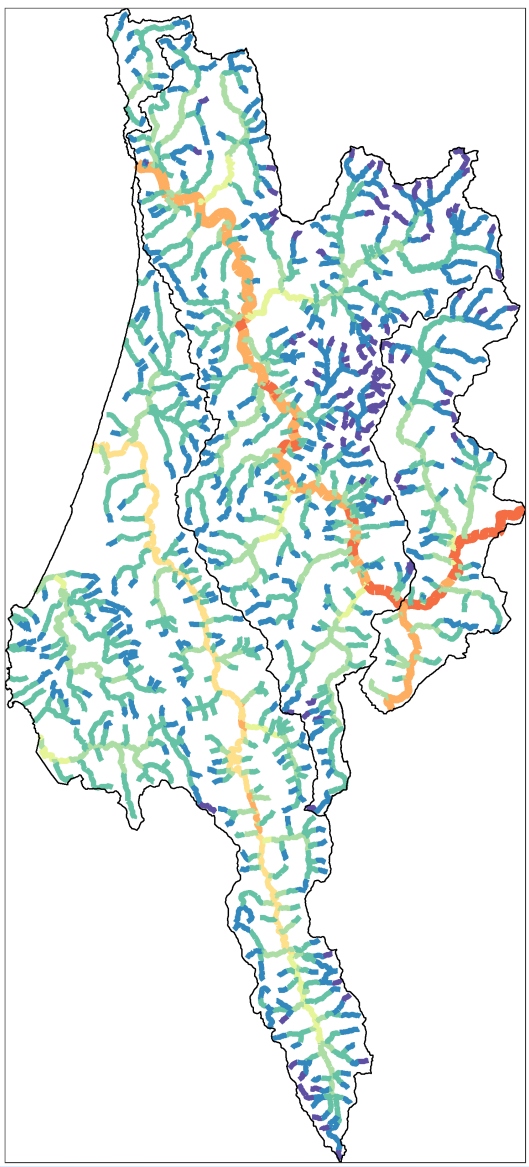


# GIS
# Stream Temperature Modeling of Yurok Ancestral Territory


**J. Eli Asarian**

**Riverbend Sciences**


September 8, 2017

Prepared for:
**Yurok Tribe**
**Environmental Program**


This research is funded by
U.S. EPA - Science To Achieve Results (STAR) Program
Grant # RD-83560401

# GIS Stream Temperature Modeling of Yurok Ancestral Territory

**J. Eli Asarian**
Riverbend Sciences
Eureka, CA

Prepared for:
**Yurok Tribe Environmental Program**
Klamath, CA

Funded by:
**United States Environmental Protection Agency**
**Science To Achieve Results (STAR) Program**
Grant #RD-83560401

September 8, 2017

*Suggested citation:*

Asarian, J.E. 2017. GIS Stream Temperature Modeling of Yurok Ancestral Territory. Prepared by Riverbend Sciences for the Yurok Tribe Environmental Program, Klamath, CA. 39 p. + appendices.

*Photo credits for cover page (clockwise from top left):*

All photos by Eli Asarian: A. Confluence of the Klamath and Trinity River at Weitchpec 4/19/2015, B. McGarvey Creek 9/13/2013, C. Redwood Creek 9/10/2011.

# EXECUTIVE SUMMARY

**Key Points**

- This study compiled nearly all available water temperature data collected in rivers and streams within Yurok Ancestral Territory since 1992.
- Data were input into spatial stream-network models to estimate August stream temperatures for each 1 kilometer stream reach, adapting methods from the U.S. Forest Service's NorWeST model.
- The original 2015 NorWeST version predicted warmer temperatures along the coast and cooler temperatures inland than field measurements supported. The new model corrects that issue.
- The NorWeST model indicates that compared to other areas in the Western U.S., stream temperatures in Yurok Ancestral Territory should be relatively resilient to climate change.
- The resulting stream temperature maps can be used for many purposes, including prioritizing areas for stream restoration/protection and climate change adaptation planning.

**Summary**

The goals of this study were to 1) acquire, compile, and quality check on all available continuous water temperature data that has been collected in rivers and streams within Yurok Ancestral Territory and adjacent areas since the early 1990s, 2) calculate summary temperature metrics for each site and year, 3) use spatial stream-network models to produce spatially continuous predictions of summer stream temperatures, and 4) compare model results to previous efforts.

The study area spans from Damnation Creek near Crescent City south to Little River near Trinidad, and includes the Lower Klamath River and its tributaries from Slate Creek downstream to the Klamath Estuary. This project was performed for the Yurok Tribe Environmental Program (YTEP) and funded by the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) Program, grant #RD-83560401.

The compiled stream temperature dataset spans 1992 to 2016, with 287 sites and 1276 site-years, of which 1157 had sufficient data to calculate mean August temperature that was the required input for the model. Data sources included the Yurok Tribe's Environmental and Forestry Programs, federal and state agencies, and Humboldt State University. The only major dataset not acquired was Green Diamond Resource Company. After an intensive screening process which corrected errors and inconsistencies, seasonal statistics were calculated for each site and year.

To prepare data for statistical modeling, all sites were assigned to reaches in a Geographic Information System (GIS) stream network modified from the National Stream Internet (NSI) project. Each NSI reach includes GIS variables which are useful predictors of stream temperature, including watershed area and vegetative canopy derived from satellites. In addition to the NSI variables, new predictor variables were also calculated: coastal proximity, basin shape factor, and different versions of air temperature. The watershed area calculation was refined to be more accurate for the uppermost reaches of small headwater streams.

Spatial stream-network models were used to produce estimates of mean August and mean daily maximum August stream temperatures for each 1-kilometer stream reach within the study area, with results shown in Figure ES-1 and included as Electronic Appendices. The models combine observed temperature data, GIS data about landscape attributes (i.e., the predictor variables mention in the previous paragraph), inter-annual variation in climate (i.e., air temperature and streamflow), and the spatial relationships between sites (i.e., the nearest sites having the strongest influence, and tributary relationships are taken into account). The models were adapted from NorWeST, a project led by the U.S Forest Service's Rocky Mountain Research Station (RMRS) which previously modeled stream temperatures on the North Coast of California.

The root mean squared prediction error (RMSPE) for final model for mean August temperature was only 0.50 °C. Drainage area, elevation, and air temperature were the most important predictors of mean August stream temperature, followed by streamflow, canopy, latitude, and coastal influence.

A comparison of the predicted mean August stream temperature to the original 2015 version of NorWest shows that the NorWeST's predicted temperatures were warmer along in the coast and warmer on the interior. This difference likely reflects the 2015 NorWeST model's relative lack of stream temperature data within Yurok Ancestral Territory so predictions default to the regional regression which does not including any coastal effects. All data compiled for this project were submitted to RMRS who then re-ran the NorWeST model in April 2017 using the new larger dataset. As a result, the updated 2017 NorWeST model results are nearly all within 1 °C of this study's final spatial stream-network model.

New climate change model scenarios were not run as a part of this project. Instead, results from the 2017 NorWeST model are discussed. NorWeST includes several climate scenarios but the primary one predicts that the 3.57°C increase in air temperature by the 2080s predicted by global climate models would raise mean August stream temperatures within NorWeST's Northern California/Coastal Klamath unit (including Yurok Ancestral Territory) by 0.44 to 0.77 °C. This predicted increase is small primarily because of low "air temperature sensitivity", which is change in stream temperature per unit change in air temperature. NorWeST's air temperature sensitivity for the Northern California/Coastal Klamath geographic unit is 0.135 °C/°C, which is the second-lowest of the 23 NorWeST units in the Western U.S. The air temperature sensitivity within Yurok Ancestral Territory is 0.22 °C/°C which is higher than the regional NorWeST value of 0.135 °C/°C but still relatively low. This low sensitivity suggests that compared to other geographic areas in the Western U.S., stream temperatures in coastal northwest California (including Yurok Ancestral Territory) should be relatively resilient to climate change.

Temperature affects basic water chemistry and the effectiveness of drinking water treatment including mineral properties, microbiological characteristics, pH, and odor perception. In addition, water temperature has long been identified as a primary factor limiting production of salmon and steelhead within the study area. The stream temperature maps generated in this project can be used for a variety of purposes, including prioritization of stream restoration/protection, education/outreach, land acquisition, and enforcement; climate change adaptation planning; and data analyses such as pairing with biological surveys to determine thermal tolerances for species and species distribution modeling.

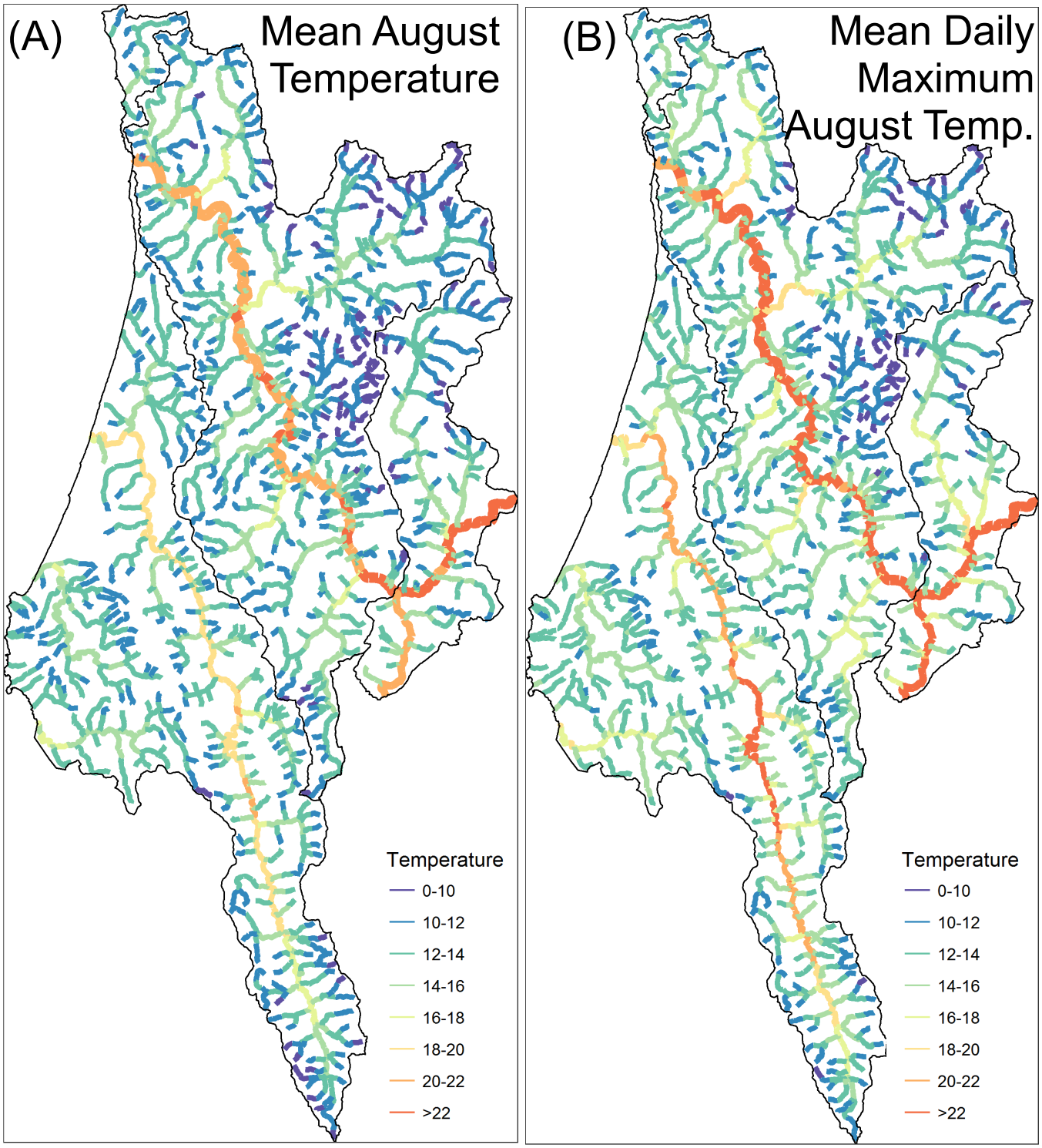



Figure ES-1. Predicted (A) mean August temperature and (B) mean daily maximum August temperature in degrees Celsius for streams within Yurok Ancestral Territory and adjacent areas for the period 1990-2016. Predictions are outputs from a spatial stream-network model which uses observed temperature data and GIS predictor variables as inputs.

# TABLE OF CONTENTS

**Executive Summary** ..... **i**
**Table of Contents** ..... **iv**
**List of Electronic Appendices** ..... **v**
**List of Figures** ..... **v**
**List of Tables** ..... **vi**
**1 Introduction** ..... **1**
1.1 Description of Study Area ..... 1
1.2 Previous Assessments of Stream Temperatures in Yurok Ancestral TerritoRy ..... 1
1.3 Study Goals ..... 2
**2 Methods** ..... **4**
2.1 Stream Temperature Data Sources Acquired and Compiled ..... 4
2.1.1 Yurok Tribe Environmental Program ..... 4
2.1.2 Yurok Tribe Fisheries Program ..... 4
2.1.3 US Forest Service, Natural Resource Information System Aquatic Surveys ..... 4
2.1.4 Humboldt State University's Forest Science Project ..... 5
2.1.5 Redwood National and State Parks ..... 5
2.1.6 U.S. Fish and Wildlife Service, Arcata Office ..... 5
2.1.7 U.S. Forest Service's Rocky Mountain Research Lab's NorWest Project ..... 5
2.1.8 Additional Datasets Not Acquired or Compiled ..... 6
2.2 Quality Control and Cleaning of Stream Temperature Data ..... 8
2.3 Calculation of Daily and Seasonal Summaries ..... 10
2.3.1 Daily Summary Statistics ..... 10
2.3.2 Initial Calculation of Seasonal and Monthly Summary Statistics ..... 10
2.3.1 Refining Seasonal Statistics According to Data Completeness ..... 11
2.4 Assigning Stream Temperature Monitoring Sites to Stream Network GIS ..... 12
2.4.1 Addition of New Reaches to the Stream Network GIS ..... 13
2.5 Spatial Covariates (Predictor variables) ..... 13
2.5.1 Assigning Covariates to Prediction points ..... 19
2.6 Spatial Stream-Network Modeling ..... 20
**3 Model Results and Discussion** ..... **21**
3.1 Model Selection and Performance ..... 21
3.2 New Stream Temperature Maps ..... 24
3.3 Comparison to NorWeST Model Results ..... 24
3.4 NorWeST Climate change Scenarios ..... 28
**4 Project Difficulties and Comparison of Accomplishments to Objectives** ..... **32**
4.1 Comparison of Accomplishments to Objectives ..... 32
4.1.1 Task 1.0: Perform GIS stream temperature modeling of Yurok Ancestral Territory ..... 32
4.1.2 Task 2.0: Manage and format stream data for compatibility with NorWest Streams Modeling ..... 32
4.1.3 Task 3.0: Develop temperature model that can be downloaded as geospatial data to enable the display and querying of stream temperatures in ArcMap for streams within the Yurok Ancestral Territory ..... 33
4.1.4 Task 4.0: Generate stream temperature scenario maps of select streams within Yurok Ancestral Territory, using spatial statistical stream network models ..... 33
4.1.5 Task 5.0: Report of project difficulties and a comparison of accomplishments with the objectives for the project ..... 33
4.2 Project Difficulties ..... 33
4.2.1 Learning STARS/SSN ..... 33
4.2.2 Acquiring Temperature data ..... 34
4.2.3 Compiling and Quality Checking the Temperature Data and Assigning Site Locations ..... 34
4.2.4 Adding new reaches to the stream network ..... 34
**5 Acknowledgments** ..... **35**
**6 References Cited** ..... **35**

# LIST OF ELECTRONIC APPENDICES

**ELECTRONIC APPENDIX 1:** Model scenario outputs for 1-kilometer prediction sites.

a. Yurok_PredictedStreamTempLines_MeanAugust.kmz: Google Earth file showing prediction lines colored by mean August stream temperature
b. Yurok_PredictedStreamTempLines_MeanDailyMaxAugust.kmz: Google Earth file showing prediction lines colored by mean daily maximum August stream temperature
c. Yurok_PredictedStreamTempLines.shp is an ArcGIS shapefile of prediction lines with attributes including predicted mean August and mean daily maximum August stream temperature, standard errors for predictions, and all predictor variables
d. Yurok_PredictedStreamTempLines_MeanAugust.lyr is an ArcGIS 10.3 layer file that provides a mean August temperature legend for Yurok_PredictedStreamTempLines.shp. It must be placed in the same folder as the shapefile in order to properly function.
e. Yurok_PredictedStreamTempLines_MeanDailyMaxAugust.lyr is an ArcGIS 10.3 layer file that provides a mean daily maximum August temperature legend for Yurok_PredictedStreamTempLines.shp. It must be placed in the same folder as the shapefile in order to properly function.
f. Yurok_PredictedStreamTempPoints.shp has all the same attributes as Yurok_PredictedStreamTempLines.shp but is points (at mid-point of prediction reaches) rather than lines

**ELECTRONIC APPENDIX 2:** Shapefile of observed mean August and mean daily maximum August stream temperatures. In contrast the Electronic Appendix 7, this includes only those sites that are located on the modified NSI hydrography, so it does not include some small streams and springs.

**ELECTRONIC APPENDIX 3:** GIS shapefile of modified version of National Stream Internet hydrography, clipped to study area and includes new reaches added for this project

**ELECTRONIC APPENDIX 4:** Model input files, including SSN file and R scripts. These are specialty format files which will not be useful to most users. It is not exhaustively documented

**ELECTRONIC APPENDIX 5:** Microsoft Access database with complete compilation of stream temperatures site location attributes, hourly (or whatever the original temporal resolution was) measurements, daily summaries, and annual summaries. Annual summaries include mean August, mean daily maximum August, MWMT, and MWAT. This database includes all sites within the study area, not just those that are located on the modified NSI hydrography. *Note: this database is a subset of a more complete upcoming database for a large part of the Klamath Basin that Riverbend Sciences is current compiling for the Klamath Tribal Water Quality Consortium. Future users are encourages to use that upcoming version instead of this electronic appendix.*

## LIST OF FIGURES

Figure 1. Map of Yurok Ancestral Territory created by the Yurok Tribe's GIS Division. ..... 3

Figure 2. Maps of Yurok Ancestral Territory and adjacent areas showing data sources and comparison of observed temperature sites used for model calibration in (A) the original 2015 NorWeST, and (B) this report. Some symbols overlap and mask those beneath. ..... 7

Figure 3. Example data quality assessment graph comparing hourly water temperature data at a single site (Upper Blue Creek data collected byYurok Tribe Fisheries Program) (black line) and Notchko air temperature (light grey line) across years 2003-2015. ..... 9

Figure 4. Daily time series of daily maximum, daily mean, daily minimum, 7-day average of daily mean, and 7-day average of daily maximum, MDMT, MWMT, and MWAT at an example site. ..... 11

Figure 5. Comparison of observed mean August stream temperature and predictions from the final spatial and non-spatial models for streams in Yurok Ancestral Territory and nearby areas. Model summary statistics are shown in Table 4. ..... 23

Figure 6. Predicted (A) mean August temperature and (B) mean daily maximum August temperature for streams within Yurok Ancestral Territory and adjacent areas for the period 1990-2016. Predictions are outputs from a spatial stream-network model which uses observed temperature data and GIS predictor variables as inputs. ..... 25

Figure 7. Mean August stream temperature predicted by the NorWeST 2015 version (years 1993-2011), YTEP's new model (1990-2016)(this report), and the difference between the two, for streams within Yurok Ancestral Territory and adjacent areas. ..... 26

Figure 8. Mean August stream temperature predicted by the NorWeST 2017 version (years 1993-2011), YTEP's new model (1990-2016)(this report), and the difference between the two, for streams within Yurok Ancestral Territory and adjacent areas. ..... 27

Figure 9. Comparison of NorWeST (2017 version) stream temperature scenarios in the Northern California/Coastal Klamath processing unit which includes Yurok Ancestral Territory. ..... 29

Figure 10. Comparison of NorWeST (2017 version) spatial stream-network model predictions for mean August stream temperature for streams within Yurok Ancestral Territory and adjacent areas for 1993-2011 and a future scenario "S32" based on global climate model ensemble averages that represents the A1B warming trajectory for 2080s (2070-2099). The right panel shows the difference between the two scenarios. ..... 30

Figure 11. Comparison of NorWeST (2017 version) spatial stream-network model predictions for mean August stream temperature for streams within Yurok Ancestral Territory and adjacent areas for 1993-2011 and a future scenario "S28" based on a mean 3°C rise in stream temps, but with cool stream warming slightly less and warm streams warming slightly more. The right panel shows the difference between the two scenarios. ..... 31

## LIST OF TABLES

Table 1. Summary of stream temperature data compiled for use in this project. ..... 4

Table 2. List of correlates used in the NorWeST stream temperature model, the type of variation included (temporal or spatial), notes, and recommendations on whether they should be included in the Yurok project. ..... 15

Table 3. Additional correlates considered for use in the Yurok project. ..... 16

Table 4. Comparison of parameter estimates and summary statistics for the final spatial and non-spatial multiple regression models used to predict mean August stream temperature in Yurok Ancestral Territory and surrounding areas. ..... 22

Table 5. Comparison of summary statistics for spatial stream-network models to predict mean August stream temperature and mean daily maximums August stream temperature for streams in Yurok Ancestral Territory and surrounding areas. ..... 23

Table 6. Proportion of total variance in the mean August temperature explained in the final spatial stream-network model by the covariates (predictor variables), spatial autocovariance, and random effects. ..... 24

# 1 INTRODUCTION

## 1.1 DESCRIPTION OF STUDY AREA

The study area includes the ancestral territory of the Yurok Tribe and adjacent areas. Yurok Ancestral Territory is located in Northwest California and spans from Damnation Creek near Crescent City in Del Norte County south to Little River in Humboldt County near Trinidad (Figure 1). Yurok Ancestral Territory includes the Lower Klamath River and its tributaries from Slate Creek downstream. The study area includes the complete watersheds of some coastal tributaries such as Little River and Redwood Creek where Ancestral Territory only includes the lower portions of the those watersheds.

## 1.2 PREVIOUS ASSESSMENTS OF STREAM TEMPERATURES IN YUROK ANCESTRAL TERRITORY

Water temperature has long been identified as a primary factor limiting production of salmon and steelhead within the study area and has been a priority for fisheries management and research (Kier Associates 1991, NRC 2004, Madej et al. 2006, NMFS 2014). Most of the Klamath Basin is listed as impaired under the Clean Water Act Section 303(d) for temperature, and the North Coast Regional Water Quality Control Board[1] and U.S. EPA[2] have established Total Maximum Daily Loads for much of the basin. Previous assessments of stream temperatures within the study area include the analysis of long-term trends (Bartholow 2005), the Klamath River TMDL (NCRWQCB 2010), regression modeling to predict Klamath Basin stream temperatures based on meteorology and topography (Flint et al. 2008), countless monitoring reports on the Klamath River and tributaries (e.g., Gale et al. 1998, Voight and Gale 1998, Gale 2003, Strange 2007, and many reports by the Yurok Tribe Environmental Program[3]), evaluation of the thermal refugia and salmonids' thermal tolerances (Strange 2010, 2011), and analysis of Redwood Creek temperatures using thermal infrared imaging (Ozaki and Anderson 2005, Madej et al. 2006).

In addition to the local analyses mentioned in the previous paragraph, there have been two major regional stream temperature compilations and analysis projects in northwest California which encompasses Yurok Ancestral Territory. The Humboldt State University (HSU) Forest Science Project (FSP) compiled data for 1990-1998 from a multitude of entities, including private timber companies, state and federal agencies, non-profit organizations, and consultants (Lewis et al. 2000). Lewis et al. (2000) then applied statistical models to these data to evaluate relationships between water temperature and variables including air temperature, distance from the Pacific Ocean, elevation, watershed area, and site-specific attributes (e.g., channel width, gradient, and canopy).

The NorWeST[4] stream temperature model uses observed temperature data, Geographic Information Systems (GIS) data, and a multivariate spatial statistics model to produce a spatially continuous prediction of mean August temperature throughout the entire stream network (Isaak et al. 2010, Isaak et al. 2016). It was first applied in the Boise River Basin in Idaho (Isaak et al. 2010). In 2015, the U.S. Forest Service's Rocky Mountain Research Laboratory (USFS RMRS) applied the NorWeST model to the North Coast of California including the Klamath Basin. NorWeST refers to this project area as the "Northern California Coastal Klamath processing

[1] http://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/
[2] https://www3.epa.gov/region9/water/tmdl/final.html
[3] http://www.yuroktribe.org/departments/ytep/water_reports.htm
[4] http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

unit". After first calibrating the model and running a scenario for current conditions, they ran a variety of climate change scenarios. Model predictions[5] and daily/annual summaries of measured water temperature data[6] are available online (Isaak et al. 2016). They compiled a large amount of stream temperature data for use as model inputs; however, the compilation focused on existing large regional compilations such as the U.S. Forest Service's Natural Resource Information System Aquatic Surveys (NRIS AqS)[7] and U.S. Geological Survey's U.S. Geological Survey's (USGS) National Water Information System (NWIS)[8]. In the Lower Klamath River, this was supplemented by a database of mainstem Klamath River water temperature data from the U.S. Fish and Wildlife Service's Arcata Office. Many existing temperature datasets within Yurok Ancestral Territory were not included, including data from YTEP, the Klamath Resource Information System (KRIS), Green Diamond Resource Company, and the Humboldt State University's Forest Science Project 1990-1998 compilation.

As a result, while the NorWeST model did make temperature predictions for all streams within Yurok Ancestral Territory, but with the exception of the mainstem Klamath River the predictions were not calibrated with local temperature data but instead relied on regression parameters from other portions of the North Coast. In the time since the 2015 NorWeST modeling began, several projects within the North Coast have compiled new stream temperature datasets. These projects include YTEP's STAR project and other Riverbend Sciences projects in the Klamath Basin (in-progress), Salmon River (in-progress), South Fork Trinity River (Asarian 2016), and Eel River (Asarian et al. 2016). Given the availability of large new temperature datasets within the North Coast, as well as previous compilations which were not utilized such as the HSU FSP project mentioned in the previous paragraph, RMRL completed a re-run of the NorWeST model for the entire North Coast in April 2017.

## 1.3 STUDY GOALS

The goals of this study were to 1) acquire, compile, and quality check on all available continuous stream temperature data within Yurok Ancestral Territory, 2) calculate summary temperature metrics for each site and year, 3) use spatial stream-network models to produce spatially continuous predictions of summer stream temperatures, and 4) compare model results to previous efforts. The results of this analysis will be used to refine watershed monitoring plans, to inform development of future projects to restore aquatic habitat and watersheds within Yurok Ancestral Territory, and to allow the planning and development of the most appropriate domestic water sources.

[5] http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml
[6] http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/StreamTemperatureDataSummaries.shtml
[7] http://www.fs.fed.us/nrm/index.shtml
[8] http://waterdata.usgs.gov/nwis

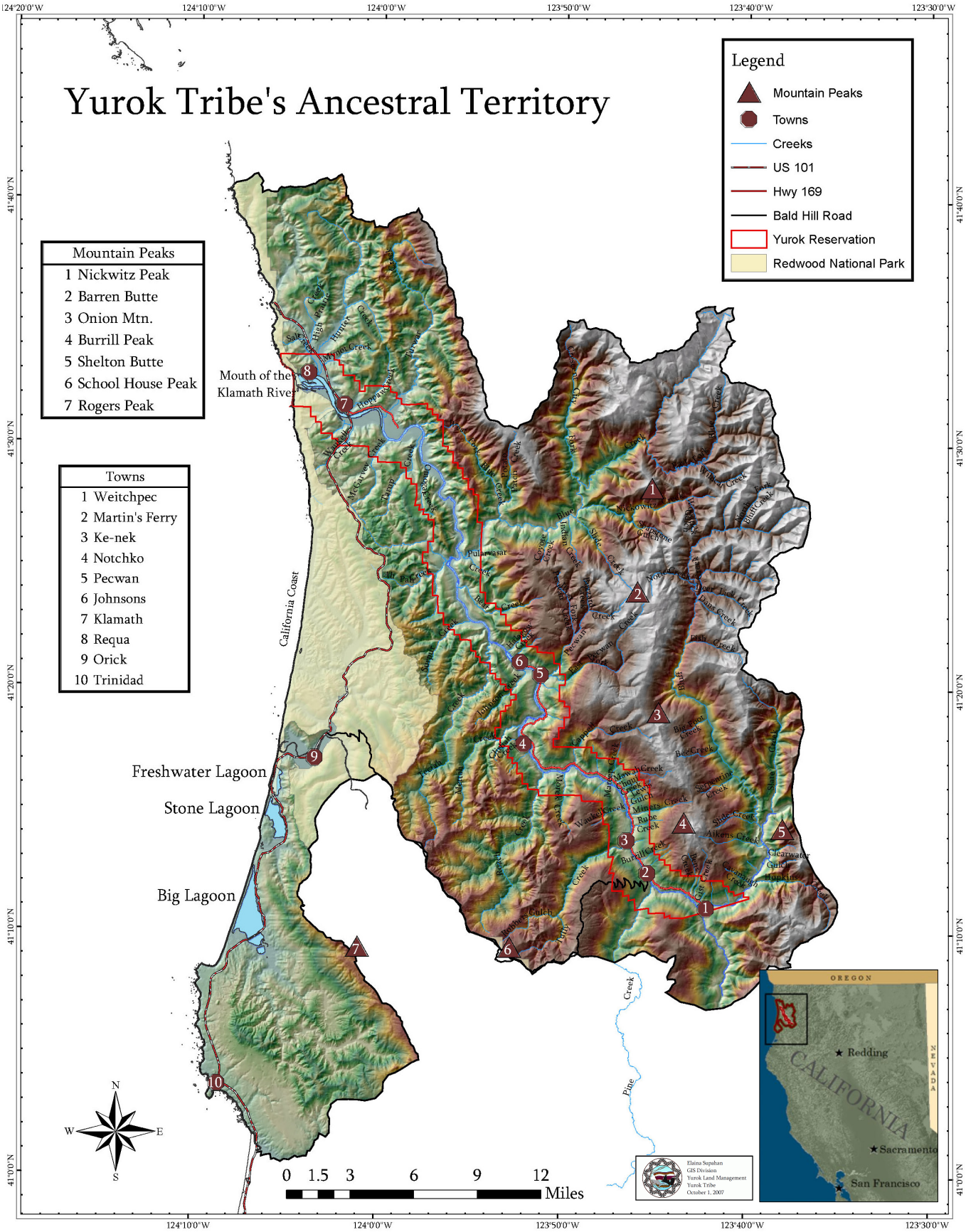



Figure 1. Map of Yurok Ancestral Territory created by the Yurok Tribe's GIS Division.

# 2 METHODS

## 2.1 STREAM TEMPERATURE DATA SOURCES ACQUIRED AND COMPILED

Data from a multitude of sources was acquired (Table 1, Figure 2) and the resulting compiled dataset spans the years 1992 through 2016, with 287 sites and 1276 site-years. 1157 had sufficient data to calculate mean August temperature. Some sites and data were duplicate deployments that may be included in the databases from multiple sources. For the purposes of this project, it was not necessary to spend the time required to identify and exclude overlapping datasets; however, users of the resulting database should be aware that issue because it might affect the results of certain types of analyses (e.g., unless duplicate data are removed, they might artificially inflate the sample size which could affect statistical tests evaluating time series trends). The compilation of many of these datasets were funded by the Klamath Tribal Water Quality Consortium under a separate in-progress Riverbend Sciences project, but were made available for use in this project.

Table 1. Summary of stream temperature data compiled for use in this project.

| Source Abbreviation | Source Full Name | Site-Years | Sites | First Year | Last Year |
|---|---|---|---|---|---|
| YTEP | Yurok Tribe Environmental Program | 143 | 75 | 2015 | 2016 |
| YTFP | Yurok Tribe Fisheries Program | 431 | 54 | 1995 | 2016 |
| USFS_NRIS_AqS | U.S. Forest Service | 210 | 22 | 1992 | 2010 |
| HSU_FSP | Humboldt State University Forest Science Project | 153 | 90 | 1994 | 1998 |
| RNSP | Redwood National and State Parks | 256 | 32 | 1997 | 2015 |
| USFWS | U.S. Fish and Wildlife Service | 83 | 14 | 1999 | 2016 |
| TOTAL | | 1276 | 287 | 1992 | 2016 |

### 2.1.1 YUROK TRIBE ENVIRONMENTAL PROGRAM

The Yurok Tribe Environmental Program (YTEP[9]) collects stream temperature data at long-term monitoring sites on the Klamath River and tributaries, primarily during the summer season. In addition, from spring 2015 through spring 2017, YTEP installed a network of more than 100 temperature monitoring sites on Lower Klamath tributaries and springs.

### 2.1.2 YUROK TRIBE FISHERIES PROGRAM

The Yurok Tribe Fisheries Program (YTFP[10]) collects temperature data on the mainstem Klamath River (McCovey 2003) and its tributaries (Gale 1998, Gale et al. 1998, Voight and Gale 1998, Gale and Randolph 2000, Gale et al. 2003). Several different divisions and projects of YTFP are involved in the temperature monitoring, and the names of those divisions has changed since consistent temperature monitoring began in the mid-1990s.

### 2.1.3 US FOREST SERVICE, NATURAL RESOURCE INFORMATION SYSTEM AQUATIC SURVEYS

Nearly all temperature data collected by U.S. Forest Service (USFS) within the study area are input into the national Natural Resource Information System (NRIS) Aquatic Surveys (AqS) database. The

[9] http://www.yuroktribe.org/departments/ytep/water_reports.htm
[10] http://www.yuroktribe.org/departments/fisheries/reportsandpublications.htm

exception is that data collected within the Lower Trinity Ranger District after 2010 have not been input into NRIS AqS but rather are available upon request from biologist Leroy Cyr. Hydrologist Callie McConnell of the USFS office in Corvallis, Oregon extracted all temperature data within the study area in December 2016 and provided it for use in this project; however, due to time/budget constraints no post-2010 USFS data from the Lower Trinity Ranger District were utilized.

The NRIS AqS databased also includes some data collected by other entities such as Redwood National and State Parks (RNSP) in the Redwood Creek watershed. I did not use the NRIS AqS version of the RNSP data (or any NRIS AqS data from outside the Klamath Basin), but rather compiled the RNSP data from the original source because it included additional years (see section 2.1.5 below).

### 2.1.4 HUMBOLDT STATE UNIVERSITY'S FOREST SCIENCE PROJECT

As noted above in section 1.2, Humboldt State University's (HSU) Forest Science Project (FSP) compiled data from the North Coast of California for 1990-1998 from a multitude of entities, including private timber companies, state and federal agencies, non-profit organizations, and consultants (Lewis et al. 2000). The FSP was later renamed the Institute for Forest and Watershed Management and is now dissolved. The data are extremely well organized and were rigorously reviewed during the Lewis et al. (2000) analysis, but one deficiency of the version of the publicly shared version of the database is that there is no way to ascertain which entity collected any particular piece of data, which inhibits transparency and made it difficult to determine potential overlap with other datasets.

### 2.1.5 REDWOOD NATIONAL AND STATE PARKS

Redwood National and State Parks (RNSP) have a long-term monitoring program in the Redwood Creek watershed which includes water temperatures (Madej et al. 2006) and geomorphology (Madej and Ozaki 2009). Vicki Ozaki provided a copy of RNSP's stream temperature data. Portions of the RNSP temperature data have been compiled into the USFS NRIS AqS database but were not utilized for this project (see section 2.1.3).

### 2.1.6 U.S. FISH AND WILDLIFE SERVICE, ARCATA OFFICE

The U.S. Fish and Wildlife Service[11] (USFWS) office in Arcata, California collects stream temperature data at a network of monitoring sites within the Klamath and Trinity River basins and maintains the data in a well-organized Microsoft Access database. Data were received from USFWS fisheries biologist Aaron David.

### 2.1.7 U.S. FOREST SERVICE'S ROCKY MOUNTAIN RESEARCH LAB'S NORWEST PROJECT

As noted above in section 1.2, in 2015 the U.S. Forest Service's Rocky Mountain Research Lab's (RMRL) NorWeST project compiled a large amount of stream temperature data for northwest California, including the study area. These data came from a multitude of entities, including USFS NRIS (see section 0), U.S. Geological Survey (USGS) National Water Information System (NWIS), and US Fish and Wildlife Service (Figure 2). Because the data in the 2015 NorWeST compilation only spanned through the year 2013, I did not use the NorWeST compilation but rather re-compiled from the USFWS and USFS NRIS datasets to include the more recent years (through 2015 or 2016); however, I did use the 'snapped' coordinates provided by NorWeST for these datasets (see section 2.4

[11] http://www.fws.gov/arcata/fisheries/activities/waterQuality/klamathWQ.html

below). The USGS data did not include any additional stations beyond what was already in the USFWS dataset, so we did not use the USGS data.

### 2.1.8 ADDITIONAL DATASETS NOT ACQUIRED OR COMPILED

During the outreach and research over the course of this project, we became aware of some datasets for which we were either not able to obtain the original electronic data, or did not have time to compile the data. These included:

- Green Diamond Resource Company (GDRC) monitors stream temperatures data at large number of streams on its timber lands in the Lower Klamath River as well as coastal tributaries such as Little River and Redwood Creek as part of their Aquatic Habitat Conservation Plan (AHCP) (GDRC 2006). The company declined requests to share the data, but some portions of older data (1990-1998) might be included in the HSU FSP compilation (section 2.1.4 above). Tables with annual summaries (MWMT, MWAT, annual maximum) of all of GDRC's stream temperature monitoring results for 1994-2000 are available in Appendix C5 of the AHCP (GDRC 2006) but no maps or coordinates are provided. The annual AHCP monitoring reports (GDRC 2017) do not contain any tables that would allow extraction of annual temperature summaries for sites.
- YTEP has long-term year-round temperature datasets (primarily year-round) at its streamflow gaging stations on Turwar, McGarvey, and Tully Creeks. In addition, YTEP has long-term summer temperature data from multi-parameter datasondes at the mouth of the Trinity River, and the Klamath River at Weitchpec, Tully Creek, and Turwar, but were not utilized due to time/budge t restraints.
- The U.S. Geological Survey's (USGS) National Water Information System (NWIS[12]) data did not include any additional stations beyond what was already available and being utilized from other data sources such as USFWS, so USGS NWIS data were not included in this project.
- A few additional temperature datasets are available in the Klamath Resource Information System (KRIS[13]). These were inventoried, but there was not sufficient time and budget to compile them. Details are available upon request from Riverbend Sciences.
- Additional water temperature (as well as dissolved oxygen, pH, and specific conductivity) data were compiled by Tetra Tech (2004) in preparation for the Klamath River TMDL (NCRWQCB 2010). Kier Associates compiled and added additional data through 2005, as part of projects funded by the Klamath Basin Tribal Water Quality Work Group. After a brief inventory of this compilation (it is available upon request from Riverbend Sciences), it was found that substantial portions of it overlap with (and are now superseded by) other datasets as USFS NRIS AqS and UFSWS. Time and budget constraints precluded utilization of this compilation which include the following unique datasets: 1) North Coast Regional Water Quality Control Board data, 2) Watercourse Engineering (2003) data for the year 2000 sponsored by the US Bureau of Reclamation and PacifiCorp, 3) USGS data for Klamath River at Walker Bridge and Klamath River above Shovel Creek[14], and 4) potentially some additional data from the Yurok Tribe.
- Humboldt State University student Alexander Wick monitored stream temperatures in 2014 and 2015 at several sites in South Fork Ah Pah Creek in as part of the riparian thinning experiment (Wick 2016, GDRC 2017). The data have been incorporated into Green Diamond Resource Company's database.

[12] https://waterdata.usgs.gov/nwis
[13] http://www.krisweb.com/krisklamathtrinity/krisdb/webbuilder/selecttopic_temperature.htm
[14] These sites are located on the Klamath River upstream of the study area, but are listed here because they are still within the Klamath Basin so may be of interest to readers of this report. Additional USGS sites are also included in the Tetra Tech 2000 database but those additional data are moot because they are also present in either in the national USGS NWIS database or the USFWS database.

- Oregon State University doctoral student David Roon is intensively monitoring temperatures (tens of probes per creek) associated with a riparian thinning experiment in the West Forks Tectah Creek and East Forks Tectah Creek on Green Diamond Resource Company Land, and Middle Fork Lost Man Creek in Redwood National and State Parks (Roon 2017, GDRC 2017). The project runs for at least the years 2016-2017.

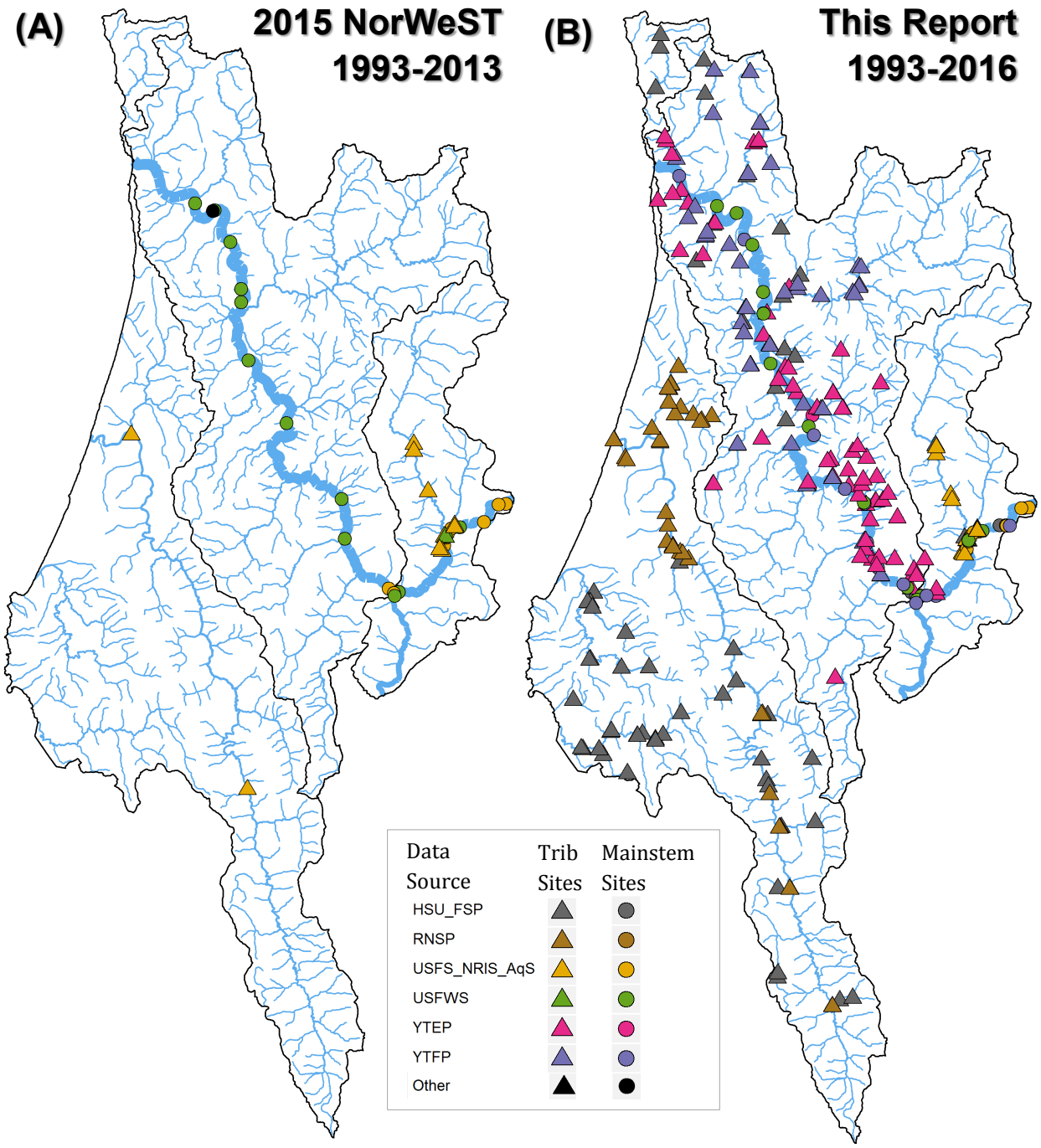



Figure 2. Maps of Yurok Ancestral Territory and adjacent areas showing data sources and comparison of observed temperature sites used for model calibration in (A) the original 2015 NorWeST, and (B) this report. Some symbols overlap and mask those beneath.

## 2.2 QUALITY CONTROL AND CLEANING OF STREAM TEMPERATURE DATA

Data collected with continuous probes, such as the temperature data that is the subject of this project, must be cleaned/trimmed to remove data corrupted when a probe malfunctions or is exposed to air during pre/post deployment or when a stream dries up. The condition of the datasets we received varied among data sources and year, so a fairly intensive screening and trimming process was initiated, informed by protocols from Dunham et al. (2005), Sowder and Steel (2012), and Stamp et al. (2014). All data values for the period when the stream appeared to be dry were removed but the data from the remainder of the probes' deployment when water was flowing in the respective stream reaches were retained.

Air temperature data is very useful for informing the cleaning of water temperature data (Sowder and Steel 2012). Local air temperature data for 2002-2016 were obtained from the Yurok Tribe Environmental Program's remote automated weather station (RAWS) at Notcho[15] (site code CYUR) located approximately halfway between Weitchpec and Klamath, available online from the Western Regional Climate Center[16].

A series of graphs for each year and site were then created and reviewed. Examples included: 1) hourly water temperature overlaid on the hourly Notcho air temperature (e.g., Figure 3 shows an example of Upper Blue Creek), and 2) multi-panel comparison of hourly temperature data at all sites within a single year and source entity. The graphs illustrate the typical seasonal temperature pattern within a site, as well as how the pattern at that site compares to other sites within the same year. The graphs helped to identify periods when water temperature showed abnormal patterns, so that such periods could then be closely investigated to see if they were erroneous and needed to be trimmed. For example, water temperatures typically follow seasonal patterns similar to air temperatures but have a compressed range (i.e., lower maximums and higher minimums); therefore, a sudden change in water temperature that does not coincide with a similar change in air temperature might indicate that the probe was exposed to air due to stream dewatering, or removal of the probe from the water by technicians, other people, or high flows.

[15] Official RAWS site name is 'Yurok' but in this report I refer to it a 'Notchko',which is the named used by YTEP.
[16] http://raws.dri.edu/cgi-bin/rawMAIN.pl?caCYUR

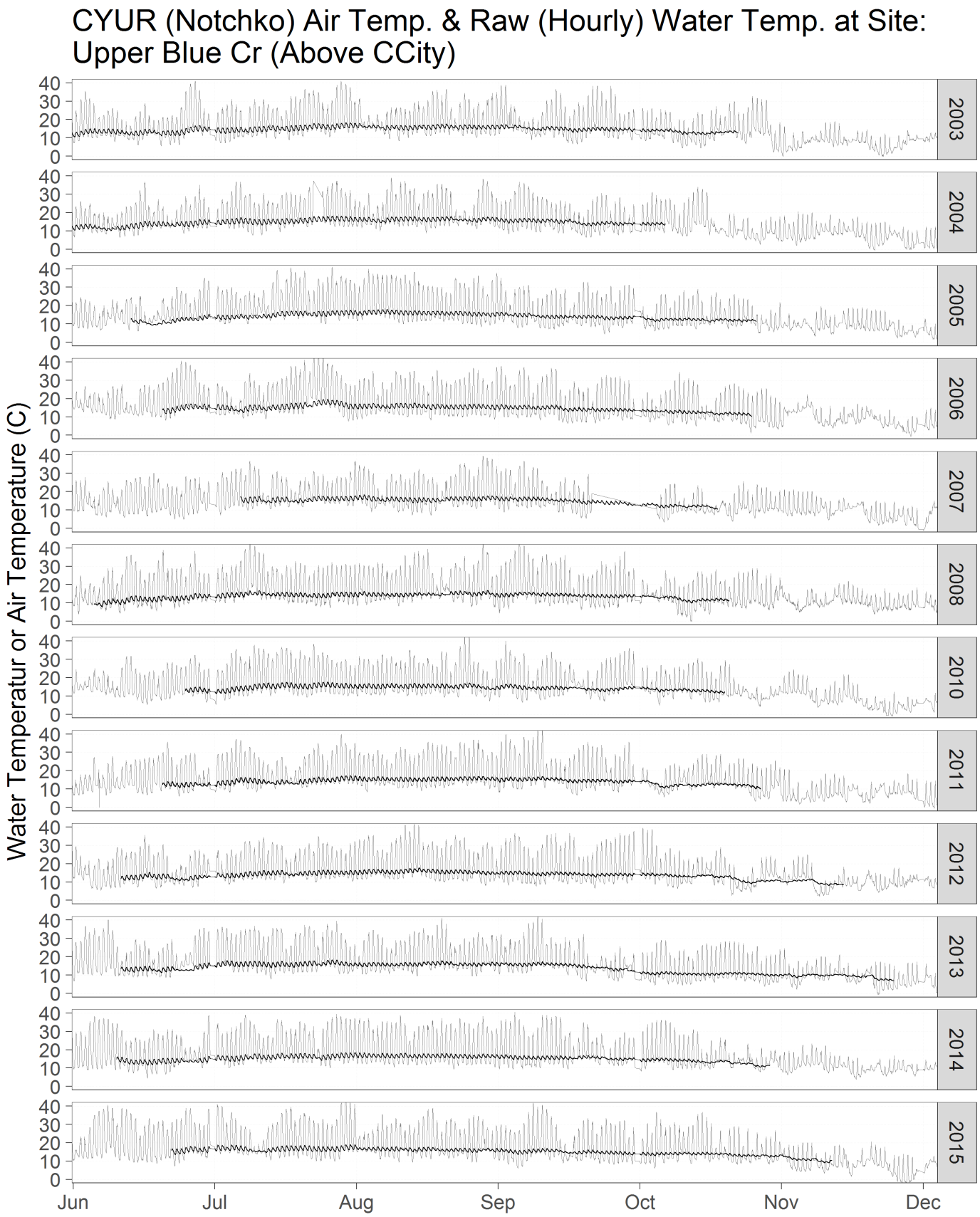



Figure 3. Example data quality assessment graph comparing hourly water temperature data at a single site (Upper Blue Creek data collected by Yurok Tribe Fisheries Program) (black line) and Notchko air temperature (light grey line) across years 2003-2015.

## 2.3 CALCULATION OF DAILY AND SEASONAL SUMMARIES

### 2.3.1 DAILY SUMMARY STATISTICS

The vast majority of the data were acquired at their original temporal resolution, which ranged from 15 to 120 minutes. For each site, daily statistics were calculated when data completeness was at least 80% (e.g., for data with temporal resolution of 30 minutes, 38 out of 48 individual measurements must be present). Daily statistics included number of measurements, minimum, maximum, mean, and range. All metrics were calculated using R (R Core Team 2012).

### 2.3.2 INITIAL CALCULATION OF SEASONAL AND MONTHLY SUMMARY STATISTICS

Key seasonal temperature metrics were selected based on a review of previous stream temperature analyses (Lewis et al. 2000, Welsh et al. 2001, Dunham et al. 2005, Isaak et al. 2010, McCullough 2010) and calculated for each site and year, including:

- *Maximum Daily Maximum Temperature (MDMT)* – The highest instantaneous maximum temperature recorded during the summer (Figure 4).
- *Maximum Weekly Maximum Temperature (MWMT)* – The highest seven-day average of the daily average temperature. In simple terms, it is the average temperature during the warmest seven-day period of the year. Steps for calculation (Figure 4):
    - Step 1. Calculate <u>maximum</u> temperature for each day.
    - Step 2. Calculate 7-Day Average of the Daily Maximum (7DADM), which is calculated for each day as the average of the daily maximum temperature (Step 1) for the three prior days, the current day, and three following days.
    - Step 3. Select highest 7DADM (Step 2) value of the year.
- *Maximum Weekly Average Temperature (MWAT)* – The highest seven-day moving average of the daily maximum temperatures. In simple terms, it is the average daily maximum temperature during the warmest seven-day period of the year. Steps for calculation (Figure 4):
    - Step 1. Calculate <u>mean</u> temperature for each day.
    - Step 2. Calculate 7-Day Average of the Daily Average (7DADA), which is calculated for each day as the average of the daily mean temperature (Step 1) for the three prior days, the current day, and three 3 following.
    - Step 3. Select highest 7DADA (Step 2) value of the year.
- *Mean August temperature (Aug_mean)* – Metric used in the NorWeST model because August is often the warmest month in snowmelt-dominated streams. Metric only calculated when data available for 90% (28 of 31) of days.
- *Mean Daily Maximum August temperature (Aug_meanMx)* – The August average of the daily maximum temperatures. Metric only calculated when data available for 90% (28 of 31) of days.

Summer temperature metrics are all highly correlated with each other (Dunham et al. 2005).

The date of occurrence of MDMT, MWMT, and MWAT was also calculated. In cases where the same maximal value was reached on more than one date, the seasonal statistic date was assigned to the date on which a larger number of sites had the maximal value[17].

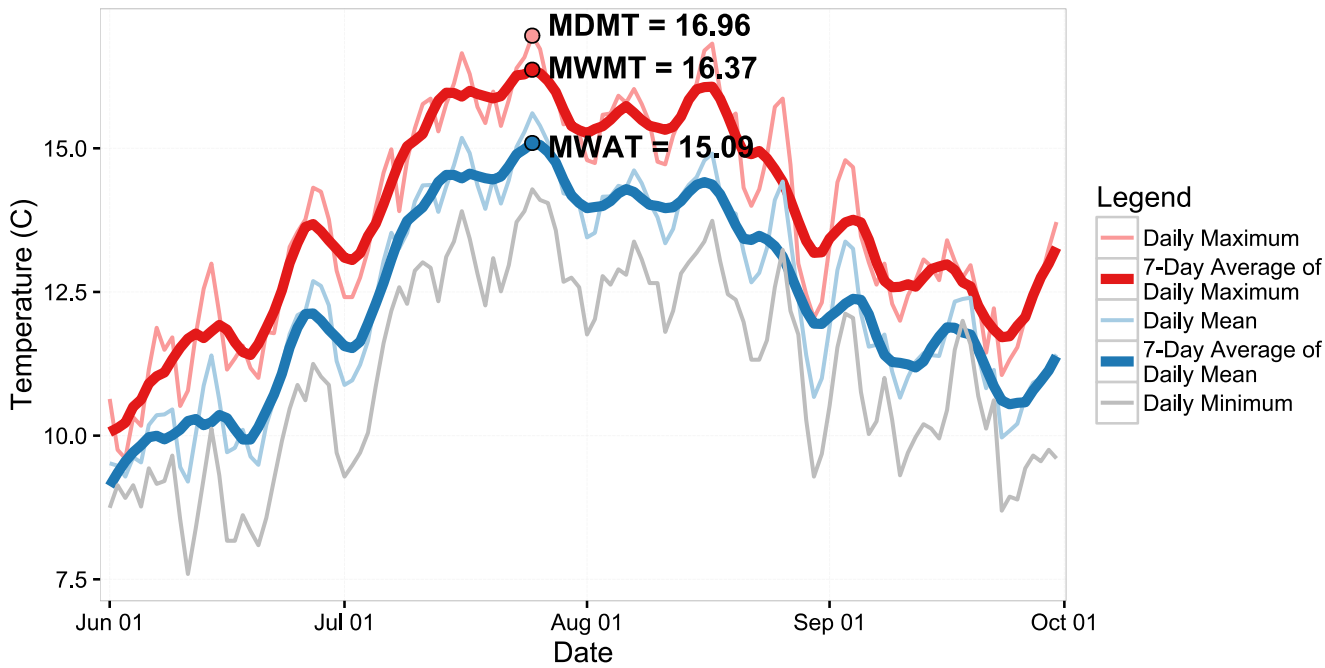



Figure 4. Daily time series of daily maximum, daily mean, daily minimum, 7-day average of daily mean, and 7-day average of daily maximum, MDMT, MWMT, and MWAT at an example site. MDMT, MWMT, and MWAT are the highest annual values for daily maximum, 7-day average of daily mean, and 7-day average of daily maximum, respectively.

### 2.3.1 REFINING SEASONAL STATISTICS ACCORDING TO DATA COMPLETENESS

Seasonal summary statistics are relatively simple to calculate when data are available for the entire warm season (i.e., June through September); however, many available datasets only contained data for part of the summer season and thus had to be screened for comparability. Seasonal statistics may be biased low if they are calculated from only a short period and did not include the warmest days of the year. Conversely, excluding seasonal statistics when gaps occurred outside the warmest days would be an unnecessary loss of important information. As described in Section 2.3.2, seasonal statistics were initially calculated for all years and sites. Values were then either retained (i.e., kept) or excluded (i.e., deleted) based on data completeness. For example, mean August temperatures were retained for 1157 of the total 1276 site-years in the database.

[17] Potential alternatives would be to randomly choose one of the dates, or to assign the mean date, but in cases where long distances separate the occurrence of maximal values, then the mean date might be during a cool period. For example, if maximal values are reached on July 1 and July 30, then the mean date would be July 16.

Riverbend Sciences developed an automated multi-step procedure to screen data completeness followed by an optional manual override. Since MWMT, MWAT, and MDMT almost always occur in July or August, seasonal statistics were retained[18] for datasets which included all of July and August[19]. For datasets that were missing some days in July or August, seasonal statistics were only automatically retained if the data were present at that site for each day on which that statistic occurred at least two other sites[20]. This approach makes maximal use of available data while minimizing the chance that un-representative statistics were retained.

## 2.4 ASSIGNING STREAM TEMPERATURE MONITORING SITES TO STREAM NETWORK GIS

All stream temperature datasets had x-y spatial coordinates (e.g., UTM or latitude/longitude) when we acquired them (or if not then I requested and receive them later); however, assigning each site to a GIS stream network (rather than solely x-y coordinates) greatly increases the utility of the data. The National Stream Internet (NSI) Hydrography Network[21] was selected as the GIS stream network due to its use in the NorWeST model. NSI network was created by the U.S. Forest Service's Rocky Mountain Research Lab by modifying the NHD-Plus[22] Version 2 medium-resolution (1:100,000-scale) hydrography layer for all streams in the contiguous United States. NHD-plus contains a large database of descriptors for each reach (e.g., stream name, watershed area, stream gradient, climate variables, and percent of various land-use types within the watershed) which are useful predictor variables in spatial analyses. Assigning the temperature monitoring points to NSI/NHD-plus stream reaches allowed the data to be easily integrated into NorWeST and other stream network models.

Each stream temperature monitoring station was assigned to a reach in the National Stream Internet (NSI) Hydrography Network GIS, using the following steps, performed by author and primary contractor Eli Asarian and/or data technician Nicholas Cusick:

- The location for each point was plotted on a base map (e.g., topographic map with labeled streams and roads) in ArcGIS and visually examined to make sure its location corresponded to available attributes such as site code and site name. If necessary, it was manually moved to be closer to the correct reach. Many monitoring sites are located near tributary junctions and thus minor inaccuracies in location (if not corrected) could result in a site being assigned to the wrong stream reach. In some cases, site locations were based on 1:24,000 scale streams GIS, but still required adjustment to correspond to the stream's location in the coarser 1:100,000 NSI/NHDplus streams GIS.
- Once the locations were adjusted as necessary, then we used the *snappoints* tool in the Geospatial Modeling Environment (GME)[23] platform to snap each point to the closest stream.

[18] Seasonal statistics were initially calculated for all years and sites. Values were then either retained (i.e., kept) or excluded (i.e. deleted) based on data completeness.
[19] Actually June 28 through September 2 because the 7-Day Average of the Daily Maximum (7DADM) and 7-Day Average of the Daily Average (7DADA) require data to be present for three days before and three days after.
[20] I chose two sites as the threshold rather than one site because a single site might have unique characteristics or a data quality issue whereas two or more sites should indicate a more widespread pattern.
[21] http://www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet/NSI_network.html
[22] http://www.horizon-systems.com/nhdplus/NHDPlusV2_home.php
[23] http://www.spatialecology.com/gme/

- Then we used a *Spatial Join* in ArcGIS ArcToolbox[24] to assign the stream reach's attributes to each point (i.e., extract the COMID and other relevant attributes).
- The newly assigned attributes of each point were then reviewed for accuracy, and if necessary corrected and re-snapped.
- The new coordinates for the snapped locations were then added to the attribute table of the temperature monitoring sites using the *Calculate Geometry* function in ArcGIS.

These steps are based on guidance provided by the NorWeST modelling team (Sherry Wollrab, pers. comm.). COMIDs and snapped coordinates for most of the sites in the USFS NRIS AqS database were already assigned by the NorWeST project in 2015, so we utilized that information where available[25].

### 2.4.1 ADDITION OF NEW REACHES TO THE STREAM NETWORK GIS

Due its coarse nature, the NSI hydrography contains some errors within the study area, and also does not include the smallest streams and springs. Some of these missing streams were deemed by YTEP staff to be important enough to justify adding new reaches to the NSI, resulting in a new local version of the NSI. The new reaches were obtained either from the Yurok Tribe's synthetic hydrography layer, the 1:24,000 scale high resolution NHD, or manually digitized. These new reaches were assigned a new unique identifier named COMID_Alt. The addition of these new reaches also necessitated splitting some existing NSI reaches into two pieces, so that the new reaches could join at a node. These split reaches were assigned a COMID_Alt value by adding a letter (a, b, c, etc.) suffix to the COMID. The new reaches then needed to have spatial covariates (predictor variables) calculated and added, using methods described below in section 2.5.

## 2.5 SPATIAL COVARIATES (PREDICTOR VARIABLES)

Due to the huge geographic area modeled (the entire western United States), the NorWeST model uses some fairly coarse GIS input data for some important variables or correlates such as stream shade, air temperature, and hydrology. Most (nine) of original eleven correlates from the 2015 NorWeST stream temperature model represent spatial variation. They vary for each stream reach but are constant over time (Table 2). The remaining two variables are climate variables (air temperature and stream discharge) which are assigned as the same value (i.e., regional averages) for all reaches but vary temporally among years (1993-2012) to characterize the influence of inter-annual climate variability on stream temperatures (Table 2).

The NorWeST team's decision to use the same air temperature and stream discharge or flow values for all reaches, may seem surprising but the NorWeST modelers' philosophical approach justifies their decision considering the original area to be covered in their model and is described below. When constructing a multi-variate regression model, there are choices to be made about

[24] The Spatial Join tool in ArcToolbox allows the user to specify a maximum distance. In contrast, the "Join data from another location based on spatial location" function in the Join Data dialogue box (accessed by right-clicking on the item in the ArcGIS Table of Contents and choosing Joins and Relates) will join points to the closest stream even if it is miles away, resulting in erroneous joins for sites located on streams that do not exist in the NSI/NHDplus stream network GIS.

[25] I acquired a Microsoft Access database of daily stream temperature data and deployment information for the "Northern California Coastal Klamath" unit of NorWeST which contained the database fields required to link NorWeST's COMID and snapped coordinates to an updated version of the USFS AqS database.

which variables to use. One alternative for air temperature would be to use a modeled grid such as PRISM (http://www.prism.oregonstate.edu, Daly et al. 2008). PRISM combines ground-based weather stations with a GIS model to produce a spatially continuous grid of climate variables such as air temperature. In Idaho where the NorWeST model was first applied, elevation explains a very high percent of the spatial variation in air temperature, and elevation is already included in the NorWeST model as a correlate. In addition, there are relatively few ground-based air temperature stations compared with the number of stream temperature stations, and the NorWeST model's interpolation of spatial patterns in stream temperature may be more accurate than PRISM's interpolation of air temperature; therefore, it was entirely appropriate to use a constant temperature for all reaches in Idaho. However, in Yurok Ancestral Territory, the Pacific Ocean exerts a strong influence over the climate close to the coast (i.e., summer cooling), so elevation alone does not adequately explain air temperature. Thus, additional spatial correlates were included in the models to represent coastal effects (Table 3).

In total, seven new covariates were calculated and used in at least one of the temperature model runs (see first page of Table 3) for this project. The new covariates are primarily five different versions of air temperature but also include coastal effects and basin shape factor.

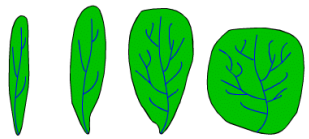
Also, two covariates were slightly modified: streamflow and drainage area (Table 2). NorWeST streamflow is based on a regional average from gages around northwest California. I used a similar approach, but chose gages close to the study area (Smith River, Redwood Creek at Orick, Little River, and Klamath River at Klamath) and normalized by the mean at each site before averaging, so final units are a ratio ranging from 0.56 (low) to 1.75 (high). NorWeST drainage areas are assigned based on the NHDplus/NSI reach that a site is located on. The drainage area at the bottom of a reach is assigned to all sites within that reach. Reaches split at tributary confluences, so most reaches are only a few kilometers long and actual drainage area does not increase much from the top to the bottom of a reach; however, in headwater reaches, actual drainage area can increase several fold along the reach, resulting in assignment of drainage areas that are too high. To account for this, a refined estimate of drainage area in R/SSN was developed which uses linear interpolation to adjust the drainage area based on its position within the reach. For example, if the drainage area at the bottom of a reach is 20 $km^2$, the drainage area at the bottom of the adjacent upstream reach is 10 $km^2$, and the site of interest is located one quarter of the way up from the bottom of the reach, then the site is assigned a drainage area of 17.5 $km^2$.

In researching possible covariates, another seven additional covariates were considered but time and budget constraints (see second and third pages of Table 3) prevented their use.

Table 2. List of correlates used in the NorWeST stream temperature model, the type of variation included (temporal or spatial), notes, and recommendations on whether they should be included in the Yurok project.

| Type of Variation | Variable Name | Notes/Rationale | Used in Yurok project? |
|---|---|---|---|
| Temporal | Air temperature mean August (˚C) | Mean August air temperature from the dynamically downscaled NCEP RegCM3 reanalysis. *Single value per year for all sites* (calculated from the average across the whole northwest California area). | No, replaced |
| Temporal | Stream discharge August (m3/s) | Mean August streamflow from average across USGS flow gages with long-term records and minimal water abstraction or storage reservoirs. *Single value per year for all sites* (calculated from the average across the whole northwest California area). | Yes, modified |
| Spatial | Elevation (m) | Elevation from NHDPlus at each site. Used to represent the vertical trend towards cooler air temperatures. | Yes, used in some models |
| Spatial | Latitude (m) | The y-coordinate at each site. Used to represent the pole ward trend towards cooler air temperatures. | Yes, used in some models |
| Spatial | Canopy % | Average percent canopy within 1-km reach from the 2001 version National Land Cover Database. Used to represent stream shade near a temperature site. | Yes |
| Spatial | Cumulative drainage area ($km^2$) | Cumulative catchment area, from NHDPlus. Used to represent stream size and amount of insolation. | Yes, modified |
| Spatial | Stream slope % | Stream slope % for reach which contains site, from NHDPlus. Steeper slopes should lower temperatures. | Yes, used in some models |
| Spatial | Mean annual precipitation (mm) | Mean annual precipitation for catchment area of site, from NHDPlus. High precip. areas may have more water and cooler streams. | Yes, used in some models |
| Spatial | Base flow index (BFI) | Base flow index is daily minimum flow divided by average annual flow. Higher baseflows may have greater influence of cool groundwater. Data from national grid developed by Wolock 2003. *Values are WAY too high for most of the North Coast, thus data are not useful and were not used.* | No, dropped |
| Spatial | Lake % | Percentage of the catchment area classified as open water at a temperature site. Lakes and reservoirs may have natural warming effect. Not used for Yurok project because observed temperature sites did not have a great enough range to obtain useful estimates. | No, dropped |
| Spatial | Tailwater | Categorical predictor variable coded as 0/1 to indicate whether a site is downstream from a reservoir that creates an anomalously cold tailwater. | No, dropped |

Table 3. Additional correlates considered for use in the Yurok project.

| Type of Variation | Variable Name | Description/Source | Used in Yurok project? | Acquisition and Processing Methods |
|---|---|---|---|---|
| Temporal and spatial | PRISM Air temperature mean August (˚C) | Mean august air temperature each site and year (in contrast to NorWeST model which used same regional value for all sites) from PRISM (Parameter elevation Regression on Independent Slopes Model) (Daly et al. 2008). | Yes, used in some models | Downloaded GIS file from http://www.prism.oregonstate.edu/ for each month and year. Spatial resolution is 4 km. |
| Spatial | PRISM Air temperature mean August normals (˚C) | Mean august air temperature each site, averaged across years (in contrast to NorWeST model which used same value for all sites) from PRISM. | Yes, used in some models | PRISM (see above). 4 km resolution used for Yurok project, but 1km spatial resolution also available. I used spatial overlay in R to assign values to each site. |
| Temporal and spatial | PRISM Air temperature mean August anomaly (˚C) | Anomaly for mean august air temperature each site. Anomaly is current value minus the long-term mean for that time of year. | Yes, used in some models | PRISM (see above). Spatial resolution is 4 km. Anomaly calculated in R. |
| Spatial | BCM Air temperature mean August normals (˚C) | Mean august air temperature each site, averaged across years from USGS BCM model (Flint et al. 2013). It is a derived from the 1km PRISM data by downscaling to 250m resolution. | Yes, used in some models | Downloaded from: http://climate.calcommons.org/dataset/2014-CA-BCM. |
| Temporal and spatial | BCM Air temperature mean August (˚C) | PRISM anomaly can be added to BCM normals to obtain a 250m resolution<br>Anomaly for mean august air temperature each site. Anomaly is current value minus the long-term mean for that time of year. | Yes, used in some models | Calculated for each cells as PRISM anomaly plus BCM normals |
| Spatial | Basin shape factor | An index of how round or long a basin is:  | Yes, used in some models | Calculated as the square of the longest flow path divided by drainage area. Automated calculation of longest flow path is difficult. I used an intricate series of steps to calculate this in R using SSN and spatial info from STARS. Details (including R code) are available upon request. |
| Spatial | PRISM coastal proximity | PRISM represents coastal influence as a combination of linear distance from coast and the topographic influences (allows greater penetration for flow paths from the west and northwest). | Yes, used in some models | Obtained from PRISM's Chris Daly via email request. PRISM considers this to be proprietary intellectual property, so there are restrictions on re-distribution. |

| Type of Variation | Variable Name | Description/Source | Used in Yurok project? | Acquisition and Processing Methods |
|---|---|---|---|---|
| Spatial | Distance from coast | Linear distance from coast would be relatively simple to calculate in GIS. This would have been an alternative for representing coastal influence, but since I obtained PRISM coastal influence, this was not necessary. | No | NA |
| Spatial | Fog and low clouds frequency August (hours/day) | Torregrosa et al. (2016) produced GIS of average hours of summertime fog and low cloud cover (FLCC) per day for each month. This would have been an alternative for representing coastal influence, but since I obtained PRISM coastal influence, this was not necessary. | No | GIS grids of monthly normals available for download: http://climate.calcommons.org/datasets/summertime-fog. |
| Temporal and spatial | PDSI drought index | Palmer Drought Severity Index (PDSI) is simplified water budget that considers water supply (precipitation), demand (evapotranspiration), and loss (runoff) over a 9-12 month period. Data inputs are fixed soil characteristics (water holding capacity of top 2.5m) and monthly precipitation and temperature data. Would be an alternative to using measured streamflow to characterize inter-annual and spatial variation in climate. | No | Available for download at http://www.wrcc.dri.edu/wwdt/ as GIS file for each timestep, or as a time series for specific sites. Would have to be accumulated (i.e., calculated average of) for the upstream catchment area contributing to each reach. |
| Temporal and spatial | SPEI drought index | Average Standardized Precipitation Evapotranspiration Index (SPEI), averaged across each site's catchment area. SPEI is a drought index calculated from precipitation and potential evapotranspiration (PET). It includes the effect of temperatures on water demand. Would be an alternative to using measured streamflow. | No | Available for download at http://www.wrcc.dri.edu/wwdt/ as GIS file for each timestep, or as a time series for specific sites. Or can be calculated in R using the "SPEI" package. Would have to be accumulated (i.e., calculated average of) for the upstream catchment area contributing to each reach. |

| Type of Variation | Variable Name | Description/Source | Used in Yurok project? | Acquisition and Processing Methods |
|---|---|---|---|---|
| Temporal and spatial | Climatic water deficit anomaly | Climatic water deficit (CWD) integrates energy loading and moisture availability from precipitation with available soil water. Somewhat similar to SPEI and PDSI but more complex because: 1) simulates snow accumulation and melt, 2) it takes into account timing rather than just totals over a period, and 3) previous runoff is deducted from precip rather than accumulating. Would be most useful as an anomaly rather than absolute. Would be an alternative to using measured streamflow. | No | Normals for each month are available for download at: http://climate.calcommons.org/dataset/2014-CA-BCM. Timesteps in NetCDF GIS file format are available from http://cida.usgs.gov/gdp/. Currently only available thru 2010, but will soon be updated. Would have to be accumulated (i.e., calculated average of) for the upstream catchment area contributing to each reach. |
| Temporal and spatial | Solar radiation anomaly | Remote sensed estimates of solar radiation (Surface DW shortwave radiation flux) from GOES weather satellites at 14-km resolution. Could help improve predictions a bit to account for localized clouds. Would be most useful as an anomaly rather than absolute. | No | Time series for specific stations available for download at: disc.sci.gsfc.nasa.gov/hydrology/data-rods-time-series-data, or clipped versions are available in NetCDF GIS format at http://cida.usgs.gov/gdp/ |
| Spatial | Effective shade | Method developed by USEPA's Peter Leinenbach and colleagues for calculating effective stream shade (Detenbeck 2017). It is a multi-step process with inputs of stream aspect, topographic angle, channel width, vegetation height and canopy cover, which are then fed into the Washington Ecology shade model. | No | Aspect and angle could be calculated in GIS. There are two possible sources for canopy height and canopy cover: LandFire (https://www.landfire.gov/) or LEMMA GNN (https://lemma.forestry.oregonstate.edu/data/structure-maps) (Ohmann and Gregory 2002). Channel width is calculated from watershed area using formula (could use formula from NOAA intrinsic potential for salmonids). |

### 2.5.1 ASSIGNING COVARIATES TO PREDICTION POINTS

NorWeST prediction points were obtained from David Nagel. These prediction points are located approximately 1 kilometer apart on all the existing NSI reaches, and include all the covariates used by NorWeST.

The new reaches generated during this project (section 2.4.1 above) needed prediction points and covariates; therefore, for each newly added reach, a prediction point was created at the reach mid-point using the *Create Points on Lines*[26] toolbox in ArcGIS. Then, following as closely as possible the methods used by NorWeST to generate those covariates for the existing NSI reaches, six covariates were calculated for each new reach: watershed area, slope, elevation, latitude, mean annual precipitation, and mean canopy cover (Table 2).

1) Watershed area: The boundaries of the watershed contributing to each reach were delineated, from which the contributing watershed area was calculated using the *Calculate Geometry* function in ArcGIS.
2) Slope: Slope for new reaches was estimated by 1) calculating calculate the length of each reach using the *Calculate Geometry* function in ArcGIS, 2) creating points at start and end of each reach using the *Create Points on Lines* toolbox in ArcGIS, 3) using the *extract* function in R's *raster* package to obtain the elevation from the National Elevation Dataset (NED[27]) for the reach start/end points, and 4) calculating slope as rise (upstream elevation minus downstream elevation) divided by run (reach length).
3) Elevation: The elevation for each reach mid-point was calculated using the same *extract* function described above.
4) Latitude: The latitude for each mid-point was extracted using the *readOGR* function in R's *rgdal* package.
5) Mean annual precipitation: The original GIS file of PRISM mean annual precipitation for the period 1971-2000 is no longer available from the PRISM website because it has been superseded by 1981-2010 mean annual precipitation. However, an alternative version by O'Donnel and Ignizio (2012) is available online in ScienceBase[28]. Using the delineated watersheds and the *cellStats* function in R's *raster* package, the mean precipitation was calculated for the watershed contributing to each reach.
6) Mean canopy cover: The 2011 National Land Cover Database (Homer et al. 2015) from the Multi-Resolution Land Characteristics (MRLC) Consortium Viewer[29] was downloaded and utilized to calculate mean canopy for each reach using the *zonal* function in R's *raster* package.

Calculations for open water, glaciers, baseflow index, or tailwater were not generated for the new reaches because those covariates were not utilized in any of this project's spatial stream-network models (Table 2).

The new covariates (first page Table 3) were assigned to the new prediction points using the *extract* function described above.

[26] http://ianbroad.com/arcgis-toolbox-create-points-polylines-arcpy/
[27] http://www.horizon-systems.com/NHDPlusData/NHDPlusV21/Data/NHDPlusCA/NHDPlusV21_CA_18_18c_NEDSnapshot_01.7z
[28] https://www.sciencebase.gov/catalog/item/4fe0f9f4e4b05d4ed81d9392
[29] https://www.mrlc.gov/viewerjs/

## 2.6 SPATIAL STREAM-NETWORK MODELING

Spatial stream-network models were used to produce estimates of mean August and mean daily maximum August stream temperatures for each 1-kilometer stream reach within Yurok Ancestral Territory which presented in this report including the Electronic Appendices.

To accomplish this, version 1.1.8 of the SSN package for R (Ver Hoef et al. 2014) was used, adapting the R code used by RMRS for the NorWeST modeling of the Northern California/Coastal Klamath processing unit which encompasses Yurok Ancestral Territory (Isaak et al. 2016). Prior to running the spatial models, version 2.04 of the STARS toolbox in ArcGIS was run to prepare the data for analysis (Peterson and Ver Hoef. 2014), following the procedures in Nagel et al. (2017). SSN and STARS were downloaded from the RMRS website[30].

The statistical theory behind SSN and STARS is quite complex with many intricate details, and there are many potential applications for the models, not just stream temperature. Isaak et al. (2014) provides an excellent introduction to the topic, including the following excerpt from the abstract:

> "Streams and rivers host a significant portion of Earth's biodiversity and provide important ecosystem services for human populations. Accurate information regarding the status and trends of stream resources is vital for their effective conservation and management. Most statistical techniques applied to data measured on stream networks were developed for terrestrial applications and are not optimized for streams. A new class of spatial statistical model, based on valid covariance structures for stream networks, can be used with many common types of stream data (e.g., water quality attributes, habitat conditions, biological surveys) through application of appropriate distributions (e.g., Gaussian, binomial, Poisson). The spatial statistical network models account for spatial autocorrelation (i.e., nonindependence) among measurements, which allows their application to databases with clustered measurement locations. Large amounts of stream data exist in many areas where spatial statistical analyses could be used to develop novel insights, improve predictions at unsampled sites, and aid in the design of efficient monitoring strategies at relatively low cost."

The stream temperature model applied in this project combines observed temperature data, Geographic Information Systems (GIS) data about landscape attributes, inter-annual variation in climate, and a spatial stream-network model. In the following paragraphs, some key model concepts are briefly described for the lay person. *These explanations are <u>not</u> mathematically correct, but rather use approximations to attempt to explain the model using the least amount of technical jargon possible.*

The model accounts for inter-annual differences in the observed stream temperature data that is used to calibrate the model. This is necessary because stream temperatures a site vary from year to year. If one reach was monitored only in a hot year and another reach was monitored only in a cool year, then using those single years to represent temperatures in those reaches would produce a biased map unless those inter-annual differences were addressed. The model resolves this is two ways. The first is to include year-specific air temperatures and streamflow as predictor variables in the regression. The second is to include year as random effect, meaning that after

[30] https://www.fs.fed.us/rm/boise/AWAE/projects/SSN_STARS/latest_releases.html

accounting for inter-annual differences due to flow and temperature, the model assigns an additional adjustment to each year which represents the remaining unexplained variation.

The model estimates temperatures at the center point of each 1-kilometer reach by blending several components. To estimate stream temperature, each observed data point (e.g., mean August temperature for a site and year) was regressed against the GIS predictor variables (e.g., drainage area, canopy, etc., as described in section 2.5), inter-annual variations in climate (air temperature and streamflow), and observed stream temperatures at other sites (with the nearest sites having the strongest influence). Sites closest to the prediction site have greater influence on predicted temperatures than do sites that are further away. The model also takes into account tributary relationships. For example, if there are observed data on both forks upstream of a confluence, the predicted temperature downstream of the confluence will be highly influenced by those observed data points. Different types of distance between sites are accounted for in the model including straight-line distance (i.e. "as the crow flies") and distance measured along the stream network.

# 3 MODEL RESULTS AND DISCUSSION

## 3.1 MODEL SELECTION AND PERFORMANCE

Table 4 compares the performance and structure of the final spatial and non-spatial models for mean August temperature[31]. Both models indicate excellent performance. The root mean squared prediction error (RMSPE) of the spatial model was slightly lower (0.495 °C) than the non-spatial model (0.565 °C).

Drainage area, elevation, and air temperature anomaly were the most important predictors of mean August stream temperature, followed by streamflow anomaly, canopy, latitude, and coastal influence (Table 4). The air temperature coefficient for the spatial model is 0.223, meaning that mean August stream temperature increased by 0.223 °C for each 1 °C increase in August air temperature (Table 4), which can be used to infer the expected response to climate change (see section 3.4 below). The canopy[32] coefficient for the spatial model is -0.0236, meaning that each 1% increase in canopy would cool mean August temperature by 0.0236 C. For example, changing a reach from 0% canopy to 100% canopy would reduce predicted temperature by 2.4 degrees, which seems like a lesser effect on temperature than would occur in the real world. The explanatory power of canopy in the model is likely affected (i.e., reduced) by the presence of drainage area, which is highly correlated with canopy, in the model. PRISM coastal influence has a counter-intuitive scale of 0 (ocean) to 1000 (inland), so the negative coefficient (-0.344) means that the sites further from the coast are warmer, which is the opposite of the expected and is likely an artifact. The coastal influence coefficient was not statistically different from zero ($p = 0.148$), but it is still included in the final model because if the model were re-run for a larger geographic area that included more inland areas, then coastal influence could play a more substantive role. By leaving coast effects as a model parameter, this allows a greater utility of the model for other applications outside the Yurok Territory.

[31] I also modeled mean daily maximum August temperature but do not present the diagnostics in this report, although the resulting maps are available in section 3.2 and in the electronic appendices to this report.
[32] Canopy density values are calculated as the average across a 1-km long reach [not a buffer, just looking at the canopy values right underneath the 1:100k scale stream] and range from a low of 0% to a high of 96%

Models using several different sets of predictor variables (Table 5) were run to determine if alternative configurations would substantively affect the model outputs. All of these alternative models also performed well (Table 5), indicating the models are relatively insensitive to the exact choice of predictor variables. In the final spatial model, the predictor variables and the spatial "exponential tailup" component explained a majority of the stream temperature variance while other spatial components ("exponential taildown" and "exponential Euclid") and the random effects (year and site) explained a relatively small fraction (Table 6, see caption for definitions).

Table 4. Comparison of parameter estimates and summary statistics for the final spatial and non-spatial multiple regression models used to predict mean August stream temperature in Yurok Ancestral Territory and surrounding areas. Variables are listed in order of importance (i.e., absolute value of t statistic) in the final spatial model. b = coefficient (i.e., change in temperature per unit change in the variable); SE = standard error of coefficient (i.e., uncertainty in estimate of coefficient); p-value = probability that the coefficient is equal to zero (i.e., no effect), with lower p-values indicating greater degree of statistical significance; t = coefficient divided by standard error. The greater the absolute value (i.e., how far it is from zero in either a positive or negative direction) of the t statistic, the less uncertain in the coefficient and the greater the influence of the variable on the predicted stream temperatures.

| | Predictor Variables | | | | Model Summary | |
|---|---|---|---|---|---|---|
| **Model Name** | **Variable Name** | **b (SE)** | **p-value** | **t** | **$r^2$** | **RMSPE (°C)** |
| Final Spatial | Intercept | 16.423 (0.183) | p <0.001 | 89.54 | 0.980 | 0.495 |
| | Drainage area (log $km^2$) | 0.55 (0.057) | p <0.001 | 9.63 | | |
| | Elevation (m) | -0.00411 (0.00045) | p <0.001 | -9.06 | | |
| | August Air Temperature Anomaly (°C) | 0.223 (0.025) | p <0.001 | 8.78 | | |
| | August Streamflow Relative Anomaly | 0.0041 (0.00064) | p <0.001 | 6.44 | | |
| | Canopy (%) | -0.0227 (0.0046) | p <0.001 | -4.91 | | |
| | Latitude (m) | -0.0000121 (0.0000052) | p = 0.019 | -2.34 | | |
| | PRISM Coastal Influence | -0.344 (0.238) | p = 0.148 | -1.45 | | |
| Final Non-Spatial | Intercept | 16.707 (0.094) | p <0.001 | 177.39 | 0.97 | 0.565 |
| | Drainage area (log $km^2$) | 0.725 (0.04) | p <0.001 | 17.92 | | |
| | Elevation (m) | -0.00326 (0.00047) | p <0.001 | -6.94 | | |
| | August Air Temperature Anomaly (°C) | 0.225 (0.026) | p <0.001 | 8.61 | | |
| | August Streamflow Relative Anomaly | 0.00265 (0.00046) | p <0.001 | 5.82 | | |
| | Canopy (%) | -0.0215 (0.0049) | p <0.001 | -4.34 | | |
| | Latitude (m) | -0.0000198 (0.0000036) | p <0.001 | -5.48 | | |
| | PRISM Coastal Influence | -0.327 (0.238) | p = 0.17 | -1.37 | | |

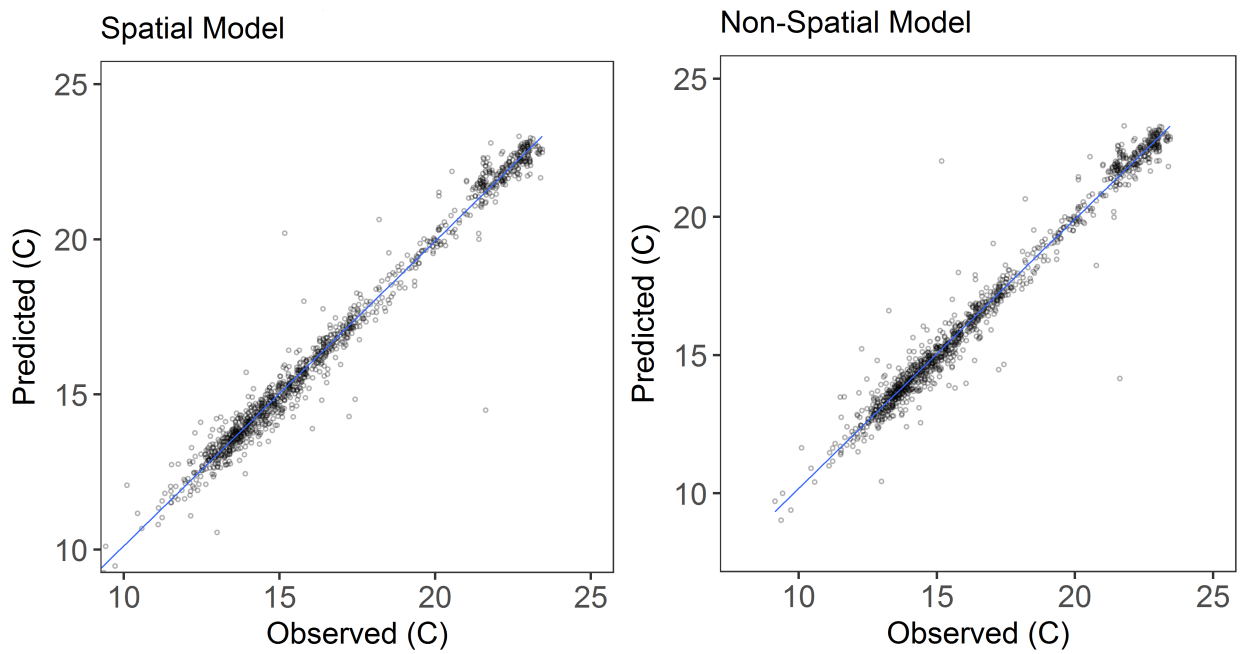



Figure 5. Comparison of observed mean August stream temperature and predictions from the final spatial and non-spatial models for streams in Yurok Ancestral Territory and nearby areas. Model summary statistics are shown in Table 4.

Table 5. Comparison of summary statistics for spatial stream-network models to predict mean August stream temperature and mean daily maximums August stream temperature for streams in Yurok Ancestral Territory and surrounding areas.

| | | Spatial Model | | Non-Spatial Model | |
|---|---|---|---|---|---|
| **Model Name** | **Predictor Variables in Model** | **$r^2$** | **RMSPE (°C)** | **$r^2$** | **RMSPE (°C)** |
| Final | Log Drainage Area, Elevation, Local Air Temp Anomaly, Streamflow, Canopy, Latitude, Coastal Influence | 0.980 | 0.495 | 0.973 | 0.565 |
| Basin Air Temp Anomaly | Log Drainage Area, Elevation, Basin Air Temp Anomaly, Streamflow, Canopy, Latitude, Coastal Influence | 0.978 | 0.509 | 0.972 | 0.579 |
| Basin Shape | Log Drainage Area, Elevation, Local Air Temp Anomaly, Streamflow, Canopy, Latitude, Coastal Influence, Basin Shape | 0.979 | 0.496 | 0.973 | 0.568 |
| BCM Air Temp Normal | Log Drainage Area, Elevation, Local Air Temp Anomaly, Streamflow, Canopy, Latitude, BCM Air Temp Normal | 0.979 | 0.498 | 0.974 | 0.561 |
| BCM Air Temp Absolute | Log Drainage Area, BCM Air Temp Absolute, Streamflow, Canopy | 0.979 | 0.504 | 0.972 | 0.582 |
| PRISM Air Temp Absolute | Log Drainage Area, PRISM Air Temp Absolute, Streamflow, Canopy | 0.979 | 0.505 | 0.971 | 0.590 |
| No Inter-Annual Climate | Log Drainage Area, Elevation, Canopy, Latitude, Coastal Influence | 0.978 | 0.510 | 0.972 | 0.579 |
| Precipitation | Log Drainage Area, Elevation, Local Air Temp Anomaly, Streamflow, Canopy, Latitude, Coastal Influence | 0.980 | 0.494 | 0.973 | 0.566 |

Table 6. Proportion of total variance in the mean August temperature explained in the final spatial stream-network model by the covariates (predictor variables), spatial autocovariance, and random effects.

| Model Component | Purpose/Description | Proportion of Variance Explained |
|---|---|---|
| Covariates | Predictor variables (drainage area, canopy, etc.) | 0.34 |
| Exponential tailup | Upstream-facing spatial autocovariance of flow-connected sites. Spatial weighting at tributary confluences is apportioned according to watershed area. Distance is measured along the channel length and its influence declines exponentially. | 0.39 |
| Exponential taildown | Downstream-facing spatial autocovariance of both flow-unconnected and flow-connected sites. Distance is measured along the channel length and its influence declines exponentially. | 0.04 |
| Exponential Euclid | Spatial autocovariance measured as straight-line distance between sites (i.e. as the crow flies). Influence of distance declines exponentially. | 0.09 |
| Site | Random effect for site. Data collected at the same site in multiple years are nested together. Each unique site is assigned a random intercept (i.e., add or subtract a set number of degrees) to account for intrinsic differences between sites not explained by other factors already included in the model. | 0.02 |
| Year | Random effect for year. Data collected in the same year are nested together. Each year is assigned a random intercept (i.e., add or subtract a set number of degrees) to account for intrinsic differences between years not explained by other factors already included in the model. | 0.05 |
| Nugget | Residual error (i.e., not explained by covariates or spatial autocovariance, or random effects). | 0.08 |

## 3.2 NEW STREAM TEMPERATURE MAPS

Figure 6 shows predicted mean August temperature and mean daily maximum August temperature predicted by the final spatial stream-network models. Prediction uncertainty (standard error) for every reach is included in the models outputs, but not illustrated in this report's figures.

## 3.3 COMPARISON TO NORWEST MODEL RESULTS

Figure 7 compares mean August temperature predicted by the 2015 version of the NorWeST model and this study's final spatial stream-network model. NorWeST temperatures are warmer along in the coast and warmer on the interior (Figure 7). This difference likely reflects the 2015 NorWeST model's relative lack of stream temperature data within Yurok Ancestral Territory (Figure 2) so predictions default to the regional regression which does not including any coastal effects. In contrast, the 2017 NorWeST model results, which use much more local stream temperature calibration data, are nearly all within 1 °C of this study's final spatial stream-network model (Figure 8). The only remaining substantive difference was that this study's model predicts cooler temperatures in the uppermost reaches of headwater streams due to the more refined calculation of drainage area (see discussion at end of section 2.5 above)(Figure 8).

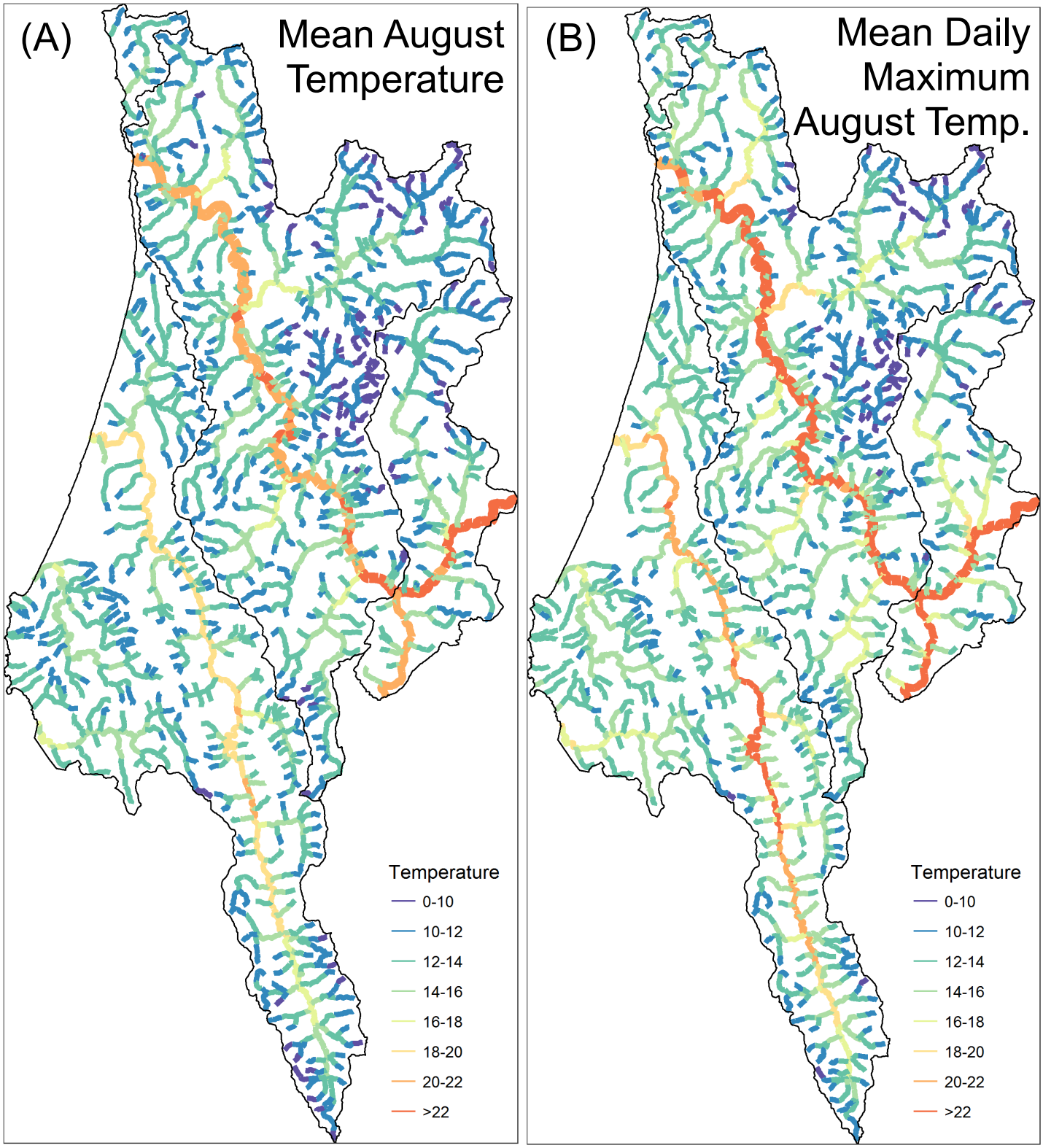



Figure 6. Predicted (A) mean August temperature and (B) mean daily maximum August temperature for streams within Yurok Ancestral Territory and adjacent areas for the period 1990-2016. Predictions are outputs from a spatial stream-network model which uses observed temperature data and GIS predictor variables as inputs.

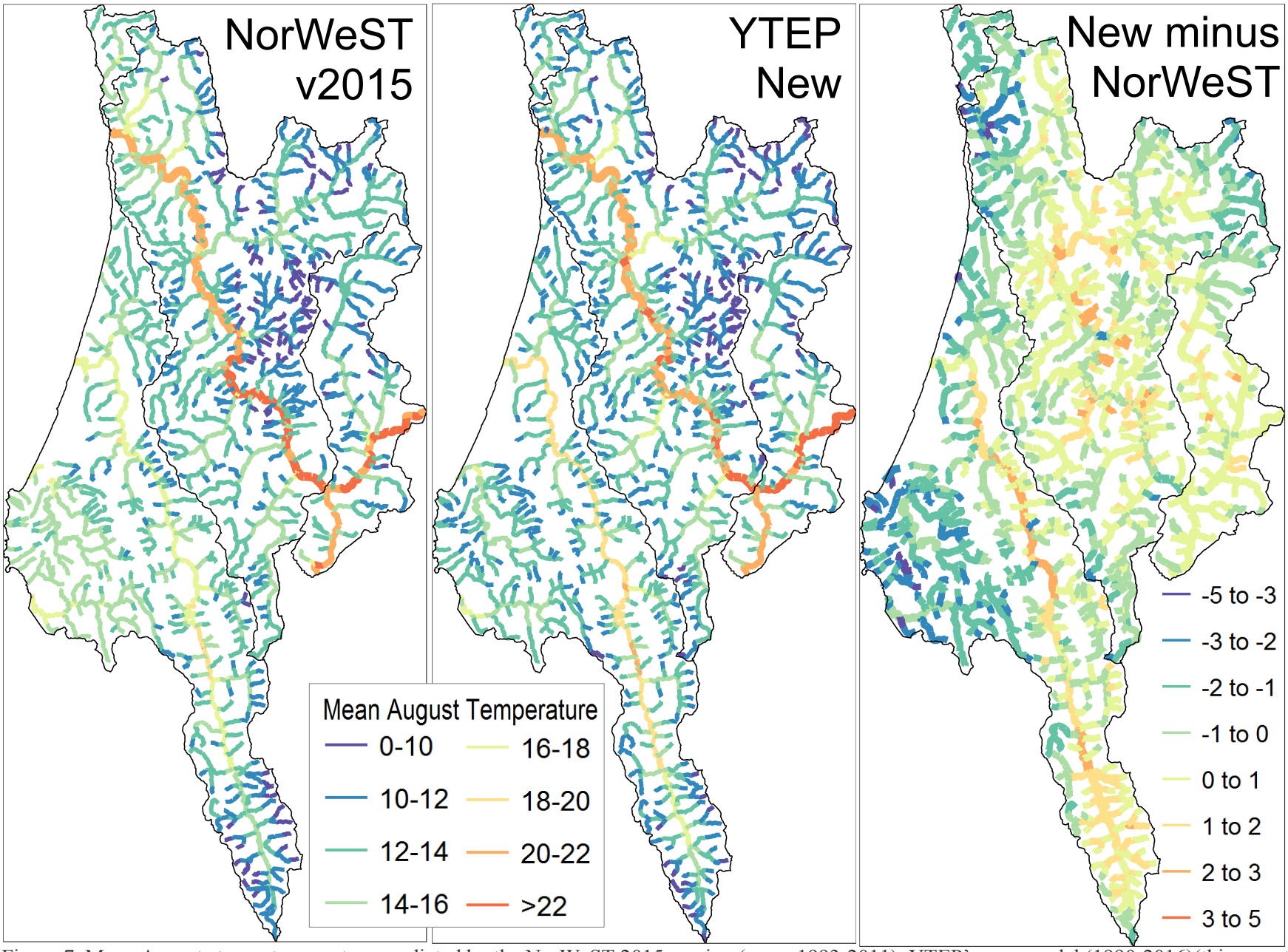



Figure 7. Mean August stream temperature predicted by the NorWeST 2015 version (years 1993-2011), YTEP's new model (1990-2016)(this report), and the difference between the two, for streams within Yurok Ancestral Territory and adjacent areas. Predictions are outputs from a spatial stream-network model which used observed temperature data and GIS predictor variables as inputs.

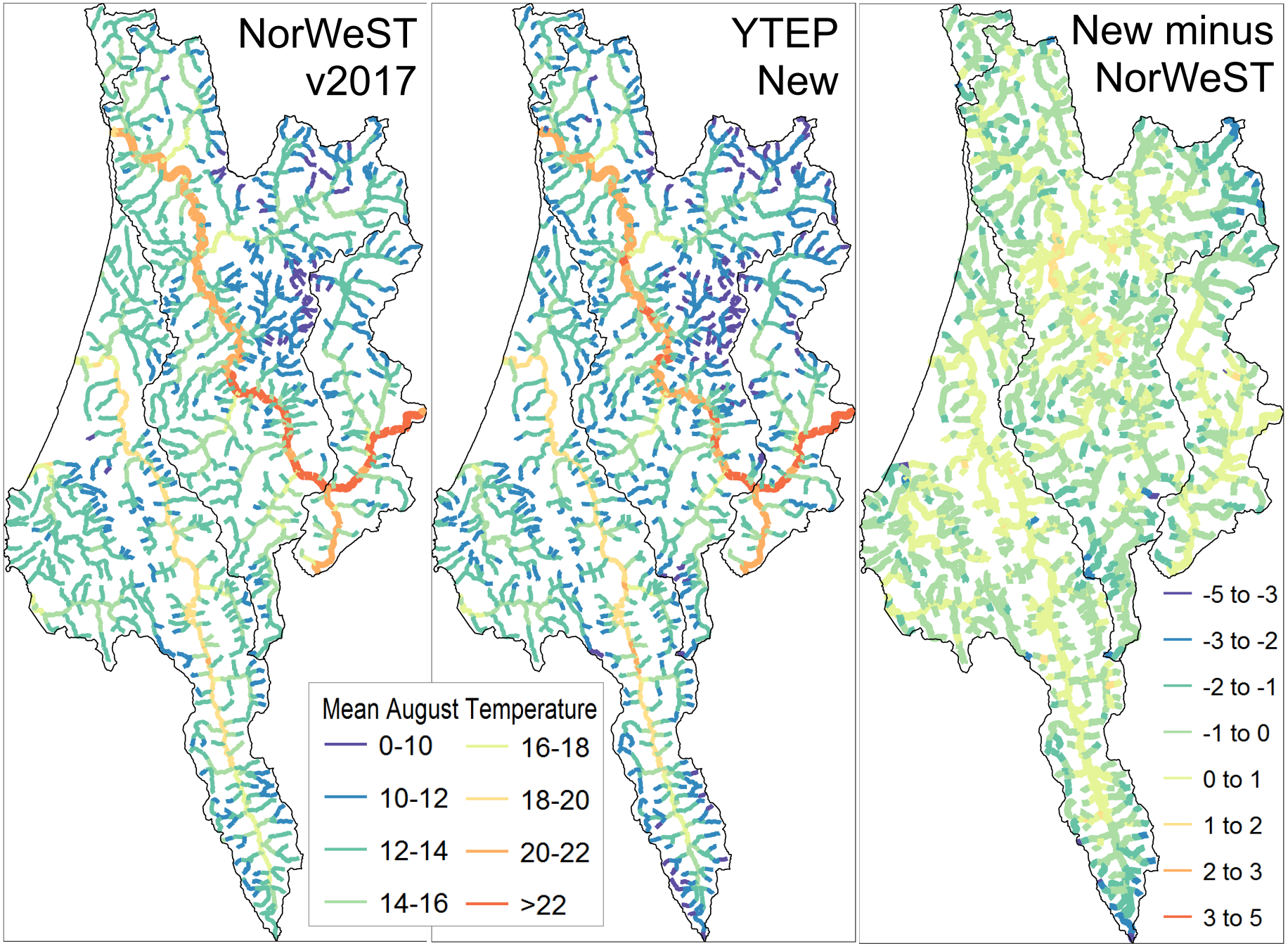



Figure 8. Mean August stream temperature predicted by the NorWeST 2017 version (years 1993-2011), YTEP's new model (1990-2016)(this report), and the difference between the two, for streams within Yurok Ancestral Territory and adjacent areas. Predictions are outputs from a spatial stream-network model which used observed temperature data and GIS predictor variables as inputs.

## 3.4 NORWEST CLIMATE CHANGE SCENARIOS

Due to time and budget constraints, new climate change model scenarios were not run as a part of this project. Instead, this section discusses the results from the 2017 NorWeST model.

The following excerpt from NorWeST documentation summarizes the methods for climate change scenarios:

> "Future scenarios were developed by adding stream temperature deltas to historical Scenario 1, which represented the composite of years from 1993-2011. Stream temperature deltas consisted of three types: 1) simple integer values (e.g., +1.0˚C, +2.0˚C, +3.0˚C; scenarios 23 - 28); 2) values obtained by multiplying global climate model projections of changes in August air temperatures and discharge by the associated parameters in the stream temperature model (future scenarios 29 and 31), and 3) values based on global climate model projections, which were also adjusted for differential stream sensitivity (future scenarios 30 and 32).
>
> The global climate model projections of August air temperature changes were based on an ensemble mean of the 10 IPCC climate models with the lowest bias in simulating observed climate across the Northwest U.S. (Hamlet et al. 2013). The global climate model simulations were downscaled using a spatially explicit delta method (Hamlet et al. 2010, 2013, in review) to represent the A1B greenhouse gas emissions trajectory (IPCC 2007) for the 2040s (2030-2059) and 2080s (2070-2099). The same global climate model projections were used with the Variable Infiltration Capacity (VIC) model to generate hydrographs, from which August mean flows were extracted at the USGS gage locations used in stream temperature model development (predictor #2 above). Those data were downloaded when available from the Hydrologic Climate Change website (http://warm.atmos.washington.edu/2860/) developed by the Climate Impacts Group or were derived using identical techniques at other gage locations (Wenger et al. 2010).
>
> Differential sensitivity of streams to climate forcing (i.e., some streams warming more than others) was incorporated by scaling future stream temperature increases relative to the average historical stream temperatures represented by Scenario 1. Basin-specific sensitivity parameters were developed by regressing the observed stream temperatures for each year (1993, 1994, …, 2011) against Scenario 1 predictions at the same site. The slopes of those relationships were then regressed against the network average stream temperature value predicted for the same observation year (Scenarios 3 – 21). The slope of that relationship described the sensitivity of the temperature gradient across a river network relative to inter-annual variation in stream temperatures. That relationship consistently indicated that cold streams were less sensitive than warmer streams as described elsewhere (Luce et al. 2014; Isaak et al. 2016). The stream temperature deltas based on global climate model predictions were used with the sensitivity relationship for a river basin to adjust future temperature gradients while maintaining the same overall stream temperature delta. Incorporating differential stream sensitivity created future scenarios in which the coldest streams often warmed 40% - 60% less than the warmest streams, although differences existing among individual processing units."

Figure 9 illustrates the concept of differential sensitivity (cool streams warming slightly less and warm streams warming slightly more) described in the paragraph above. Figure 10 compares the NorWeST "S1" scenario for current conditions (1993-2011) and "S32" scenario for estimated

temperatures in the 2080s (2070-2099), with differential sensitivity. Figure 11 compares the NorWeST "S1" scenario for current conditions (1993-2011) and the NorWeST "S28" scenario which is based on mean 3°C rise in stream temperature with differentiate sensitivity.

The NorWeST S32 scenario predicts that mean August stream temperatures within NorWeST's Northern California/Coastal Klamath unit (which includes Yurok Ancestral Territory) would increase by only 0.44-0.77 °C by the 2080s, despite the much larger 3.57°C increase in air temperature predicted by the global climate models (Isaak et al. *in review*). This small predicted increase is driven in large part by the low sensitivity to air temperature (D. Isaak, pers. comm.). As described above in section 3.1, air temperature sensitivity is the air temperature coefficient in the stream temperature model (i.e., change in stream temperature per unit change in air temperature). The air temperature sensitivity for the Northern California/Coastal Klamath NorWeST unit is 0.135 °C/°C, which is the second-lowest of the 23 NorWeST geographic units in the Western U.S. (Isaak et al. *in review*). This low temperature sensitivity suggests that, relative to other geographic areas, stream temperatures in northwest California should be resilient to climate change. Alternatively, the NorWeST air temperature sensitivity might be skewed low due to complex spatial patterns of inter-annual air temperatures in northwest California that are not represented in the NorWeST model which uses a single air temperature within a year for all sites. For example, maps of August air temperature anomaly (i.e., observed minus long-term mean) from PRISM (http://www.prism.oregonstate.edu/comparisons/anomalies.php) indicate that 1) air temperature anomalies in the fog zone immediately adjacent to the coast are often quite low (i.e., inter-annual variability in air temp is lower than in inland areas), 2) it is not uncommon for there to be north/south or east/west gradients in air temp anomaly within a year. The air temperature sensitivity within Yurok Ancestral Territory is 0.22 °C/°C (Table 4) which is higher than the regional NorWeST value of 0.135 °C/°C but still relatively low. For comparison, air temperature sensitivities from previous studies in other areas include: 0.43 °C/°C preliminary results from in-progress Riverbend Sciences analysis of stream temperature in the Salmon River, 0.47 °C/°C for 104 Pacific Northwest streams (Mayer et al. 2012), and 0.51 °C/°C for 246 Pacific Northwest streams (Luce et al. 2014).

A previous modeling effort predicted that the decadal mean (not specifically summer) mainstem Klamath River water temperatures would rise approximately 1–2.3°C over the 50-year period 2012-2061, depending on the global climate model (Perry et al. 2011).

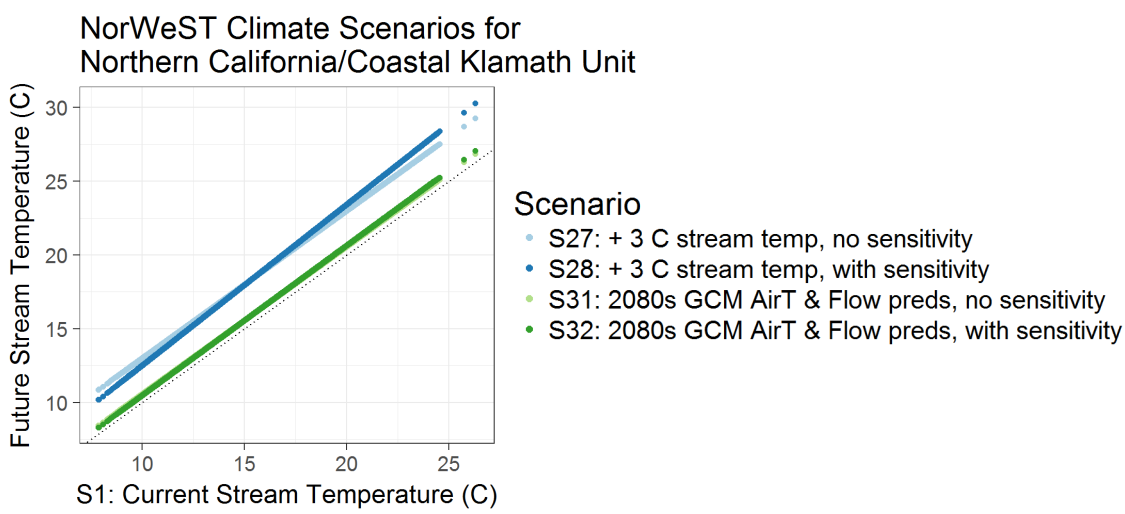



Figure 9. Comparison of NorWeST (2017 version) stream temperature scenarios in the Northern California/Coastal Klamath processing unit which includes Yurok Ancestral Territory.

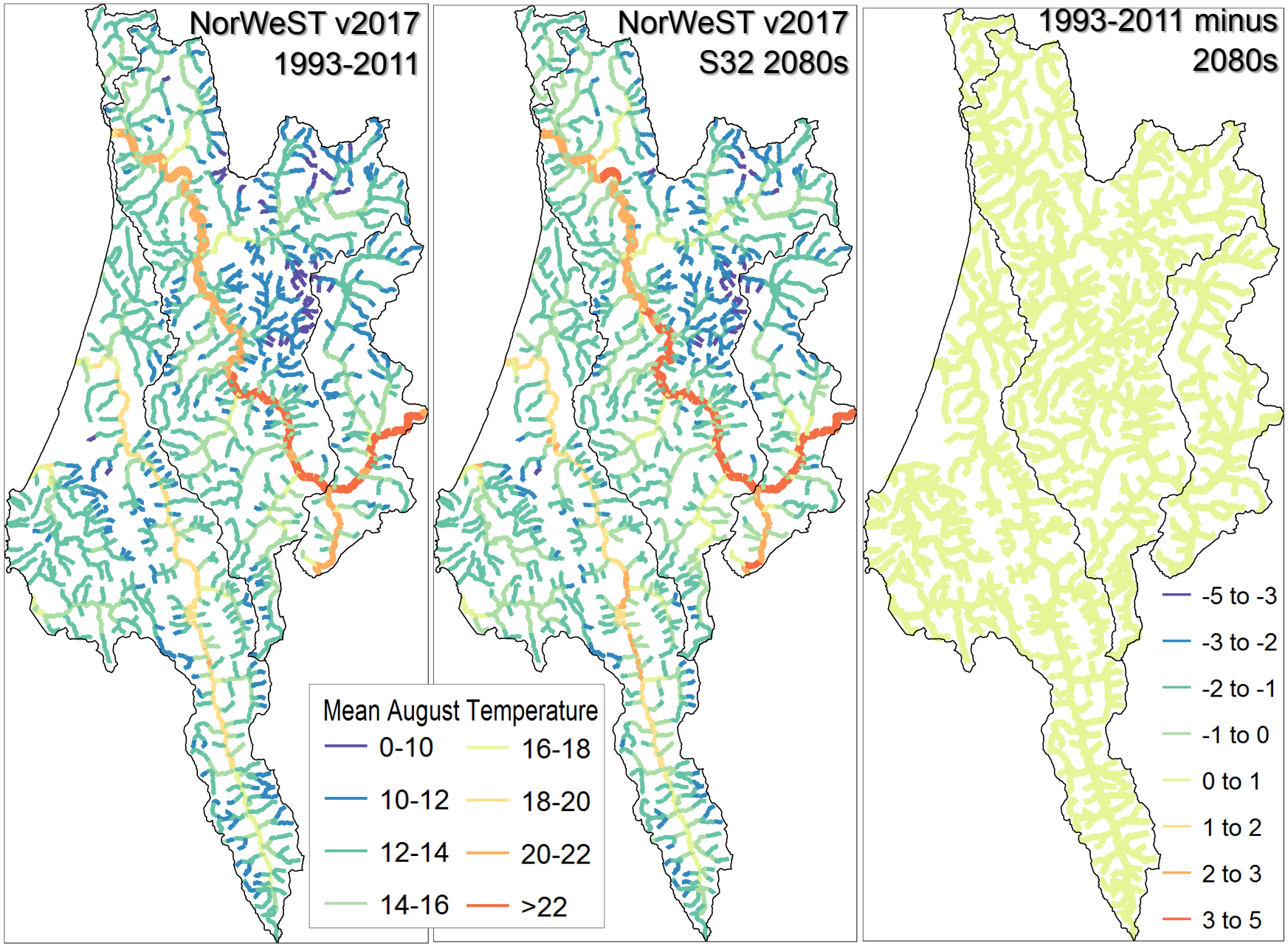



Figure 10. Comparison of NorWeST (2017 version) spatial stream-network model predictions for mean August stream temperature for streams within Yurok Ancestral Territory and adjacent areas for 1993-2011 and a future scenario "S32" based on global climate model ensemble averages that represents the A1B warming trajectory for 2080s (2070-2099). The right panel shows the difference between the two scenarios.

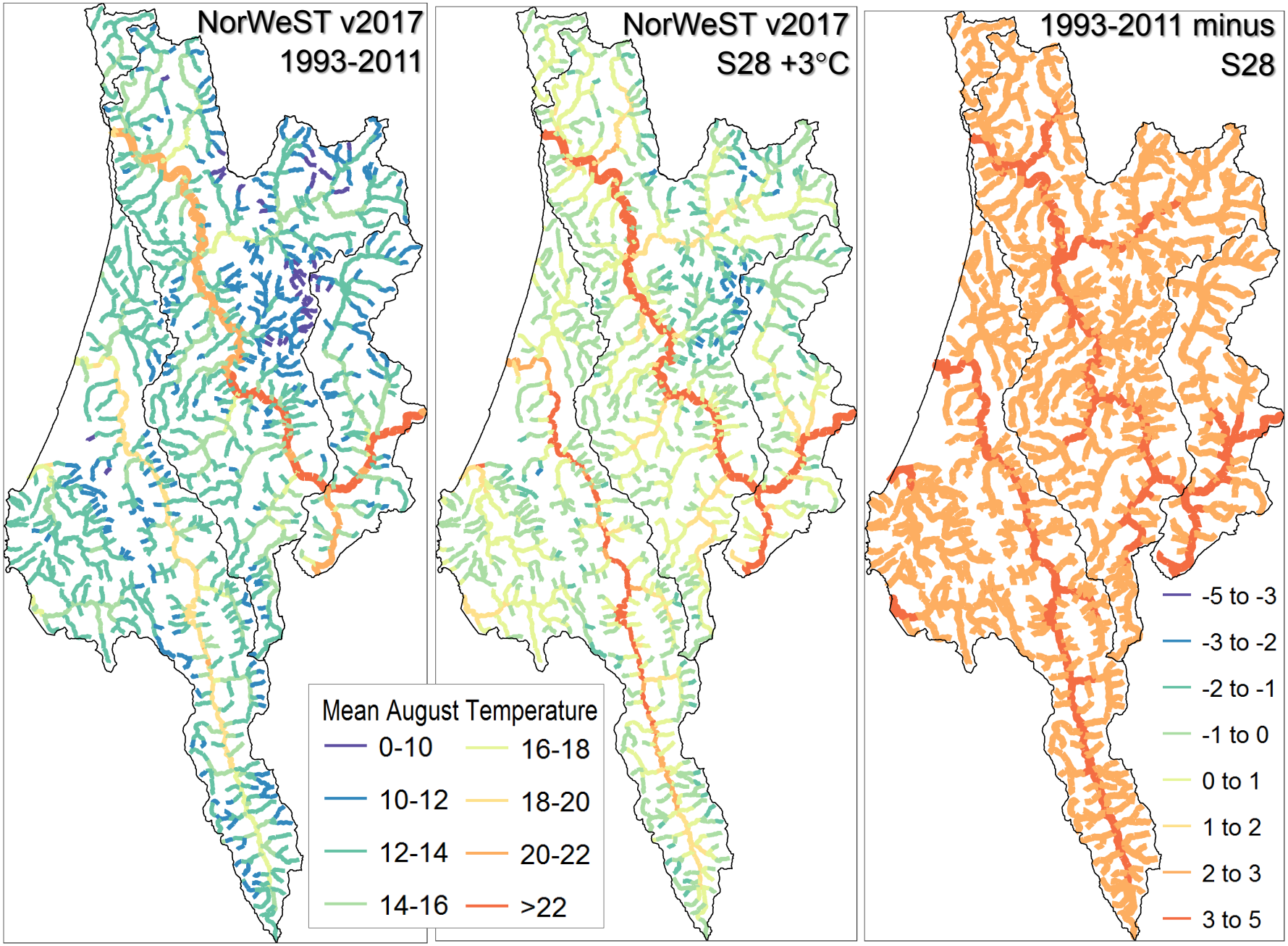



Figure 11. Comparison of NorWeST (2017 version) spatial stream-network model predictions for mean August stream temperature for streams within Yurok Ancestral Territory and adjacent areas for 1993-2011 and a future scenario "S28" based on a mean 3°C rise in stream temps, but with cool stream warming slightly less and warm streams warming slightly more. The right panel shows the difference between the two scenarios.

# 4 PROJECT DIFFICULTIES AND COMPARISON OF ACCOMPLISHMENTS TO OBJECTIVES

This section addresses the requirements in YTEP's request for proposals (RFP) that the final report for this project include a "Report of project difficulties and a comparison of accomplishments with the objectives for the project."

## 4.1 COMPARISON OF ACCOMPLISHMENTS TO OBJECTIVES

The project met all objectives outlined in the original RFP. Each objective is discussed in the following sections. The deliverable is stated at the top of each section, followed by a comparison of objects to the accomplishments.

### 4.1.1 TASK 1.0: PERFORM GIS STREAM TEMPERATURE MODELING OF YUROK ANCESTRAL TERRITORY

Deliverable: Operational Model and Final Report

This is the summary/overarching task. As described in this report, all tasks were successfully accomplished. This report and its electronic appendices serve as the deliverable.

### 4.1.2 TASK 2.0: MANAGE AND FORMAT STREAM DATA FOR COMPATIBILITY WITH NORWEST STREAMS MODELING

Deliverable: Interface-ready Dataset

YTEP staff's direction at the outset of the project was that essential stream temperature dataset to compile and format was the data collected by YTEP under the USEPA STAR grant in 2015-2016, and that any additional data would be beneficial. By leveraging other Riverbend Sciences projects compiling data within the study area, I was able to exceed expectations by compiling a nearly comprehensive database of stream temperature data stretching back to this early 1990s (section 2.1 above). The only major collection of data that I was not able to acquire was Green Diamond Resource Company (section 2.1.8). A major benefit of compiling and using the long-term dataset in the spatial stream-network model is that it allows for accurate calculation of air temperature sensitivity which is important for understanding how stream temperature responds to climatic variation and climate warming (as discussed in section 3.4). All data stream temperature data were summarized (section 2.3), snapped to the NorWeST prediction points (sections 2.4 and 2.5), and then processed with STARS (section 2.6). The compiled stream temperature data are available as an electronic appendix to this report. I forwarded the compiled data to RMRS who incorporated them in to the NorWeST stream temperature data summaries, available for download at:
https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/StreamTemperatureDataSummaries.shtml#NorthernCA_CoastalKlamath.

#### 4.1.3 TASK 3.0: DEVELOP TEMPERATURE MODEL THAT CAN BE DOWNLOADED AS GEOSPATIAL DATA TO ENABLE THE DISPLAY AND QUERYING OF STREAM TEMPERATURES IN ARCMAP FOR STREAMS WITHIN THE YUROK ANCESTRAL TERRITORY.

Deliverable: Final Working Model

Using the methods described in section 2.6 of this report, I successfully developed and calibrated a stream temperature model (sections 3.1 and 3.2). The model inputs and outputs are available as an electronic appendix to this report.

#### 4.1.4 TASK 4.0: GENERATE STREAM TEMPERATURE SCENARIO MAPS OF SELECT STREAMS WITHIN YUROK ANCESTRAL TERRITORY, USING SPATIAL STATISTICAL STREAM NETWORK MODELS.

Deliverable: Electronic and hard copy of temperature maps

I generated two stream temperature scenarios: mean August temperature and mean daily maximum temperature, provided as figures in this report (section 3.2) as well as GIS files in the electronic appendices. YTEP ended up not needing hard copy maps so I did not create any.

I also compared the results to the 2015 and 2017 versions of the NorWeST model (section 3.3). Because the new model results are very similar to the 2017 version of NorWeST, I did not run any climate change scenarios but rather present NorWeST climate change scenarios in this report (section 3.4). I also presented preliminary results at the Klamath Basin Monitoring Program conference on March 15, 2017, and demonstrated the final results at a workshop at the Yurok Tribe's office on July 24, 2017.

#### 4.1.5 TASK 5.0: REPORT OF PROJECT DIFFICULTIES AND A COMPARISON OF ACCOMPLISHMENTS WITH THE OBJECTIVES FOR THE PROJECT.

Deliverable: Report of project difficulties and a comparison of accomplishments with the objectives for the project.

The comparison of accomplishments to objectives is provided above. Project difficulties are discussed in the following section

### 4.2 PROJECT DIFFICULTIES

#### 4.2.1 LEARNING STARS/SSN

Spatial stream-network models are quite complicated. There are many steps required to go from observed temperature data all the way through to final model scenario outputs. It is not a one-button exercise, but rather a series of intricate steps that requires expert knowledge and a high level of proficiency with several complex software programs including the STARS ArcGIS toolset and the SSN package for R Statistical Software. The USFS RMRS uses a team of several highly-trained people for the process.

It was quite challenging to learn the process, requiring learning new skills in statistics and GIS. I read, re-read, and re-read again many articles, protocols, and statistical reference books

(including substantial time outside of the project budget). I was able attend a four-day hands-on training workshop on STARS/SSN at the RMRS in Boise in April 2016, which was invaluable. RMRS staff also answered many questions through email and phone correspondence which was extremely helpful. Without the advice from RMRS staff I would likely not have been able to perform the project.

### 4.2.2 ACQUIRING TEMPERATURE DATA

It took considerable effort to acquire all the temperature data, with repeated emails, phone calls, and reminders. I did not initially understand the organization structure of the Yurok Tribe Fisheries Department, nor realize that those different departments each had their own water temperature monitoring programs, so it was not until relatively late in the project that I realized that there were significantly more data available than I had previously realized.

### 4.2.3 COMPILING AND QUALITY CHECKING THE TEMPERATURE DATA AND ASSIGNING SITE LOCATIONS

The sheer number of site-years of stream temperature data made it time consuming and difficult to manage the data. Data from some periods and entities was more organized and documented than others. In addition, some of the data was over twenty years old and there had been staff turnover. As a result, to determine some of the site locations, I had to scour the Internet for archival reports and contact former employees of the data collection entities. With persistence, I was able to resolve nearly all the issues, and only a few datasets had to be discarded for lack of documentation. I have worked on a lot of stream temperature projects over the past few years, so was able to apply the knowledge gained from those projects on this project.

### 4.2.4 ADDING NEW REACHES TO THE STREAM NETWORK

As noted above in section 2.4.1 above, I created a modified local version of the NSI hydrography to address some errors add some small streams and springs which were deemed by YTEP staff to be important enough to justify the effort. I knew that was going to require substantial effort to do that, but thought that there would be room in the project budget so I agreed to do it. In retrospect, it was a bad decision. Adding those few new reaches required many hours to perform the required GIS analyses to calculate covariates and modify my data processing scripts. Those additional reaches represented only a tiny fraction (much less than 1%) of the stream miles in the study area, but dealing with those issues probably consumed 15-20% of the project budget. I highly recommend future users of STARS/SSN to not add new reaches to the NSI. Those funds would have been better spent on developing new covariates such as effective shade (section 2.5) which I researched but did not have time to implement.

# 5 ACKNOWLEDGMENTS

This project was funded by the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) Program, grant #RD-83560401.

Countless people from many different entities have contributed to collection and compilation of the stream temperature data included in this report. I list here only those people with whom I directly interacted, but am grateful to all those who contributed. The reports cited in the methods section list additional persons who have collected and organized data. Special thanks to Nicholas Cusick who compiled and did the initial cleaning of the YTEP and YTFP temperature datasets. Suzanne Fluharty, Richard Meyers, and Micah Gibson of YTEP collected/organized data or answered questions about site locations and quality control. Suzanne Fluharty also provided helpful edits and comments on a draft version of this report. Callie McConnell of the U.S. Forest Service (USFS) provided data from the USFS AqS database. Dan Gale (USFWS, formerly YTFP), Jamie Holt (YTFP), Sarah Beesley (YTFP), Joshua Strange (Sweet River Sciences, formerly YTFP), Vicki Ozaki (RNSP), Rachel Truesdell (RNSP), and Aaron David (USFWS) provided data and/or helped resolve questions about site locations. Daniel Isaak, Sherry Wollrab, Gwynne Chandler, and David Nagel (USFS) and Seth Wenger (University of Georgia) provided information on the NorWeST model and tips on snapping the temperature sites to the GIS streams network. Erin Peterson and Jay Ver Hoef provided training on how to use STARS and SSN.

# 6 REFERENCES CITED

Asarian, J.E. 2016. Stream Temperatures in the South Fork Trinity River Watershed 1989-2015. Prepared by Riverbend Sciences for The Watershed Research and Training Center, Hayfork, CA.

Asarian, J.E., P. Higgins, P. Trichilo. 2016. Stream Temperatures in the Eel River Basin 1980-2015, Phase 1: Compilation and Preliminary Analysis. Prepared by Riverbend Sciences and the Eel River Recovery Project for State Water Resources Control Board, Sacramento, CA. 73p. + appendices.

Bartholow, J.M., 2005. Recent Water Temperature Trends in the Lower Klamath River, California. North American Journal of Fisheries Management 25:152–162.

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris, 2008. Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States. International Journal of Climatology 28:2031–2064. doi: 10.1002/joc.1688.

Detenbeck, N. 2017. Quality Assurance Project Plan, Project Title: Big Cold and Small Cold: Quantifying Thermal Regime Metrics for Policy Development, QAPP-AED-WDB-ND-2016-01-000. U.S. EPA – Atlantic Ecology Division.

Dunham, J., G. Chandler, B. Rieman, and D. Martin. 2005. Measuring Stream Temperature with Digital Data Loggers: A User's Guide. http://www.fs.fed.us/rm/pubs/rmrs_gtr150.pdf? Accessed 3 Jun 2015.

Flint, L.E. and A.L. Flint, 2008. A Basin-Scale Approach to Estimating Stream Temperatures of Tributaries to the Lower Klamath River, California. Journal of Environment Quality 37:57. doi: 10.2134/jeq2006.0341.

Flint, L.E., A.L. Flint, J.H. Thorne, and R. Boynton. 2013. Fine-Scale Hydrologic Modeling for Regional Landscape Applications: The California Basin Characterization Model Development and Performance. Ecological Processes 2:1–21. doi: 10.1186/2192-1709-2-25.

Gale, D. B. 1998. Memo to: Bessie Lee, from: Dan Gale, Sr. Fisheries Biologist, subject: Lower Klamath Water Quality Data. Dated September 22, 1998. Yurok Tribal Fisheries Program, Klamath, CA. 5p.

Gale, D. B., T. R. Hayden, L. S. Harris, and H. N. Voight. 1998. Assessment of anadromous fish stocks in Blue Creek, Lower Klamath River, California, 1994-1996. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Technical Report No. 4. Klamath, CA. 101 pp. http://www.krisweb.com/biblio/klamath_yuroktfp_galeetal_1998_4.pdf

Gale, D. B., and D. B. Randolph. 2000. Lower Klamath River sub-basin watershed restoration plan. Yurok Tribal Fisheries Program, Klamath California. 78 pp. http://www.yuroktribe.org/departments/fisheries/documents/LowerKlamathRestorationPlanFINAL2000_000.pdf

Gale, D. B. 2003. Assessment of anadromous fish stocks in Blue Creek, Lower Klamath River, California, 1997-1998. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Technical Report No. 11. Klamath, CA.

Green Diamond Resource Company (GDRC). 2006. Final Aquatic Habitat Conservation Plan and Candidate Conservation Agreement with Assurances. Volume 1-2 plus appendices. Prepared for National Marine Fisheries Service and U.S. Fish and Wildlife Service, October 2006. 568 p. https://greendiamond.com/responsible-forestry/certification/FSC/

Green Diamond Resource Company (GDRC). 2017. 5th Biennial Report Submitted to National Marine Fisheries Service and United States Fish and Wildlife Service by Green Diamond Resource Company in fulfillment of requirements pursuant to NMFS Permit No. 1613 and USFWS Permit No. TE156839-0. March 15, 2017. https://greendiamond.com/responsible-forestry/certification/FSC/reports/5thBiennialReport_3-15-2017_(Final_with_Appendices).pdf

Hamlet, A.F., M.M. Elsner, G.S. Mauger, S-Y. Lee, I. Tohver, and R.A. Norheim. 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. Atmosphere-Ocean 51:392-415.

Hamlet, A. F., P. Carrasco, J. Deems, M. M. Elsner, T. Kamstra, C. Lee, S-Y. Lee, G. Mauger, E.P. Salathe, I. Tohver, and L.W. Binder. 2010. Final project report for the Columbia Basin Climate change scenarios project. Retrieved from http://warm.atmos.washington.edu/2860/report/

Hamlet, A.F., E.P. Salathé, and S.J. Burges. In review. A review of three statistical downscaling techniques with application to water resources planning studies in the Pacific Northwest. Journal of the American Water Resources Association

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354

Isaak, D.J., C.H. Luce, B.E. Rieman, D.E. Nagel, E.E. Peterson, D.L. Horan, S. Parkes, and G.L. Chandler. 2010. Effects of Climate Change and Wildfire on Stream Temperatures and Salmonid Thermal Habitat in a Mountain River Network. Ecological Applications 20:1350–1371. doi: 10.1890/09-0822.1.

Isaak, D.J., E.E. Peterson, J.M. Ver Hoef, S.J. Wenger, J.A. Falke, C.E. Torgersen, C. Sowder, E.A. Steel, M.-J. Fortin, C.E. Jordan, A.S. Ruesch, N. Som, and P. Monestiez, 2014. Applications of Spatial Statistical Network Models to Stream Data. Wiley Interdisciplinary Reviews: Water 1:277–294. doi: 10.1002/wat2.1023.

Isaak, D.J.; Wenger, S.J.; Peterson, E.E.; Ver Hoef, J.M.; Hostetler, S.W.; Luce, C.H.; Dunham, J.B.; Kershner, J.L.; Roper, B.B.; Nagel, D.E.; Chandler, G.L.; Wollrab, S.P.; Parkes, S.L.; Horan, D.L. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0033.

Isaak, D.J, S.J. Wenger, E.E. Peterson, J.M. Ver Hoef, D.E. Nagel, C.H. Luce, S.W. Hostetler5, J.B. Dunham, B.B. Roper, S.P.Wollrab1, G.L Chandler1, D.L. Horan1, S. Parkes-Payne. *In review*. 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

Kier Associates. 1991. Long Range Plan for the Klamath River Basin Conservation Area Fishery Restoration Program. U.S. Fish and Wildlife Service, Klamath River Fishery Resource Office. Yreka, CA. 403 pp. http://www.krisweb.com/biblio/gen_usfws_kierassoc_1991_lrp.pdf

Lewis, T.E. 1999. Stream Temperature Survey Protocol. Forest Science Project. Humboldt State University Foundation, Arcata, CA. 14 p. http://www.krisweb.com/biblio/ncc_hsu_lewis_1999_temp.pdf

Lewis, T.E., D.R. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W.D. Conroy. 2000. Regional Assessment of Stream Temperatures across Northern California and Their Relationship to Various Landscape-Level and Site-Specific Attributes. Humboldt State University Foundation Arcata, California, USA. http://wvvvv.krisweb.com/biblio/ncc_hsu_lewisetal_2000_fspregass.pdf

Luce, C., B. Staab, M. Kramer, S. Wenger, D. Isaak, and C. McConnell, 2014. Sensitivity of Summer Stream Temperatures to Climate Variability in the Pacific Northwest. Water Resources Research 50:3428–3443. doi: 10.1002/2013WR014329.

Madej, M.A., C. Currens, V. Ozaki, J. Yee, and D.G. Anderson. 2006. Assessing Possible Thermal Rearing Restrictions for Juvenile Coho Salmon (*Oncorhynchus Kisutch*) through Thermal Infrared Imaging and in-Stream Monitoring, Redwood Creek, California. Canadian Journal of Fisheries and Aquatic Sciences 63:1384–1396.

Madej, M.A. and V. Ozaki. 2009. Persistence of Effects of High Sediment Loading in a Salmon-Bearing River, Northern California. Geological Society of America Special Papers. Geological Society of America, pp. 43–55.

Mayer, T.D., 2012. Controls of Summer Stream Temperature in the Pacific Northwest. Journal of Hydrology 475:323–335. doi: 10.1016/j.jhydrol.2012.10.012.

McCovey , B.W. Jr. 2003. Klamath River Basin Water Temperature Monitoring Project 2003. Yurok Tribal Fisheries Program, Water Management and Rights Protection Division, Hoopa, CA 95546, USA.

McCullough, D.A. 2010. Are Coldwater Fish Populations of the United States Actually Being Protected by Temperature Standards? Freshwater Reviews 3:147–199. doi: 10.1608/FRJ-3.2.4.

Nagel, D., E. Peterson, D. Isaak, J. Ver Hoef, and D. Horan. 2017. National Stream Internet Protocol and User Guide, version 3-22-2017. U.S. Forest Service, Rocky Mountain Research Station, Boise, Idaho. https://www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet/downloads/NationalStreamInternetProtocolandUserGuide.pdf

National Research Council (NRC). 2004. Endangered and Threatened Fishes in the Klamath River Basin: Causes of Decline and Strategies for Recovery. Washington, DC: The National Academies Press. https://doi.org/10.17226/10838.

National Marine Fisheries Service (NMFS). 2014. Final Recovery Plan for the Southern Oregon/Northern California Coast Evolutionarily Significant Unit of Coho Salmon *(Oncorhynchus kisutch).* National Marine Fisheries Service. Arcata, CA. http://www.nmfs.noaa.gov/pr/recovery/plans/cohosalmon_soncc.pdf

North Coast Regional Water Quality Control Board (NCRWQCB). 2010. Final Staff Report for the Klamath River Total Maximum Daily Loads (TMDLs) Addressing Temperature, Dissolved Oxygen, Nutrient and Microcystin Impairments in California, the Proposed Site Specific Dissolved Oxygen Objectives for the Klamath River and California, and the Klamath River and Lost River Implementation Plans. NCRWQCB, Santa Rosa, CA. http://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/klamath_river/

O'Donnel, M.S. and D.A. Ignizio. 2012. Bioclimatic Predictors for Supporting Ecological Applications in the Conterminous United States. USGS Numbered Series, U.S. Geological Survey, Reston, VA.

Ohmann, J.L. and M.J. Gregory, 2002. Predictive Mapping of Forest Composition and Structure with Direct Gradient Analysis and Nearest- Neighbor Imputation in Coastal Oregon, U.S.A. Canadian Journal of Forest Research 32:725–741. doi: 10.1139/x02-011.

Oyler, J.W., A. Ballantyne, K. Jencso, M. Sweet, and S.W. Running, 2014. Creating a Topoclimatic Daily Air Temperature Dataset for the Conterminous United States Using Homogenized Station Data and Remotely Sensed Land Skin Temperature. International Journal of Climatology 35:2258–2279. doi: 10.1002/joc.4127.

Ozaki, V. and D. Anderson, 2005. Evaluation of Stream Temperature Regimes for Juvenile Coho Salmon in Redwood Creek Using Thermal Infrared. Technical Report/NPS/NRWRD/NRTR-2005/331. https://www.nature.nps.gov/water/technicalreports/Pacific_West/REDW_2005.pdf

Peterson E.E. and J.M. Ver Hoef. 2014. STARS: An ArcGIS toolset used to calculate the spatial information needed to fit spatial statistical models to stream network data. Journal of Statistical Software, 56(2).

Perry, R.W., Risley, J.C., Brewer, S.J., Jones, E.C., and Rondorf, D.W. 2011. Simulating Daily Water Temperatures of the Klamath River under Dam Removal and Climate Change Scenarios. U.S. Geological Survey Open-File Report 2011-1243:78pp.

Peterson E.E. and Ver Hoef J.M. (2014) STARS: An ArcGIS toolset used to calculate the spatial information needed to fit spatial statistical models to stream network data. Journal of Statistical Software, 56(2).

R Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

Roon, D. 2017. In-stream Responses to Riparian Thinning in Redwood Forests. Presentation at the Coast Redwood Science Symposium, September 13, 2016, Eureka, California. Abstract: http://ucanr.edu/sites/Redwood2016/files/242615.pdf. Video: https://www.youtube.com/watch?v=o0GUwR-JNVw

Sowder, C. and E.A. Steel. 2012. A Note on the Collection and Cleaning of Water Temperature Data. Water 4:597–606. doi: 10.3390/w4030597. http://www.mdpi.com/2073-4441/4/3/597/pdf

Stamp, J., A. Hamilton, M. Craddock, L. Parker, A.H. Roy, D.J. Isaak, Z. Holden, M. Passmore, and B.G.; Bierwagen. 2014. Best Practices for Continuous Monitoring of Temperature and Flow in Wadeable Streams. http://www.treesearch.fs.fed.us/pubs/46926. Accessed 8 Jun 2015. http://www.treesearch.fs.fed.us/pubs/46926

Strange, J., 2007. Adult Chinook Salmon Migration in the Klamath River Basin: 2006 Telemetry Study Final Report.

Strange, J.S., 2010. Upper Thermal Limits to Migration in Adult Chinook Salmon: Evidence from the Klamath River Basin. Transactions of the American Fisheries Society 139:1091–1108. doi: 10.1577/T09-171.1.

Strange, J. 2011. Salmonid Use of Thermal Refuges in the Klamath River: 2010 Annual Monitoring Study. Yurok Tribal Fisheries Program, Hoopa, CA. Available online at: http://www.yuroktribe.org/departments/fisheries/documents/thermal_refguia_report_FINAL_2010_YTFP_000.pdf

Tetra Tech, Inc. 2004. Description of the Klamath and Lost Rivers Water Quality Databases. Draft July 16, 2004. Prepared for U.S. Environmental Protection Agency Region 10, U.S. Environmental Protection Agency Region 9, Oregon Department of Environmental Quality, and the North Coast Regional Water Quality Control Board. Tetra Tech, Inc.

Torregrosa, A., C. Combs, and J. Peters, 2016. GOES-Derived Fog and Low Cloud Indices for Coastal North and Central California Ecological Analyses: COASTAL FLC FREQUENCY. Earth and Space Science 3:46–67. doi: 10.1002/2015EA000119.

Watercourse Engineering, Inc. 2003. Klamath River Water Quality 2000 Monitoring Program - Project Report. Sponsored by U.S. Bureau of Reclamation Klamath Falls Area Office with support from PacifCorp. Watercourse Engineering, Inc. Napa, CA. 92p.

Welsh Jr, H.H., G.R. Hodgson, B.C. Harvey, and M.F. Roche, 2001. Distribution of Juvenile Coho Salmon in Relation to Water Temperatures in Tributaries of the Mattole River, California. North American Journal of Fisheries Management 21:464–470.

Wick, A.R., 2016. Adaptive Management of a Riparian Zone in the Lower Klamath River Basin, Northern California: The Effects of Riparian Harvest on Canopy Closure, Water Temperatures and Baseflow. Thesis, Humboldt State University. http://scholarworks.calstate.edu/handle/10211.3/177079.

Ver Hoef J.M., Peterson E.E., Clifford D., and Shah R. 2014. SSN: An R package for spatial statistical modeling on stream networks. Journal of Statistical Software, 56(3).

Voight, H. N. and D. B. Gale. 1998. Distribution of fish species in tributaries of the lower Klamath river: An interim report, FY 1996. Technical Report No. 3. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Klamath, CA. 80 pp. http://www.krisweb.com/biblio/klamath_yuroktfp_voightetal_1998_3.pdf