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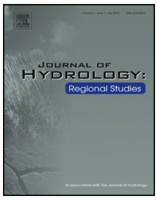

Stream temperature data collection standards for Alaska: Minimum standards to generate data useful for regional-scale analyses

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ABSTRACT

Study focus: Statewide interest in thermal patterns and increasing data collection efforts provides Alaska's scientific and resource management communities an opportunity to meet broader regional-scale data needs. A basic set of stream temperature monitoring standards is needed for Alaskans to begin building robust datasets suitable for regional analyses. The goal of this project is to define minimum (base) standards for collecting freshwater temperature data in Alaska that must be met so that observations can support regional assessment of status and recent trends in freshwater temperatures and predictions of future patterns of change in these aquatic thermal regimes using downscaled climate projections.
New hydrological insights for the region: We defined 10 minimum data collection standards for continuous stream temperature data in Alaska. The standards cover data logger accuracy and range, data collection sampling frequency and duration, site selection, logger accuracy checks, data evaluation, file formats, metadata, and data sharing. We hope that the adoption of minimum standards will encourage rapid, but structured, growth in comparable stream temperature monitoring efforts in Alaska that will be used to understand current and future trends in thermal regimes.

1. Introduction

The availability of stream temperature data in the contiguous U.S. has enabled rapid advances in our understanding of stream temperature drivers, trends, and future projections. Analysis of historic stream temperature trends in the Western U.S. indicate that some aspects of the thermal regime are coherent across regional scales, such as increasing summer temperatures (Isaak et al., 2011), while other aspects of the thermal regime are responding in complex ways, such as daily minimums advancing more rapidly than maximums, but not for all streams, and no consistent changes to stream temperature variability (Arismendi et al., 2012, 2013). Projected increases in the annual maximum weekly water temperatures by

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2080 are on the order of 2–5°C for Washington State (Mantua et al., 2010). Future projections of increasing stream temperatures across regional river networks indicate decreases in suitable habitat and fragmentation of existing habitat for salmonids in the Western U.S. (Rieman et al., 2007; Isaak et al., 2010; Wenger et al., 2011; Ruesch et al., 2012; Jones et al., 2013). The identification of important drivers of stream temperatures allows for targeted management strategies that can increase resiliency in aquatic ecosystems, such as improving riparian vegetation to shade streams, restoring stream flows in summertime to decrease stream sensitivity, restoring fish passage to provide access to thermal refugia, and identifying sensitive areas for conservation (Rieman and Isaak, 2010; Isaak et al., 2010).

In Alaska, climate is changing more rapidly than in the contiguous U.S.; annual air temperatures have increased in Alaska by 1.7 °C (3°F) over the last 60 years while winter temperatures have increased by 3.3 °C (6°F, Chapin et al., 2014). In addition, dates of snowmelt and freeze-up have shifted so that the growing season is now 45% longer in Interior Alaska than it was at the beginning of the 20th century (Chapin et al., 2014). As Alaskans continue to feel the impacts of a changing climate, the need for resource managers to understand how these changes will alter aquatic systems and fisheries resources grows. Stream temperature data collection efforts have increased in recent years to begin to fill our gaps in knowledge about current thermal profiles. Several regional analyses have been conducted in an effort to differentiate the watershed characteristics driving differences in summertime stream temperatures across stream and river systems; important factors have included glacier cover (Kyle and Brabets, 2001; Fellman et al., 2014), elevation (Mauger, 2013; Lisi et al., 2013), wetlands (Mauger, 2013), and lakes (Lisi et al., 2013). Due to the limited spatial and temporal coverage of stream temperature data in Alaska, there is a lack of information describing historic trends or generation of future projections, especially as they relate to salmonids.

A recent effort to catalog historic and existing stream temperature data across Alaska found more than 150 continuous stream temperature sensors deployed across the state maintained by over 15 agencies. These agencies are likely using one of the many existing stream temperature data protocols specific to Alaska, such as the National Park Service (Shearer and Moore 2011 Sergeant et al., 2013), Cook Inletkeeper (Mauger, 2008), and the USGS in cooperation with U.S. Fish and Wildlife Service (Toohey et al., 2014). While these protocols provide excellent guidance regarding temperature monitoring, they are often focused on specific agency procedures and goals that are not applicable beyond their source entity. None of the aforementioned protocols direct the reader toward clear, minimum standards regarding sample frequency, sample duration, or data management. A basic set of stream temperature monitoring standards is still needed for Alaskans to begin building robust datasets suitable for regional analyses.

The goal of this project is to define minimum (base) standards for collecting freshwater temperature data in Alaska that must be met so that observations can support regional assessment of status and recent trends in freshwater temperatures and prediction of future patterns of change in these aquatic thermal regimes using downscaled climate projections. By identifying minimum data standards, our objective is to encourage rapid, but structured, growth in comparable stream temperature monitoring efforts in Alaska that will be used to understand current and future trends in thermal regimes. These trends can then inform strategies for maintaining ecosystem resilience.

2. Methods

We identified a sequence of steps essential to any stream temperature data collection project and within these steps, identified components where minimum standards should be established to ensure that data could be used in regional-scale analyses. The steps include selection of a data logger, data collection, data quality assurance and quality control, and data storage. We used a combination of empirical evidence, published research, and expert opinion in order to define each of the minimum standards. For each minimum standard, we have described the methodology along with a justification for the final standard.

3. Results

We defined ten minimum data collection standards to generate data useful for regional-scale analyses of stream thermal regimes. The standards cover data logger accuracy and range; sampling frequency and duration; data quality assurance steps including accuracy checks, site selection and data evaluation; and finally, metadata, data storage and sharing (Table 1). In some cases we have included recommendations beyond the minimum standards for the reader to consider. Guidance on how to implement these standards is provided in a separate report: Stream Temperature Data Collection Standards and Protocol for Alaska (Mauger et al., 2014).

3.1. Data logger

There are two minimum standards for data loggers: accuracy of ±0.25 °C and range from −4° to 37°C. The accuracy and range minimum standards are based on the best available technology for water temperature data loggers currently on the market. We set the minimum accuracy standard at ±0.25 °C as opposed to 0.2 °C to be clear that commonly used data loggers with accuracy specifications of 0.21 °C are appropriate. Examples of data loggers currently available that meet these specifications include TidbiT v2, HOBO Water Temp Pro v2 (Onset Computer Corporation), Levelogger Edge (Solinst Canada Ltd.) and YSI 6920 V2 sonde (YSI Incorporated). There are additional brands with less accuracy that should not be used (e.g.,

Table 1
Minimum data collection standards for regional analysis of stream thermal regimes.

Minimum standards		
Data logger	Accuracy	±0.25 °C
	Measurement range	−4° to 37 °C (24°–99°F)
Data collection	Sampling frequency	1 h interval
	Sampling period/duration	1 calendar month
Quality assurance and quality control	Accuracy checks	Water bath at two temperatures: 0 °C and 20 °C before and after field deployment to verify logger accuracy (varies ≤0.25 °C compared with a NIST-certified thermometer)
	Site selection	Five measurements across the stream width to verify that the site is well-mixed (i.e., varies ≤0.25 °C)
	Data evaluation	Remove erroneous data from the dataset
Data storage	File formats	CSV format in 2 locations
	Metadata	Unique site identifier, agency/organization name and contact, datum, latitude and longitude, and sample frequency; stored with temperature data
	Sharing	Quality-controlled hourly data

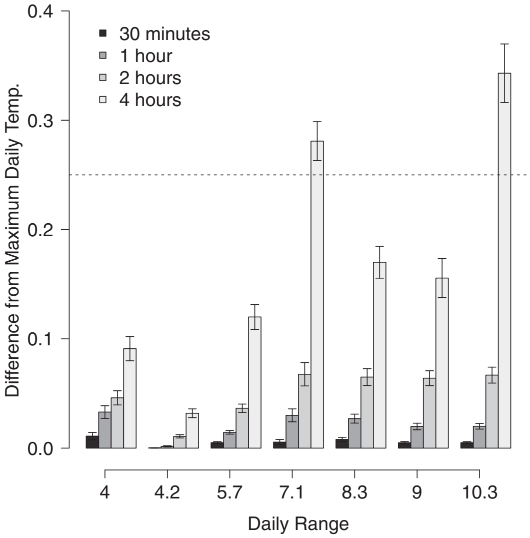

Fig. 1. Difference in daily maximum stream temperatures for 30 min, 1 h, 2 h, and 4 h sampling intervals based on seven stream monitoring sites in Cook Inlet. The horizontal line indicates the minimum standard for logger accuracy, 0.25 °C.

iButtons). Introduction of additional measurement error into stream temperature datasets can reduce our ability to detect trends. The range is set well beyond the expected values for stream temperature in Alaska.

3.2. Data collection

3.2.1. Sampling frequency

The minimum standard for sampling frequency is a 1 h interval because it is the maximum interval that effectively captures the daily maximum and minimum temperatures. The probability of capturing the daily maximum or minimum given a specified sampling interval is affected by the daily range in stream temperature. Dunham et al. (2005) compared several sampling intervals to their baseline of 30 min to estimate the probabilities of missing the maximum daily temperature by more than 1 °C. Given a daily range of 12 °C, there is less than a 2% probability of missing the true daily maximum by more than 1 °C using a two-hour sampling interval (Fig. 5, Dunham et al., 2005). These results are relevant for a dataset of 48 non-glacial salmon streams in Cook Inlet where the daily range among sites varied from 3.9 °C to 11.6 °C (Table 6, Mauger, 2013). However, a 1 °C accuracy goal may not be sensitive enough for tracking maximum and minimum temperature trends during specific seasons important for aquatic organisms.

We resampled stream temperature data collected at 15 min intervals for seven Cook Inlet streams whose daily ranges varied from 4.0° to 10.3 °C. For each of the sampling intervals studied – 30 min, 1 h, 2 h, and 4 h – we calculated the difference in daily maximum from the 15 min interval dataset to determine the loss in accuracy from recording temperatures at longer time intervals (Fig. 1). Error bars reflect the standard error of the mean differences based on 76–149 days of data within one year for each site. A 4 h sampling interval results in a reduction to the maximum daily temperature of 0.3 °C at the site with the largest daily range. This introduced bias is greater than the accuracy of the data loggers used. The 2 h, 1 h, and 30 min

Table 2
Frequencies of MWAT and MWMT by month for streams in Cook Inlet, 2008–2012.

	June	July	August	September
Maximum weekly average temperature (MWAT)				
2008	1	17	22	0
2009	0	42	0	0
2010	1	25	11	1
2011	2	38	2	0
2012	17	1	10	0
Maximum weekly maximum temperature (MWMT)				
2008	3	25	12	0
2009	0	42	0	0
2010	2	30	4	2
2011	3	38	1	0
2012	17	3	8	0

sampling intervals result in a minor loss of accuracy in measuring the daily maximum. We chose a 1 h minimum standard for the sampling interval to reduce the possibility of introducing bias into the daily maximum and minimum values, which get compounded when calculating maximum weekly values. A 1 h interval also minimizes waiting time when performing synchronized data quality assurance checks in the field. When considering inclusion of historical data for a regional analysis, a 2 h sampling interval may be sufficient for calculating daily mean and daily maximum values. But, historical data should also be carefully reviewed to ensure that it meets all of the minimum standards (e.g., the data logger's accuracy can be confirmed and all quality assurance and quality control steps were taken).

3.2.2. Sampling duration

The minimum standard for sampling duration is one calendar month. However, we recommend year round data collection or as much of the open water season as possible, and at least three years of data collection. We decided on a one month minimum standard after reviewing existing regional analyses for the shortest duration of data collection useful for understanding status and trends in stream thermal regimes. Several regional analyses developed statistical models for predicting monthly average temperatures (e.g., Wehrly et al., 2009; Hrachowitz et al., 2010; Mayer 2012; Fellman et al., 2014). The months most commonly modeled were July and August, but some studies also modeled other months of the year.

We recommend year round data collection because winter air temperatures are increasing faster in Alaska than summer temperatures (Chapin et al., 2014), and these may have important implications on the development and timing of life history events for salmon (Bryant, 2009). Adult salmon migration to freshwater and smolt migration to the ocean are both closely tied to stream temperature. Adults return earlier to spawn in colder streams because of the required accumulated temperature needed for egg incubation (Kovach et al., 2012; Lisi et al., 2013). Smolts leave for the ocean earlier in warmer streams because growth is more rapid and size is an important cue for migration (Rich et al., 2009). For multiple species and life histories of salmon in a warming stream in Southeast Alaska, both adult and smolt migrations have advanced over the last 30–50 years (Kovach et al., 2013). Future predictions of coho production in response to stream temperatures and discharge in Western Cook Inlet show that the responses vary depending upon the interaction of changing temperature and discharge (Leppi et al., 2014). The complex response of salmon to climate change highlights the need for monitoring stream temperatures during all seasons of the year.

The majority of regional analyses evaluating climate change effects on fish distributions have modeled one or more measures of the thermal maxima (e.g., MWAT, Eaton et al., 1995; and MWMT, Isaak et al., 2010). In order to provide a recommendation for the deployment period needed to capture the thermal maxima in Southcentral Alaska, we reviewed five summers of stream temperature data collected in the Cook Inlet basin. We used the dates of maximum weekly average temperature (MWAT) and maximum weekly maximum temperature (MWMT) to evaluate the timing of the thermal maxima (Table 2). The MWMT occurs more frequently in July than MWAT, but warm events in June and August indicate the importance of measuring stream temperatures for all three summer months. For two sites in southern Cook Inlet, the MWMT was observed as late as September in 2010. We recommend a minimum deployment period of June 1–August 31 to capture the thermal maxima for streams in Southcentral Alaska. The timing of thermal maxima may be different in other regions of Alaska. If the timing is not known, multiple years of data should be collected over the entire open water period before narrowing your sampling period to target the thermal maxima. In addition, climate change may be shifting the thermal maxima earlier in the summer due to decreasing snowpack and increasing temperatures.

It is also important to consider inter-annual variability in stream temperature regimes when planning stream temperature data collection efforts. Values for MWAT and MWMT were highly variable over a five year monitoring period in Cook Inlet salmon streams. For streams with at least three summers of data ($n = 44$), the difference between the lowest and highest MWAT ranged from 0.8° to 6.4 °C and for MWMT ranged from 1.4° to 7.3 °C. We recommend at least three years of data collection in order to accurately capture the effect of inter-annual variability on a stream's thermal regime. If you are unable to collect data year round, it is important to consider sampling the same month (or set of months) year after year for consistency. A data logger can be used to record measurements for several years as the battery life for a typical logger is 5 years at a 1 min or greater interval. But, due to limitations in storage capacity and recommended steps for quality assurance, loggers should be retrieved annually so that accuracy checks can be performed and data can be downloaded before redeploying.

3.3. Quality assurance and quality control

3.3.1. Accuracy checks

The minimum standard to ensure logger accuracy includes water bath accuracy checks at two temperatures: 0 °C and 20 °C, before and after field deployment using a NIST (National Institute of Standards and Technology) traceable (calibrated and maintained) thermometer accurate to ±0.25 °C. NIST-certified thermometers can be liquid-in-glass thermometers or they can be a data logger which has been NIST-certified. We recommend a 4-point (0, 10, 20, 30 °C) calibration by the manufacturer. It is good practice to send the NIST-certified thermometer back to the manufacturer for re-calibration every two years. Loggers must measure water temperatures within 0.25 °C of the NIST-certified thermometer for at least 3 measurements in each bath. Record these values in a logbook or spreadsheet.

These accuracy checks are needed to verify that each logger meets its technical specifications throughout the deployment period and that measurement drift has not occurred over time. Loggers that fail pre-deployment accuracy checks are not used, while loggers that fail post-deployment accuracy checks may result in a failure to meet the minimum standards for regional analysis. We recommend that loggers go through an accuracy check at least once a year. When collecting data for multiple years at a site, loggers should be swapped out once a year if possible. Accuracy checks ensure that data can be confidently shared with other users. We do not recommend using them to calibrate or modify values recorded by the data logger.

3.3.2. Site selection

Site selection at the reach scale includes two components: identifying a stable location within the reach and deploying the logger in a well-mixed section of the stream channel. Due to the diversity in stream and river ecosystems within Alaska, we can only provide general guidance for site selection within the reach. High velocity habitats, such as those found along the outside bank of a bend, should be avoided to reduce the likelihood of losing a logger during high flow events. Low velocity habitats, like those along the inside of a bend or in eddies or pools, should be avoided because sediment deposition may bury a logger. Loggers should be deployed within the active channel to prevent exposure to air temperatures during low flows.

If the logger does not come with a protective case (e.g., TidbiT v2 Temp Logger), it should be placed in a flow-through housing to protect the equipment from natural, wildlife, or human disturbance. Housings also provide shade for the logger, protect the logger from moving debris, and allow for secure attachment with a cable. Housings should allow for good water circulation past the logger but not be in direct contact with the temperature sensor because the housing may absorb heat. If possible, loggers with a protective case or within a housing should be placed in a well shaded location to reduce the influence of direct solar radiation.

The choices made to secure a logger at the site will have the greatest influence on the successful collection of stream temperature data. When selecting a deployment method, consideration should be given to how it will work at high and low flows, how much streambed movement there is at the site, and how to prevent people from accidentally dislodging equipment at high traffic sites (e.g., tripping over rebar, sand bags or cables). Generally, attaching a logger to a bank-secured cable is preferred for streams with soft substrates or significant movement of the streambed during high flows. Rebar can be inserted into the stream bank in treeless areas. Rebar or duckbill earth anchors sunk into the streambed are preferred if there is only moderate streambed movement and the stream is shallow. Sandbags can be used to weigh down a logger, but this method is only recommended in streams with minimal streambed movement. If a site has large rocks or a bridge support, underwater epoxy is another alternative (Isaak et al., 2013).

Ice movement might destabilize an anchoring method if a logger is left in stream over the winter. Anchoring the logger to the streambed as opposed to the stream bank should prevent loss due to ice movement in the spring. We recommend deploying two loggers at a site to provide backup in the event that one is lost. When a site is first established, and especially when deploying loggers for winter data collection, multiple backup loggers using different anchoring methods is the best way to guarantee loggers are recovered the following year.

The minimum standard for site selection includes five measurements of stream temperature across the width of the stream to ensure that the logger is deployed in a location that varies ≤0.25 °C. Temperature loggers should be placed in a well-mixed section of the main stream channel if the data are to be useful for regional-scale analysis of stream temperatures. Stream thermal regimes can be highly variable at the reach scale depending upon the diversity of habitat types present. Thermal imaging of the Anchor River in Southcentral Alaska indicates that sloughs and side channels may be warmer or colder than the main channel by as much as 4 °C (Table 5, Watershed Sciences, 2010). Stream reach features with unique temperature characteristics, such as off-channel habitat, groundwater upwelling areas, or anthropogenic features (e.g., dam or point discharge), should be avoided if they are not part of the study objectives.

Site selection also includes the location of a monitoring site within the stream network, which is typically related to project objectives and may not be based on regional analysis of stream temperatures. Probabilistic designs, such as those used for EPA's National Aquatic Resource Surveys (Stevens and Olsen, 2004), can be used to locate random sampling sites that are spatially balanced across a stream network, but they are logistically challenging to apply in remote locations. In order to capture the range of thermal regimes and inform predictive models of stream temperatures across a network, sites may be strategically placed to capture the full range of the dominant geomorphic conditions driving stream temperatures (Isaak et al., 2010; Lisi et al., 2015). Depending upon the region, important geomorphic factors to consider include elevation, slope, stream size, and wetland and lake coverage. Spatial data for the region can be assembled in a GIS and used to attribute the stream network with the necessary stream or watershed information required for site selection.

Other suggestions for site selection include utilizing confluences and targeting unique features in a stream network. Confluences provide an opportunity to gather information about three distinct stream reaches by deploying loggers in the two incoming tributaries and also within the downstream reach below where the two source waters have become well-mixed. Discrete features in a region that may affect stream temperatures, such as a large lake or wildfire, can be bracketed to better capture their effect. Recent guidance on sampling designs for stream networks recommends placing multiple samples in clusters at confluences and also single samples at outlet and headwater reaches (Som et al., 2014).

3.3.3. *Data evaluation*

The minimum standard for data evaluation is that all erroneous data are removed from the dataset. Data evaluation steps can only be performed with confidence by the field staff familiar with the sampling events and site conditions and should occur immediately after returning from the field to prevent any loss of information sharing needed to diagnose erroneous data. Data evaluation steps include removing air temperature measurements before deployment and after retrieval and screening for anomalous readings caused by dewatering or burial of the logger. There are several publications that provide examples of visual checks for anomalous data: Mauger et al. (2014), Sowder and Steel (2012), and Toohey et al. (2014).

3.4. *Data storage*

Data management and sharing standards are also included to ensure data collected for regional analysis are made available in an easily exchangeable format.

3.4.1. *File format*

The minimum standard for file format is a comma-separated value (csv) file stored in two locations. We specified a software neutral file format so that it is easily imported into a variety of database and analysis programs, such as Excel, Access, and R. Additionally, data and associated metadata need to be stored in at least two locations, with one of those locations being publicly accessible.

3.4.2. *Metadata*

Regional scale assessments of stream temperatures will require scientists to use data from numerous sensors sourced from many agencies. The minimum standard requires that metadata information be stored with the temperature data files so that future users can easily use the data. The creation, maintenance, and distribution of metadata are critical. As the number of temperature monitoring datasets increases rapidly, our ability to discern which datasets are useful to a given research interest will be related to our capacity to sort through metadata which have common fields. Using consistent fields and formats will improve comparisons between datasets collected by different groups and at different times. At a minimum, metadata shall include the following attributes: unique site identifier, data source agency or organization name and contact information, datum, latitude, longitude, and sample frequency (1 h, 30 min, 15 min). We strongly encourage investigators working in Alaska to submit project metadata to AK-OATS (http://aknhp.uaa.alaska.edu/aquatic-ecology/akoats/).

3.4.3. *Data sharing*

The minimum standard for sharing data is quality-controlled hourly data, which provides the information needed to characterize key aspects of a stream's thermal regime (Dunham et al., 2005; Nelitz et al., 2007; Arismendi et al., 2013). Although many regional analyses have focused on stream temperature responses associated with the summertime thermal maxima (e.g., mean July temperature or MWMT), there are many other components to the stream thermal regime: magnitude (e.g., minimums), variability (e.g., daily range), frequency (e.g., number of days that exceed a threshold), duration (e.g., number of contiguous days above a threshold), and timing (e.g., day of year, Poole et al., 2001). We also recommend providing daily summaries of minimum, maximum, and mean stream temperatures. Calculating these daily summary statistics serves as an important quality assurance step by forcing the data collector to review the data soon after data retrieval so that erroneous measurements can be identified and deleted. Daily summary statistics should only be calculated for quality controlled data with at least 90% of daily measurements (e.g., 22 hourly measurements).

4. Conclusions

Many entities are collecting stream temperature data in Alaska for a variety of purposes to meet project or agency specific goals. Statewide interest in thermal patterns and increasing data collection efforts provides Alaska's scientific and resource management communities an opportunity to address broader regional-scale data needs. We have endeavored to identify minimum standards for stream temperature data collection that will result in datasets useful for answering most research and monitoring questions asked at the regional scale. We hope that investigators will consider these minimum standards when developing a field plan, as they will reduce the variability of data quality due to disparate sampling methods. This will enable researchers to easily evaluate a project's metadata and determine the utility of the data for assessing patterns and trends in Alaska's freshwater systems. These standards may also provide a useful starting point for collaborative efforts to combine stream temperature data collected by multiple entities across regional scales in the Lower 48.

We have provided additional recommendations beyond the minimum standards as guidance for entities whose primary objective is to understand stream thermal patterns and also for those who have an interest in making their data as broadly useful as possible. Most notably we recommend at least three years of year-round data collection and deploying two data loggers at a site in the event one logger fails or is lost. Tips are offered to address Alaska's uniquely challenging conditions including ice movement, high flow events, treeless areas, and remote access, which all need to be considered when establishing a sampling site. We hope establishing a set of standards and providing recommendations will encourage additional groups to deploy temperature sensors, and particularly benefit field staff whose primary tasks may not be hydrology or monitoring as well as personnel at smaller organizations.

In some cases, investigators may choose more rigorous quality assurance methods or shorter sampling intervals. Fortunately, these decisions will not preclude the usefulness of these data for regional analysis as they are above and beyond the minimum standards. We realize that some project-specific needs, particularly related to sampling location, may not be compatible with these standards and will not result in useful data at a regional scale. Nevertheless, in Alaska, where travel costs can eat up field budgets quickly, voluntary adoption of minimum standards will go a long way to help stretch limited research dollars and, most importantly, to generate valuable datasets for understanding thermal patterns across Alaska's vast freshwater ecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.07.008.

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