STREAM TEMPERATURE MONITORING NETWORK FOR MAT-SU SALMON STREAMS

2008 - 2012

SYNTHESIS REPORT

By

COOK INLETKEEPER

This document serves as a final project report for:

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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 Mat-Su 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 21 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: 9.1 – 24.5^{o}C, with average summer temperatures across all five years ranging from 5.0 – 16.2^{o}C. Average temperatures across all sites were 5.2 – 17.3^{o}C in July and 5.1 – 15.3^{o}C in August. 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 20 sites, 15^{o}C at 18 sites, and 20^{o}C at 11 sites. We recorded frequent exceedances (> 30 days/year) of the 13^{o}C criteria at 13 sites (62%) and of the 15^{o}C criteria at nine sites (43%). 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 43% 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 10% of the streams, with no significant impacts to salmon health for 47% of the streams.

The Stream Temperature Monitoring Network has proven to be a successful collaborative regional monitoring effort coordinated by Cook Inletkeeper, with six different Mat-Su partners involved. 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 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^{o}C) on more than 50 days in the summer. In 2005, exceedances happened on more than 80 days with maximum temperatures above 20^{o}C.[4] Monitoring in Mat-Su 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 Mat-Su salmon streams in 2008. The Mat-Su basin encompasses 24,000 square miles and contains high quality freshwater and marine salmon habitat. 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 Mat-Su 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 Mat-Su 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 Mat-Su sampling design includes 21 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

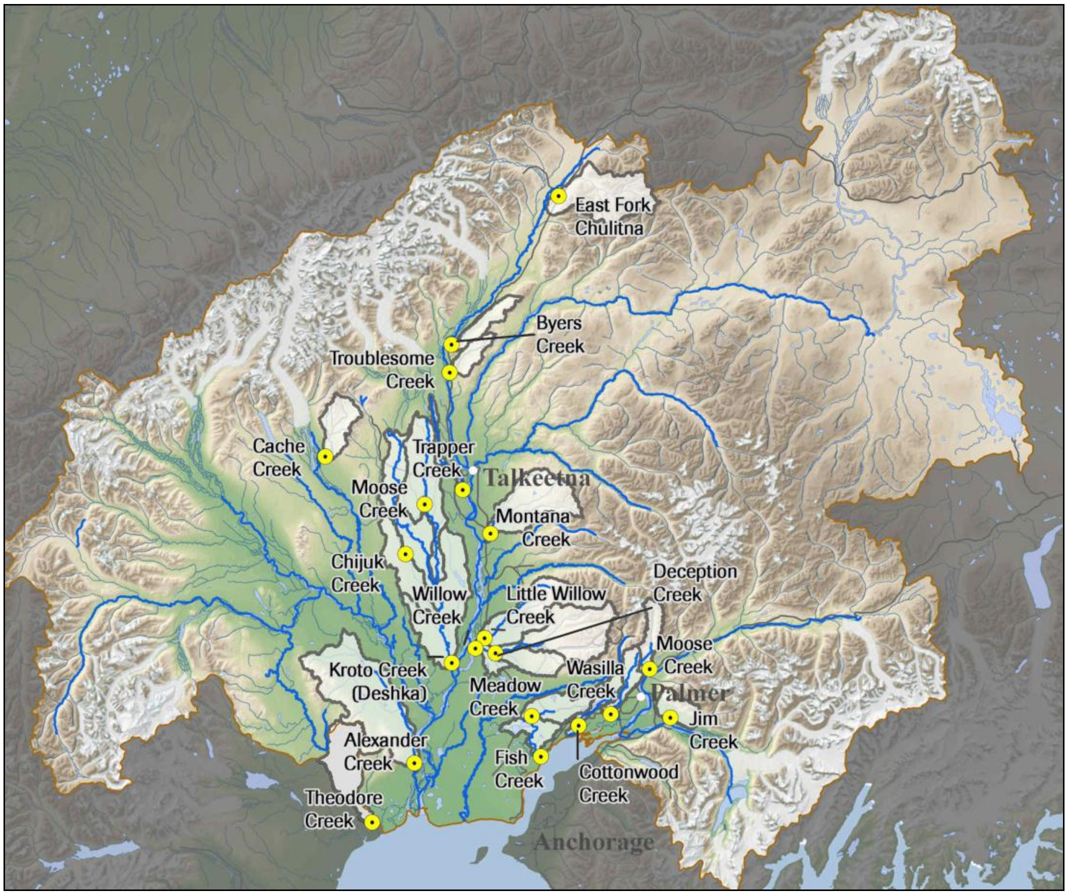
A detailed description of methods, equipment used, and how we deployed data loggers in the field can be found in *Water temperature data logger protocol for Cook Inlet salmon streams*.[10] Prior to deployment, we checked data logger accuracy against a National Institute of Science and Technology (NIST)-certified 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. Mat-Su Stream Temperature Monitoring Network data logger locations.

LOCATION	DESCRIPTION	Latitude	Longitude
Alexander Creek	approx. 2 miles upstream from Susitna River	61.44000	-150.59600
Bodenburg Creek	Downstream of mile 10 of Old Glenn Highway	61.51722	-149.04233
Byers Creek	upstream from Park's Highway	62.71158	-150.20407
Cache Creek	1/2 mile downstream from east end of landing	62.38900	-151.08100
Chijuk Creek	Oilwell Road crossing	62.07963	-150.58314
Cottonwood Creek	upstream from Surrey Road	61.52500	-149.52700
Deception Creek	upstream from Willow-Fishook Road	61.76200	-150.03400
East Fork Chulitna River	downstream from Park's Highway	63.14500	-149.42100
Fish Creek	below Knik-Goose Bay Road	61.43800	-149.78100
Jim Creek	1 mile upstream of Jim Creek Flats	61.52900	-148.93300
Kroto (Deshka) Creek	1.0 miles upstream from Susitna River	61.74000	-150.32000
Little Willow Creek	0.25 miles downstream from Parks Highway	61.81000	-150.09900
Meadow Creek	Beaver Lakes Road Crossing	61.56300	-149.82400
Montana Creek	end of Access Road South of Helena	62.12800	-150.01900
Moose Creek (Palmer)	150 yards downstream of Glenn Hwy bridge	61.68200	-149.04300
Moose Creek (Talkeetna)	Oilwell Road Crossing	62.22900	-150.44100
Theodore River	500 yards upstream from Beluga Hwy bridge	61.26600	-150.88400
Trapper Creek	Bradley Road Crossing	62.26600	-150.18400
Troublesome Creek	downstream from Park's Highway	62.62700	-150.22700
Wasilla Creek	Nelson Road access	61.55300	-149.31400
Willow Creek	0.25 miles upstream from Susitna River	61.78000	-150.16100



Map 1. Mat-Su Stream Temperature Monitoring Network data logger locations with contributing watershed areas.

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

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°C
> spawning areas = 13°C
> migration routes = 15°C
> rearing areas = 15°C
> and may not exceed 20°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°C) and upper (>20°C) ends of the range; however, this study focused on temperatures recorded from June – September, when the vast majority of values fell between 4°C and 20°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 stream temperature profiles. These models provide predictive power to estimate stream temperature responses (average daily sensitivity, average July, MWAT, MWMT) in other Mat-Su 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 Mat-Su 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	
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 Mat-Su 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 21 sites each year. We had a 90.5% retrieval rate for water loggers and an 89.5% retrieval rate for air loggers. We lost two water loggers in 2008, one in 2010, and during high flow events in September 2012, we lost water loggers at seven sites. Jim Creek is the only site where we lost two years of water temperature data during the 5-year period (Table 5); however, missing data are from 2008 and 2012 – the two coolest years. Summary statistics for this site likely over represent temperatures.

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	√	√	√	√		√	√	√	√	√
Bodenburg Creek		√	√	√	√		√	√		√
Byers Creek	√	√	√	√	√	√	√	√	√	√
Cache Creek	√	√		√	√	√	√	√	√	√
Chijuk Creek	√	√	√	√	√	√	√	√	√	√
Cottonwood Creek	√	√	√	√	√	√	√	√		√
Deception Creek	√	√	√	√		√	√	√	√	
East Fork Chulitna	√	√	√	√	√	√	√	√	√	√
Fish Creek	√	√	√	√	√	√	√		√	√
Jim Creek		√	√	√		√	√	√	√	√
Kroto (Deshka) Creek	√	√	√	√	√	√	√	√	√	√
Little Willow Creek	√	√	√	√	√	√	√	√	√	√
Meadow Creek	√	√	√	√		√			√	√
Montana Creek	√	√	√	√		√	√		√	√
Moose Creek (Palmer)	√	√	√	√		√	√	√	√	√
Moose Creek (Talkeetna)	√	√	√	√	√	√	√	√	√	√
Theodore Creek	√	√	√	√	√	√	√	√	√	√
Trapper Creek	√	√	√	√	√	√	√		√	√
Troublesome Creek	√	√	√	√	√	√	√	√	√	√
Wasilla Creek	√	√	√	√	√	√	√	√	√	√
Willow Creek	√	√	√	√		√	√		√	

Range of Variability

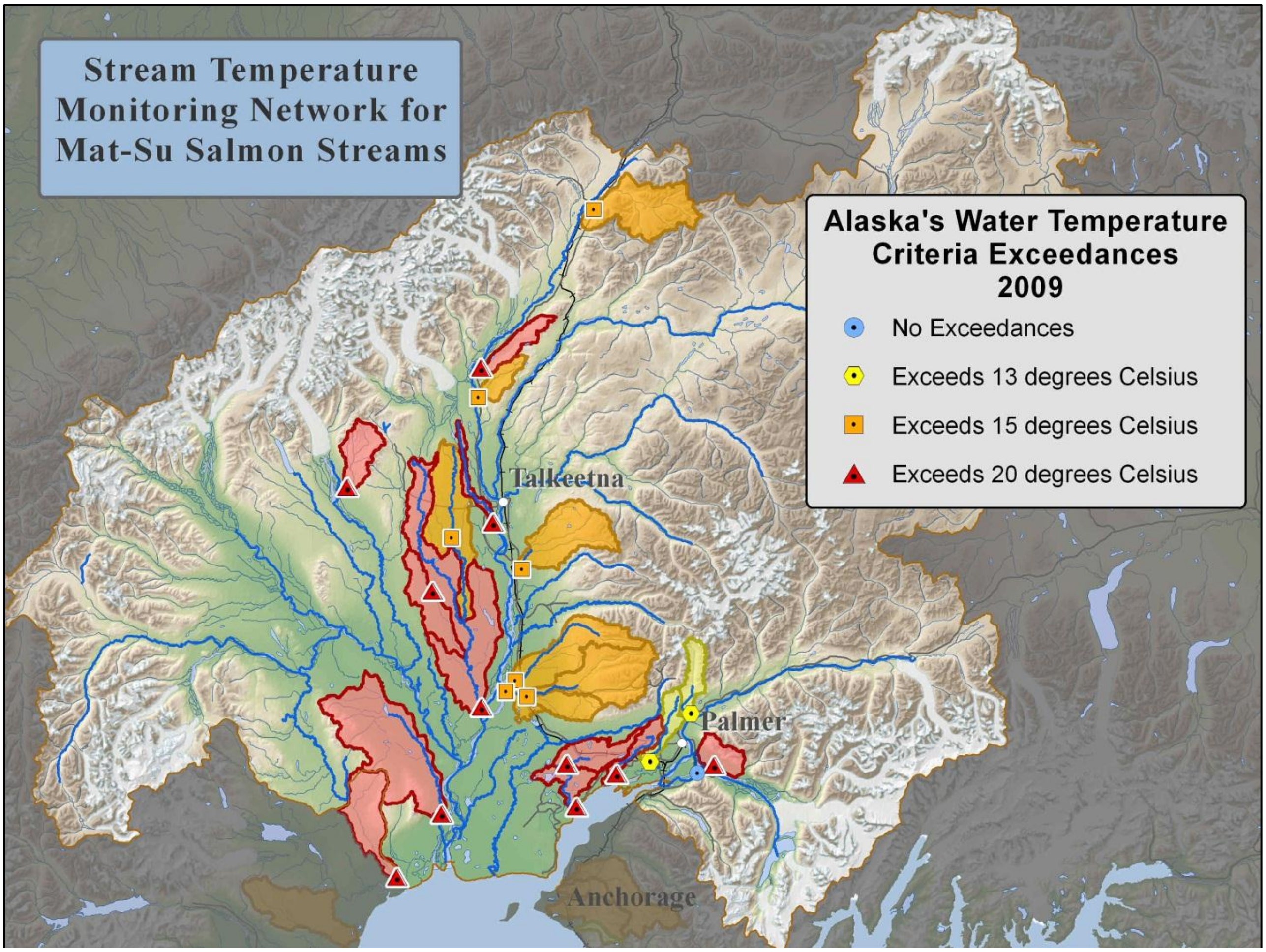
Maximum stream temperatures, which predominantly occurred in 2009, varied broadly among sites: 9.1 – 24.5^{o}C, with average summer (June, July and August) temperatures across all five years ranging from 5.0 – 16.2^{o}C (Table 6). Average temperatures across all sites were 5.2 – 17.3^{o}C in July and 5.1 – 15.3^{o}C in August. The maximum daily fluctuation recorded was greatest at Alexander Creek (10.2^{o}C) and smallest at Bodenburg Creek (4.0^{o}C).

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

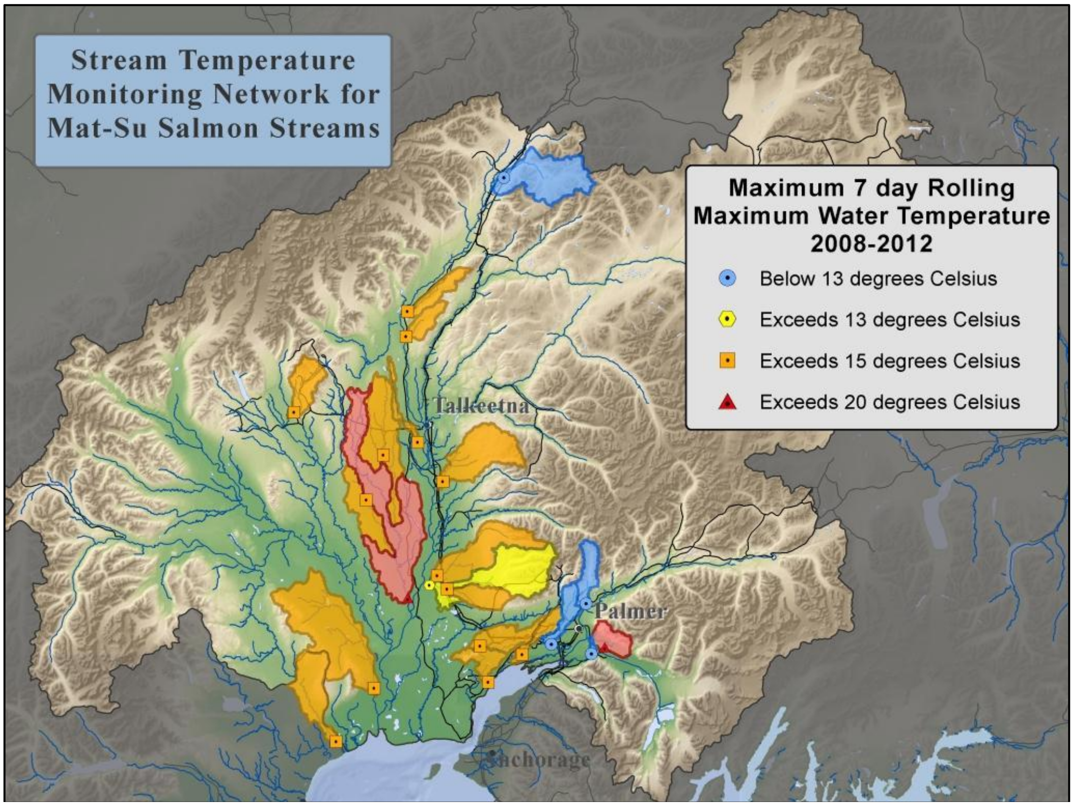
Stream Name	Average summer (JJA) temperature	June average temperature	July average temperature	August average temperature	September average temperature	June degree days	July degree days	August degree days	September degree days	Maximum 7-day rolling average temperature	Maximum 7-day rolling maximum temperature	Maximum Daily Difference
Alexander Creek			15.8	14.0	9.8		489	434	288	16.6	19.8	10.2
Bodenburg Creek	5.0	5.1	5.2	5.1	4.5	152	160	157	136	5.5	6.6	4.0
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
Chijuk Creek	14.1	13.9	15.1	13.1	9.0	416	469	401	251	16.9	19.4	8.1
Cottonwood Creek	14.6	14.1	15.3	14.1	9.8	424	473	437	292	16.6	18.6	6.6
Deception Creek	11.1	10.4	12.2	10.7	7.2	313	378	332	216	13.5	15.5	9.4
East Fork Chulitna River	7.8	6.7	8.6	7.8	5.1	200	267	242	153	9.8	12.4	7.1
Fish Creek	15.1	14.9	16.0	14.4	9.7	446	498	438	291	17.1	18.8	6.4
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
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
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

Temperature Exceedances

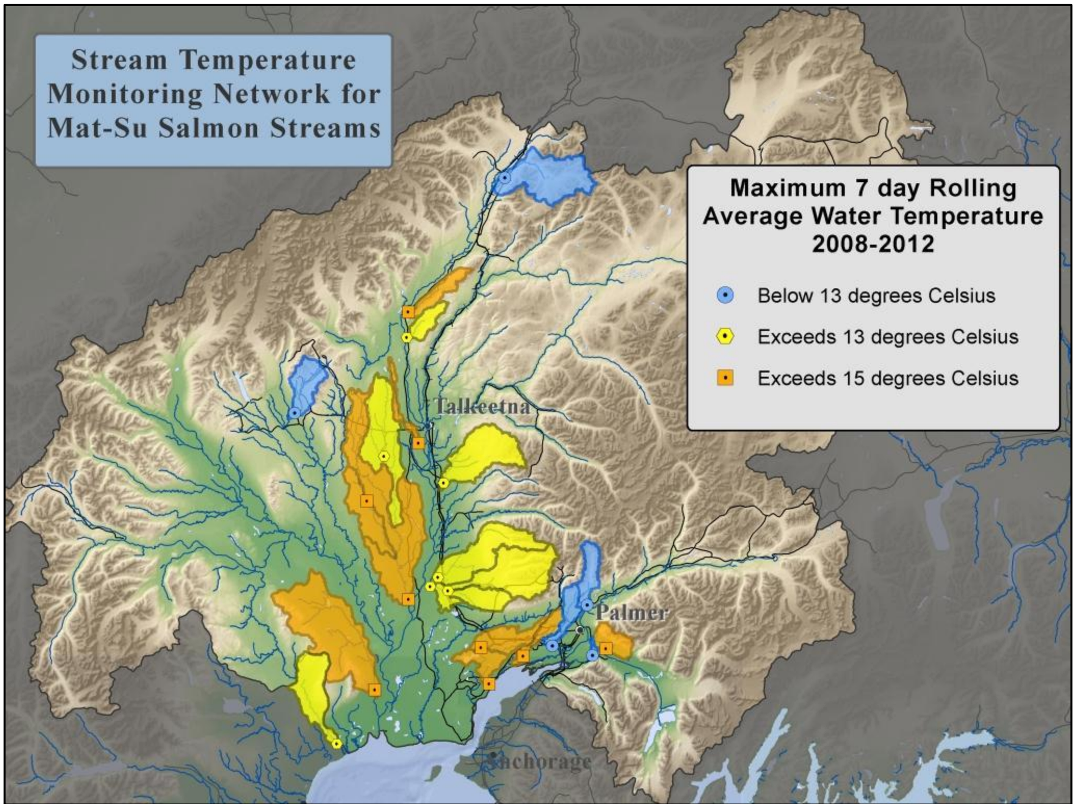
With the exception of Bodenburg Creek, all streams exceeded Alaska's water temperature criteria set for the protection of fish especially in 2009, the warmest year, when stream temperatures exceeded the criteria of 13°C at 20 sites, 15°C at 18 sites, and 20°C at 11 sites (Map 2, Table 7). We recorded frequent exceedances (> 30 days/year) of the 13°C criteria at 13 sites (62%) and of the 15°C criteria at nine sites (43%). Sixteen sites (76%) had maximum 7-day rolling maximums (MWMT) above 15°C (Map 3). Nine sites (43%) 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.



Map 2. Summer temperatures exceeded Alaska's Water Temperature Criteria of 13°C at 20 sites, 15°C at 18 sites, and 20°C at 11 sites in 2009. Temperature logger sites and their contributing watersheds are color-coded by the highest exceedances value.



Map 3. The five year average of the maximum 7-day rolling maximums (MWMT) or the maximum recorded value of daily maximum water temperature when averaged over 7 consecutive days.



Map 4. The five year average of the maximum 7-day rolling averages (MWAT) or the maximum recorded value of daily average water temperature when averaged over 7 consecutive days.

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
Bodenburg Creek	0	0	0	9.06
Byers Creek	74	44	3	22.80
Cache Creek	23	10	1	20.65
Chijuk Creek	62	38	5	24.26
Cottonwood Creek	77	52	2	22.01
Deception Creek	30	10	0	18.79
East Fork Chulitna River	6	1	0	15.46
Fish Creek	67	49	4	22.73
Jim Creek	76	61	13	23.87
Kroto (Deshka) Creek	54	43	8	24.53
Little Willow Creek	27	8	0	19.51
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
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

Air Temperature Patterns

Across the five years, average July air temperature measured at each site ranged from 11.8°C (EF Chulitna River) to 14.5°C (Willow Creek) with 66.7% of the sites between 12.0 - 13.9°C. Across the region, air temperature was coldest in 2008 and warmest in 2009 (Figure 1).

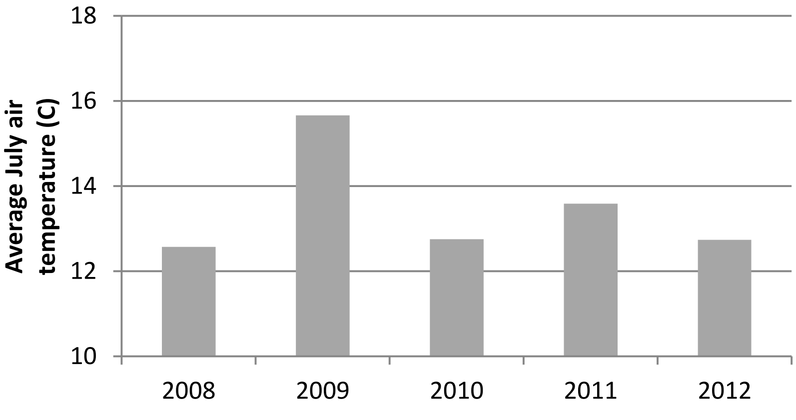


Figure 1. Average July air temperature across the region by year.

Sensitivity

Sensitivity is the slope (or coefficient from the regression equation) of the air and water relationship. The higher the coefficient the higher the stream's sensitivity to air temperature increases. For instance, for every degree of air temperature increase at Fish Creek, the average daily water temperature will increase 0.95^{o}C (Table 8). Sensitivity at each site ranged from 0.14 - 0.95 (average daily), 0.16 - 0.80 (maximum daily), 0.13 – 1.14 (average weekly) and 0.16 – 1.18 (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
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
Kroto (Deshka)	0.92	0.66	1.01	0.97
Chijuk Creek	0.89	0.64	0.96	0.88
Cottonwood Creek	0.88	0.72	0.92	0.96
Theodore River	0.85	0.69	0.92	0.96
Meadow Creek	0.84	0.77	0.92	1.18
Trapper Creek	0.81	0.60	0.87	0.82
Troublesome Creek	0.72	0.56	0.75	0.71
Moose Creek (Talkeetna)	0.69	0.49	0.76	0.68
Byers Creek	0.68	0.52	0.72	0.66
Deception Creek	0.67	0.48	0.72	0.72
Little Willow Creek	0.63	0.48	0.66	0.68
Cache Creek	0.61	0.53	0.65	0.66
Willow Creek	0.61	0.58	0.64	0.69
Montana Creek	0.57	0.52	0.60	0.64
Wasilla Creek	0.57	0.46	0.60	0.61
Moose Creek (Palmer)	0.50	0.50	0.54	0.63
East Fork Chulitna River	0.47	0.43	0.49	0.50
Bodenburg Creek	0.14	0.16	0.13	0.16

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. (Jim Creek was removed from model datasets because of missing data that likely resulted in summary statistics which over represent temperatures. Bodenburg Creek was deemed an outlier due to its groundwater-dominated temperature profile.) Examination of model vs. observed plots shows 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)

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 2). We then classified streams as “cold” and “warm”, based on the 13^{o}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^{o}C by 2099 at all sites. For “high sensitivity” streams, this will result in a 2.0 – 2.9^{o}C average July water temperature increase. For “low sensitivity” streams, the increase will be less than 2.0^{o}C.

The nine 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 two streams in the “warm, low sensitivity” category will see more moderate impacts. Ten streams fall in the “cold, low sensitivity” category and should provide high quality, cold-water habitat for Mat-Su salmon for at least the next century.

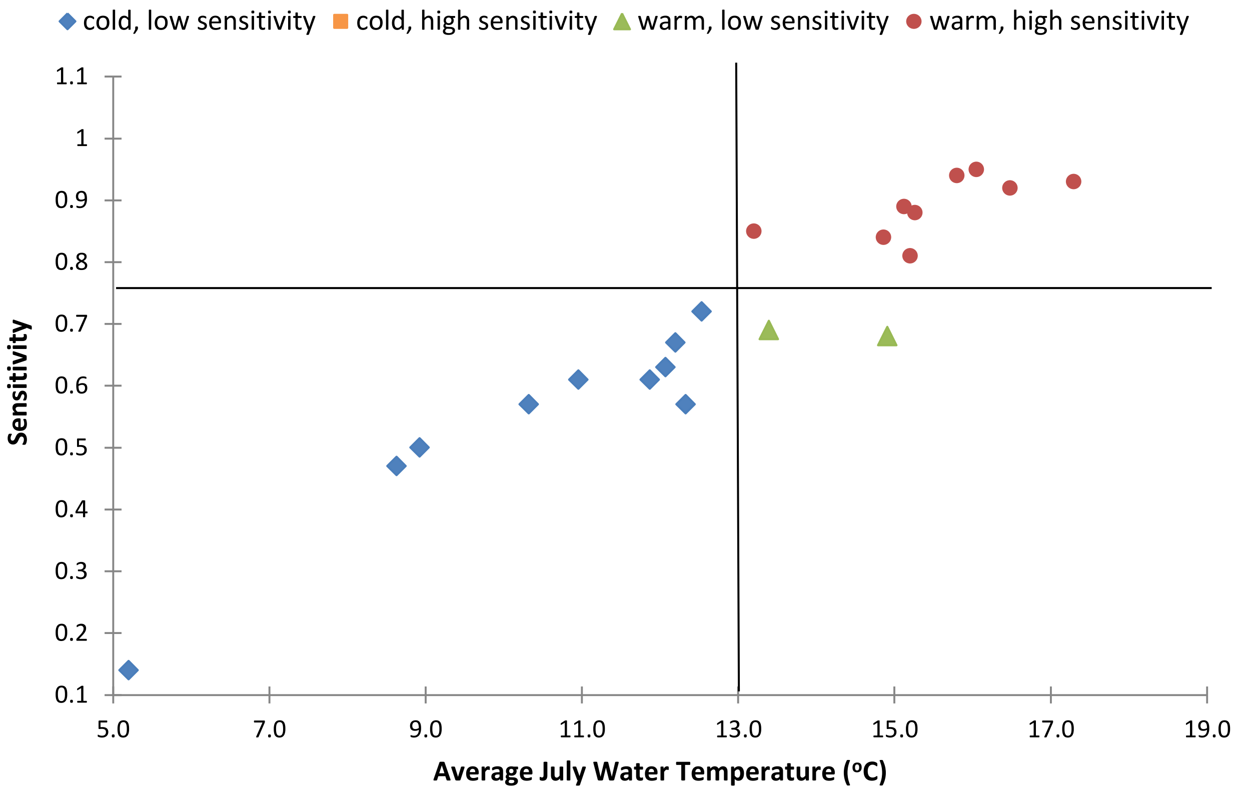


Figure 2. Framework for assessing climate change vulnerability based on threshold values of 13°C for average July water temperature and 0.75 for sensitivity.

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
Bodenburg Creek East Fork Chulitna River Moose Creek (Palmer) Wasilla Creek Cache Creek Willow Creek Little Willow Creek Deception Creek Montana Creek Troublesome Creek		Moose Creek (Talkeetna) Byers Creek	Theodore River Meadow Creek Chijuk Creek Trapper Creek Cottonwood Creek Alexander Creek Fish Creek Kroto (Deshka) Creek Jim 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 Mat-Su basin. Consistently coordinated by Cook Inletkeeper, with six different Mat-Su Basin Salmon Habitat Partnership entities involved, the Temperature Network is a great example of a partnership of federal and state agencies, 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 staff turnover; 2) loss of data from high flow events; 3) management of millions of 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 basin. 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 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 seven 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 Mat-Su basin, with the highest temperatures recorded in streams draining 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 and Alexander Creek are significantly warmer than small, steep systems like Moose Creek (Palmer) and Troublesome 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^oC or more with a doubling of carbon emissions.[19] Our results using the A1B scenario support this finding with the 3^oC 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 Mat-Su 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 43% of the streams by 2099. Thermal impacts will be more moderate in 10% of the streams, with no significant impacts to salmon health for 47% of the streams.

This thermal vulnerability framework can be a useful tool to the Mat-Su Basin Salmon Habitat Partnership to prioritize future research, protection and restoration activities. For example, the nine “warm, high sensitivity” streams could be prioritized for additional research at the reach-level to identify critical cool water refugia that might be important to help salmon move up and down an otherwise warm channel. Restoring riparian areas in these systems might improve temperature profiles by increasing stream shading. For the “cold, low sensitivity” streams, resolving fish passage issues in these systems and protecting key habitats through conservation easements could help maintain fish populations for both the short and long term.

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.

Next Steps

Cook Inletkeeper will continue to fine tune models and discussion points. We expect to submit pieces of this work to peer-reviewed journals in 2014. We deployed temperature loggers in four Mat-Su streams: Fish Creek, Kroto (Deshka) Creek, Wasilla Creek and Little Willow Creek, in 2013 to continue these long-term datasets.

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