Use of NorWeST for Regionally Consistent Status & Trend Assessments of Stream Temperature

Dan Isaak, Seth Wenger¹, Erin Peterson², Jay Ver Hoef³ Charlie Luce, Steve Hostetler⁴, Jason Dunham⁴, Jeff Kershner⁴, Brett Roper, Dave Nagel, Dona Horan, Gwynne Chandler, Sharon Parkes, Sherry Wollrab

U.S. Forest Service
¹Trout Unlimited
²CSIRO
³NOAA
⁴USGS
>45,000,000 hourly records
>15,000 unique stream sites
>60 agencies
$10,000,000
Regional Temperature Model

Accurate temperature models

Cross-jurisdictional “maps” of stream temperatures

Consistent information across 350,000 stream kilometers

NorWeST Stream Temp

y = 0.68x + 3.82

4 9 14 19

Summer Mean

y = 0.55x + 7.79

5 10 15 20 25 30

y = 0.86x + 2.43

5 10 15 20 25 30

y = 0.93x + 0.830

4 9 14 19

Predicted (°C)

Observed (°C)

Replace with validation Data from 2007
Temperature is Important for Aquatic Critters

Metabolism

Brown 2004

Endo

Ecto

Thermal Niche

Isaak & Hubert 2004

In the lab...

McMahon et al. 2007

& the field

Isaak & Hubert 2004
Thermal Status is Important Within Regulatory Contexts

Stream Temperature (°C)

TMDL limit

Too Hot!

Status Map

Temperature (°C)

- 5.35 - 7.92
- 7.92 - 10.5
- 10.5 - 13.1
- 13.1 - 15.6
- 15.6 - 18.2
Thermal Status is Changing
Regional Trends In Northwest Rivers

Fraser River - Annual
\[ \Delta = 0.18^\circ \text{C/decade} \]
Morrison et al. 2002

Columbia River - Summer
\[ \Delta = 0.40^\circ \text{C/decade} \]
Crozier et al. 2008

Snake River, ID - Summer
\[ \Delta = 0.27^\circ \text{C/decade} \]

Missouri River, MT - Summer
\[ \Delta = 0.33^\circ \text{C/decade} \]
Information From Data?

Spatial Statistical Models for Stream Networks

Advantages:
- valid covariance structures account for network topology
- account for spatial autocorrelation among sites
- improved predictive power & less bias

…let us interpolate on networks
& aggregate datasets
…so we can connect the dots
Information From Data?
Spatial Statistical Models for Stream Networks

Advantages:
- valid covariance structures account for network topology
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Ver Hoef et al. 2006; Peterson & Ver Hoef 2010; Ver Hoef & Peterson 2010

...let us interpolate on networks & aggregate datasets

...so we can connect the dots
“Smart” Maps Developed from Lots of Data to Show Resource Status

Maps are useful... even when imperfect
Spatial Statistical Network Models Work the Way that Streams Do...

Gradual trends within networks...

...but also changes at tributary confluences

...& are significantly better mousetraps
Stream Models are Generalizable…

- Genetic Attributes
- Water Quality Parameters
- Distribution & abundance

Response Metrics
- Gaussian
- Poisson
- Binomial

Statistical stream models

Stream Temperature

Genetic Attributes

Water Quality Parameters
An Example: Boise River Network Stream Temperature Model & Climate Assessment

Dan Isaak, Charlie Luce, Bruce Rieman, Dave Nagel, Erin Peterson, Dona Horan, Sharon Parkes, and Gwynne Chandler

Boise Aquatic Sciences Lab
U.S. Forest Service
Rocky Mountain Research Station
Boise, ID 83702

CSIRO Mathematical and Information Sciences
Indooroopilly, Queensland, Australia
Boise River Temperature Database

Stream Temperature Database
14 year period (1993 – 2006)
780 observations
518 unique locations

Watershed Characteristics
Elevation range 900 – 3300 m
Fish bearing streams ~2,500 km
Watershed area = 6,900 km²
Boise River Temperature Model

Non-spatial Stream Temp =
- 0.0064*Elevation (m)
+ 0.0104*Radiation
+ 0.39*AirTemp (°C)
- 0.17*Flow (m³/s)

Parameter estimates are different because of autocorrelation in database

Spatial Stream Temp =
- 0.0045*Elevation (m)
+ 0.0085*Radiation
+ 0.48*AirTemp (°C)
- 0.11*Flow (m³/s)

Mean Summer Stream Temp

\[ r^2 = 0.68; \text{RMSE} = 1.54°C \]

Non-spatial Model

\[ r^2 = 0.93; \text{RMSE} = 0.74°C \]

Spatial Model

Isaak et al. 2010. Ecol. Apps. 20:1350-1371
Application: River Temperature Status Map

2006 Mean Summer Temperatures
Mapping Uncertainty
Temperature Prediction Precision
Application: Efficient Monitoring Designs

Summer Stream Temperature

Distance between samples (km)

Redundant information

Optimize Sampling

Too many...

Too few...

Just right
Trend Assessment = Change in Status Between Time 1 & Time 2

Summer Air Temperature

- Study period: 1976-2006
- Trend: +0.44°C/decade

Recent Wildfires

- 14% burned during 93–06 study period
- 30% burned from 92-08

Summer Stream Flow

- Study period: 1946–2006
- Trend: -4.8%/decade
Climate Change Map – Thermal Gains 93-06
Change in Summer Temperature Status

Isaak et al. 2010. Eco. Apps. 20:1350-1371
Application: Effects on Thermal Habitats

**Bull Trout**

- Suitable habitat: < 12.0°C
- High-quality habitat: < 10.0°C

**Rainbow Trout**

- Suitable habitat: > 9.0°C
- High-quality habitat: 11.0-14.0°C
93’-06’ Rainbow Trout Habitat Changes

Habitat is shifting, but no net gain or loss

93’-06’ Bull Trout Habitat Changes
Habitat is decreasing 8%-16% / decade

Isaak et al. 2010. Eco. Apps. 20:1350-1371
Infrastructure for Regional Analysis Developed Through NorWeST

Spatial models

NorWeST

Just need spatial stream datasets

GIS infrastructure

~350,000 Stream kilometers
Example: Clearwater River Basin

Data extracted from NorWeST

16,700 stream km
Example: Clearwater River Basin

Data extracted from NorWeST

16,700 stream km

- 4,487 August means
- 746 stream sites
- 19 summers (1993-2011)

Temperature site
Climatic Variability in Historical Record

Extreme years include mid-21st-Century “averages”

Air Temperature (°C)

Discharge (m³/s)

Δ = 5°C

3x change

Year

Air Temp (C)  Discharge (m³/s)

Clearwater River Temp Model

$n = 4,487$

Covariate Predictors
1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Baseflow Index
8. Watershed size (km$^2$)
9. Discharge (m$^3$/s)
   **USGS gage data**
10. Air Temperature (°C)
   **RegCM3 NCEP reanalysis**
   **Hostetler et al. 2011**

Mean August Temperature

$r^2 = 0.95; \text{RMSE} = 0.60\text{°C}$
Riparian Canopy Predictor

%Canopy variable from 2001 NLCD

%Canopy adjusted by MTBS through 2008

Also tested:
- LandFire
- TreeFrac
- Radiation measurements

Post 2001 Wildfires
### Why August Mean Temperature?

1) 95% of temperature data are summer only
2) All summer metrics are strongly correlated
3) Monthly mean is easily linked to regional climate model

<table>
<thead>
<tr>
<th></th>
<th>Summer_mn</th>
<th>Mwmt</th>
<th>Mwat</th>
<th>awat_mn</th>
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<th>August Mean</th>
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</table>

*Modeling each additional metric doubles computational time
*Conversion factors can facilitate metric translation
### Summer Temperatures ~ Other Seasons

<table>
<thead>
<tr>
<th></th>
<th>Fall mean</th>
<th>Fall SD</th>
<th>Winter Mean</th>
<th>Winter SD</th>
<th>Spring mean</th>
<th>Spring SD</th>
<th>Summer Mean</th>
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<td>Winter Mean</td>
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<td>Winter SD</td>
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<td>Spring mean</td>
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<td>0.51</td>
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<td>Spring SD</td>
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<td>-0.02</td>
<td>0.15</td>
<td>0.48</td>
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</tbody>
</table>

**Legend**
- Stream Temp Sensor (64)
- Air Temp Sensor (47)

**Full Year Temperature Cycle**

- Egg development
- Nymph hatching
- Nymph emergence
- Egg and aquatic life only
Salmon River Temperature Model

\[ n = 4,401 \]

**Covariate Predictors**
1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Baseflow Index
8. Watershed size (km\(^2\))
9. Discharge (m\(^3\)/s)

**USGS gage data**
10. Air Temperature (°C)

**RegCM3 NCEP reanalysis**

**Hostetler et al. 2011**

![Graph showing predicted vs. observed mean August temperature with a regression line.](image)

Spatial Model

Mean August Temperature

\[ r^2 = 0.89; \text{ RMSE} = 0.86°C \]
SpoKoot River Temp Model

\[ n = 5,482 \]

Covariate Predictors
1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Baseflow Index
8. Watershed size (km\(^2\))
9. Discharge (m\(^3\)/s)  
   USGS gage data
10. Air Temperature (°C)  
    RegCM3 NCEP reanalysis  
    Hostetler et al. 2011

\[ r^2 = 0.90; \text{ RMSE} = 0.97°C \]

Spatial Model
SpoKoot Temp Model Parameter Comparisons

* = significant at p < 0.05

**Spatial covariates**
- Elevation
- Stream slope
- Lake
- Annual precip
- Latitude
- Baseflow index
- Drainage area
- Riparian canopy
- Air temperature
- Discharge

**Temporal covariates**

Manage?
Models Enable Climate Scenario Maps

Many possibilities exist...

Adjust...
- Air
- Discharge
- %Canopy

...values to create scenarios
## Climate Scenario Descriptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>S1_93_11</td>
<td>Historical scenario representing 19 year average August mean stream temperatures for 1993-2011</td>
</tr>
<tr>
<td>S2_02_11</td>
<td>Historical scenario representing 10 year average August mean stream temperatures for 2002-2011</td>
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<tr>
<td>S3_1993</td>
<td>Historical scenario representing August mean stream temperatures for 1993</td>
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<td>S4_1994</td>
<td>Historical scenario representing August mean stream temperatures for 1994</td>
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<td>Etc…</td>
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<tr>
<td>S21_2011</td>
<td>Historical scenario representing August mean stream temperatures for 2011</td>
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<tr>
<td>S22_025C</td>
<td>Future scenario adds 0.25°C to S1_93-11</td>
</tr>
<tr>
<td>S23_050C</td>
<td>Future scenario adds 0.50°C to S1_93-11</td>
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<tr>
<td>Etc…</td>
<td></td>
</tr>
<tr>
<td>S33_300C</td>
<td>Future scenario adds 3.00°C to S1_93-11</td>
</tr>
<tr>
<td>S34_PredSE</td>
<td>Standard errors of stream temperature predictions</td>
</tr>
</tbody>
</table>
Historical Year Sequence (1993-2011)
Mean August Temperature - Clearwater Basin

2011

Temperature (°C)
- 3.0 - 8.0
- 8.1 - 10.0
- 10.1 - 12.0
- 12.1 - 15.0
- 15.1 - 27.0

Clearwater R.
Lochsa R.
Selway R.

Air Temp (°C) Discharge (m³/s)

Observed
Predicted

2011
r² = 0.95

1 km prediction resolution
16,700 stream km

Adding n to these?
Future Scenarios (S1, S25, S29)
1993-2011, +1.0°C, +2.0°C

Temperature (°C)
- 3.0 - 8.0
- 8.1 - 10.0
- 10.1 - 12.0
- 12.1 - 15.0
- 15.1 - 27.0
Historic Scenario: SpoKoot Unit (S1_93-11)
1993-2011 mean August stream temperatures

1 kilometer resolution
55,000 stream kilometers
Historic Scenario: SpoKoot Unit (S1_93-11)
1993-2011 mean August stream temperatures

Scenarios are Shapefile Tables Easily Displayed & Queried in ArcMap
Application: Quantify Thermal Degradation

What is the thermal “intrinsic potential” of a stream?

“How much cooler could we make this stream?”

1) Pick “degraded” and “healthy” streams to compare
Application: Quantify Thermal Degradation

2) Block-krige estimates of temperature at desired scale

Bear Valley Creek Mean Temperature

Precise & unbiased estimates
Application: Quantify Thermal Degradation

3) Compare estimates among streams

~2°C cooling is possible

![Diagram showing summer temperature comparison between block kriging and simple random methods.](image-url)
Complimentary Model Information
Strategic & Tactical Information

• QUAL2Kw
• SSTEMP/SNTEMP
• BasinTemp
• Heat Source
• WET-Temp

Mechanistic models...
Application: Regionally Consistent Thermal Niche Definitions

Stream temperature maps + Regional fish survey databases (n ~ 30,000)

NorWeST

Occurrence probability

Temperature (°C)

Wenger et al. 2011b. *CJFAS* **68**:988-1008; Wenger et al., *In Preparation*
Thermal Niches For All Stream Critters

Just need georeferenced biological survey data
Salmon River Bull Trout Habitats

2002-2011 Historical

11.2 °C isotherm

Suitable

Unsuitable
Salmon River Bull Trout Habitats

+1°C Stream Temperature

11.2 °C isotherm

Suitable

Unsuitable
Salmon River Bull Trout Habitats

+2°C Stream Temperature

11.2 °C isotherm

Suitable

Unsuitable
Spatial Variation in Habitat Loss

2002-2011 historical scenario

11.2 °C isotherm
Spatial Variation in Habitat Loss

+1°C stream temperature scenario

11.2 °C isotherm

EFK. Salmon

White Clouds

11.2 °C isotherm
Difference Map Shows Vulnerable Habitats

+1°C stream temperature scenario

11.2 °C isotherm

Where to invest?
Precise Information Regarding Potential Species Invasions & Population Extirpations

1) How much time is left on the clock?

2) Where & how fast could invasions occur?

Small headwater populations may face thermal extirpation this century

x km upstream shift by 2050
Climate Change is Causing Stream Fish Distributions to Shift...

French Fish survey sites (n = 3,500)

Difference in stream fish distributions (1980’s vs 2000’s)

Change in Elevation (m)

32 species

March of the fishes...

Strategic Prioritization of Restoration Actions is Possible

• Maintaining/restoring flow...
• Maintaining/restoring riparian...
• Restoring channel form/function...
• Prescribed burns limit wildfire risks...
• Non-native species control...
• Improve/impede fish passage...

Work here? or here?
NorWeST is a “Crowd-Sourced” Model Developed from Everyone’s Data

Coordinated, Interagency Responses?

Data Collected by Local Bios & Hydros

Management Actions
NorWeST Website Distributes Temperature Products GIS Data

1) GIS shapefiles of stream temperature scenarios

2) GIS shapefiles of stream temperature model prediction precision

3) Temperature data summaries

Google “NorWeST” or go here... http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.shtml
S34_PredSE = Spatially Explicit Maps of Prediction Uncertainty

**Model Predictions**

**Temperature Prediction SE’s**

+ = Thermograph

= SE

SE’s at Prediction Sites

SE’s are small near sites with temperature measurements

Design of “optimal” monitoring networks now possible
Data Availability Provides Flexibility

Daily Data Summaries (Min/Max/Mean)

- Mean
- Maximum
- Minimum
- STD = Standard deviation
- AWAT = Moving 7 day mean
- AWMT = Moving 7 day max
- MWAT = Max of the running 7 day mean
- MWMT = Max of the running 7 day max
- C_12 = # days exceeding 12 °C
- C_14 = # days exceeding 14 °C
- C_16 = # days exceeding 16 °C
- C_18 = # days exceeding 18 °C
- C_20 = # days exceeding 20 °C

• Calculate other metrics
• Fit other models
NorWeST Schedule

Interior Columbia Done by end of 2013
Analytical Stream Ecosystem is Growing
Supporting Research...

Regional Stream Temperature Modeling Approach...

Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes

D. J. Isaak, S. Wollrab, G. Chandler

Climate “Velocity” in streams...

The Blob is Growing...

- 14,370 summers of data swallowed
- 92,000 stream kilometers of thermal ooze mapped
NorWeST Facilitating Related Projects

• Regional bull trout climate vulnerability assessment (J. Dunham)

• Cutthroat & bull trout climate decision support tools (Peterson et al., 2013)

• Landscape-scale bull trout monitoring protocol (Isaak et al. 2009)

• Consistent thermal niche definitions & more accurate bioclimatic models for trout & nongame fishes (S. Wenger, In Prep.)

• Efficient stream temperature monitoring designs
NorWeST Facilitating Related Projects

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“Apps” Run on a Consistent Data Network
Need to Do More With Less, but What If... We Did Much More?

Climate Change

Urbanization & Population Growth

Shrinking Budgets
A Special Thanks to The 60+ Data Contributors and Partner Agencies...