.58E-06	-0.774	0.419	-1.849	0.065		
LK (%)	7.42E-01	7.19E-02	1.581	0.153	10.322	0.000		
BFI (%)	-6.54E-02	1.77E-02	-1.172	0.317	-3.694	0.000		
AT (°C)	4.30E-01	7.00E-02	0.757	0.123	6.145	0.000		
Q (m ³ /s)	-5.57E-02	8.63E-02	-0.091	0.141	-0.646	0.519		
TW (0/1)	-6.26E-01	6.31E-01	-0.626	0.631	-0.991	0.322		

S4. Mid-Col Figure 1. Plot of predicted and observed temperatures.

MidColumbia Basin NorWeST Stream Temperature Model



S4. Mid-Col Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



H. OR Coast

S4. OR Coast Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	3,472	321	268	284	0	1,589
SL (m/m)	3,472	0.0278	0.0165	0.0336	0	0.377
LK (%)	3,472	0.193	0	0.848	0	13.1
GLA (km ² /km ²)	3,472	0.00017	0	0.00222	0	0.08
AP (mm)	3,472	1,687	1,553	606	523	4,149
NOR (m)	3,472	1,585,655	1,572,018	130,106	1,355,651	1,865,999
BFI (%)	3,472	50.7	47	11.4	32	80
DA (km ²)	3,472	3,286	39.8	41,345	0.07	620,000
RC (%)	3,472	56.9	68.1	30.7	0	96.4
AT (°C)	19	16.6	16.6	0.686	14.4	17.7
Q (m ³ /s)	19	2.87	2.64	0.870	1.84	5.42
TW (0/1)	7 ¹					
AugT (°C)	9,128	15.4	15.2	2.86	3.69	24.1

¹Stream length coded as cold tailwater was 103 km.

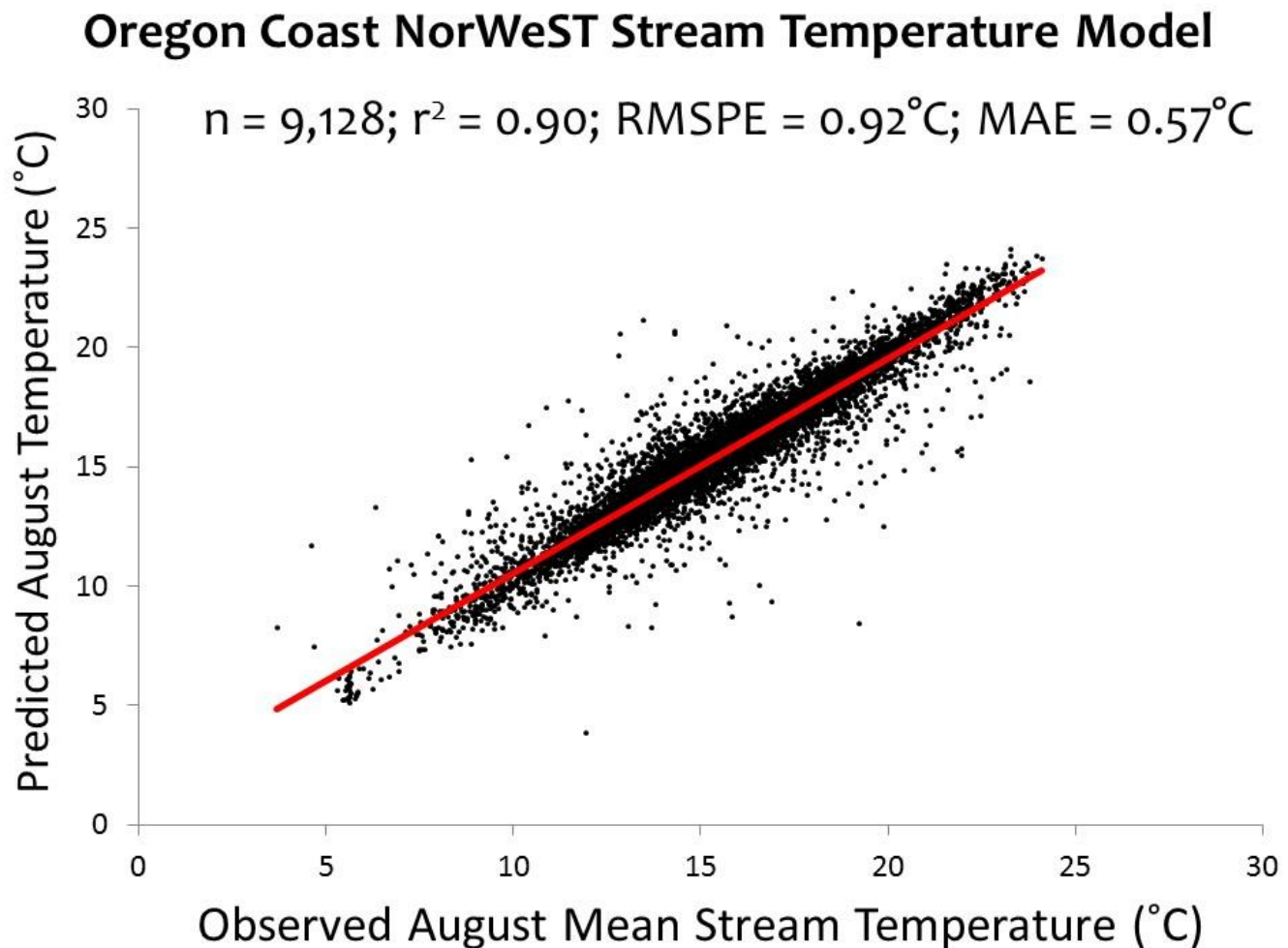
S4. OR Coast Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.34	1.00									
LK	0.16	-0.05	1.00								
GLA	0.06	-0.02	-0.01	1.00							
AP	-0.23	0.15	-0.02	0.05	1.00						
NOR	-0.33	-0.06	0.05	0.11	0.48	1.00					
BFI	0.72	0.16	0.15	0.10	-0.16	0.04	1.00				
DA	-0.08	-0.06	0.07	-0.01	0.01	0.10	0.00	1.00			
RC	0.21	0.28	-0.07	0.03	0.25	0.21	0.12	-0.14	1.00		
AT	0.01	0.00	0.01	0.00	0.02	0.02	0.04	0.00	0.01	1.00	
Q	0.02	0.01	0.00	0.00	-0.01	-0.02	0.03	0.00	-0.03	0.22	1.00
AugT	-0.40	-0.39	-0.07	-0.13	-0.35	-0.20	-0.35	0.15	-0.44	0.08	0.05

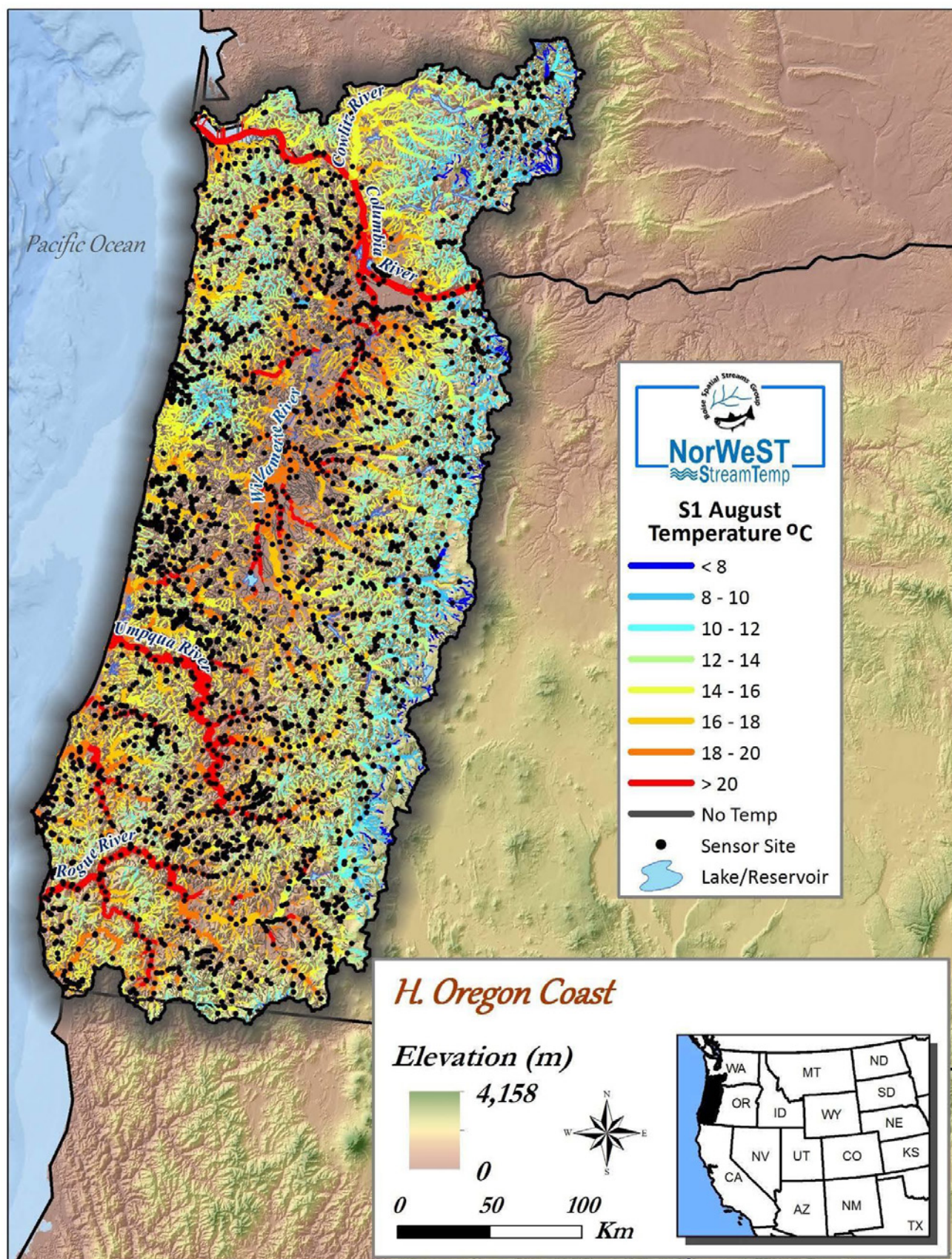
S4. OR Coast Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.51E+01	1.76E-01	15.064	0.176	85.504	0.000	0.897	0.919
ELE (m)	-5.33E-03	3.14E-04	-3.025	0.178	-16.966	0.000		
RC (%)	-1.52E-02	1.39E-03	-0.935	0.085	-10.953	0.000		
SL (m/m)	-6.95E+00	1.08E+00	-0.466	0.073	-6.411	0.000		
AP (mm)	-6.81E-04	1.47E-04	-0.825	0.178	-4.624	0.000		
DA (km ²)	7.02E-06	1.82E-06	0.581	0.150	3.862	0.000		
NOR (m)	-4.88E-06	1.12E-06	-1.270	0.290	-4.372	0.000		
LK (%)	1.60E-01	6.67E-02	0.272	0.113	2.404	0.016		
GLA (%)	-5.00E+01	1.33E+01	-0.222	0.059	-3.767	0.000		
BFI (%)	7.71E-03	1.21E-02	0.175	0.275	0.637	0.524		
AT (°C)	4.74E-01	9.89E-02	0.651	0.136	4.794	0.000		
Q (m ³ /s)	-3.89E-02	9.79E-02	-0.068	0.170	-0.398	0.691		
TW (0/1)	-3.60E+00	4.49E-01	-3.599	0.449	-8.014	0.000		

S4. OR Coast Figure 1. Plot of predicted and observed temperatures.



S4. OR Coast Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



I. OR Southcentral

S4. OR Southcentral Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	578	1,574	1,551	202	1,239	2,350
SL (m/m)	578	0.026	0.019	0.023	0.001	0.130
LK (%)	578	0.12	0.00	0.46	0.00	4.02
GLA (km ² /km ²)	na	na	na	na	na	Na
AP (mm)	578	653	586	266	195	1,528
NOR (m)	578	1,418,679	1,406,398	55,344	1,327,310	1,579,605
BFI (%)	578	68.8	66.0	8.4	56.0	84.0
DA (km ²)	578	273.7	36.9	1,041	1.1	9,164
RC (%)	578	33.6	30.7	25.0	0.0	87.7
AT (°C)	19	17.3	17.4	1.0	14.8	18.9
Q (m ³ /s)	19	0.753	0.717	0.226	0.405	1.25
TW (0/1)	0					
AugT (°C)	1,676	13.5	13.6	3.55	5.26	23.5

S4. OR Southcentral Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

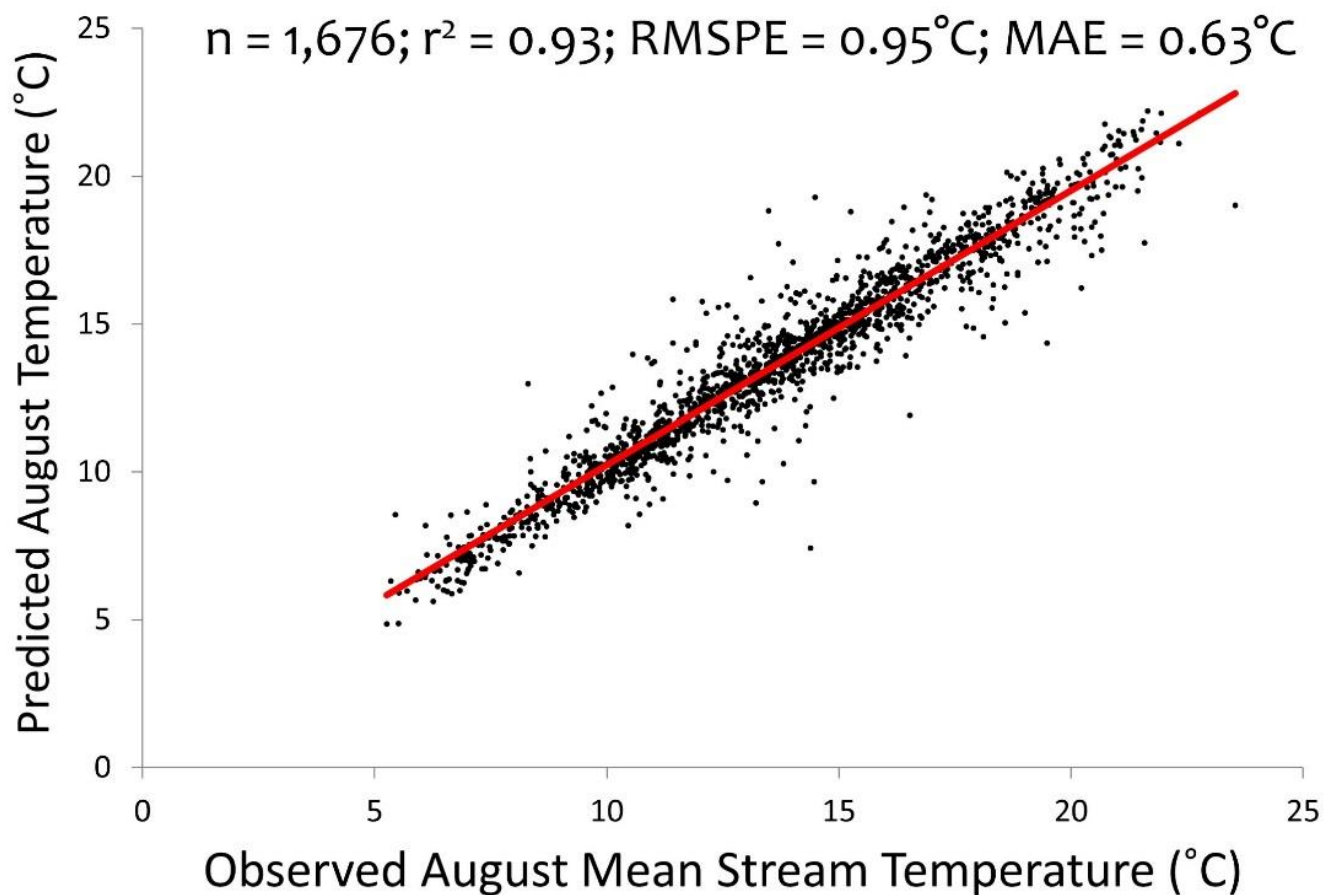
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.38	1.00									
LK	-0.24	-0.18	1.00								
GLA	na	na	na	1.00							
AP	0.28	0.50	-0.10	na	1.00						
NOR	-0.30	-0.16	-0.13	na	-0.09	1.00					
BFI	-0.28	0.01	0.14	na	0.44	0.12	1.00				
DA	-0.31	-0.24	0.76	na	-0.18	-0.06	0.20	1.00			
RC	0.09	0.41	-0.14	na	0.52	0.24	0.23	-0.18	1.00		
AT	-0.04	0.00	0.04	na	-0.06	-0.01	-0.03	0.04	-0.05	1.00	
Q	0.04	0.05	-0.03	na	0.15	0.01	0.20	-0.01	0.10	-0.06	1.00
AugT	-0.35	-0.50	0.27	na	-0.64	-0.14	-0.35	0.33	-0.57	0.13	-0.24

S4. OR Southcentral Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

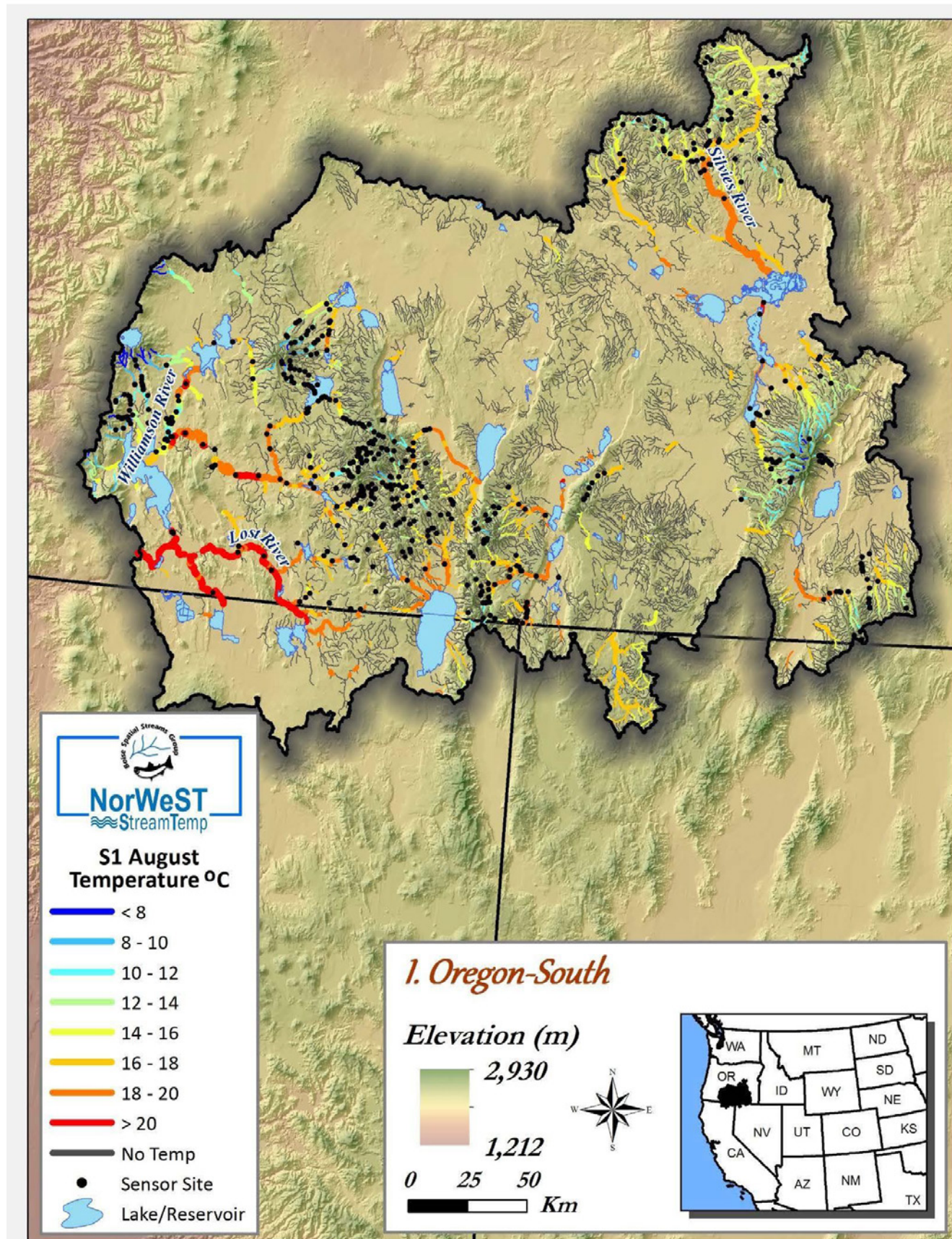
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.40E+01	2.52E-01	13.958	0.252	55.488	0.000	0.928	0.949
ELE (m)	-5.59E-03	8.69E-04	-2.265	0.352	-6.440	0.000		
RC (%)	-1.08E-02	4.53E-03	-0.542	0.227	-2.391	0.017		
SL (m/m)	-2.05E+01	5.00E+00	-0.958	0.234	-4.094	0.000		
AP (mm)	-2.97E-03	8.87E-04	-1.581	0.471	-3.352	0.001		
DA (km ²)	5.51E-04	1.66E-04	1.149	0.346	3.322	0.001		
NOR (m)	-1.32E-05	3.47E-06	-1.463	0.385	-3.804	0.000		
LK (%)	4.11E-01	3.24E-01	0.374	0.295	1.265	0.206		
BFI (%)	-9.56E-02	3.09E-02	-1.599	0.516	-3.096	0.002		
AT (°C)	3.40E-01	5.24E-02	0.655	0.101	6.486	0.000		
Q (m ³ /s)	-1.16E+00	2.30E-01	-0.527	0.104	-5.065	0.000		

S4. OR Southcentral Figure 1. Plot of predicted and observed temperatures.

Southcentral Oregon NorWeST Stream Temperature Model



S4. OR Southcentral Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



J. Lahontan

S4. Lahontan Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	310	1,831	1,827	242	1,206	2,645
SL (m/m)	310	0.0284	0.0170	0.0303	0.00001	0.215
LK (%)	310	0.809	0	4.38	0	38.3
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	310	534	402	312	127	1,691
NOR (m)	310	2,118,659	2,103,190	95,443	1,943,836	2,329,746
BFI (%)	310	65.7	65	3.89	54	76
DA (km ²)	310	381	37.2	1,032	2.41	6,911
RC (%)	310	20.2	15.4	17.6	0	63.1
AT (°C)	21	20.4	19.8	1.05	18.4	21.8
Q (m ³ /s)	21	0.349	0.243	0.236	0.151	0.930
TW (0/1)	0					
AugT (°C)	576	15.3	15.2	3.32	7.26	24.0

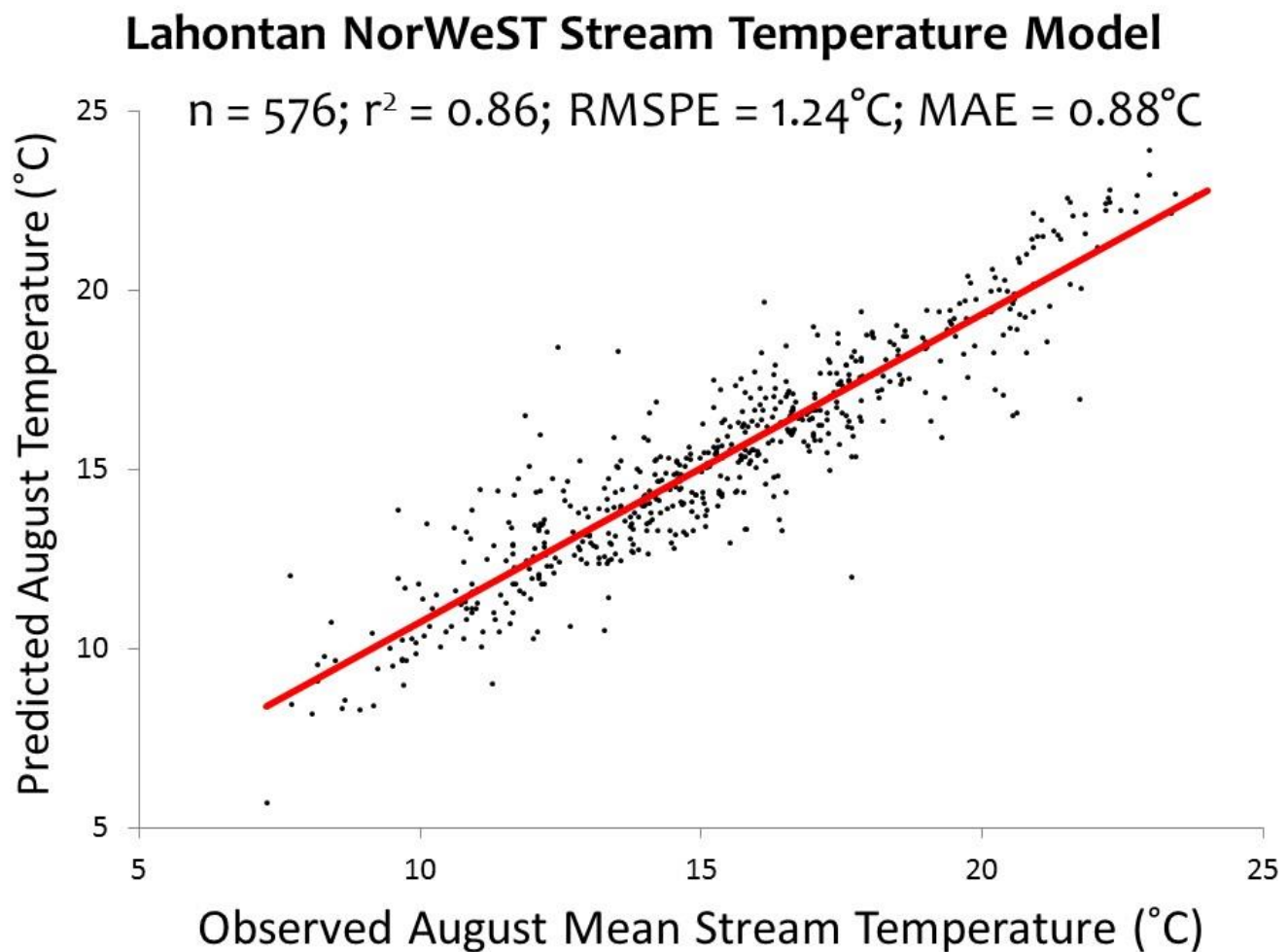
S4. Lahontan Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.43	1.00									
LK	-0.04	-0.14	1.00								
GLA	na	na	na	1.00							
AP	0.46	0.37	0.12	na	1.00						
NOR	-0.24	-0.15	-0.12	na	-0.33	1.00					
BFI	0.17	0.26	0.14	na	0.15	-0.39	1.00				
DA	-0.51	-0.30	0.16	na	-0.30	-0.23	-0.25	1.00			
RC	0.51	0.37	0.14	na	0.71	-0.52	0.23	-0.08	1.00		
AT	0.17	0.03	0.04	na	0.08	-0.21	0.25	0.01	0.19	1.00	
Q	0.01	-0.02	0.01	na	0.11	0.14	0.00	-0.15	-0.02	0.14	1.00
AugT	-0.63	-0.60	0.16	na	-0.54	0.04	-0.23	0.57	-0.49	0.01	-0.23

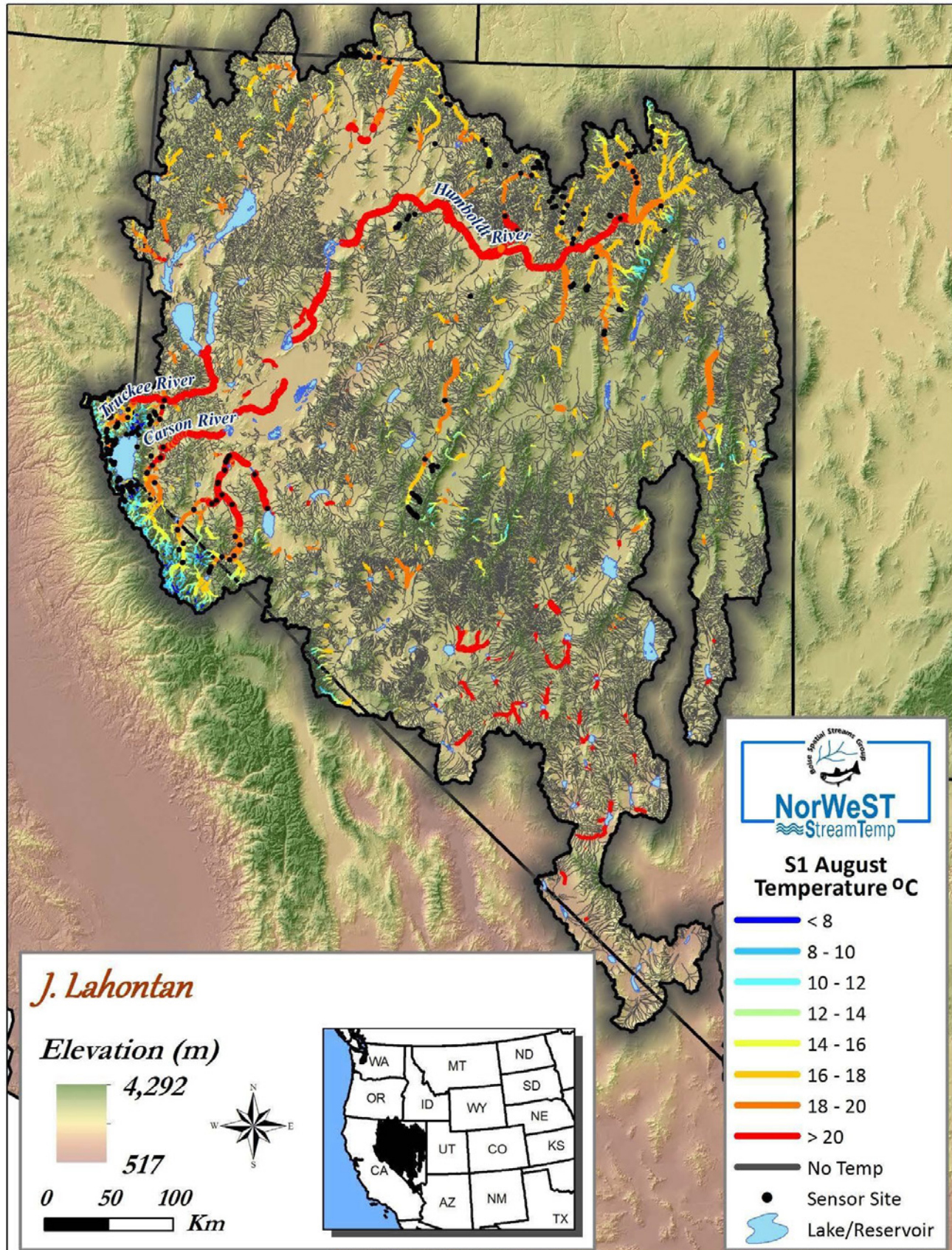
S4. Lahontan Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.54E+01	1.96E-01	15.350	0.196	78.244	0.000	0.860	1.243
ELE (m)	-4.44E-03	7.45E-04	-2.155	0.362	-5.960	0.000		
RC (%)	-4.43E-02	9.70E-03	-1.569	0.343	-4.569	0.000		
SL (m/m)	-1.96E+01	3.77E+00	-1.187	0.229	-5.190	0.000		
AP (mm)	-1.42E-03	6.33E-04	-0.888	0.395	-2.247	0.025		
DA (km ²)	5.11E-04	1.67E-04	1.054	0.346	3.049	0.002		
NOR (m)	-4.78E-06	1.99E-06	-0.912	0.380	-2.401	0.017		
LK (%)	9.26E-02	3.62E-02	0.813	0.318	2.556	0.011		
BFI (%)	-9.90E-02	4.05E-02	-0.771	0.315	-2.446	0.015		
AT (°C)	2.95E-01	1.23E-01	0.624	0.260	2.396	0.017		
Q (m ³ /s)	-1.87E+00	5.30E-01	-0.884	0.251	-3.521	0.000		

S4. Lahontan Figure 1. Plot of predicted and observed temperatures.



S4. Lahontan Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



K. WA East

S4. WA East Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	741	636	610	275	142	1,866
SL (m/m)	741	0.0260	0.0186	0.0269	0	0.241
LK (%)	741	0.338	0.039	0.919	0	10.0
GLA (km ² /km ²)	741	0.000195	0	0.00166	0	0.02
AP (mm)	741	707	630	401	170	2,648
NOR (m)	741	1,964,693	1,975,545	83,457	1,783,931	2,106,507
BFI (%)	741	68.8	69	3.64	41	77
DA (km ²)	741	3,085	172	21,654	0.56	230,307
RC (%)	741	41.4	42.9	27.7	0	93.4
AT (°C)	19	16.8	16.8	0.682	13.5	18.2
Q (m ³ /s)	19	16.8	14.6	8.09	8.95	47.3
TW (0/1)	0					
AugT (°C)	2,609	14.2	13.9	3.23	5.94	25.2

S4. WA East Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

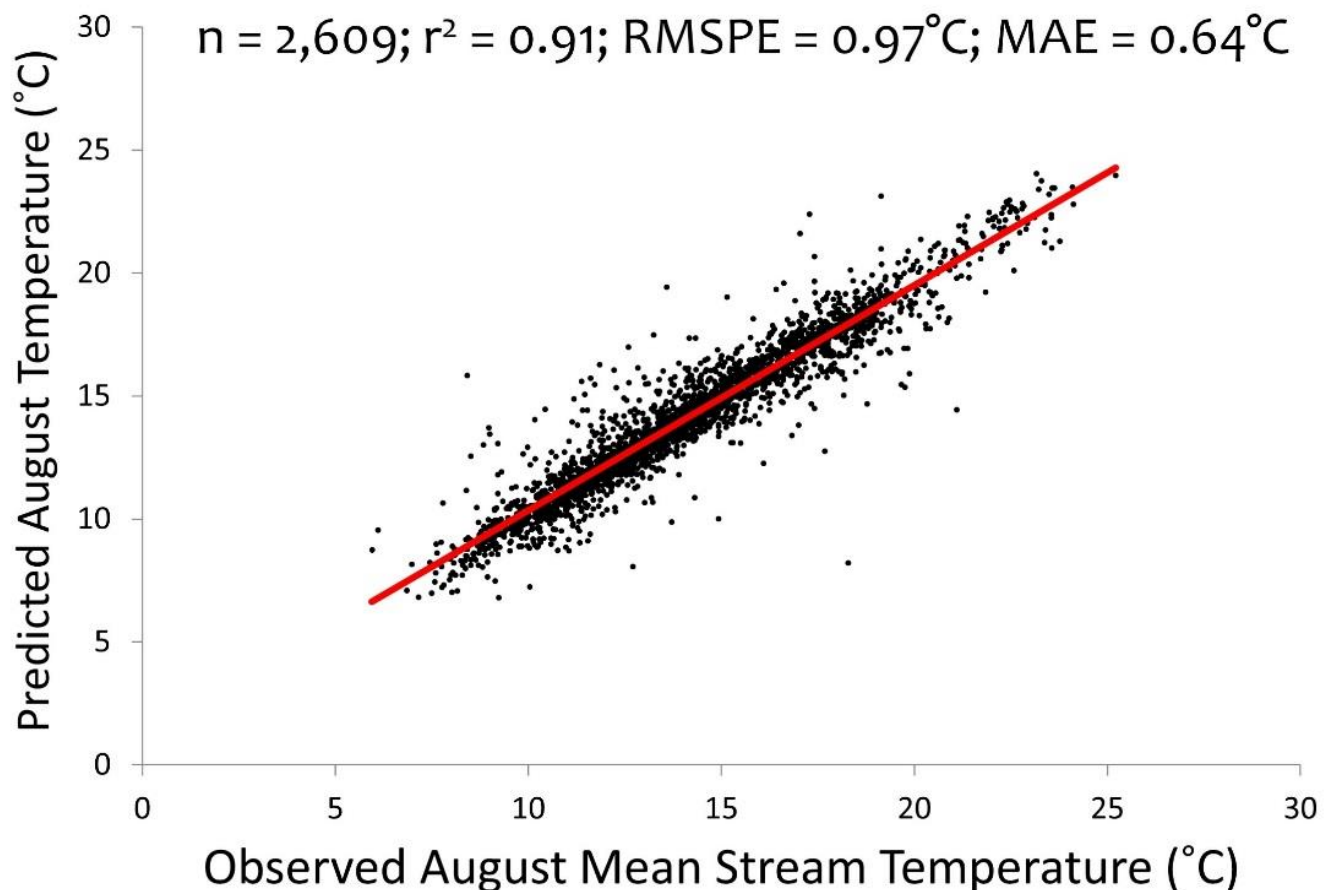
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.33	1.00									
LK	0.01	-0.11	1.00								
GLA	0.09	-0.08	0.01	1.00							
AP	0.56	0.11	0.23	0.13	1.00						
NOR	0.16	0.23	-0.11	-0.06	-0.04	1.00					
BFI	0.10	0.18	-0.19	-0.02	-0.13	0.24	1.00				
DA	-0.20	-0.10	0.10	-0.02	-0.15	-0.04	-0.04	1.00			
RC	0.56	0.32	-0.05	0.07	0.50	0.12	0.08	-0.19	1.00		
AT	0.06	0.02	0.00	0.03	0.05	0.02	0.02	-0.02	0.04	1.00	
Q	0.02	0.02	-0.03	0.00	0.04	0.02	0.03	0.03	0.02	-0.22	1.00
AugT	-0.68	-0.44	0.18	-0.07	-0.42	-0.28	-0.29	0.20	-0.56	0.09	-0.21

S4. WA East Table 3. Parameter estimates and summary statistics for SSN models that predict mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

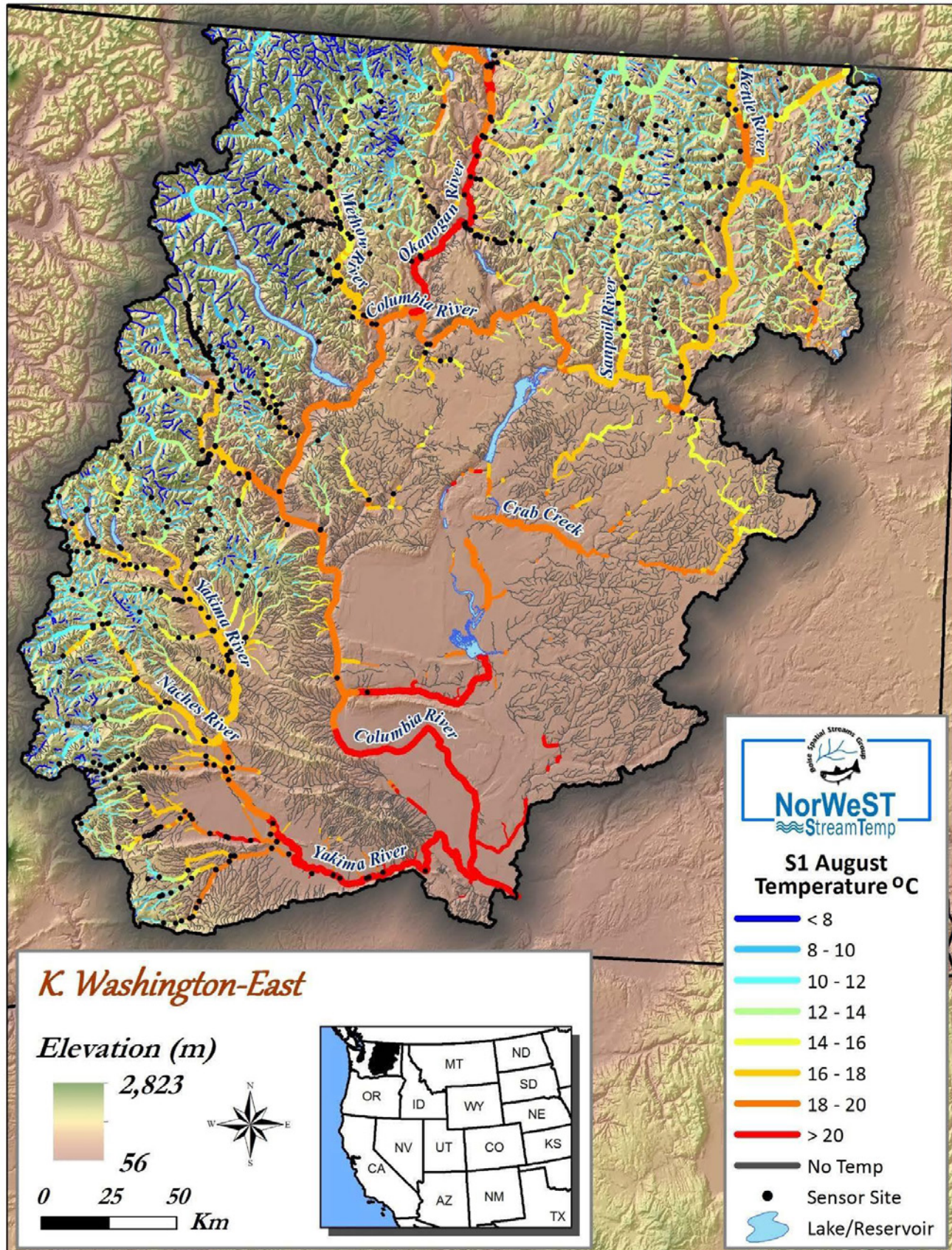
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.39E+01	2.41E-01	13.939	0.241	57.933	0.000	0.910	0.972
ELE (m)	-5.06E-03	4.03E-04	-2.785	0.222	-12.562	0.000		
RC (%)	-9.99E-03	2.60E-03	-0.555	0.145	-3.841	0.000		
SL (m/m)	-1.22E+01	2.66E+00	-0.658	0.143	-4.587	0.000		
AP (mm)	-9.47E-04	3.52E-04	-0.760	0.283	-2.687	0.007		
DA (km ²)	6.99E-06	5.47E-06	0.303	0.237	1.278	0.202		
NOR (m)	-4.34E-06	2.30E-06	-0.724	0.384	-1.886	0.059		
LK (%)	6.63E-01	1.03E-01	1.220	0.189	6.455	0.000		
GLA (%)	-8.06E+01	5.11E+01	-0.268	0.170	-1.579	0.115		
BFI (%)	-9.49E-02	3.31E-02	-0.691	0.241	-2.865	0.004		
AT (°C)	3.81E-01	8.84E-02	0.520	0.121	4.303	0.000		
Q (m ³ /s)	-4.73E-02	9.26E-03	-0.766	0.150	-5.106	0.000		

S4. WA East Figure 1. Plot of predicted and observed temperatures.

WA East/Upper Columbia NorWeST Stream Temperature Model



S4. WA East Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



L. WA West

S4. WA West Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	1,146	117	62	155	0	1,638
SL (m/m)	1,146	0.0252	0.0111	0.0389	0	0.320
LK (%)	1,146	0.739	0.071	1.77	0	14.8
GLA (km ² /km ²)	1,146	0.00211	0	0.0155	0	0.38
AP (mm)	1,146	1,794	1,427	855	453	5,710
NOR (m)	1,146	1,995,880	1,987,085	52,095	1,844,229	2,120,074
BFI (%)	1,146	57.2	57	6.56	43	71
DA (km ²)	1,146	187	31.5	490	0.34	8,014
RC (%)	1,146	58.5	66.1	26.5	0	96.4
AT (°C)	21	15.4	15.4	0.687	12.7	16.7
Q (m ³ /s)	21	10.3	9.19	3.62	5.99	21.8
TW (0/1)	0					
AugT (°C)	3,668	14.2	14.1	2.52	3.89	23.6

S4. WA West Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

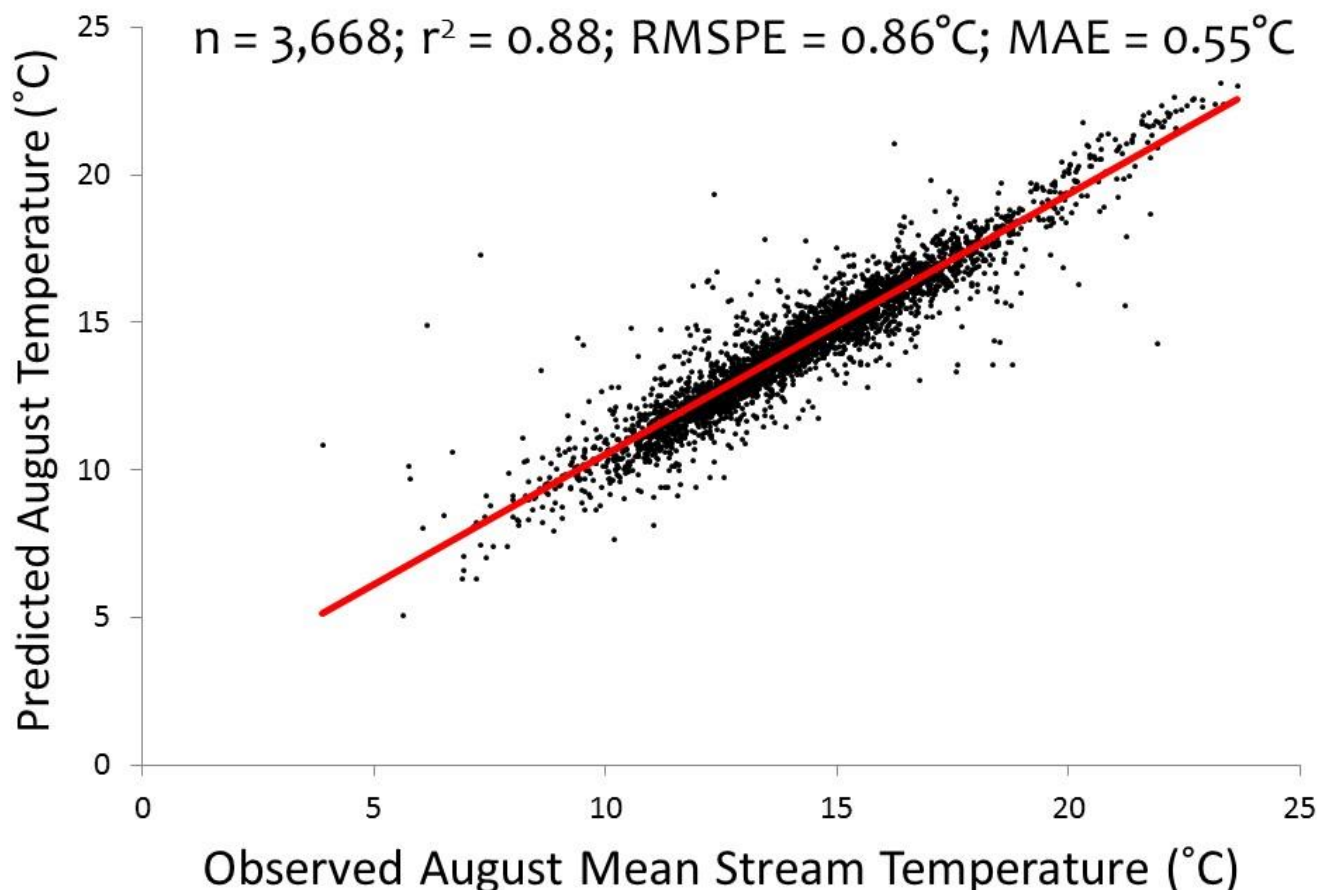
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.39	1.00									
LK	-0.09	-0.13	1.00								
GLA	0.20	0.05	-0.04	1.00							
AP	0.44	0.38	-0.20	0.08	1.00						
NOR	-0.03	0.13	-0.13	0.19	0.02	1.00					
BFI	0.01	-0.07	0.24	0.04	-0.47	-0.21	1.00				
DA	-0.12	-0.20	0.04	0.14	-0.09	0.08	-0.01	1.00			
RC	0.37	0.36	-0.13	-0.05	0.39	-0.02	-0.15	-0.34	1.00		
AT	-0.03	0.06	-0.03	0.02	0.03	0.04	-0.01	0.00	0.04	1.00	
Q	0.03	0.03	-0.01	0.01	0.07	0.03	-0.10	-0.04	0.03	-0.25	1.00
AugT	-0.50	-0.36	0.29	-0.22	-0.39	-0.05	0.14	0.18	-0.38	0.15	-0.08

S4. WA West Table 3. Parameter estimates and summary statistics for SSN models that predict mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

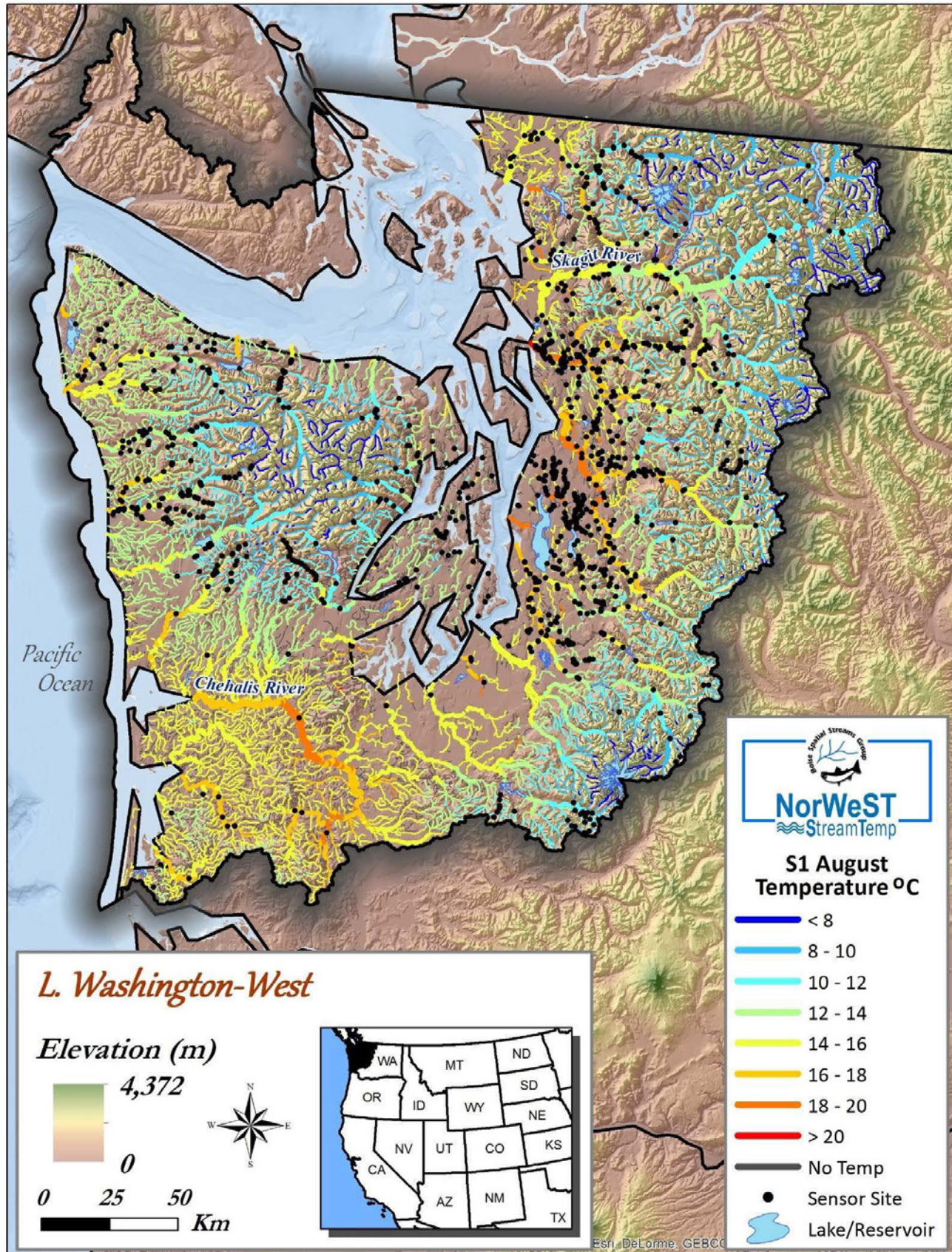
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.39E+01	3.24E-01	13.872	0.324	42.758	0.000	0.884	0.861
ELE (m)	-4.84E-03	5.67E-04	-1.506	0.176	-8.535	0.000		
RC (%)	-8.10E-03	1.99E-03	-0.431	0.106	-4.081	0.000		
SL (m/m)	-8.97E-01	1.47E+00	-0.070	0.114	-0.612	0.541		
AP (mm)	-1.05E-04	1.88E-04	-0.180	0.322	-0.558	0.577		
DA (km ²)	1.72E-04	1.37E-04	0.169	0.134	1.261	0.207		
NOR (m)	-4.49E-06	3.64E-06	-0.468	0.379	-1.235	0.217		
LK (%)	3.18E-01	4.27E-02	1.127	0.151	7.451	0.000		
GLA (%)	-1.26E+01	3.69E+00	-0.390	0.115	-3.403	0.001		
BFI (%)	-7.64E-03	2.51E-02	-0.100	0.330	-0.304	0.761		
AT (°C)	4.69E-01	7.17E-02	0.644	0.099	6.533	0.000		
Q (m ³ /s)	-1.00E-02	1.60E-02	-0.072	0.116	-0.624	0.532		

S4. WA West Figure 1. Plot of predicted and observed temperatures.

Coastal Washington NorWeST Stream Temperature Model



S4. WA West Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



M. Yellowstone

S4. Yellowstone Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	321	1,824	1,827	425	938	2,873
SL (m/m)	321	0.0311	0.0198	0.0313	0.00002	0.157
LK (%)	321	0.196	0.012	0.548	0	4.07
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	321	567	529	216	178	1,288
NOR (m)	321	1,650,543	1,653,435	86,896	1,406,793	1,792,602
BFI (%)	321	66.5	67	6.73	36	79
DA (km ²)	321	1,136	77.2	3,377	1.86	34,301
RC (%)	321	31.7	26.6	24.7	0	94.5
AT (°C)	21	18.6	19.5	1.68	15.1	20.6
Q (m ³ /s)	21	14.6	11.2	7.17	7.20	31.3
TW (0/1)	0					
AugT (°C)	513	13.3	12.4	4.08	5.42	26.1

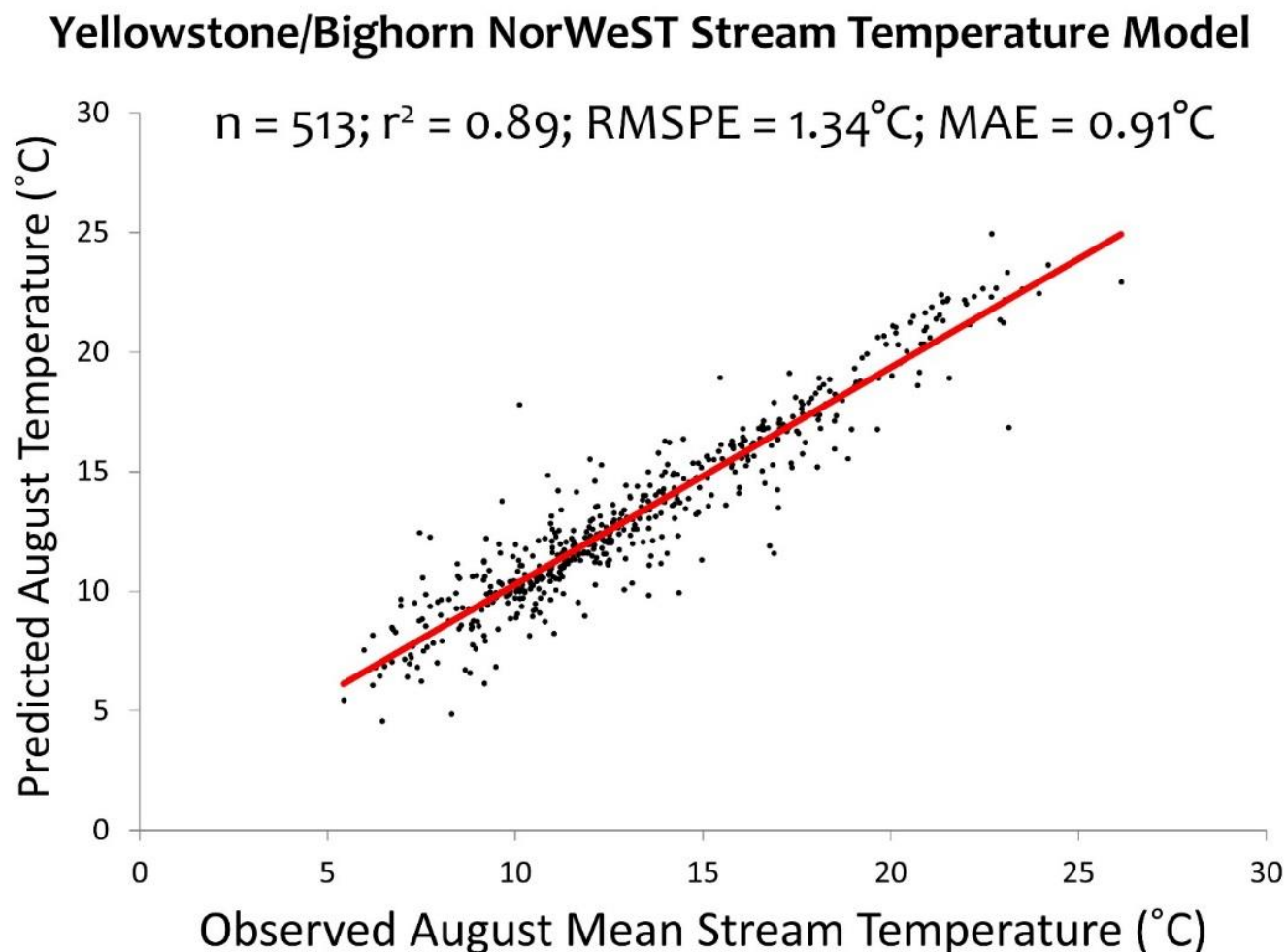
S4. Yellowstone Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.39	1.00									
LK	-0.29	-0.25	1.00								
GLA	na	na	na	1.00							
AP	0.60	0.48	-0.19	na	1.00						
NOR	-0.29	0.19	0.13	na	0.35	1.00					
BFI	0.30	0.35	-0.05	na	0.32	0.20	1.00				
DA	-0.42	-0.30	0.49	na	-0.33	-0.04	-0.37	1.00			
RC	0.30	0.40	-0.18	na	0.42	0.13	0.22	-0.26	1.00		
AT	0.07	0.08	0.03	na	0.05	0.12	0.09	-0.01	0.10	1.00	
Q	-0.04	0.04	0.00	na	0.02	0.14	0.00	-0.07	0.01	0.04	1.00
AugT	-0.72	-0.60	0.30	na	-0.68	-0.14	-0.53	0.51	-0.48	-0.05	-0.08

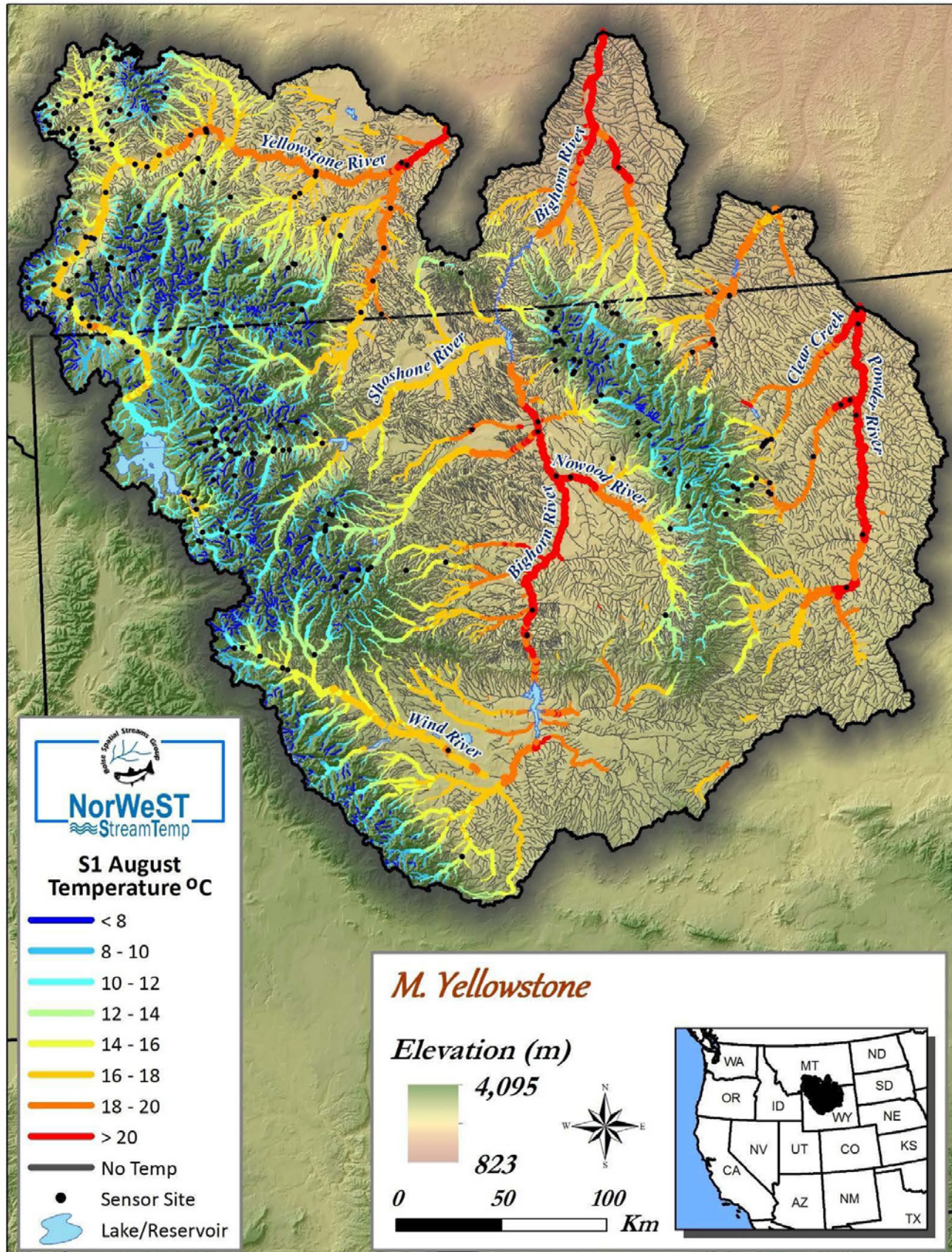
S4. Yellowstone Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.34E+01	2.95E-01	13.366	0.295	45.277	0.000	0.890	1.335
ELE (m)	-4.59E-03	5.93E-04	-3.901	0.504	-7.737	0.000		
RC (%)	-2.30E-02	4.92E-03	-1.138	0.244	-4.665	0.000		
SL (m/m)	-9.41E+00	3.66E+00	-0.591	0.230	-2.573	0.010		
AP (mm)	-2.53E-03	1.20E-03	-1.097	0.521	-2.107	0.036		
DA (km ²)	1.59E-05	3.11E-05	0.108	0.210	0.513	0.608		
NOR (m)	-4.39E-06	3.98E-06	-0.763	0.692	-1.102	0.271		
LK (%)	3.83E-01	2.59E-01	0.420	0.284	1.476	0.141		
BFI (%)	-1.29E-01	3.85E-02	-1.734	0.518	-3.344	0.001		
AT (°C)	3.45E-01	3.65E-02	1.160	0.123	9.456	0.000		
Q (m ³ /s)	-6.01E-02	8.26E-03	-0.862	0.119	-7.271	0.000		

S4. Yellowstone Figure 1. Plot of predicted and observed temperatures.



S4. Yellowstone Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



N. Miss-Marias

S4. Miss-Marias Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	206	1,521	1,536	290	781	2,277
SL (m/m)	206	0.0313	0.0200	0.0378	0.00005	0.233
LK (%)	206	0.130	0	0.342	0	2.33
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	206	635	534	340	277	2,305
NOR (m)	206	1,898,631	1,875,423	76,249	1,764,769	2,092,549
BFI (%)	206	67.7	68	2.42	60	73
DA (km ²)	206	868	32.5	4,657	1.96	42,955
RC (%)	206	38.4	34.0	24.7	0	94.3
AT (°C)	21	16.3	16.6	1.30	13.5	18.5
Q (m ³ /s)	21	3.13	3.35	0.903	1.71	4.92
TW (0/1)	0					
AugT (°C)	300	12.0	11.2	3.72	5.54	25.0

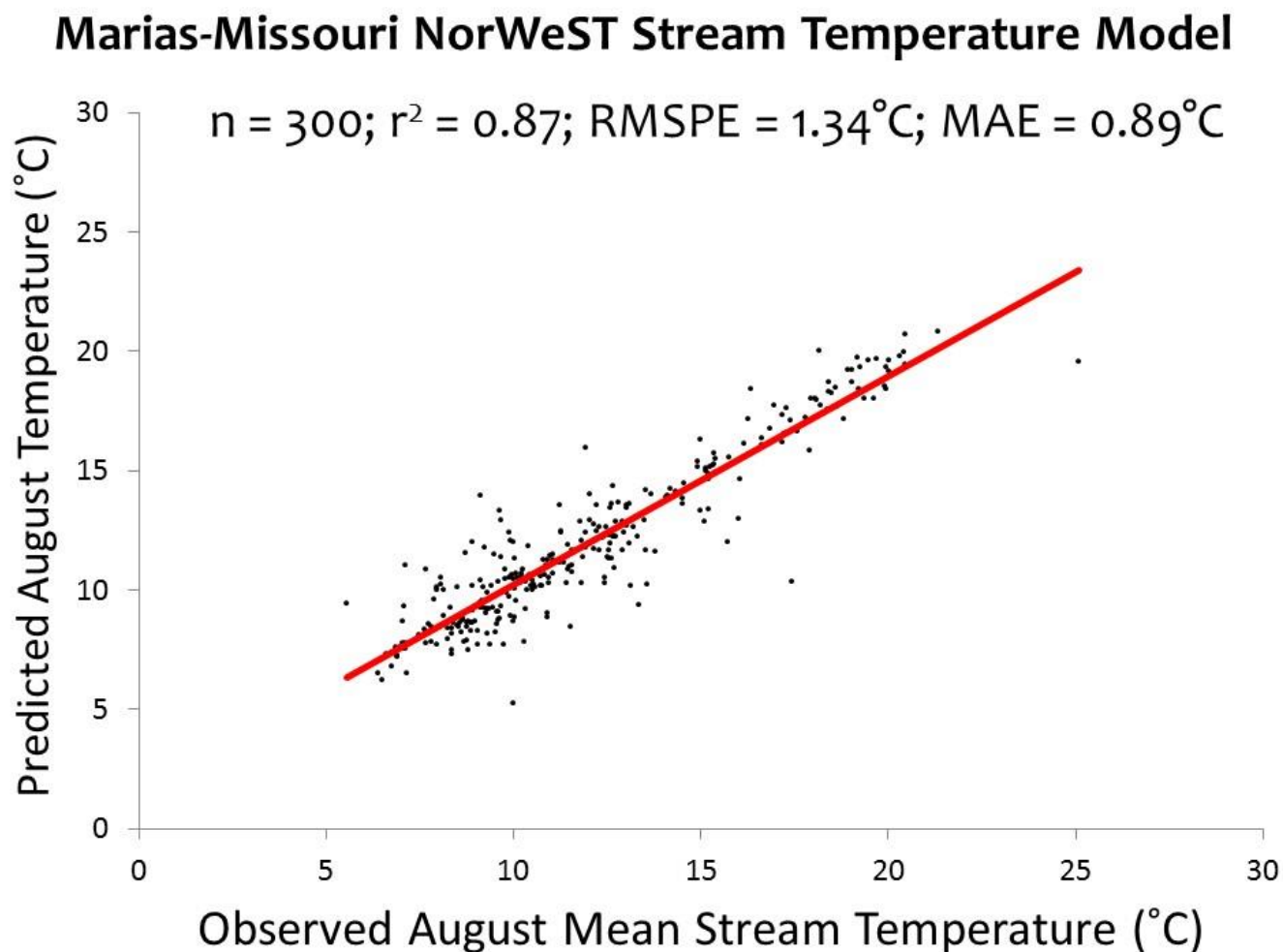
S4. Miss-Marias Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.49	1.00									
LK	-0.09	-0.17	1.00								
GLA	na	na	na	1.00							
AP	0.50	0.46	0.24	na	1.00						
NOR	-0.26	-0.04	0.36	na	0.48	1.00					
BFI	0.46	0.18	-0.05	na	0.06	-0.14	1.00				
DA	-0.26	-0.14	0.20	na	-0.16	-0.08	-0.02	1.00			
RC	0.46	0.29	-0.06	na	0.07	-0.36	0.24	-0.23	1.00		
AT	-0.12	-0.02	-0.03	na	-0.09	-0.03	-0.06	0.13	-0.06	1.00	
Q	-0.04	0.02	0.04	na	0.09	0.09	-0.04	-0.04	-0.10	-0.28	1.00
AugT	-0.76	-0.46	0.18	na	-0.46	0.10	-0.40	0.35	-0.44	0.23	-0.11

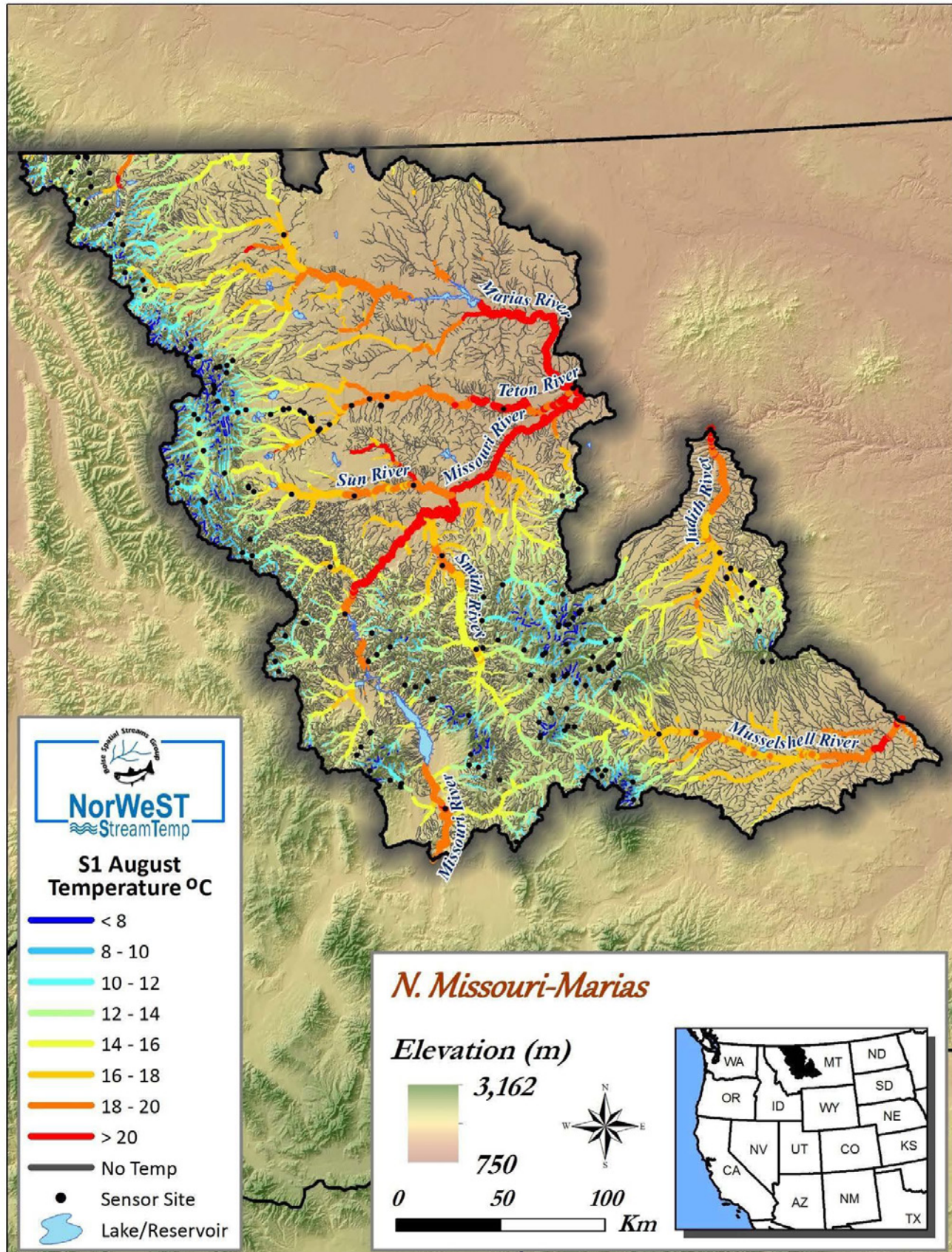
S4. Miss-Marias Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.24E+01	3.00E-01	12.401	0.300	41.293	0.000	0.870	1.340
ELE (m)	-7.74E-03	1.32E-03	-4.502	0.771	-5.844	0.000		
RC (%)	-2.28E-02	6.68E-03	-1.128	0.331	-3.410	0.001		
SL (m/m)	3.41E+00	5.69E+00	0.258	0.430	0.599	0.549		
AP (mm)	-1.57E-03	1.11E-03	-1.068	0.754	-1.417	0.157		
DA (km ²)	8.54E-05	3.89E-05	0.796	0.362	2.196	0.029		
NOR (m)	-4.43E-06	4.81E-06	-0.675	0.734	-0.920	0.358		
LK (%)	1.39E+00	5.20E-01	0.955	0.356	2.683	0.008		
BFI (%)	-1.63E-01	9.42E-02	-0.789	0.457	-1.727	0.085		
AT (°C)	2.25E-01	6.64E-02	0.588	0.173	3.397	0.001		
Q (m ³ /s)	-2.50E-01	9.58E-02	-0.452	0.173	-2.610	0.010		

S4. Miss-Marias Figure 1. Plot of predicted and observed temperatures.



S4. Miss-Marias Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



O. Wyoming

S4. Wyoming Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	219	2,168	2,172	387	1,509	3,218
SL (m/m)	219	0.0226	0.00636	0.0314	0	0.140
LK (%)	219	0.269	0.086	0.399	0	3.75
AP (mm)	219	567	433	327	178	1,294
NOR (m)	219	1,251,936	1,234,092	86,187	1,124,898	1,480,300
BFI (%)	219	57.8	57	4.76	46	74
DA (km ²)	219	7,317	267	13,008	1.78	43,116
RC (%)	219	29.2	25.0	25.4	0	81.8
AT (°C)	21	17.9	18.2	1.33	14.8	20.0
Q (m ³ /s)	21	1.37	1.09	0.598	0.552	2.97
TW (0/1)	1 ¹					
AugT (°C)	464	15.6	16.1	3.93	5.33	23.0

¹Stream length coded as cold tailwater was 140 km.

S4. Wyoming Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

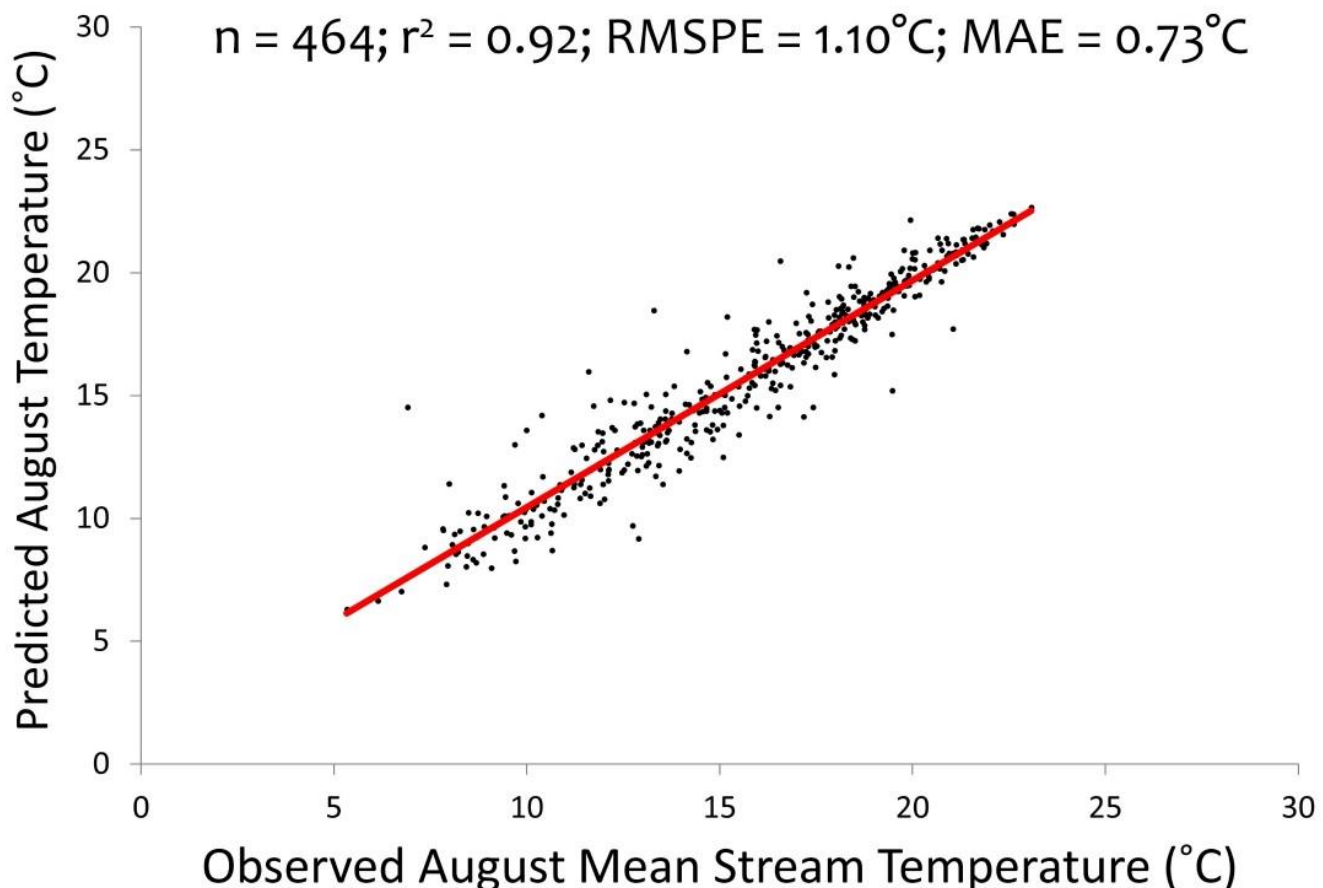
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.74	1.00									
LK	-0.37	-0.31	1.00								
GLA	na	na	na	1.00							
AP	0.88	0.82	-0.36	na	1.00						
NOR	0.06	-0.17	0.02	na	-0.18	1.00					
BFI	0.47	0.35	0.00	na	0.41	-0.07	1.00				
DA	-0.70	-0.37	0.48	na	-0.49	-0.28	-0.37	1.00			
RC	0.72	0.72	-0.16	na	0.72	0.01	0.38	-0.36	1.00		
AT	0.01	0.01	0.02	na	0.06	-0.04	-0.03	0.01	0.00	1.00	
Q	0.01	0.08	-0.07	na	0.03	-0.11	-0.03	0.04	0.08	-0.25	1.00
AugT	-0.79	-0.76	0.21	na	-0.75	-0.08	-0.35	0.33	-0.78	0.17	-0.12

S4. Wyoming Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

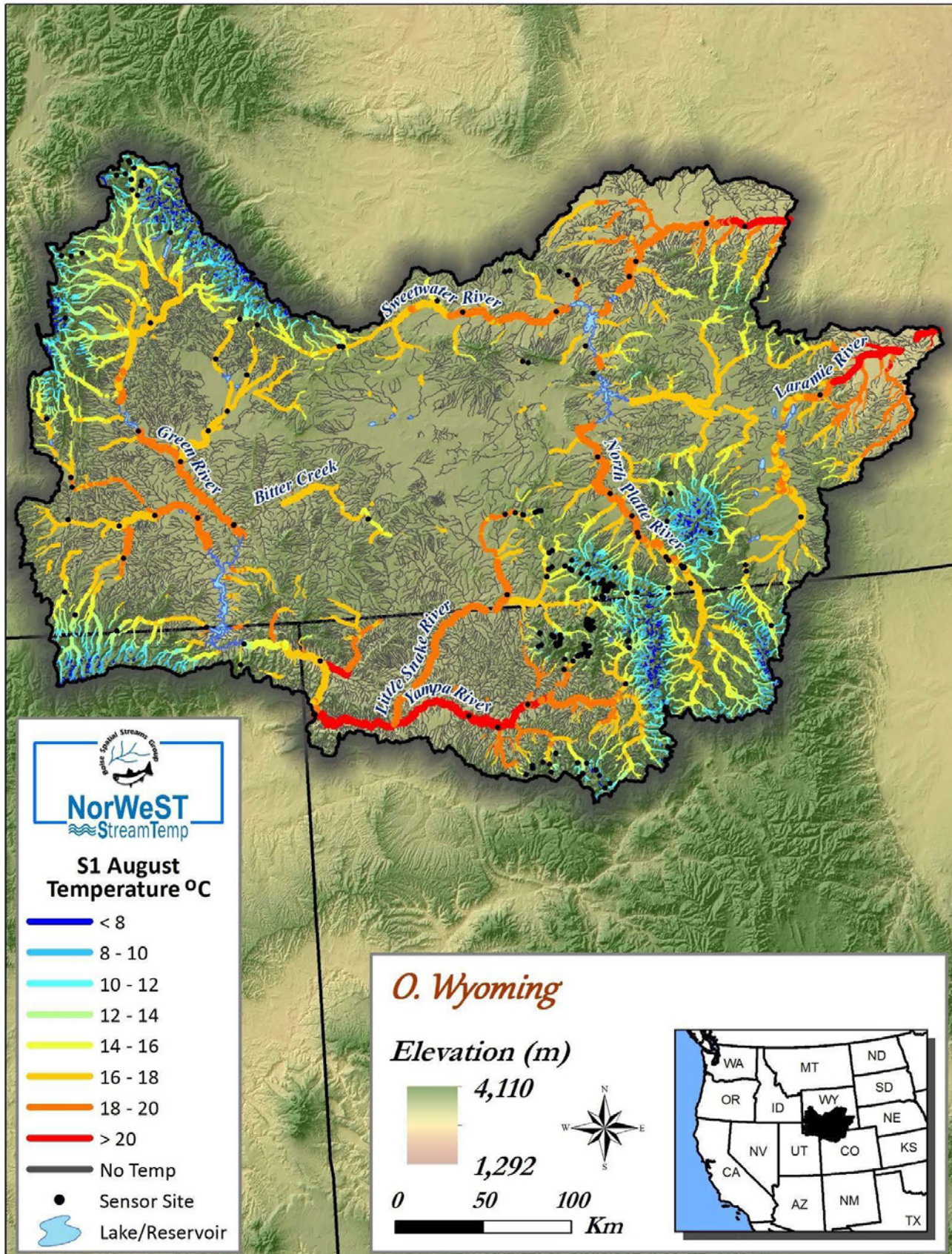
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.57E+01	2.42E-01	15.720	0.242	64.903	0.000	0.923	1.095
ELE (m)	-5.63E-03	7.60E-04	-4.371	0.590	-7.412	0.000		
RC (%)	-2.42E-02	5.76E-03	-1.230	0.293	-4.201	0.000		
SL (m/m)	-2.55E+01	5.35E+00	-1.603	0.336	-4.764	0.000		
AP (mm)	-1.14E-03	8.18E-04	-0.749	0.535	-1.400	0.162		
DA (km ²)	2.69E-05	3.10E-05	0.699	0.807	0.867	0.386		
NOR (m)	-7.61E-06	1.81E-06	-1.312	0.312	-4.201	0.000		
LK (%)	1.48E-01	2.90E-01	0.118	0.232	0.510	0.610		
BFI (%)	-1.44E-02	2.95E-02	-0.137	0.281	-0.488	0.626		
AT (°C)	3.77E-01	5.61E-02	1.008	0.150	6.706	0.000		
Q (m ³ /s)	-2.26E-01	1.21E-01	-0.271	0.145	-1.874	0.062		
TW (0/1)	-5.23E+00	1.28E+00	-5.231	1.283	-4.078	0.000		

S4. Wyoming Figure 1. Plot of predicted and observed temperatures.

Wyoming (Green/Platte/Yampa) NorWeST Stream Temperature Model



S4. Wyoming Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



P. Utah

S4. Utah Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	127	2,021	1,976	513	1,239	2,974
SL (m/m)	127	0.0309	0.0186	0.0363	0	0.160
LK (%)	127	0.30	0.00	1.33	0	14.5
AP (mm)	127	478	526	207	176	960
NOR (m)	127	1,020,269	1,020,448	138,293	789,089	1,238,221
BFI (%)	127	64.8	67.0	9.1	44.0	79.0
DA (km ²)	127	9,010	86.4	20,717	4.79	65,000
RC (%)	127	14.5	8.1	16.8	0.0	54.2
AT (°C)	21	21.7	21.8	1.25	18.8	23.6
Q (m ³ /s)	21	0.70	0.54	0.41	0.28	1.68
TW (0/1)	0					
AugT (°C)	248	16.2	15.3	4.69	7.11	26.2

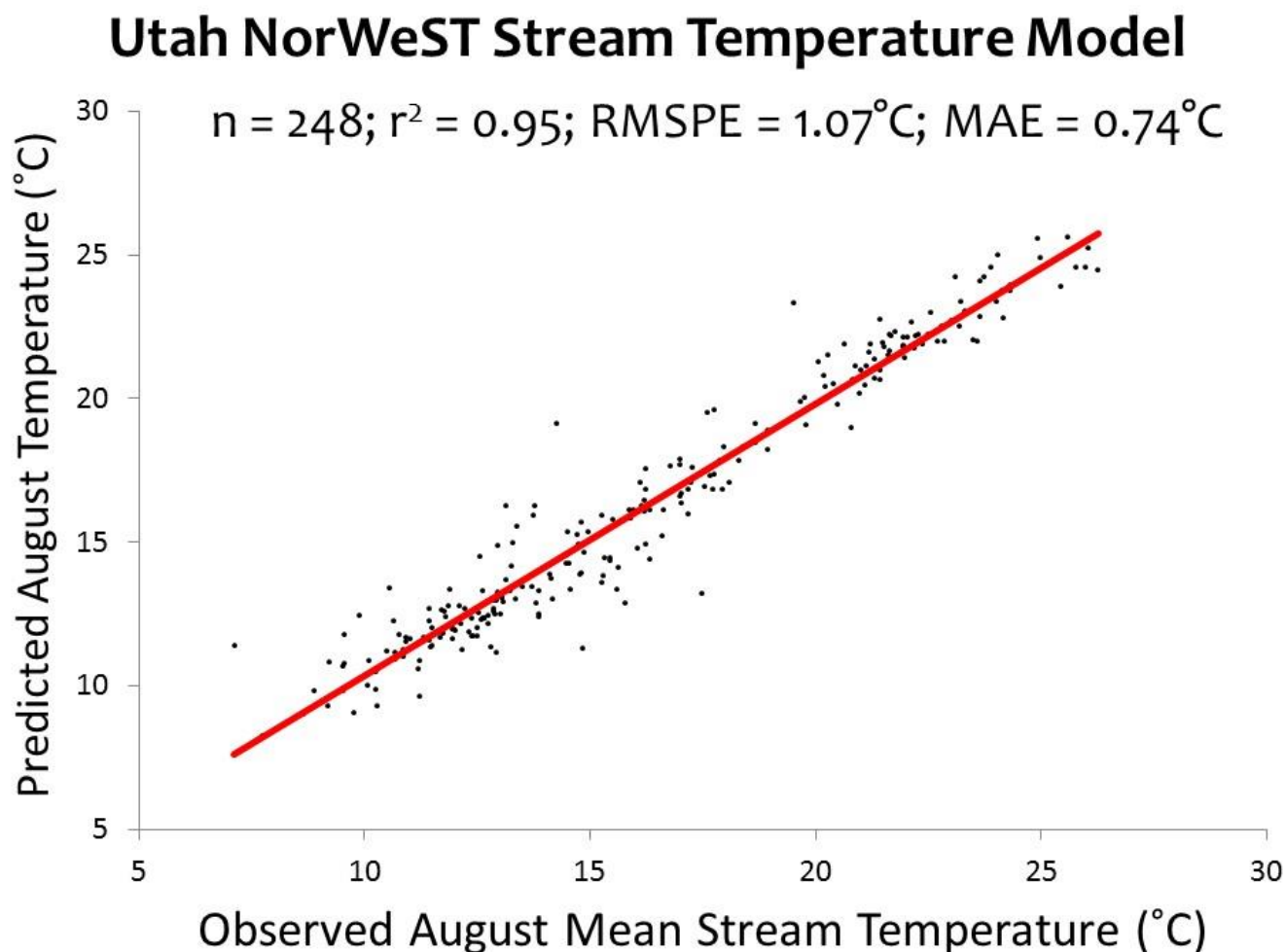
S4. Utah Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.49	1.00									
LK	0.03	-0.13	1.00								
GLA	na	na	na	1.00							
AP	0.75	0.50	-0.02	na	1.00						
NOR	-0.18	-0.22	-0.02	na	0.21	1.00					
BFI	0.62	0.52	-0.08	na	0.64	0.07	1.00				
DA	-0.57	-0.37	0.04	na	-0.57	-0.17	-0.72	1.00			
RC	0.20	0.61	-0.15	na	0.38	-0.12	0.58	-0.37	1.00		
AT	0.10	0.01	-0.01	na	-0.11	-0.13	0.01	-0.04	-0.16	1.00	
Q	0.12	0.18	-0.01	na	0.12	0.01	0.09	-0.04	0.04	0.18	1.00
AugT	-0.89	-0.62	0.06	na	-0.77	0.08	-0.74	0.61	-0.41	0.05	-0.17

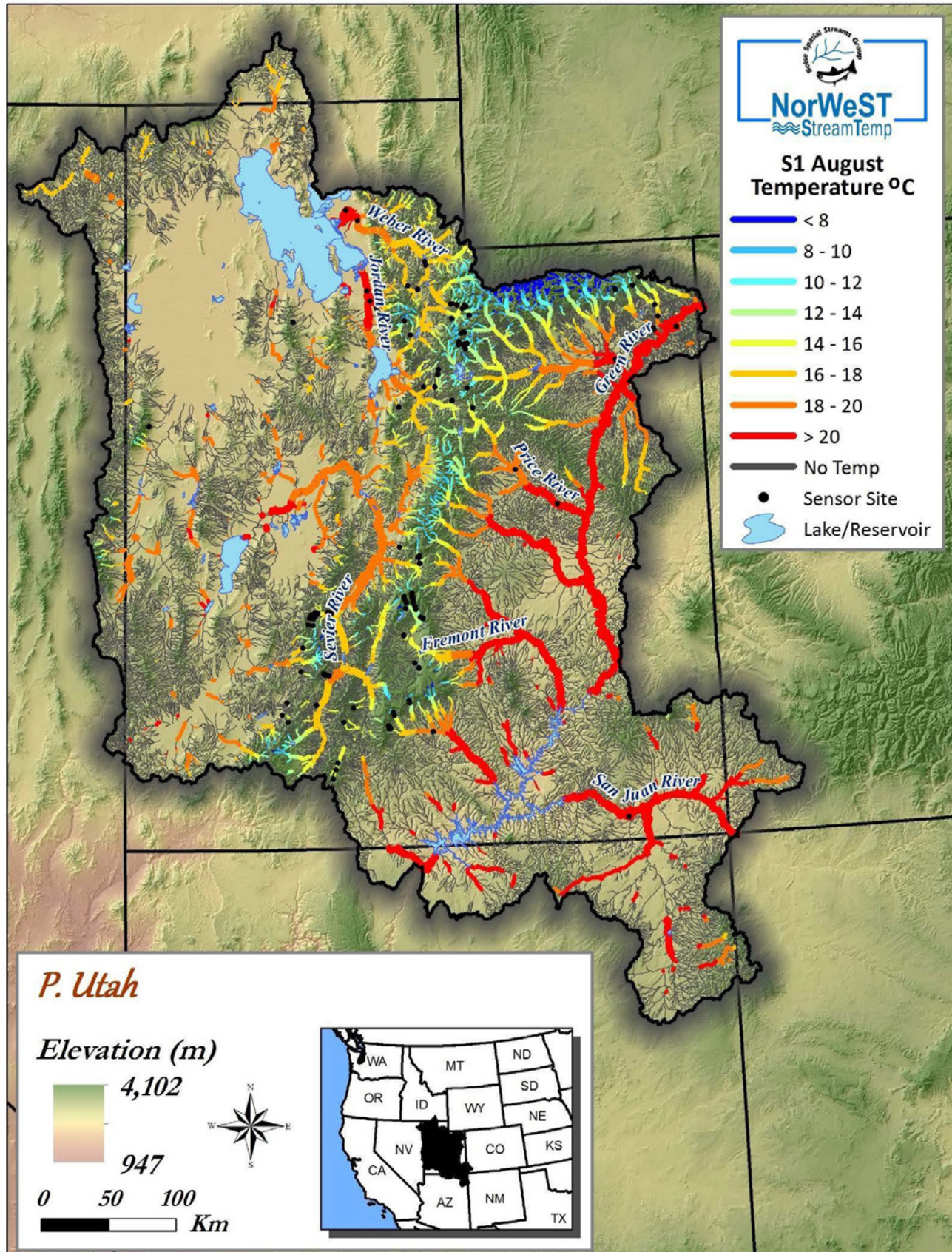
S4. Utah Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.62E+01	3.13E-01	16.162	0.313	51.690	0.000	0.947	1.074
ELE (m)	-6.13E-03	7.84E-04	-6.288	0.804	-7.818	0.000		
RC (%)	-1.80E-02	1.35E-02	-0.605	0.455	-1.329	0.185		
SL (m/m)	-7.51E+00	5.00E+00	-0.544	0.363	-1.500	0.135		
AP (mm)	-1.59E-03	1.72E-03	-0.661	0.713	-0.928	0.355		
DA (km ²)	1.04E-05	2.19E-05	0.431	0.906	0.476	0.635		
NOR (m)	-3.12E-06	2.42E-06	-0.862	0.669	-1.288	0.199		
LK (%)	1.61E-01	9.57E-02	0.429	0.255	1.684	0.094		
BFI (%)	-8.27E-02	3.96E-02	-1.511	0.723	-2.090	0.038		
AT (°C)	4.83E-01	9.51E-02	1.206	0.238	5.078	0.000		
Q (m ³ /s)	-3.89E-01	3.68E-01	-0.322	0.305	-1.055	0.292		

S4. Utah Figure 1. Plot of predicted and observed temperatures.



S4. Utah Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



Q. CA Northwest

S4. CA Northwest Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	2,608	416	336	365	0	1,988
SL (m/m)	2,608	0.0312	0.0176	0.0394	0.001	0.285
LK (%)	2,608	0.303	0.0171	0.724	0	8.64
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	2,608	1,388	1,389	416	372	3,600
NOR (m)	2,608	1,218,229	1,220,214	94,794	963,779	1,380,199
BFI (%)	2,608	45.3	44.0	13.3	26.0	79.0
DA (km ²)	2,608	1,768	58.5	5,663	0.74	34,575
RC (%)	2,608	58.7	65.5	23.5	0	93.9
AT (°C)	23	18.5	18.6	0.890	16.7	19.9
Q (m ³ /s)	23	1.91	1.88	0.605	0.991	3.08
TW (0/1)	4 ¹					
AugT (°C)	8,118	17.2	16.5	3.17	7.51	26.6

¹Stream length coded as cold tailwater was 132 km.

S4. CA Northwest Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

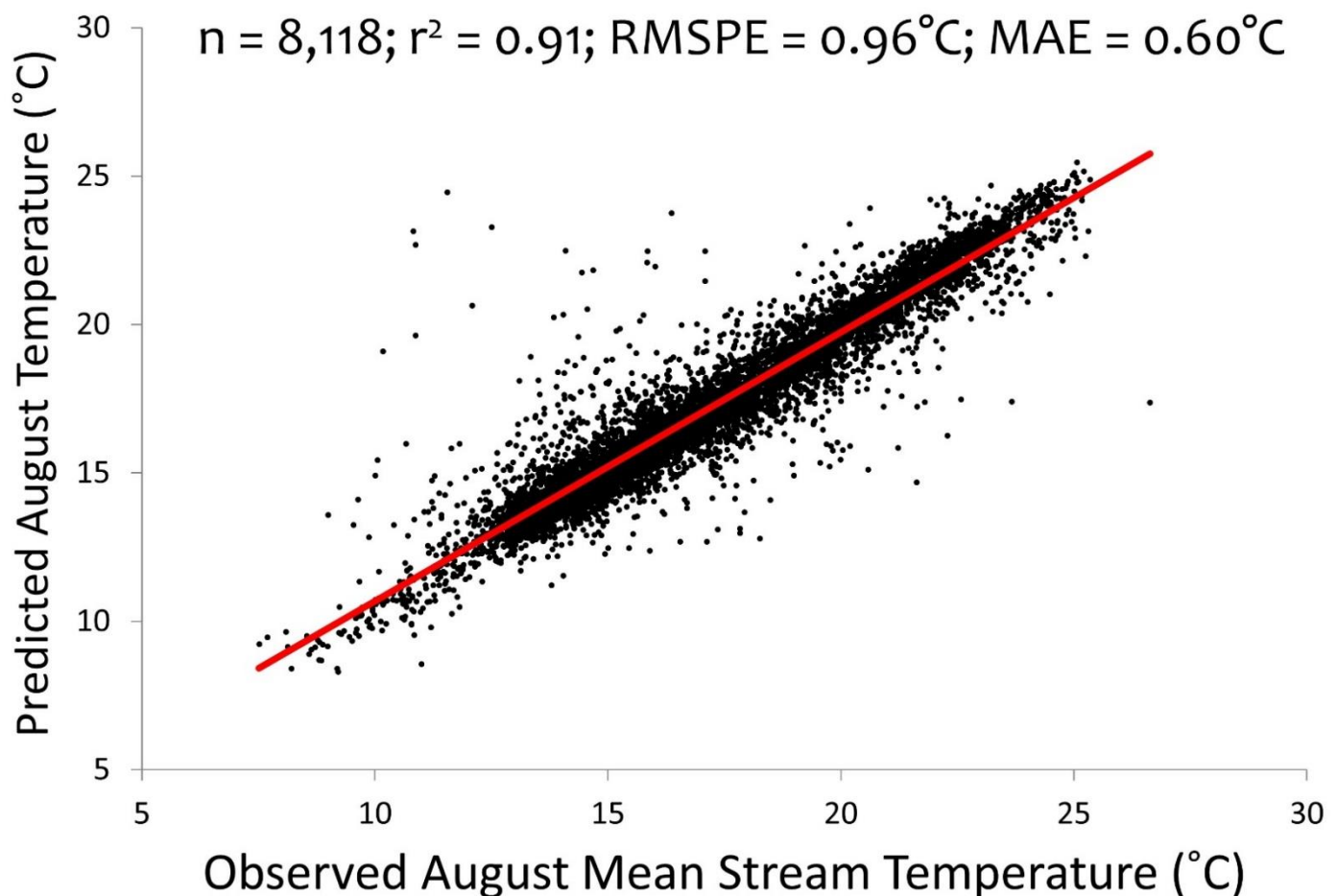
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.24	1.00									
LK	0.10	-0.21	1.00								
GLA	na	na	na	1.00							
AP	-0.37	0.14	-0.28	na	1.00						
NOR	0.27	0.09	0.25	na	-0.08	1.00					
BFI	0.59	0.08	0.34	na	-0.52	0.77	1.00				
DA	-0.15	-0.21	0.70	na	-0.05	0.22	0.14	1.00			
RC	0.05	0.37	-0.40	na	0.25	-0.04	-0.10	-0.44	1.00		
AT	0.02	0.02	0.02	na	-0.01	0.02	0.02	0.02	-0.02	1.00	
Q	-0.08	-0.05	-0.01	na	-0.07	-0.10	-0.05	0.01	0.02	0.10	1.00
AugT	-0.19	-0.33	0.30	na	-0.12	-0.08	-0.09	0.45	-0.65	0.05	-0.04

S4. CA Northwest Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

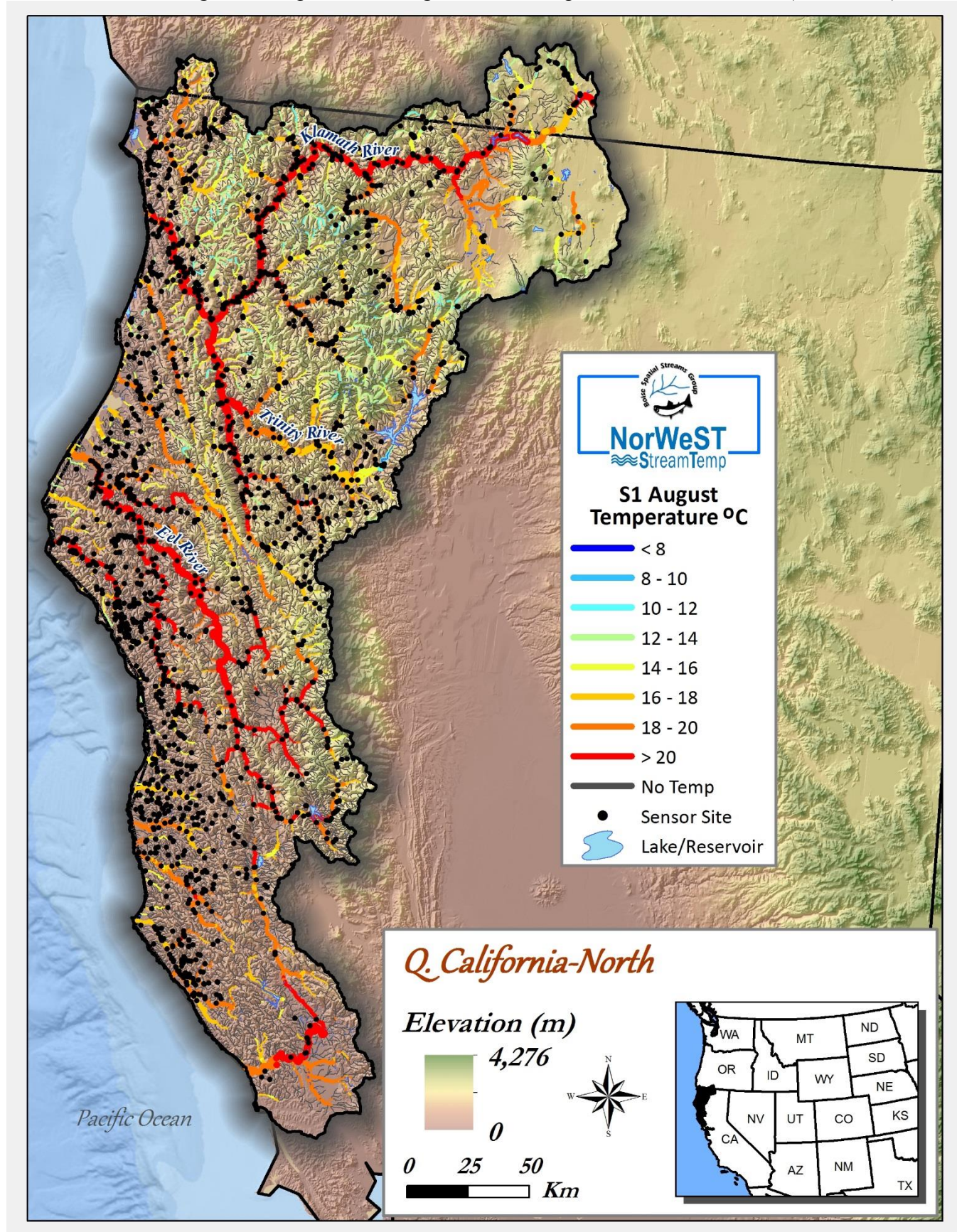
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.53E+01	1.84E+00	15.310	1.837	8.336	0.000	0.908	0.961
ELE (m)	-3.69E-03	3.39E-04	-2.689	0.247	-10.873	0.000		
RC (%)	-2.87E-02	2.27E-03	-1.350	0.107	-12.612	0.000		
SL (m/m)	-7.65E+00	1.05E+00	-0.602	0.083	-7.284	0.000		
AP (mm)	-3.42E-04	2.79E-04	-0.285	0.232	-1.225	0.221		
DA (km ²)	9.92E-05	2.70E-05	1.123	0.306	3.676	0.000		
NOR (m)	4.53E-06	9.71E-06	0.858	1.840	0.466	0.641		
LK (%)	1.33E-01	1.21E-01	0.193	0.175	1.101	0.271		
BFI (%)	-8.04E-03	3.05E-02	-0.213	0.810	-0.263	0.792		
AT (°C)	1.35E-01	7.97E-02	0.241	0.142	1.698	0.090		
Q (m ³ /s)	-2.19E-01	1.11E-01	-0.265	0.134	-1.974	0.048		
TW	-4.53E+00	7.02E-01	-4.530	0.702	-6.458	0.000		

S4. CA Northwest Figure 1. Plot of predicted and observed temperatures.

Northwest California NorWeST Stream Temperature Model



S4. CA Northwest Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



R. CA coastal

S4. CA coastal Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	167	125	74.7	176	0	1,356
SL (m/m)	167	0.0177	0.00866	0.0272	0	0.178
LK (%)	167	0.625	0.141	1.20	0	8.85
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	167	566	513	238	277	1,698
NOR (m)	167	629,701	590,038	203,032	336,648	973,703
BFI (%)	167	30.5	30	6.77	15	46
DA (km ²)	167	839	130	1,616	1.94	10,587
RC (%)	167	30.2	20.2	27.8	0	84.9
AT (°C)	23	23.0	23.3	0.77	21.1	24.3
Q (m ³ /s)	23	0.118	0.0879	0.0648	0.0354	0.38
TW (0/1)	2 ¹					
AugT (°C)	447	19.6	19.1	3.78	12.4	28.7

¹Stream length coded as cold tailwater was 75 km.

S4. CA coastal Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

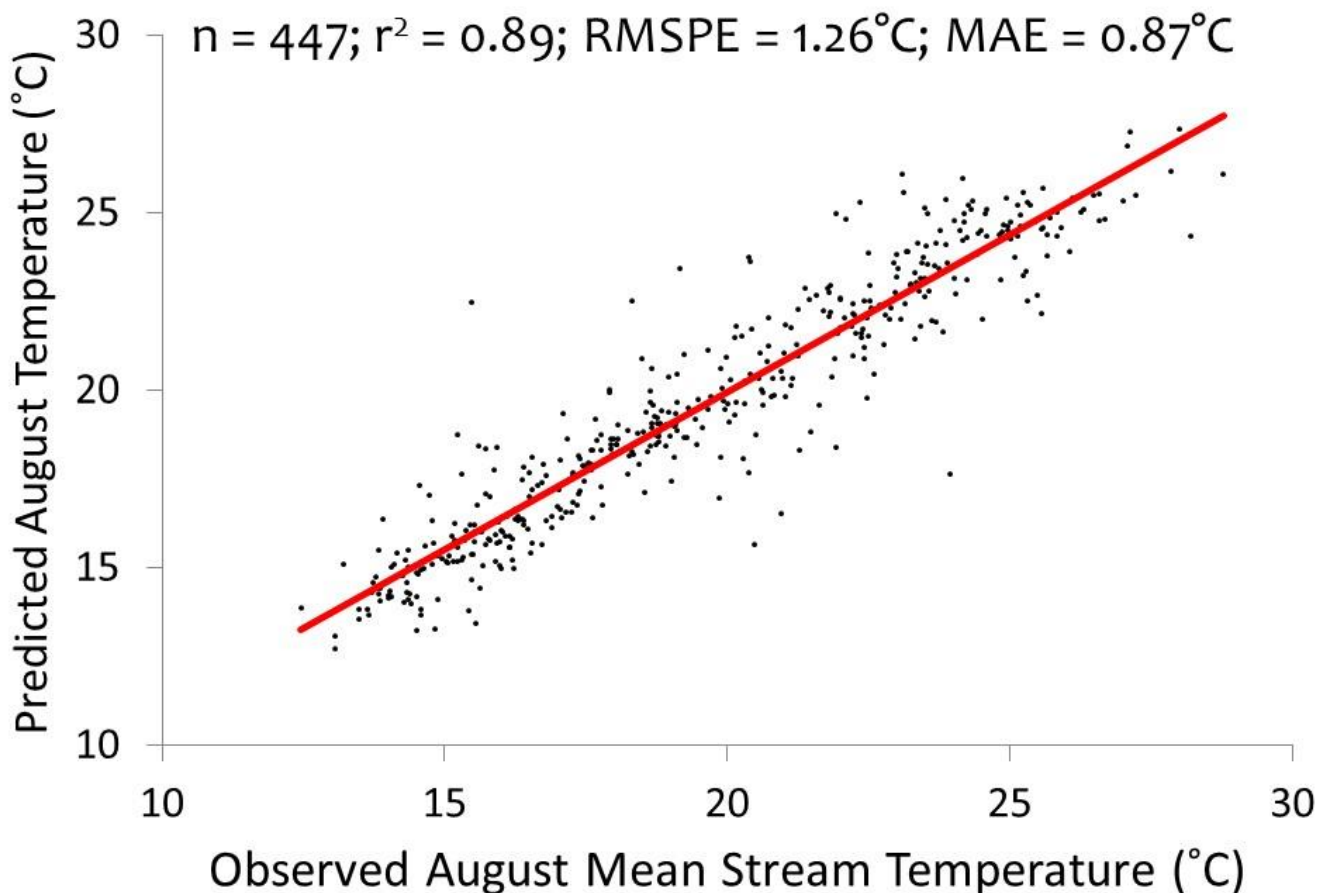
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.35	1.00									
LK	-0.04	-0.18	1.00								
GLA	na	na	na	1.00							
AP	0.17	0.52	-0.04	na	1.00						
NOR	-0.07	0.18	0.14	na	0.68	1.00					
BFI	0.23	0.22	-0.27	na	0.18	0.00	1.00				
DA	-0.07	-0.24	0.07	na	-0.31	-0.22	0.08	1.00			
RC	0.04	0.37	0.06	na	0.69	0.73	0.19	-0.31	1.00		
AT	-0.06	-0.11	-0.01	na	0.03	0.13	-0.05	0.00	0.04	1.00	
Q	-0.04	-0.03	0.02	na	-0.05	0.02	-0.08	0.07	-0.04	-0.10	1.00
AugT	0.05	-0.45	0.08	na	-0.68	-0.61	-0.15	0.37	-0.62	-0.11	-0.05

S4. CA coastal Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

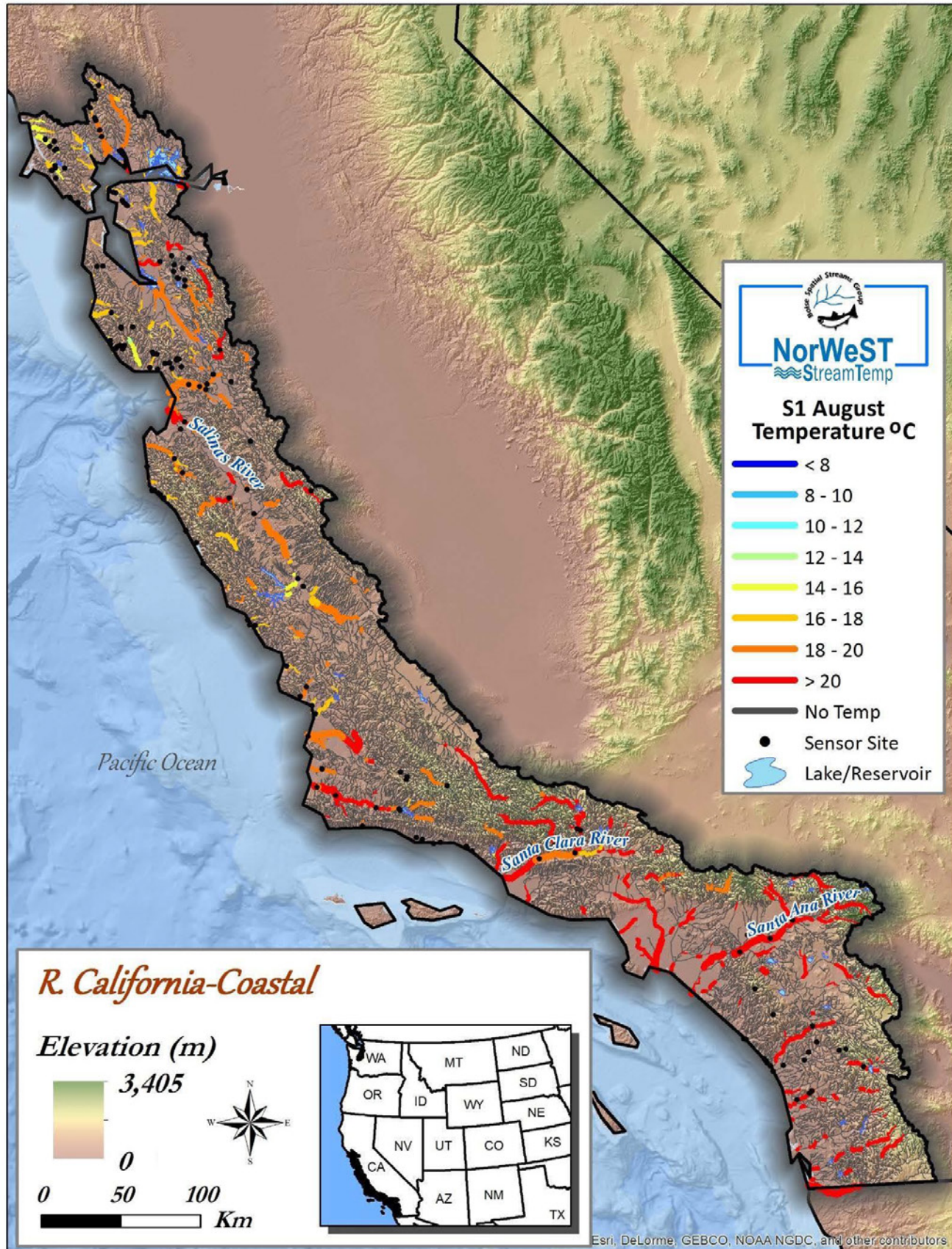
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.92E+01	3.02E-01	19.221	0.302	63.586	0.000	0.889	1.256
ELE (m)	8.56E-04	9.98E-04	0.302	0.353	0.857	0.392		
RC (%)	-6.83E-03	8.41E-03	-0.381	0.469	-0.812	0.417		
SL (m/m)	-1.65E+01	6.45E+00	-0.901	0.351	-2.565	0.011		
AP (mm)	-2.62E-03	1.44E-03	-1.253	0.689	-1.818	0.070		
DA (km ²)	2.28E-04	1.42E-04	0.739	0.460	1.607	0.109		
NOR (m)	-7.96E-06	2.01E-06	-3.232	0.815	-3.967	0.000		
LK (%)	-4.63E-02	1.89E-01	-0.111	0.456	-0.244	0.807		
BFI (%)	-5.26E-02	3.31E-02	-0.713	0.449	-1.588	0.113		
AT (°C)	-1.08E-01	1.51E-01	-0.167	0.233	-0.716	0.475		
Q (m ³ /s)	-1.06E+00	1.77E+00	-0.137	0.230	-0.598	0.550		
TW (0/1)	-4.96E+00	1.62E+00	-4.961	1.616	-3.070	0.002		

S4. CA coastal Figure 1. Plot of predicted and observed temperatures.

California Coast NorWeST Stream Temperature Model



S4. CA coastal Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



S. CA central

S4. CA central Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	906	738	532	694	0	3,559
SL (m/m)	906	0.0299	0.0127	0.0440	0	0.484
LK (%)	906	1.00	0.318	2.17	0	50
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	906	103	99.5	48.0	21.8	266
NOR (m)	906	1,031,912	1,043,352	162,654	625,195	1,288,381
BFI (%)	906	56.0	57	13.1	25	82
DA (km ²)	906	2,952	465	8,618	0	59,572
RC (%)	906	38.6	42.3	24.9	0	90.1
AT (°C)	23	21.2	21.1	0.827	19.4	22.8
Q (m ³ /s)	23	1.67	1.30	0.940	0.750	5.16
TW (0/1)	24 ¹					
AugT (°C)	2,865	16.5	16.2	4.45	5.93	38.4

¹Stream length coded as cold tailwater was 695 km.

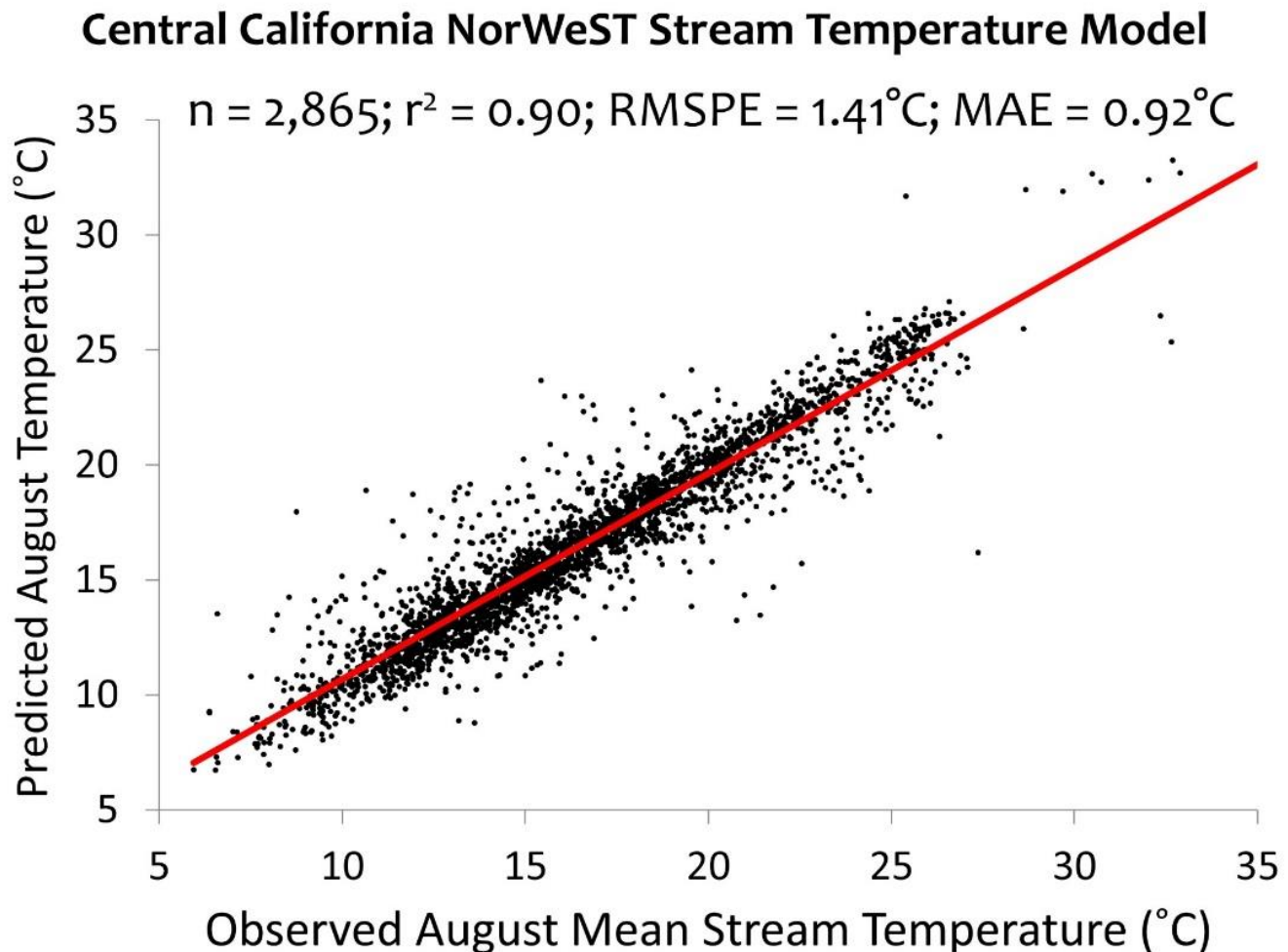
S4. CA central Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.44	1.00									
LK	-0.12	-0.13	1.00								
GLA	na	na	na	1.00							
AP	0.40	0.30	-0.18	na	1.00						
NOR	-0.06	-0.06	-0.16	na	0.53	1.00					
BFI	0.59	0.31	-0.24	na	0.69	0.48	1.00				
DA	-0.32	-0.21	0.04	na	-0.35	-0.14	-0.47	1.00			
RC	0.45	0.43	-0.24	na	0.68	0.32	0.69	-0.44	1.00		
AT	0.08	0.04	0.03	na	0.01	-0.03	0.04	-0.03	0.01	1.00	
Q	-0.07	-0.05	0.00	na	-0.03	0.03	-0.03	0.06	-0.05	-0.01	1.00
AugT	-0.50	-0.31	0.07	na	-0.40	-0.24	-0.48	0.29	-0.45	0.01	-0.08

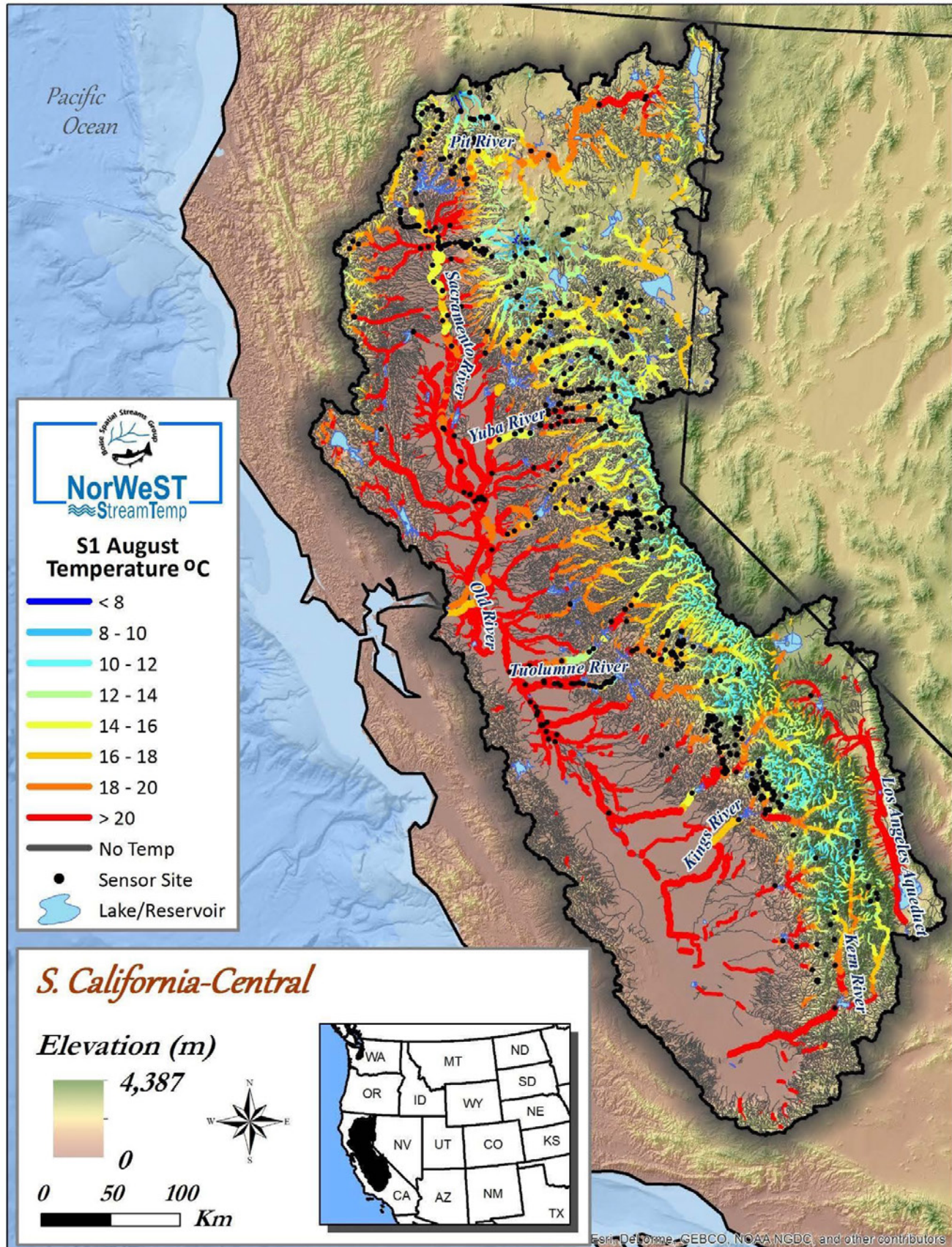
S4. CA central Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.84E+01	7.83E-01	18.382	0.783	23.464	0.000	0.900	1.410
ELE (m)	-4.17E-03	4.01E-04	-5.783	0.557	-10.376	0.000		
RC (%)	-3.17E-02	5.72E-03	-1.583	0.285	-5.550	0.000		
SL (m/m)	-4.86E+00	1.84E+00	-0.429	0.162	-2.642	0.008		
AP (mm)	-1.39E-02	5.90E-03	-1.339	0.567	-2.360	0.018		
DA (km ²)	-5.60E-05	2.20E-05	-0.965	0.380	-2.539	0.011		
NOR (m)	-4.84E-06	3.55E-06	-1.574	1.155	-1.364	0.173		
LK (%)	-3.62E-02	4.22E-02	-0.157	0.183	-0.857	0.391		
BFI (%)	2.77E-02	2.92E-02	0.727	0.766	0.950	0.342		
AT (°C)	2.10E-01	7.63E-02	0.347	0.126	2.750	0.006		
Q (m ³ /s)	-4.87E-01	6.15E-02	-0.917	0.116	-7.921	0.000		
TW (0/1)	-4.49E+00	3.79E-01	-4.494	0.379	-11.851	0.000		

S4. CA central Figure 1. Plot of predicted and observed temperatures.



S4. CA central Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



T. Colorado

S4. Colorado Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	785	2,409	2,498	591	1,184	3,576
SL (m/m)	785	0.0401	0.0210	0.0461	0	0.295
LK (%)	785	0.490	0.172	0.857	0	11.3
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	785	563	509	231	197	1,262
NOR (m)	785	1,062,422	1,096,601	104,119	751,513	1,263,976
BFI (%)	785	63.3	65	7.78	16	77
DA (km ²)	785	2,457	96.9	6,223	0.67	46,122
RC (%)	785	19.6	15.4	18.4	0	60.1
AT (°C)	23	18.1	17.8	1.16	15.5	20.1
Q (m ³ /s)	23	7.42	7.90	2.66	2.82	19.2
TW (0/1)	6 ¹					
AugT (°C)	2,681	13.7	13.0	4.50	4.35	25.3

¹Stream length coded as cold tailwater was 202 km.

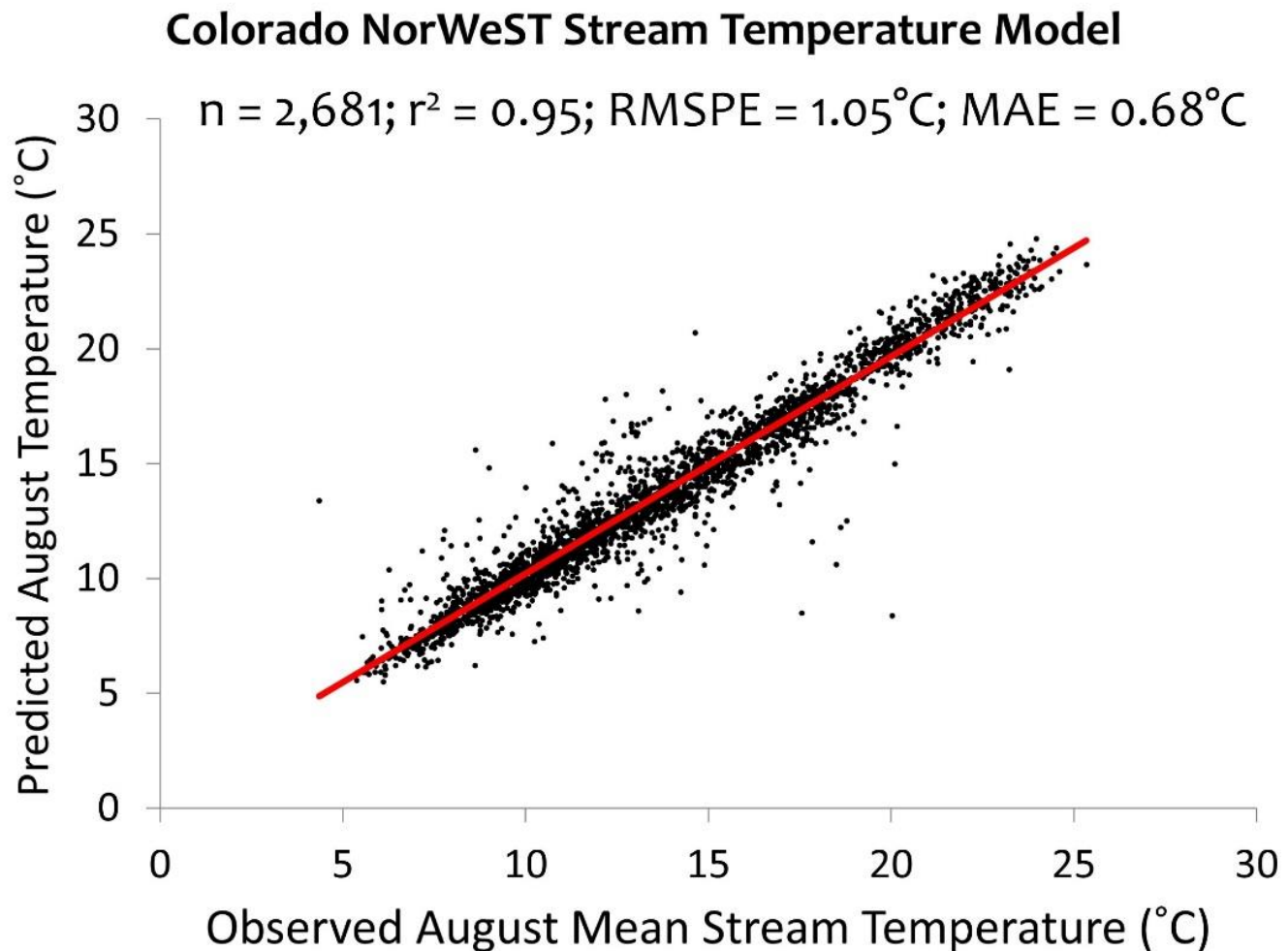
S4. Colorado Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.64	1.00									
LK	0.12	0.06	1.00								
GLA	na	na	na	1.00							
AP	0.79	0.72	0.07	na	1.00						
NOR	0.27	0.22	0.26	na	0.30	1.00					
BFI	0.50	0.23	0.11	na	0.24	0.30	1.00				
DA	-0.56	-0.32	0.01	na	-0.40	-0.21	-0.27	1.00			
RC	0.53	0.60	-0.08	na	0.56	0.19	0.27	-0.34	1.00		
AT	0.01	0.00	0.01	na	0.01	0.00	0.02	-0.04	0.04	1.00	
Q	-0.07	-0.07	0.00	na	-0.08	-0.06	-0.06	0.06	-0.05	-0.12	1.00
AugT	-0.85	-0.58	-0.01	na	-0.69	-0.31	-0.52	0.55	-0.59	0.06	0.03

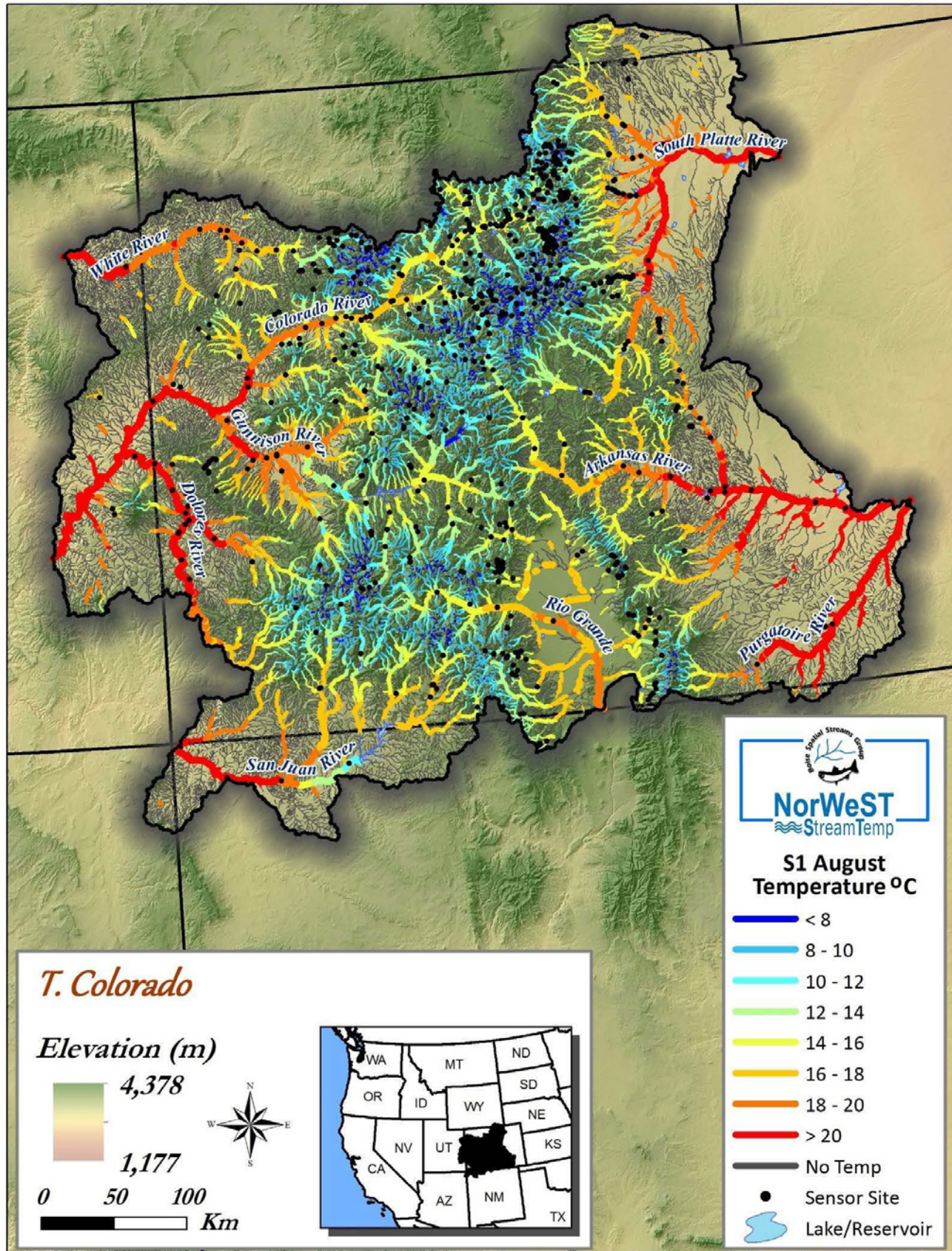
S4. Colorado Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.37E+01	2.61E-01	13.701	0.261	52.490	0.000	0.946	1.052
ELE (m)	-3.41E-03	3.87E-04	-4.043	0.458	-8.818	0.000		
RC (%)	-2.88E-02	4.56E-03	-1.062	0.168	-6.328	0.000		
SL (m/m)	-4.03E+00	2.02E+00	-0.373	0.187	-1.995	0.046		
AP (mm)	-3.53E-03	7.59E-04	-1.633	0.351	-4.647	0.000		
DA (km ²)	8.24E-05	2.70E-05	1.026	0.336	3.055	0.002		
NOR (m)	-2.29E-06	1.75E-06	-0.477	0.363	-1.312	0.190		
LK (%)	2.84E-01	8.89E-02	0.487	0.152	3.195	0.001		
BFI (%)	-1.02E-01	1.84E-02	-1.591	0.287	-5.541	0.000		
AT (°C)	3.15E-01	6.23E-02	0.733	0.145	5.055	0.000		
Q (m ³ /s)	-4.03E-02	2.08E-02	-0.215	0.111	-1.936	0.053		
TW (0/1)	-4.58E+00	9.01E-01	-4.578	0.901	-5.079	0.000		

S4. Colorado Figure 1. Plot of predicted and observed temperatures.



S4. Colorado Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



U. New Mexico

S4. New Mexico Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	543	2,306	2,405	453	871	3,151
SL (m/m)	543	0.037	0.026	0.038	0.000	0.188
LK (%)	543	0.06	0.00	0.15	0.00	1.14
GLA (km ² /km ²)	543	na	na	na	na	na
AP (mm)	543	564	576	163	222	1,046
NOR (m)	543	665,624	691,973	128,265	277,752	826,587
BFI (%)	543	56.1	60.0	15.1	1.0	81.0
DA (km ²)	543	1,653	53	6,934	3	60,881
RC (%)	543	3.6	0.0	9.8	0.0	49.2
AT (°C)	18	22.7	23.1	1.8	19.6	26.1
Q (m ³ /s)	18	1.70	1.33	1.54	0.51	6.71
TW (0/1)	0	na	na	na	na	na
AugT (°C)	755	15.4	14.9	4.14	5.97	27.8

S4. New Mexico Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

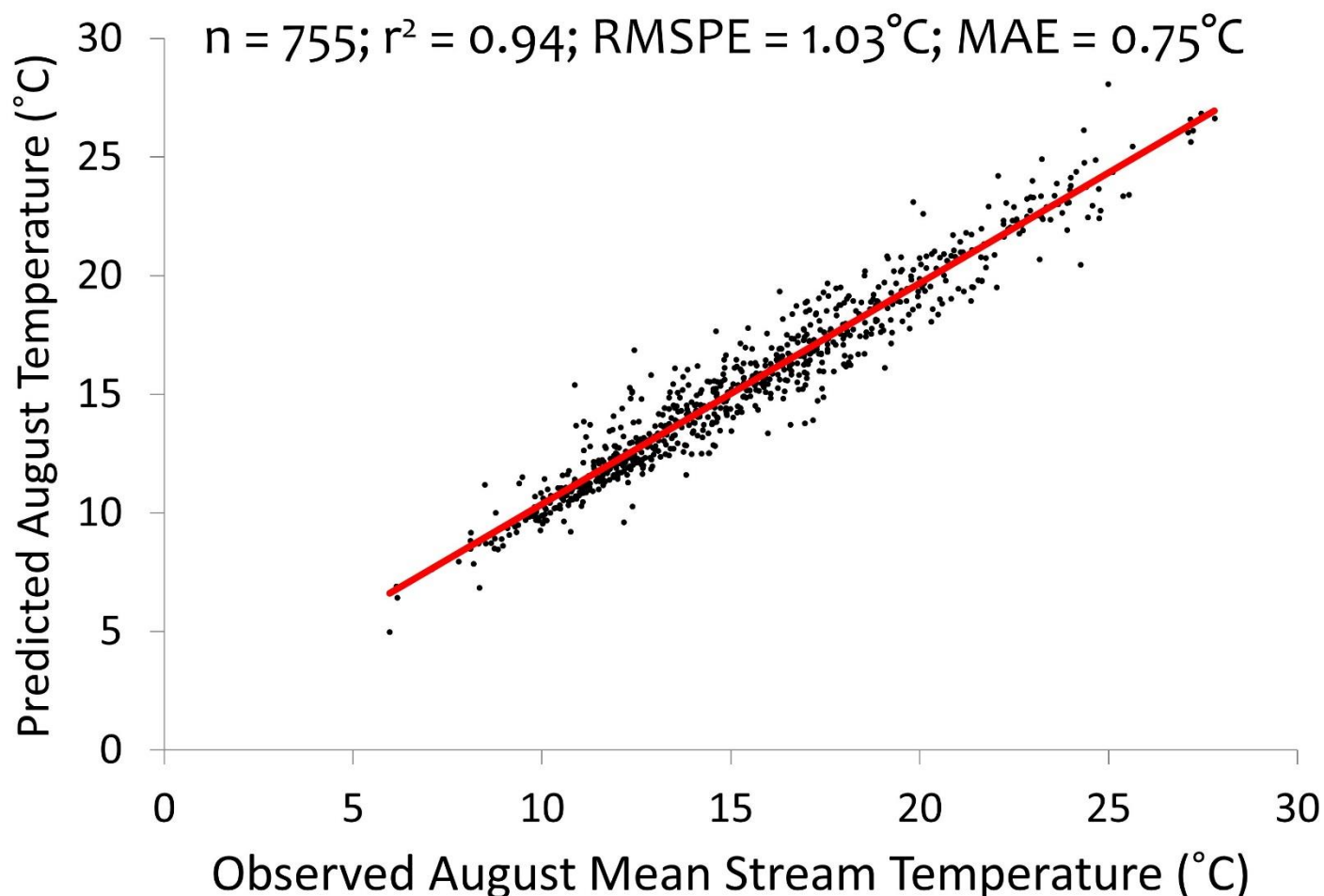
	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.46										
LK	-0.16	-0.21									
GLA	na	na	na								
AP	0.78	0.63	-0.22	na							
NOR	0.60	0.21	0.09	na	0.27						
BFI	0.60	0.38	-0.23	na	0.46	0.37					
DA	-0.43	-0.21	0.30	na	-0.38	-0.18	-0.45				
RC	-0.08	-0.02	0.01	na	0.03	-0.26	-0.04	-0.06			
AT	0.02	-0.07	-0.06	na	0.00	-0.12	0.10	-0.03	0.00		
Q	-0.05	-0.03	0.11	na	-0.04	0.14	-0.10	0.01	0.10	-0.52	
AugT	-0.85	-0.63	0.27	na	-0.78	-0.45	-0.64	0.44	0.07	0.07	0.05

S4. New Mexico Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

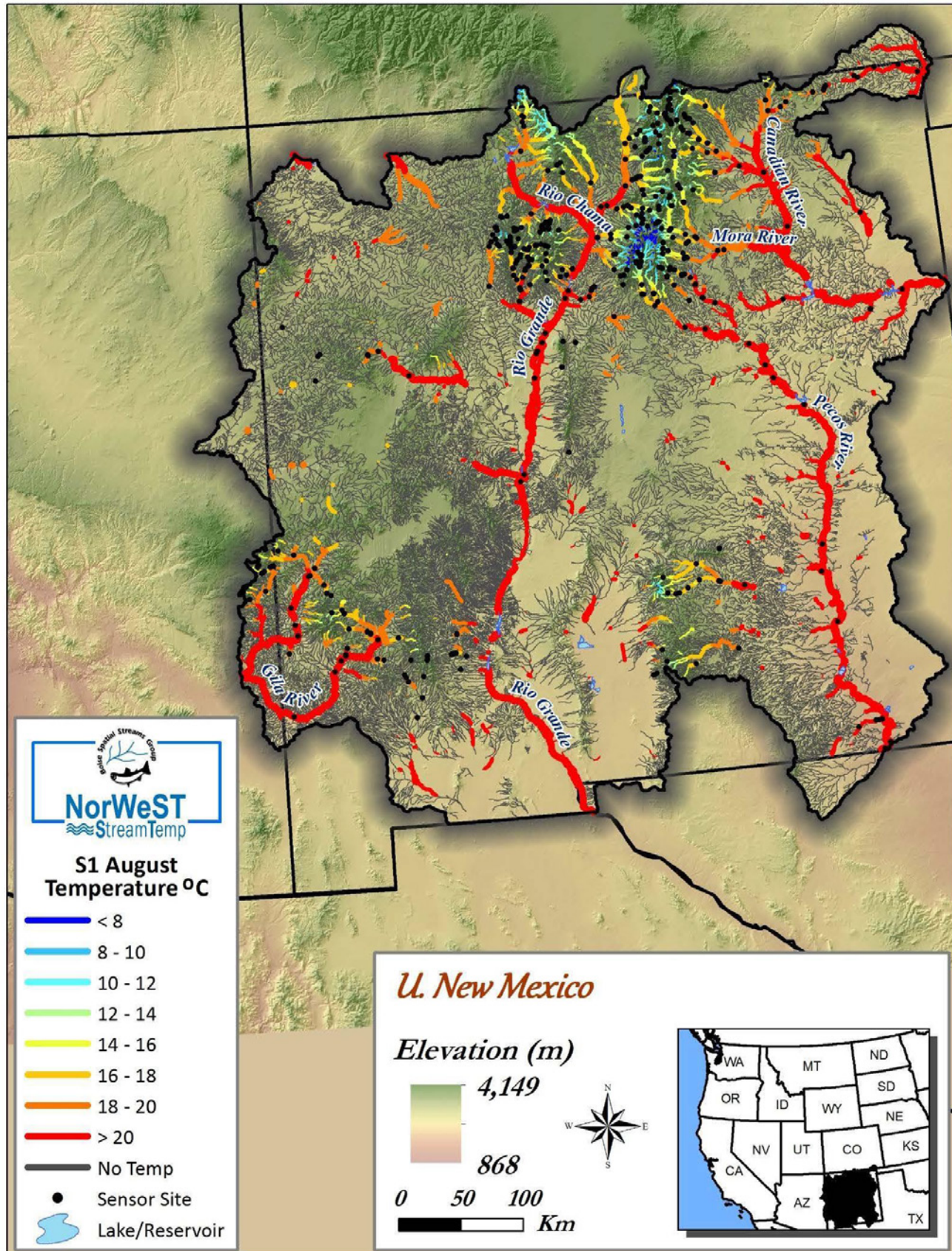
Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.56E+01	2.73E-01	15.561	0.273	57.019	0.000	0.94	1.03
ELE (m)	-5.88E-03	5.26E-04	-5.333	0.477	-11.177	0.000		
RC (%)	-3.85E-03	9.02E-03	-0.075	0.177	-0.427	0.670		
SL (m/m)	-1.11E+01	3.10E+00	-0.849	0.237	-3.581	0.000		
AP (mm)	-2.92E-03	1.19E-03	-0.953	0.389	-2.451	0.014		
DA (km ²)	2.39E-05	1.78E-05	0.332	0.247	1.345	0.179		
NOR (m)	1.37E-06	1.31E-06	0.352	0.336	1.049	0.295		
LK (%)	8.31E-01	6.10E-01	0.241	0.177	1.363	0.173		
BFI (%)	-2.66E-02	1.08E-02	-0.802	0.327	-2.452	0.014		
AT (°C)	2.16E-01	9.33E-02	0.777	0.335	2.319	0.021		
Q (m ³ /s)	3.82E-02	9.96E-02	0.118	0.306	0.384	0.701		

S4. New Mexico Figure 1. Plot of predicted and observed temperatures.

New Mexico NorWeST Stream Temperature Model



S4. New Mexico Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



V. Arizona

S4. Arizona Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	115	1,174	826	718	367	2,841
SL (m/m)	115	0.015	0.008	0.021	0.001	0.179
LK (%)	115	0.220	0.077	0.241	0	1.06
GLA (km ² /km ²)	na	na	na	na	na	Na
AP (mm)	115	387	251	239	173	989
NOR (m)	115	598,121	666,642	134,044	177,326	821,066
BFI (%)	115	56.6	61.0	16.5	17.0	77.0
DA (km ²)	115	133,887	5,959	162,084	0	362,932
RC (%)	115	5.61	0	11.4	0	48.4
AT (°C)	23	23.9	24.0	1.50	21.2	26.1
Q (m ³ /s)	23	3.06	2.55	1.86	0.914	10.0
TW (0/1)	1 ¹					
AugT (°C)	412 ²	17.5	16.5	4.11	10.6	26.9

¹Stream length coded as cold TW was 422 km and consisted of the Colorado River downstream of Lake Powell.

²Inclusion of temperature sites in the cold TW reach resulted in poor model performance, so a subset of 251 AugT values not affected by TW were used to fit the final temperature model.

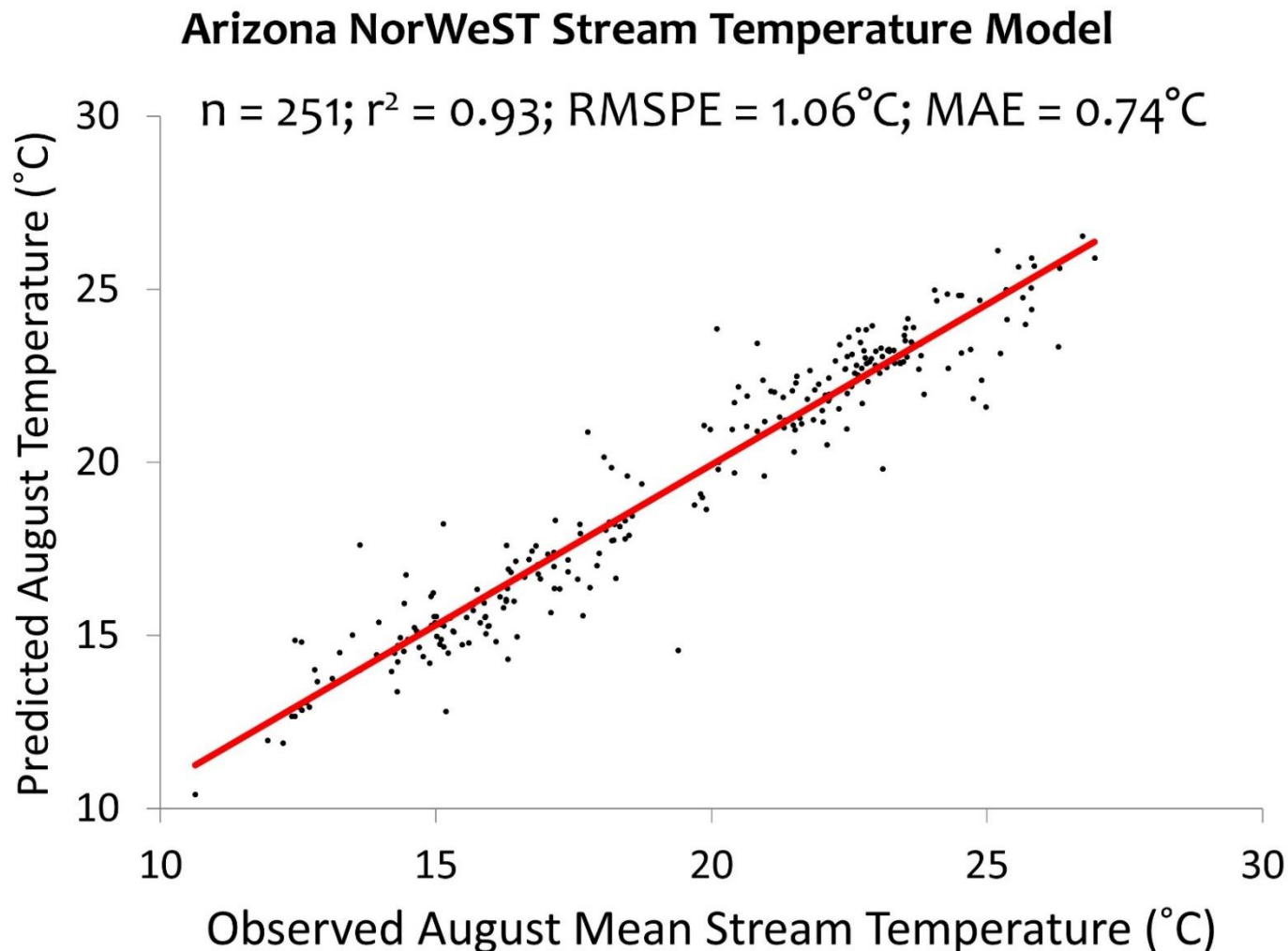
S4. Arizona Table 2. Correlations among continuous variables at 251 sites where mean August stream temperatures were observed outside of the Colorado River reach coded as TW.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.25										
LK	0.22	-0.07									
GLA	na	na	na								
AP	0.85	0.31	0.04	na							
NOR	-0.62	-0.26	-0.11	na	-0.66						
BFI	-0.40	-0.12	0.07	na	-0.63	0.77					
DA	-0.33	-0.35	0.04	na	-0.44	0.29	0.16				
RC	0.59	0.44	0.23	na	0.46	-0.30	-0.14	-0.23			
AT	0.00	-0.06	0.05	na	0.06	-0.07	-0.13	-0.03	0.06		
Q	0.01	-0.16	-0.03	na	0.06	0.05	-0.07	0.07	-0.04	-0.36	
AugT	-0.80	-0.44	-0.08	na	-0.73	0.46	0.24	0.33	-0.46	0.12	0.02

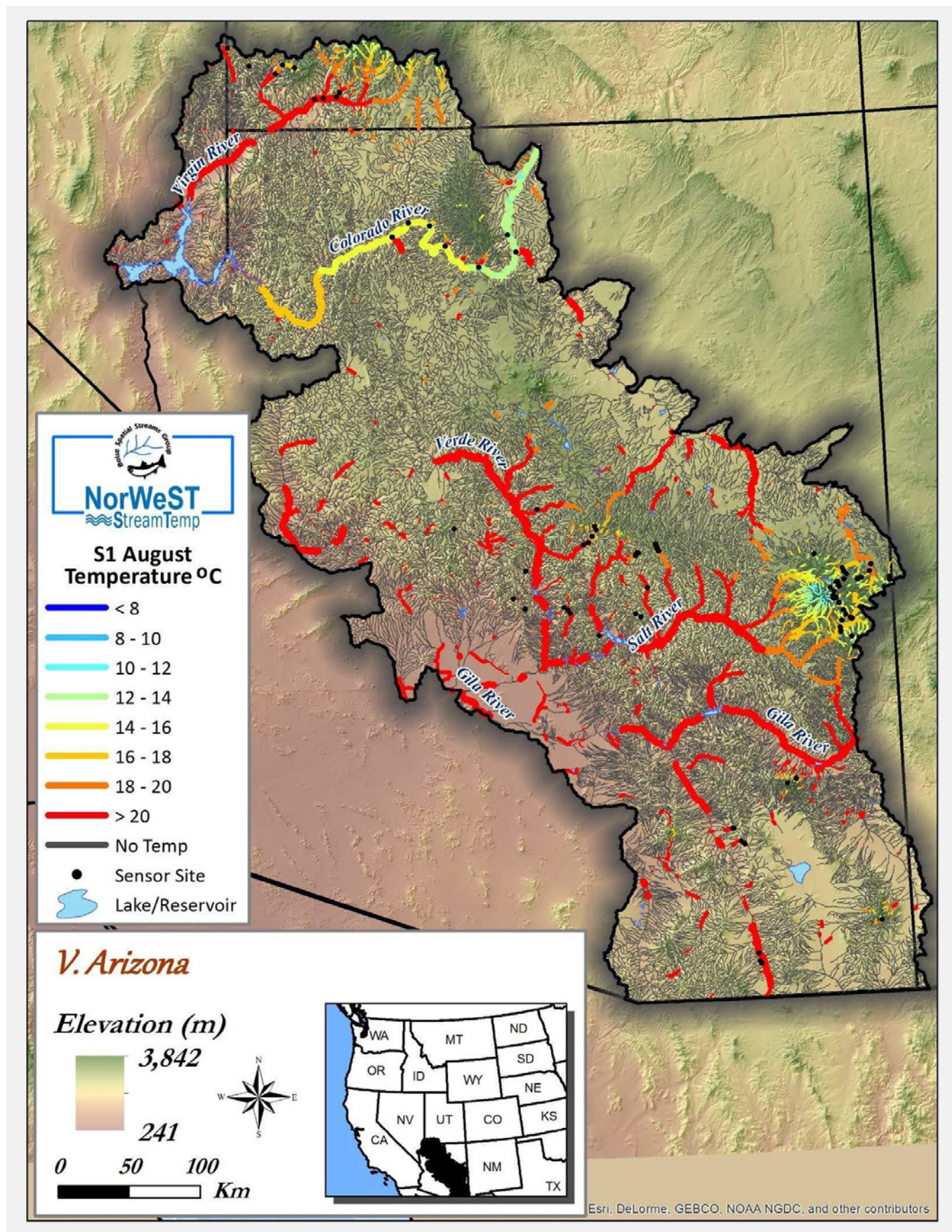
S4. Arizona Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance. Model was fit to the 251 sites where mean August stream temperatures were observed outside of the Colorado River reach coded as TW.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r^2	LOOCV RMSPE
(Intercept)	1.97E+01	2.85E-01	19.732	0.285	69.132	0.000	0.93	1.06
ELE (m)	-4.24E-03	6.70E-04	-6.261	0.991	-6.320	0.000		
RC (%)	2.93E-03	1.42E-02	0.079	0.381	0.206	0.837		
SL (m/m)	-2.74E+01	7.80E+00	-1.224	0.348	-3.517	0.001		
AP (mm)	-1.24E-03	1.92E-03	-0.619	0.961	-0.644	0.520		
DA (km ²)	-4.01E-06	2.91E-05	-0.128	0.924	-0.138	0.890		
NOR (m)	1.61E-06	2.46E-06	0.495	0.757	0.654	0.513		
LK (%)	1.07E+00	1.29E+00	0.309	0.374	0.827	0.409		
BFI (%)	-5.72E-02	2.36E-02	-1.897	0.782	-2.426	0.016		
AT (°C)	1.44E-01	8.12E-02	0.472	0.266	1.775	0.077		
Q (m ³ /s)	-4.11E-03	5.55E-02	-0.013	0.177	-0.074	0.941		

S4. Arizona Figure 1. Plot of predicted and observed temperatures.



S4. Arizona Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).



W. Black Hills

S4. Black Hills Table 1. Descriptive statistics for variables at sites where mean August stream temperatures were observed and predicted.

Variable	<i>n</i>	Mean	Median	Standard deviation	Minimum	Maximum
ELE (m)	93	1,424	1,408	370	748	1,992
SL (m/m)	93	0.0173	0.0133	0.0193	0.001	0.177
LK (%)	93	0.189	0.0327	0.239	0	0.781
GLA (km ² /km ²)	na	na	na	na	na	na
AP (mm)	93	567	560	89.7	392	781
NOR (m)	93	1,605,972	1,603,895	33,097	1,519,136	1,666,390
BFI (%)	93	68.8	72	9.24	42	81
DA (km ²)	93	1,439	122	4,875	1.24	29,012
RC (%)	93	24.1	22.6	13.7	0.8	61.2
AT (°C)	13	20.7	21.0	1.51	18.9	24.5
Q (m ³ /s)	13	0.749	0.664	0.393	0.303	1.55
TW (0/1)	2 ¹					
AugT (°C)	143	14.3	14.8	5.47	5.77	25.6

¹Stream length coded as cold tailwater was 18 km.

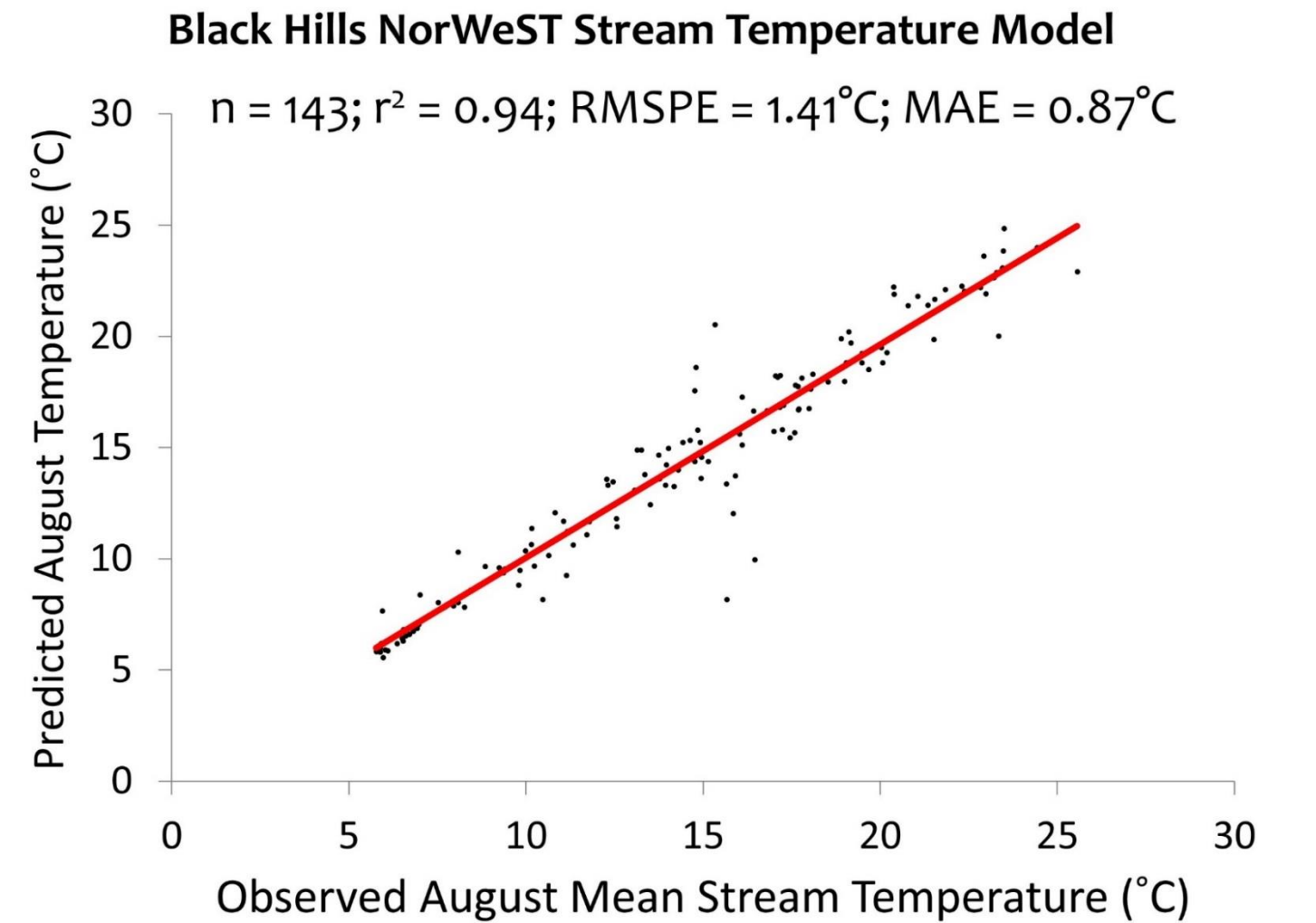
S4. Black Hills Table 2. Correlations among continuous variables at sites where mean August stream temperatures were observed.

	ELE	SL	LK	GLA	AP	NOR	BFI	DA	RC	AT	Q
SL	0.30										
LK	-0.50	-0.20									
GLA	na	na	na								
AP	0.83	0.34	-0.40	na							
NOR	-0.08	-0.09	0.23	na	0.26						
BFI	0.72	0.30	-0.40	na	0.65	-0.10					
DA	-0.38	-0.22	0.02	na	-0.41	-0.28	-0.29				
RC	0.36	0.14	-0.09	na	0.33	-0.03	0.11	-0.35			
AT	0.11	-0.02	-0.20	na	0.02	-0.15	-0.07	0.13	0.01		
Q	0.61	0.27	-0.48	na	0.50	-0.05	0.45	-0.15	0.15	0.21	
AugT	-0.83	-0.30	0.36	na	-0.72	-0.10	-0.68	0.40	-0.30	0.07	-0.54

S4. Black Hills Table 3. Parameter estimates and summary statistics for SSN model that predicts mean August stream temperature. Raw estimates were centered by subtracting the mean so the intercept is the grand mean. Standardized estimates are standardized to unit mean and variance.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p	LOOCV r ²	LOOCV RMSPE
(Intercept)	1.56E+01	6.23E-01	15.592	0.623	25.013	0.000	0.94	1.41
ELE (m)	-9.67E-03	2.48E-03	-7.163	1.836	-3.901	0.000		
RC (%)	-1.15E-02	1.76E-02	-0.317	0.483	-0.657	0.512		
SL (m/m)	-9.54E+00	7.59E+00	-0.369	0.294	-1.257	0.211		
AP (mm)	-6.84E-03	8.23E-03	-1.228	1.477	-0.832	0.407		
DA (km ²)	-1.30E-05	9.53E-05	-0.127	0.930	-0.136	0.892		
NOR (m)	-2.84E-05	1.51E-05	-1.881	0.998	-1.884	0.062		
LK (%)	3.73E+00	2.23E+00	1.788	1.071	1.669	0.097		
BFI (%)	2.74E-02	6.91E-02	0.507	1.276	0.397	0.692		
AT (°C)	2.91E-01	6.30E-02	0.876	0.190	4.618	0.000		
Q (m ³ /s)	-5.15E-01	4.55E-01	-0.404	0.358	-1.131	0.260		
TW (0/1)	-4.72E+00	1.21E+00	-4.722	1.213	-3.893	0.000		

S4. Black Hills Figure 1. Plot of predicted and observed temperatures.



S4. Black Hills Figure 2. Map of mean August stream temperature for 1993–2011 (Scenario 1).

