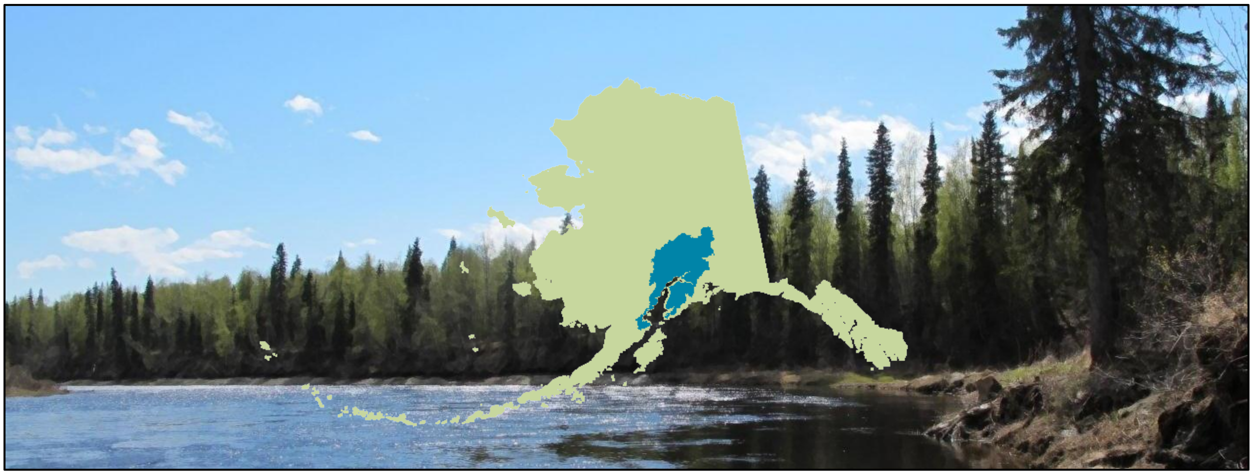

STREAM TEMPERATURE MONITORING NETWORK FOR COOK INLET SALMON STREAMS 2008 - 2012

SYNTHESIS REPORT

By

COOK INLETKEEPER

This document serves as a final project report for:

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STREAM TEMPERATURE MONITORING NETWORK FOR COOK INLET SALMON STREAMS
2008-2012

EXECUTIVE SUMMARY

Despite the importance of salmon resources to Alaska's economy and links between warm water temperature and reduced salmonid survivorship in other regions, long-term stream temperature datasets in Alaska are limited. We implemented a Stream Temperature Monitoring Network for Cook Inlet salmon streams to describe current water temperature profiles and identify watershed characteristics that make specific streams more sensitive to climate change impacts. Beginning in the summer of 2008, we collected continuous water and air temperatures in 48 non-glacial salmon streams during open-water periods. This report presents a summary of five years of data (2008-2012) from this collaborative project.

Maximum stream temperatures varied broadly among sites: 11.9 – 24.5^{o}C, with average summer temperatures across all five years ranging from 6.9 – 16.2^{o}C. The vast majority of streams exceeded Alaska's water temperature criteria set for the protection of fish especially in 2009, the warmest year, when stream temperatures exceeded the criteria of 13^{o}C at 47 sites, 15^{o}C at 39 sites, and 20^{o}C at 17 sites. We recorded frequent exceedances (> 30 days/year) of the 13^{o}C criteria at 27 sites (56%) and of the 15^{o}C criteria at 13 sites (27%). Thirty sites (63%) had maximum weekly averages above 15^{o}C over the five year period. Our modeling efforts indicate that large watersheds with low slope and low elevation are inclined to have the warmest temperature profiles and are the most sensitive to increasing air temperature.

Based on our assessment of current stream temperature profiles and sensitivities in Cook Inlet streams, average July water temperature in 27% of the streams will increase by at least 2^{o}C and may result in a greater incidence of disease, poor egg and fry incubation survival, low juvenile growth rates, and more pre-spawning mortality for salmon by 2099. Thermal impacts will be more moderate in 23% of the streams, with no significant impacts to salmon health for 50% of the streams.

The Stream Temperature Monitoring Network has proven to be a successful collaborative regional monitoring effort coordinated by Cook Inletkeeper, with fifteen different partnering entities involved. Project challenges over the five year study period included: 1) coordination of partner schedules and turnover; 2) loss of data from high flow events; 3) management of 6.8 million data points; and 4) lack of available high resolution GIS layers (land cover, NHD+, stream flow) for data analysis. This regional network can be a template for coordination, data management and analysis to facilitate expanded water temperature monitoring throughout Alaska.

BACKGROUND

Temperature is one of the most important water quality parameters as it determines many aquatic habitat attributes and the general health of stream ecosystems. In addition, thermal regimes dictate the distribution and abundance of aquatic species and overall system productivity.[1] Due to the critical role that water temperature plays in the health of organisms, function of aquatic ecosystems and because human activities may impact temperature, the Alaska Department of Environmental Conservation has adopted maximum water temperature criteria under Alaska's Water Quality Standards (18 AAC 70) to meet the federal Clean Water Act's fishable and swimmable goals.[2] These criteria provide a threshold for assessing thermal impacts on Alaska's salmon streams.

Water temperature plays a critical role in all phases of the salmonid lifecycle. In freshwater, stream temperature affects survivorship of eggs and fry, rate of respiration and metabolism, timing of migration, and availability of oxygen and nutrients. High water temperature has been shown to induce physiological stress in salmon, which makes them more vulnerable to secondary stressors such as pollution, predation and disease.[3] However, in 2002, monitoring revealed that salmon streams on the lower Kenai Peninsula exceeded Alaska's water temperature criteria for egg and fry incubation (13°C) on more than 50 days in the summer. In 2005, exceedances happened on more than 80 days with maximum temperatures above 20°C.[4] Monitoring in upper Cook Inlet streams showed similar patterns.[5, 6]

Despite the importance of salmon resources to Alaska's economy and links between warm water temperature and reduced salmonid survivorship in other regions,[7] long-term stream temperature datasets in Alaska are limited. Motivated by recent monitoring results, we initiated a Stream Temperature Monitoring Network for Cook Inlet salmon streams in 2008. The Cook Inlet watershed in Southcentral Alaska encompasses 47,000 square miles, is home to more than two-thirds of all Alaskans and supports valuable salmon runs. We established this smaller regional network with the expectation that it could be expanded in future years to cover more of Alaska's extreme size and preponderance of water bodies.

Additionally, we wanted to investigate if Cook Inlet streams are vulnerable to climate change impacts since there is a growing body of evidence that climate change has already and will continue to warm stream temperatures in the Pacific Northwest.[8] Since water temperature can vary greatly across watersheds due to climatic drivers as well as structural factors like stream morphology, land cover, and groundwater influence,[9] we need to first quantify the degree of thermal heterogeneity across streams. Once this is established, we can assess the sensitivity of an individual stream to air temperature increases and whether the resulting increase in water temperature above current conditions will be deleterious to salmon.

PROJECT GOALS AND OBJECTIVES

The goal of the Stream Temperature Monitoring Network is to describe current water temperature profiles in Cook Inlet salmon streams and identify watershed characteristics that make specific streams more sensitive to climate change impacts. Our objectives for this report are to: 1) compile stream temperature data collected from 2008-2012 and establish current conditions, 2) identify watershed characteristics that drive stream temperature profiles 3) describe site-specific sensitivity to air temperature increases, and 4) identify streams most susceptible to climate change impacts leading to stressful temperatures for salmon.

METHODS

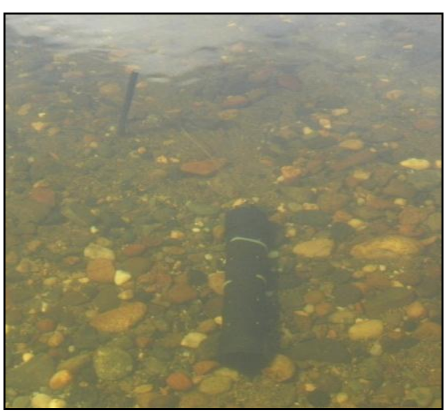
Sampling Design

The Cook Inlet sampling design includes 48 non-glacial salmon streams which represent both large and small watersheds; and a range of land cover types (Table 1, Map 1). During the design process, we considered the presence of stream gages, fish weirs, ease of access and the availability of partners to perform maintenance and quality assurance checks. The streams selected represent a range of urban development but all of them are considered reference streams (i.e. benchmarks) for the goal of establishing a baseline relationship between air and water temperature in a variety of stream types. We located our specific sampling sites as far downstream in the watershed as possible, where the stream water is flowing and well mixed and not likely to be dewatered during low flows, and with no tidal influence. Side channels, backwaters, or areas below tributary inputs were avoided. We used thermometer probes to confirm that the water was well mixed and that temperatures were consistent (within 0.3^{o}C) both vertically and horizontally.

Temperature Data Collection

A detailed description of methods, equipment used, and how we deployed data loggers in the field can be found in *Water temperature data logger protocol for Cook Inlet salmon streams*.[10] Prior to deployment, we checked data logger accuracy against a National Institute of Science and Technology (NIST)-certified thermometer. Data loggers (StowAway TidbiT, TidbiT v2, and HOBO Water Temp Pro v2 by Onset) were programmed with a recording interval of 15 minutes.

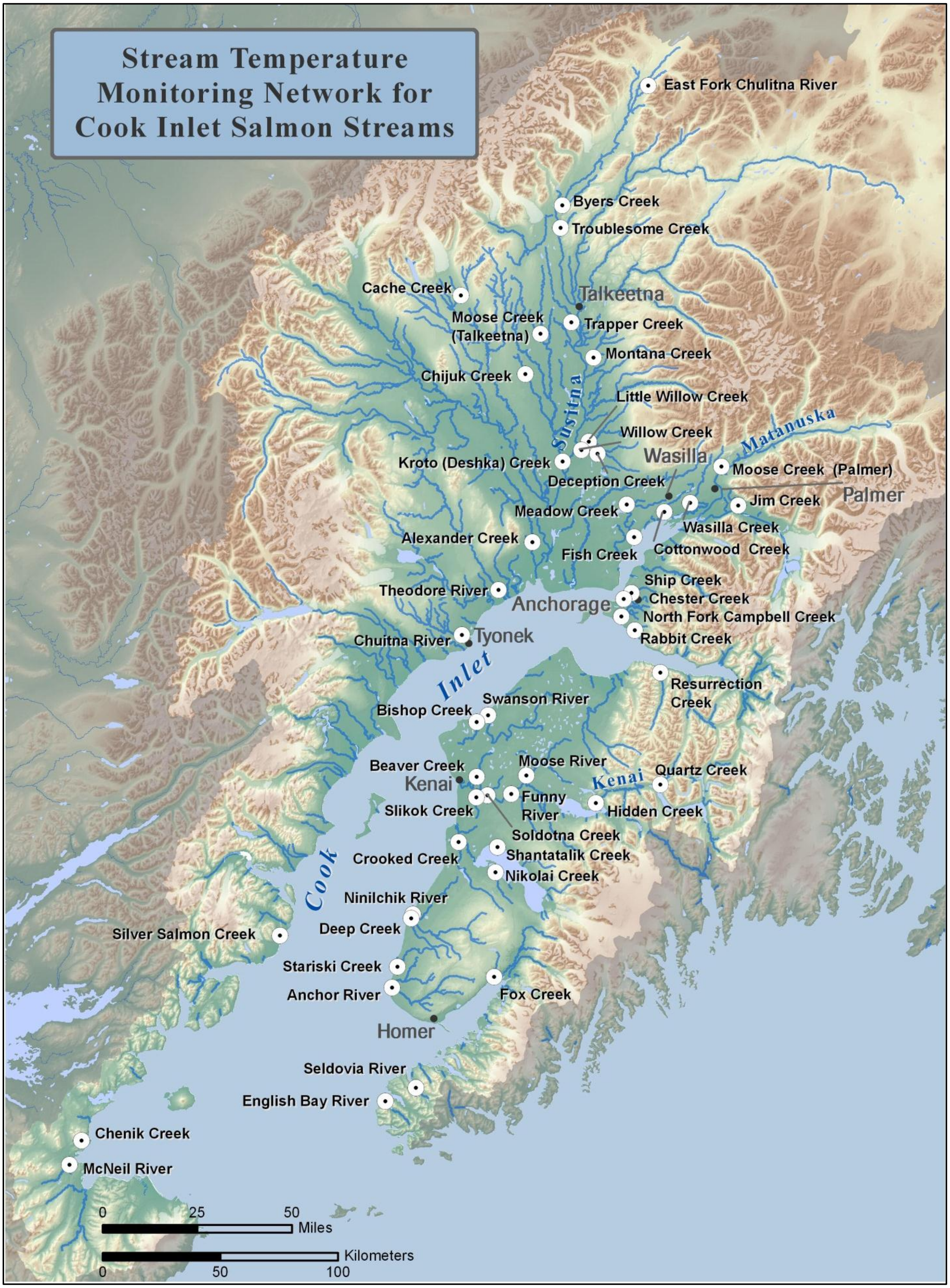
We secured water loggers in stream using one of two methods: 1) the logger was cable tied inside a protective case or PVC housing, which was attached by a cable to a rebar stake. A stake pounder was used to sink the rebar 3 feet into the stream bottom near a large rock or other landmark; or 2) the logger was attached to trees or other stationary objects on the stream bank using plastic coated cable. The cable was attached to the logger with clamps and a loop was made at the opposite end of the cable using similar clamps. The cable was wrapped around the stationary object on the bank and the logger passed through the loop and placed within the stream. The cable was buried under the grass to avoid detection and to keep it from catching on passing wildlife. A large rock or weight was placed on the cable in the stream approximately 6 inches above the logger, securing the logger in place.



Example of deployment method with data logger inside PVC housing and secured by a cable to rebar.

Table 1. Cook Inlet Stream Temperature Monitoring Network data logger locations.

LOCATION	REGION	DESCRIPTION	Latitude	Longitude
Alexander Creek	Mat-Su	approx. 2 miles upstream from Susitna River	61.44000	-150.59600
Anchor River	Kenai	immediately downstream of weir	59.77300	-151.83400
Beaver Creek	Kenai	Togiak Road access	60.56100	-151.12300
Bishop Creek	Kenai	Silvertip Road access	60.76800	-151.10300
Byers Creek	Mat-Su	upstream from Park's Highway	62.71158	-150.20407
Cache Creek	Mat-Su	1/2 mile downstream from east end of landing	62.38900	-151.08100
Chenik Creek	West Inlet	incorporated into stream gage set up	59.20900	-154.19000
Chester Creek	Anchorage	downstream of Arctic Blvd.	61.20500	-149.89600
Chijuk Creek	Mat-Su	Oilwell Road crossing	62.07963	-150.58314
Chuitna River	West Inlet	1/4 mile upstream of Beluga Highway bridge	61.10100	-151.19000
Cottonwood Creek	Mat-Su	upstream from Surrey Road	61.52500	-149.52700
Crooked Creek	Kenai	lower site below hwy, Cohoe King Road access	60.31600	-151.28400
Deception Creek	Mat-Su	upstream from Willow-Fishook Road	61.76200	-150.03400
Deep Creek	Kenai	1/4 mile upstream from highway bridge	60.03300	-151.67100
East Fork Chulitna River	Mat-Su	downstream from Park's Highway	63.14500	-149.42100
English Bay River	Kenai	20 feet upstream of weir	59.34300	-151.91200
Fish Creek	Mat-Su	below Knik-Goose Bay Road	61.43800	-149.78100
Fox Creek	Kenai	public access trail above private land at m	59.79900	-151.05600
Funny River	Kenai	upstream of Funny River Road bridge	60.49000	-150.86000
Hidden Creek	Kenai	1000 feet upstream of Kenai River confluence	60.43900	-150.20800
Jim Creek	Mat-Su	1 mile upstream of Jim Creek Flats	61.52900	-148.93300
Kroto (Deshka) Creek	Mat-Su	1.0 miles upstream from Susitna River	61.74000	-150.32000
Little Willow Creek	Mat-Su	0.25 miles downstream from Parks Highway	61.81000	-150.09900
McNeil River	West Inlet	incorporated into stream gage set up above	59.11700	-154.27900
Meadow Creek	Mat-Su	Beaver Lakes Road Crossing	61.56300	-149.82400
Montana Creek	Mat-Su	end of Access Road South of Helena	62.12800	-150.01900
Moose Creek (Palmer)	Mat-Su	150 yards downstream of Glenn Hwy bridge	61.68200	-149.04300
Moose Creek (Talkeetna)	Mat-Su	Oilwell Road Crossing	62.22900	-150.44100
Moose River	Kenai	1 mile up, Otter Trail Road	60.55700	-150.73500
NF Campbell Creek	Anchorage	upstream of Diamond Blvd. and Campbell Lake	61.14000	-149.92300
Nikolai Creek	Kenai	boat to mouth, 75 feet downstream of weir	60.19500	-151.00900
Ninilchik River	Kenai	immediately downstream of highway bridge	60.04900	-151.65600
Quartz Creek	Kenai	1.5 miles upstream along highway corridor	60.49300	-149.70000
Rabbit Creek	Anchorage	upstream of Old Seward Hwy crossing	61.08500	-149.82300
Resurrection Creek	Kenai	1/4 mile upstream from highway bridge	60.91800	-149.64300
Seldovia River	Kenai	3/4 mile upstream of mouth	59.38900	-151.68000
Shantatalik Creek	Kenai	boat to mouth, 75 feet upstream of weir	60.29100	-150.98500
Ship Creek	Anchorage	downstream of Reeve Blvd.	61.22700	-149.83100
Silver Salmon Creek	West Inlet	1/2 mile upstream from Ranger station	59.98184	-152.67859
Slikok Creek	Kenai	Chugach Road access	60.48300	-151.13100
Soldotna Creek	Kenai	upstream of East Redoubt Road crossing	60.48900	-151.04400
Stariski Creek	Kenai	1/4 mile upstream from highway bridge	59.85100	-151.78700
Swanson River	Kenai	North Kenai Road crossing	60.79200	-151.01200
Theodore River	Mat-Su	500 yards upstream from Beluga Hwy bridge	61.26600	-150.88400
Trapper Creek	Mat-Su	Bradley Road Crossing	62.26600	-150.18400
Troublesome Creek	Mat-Su	downstream from Park's Highway	62.62700	-150.22700
Wasilla Creek	Mat-Su	Nelson Road access	61.55300	-149.31400
Willow Creek	Mat-Su	0.25 miles upstream from Susitna River	61.78000	-150.16100



Map 1. Cook Inlet Stream Temperature Monitoring Network data logger locations.

In addition to water temperature data, we collected air temperature at each monitoring location. Temperature loggers were secured within a solar radiation shield. The solar shield and logger were secured to a post or suspended from vegetation in the area at least 6 feet off of the ground. The air temperature logger was placed 25 - 100 feet from the stream in an effort to prevent water temperature from influencing local air temperature data. Supplemental site and reach information was also collected including latitude and longitude, elevation and channel width and depth.

We deployed loggers from mid-May to mid-June as conditions allowed. Data-collecting partners periodically checked on loggers to ensure that they were still in place and operating. At the end of the field season (after October 1), the loggers were retrieved and the data downloaded on a data shuttle or base station. Data loggers were checked a second time for sufficient battery power, and temperature accuracy at approximately 0 and 20°C using a NIST thermometer. For more details, the Quality Assurance Project Plan is available from Cook Inletkeeper upon request.

Watershed Characteristics

We used a variety of methods to generate watershed metrics (see Table 2). We used Hydrologic Unit Codes (HUC, Hydrography and Watersheds USGS, BLM 2006) to categorize watershed size. Land-cover statistics (% wetlands, % forested, % open water, % developed, and % scrub/shrub) were derived for each watershed from 30 meter resolution LANDSAT imagery (1999, 2003) from the USGS (2007).

All other watershed (polygon) calculations, including elevation, slope, aspect and area, were derived from the USGS's National Elevation Dataset (NED) 2-arc-second (about 60 meter grid spacing) Digital Elevation Models (DEMs). The 2-arc-second DEM was chosen for this project based on its seamless coverage of the project area. All DEMs calculations were done with ArcGIS Desktop 10.1 tools. Stream (line) calculations, including total stream gradient and 1 km upstream stream gradient, were derived from the USGS's National Hydrography Dataset (NHD). NHD was chosen for this project based on its standardized and continuous coverage of the project area.

Table 2: Summary of the methods used to calculate watershed and stream characteristics.

Characteristic	Description	General Method	Summary	Notes
Watershed size	HUC size	Visual assessment	A priori categorization: large (HUC 10), medium (multi-HUC 12), small (HUC 12), tiny (less than HUC 12)	10-digit (5th level) HUC watersheds are 40,000 to 250,000 acres; 12-digit (6th level) HUC sub-watersheds are 10,000 to 40,000 acres
	Acres	ArcGIS	Sum of total and partial number of grids within a watershed polygon	Indication of stream size and exposure to solar radiation
Region	Regional category	Visual assessment	Mat-Su, Kenai, Anchorage, West side	May reflect climate variability across larger region

Characteristic	Description	General Method	Summary	Notes
Color	Water color	Visual assessment	Clear or brown/stained	Reflects wetland influence
Land cover	Wetlands, forested, open water, developed, scrub/shrub	ArcGIS	Percent of each cover type derived from 30-meter resolution LANDSAT imagery	Indication of residency time and exposure to solar radiation
Slope	Watershed slope	ArcGIS	Spatial Analyst extension “Slope” tool identifies the gradient, or rate of maximum change in z-value, from each cell of raw DEM	Indication of residency time and velocity of flow
	Channel slope	ArcGIS	1 km upstream elevation minus elevation at logger site/upstream length	Manually measured and clipped NHD layer 1 km upstream of all sites
Elevation	Maximum elevation	ArcGIS	Calculated from raw DEM and found in Raster Statistics Summary	indicates the contribution of snow pack to flow and temp
	Average elevation	ArcGIS	Calculated from raw DEM and found in Raster Statistics Summary	
	Site elevation	ArcGIS	Spatial Analyst extension “Extract Values to Point” tool	
Aspect	South aspect	ArcGIS	Spatial Analyst extension “Aspect” tool derives aspect from raw DEM	each grid receives an aspect value and is re-assigned a categorical value; north facing (313 – 45^{o}), east facing (45-135^{o}), south facing (135-225^{o}), and west facing (225-315^{o})
	Dominant aspect	ArcGIS	Spatial Analyst extension “Aspect” tool derives aspect from raw DEM	influences snow melt rate in spring and resulting summer water volume
	Channel aspect	ArcGIS	Spatial Analyst extension “Aspect” tool derives aspect from raw DEM for 1 km reach above the water logger site	influences amount of solar gain in lower reach where stream is widest
Lake Influence	Lake influence	ArcGIS	lake influence was high (2) if within 100 stream widths of the logger; lake influence was low (1) if greater than 100 stream widths of the logger; lake influence was none (0) if there were no lakes	calculated the channel distance using the NHD layer to the lowermost lake mouth to the water logger site
Summer discharge	Summer discharge	calculation	SNAP precipitation data at each site x watershed area	Influences water volume and resulting groundwater contribution

Temperature Metrics

Temperature statistics - calculated for each site and averaged over the 5 years - include overall maximum temperature; daily, weekly, monthly and seasonal average, maximum, and minimum temperature; monthly cumulative degree days (sum of average daily temperatures); maximum 7-day rolling average (MWAT), maximum 7-day rolling maximum temperature (MWMT); and maximum daily fluctuation. If less than 90% of the daily temperatures were collected in a month, no monthly or seasonal averages were calculated.

Water temperature data were also compared to Alaska's numeric water temperature criteria for the growth and propagation of freshwater fish, shellfish, other aquatic life and wildlife.[2] The criteria below were based on a review of relevant literature and adopted in 1999.

> "The following maximum temperatures shall not be exceeded, where applicable:
>
> egg & fry incubation = 13^{o}C
> spawning areas = 13^{o}C
> migration routes = 15^{o}C
> rearing areas = 15^{o}C
> and may not exceed 20^{o}C at any time."

We used linear regression equations to determine the relationship between daily and weekly average and maximum water temperature and air temperature. Some studies[11] have shown a non-linear relationship between air and water temperature at the lower (<4^{o}C) and upper (>20^{o}C) ends of the range; however, this study focused on temperatures recorded from June – September, when the vast majority of values fell between 4^{o}C and 20^{o}C. Regression coefficients (slope of the linear relationship) quantify the correlation of water temperature to air temperature and describe "sensitivity".[12]

Models

We used multiple linear regression models to explain differences in the temperature profiles of the 48 streams. These models provide predictive power to estimate stream temperature responses (average daily sensitivity, average July, MWAT, MWMT) in other Cook Inlet streams not included in this study. Watershed characteristics were evaluated for outliers, normality, and collinearity. Many variables were strongly collinear and removal of strongly related variables reduced the list to eight predictor variables (Table 3). Pairwise plots were used to evaluate the relationship between each temperature response variable and the eight watershed predictors. Coplots and xyplots were used to evaluate possible interactions between predictors. No non-linear relationships and/or interactions were apparent during data exploration.

Model selection was based on the information theoretic approach; a set of candidate multiple regression models was built based on the suite of eight predictor variables (Table 4) and compared using Akaike's Information Criterion (AIC). A global modal was included with all predictors in addition to alternative models based on hypothesized relationships between watershed attributes and stream temperature metrics.[13,14] Assumptions were evaluated for each model, which included normality of the residuals and homogeneity of variances (normalized residuals plotted against fitted values and each predictor).

AIC balances model precision and model complexity and is calculated as two times the number of parameters in the model minus two times the maximum log-likelihood of the model; a lower AIC indicates a better model. AIC values were rescaled so that the model with the lowest AIC has a value of 0 and other models were ranked based on the difference between their AIC value and the minimum AIC (Δ_I). In addition, Akaike weights (w_i) were calculated and are interpreted as the weight of evidence that a specific model is the best model given the candidate model set and the data. Both Δ_I and w_i were used as evidence that any given model in the model set could be considered a single "best" model used for inference.

Table 3. Watershed variables used for predicting temperature responses in Cook Inlet streams. Bolded variables were used in model development.

Variable	Type	Units	Notes
Size category	class	Based on HUCs	Correlated to acres
Watershed size	continuous	Acres	
Region	class	Mat-Su, Kenai, Anchorage, West side	Differences in climate by region related to air temperature
Water color	class	Clear or brown	Correlated to wetland percentage
Wetland percentage	continuous	0-100	
Forested percentage	continuous	0-100	Correlated to shrub/scrub percentage
Open water percentage	continuous	0-100	Captured by lake influence
Developed percentage	class	0 = <5% impervious surface 1 = >5% impervious surface	
Shrub/scrub percentage	continuous	0-100	Correlated to wetland percentage
Dominant land cover	class	Land cover class with highest percentage	Captured by percentages of other land cover classes
Watershed slope	continuous	0-100	
Channel slope	continuous	0-100	Confidence in data accuracy was low due DEM scale
Maximum elevation	continuous	meters	Correlated to average elevation
Average elevation	continuous	meters	
Logger elevation	continuous	meters	Correlated to average elevation
South aspect percentage	continuous	0-100	
Dominant aspect	class	North, south, east, west	Captured by south aspect percentage and no relationship to predictors
Channel aspect	class	North, south, east, west	Captured by south aspect percentage and no relationship to predictors
Stream width	continuous	meters	Correlated to acres
Lake influence	class	2 = within 100 reaches of site 1 = >100 reaches 0 = no lake	
Summer discharge		Precipitation at site x watershed size (m^3/s)	Correlated to acres
Latitude	continuous	Decimal degrees (WGS84)	Expected that air temp is more important aspect of spatial variability
Longitude	continuous	Decimal degrees (WGS84)	Expected that air temp is more important aspect of spatial variability
Air temperature	continuous	Degrees C, monitoring data, used same time step as response variable	

Table 4. Candidate multiple regression models for four water temperature response variables built based on eight predictor variables.

Candidate Models	water temp response variables	Predictor variables							
		air temp	area	% wetland	% develop-ed	lake influence	% south aspect	average elevation	average slope
global	Sensitivity		X	X	X	X	X	X	X
	Average July	Average July	X	X	X	X	X	X	X
	MWAT	MWAT	X	X	X	X	X	X	X
	MWMT	MWMT	X	X	X	X	X	X	X
geomorphic and area	Sensitivity		X				X	X	X
	Average July	Average July	X				X	X	X
	MWAT	MWAT	X				X	X	X
	MWMT	MWMT	X				X	X	X
geomorphic	Sensitivity						X	X	X
	Average July	Average July					X	X	X
	MWAT	MWAT					X	X	X
	MWMT	MWMT					X	X	X
Land cover and area	Sensitivity		X	X	X	X			
	Average July	Average July	X	X	X	X			
	MWAT	MWAT	X	X	X	X			
	MWMT	MWMT	X	X	X	X			
Land cover	Sensitivity			X	X	X			
	Average July	Average July		X	X	X			
	MWAT	MWAT		X	X	X			
	MWMT	MWMT		X	X	X			
Air temp and area	Sensitivity		X						
	Average July	Average July	X						
	MWAT	MWAT	X						
	MWMT	MWMT	X						
Air temp only	Sensitivity								
	Average July	Average July							
	MWAT	MWAT							
	MWMT	MWMT							

Climate Change Analysis

The University of Alaska Fairbanks, Scenarios Network for Alaska Planning (SNAP) used climate projections based on the five best-performing Global Circulation Models (GCM's) to generate future scenarios of air temperature and precipitation conditions in the Cook Inlet basin.[15] We used results from the A1B scenario (a mid-range scenario) which assumes a world of very rapid economic growth, a global population that peaks in mid-century, rapid introduction of new and more efficient technologies, and a balance between fossil fuels and other energy sources. SNAP provided point data for each temperature monitoring site including monthly averages for air temperature (degrees C) by decade; and monthly averages for precipitation (cm) by decade from 2000 to 2100. We used future July air temperature data to predict future July water temperature based on current water temperature data and sensitivities.

Partners in the field: please see the full list of individuals and state, federal, Tribal and NGO partners who helped in the data collection phase of this project in the Acknowledgments section of this report.

Results

Water and Air Temperature (2008-2012)

We deployed water and air temperature data loggers at 48 sites each year. We had an 89.6% retrieval rate for water loggers and a 94.6% retrieval rate for air loggers. We lost two water loggers in 2008, one in 2009, two in 2010, and one in 2011. During high flow events in September 2012, we lost water loggers at 17 sites. At four sites (Deep Creek, Jim Creek, Rabbit Creek and Silver Salmon Creek) we lost two years of water temperature data during the 5-year period (Table 5). Silver Salmon Creek is the only site missing data from 2009 – the warmest year. Jim Creek is the only site missing data from both 2008 and 2012 – the two coolest years. Summary statistics for these sites likely under and over represent temperatures respectively.

Range of Variability

Maximum stream temperatures, which predominantly occurred in 2009, varied broadly among sites: 11.9 – 24.5°C, with average summer (June, July and August) temperatures across all five years ranging from 6.9 – 16.2°C (Table 6). Average temperatures across all sites were 8.0 – 16.0°C in July and 7.6 – 14.4°C in August. The maximum daily fluctuation recorded was greatest at Fox Creek (11.6°C) and smallest at Silver Salmon Creek (3.9°C).

Temperature Exceedances

The vast majority of streams exceeded Alaska's water temperature criteria set for the protection of fish especially in 2009, the warmest year, when stream temperatures exceeded the criteria of 13°C at 47 sites, 15°C at 39 sites, and 20°C at 17 sites (Map 2, Table 7). We recorded frequent exceedances (> 30 days/year) of the 13°C criteria at 27 sites (56%) and of the 15°C criteria at 13 sites (27%). Thirty sites (63%) had maximum 7-day rolling maximums (MWMT) above 15°C (Map 3). Thirteen sites (27%) had maximum 7-day rolling averages (MWAT) above 15°C (Map 4). The number of days of exceedances at sites with shorter deployment dates may be under reported.

Air Temperature Patterns

Across the five years, average July air temperature measured at each site ranged from 10.9°C (Seldovia River, Stariski Creek) to 14.5°C (Willow Creek) with 81% of the sites between 11.0 - 13.9°C. Anchorage and Mat-Su regions had consistently warmer air temperatures than the Kenai Peninsula and west side of Cook Inlet (Figure 1).

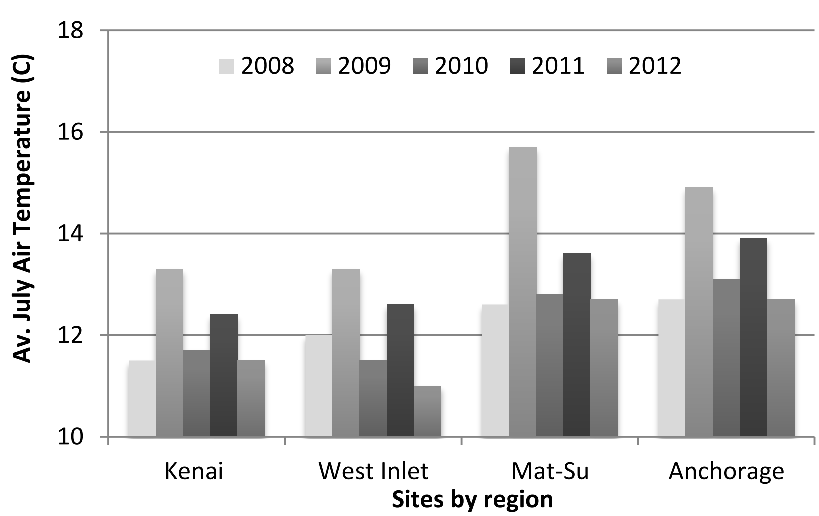


Figure 1. Average July air temperatures by region.

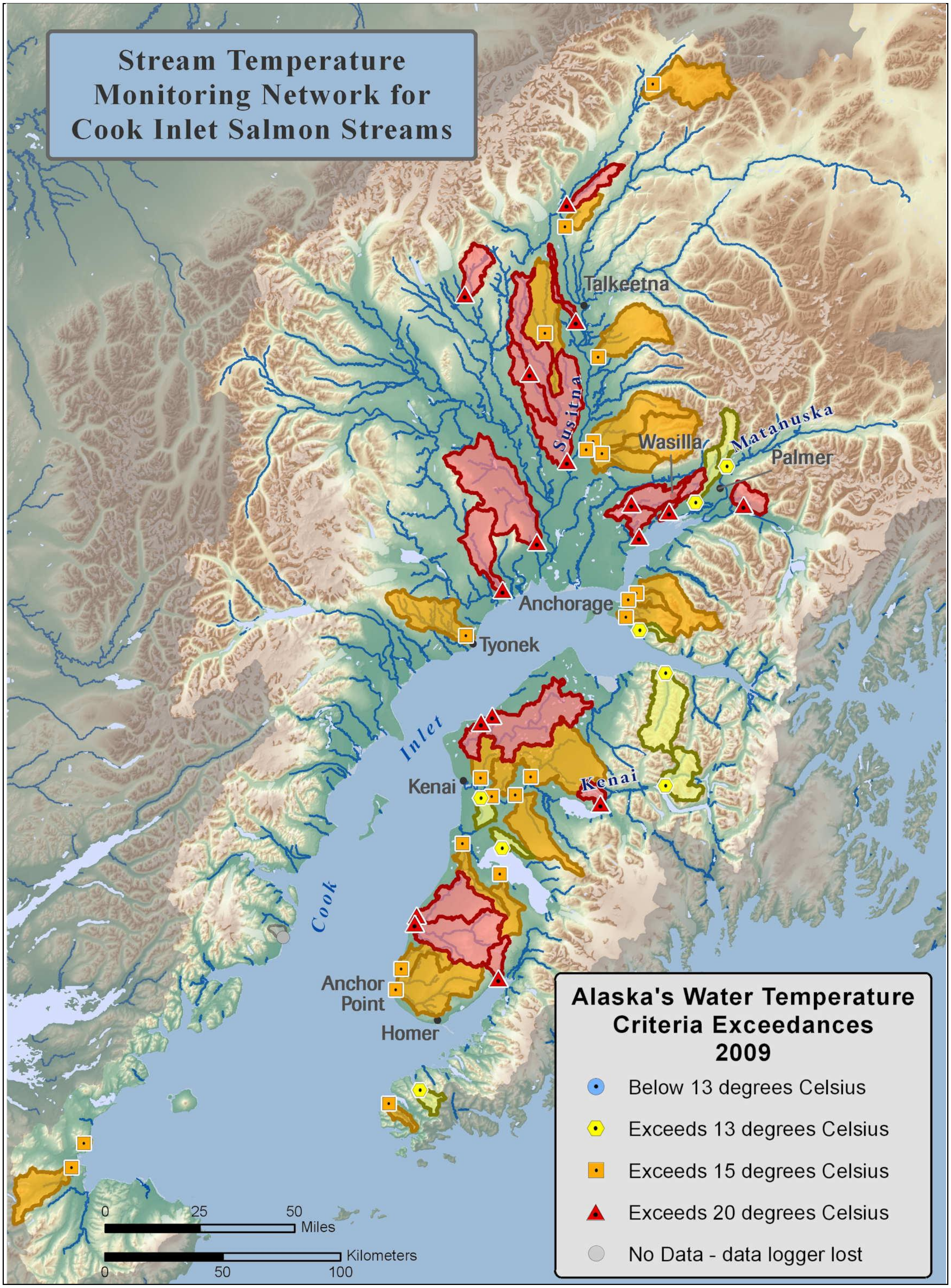
Table 5. Summary of water and air temperature datasets collected over the 5-year study period.

Stream Name	Water Data					Air Data				
	2008	2009	2010	2011	2012	2008	2009	2010	2011	2012
Alexander Creek	√	√	√	√		√	√	√	√	√
Anchor River	√	√	√	√	√	√	√	√	√	√
Beaver Creek	√	√	√	√	√	√	√	√	√	√
Bishop Creek	√	√	√	√		√	√	√	√	√
Byers Creek	√	√	√	√	√	√	√	√	√	√
Cache Creek	√	√		√	√	√	√	√	√	√
Chenik Creek	√	√	√	√	√	√	√	√	√	√
Chester Creek	√	√	√	√			√	√	√	√
Chijuk Creek	√	√	√	√	√	√	√	√	√	√
Chuitna River	√	√	√	√		√	√	√	√	
Cottonwood Creek	√	√	√	√	√	√	√	√		√
Crooked Creek	√	√	√	√	√		√	√	√	√
Deception Creek	√	√	√	√		√	√	√	√	
Deep Creek	√	√		√		√	√	√	√	√
East Fork Chulitna	√	√	√	√	√	√	√	√	√	√
English Bay River	√	√	√	√	√	√	√	√	√	√
Fish Creek	√	√	√	√	√	√	√		√	√
Fox Creek		√	√	√	√	√	√	√	√	√
Funny River	√	√	√	√	√	√	√	√	√	√
Hidden Creek	√	√	√	√	√	√	√	√	√	√
Jim Creek		√	√	√		√	√	√	√	√
Kroto (Deshka) Creek	√	√	√	√	√	√	√	√	√	√
Little Willow Creek	√	√	√	√	√	√	√	√	√	√
McNeil River	√	√	√	√		√	√	√	√	√
Meadow Creek	√	√	√	√		√			√	√
Montana Creek	√	√	√	√		√	√		√	√
Moose Creek (Palmer)	√	√	√	√		√	√	√	√	√
Moose Creek (Talkeetna)	√	√	√	√	√	√	√	√	√	√
Moose River	√	√	√	√	√	√	√	√	√	√
NF Campbell Creek	√	√	√	√	√	√	√	√	√	√
Nikolai Creek	√	√	√	√	√	√	√	√	√	√
Ninilchik River	√	√	√	√	√	√	√	√	√	√
Quartz Creek	√	√	√	√		√	√	√	√	√
Rabbit Creek	√	√	√			√	√	√	√	√
Resurrection Creek	√	√	√	√	√	√	√	√	√	√
Seldovia River	√	√	√	√	√	√	√	√	√	√
Shantatalik Creek	√	√	√	√	√	√	√	√	√	√
Ship Creek	√	√	√	√		√	√	√	√	√
Silver Salmon Creek	√		√	√		√	√	√	√	√
Slikok Creek	√	√	√	√	√	√	√	√	√	√
Soldotna Creek	√	√	√	√	√	√	√		√	√
Stariski Creek	√	√	√	√	√	√	√	√	√	√
Swanson River	√	√	√	√		√	√	√	√	√
Theodore Creek	√	√	√	√	√	√	√	√	√	√
Trapper Creek	√	√	√	√	√	√	√		√	√
Troublesome Creek	√	√	√	√	√	√	√	√	√	√
Wasilla Creek	√	√	√	√	√	√	√	√	√	√
Willow Creek	√	√	√	√		√	√		√	

Table 6: Summary of water temperature statistics for 2008- 2012. All values are in degrees Celsius (C).

Stream Name	Average summer (JJA) temperature	June average temperature	July average temperature	August average temperature	September average temperature	June degree days	July degree days	August degree days	September degree days	Maximum 7-day rolling average temperature	Maximum 7-day rolling maximum temperature	Maximum Daily Difference
Alexander Creek			15.8	14.0	9.8		489	434	288	16.6	19.8	10.2
Anchor River	11.8	10.5	12.2	11.3	7.9	314	377	351	238	13.7	16.4	8.1
Beaver Creek	11.8	11.4	12.6	11.8	8.3	342	391	367	247	13.8	15.2	5.1
Bishop Creek	14.8	14.4	15.8	14.3	10.0	433	489	444	300	17.2	19.1	6.2
Byers Creek	13.4	11.7	14.9	13.3	9.6	350	462	413	288	15.9	18.8	7.7
Cache Creek	10.1	8.1	11.0	9.5	6.4	244	339	294	192	12.3	15.3	9.0
Chenik Creek		6.6	10.2	11.1		191	316	334		12.6	13.5	5.7
Chester Creek	11.8	11.2	12.6	11.7	9.1	336	389	363	274	13.2	14.8	5.6
Chijuk Creek	14.1	13.9	15.1	13.1	9.0	416	469	401	251	16.9	19.4	8.1
Chuitna River	12.4	10.0	13.8	12.3	8.2	300	429	380	245	14.8	17.2	7.3
Cottonwood Creek	14.6	14.1	15.3	14.1	9.8	424	473	437	292	16.6	18.6	6.6
Crooked Creek	11.2	10.9	11.6	10.7	7.3	326	361	330	219	13.2	15.6	6.5
Deception Creek	11.1	10.4	12.2	10.7	7.2	313	378	332	216	13.5	15.5	9.4
Deep Creek	11.9	10.5	12.7	11.4	7.8	315	392	355	233	14.4	17.1	7.9
East Fork Chulitna River	7.8	6.7	8.6	7.8	5.1	200	267	242	153	9.8	12.4	7.1
English Bay River			13.3	13.7	11.1		411	424	332	14.9	15.7	4.1
Fish Creek	15.1	14.9	16.0	14.4	9.7	446	498	438	291	17.1	18.8	6.4
Fox Creek	12.6	11.7	13.5	12.4	8.6	351	418	384	259	14.8	18.7	11.6
Funny River	9.9	9.1	10.4	9.7	6.6	274	323	302	199	12.0	13.8	5.6
Hidden Creek	13.3	11.7	14.3	13.9	11.2	348	444	432	330	15.9	18.2	7.8
Jim Creek	16.2	15.6	17.3	15.3	10.6	468	536	464	318	19.3	20.7	6.4
Kroto (Deshka) Creek	14.6	15.0	16.5	13.3	9.2	442	511	413	272	18.4	20.1	9.1
Little Willow Creek	10.9	9.7	12.1	10.9	7.4	289	374	338	221	13.6	15.4	5.7

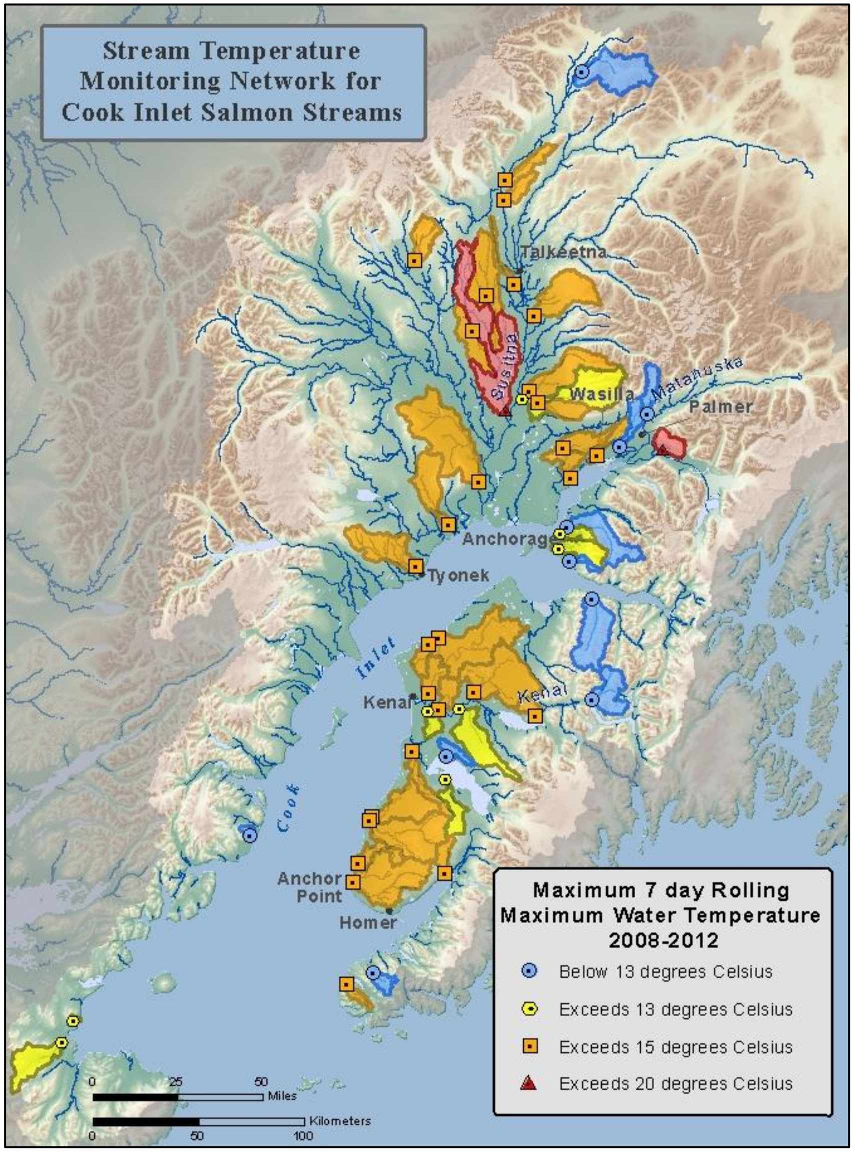
Stream Name	Average summer (JJA) temperature	June average temperature	July average temperature	August average temperature	September average temperature	June degree days	July degree days	August degree days	September degree days	Maximum 7-day rolling average temperature	Maximum 7-day rolling maximum temperature	Maximum Daily Difference
McNeil River			8.5				265			11.4	13.7	8.0
Meadow Creek	14.1	13.9	14.9	13.0	8.8	418	461	403	263	16.4	19.0	7.9
Montana Creek	11.1	9.9	12.3	11.2	8.1	295	382	346	242	13.4	15.6	6.7
Moose Creek (Palmer)	7.9	7.2	8.9	8.2	6.3	211	277	255	189	9.8	11.9	7.7
Moose Creek (Talkeetna)	12.8	12.6	13.4	12.3	8.3	378	416	376	244	14.6	16.4	8.6
Moose River	13.1	12.5	13.6	12.7	8.5	376	423	392	256	15.4	16.5	5.6
NF Campbell Creek	10.3	9.1	11.3	10.7	7.4	272	352	330	223	12.6	14.3	5.8
Nikolai Creek	9.4	8.4	10.5	9.7	6.6	248	324	300	199	12.1	14.9	8.5
Ninilchik River	12.0	10.9	12.5	11.4	7.8	328	388	353	234	14.1	16.7	7.8
Quartz Creek	8.5	7.1	8.5	8.8	7.0	213	264	266	206	9.6	11.3	6.4
Rabbit Creek	7.6	6.1	8.3	8.3	6.4	182	258	258	191	9.4	10.5	5.9
Resurrection Creek	7.8	6.4	8.4	8.2	6.3	193	260	255	188	9.2	10.7	5.9
Seldovia River	9.2	7.5	8.3	9.3	7.7	218	258	289	232	10.3	11.4	4.6
Shantatalik Creek	9.4	8.6	10.1	9.6	6.9	253	312	299	209	11.2	12.5	4.9
Ship Creek	9.1	7.8	9.9	9.4	7.0	234	306	292	210	10.8	12.4	6.0
Silver Salmon Creek	8.1	7.2	8.0	8.2	7.3	216	249	253	218	8.9	10.1	3.9
Slikok Creek	10.3	9.9	10.8	10.1	7.2	297	336	313	214	12.2	14.5	7.5
Soldotna Creek	11.8	11.2	12.5	11.6	8.3	336	388	360	246	14.1	16.3	7.8
Stariski Creek	11.5	10.7	12.1	11.3	7.9	322	376	349	236	13.6	15.9	7.1
Swanson River	14.6	14.1	15.3	13.9	9.5	423	473	432	284	16.9	18.6	6.3
Theodore Creek			13.2	11.4	8.2		409	353	246	14.5	16.4	5.5
Trapper Creek	14.1	13.6	15.2	13.4	8.9	409	471	415	267	16.8	18.5	5.0
Troublesome Creek	11.1	9.9	12.5	10.9	7.3	296	389	336	220	13.7	16.2	8.3
Wasilla Creek	9.8	9.5	10.3	9.6	6.8	280	320	297	206	11.1	12.3	4.2
Willow Creek	10.4	9.6	11.9	10.7	7.8	289	368	332	233	13.1	14.7	5.2

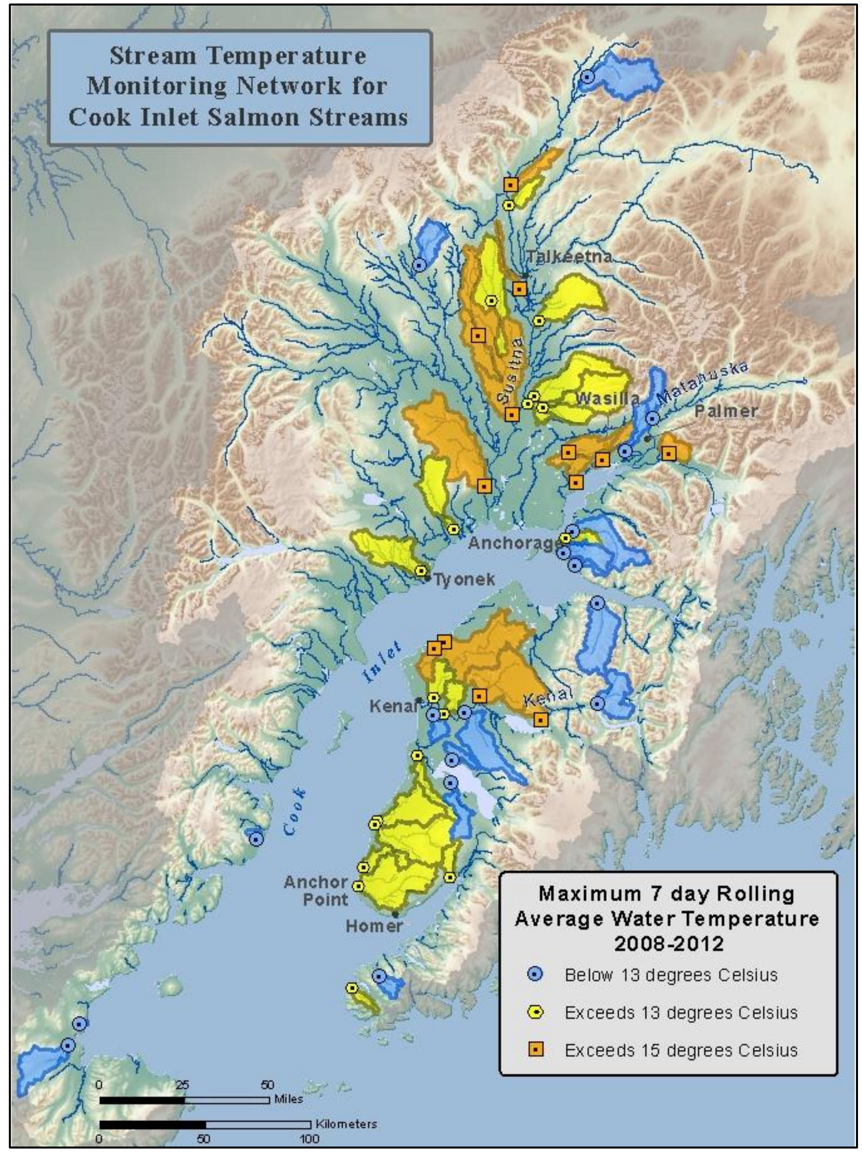


Map 2. Summer temperatures exceeded Alaska's Water Temperature Criteria of 13°C at 47 sites, 15°C at 39 sites, and 20°C at 17 sites in 2009. Temperature logger sites and their contributing watersheds are color-coded by the highest exceedance value.

Table 7. Average number of days of temperature exceedances for the period: June 21- September 22 (94 days total) and the highest temperature recorded over the 5-year sampling effort.

Temperature Logger Site	# Days Exceeds 13°C	# Days Exceeds 15°C	# Days Exceeds 20°C	Highest Temp Recorded
Alexander Creek	72	51	8	22.61
Anchor River	41	18	0	19.98
Beaver Creek	39	10	0	16.48
Bishop Creek	77	51	3	22.21
Byers Creek	74	44	3	22.80
Cache Creek	23	10	1	20.65
Chenik Creek	10	1	0	17.70
Chester Creek	39	8	0	16.44
Chijuk Creek	62	38	5	24.26
Chuitna River	37	24	1	21.96
Cottonwood Creek	77	52	2	22.01
Crooked Creek	30	12	0	18.03
Deception Creek	30	10	0	18.79
Deep Creek	43	24	1	20.63
East Fork Chulitna River	6	1	0	15.46
English Bay River	56	11	0	19.56
Fish Creek	67	49	4	22.73
Fox Creek	68	42	5	22.03
Funny River	12	2	0	16.09
Hidden Creek	77	45	3	22.84
Jim Creek	76	61	13	23.87
Kroto (Deshka) Creek	54	43	8	24.53
Little Willow Creek	27	8	0	19.51
McNeil River	9	1	0	15.53
Meadow Creek	71	41	4	22.68
Montana Creek	35	13	0	18.84
Moose Creek (Palmer)	3	0	0	14.77
Moose Creek (Talkeetna)	43	18	0	18.13
Moose River	49	15	0	19.27
NF Campbell Creek	18	5	0	17.58
Nikolai Creek	17	7	0	18.15
Ninilchik River	40	18	0	20.22
Quartz Creek	3	0	0	14.37
Rabbit Creek	1	0	0	13.14
Resurrection Creek	2	0	0	13.86
Seldovia River	1	0	0	14.12
Shantatalik Creek	3	0	0	13.69
Ship Creek	7	0	0	15.13
Silver Salmon Creek	0	0	0	11.90
Slikok Creek	22	5	0	16.13
Soldotna Creek	40	16	0	19.01
Stariski Creek	37	14	0	19.53
Swanson River	73	47	2	21.67
Theodore River	39	15	1	20.75
Trapper Creek	66	37	2	22.23
Troublesome Creek	33	17	0	19.94
Wasilla Creek	2	0	0	14.98
Willow Creek	21	8	0	18.79





Maps 3 and 4. Maximum 7-day rolling maximums (MWMT) and maximum 7-day rolling averages (MWAT) or the maximum recorded value of daily maximum/average water temperature when averaged over 7 consecutive days.

Sensitivity

Sensitivity is the slope (or coefficient from the regression equation) of the air and water relationship. For instance, for every degree of air temperature increase at Fox Creek, the average daily water temperature will increase 0.99^{o}C (Table 8). The higher the coefficient the higher the stream's sensitivity to air temperature increases. Sensitivity at each site ranged from 0.34 - 0.99 (average daily), 0.23 - 0.97 (maximum daily), 0.41 – 1.14 (average weekly) and 0.38 – 1.41 (maximum weekly).

Table 8. Comparison of regression coefficients (slope) of daily and weekly average and maximum air temperature and water temperature. Streams are sorted based on average daily values.

Stream Name	average daily	maximum daily	average weekly	maximum weekly
Fox Creek	0.99	0.86	1.08	1.24
Swanson River	0.98	0.81	1.14	1.17
Chuitna River	0.96	0.85	1.03	1.22
Fish Creek	0.95	0.80	0.98	0.98
Alexander Creek	0.94	0.58	1.14	0.86
Jim Creek	0.93	0.79	1.10	1.12
Deep Creek	0.92	0.97	1.08	1.41
Kroto (Deshka)	0.92	0.66	1.01	0.97
Chijuk Creek	0.89	0.64	0.96	0.88
Bishop Creek	0.88	0.75	1.04	1.03
Cottonwood Creek	0.88	0.72	0.92	0.96
Anchor River	0.85	0.79	0.97	1.15
Theodore River	0.85	0.69	0.92	0.96
Meadow Creek	0.84	0.77	0.92	1.18
Ninilchik River	0.83	0.90	0.98	1.25
Trapper Creek	0.81	0.60	0.87	0.82
Crooked Creek	0.79	0.62	0.90	0.97
Stariski Creek	0.78	0.69	0.95	1.06
Moose River	0.73	0.40	0.87	0.69
Troublesome Creek	0.72	0.56	0.75	0.71
McNeil River	0.71	0.49	1.02	0.70
Beaver Creek	0.71	0.39	0.83	0.66
Soldotna Creek	0.71	0.50	0.79	0.70
Moose Creek (Talkeetna)	0.69	0.49	0.76	0.68
Nikolai Creek	0.69	0.63	0.78	0.81
Byers Creek	0.68	0.52	0.72	0.66
Deception Creek	0.67	0.48	0.72	0.72
NF Campbell Creek	0.65	0.49	0.69	0.71
Slikok Creek	0.64	0.47	0.67	0.68
Little Willow Creek	0.63	0.48	0.66	0.68
Funny River	0.62	0.45	0.69	0.69
Cache Creek	0.61	0.53	0.65	0.66
English Bay River	0.61	0.47	0.74	0.68
Willow Creek	0.61	0.58	0.64	0.69
Chester Creek	0.60	0.55	0.66	0.72
Hidden Creek	0.60	0.59	0.61	0.65
Shantatalik Creek	0.59	0.44	0.67	0.68
Chenik Creek	0.57	0.23	0.89	0.38

Montana Creek	0.57	0.52	0.60	0.64
Wasilla Creek	0.57	0.46	0.60	0.61
Ship Creek	0.56	0.48	0.58	0.68
Rabbit Creek	0.51	0.45	0.52	0.54
Moose Creek (Palmer)	0.50	0.50	0.54	0.63
Resurrection Creek	0.49	0.36	0.51	0.47
East Fork Chulitna River	0.47	0.43	0.49	0.50
Seldovia River	0.46	0.40	0.51	0.47
Quartz Creek	0.37	0.30	0.41	0.38
Silver Salmon Creek	0.34	0.35	0.43	0.47

Model Results

For all four water temperature response variables: daily average sensitivity, average July water temperature, MWAT and MWMT, the 'geomorphic and area' model was the best fit. (Silver Salmon Creek and Jim Creek were removed from model datasets because of missing data that likely resulted in summary statistics which under and over represent temperatures, respectively.) From the model vs. observed plots (Figure 2), we can see that our models all overestimate sites with cold water temperature and underestimates sites with warm water temperature. Since this is a consistent pattern it suggests that we are missing the same predictor variable for all these models. R-square values (0.52-0.62) also suggest we are missing predictors.

Sensitivity

Based on the model output (Table 9), larger watershed size and lower watershed slope result in greater sensitivity. Specifically:

- Increasing watershed size by 100,000 acres increases sensitivity by 0.07
- Increasing watershed slope by 1% decreases sensitivity by 0.02
- Average elevation and percent of south aspect had little to no effect on sensitivity (i.e. 95% confidence interval overlaps zero)

Average July Water Temperature

Based on the model output, larger watershed size, lower watershed slope and lower average watershed elevation result in higher average July stream temperatures. Specifically:

- Increasing watershed size by 100,000 acres increases water temperature by 0.85^{o}C
- Increasing watershed slope by 1% decreases water temperature by 0.244^{o}C
- Increasing average elevation by 100 meters decreases water temperature by 0.296^{o}C
- Average July air temperature and percent of south aspect had little to no effect on average July water temperature (i.e. 95% confidence interval overlaps zero)

MWAT

Based on the model output, larger watershed size and lower average watershed elevation result in higher maximum weekly average stream temperatures. Specifically:

- Increasing watershed size by 100,000 acres increases water temperature by 0.9^{o}C
- Increasing average elevation by 100 meters decreases water temperature by 0.532^{o}C

- MWAT (air), percent slope and percent of south aspect had little to no effect on MWAT (water) (i.e. 95% confidence interval overlaps zero)

MWMT

Based on the model output, larger watershed size and lower watershed slope result in higher maximum weekly maximum stream temperatures. Specifically:

- Increasing watershed size by 100,000 acres increases water temperature by 1.0^{o}C
- Increasing watershed slope by 1% decreases water temperature by 0.31^{o}C
- MWMT (air), average elevation and percent of facing aspect had little to no effect on MWMT (water) (i.e. 95% confidence interval overlaps zero)

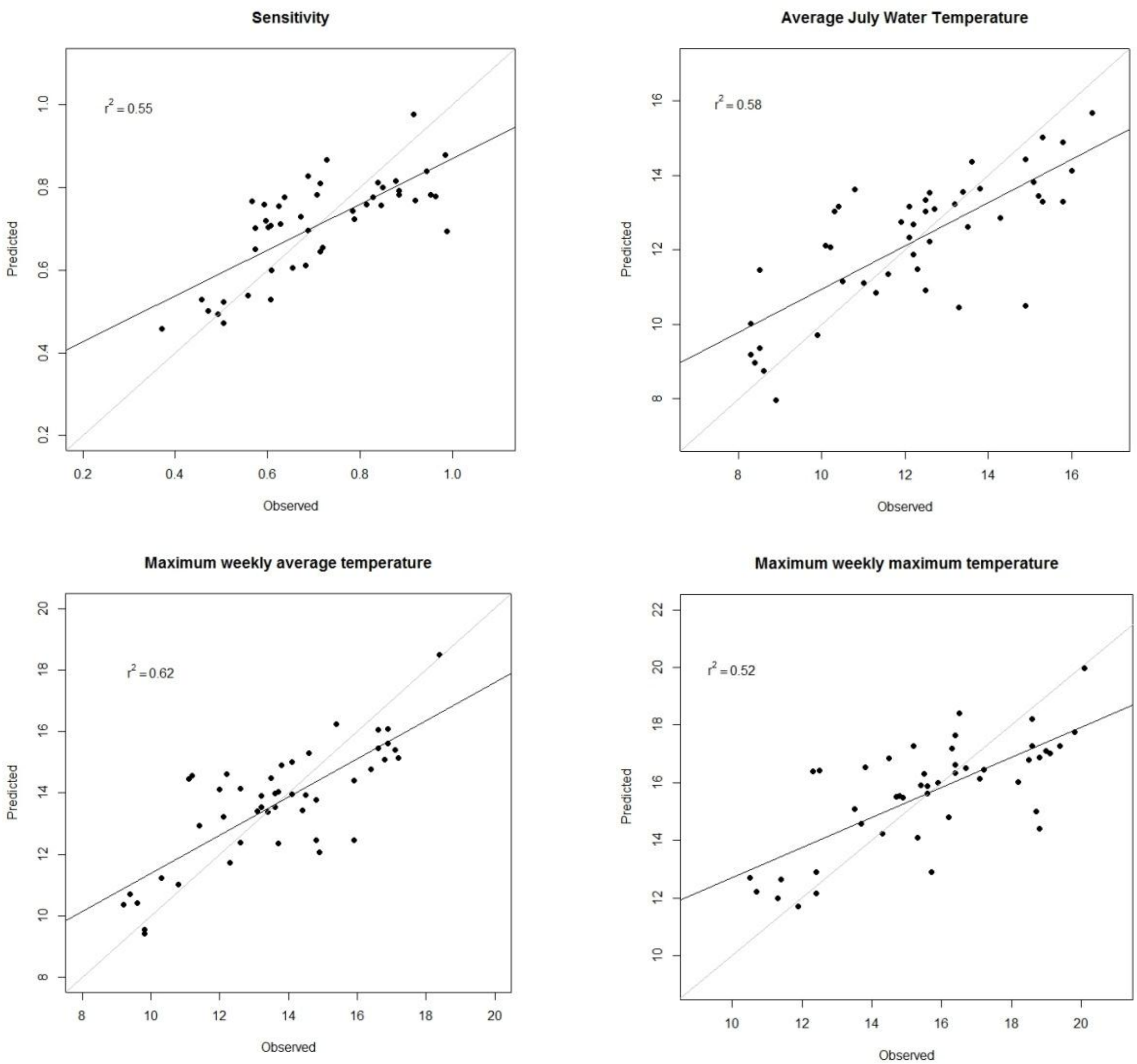


Figure 2. Observed data plotted against predicted values based on the best fit model for the four response variables.

Table 9. Parameter estimates and summary statistics of final stream temperature models. Predictors with a p-value <0.05 are in bold for each model.

Response	Predictor	Estimate	95% CI	p	Adjusted r-square
Sensitivity	(Intercept)	0.75960000	0.12222560	<0.00001	0.5098
	acres	0.00000069	0.00000047	0.00719	
	south aspect	0.00161100	0.00375536	0.40540	
	slope	-0.02134000	0.01450988	0.00625	
	average elevation	-0.00014400	0.00019465	0.15470	
Average July	(Intercept)	6.26800000	6.91292000	0.08320	0.5266
	average July Air	0.61920000	0.61504800	0.05540	
	acres	0.00000849	0.00000710	0.02420	
	south aspect	0.02495000	0.05456640	0.37540	
	slope	-0.24350000	0.21148400	0.02950	
	average elevation	-0.00295800	0.00285376	0.04880	
MWAT	(Intercept)	11.130000	3.88472000	<0.00001	0.5719
	MWAT Air	0.243700	0.24970400	0.06295	
	acres	0.000009	0.00000588	0.01277	
	south aspect	0.011360	0.05419400	0.68350	
	slope	-0.149400	0.20638800	0.16376	
	average elevation	-0.005321	0.00293216	0.00099	
MWMT	(Intercept)	15.200000	4.65696000	<0.00001	0.4626
	MWMT Air	0.069140	0.19094320	0.48200	
	acres	0.000010	0.00000784	0.02500	
	south aspect	0.016840	0.06485640	0.61360	
	slope	-0.309300	0.25538800	0.02250	
	average elevation	-0.002864	0.00349272	0.11590	

Climate Change Implications

We plotted average July water temperature, as a measure of current thermal heterogeneity, and sensitivity (Figure 3). We then classified streams as "cold" and "warm", based on the 13°C threshold for average July temperature, and as "high sensitivity" and "low sensitivity", based on a threshold sensitivity value of 0.75 (Table 10). Using SNAP's decadal July air temperature predictions for each monitoring site, air temperature will increase by 2.6 - 2.9°C by 2099 at all sites. For "high sensitivity" streams, this will result in a 2.0 – 2.9°C average July water temperature increase. For "low sensitivity" streams, the increase will be less than 2.0°C.

The 13 streams categorized as "warm, high sensitivity" will be the most vulnerable to climate change impacts and may reach consistently stressful temperatures to salmon over the next decades. The five streams in the "cold, high sensitivity" category will likely exceed the 13°C threshold in the future more quickly than the "cold, low sensitivity" streams. More than 50% of the streams fall in this "cold, low sensitivity" category and should provide high quality, cold-water habitat for Cook Inlet salmon for at least the next century.

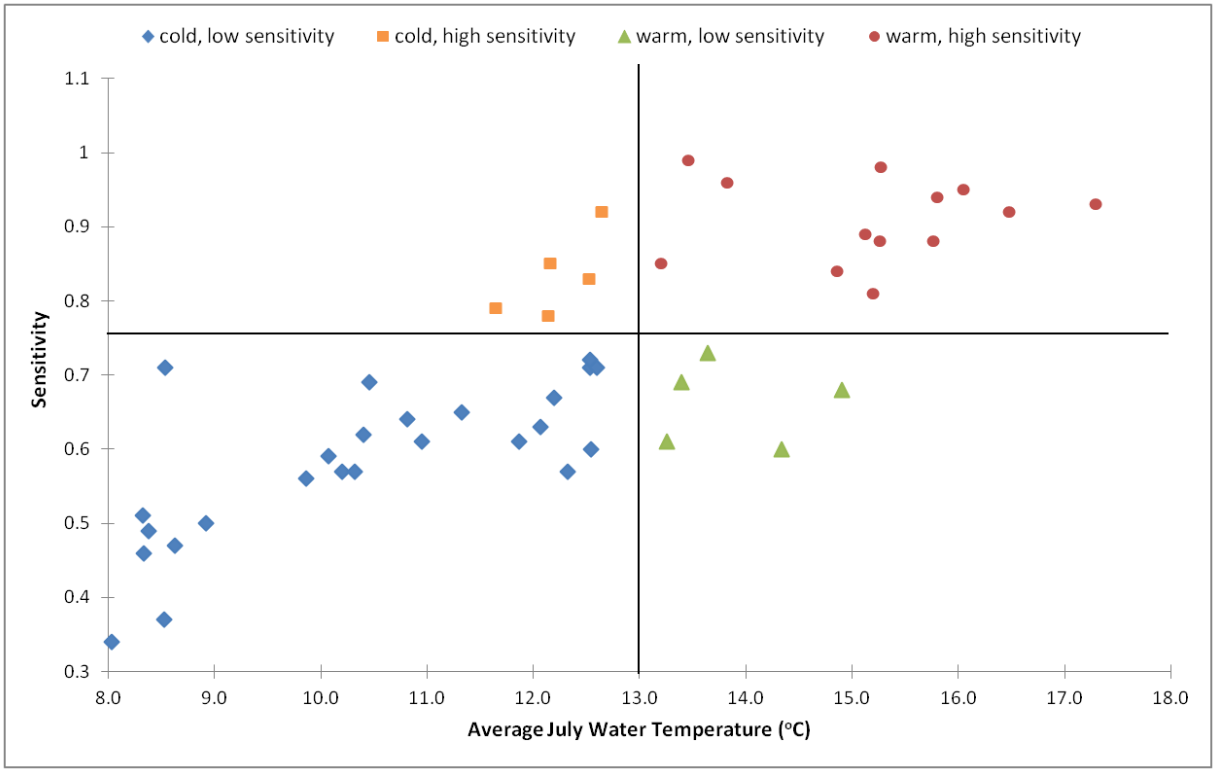


Figure 3. Framework for assessing climate change vulnerability based on threshold values of 13°C for average July water temperature and 0.75 for sensitivity.

Table 10. Streams categorized by their current temperature profile and sensitivity to air temperature.

Cold, low sensitivity	Cold, high sensitivity	Warm, low sensitivity	Warm, high sensitivity
Silver Salmon Creek	Crooked Creek	English Bay River	Theodore River
Rabbit Creek	Stariski Creek	Moose Creek (Talkeetna)	Fox Creek
Seldovia River	Anchor River	Moose River	Chuitna River
Resurrection Creek	Ninilchik River	Hidden Creek	Meadow Creek
Quartz Creek	Deep Creek	Byers Creek	Chijuk Creek
McNeil River			Trapper Creek
East Fork Chulitna River			Cottonwood Creek
Moose Creek (Palmer)			Swanson River
Ship Creek			Bishop Creek
Shantatalik Creek			Alexander Creek
Chenik Creek			Fish Creek
Wasilla Creek			Kroto (Deshka) Creek
Funny River			Jim Creek
Nikolai Creek			
Slikok Creek			
Cache Creek			
NF Campbell Creek			
Willow Creek			
Little Willow Creek			
Deception Creek			
Montana Creek			
Soldotna Creek			
Troublesome Creek			
Chester Creek			
Beaver Creek			

Discussion

The Stream Temperature Monitoring Network has proven to be a successful collaborative regional monitoring effort to collect comparable stream temperature data across the Cook Inlet watershed. Consistently coordinated by Cook Inletkeeper, with fifteen different partner entities involved, the Temperature Network is a great example of a partnership of federal and state agencies, tribal entities and community-based organizations and volunteers accomplishing more together, and more effectively, than any group could working alone. This regional network can be a template for coordination, data management and analysis to facilitate expanded water temperature monitoring throughout Alaska.

Project Challenges

Project challenges over the five year study period included: 1) coordination of partner schedules and turnover; 2) loss of data from high flow events; 3) management of 6.8 million data points; and 4) lack of available high resolution GIS layers (land cover, NHD+, stream flow) for data analysis.

1) This regional network would not have been possible without the involvement of many partners spread across the watershed. Our window to deploy water loggers in the spring, after snow melt when water levels come down to safe levels but before stream temperatures start to warm, required a coordinated effort every year. Due to river levels, staff turnover and field schedules, it was challenging to get all 48 sites established by June each year. A training or annual review session with all field personnel in late winter might improve consistency among partners and result in earlier deployment dates.

2) One of the biggest challenges of this project was fine tuning the method of securing data loggers in-stream at different sites. The majority of water loggers that we lost were due to soft sediment bottoms and highly mobile stream beds. By switching from a rebar deployment method to a bank-secured cable we resolved this problem at specific sites. However, the majority of datasets we threw out because of erroneous data were the result of bank-secured cables getting caught up on the bank during high flows. Regular maintenance visits help reduce the loss of data although this is not always practical at more remote sites.

Our 90% overall retrieval rate is an impressive achievement but September floods in 2012 were hard on our in-stream equipment. We lost 17 water loggers. Although this is an unfortunate loss of data and equipment, it is not a surprising outcome for 50-100 year flood events, and it serves as a reality check on the types of deployment methods required to establish year-round, long term monitoring sites in the future. Recent work in Rocky Mountain systems has focused on deployment methods using epoxy.[16] For streams with larger boulders or bridge abutments, this might be a good solution.

3) One outcome of our decision to collect both water and air data at 15-minute intervals was the sheer quantity of data we collected. Data management required a significant amount of the project time and budget. Initially, we intended to store and analyze data using a database format; however, we found this to be cumbersome for our analysis needs. By the second year

we moved into spreadsheets with custom built macros to generate summary statistics. By the end of the project, we were working in R – a free software environment for statistical computing and graphics - that greatly improved the ease of data manipulation for analysis. We also spent significant project time uploading data into EPA's STORET (national water quality database); however, data requests are presently fulfilled using spreadsheets.

4) Our most significant data limitation was the lack of high resolution GIS layers from which to derive watershed characteristics. In Alaska, we lack an accurate hydrography or stream network GIS layer. We used a 60 meter DEM because it provided complete coverage of our study area but it did not match well with stream lines in the National Hydrography Dataset (NHD). As a consequence our channel characteristics are limited and likely inaccurate. Additionally, the lack of a connected stream network layer made flow statistics and drainage density difficult to calculate, and limited our ability to evaluate lake connectivity. We used the percent open water data from the land cover dataset as a measure of lake size but we don't feel we have captured lake influence well with these data. Recent funding through the Landscape Conservation Cooperatives will facilitate improvement of the NHD layer in Alaska.

Thermal Heterogeneity

Summer water temperatures varied greatly across non-glacial salmon streams in the Cook Inlet basin, with the highest temperatures recorded in streams draining lakes or lowland areas west of the Susitna River. This thermal heterogeneity may expand the temporal availability of suitable salmon spawning conditions across the landscape, which in turn may provide greater options in foraging locations for wide-ranging consumers (i.e. bears, eagles) that rely on the seasonal pulses of salmon resources for maintaining their fitness.[17,18] However, the vast majority of streams consistently exceeded Alaska's water temperature criteria set for the protection of fish during this 5-year study period. And although we captured a warmer summer in 2009, this period was cooler than we experienced in 2004-05 and now in 2013. So these data may be underestimating the frequency of thermal stress for spawning salmon in specific streams.

Watershed Characteristics

Based on our modeling efforts, the watershed characteristics that drive stream temperature profiles include watershed size, watershed slope and average watershed elevation. For example, larger, lowland systems like Kroto (Deskhka) Creek, Alexander Creek and Swanson River are significantly warmer than small, steep systems like Seldovia River, Resurrection Creek and Rabbit Creek. Similar results were found in streams in Southwestern Alaska.[17]

Our model results also suggest we are missing one or more significant predictor variables. Based on other studies, we anticipate that these variables are related to stream flow,[14] groundwater influence[12] or lake size.[17] We attempted to generate a summer discharge metric using watershed area and precipitation. We used SNAP precipitation values at each site. In the future we will improve this by integrating the precipitation values across the entire watershed area. But if watershed area has a strong influence over stream flow (i.e. larger drainage area means greater discharge) then we would expect larger systems to be cooler as they have more water to warm up. Instead, larger watersheds have warmer temperatures suggesting flow path length may be important in a larger drainage as it allows more time for warming of the water. Additionally, larger drainages typically have larger stream widths and more open canopies allowing more direct solar radiation to hit the water surface. We will seek out new datasets and GIS layers to help us improve our model predictions as funding allows.

Climate Change Impacts

In 2001, USGS with limited stream temperature data and predictive models surmised that non-glacial sites that drain Cook Inlet lowlands would see a water temperature change of 3^{o}C or more with a doubling of carbon emissions.[19] Our results using the A1B scenario support this finding with the 3^{o}C increase to happen by 2099; however, it is important to note that current trends indicate that the A1B scenario may be too optimistic in terms of greenhouse gas emissions and global climate change.

As has been found in the Pacific Northwest, future climate projections of stream temperature change are small in comparison to the range of summer stream temperatures that exist across the region today.[12] Therefore it is important to understand current temperature profiles as well as thermal sensitivities when assessing climate change impacts to regional stream temperatures. Based on our assessment of current stream temperature profiles and sensitivities in 48 Cook Inlet streams, average July water temperature may have sub-lethal effects on salmon including poor egg and fry incubation survival, low juvenile growth rates, and pre-spawning mortality in 27% of the streams by 2099. Thermal impacts will be more moderate in 23% of the streams, with no significant impacts to salmon health for 50% of the streams.

New Temperature Networks

Across Alaska's freshwater systems the influence of rising temperatures may be quite variable on salmon populations. In southwestern Alaska, growth rates of juvenile sockeye have been enhanced due to warming temperatures.[20] But in the glacially-fed Skilak Lake in the Kenai River system, researchers found that persistent levels of higher turbidity due to increased glacier melting was affecting the interaction between copepods and juvenile salmon which was influencing salmon production.[21] And in July 2013, warm stream temperatures and associated low dissolved oxygen levels were cited as the cause of a Chinook salmon die off near Petersburg in Southeast Alaska.[22] Clearly, more research into the implications of rising temperatures on salmon stocks - and improved adaptive management strategies to address thermal change – are vital to improve forecasting and in-season management to sustain healthy salmon returns in the face of warming temperatures.

As salmon populations continue to decline in the southern part of their range, numerous synthesis papers have come out in an attempt to determine the maximum temperature limits for Pacific salmon.[23,24] More recent work highlights the complexity of ensuring salmonid survival due to the need to consider climate change, the evolution of historic population structure, spatio-temporal variability, and the need for rigorous monitoring programs.[1] We hope that our model results can inform the development of temperature monitoring networks in other basins and ensure gradients of important watershed characteristics are captured in the sampling design.

Temperature Working Group

Since the inception of the Cook Inlet Monitoring Network in 2008, interest in water temperature has increased rapidly and new data collection efforts are underway across Alaska. This momentum provides an opportunity for the state of Alaska to establish an interagency and stakeholder working group to assess current temperature issues. Alaska's water temperature criteria have not been revised since EPA's new guidance came out in 2003;[25] however, Alaska's criteria and threshold values are presently more protective for wild salmon than other states. Yet, exceedances of these water temperature criteria are occurring with no on-the-ground human impact at many sites and over many years. If these criteria are simply assumed unattainable in certain systems and we take no further action, we run the risk of ignoring a key indicator of the health of wild salmon and their habitat. A working group could provide ADEC with an evaluation of the existing water temperature criteria and explore the following issues:

1. Is an instantaneous water temperature criterion useful for dealing with nonpoint sources of thermal impairment?
2. Are the threshold values physiologically and behaviorally relevant to Alaska's salmon populations? Would a rolling 7-day average or 7-day maximum average be more biologically relevant?
    - are these thresholds values relevant for other fish species?
    - how can we account for regional differences?
    - are salmon populations able to adapt over time to local conditions?
3. How do stream temperatures affect other aquatic species like macro-invertebrates at different life stages? How might this affect food availability for fish?
4. How do we implement stream temperature monitoring networks in other areas of the state, especially more remote areas?

Next Steps

Cook Inletkeeper will continue to work with the analysis team to fine tune models and discussion points. We expect to submit pieces of this work to peer-reviewed journals by January 2014. We have deployed temperature loggers in 15 of the 48 streams in 2013 in an effort to continue these long-term datasets.

CITATIONS

[1] Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51:1389-1406.

[2] Alaska Department of Environmental Conservation. 2011. 18 AAC 70, Water Quality Standards. http://dec.alaska.gov/water/wqsar/wqs/pdfs/18_AAC_70_as_Amended_Through_May_26_2011.pdf

[3] Richter A. and S.A. Kolmes. 2005. Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science, 13:23-49.

[4] Mauger, S. 2005. Lower Kenai Peninsula's Salmon Streams: Annual Water Quality Assessment. Homer Soil and Water Conservation District and Cook Inletkeeper, Homer, Alaska. 62 p.

[5] Davis, J.C., and G.A. Davis. 2006. Montana Creek Ecological and Water Quality Assessment. Aquatic Restoration and Research Institute. Final Report for the Alaska Department of Environmental Conservation, Talkeetna, Alaska.

[6] Davis, J.C., and G.A. Davis. 2006a. Cottonwood Creek Ecosystem Assessment. Aquatic Restoration and Research Institute. Final Report for the Alaska Department of Environmental Conservation, ACWA 06-02. Talkeetna, Alaska.

[7] Keefer, M.L., C. A. Peery, and M. J. Heinrich. 2008. Temperature-mediated en route migration mortality and travel rates of endangered Snake River sockeye salmon. Ecology of Freshwater Fish 17: 136-145.

[8] Isaak, D.J., Wollrab, D., Horan, D.L., Chandler, G.L., 2011. Climate Change Effects on Stream and River Temperatures Across the Northwest US from 1980–2009 and Implications for Salmonids Fishes. Climatic Change. DOI 10.1007/s10584-011-0326-z.

[9] Poole, G.C. and C.H. Berman. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management, 27: 787-802.

[10] Mauger, S. 2008. Water temperature data logger protocol for Cook Inlet salmon streams. Cook Inletkeeper, Homer, Alaska. 10 p.

[11] Mohseni, O., Stefan, H.G., 1999. Stream temperature air temperature relationship: a physical interpretation. J. Hydrol. 218: 128–141.

[12] Mayer, T.D. 2012. Controls of summer stream temperature in the Pacific Northwest. J. Hydrol. 475: 323-335.

[13] Burnham, K.P. and D.R. Anderson. 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach. 2nd edition Springer-Verlag, New York.

[14] Isaak D.J., Luce C.H., Rieman B.E., Nagel D.E., Peterson E.E., Horan D.L., Parkes S., and G.L. Chandler. 2010. Effects of climate change and recent wildfires on stream temperature and thermal habitat for two salmonids in a mountain river network. Ecol Appl 20:1350–1371.

[15] Walsh, J.E., Chapman, W.L., Romanovsky, V., Christensen J.H. and M. Stendel. 2008. Global Climate Model Performance over Alaska and Greenland. Journal of Climate. Vol. 21, pp. 6156-6174.

[16] Isaak, D.J.; Horan, D.L.; and S.P. Wollrab. 2013. A Simple Protocol Using Underwater Epoxy to Install Annual Temperature Monitoring Sites in Rivers and Streams**.** Gen. Tech. Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 31 p.

[17] Lisi, P.J., Schindler, D.E., Betley, K.T., and G.R. Pess. 2013. Association between geomorphic attributes of watersheds, water temperature, and salmon spawn timing in Alaskan streams. Geomorphology 185:78-86.

[18] Schindler, D.E., Hilborn, R., Chasco, B., Boatright, C.P., Quinn, T.P., Rogers, L.A., and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465, 609–612.

[19] Kyle, R.E. and T.B. Brabets, 2001. Water temperature of streams in the Cook Inlet basin, Alaska, and implications of climate change. U.S. Geological Survey Water-Resources Investigation Report 01-4109.

[20] Schindler, D.E., Rogers, D.E., Scheuerell, M.D. and C.A. Abrey. 2005. Effects of changing climate on zooplankton and juvenile sockeye salmon. Ecology 86:198-209.

[21] Edmundson, J. A., T. M. Willette, J. M. Edmundson, D. C. Schmidt, S. R. Carlson, B. G. Bue and K. E. Tarbox. 2003. Sockeye salmon overescapement (Kenai River Component), *Exxon Valdez* Oil Spill Restoration Project Final Report Restoration Project 96258A-1), Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage, Alaska.

[22] Fleming, D. personal communication on July 29, 2013. See also:
http://www.adn.com/2013/07/27/2994028/warm-weather-blamed-for-king-salmon.html

[23] U.S. Environmental Protection Agency. 2001. EPA Issue Paper 5: Summary of Technical Literature examining the Physiological Effects of Temperature on Salmonids, Prepared as Part of EPA Region 10 Temperature Water Quality Criteria Guidance Development Project. EPA-910-D-01-005.

[24] Hicks, M. 2000. Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards, Temperature Criteria, Draft Discussion Paper and Literature Summary. Revised 2002. Washington State Department of Ecology, Olympia, WA. 197 pp.

[25] U.S. Environmental Protection Agency. 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA 910-B-03-002. Region 10 Office of Water, Seattle, WA.