

## **Climate-Aquatics Blog Post #8: Thoughts on monitoring designs for temperature sensor networks across river and stream basins**

With growing interest in climate change and the relative ease & inexpensive of monitoring of stream temperatures, efforts to establish river basin, regional and even national monitoring networks are rapidly emerging. Moreover, establishing a monitoring network across even a large river basin is surprisingly easy to do, requiring only a couple weeks of technician time and \$5,000 - \$10,000 of equipment (mostly for temperature sensors). Not surprisingly, questions regarding appropriate sampling designs are also becoming common, so this week, I thought I'd try to distill a few thoughts from some of my research & several projects I've been involved in to help national forests and other entities develop temperature monitoring networks for river systems. The upfront disclaimer, of course, is that no one sampling design is "best" or "optimal" in all cases, as the motivations for monitoring, idiosyncrasies of individual river networks and streams, and available resources vary widely and will ultimately dictate the sort of design that is implemented. That said, there are some general principles & readily available tools that can be applied to assist in customizing a design for rivers and streams in your area.

### **Types of monitoring designs**

Before going into some of the details, however, I probably need to be a bit more specific with regards to the sorts of temperature monitoring design applications that are common. Many designs are possible, so to narrow the field some, I'll group them into four basic application categories, these being:

- 1) experimental designs (monitoring points spread in space and placed randomly to obtain a representative sample and minimize spatial autocorrelation; think EMAP, AREMP, or PIBO designs for examples; inference is mainly, though not entirely, descriptive),
- 2) site-specific, project-level designs (e.g., local monitoring to track stream temperature response to habitat restoration, recovery from a wildfire, or to understand local heat budget mechanisms),
- 3) regression designs (monitoring points spread along major environmental gradients that affect stream temperatures; think spatial statistical models like those described in Blog post #7; goal is mainly data acquisition to make a predictive model for deriving spatially continuous temperature maps and less of a focus on description),
- 4) ecologically motivated designs (placement of temperature sensors is motivated primarily by biological considerations; think boundaries of a species distributions, natal habitats, migratory habitats; physical factors are of lesser concern in sensor locations).

In all cases, empirical data collected in association with the designs described above could also be used to calibrate process-based, mechanistic temperature models and it is assumed (rightly or wrongly) that sampling designs described herein would be sufficient for this class of models.

Of the categories described above, we'll only spend time on categories #3 & #4 above, as they're the ones seeing the most rapid increases in association with climate change considerations. This week I'll go over some of the basics regarding sampling designs useful for building predictive

regression models (#3 above). In a subsequent week, we'll then have Brad Trumbo & Mark Hudy guest blogging about some of their research with eastern brook trout and the ecological temperature sensor network design that they've implemented to assess the relative sensitivities of different conservation populations to climate change (#4 above).

### **A design for predictive regression modeling**

The need to have more precise answers from models tailored to local landscapes & river networks seems to be the primary motivation behind the increased interest in regression based temperature monitoring designs the last few years. Fortunately, in many cases, with a relatively modest amount of temperature data (which may already exist in many areas), and some basic GIS and statistical tools like those in Excel, traditional multiple regression models can be built that account for 60 – 70% of the variation in summer temperatures throughout a river network. Although predictive accuracy may not be as high as the spatial statistical stream models discussed in Blog post #7, this still offers a considerable improvement over the relatively imprecise answers gained through use of surrogate relationships based on air temperature or elevation. Regardless of whether the predictive statistical model that's ultimately developed is a traditional multiple regression or the newer spatial regressions, sampling design considerations for monitoring stream temperatures are similar for each type of regression, although the spatial models generally require larger sample sizes.

### **Spatial monitoring considerations**

When establishing a monitoring design for developing a predictive regression model, the basic goal should be to monitor temperatures across the full ranges of the most important environmental gradients (predictor variables) that affect stream thermal regimes in the area of interest. If these ranges are adequately represented in the dataset, it helps ensure that parameter estimates for the predictors are accurate and the model should yield similarly accurate temperature predictions. Since most of the work I'm involved in occurs in mountainous terrain, one of the more obvious & strong environmental gradients affecting stream temperature is elevation. Another important gradient that's often used is stream size because it relates to the amount of shade that riparian areas provide to streams. Yet other relevant gradients may include stream slope, distance from the headwaters, etc.

To allocate temperature monitoring sites along these gradients, it's very helpful to actually describe these gradients in a tangible manner for the river network that's being studied. Digital summaries to do just that can be easily obtained from existing GIS hydro-coverages (e.g., NHD+ or TauDEM) and detailed, step-by-step instructions for developing these sorts of summaries are attached to this email and can be downloaded from the "Multiple Regression Temperature Model" project at the RMRS Stream Temperature Modeling & Monitoring website ([http://www.fs.fed.us/rm/boise/AWAE/projects/stream\\_temp/multregression/methods.shtml](http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/multregression/methods.shtml)).

Once the important spatial gradients can be described, the idea is to simply spread the monitoring sites along these gradients. To do this step efficiently, it's ideal if all the available stream temperature data that your agency or other agencies have already collected for the study area have been organized into a central database. That way, sites with pre-existing temperature data can be plotted along these gradients and new monitoring sites simply added to fill in gaps as necessary. The next step is translating the new monitoring locations to a 'real-world' sampling

location and set of geographic coordinates that can be developed into a GIS file and downloaded to a GPS unit for navigation in the field (all the technical steps for doing this can be accessed at the above link). You have some flexibility here in choosing specific locations because there may be dozens of stream reaches that meet the necessary criteria and at this point logistical issues and travel time considerations become important.

Although most of the river basins I have a chance to work in are dominated by public lands & trespass issues are a minor concern, the streams are often less accessible in the sense of their remoteness. It may take a half day or more to drive to the river basin, and then another 2 – 20 hours to hike to specific stream locations in many wildland landscapes across the western US. Targeting information rich areas on a stream network and using the available road network to gain the best stream access are absolute necessities for maximizing efficiency. In terms of high information content over a limited spatial area, no place exceeds that of tributary confluences in a river network. These locations provide access to stream segments of three different sizes and relatively abrupt changes in thermal gradients often occur at confluences. Putting 3 sensors at these locations is often a good bet (one each on the segments just upstream of the confluence, then another downstream from the confluence where the two streams are fully mixed). Moreover, the spatial autocorrelation structure for a passively diffusing stream attribute like temperature or other water quality parameters is often very strong and extends in an upstream direction anywhere from 5 – 40 kilometers from individual sites. In practical terms, this means that one temperature sensor at the downstream end of a stream provides large amounts of information about the upstream thermal characteristics and you can save yourself the trouble of hiking up that sucker.

The foundation, then, to efficiently setting up a regression based sampling design is often going to be identifying a set of tributary confluences that cover the important spatial gradients like elevation/stream size and having these spread throughout the study basin. After that, additional site locations can be selected to fill in gaps along the important spatial gradients that were not covered adequately by the confluence areas. On longer streams, or where there are especially important resource issues and the need exists for better local predictions and temperature data, additional sites could be added upstream from the confluence. One last important spatial sampling consideration pertains to those discrete features of landscapes and river networks that may cause pronounced local warming or cooling. These might include beaver dam complexes, wildfire areas, large lakes/reservoirs, or significant water diversions. In these instances, it's desirable to "bracket" the feature by putting temperature sensors immediately up and downstream. By having data from both areas, the thermal influence is well captured and the effects of these features can be included in a regression model using categorical predictor variables. Judgement has to apply with regards to how important these features ultimately are for thermal regimes within the study area and the degree of consideration they ultimately warrant.

### **Temporal monitoring considerations**

Equally important to distributing monitoring locations along the important spatial gradients, it's important to monitor stream temperatures across years so that the effects of inter-annual climate variability can be assessed. At a minimum, I recommend temperature sensors remain at the same site recording full-year thermal conditions for 2 – 3 years (Blog post #3 details an underwater epoxy technique that makes this easy, at least where large rocks occur in stream), which will

provide some measure of how stream temperatures respond to inter-annual differences in air temperature and stream flow. If a regression model is built from the monitoring data, you'd want to include these latter two factors as predictor variables in that model, which also then makes the model more flexible as it can be used to hindcast/forecast stream temperatures for historic or future climate scenarios. Even if a regression model is not built, collecting 2 – 3 years of data at each monitoring site enables simple sensitivity analyses wherein inter-annual differences across many sites are summarized and used to highlight streams that are more/less sensitive to warming and climate forcing.

After 2 – 3 years of monitoring at a stream site, most of the useful thermal information about that site that's relevant for building a predictive temperature model and understanding thermal patterns at the river network scale has been obtained. At this point, sensors could be rotated to new locations, another 2 – 3 years of data collected, and the sequence repeated until the end of the instrument's service life. Even with a relatively small number of sensors, therefore, a good temperature database representing the spatial & temporal variation in the study system can be developed over the span of 5 – 10 years. If the intent is to someday have enough data to build a traditional multiple regression model for predictive purposes, 30 – 50 observations from unique stream sites are needed at a minimum (statistical rule of thumb is 10 observations for every predictor included in the model). If the intent is to someday develop a spatial regression model for more accurate predictions, the minimum sample size is more like 100 (typically seven parameters are associated with modeling the spatial structure in residual errors).

One last note regarding the duration of monitoring at individual stream sites. Because long-term time-series of stream temperature monitoring data are so rare, it would be a wise investment to designate a subset of sites in the monitoring network as permanent monitoring sites. There wouldn't have to be a lot of these sites because the correlations among them are likely to be very high (barring a local disturbance), but having 10 or 20 permanent monitoring sites across an area the size of an individual national forest or 3<sup>rd</sup>/4<sup>th</sup> level USGS hydrologic unit code (HUC) would be a good start. Given that the equipment costs associated with permanently installing a temperature sensor that will collect data for up to 5 years are only \$100, this sort of permanent local sensor network would cost only \$1,000 - \$2,000 plus a few days of maintenance each year.

As the length of the monitoring record increases at these permanent sites, it will become possible in future decades to describe the observed rate of climate warming through simple descriptive summaries of the data rather than having to rely on models to extrapolate shorter-term monitoring records. The other benefit to monitoring some sites over longer periods of time is that the monitoring record will eventually encompass extreme climate years with very warm temperatures, low flow conditions, or combinations thereof. These sorts of years can act as analogues for what may become "average" conditions at some point in the future. Having these data in the database means that any predictive models that were someday developed would incorporate a wide range of climatic variability. It also minimizes or eliminates concerns about extrapolating temperature predictions past the range of previously observed conditions. In many of the temperature monitoring databases I've worked with, for example, extreme warm years in the last decade generally equal or surpass most climate model projections for what will become "average" conditions for at least 50 years into the future.

## Ending thoughts

So that's pretty much all I know with regards to the sampling design basics for the sorts of temperature monitoring networks that are often being set up these days. Each individual application will require some level of local customization but hopefully these thoughts can point people in the right direction. One of the potential future applications of the spatial statistical stream models (Blog post #7) is that they could someday be used to design optimal monitoring strategies for temperatures and other stream attributes because the spatial techniques quantify the distances over which stream attributes are correlated, and therefore, the distances that monitoring locations should be spaced to maximize information gains, but that's an application yet to be developed. So for now, guiding principles are about the best that can be done in many cases. For additional guidance, details regarding the nuts & bolts of designing and deploying temperature monitoring networks are on the RMRS Stream Temperature Webpage in association with the "Multiple Regression Temperature Model" subpage ([http://www.fs.fed.us/rm/boise/AWAE/projects/stream\\_temp/multregression/methods.shtml](http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/multregression/methods.shtml)), where there's a cookbook, step-by-step set of instructions for the GIS procedures, developing temperature databases from existing data sources, stratifying the sampling domain, selecting sites, and building a multiple regression model in Excel. There's also a couple overview presentations with annotated notes entitled "Collecting, Organizing, and Applying Stream Temperature Data" and "Stream Thermal Regimes and Aquatic Ecosystems in a Changing Climate" towards the bottom of the main Stream Temperature webpage ([http://www.fs.fed.us/rm/boise/AWAE/projects/stream\\_temperature.shtml](http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml)).

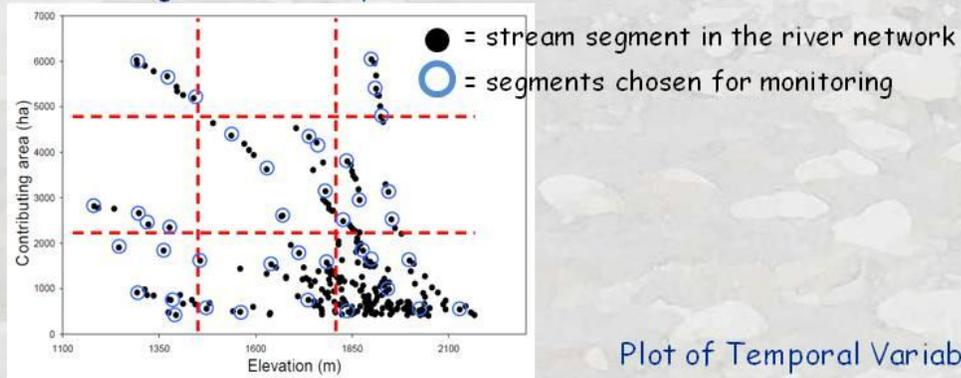
Next time out, we'll have Brad Trumbo & Mark Hudy guest blogging about their ecological temperature sensor network for eastern brook trout. The remainder of this month is going to be a bit hectic, so I'm not sure exactly when that post will occur, but hope to have it out sometime in mid to late May. After that, there's several additional topics on stream temperature & climate change to cover, then we'll transition to a module on hydrology & climate change, and then finally talk biology with a module on bioclimatic considerations.

Best regards,  
Dan



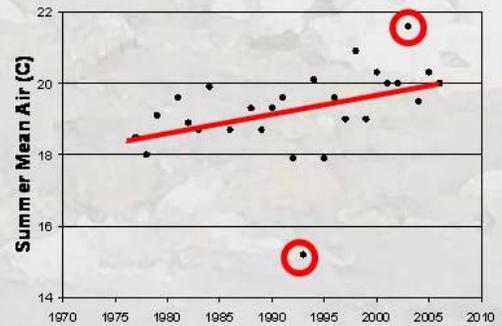
# Sample to Encompass Important Spatial & Temporal Variation in the Study System

Plot of Spatial Gradients Affecting Stream Temperatures



Long-term monitoring at a subset of sites increases the odds of measuring temperature responses during extreme climate years. These years can serve as valuable analogues for future climatic conditions and improve the accuracy of a temperature model in making future projections.

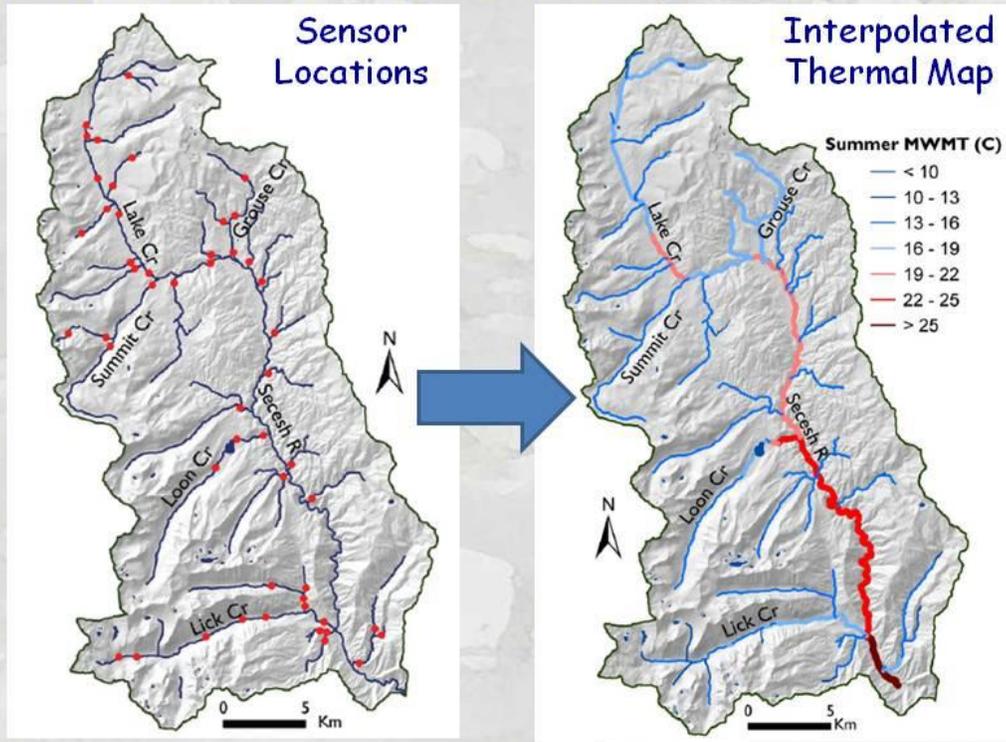
Plot of Temporal Variability





## Example of a Temperature Sensor Network & Continuous Thermal Map Built Using the Data to Parameterize a Multiple Regression Model

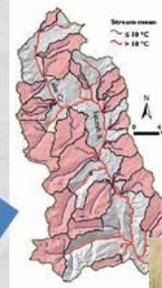
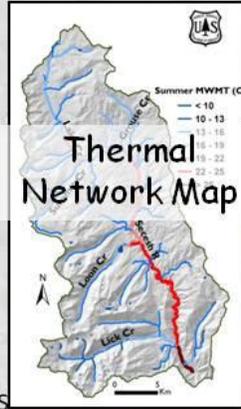
This sensor network was deployed by three people and required 4 days of field work across a smaller river basin in central Idaho.



# Applying the Data & Temperature Models

Numerous applications of temperature monitoring data are possible, not just for climate assessments, but also basic management applications associated with habitat designations, biological sampling designs, and impact assessments.

## Stream Temperature Model



- Suitable habitat delineations
- biological sampling designs
- Assessing disturbance/management effects

Climate reconstructions

Climate forecasts & what-if games

