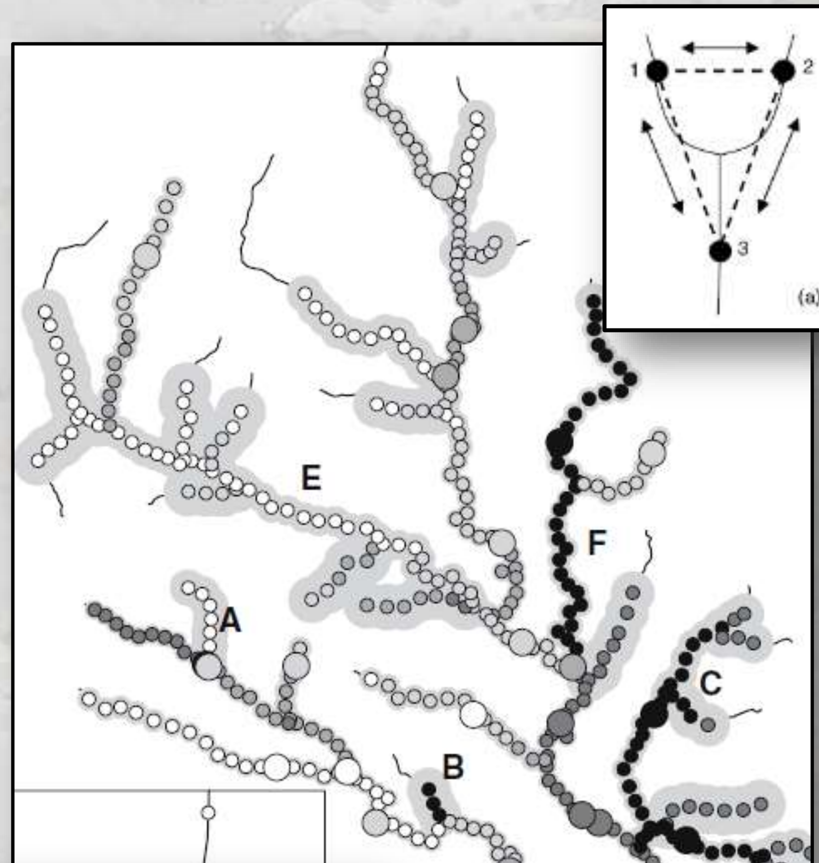
# New Information from Old Stream Data Through Applications of Spatial Statistical Network Models


Dan Isaak

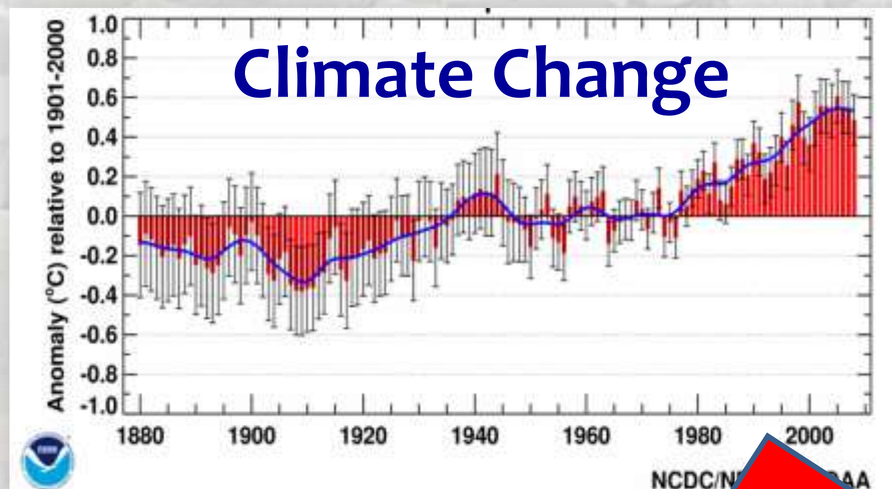
Jay Ver Hoef

Erin Peterson

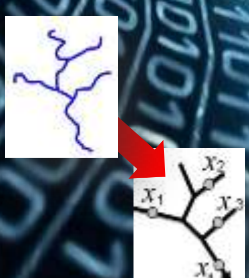

# More Pressure, Fewer Resources

Climate Change



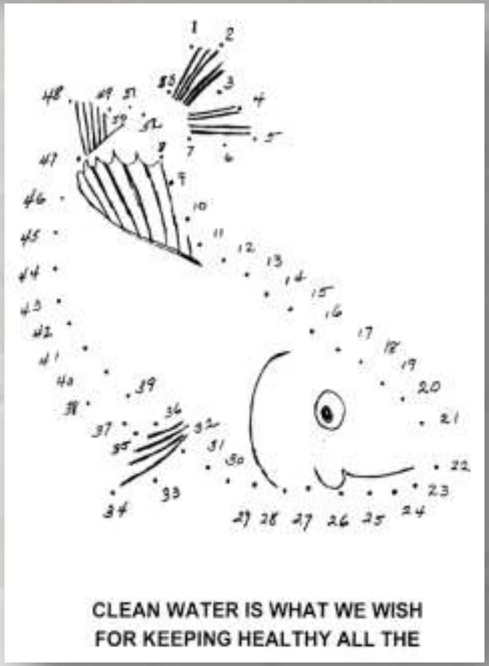

Urbanization & Population Growth

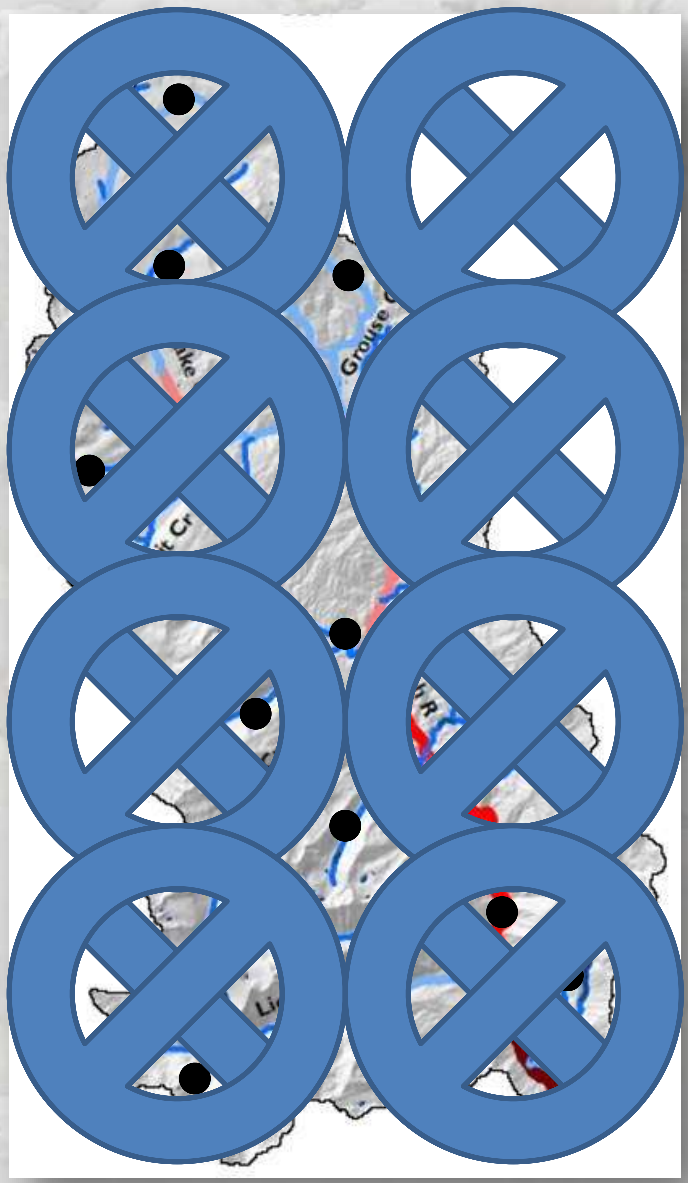
Shrinking Budgets



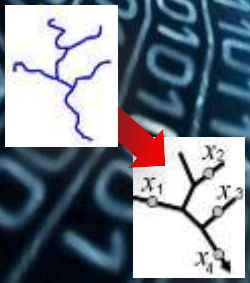

Need to do more with less

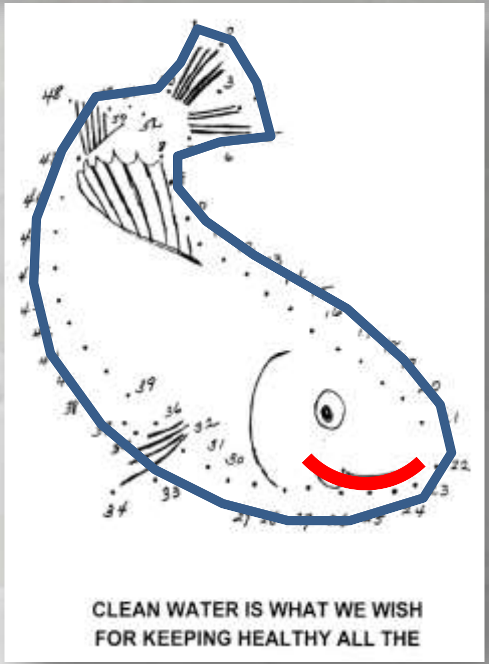
# Stop Viewing Streams as Dots

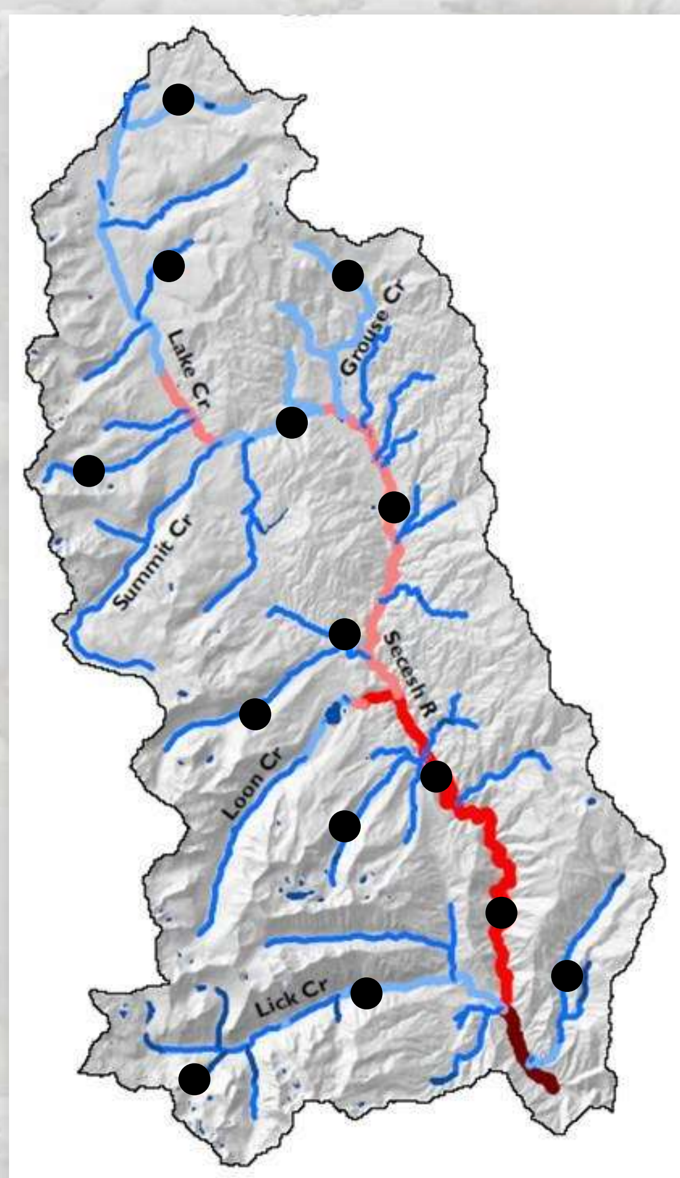


# Connect the Dots to See Networks

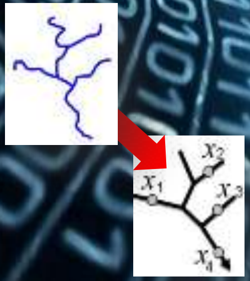




# Where do Fish Fit in a Terrestrial World?

## This is a Tree not a Fish

# A New Type of Statistical Model for Data on Stream Networks

Environ Ecol Stat (2006) 13:449–464
DOI 10.1007/s10651-006-0022-8

ORIGINAL ARTICLE

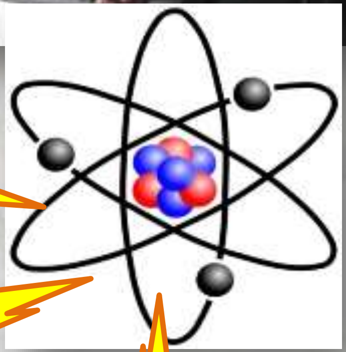
**Spatial statistical models that use flow and stream distance**

Jay M. Ver Hoef · Erin Peterson ·
David Theobald

*Freshwater Biology* (2007) 52, 267–279 doi:10.1111/j.1365-2427.2006.01686.x

**Geostatistical modelling on stream networks: developing valid covariance matrices based on hydrologic distance and stream flow**

ERIN E. PETERSON,* DAVID M. THEOBALD† AND JAY M. VER HOEF‡



**Functional Linkage of Water basins and Streams (FLoWS) v1 User's Guide:**

ArcGIS tools for Network-ba

Authors:
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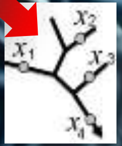
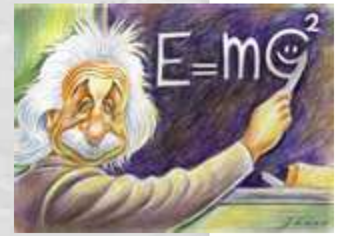
Spatial modelling and prediction on river networks: up model, down model or hybrid?

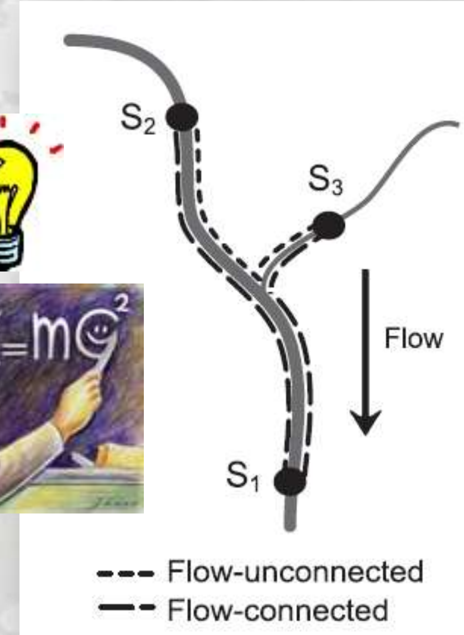
Vincent Garreta[1*,†], Pascal Monestiez[2] and Jay M. Ver Hoef[3]

[1]CEREGE, UMR 6635, CNRS, Université Aix-Marseille, Europôle de l'Arbois, 13545 Aix-en-Provence, France
[2]INRA, Unité de Biostatistique et Processus spatiaux, Domaine St Paul, Site Agroparc, 84914 Avignon Cedex 9, France
[3]NOAA National Marine Mammal Lab, Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115, USA

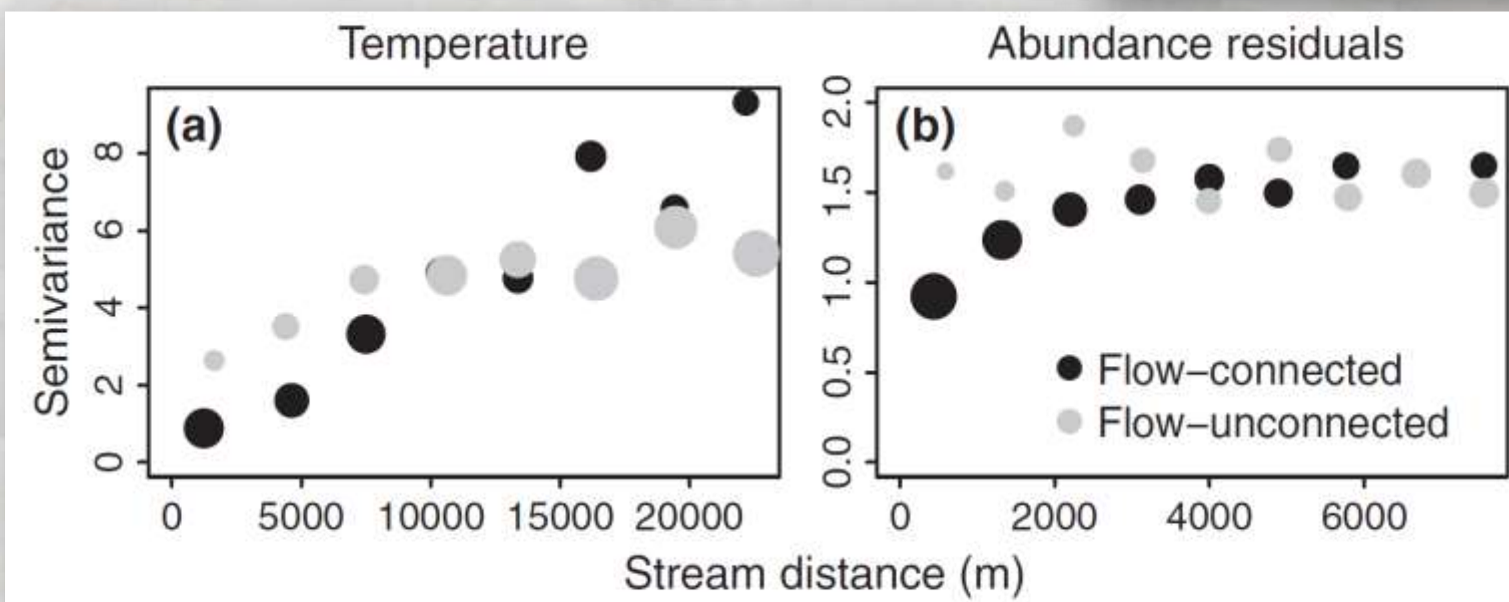


# Key Innovation of Stream Models is Covariance Structure Based On Network Structure



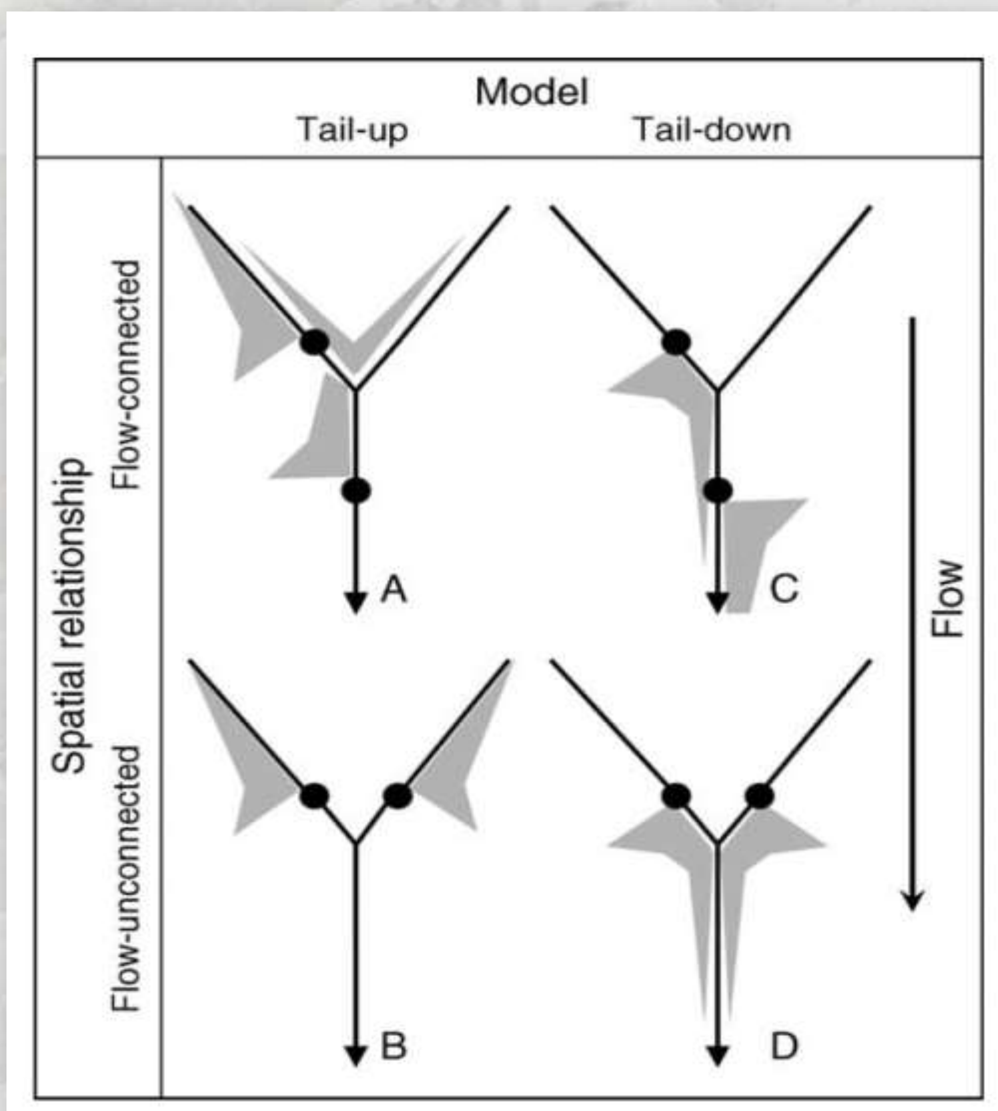

**Models "understand"
how information moves among
locations based on network topology**



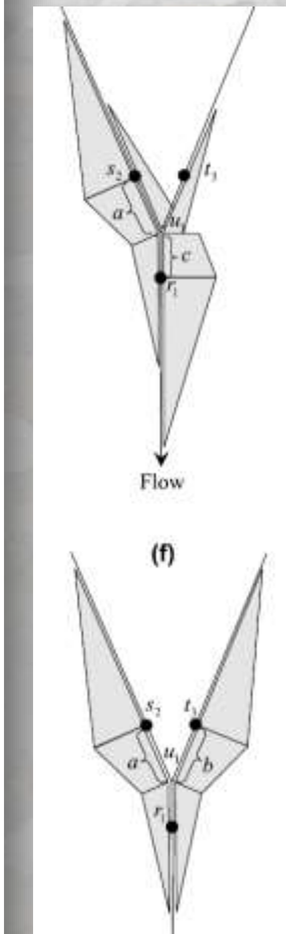


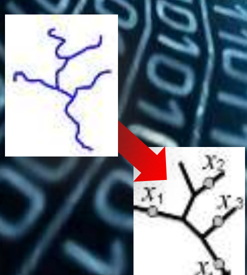
Peterson et al. 2007. *Freshwater Biology* **52**:267-279;
Peterson & Ver Hoef. 2010. *Ecology* **91**:644-651.

# Different Autocovariance Functions Describe Stream Relationships



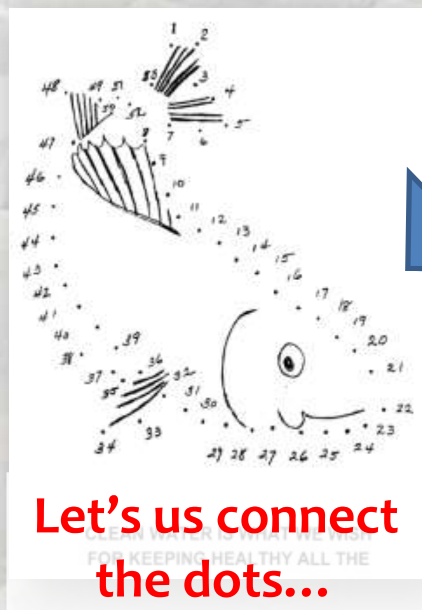

**Mixed**



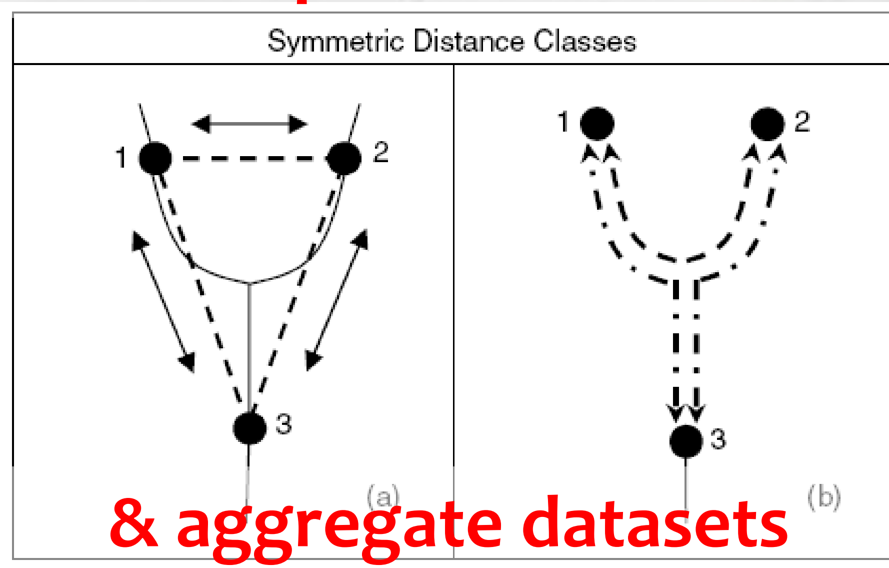
Ver Hoef & Peterson. 2010. *J American Statistical Association* **105:**6-18.

# Spatial Statistical Network Models



Let's us connect the dots…

**Valid interpolation on networks**




**& aggregate datasets**

## Advantages:

-flexible & valid autocovariance structures
that accommodate network topology & non-independence among observations

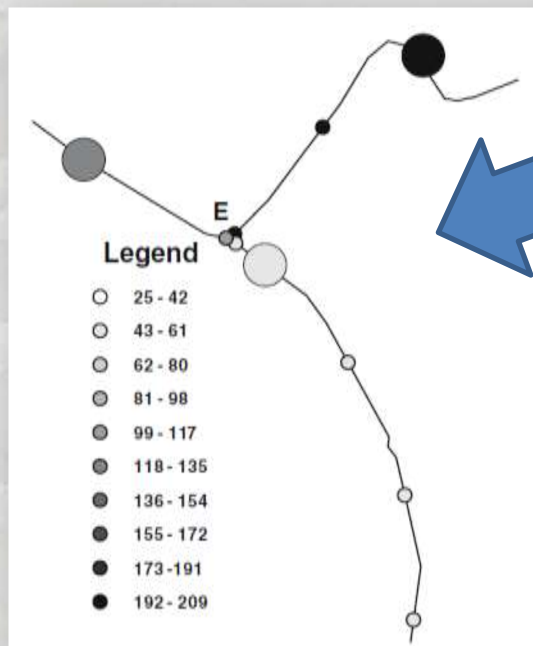
-improved predictive ability & parameter
estimates relative to non-spatial models

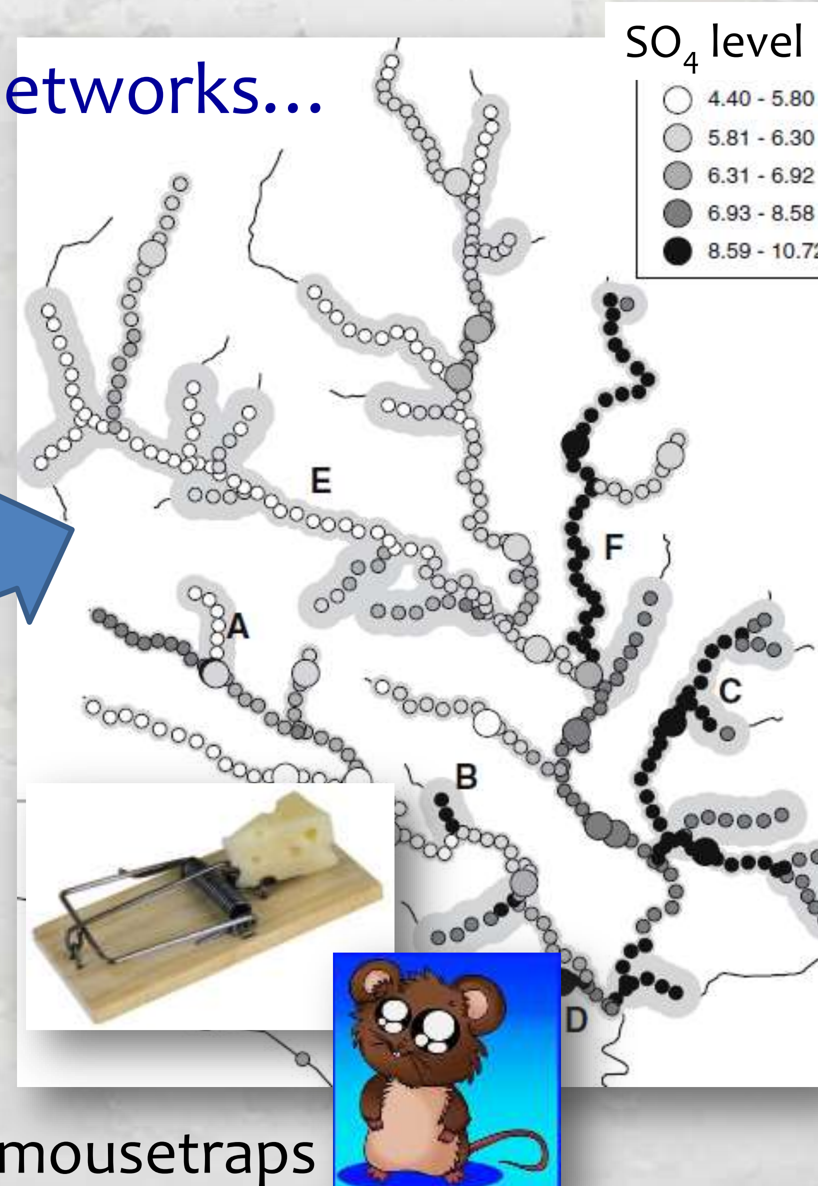
Ver Hoef et al. 2006; Ver Hoef & Peterson 2010; Peterson & Ver Hoef 2013

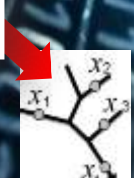
# Spatial Statistical Network Models Work the Way that Streams Do

Gradual trends within networks…

…but also changes at tributary confluences



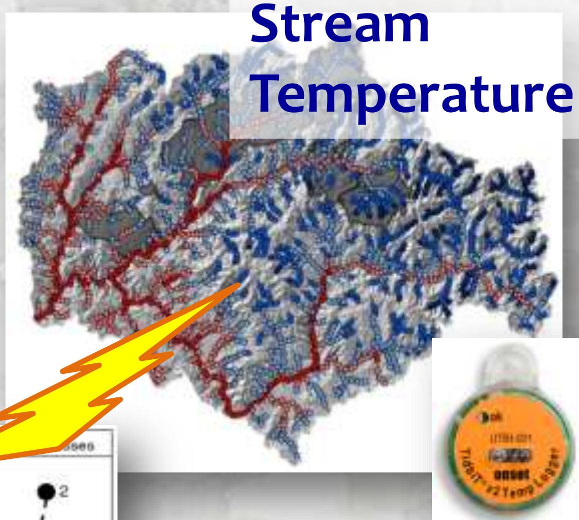

…& are significantly better mousetraps

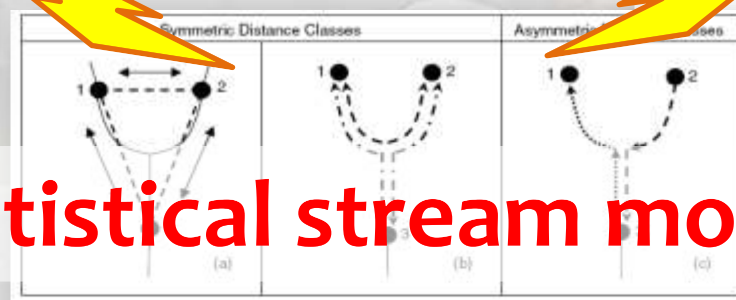
# Stream Models are Generalizable…

Distribution & abundance

Response Metrics
- Gaussian
- Poissan
- Binomial

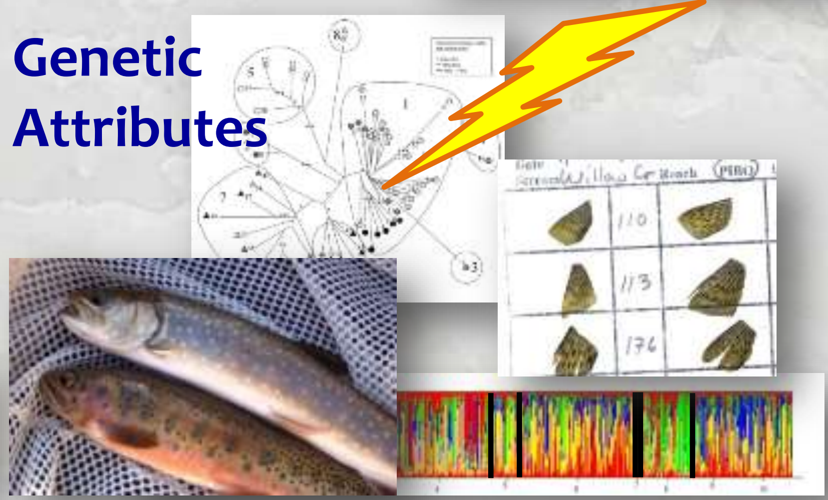
Stream Temperature






**Statistical stream models**

Genetic Attributes



Water Quality Parameters

# Theory – Spatial Statistical Network Models

Cressie N, Frey J, Harch B, and Smith M. 2006. Spatial prediction on a river network. ***J Agricultural, Biological, and Environmental Statistics***. 11:127–150.

Ver Hoef, J.M., E.E. Peterson, and D.M. Theobald. 2006. Spatial statistical models that use flow and stream distance. ***Environmental and Ecological Statistics*** 13:449–464.

Ver Hoef, J.M., and E.E. Peterson. 2010. A moving average approach for spatial statistical models of stream networks. ***J American Statistical Association*** 105:6-18.

*Covariance structure…*

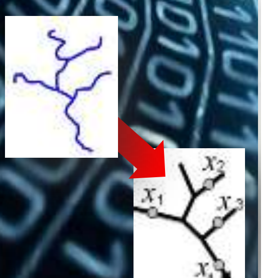
Peterson, E.E., D.M. Theobald, and J.M. Ver Hoef. 2007. Geostatistical modeling on stream networks: developing valid covariance matrices based on hydrologic distance and stream flow. ***Freshwater Biology*** 52:267-279.

Peterson, E.E., J.M. Ver Hoef. 2010. A mixed-model moving-average approach to geostatistical modeling in stream networks. ***Ecology*** 91:644-651.

*Free Software…*

Peterson, E.E., J.M. Ver Hoef. *In Press.* STARS: An ArcGIS toolset used to calculate the spatial data needed to fit spatial statistical models to stream network data. ***Journal of Statistical Software*** x:xxx-xxx.

Ver Hoef, J.M., E.E. Peterson, D. Clifford, and R. Shah. *In Press*. SSN: An R package for spatial statistical modeling on stream networks. ***Journal of Statistical Software*** x:xxx-xxx.



# Applications – Spatial Statistical Network Models


Gardner K, McGlynn B. 2009. Seasonality in spatial variability and influence of land use/land cover and watershed characteristics on stream water nitrate concentrations in a developing watershed in the Rocky Mountain West. ***Water Resources Research* 45**, DOI: 10.1029/2008WR007029.

Isaak DJ, Luce CH, Rieman BE, Nagel DE, Peterson EE, Horan DL, Parkes S, Chandler GL. 2010. Effects of climate change and recent wildfires on stream temperature and thermal habitat for two salmonids in a mountain river network. ***Ecological Applications* 20**:1350-1371.

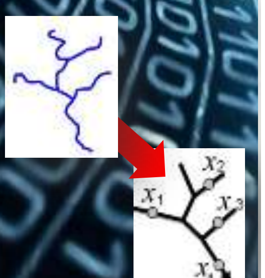
Isaak, D.J., E. Peterson, J. V. Hoef, S. Wenger, J. Falke, C. Torgersen, C. Sowder, A. Steel, M.J. Fortin, C. Jordan, A. Reusch, N. Som, P. Monestiez. In Review. Applications of spatial statistical stream network models to stream data. ***WIREs - Water*** xxx:xxx.

Money E, Carter G, and Serre M. 2009. Using river distances in the space/time estimation of dissolved oxygen along two impaired river networks in New Jersey. ***Water Research* 43**:1948–1958.

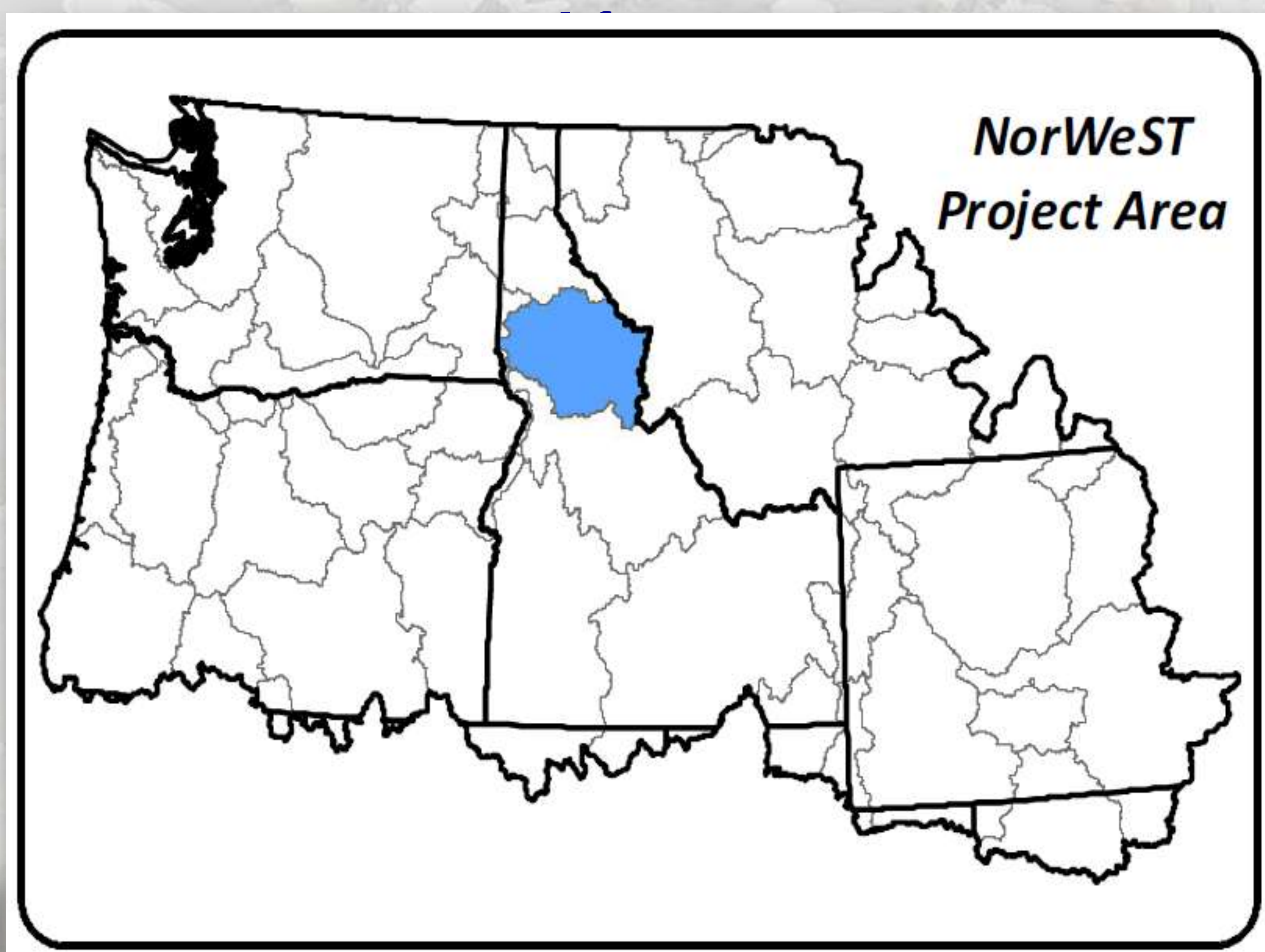
Peterson, EE, Merton AA, Theobald DM, and Urquhart NS. 2006. Patterns of spatial autocorrelation in stream water chemistry. ***Environmental Monitoring and Assessment* 121**:569–594.

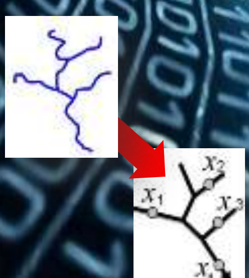
Peterson, EE, and Urquhart NS. 2006. Predicting water quality impaired stream segments using landscape-scale data and a regional geostatistical model: a case study in Maryland. ***Environmental Monitoring and Assessment* 121**:615–638.

Ruesch AS, Torgersen CE, Lawler JJ, Olden JD, Peterson EE, Volk CJ, and Lawrence DJ. 2012. Projected climate-induced habitat loss for salmonids based on a network model of stream temperature. ***Conservation Biology* 26**:873-882.

# Example: Clearwater River Basin



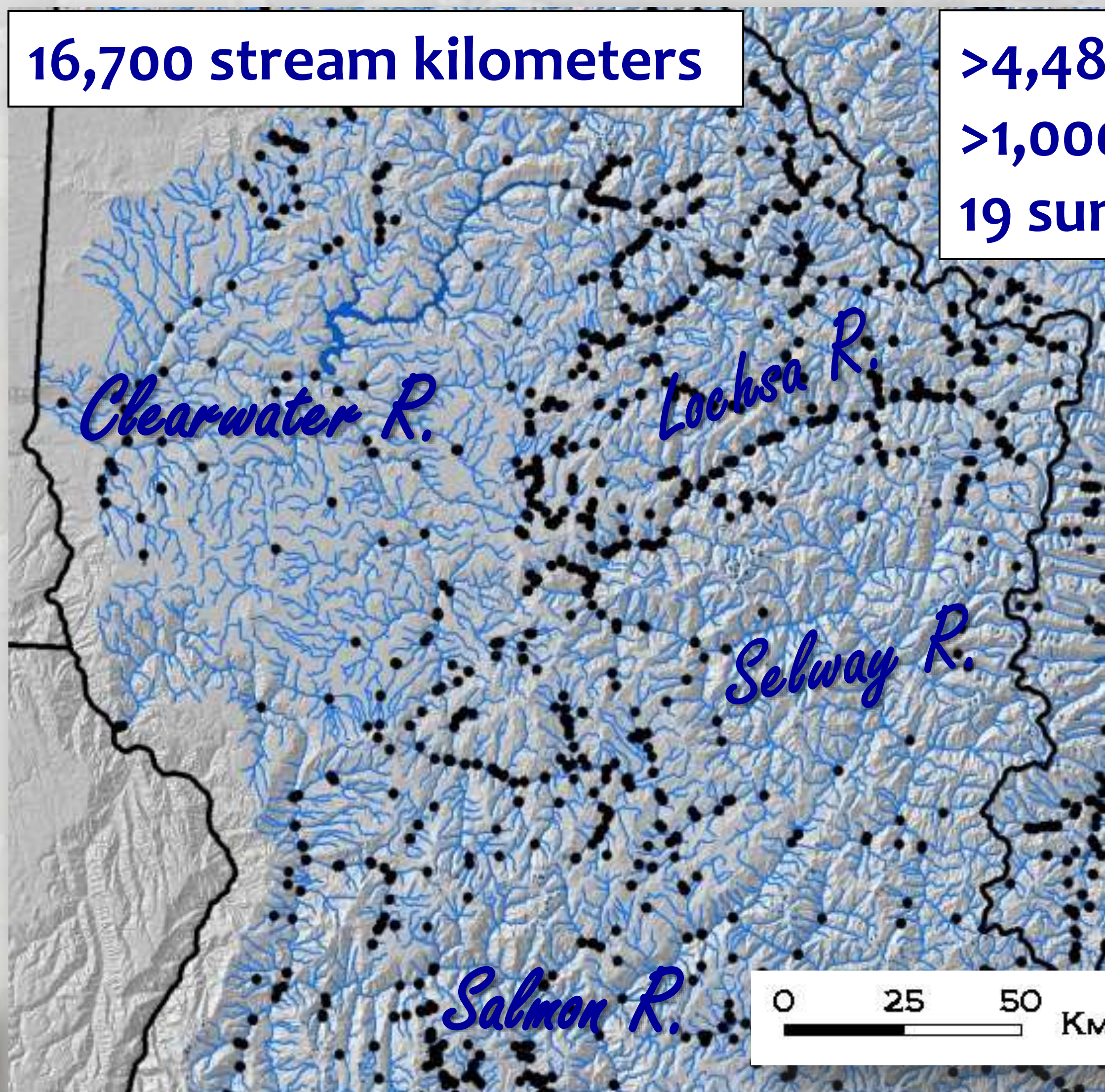



# Example: Clearwater River Basin

## Data extracted from NorWeST

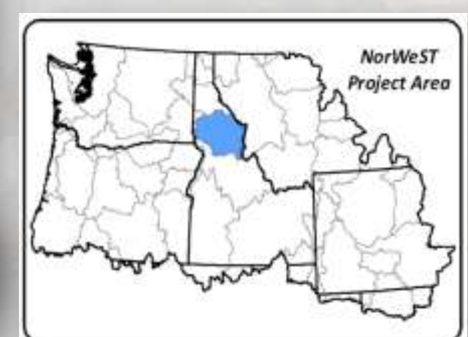
16,700 stream kilometers

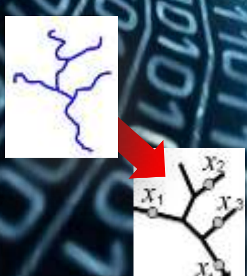
>4,487 August means
>1,000 stream sites
19 summers (1993-2011)





•Temperature site



# Spatial vs Non-Spatial Model Results

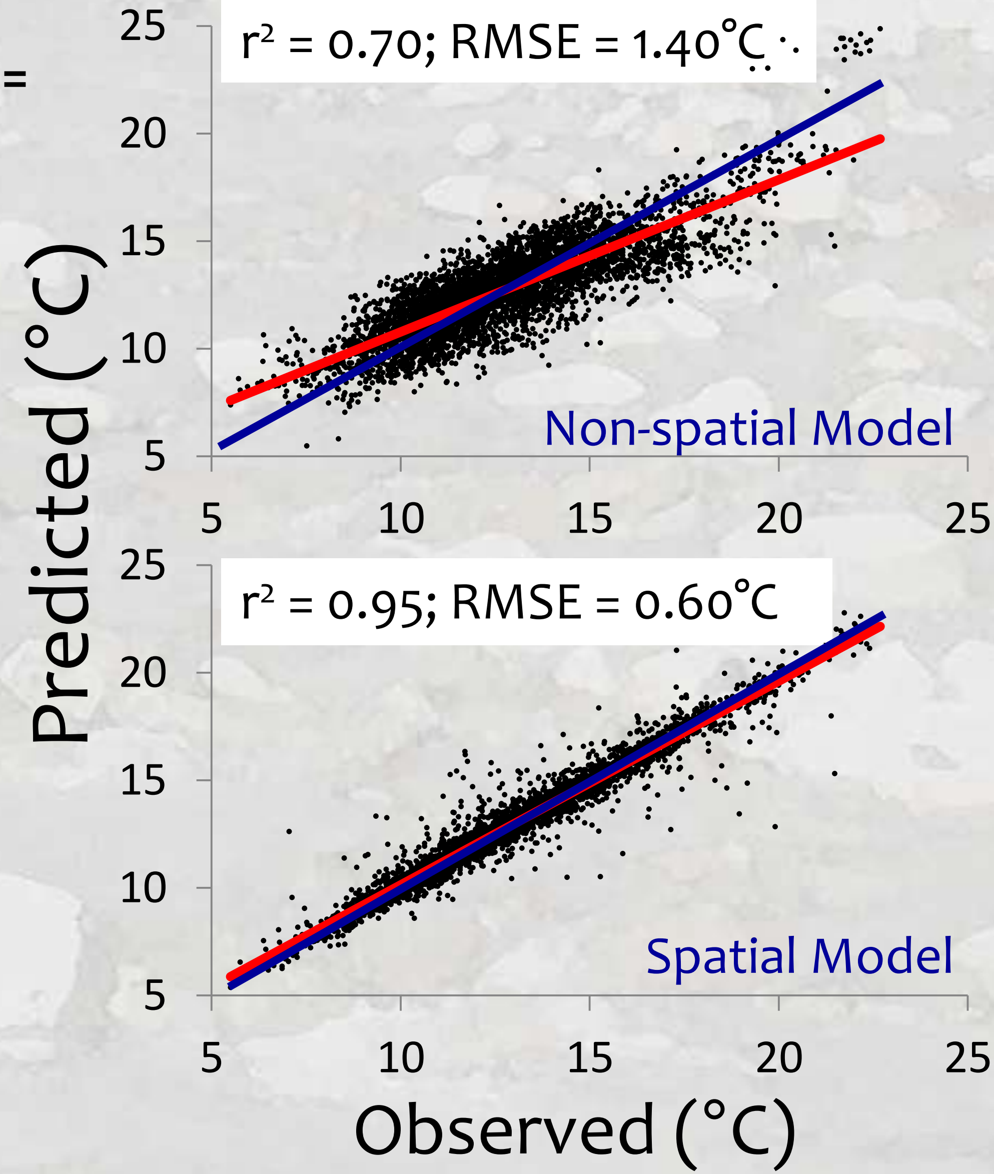
## n = 4,487

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

**Autocorrelation causes parameter bias**

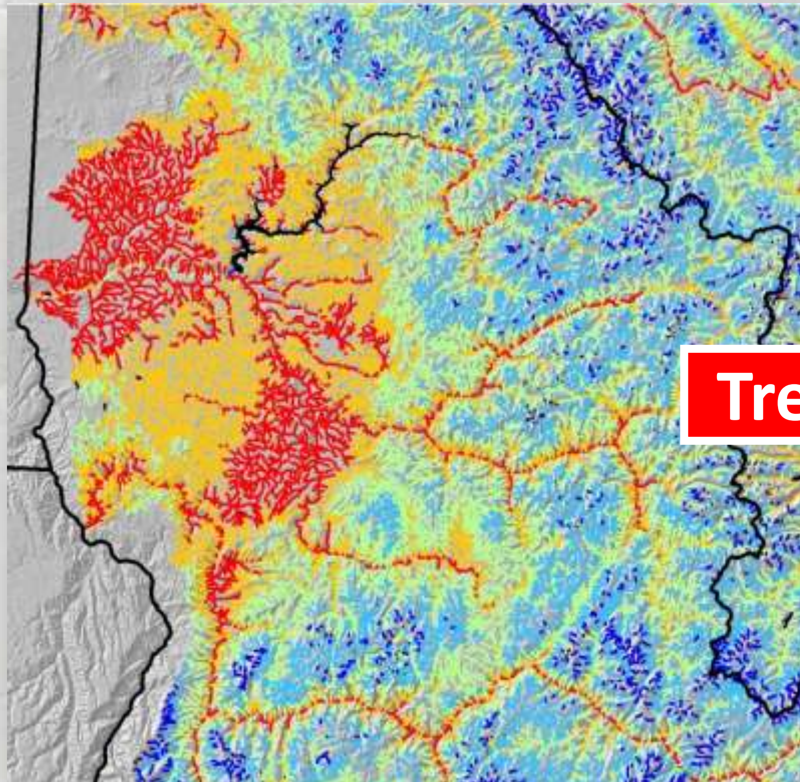
**Spatial Stream Temp =**
– 0.0045*Elevation (m)
+ 0.0085*Radiation
+ 0.48*AirTemp (°C)
– 0.11*Flow (m³/s)

**Mean August Temperature**

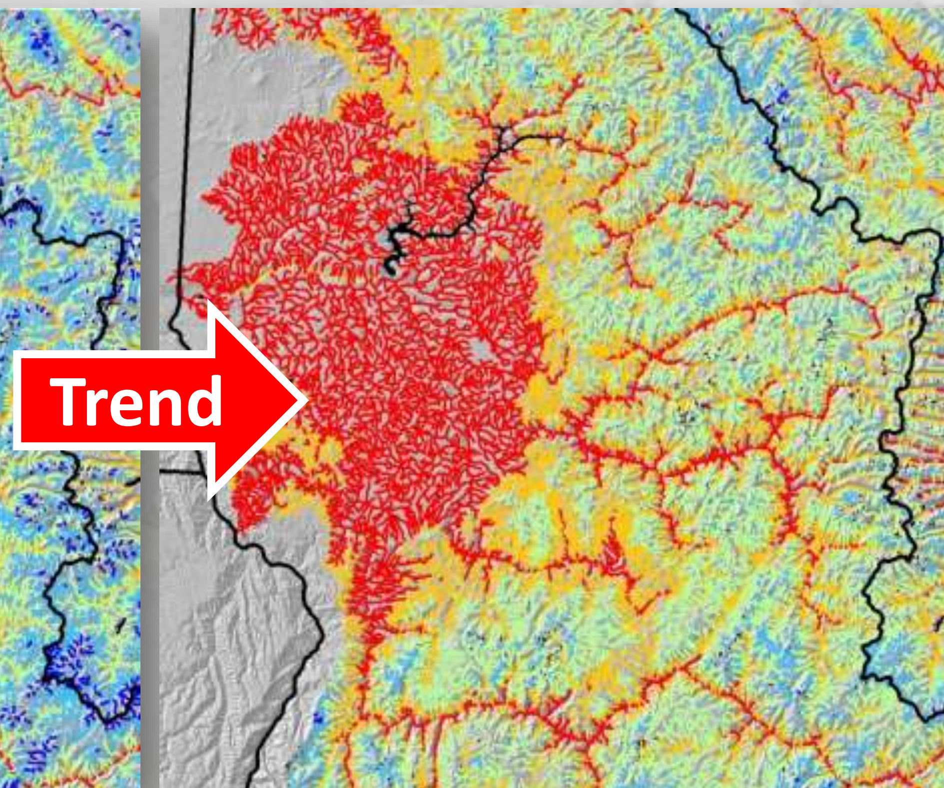


# Accurate Predictions at Sampled (*& Unsampled*) Locations Enable Spatially Continuous *Status* Maps

**Time 1**



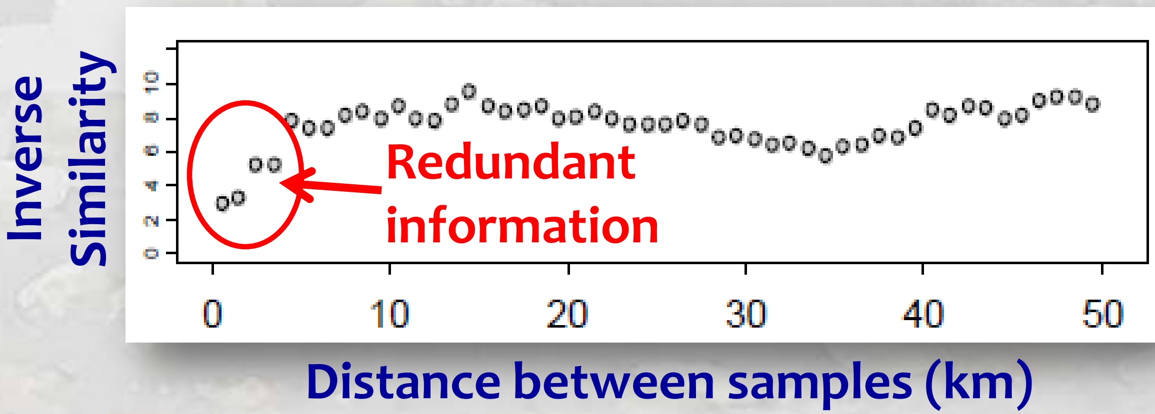
**Time 2**




**Which then facilitate trend assessments…**

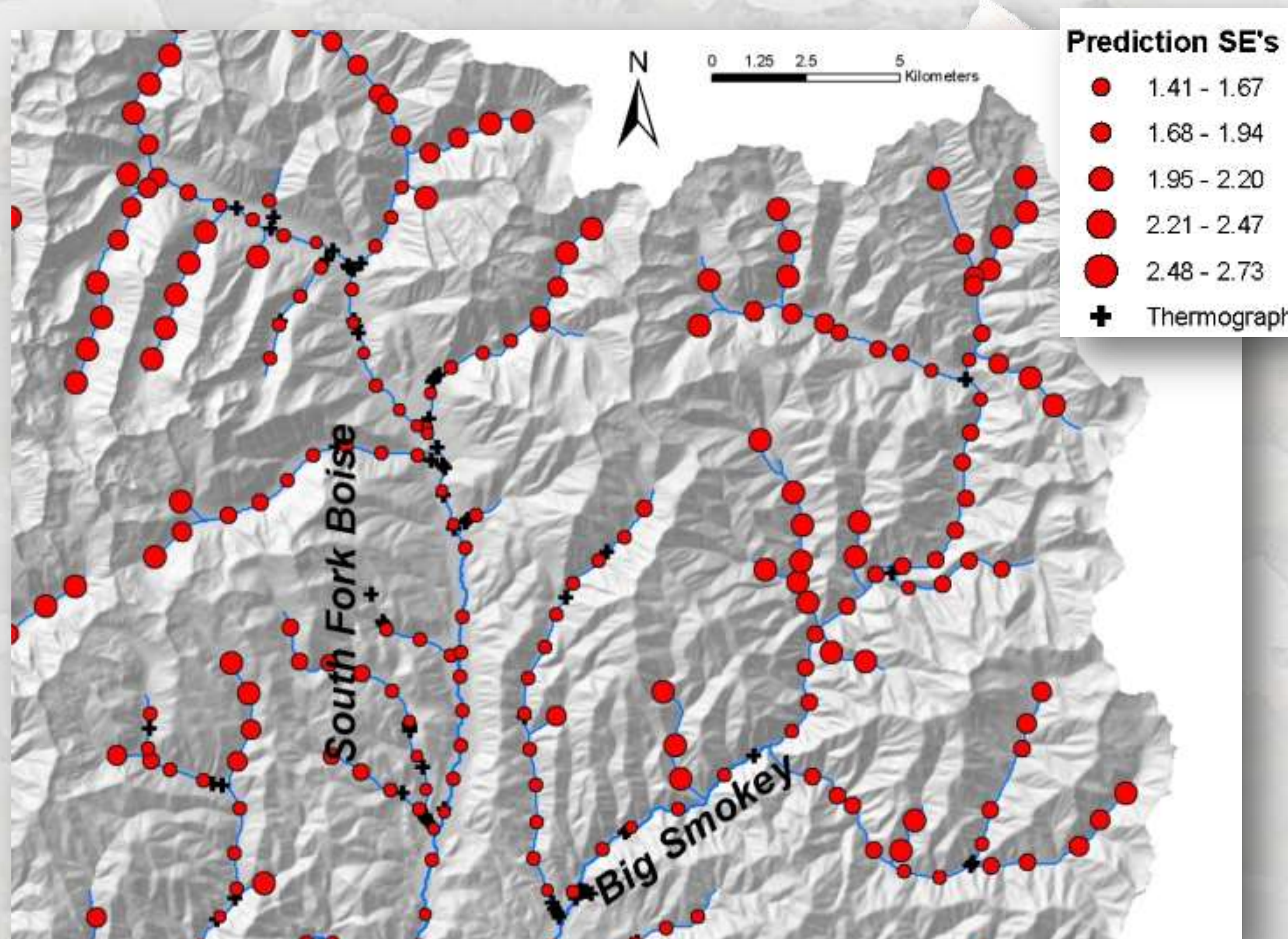
# Efficient Monitoring Designs

## Models Describe Autocorrelation Distances

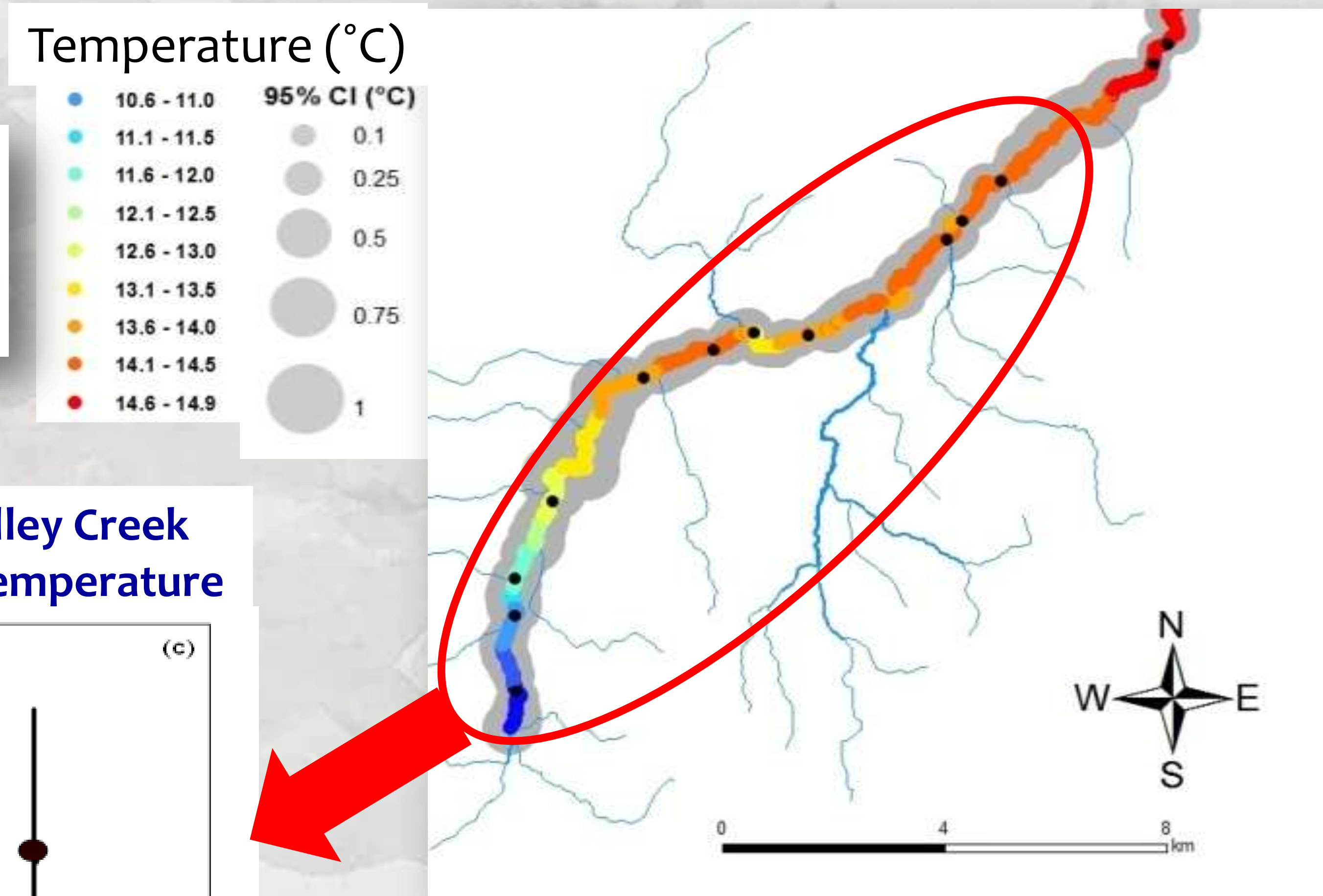




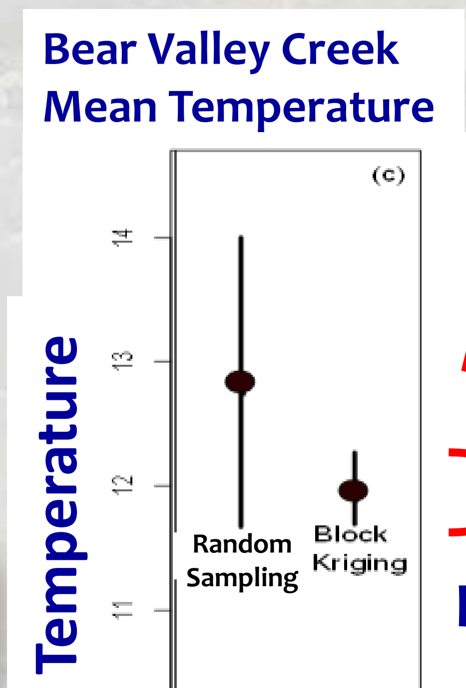
# Spatial Variation in Prediction Precision




# Block-krige Estimates of Mean & Variance at User-Defined Scale







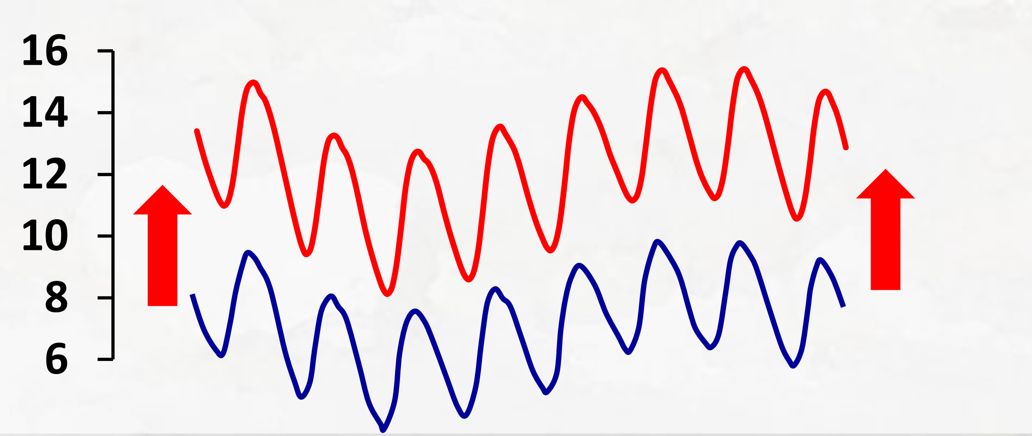

Precise & unbiased estimates

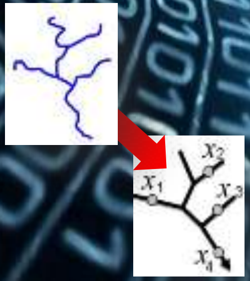
**Does this reach meet the TMDL standard?**

# Reference Site Comparison Approach

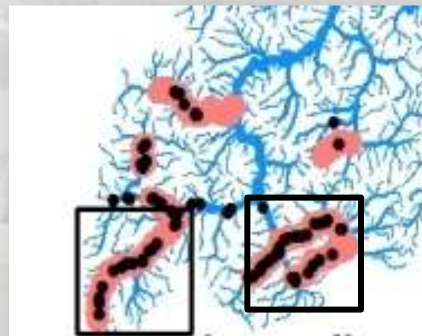
## Pick "degraded" & "healthy" streams to compare

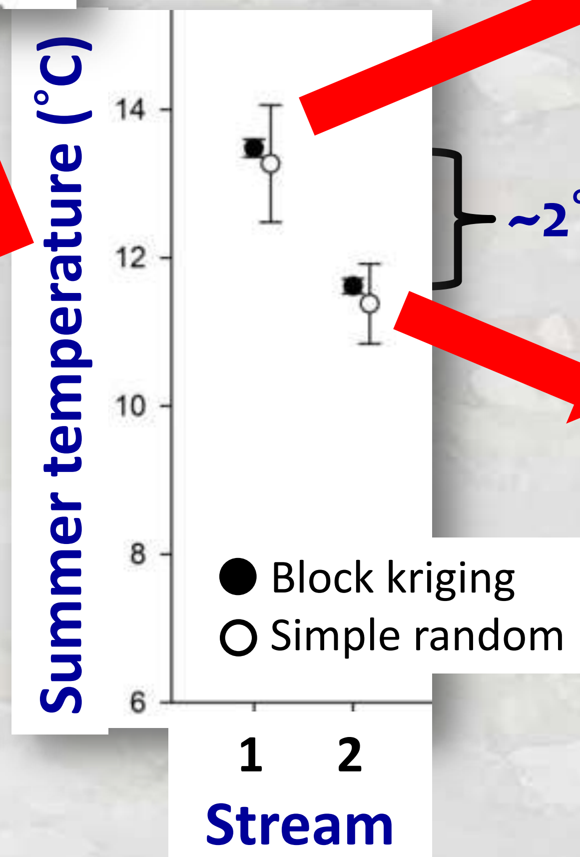
## How altered is this stream?



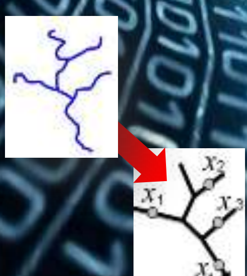



# Block-Krige Estimates for Both Streams

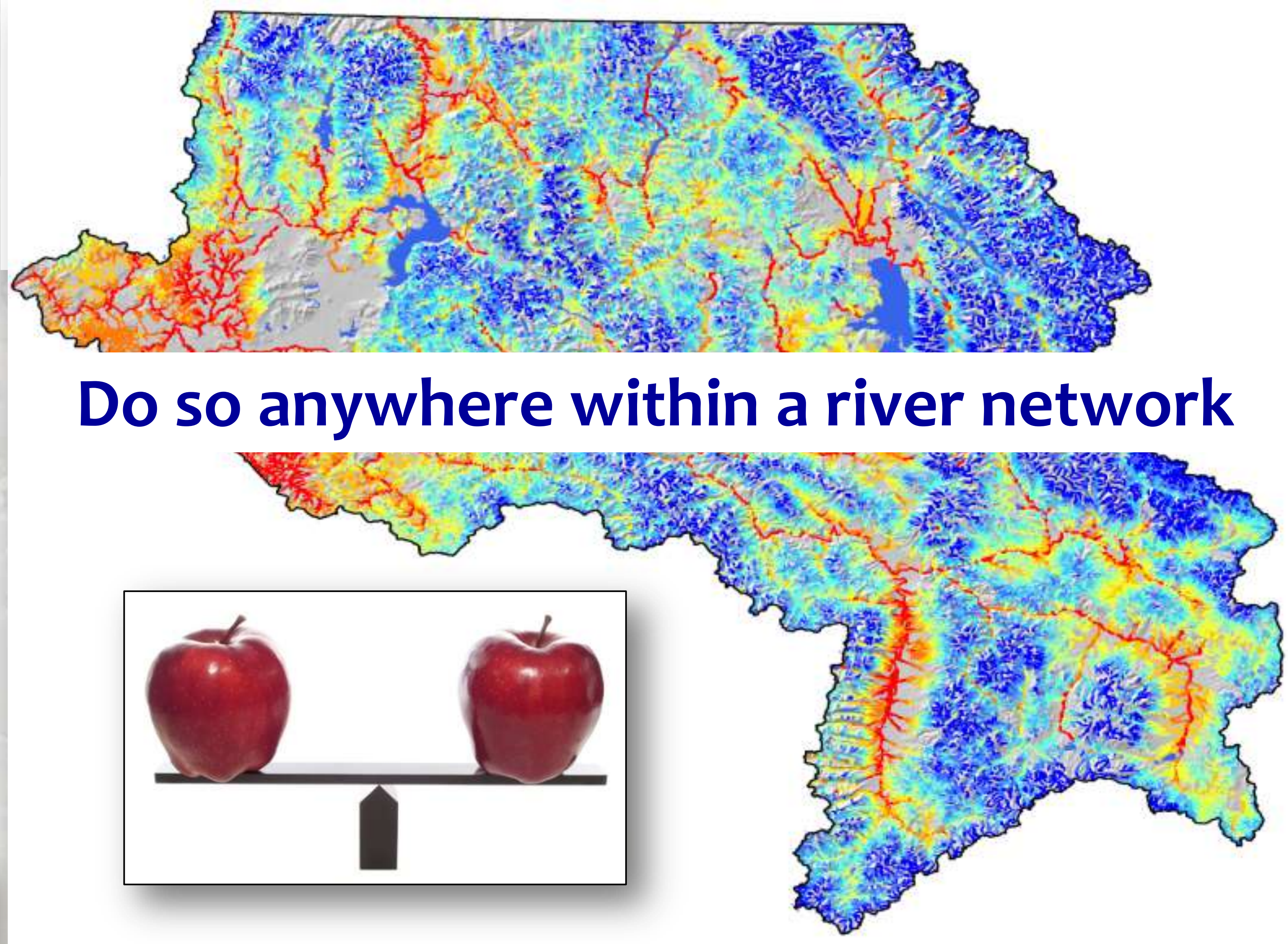





~2°C difference



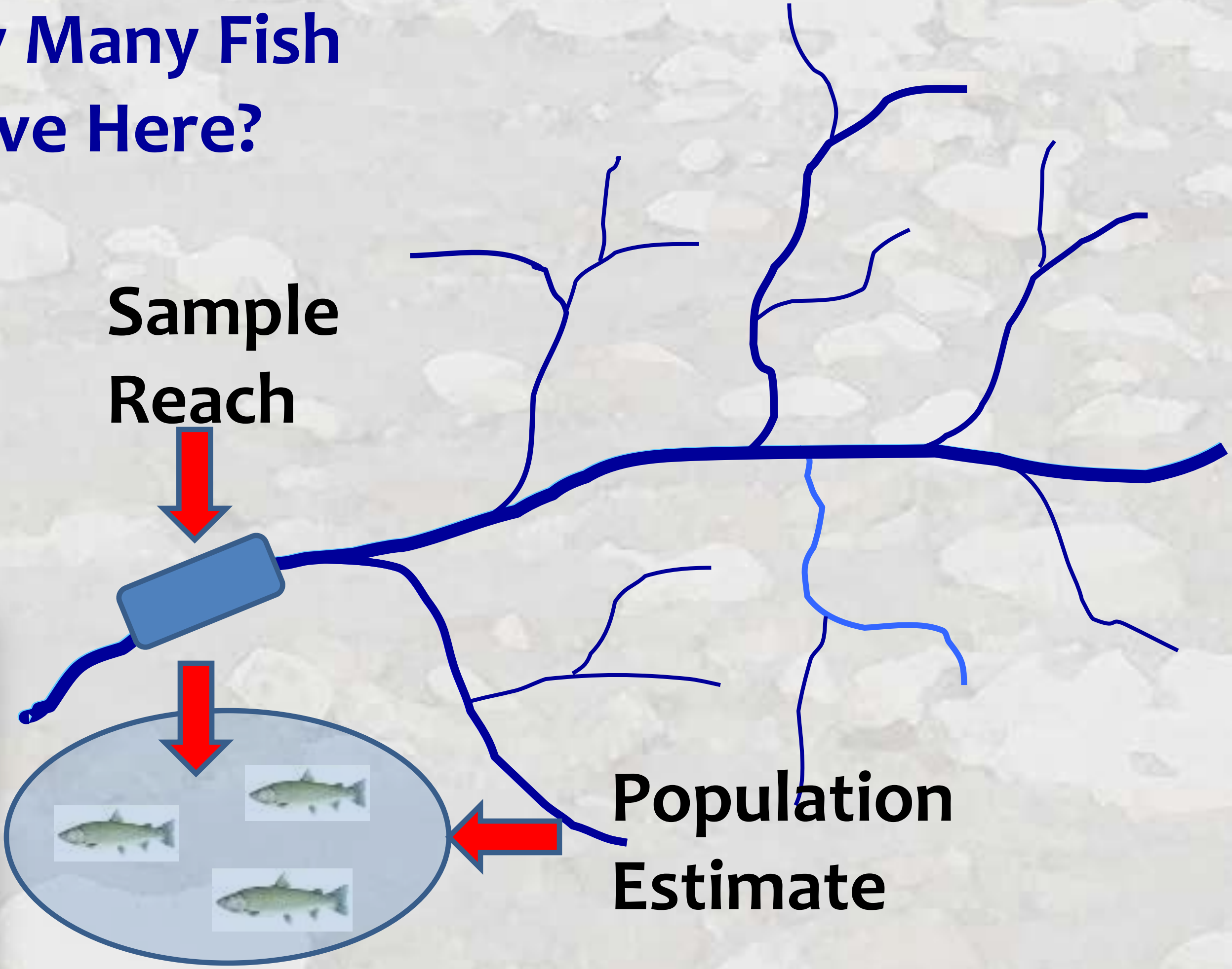
# Block-Krige Estimates for Both Streams

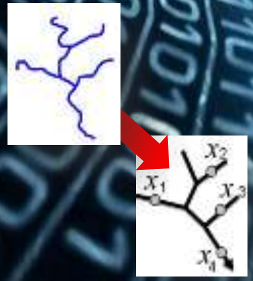


**Do so anywhere within a river network**

# Block-Kriging Fish Population Estimates

**How Many Fish Live Here?**

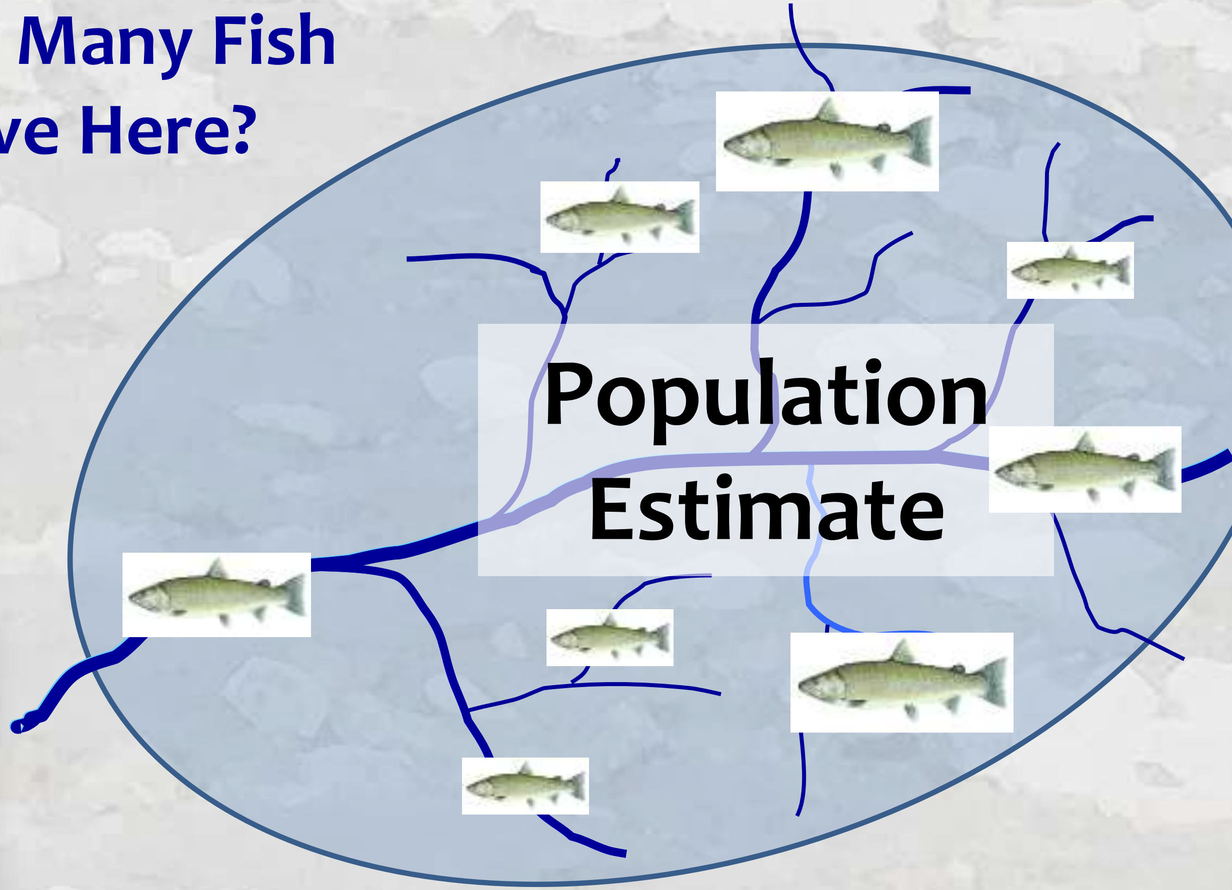


**Traditional Estimation Scale = Reach (10’s – 100’s meters)**

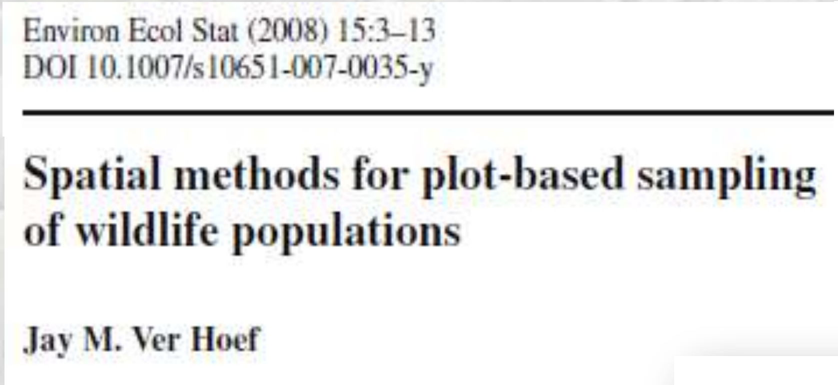
# Block-Kriging Fish Population Estimates

**How Many Fish Live Here?**




**Desired Estimation Scale =**
**Stream & Network (1000's – 10,000's meters)**

# Block-Kriging Fish Population Estimates

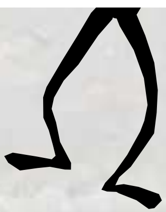


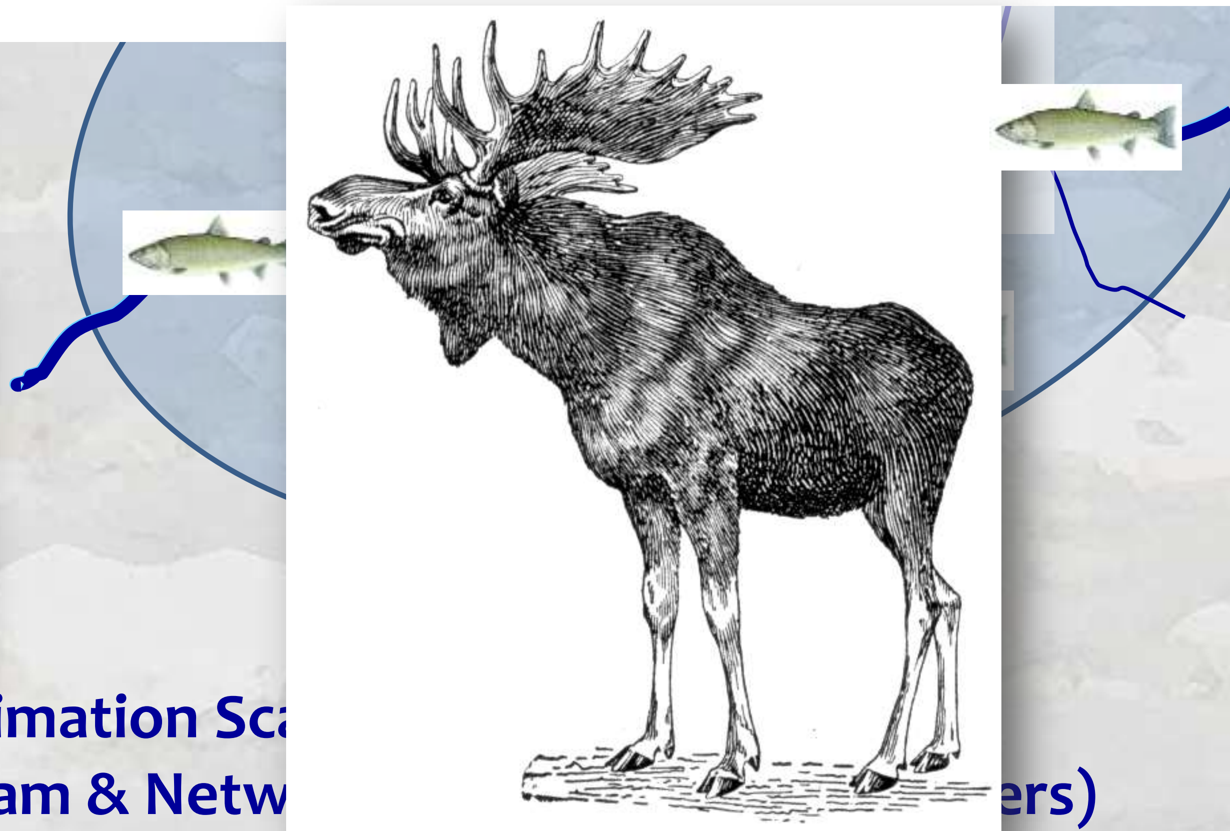
Environ Ecol Stat (2008) 15:3–13
DOI 10.1007/s10651-007-0035-y

**Spatial methods for plot-based sampling of wildlife populations**

Jay M. Ver Hoef

- Terrestrial applications are common
- Theory now exists for streams






Desired Estimation Sca

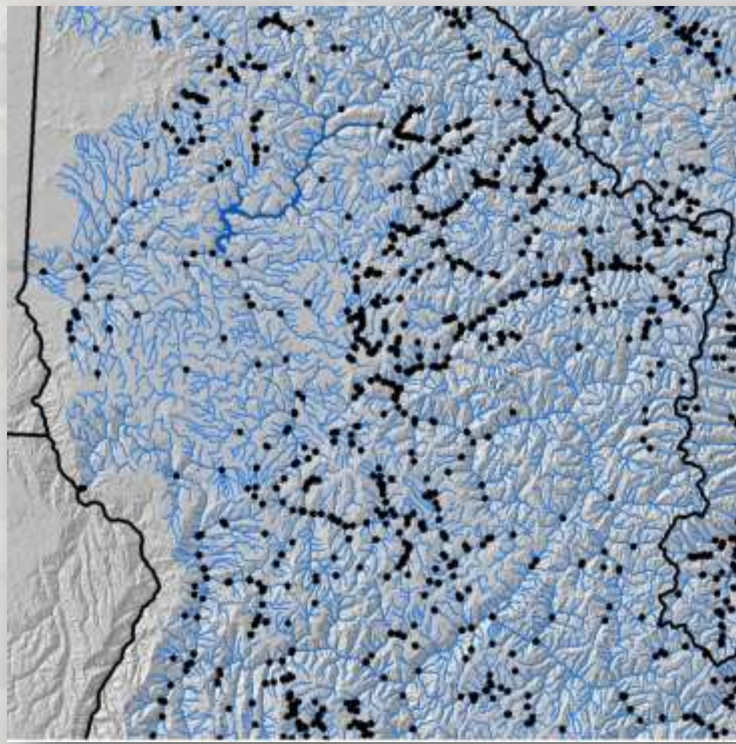
Stream & Netw ers)

# Sample size & computational requirements

**Minimum sample size ~ n ≥ 50 / 100**

**-more parameters with autocovariance**

**-spatial clustering is useful**



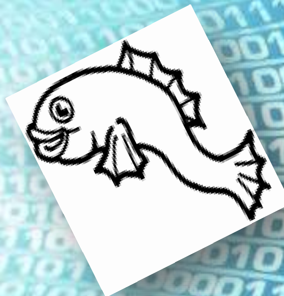
| TO site \ FROM Site | A | B | C | D |
|---|---|---|---|---|
| A | 0 | 28 | 30 | 0 |
| B | 0 | 0 | 15 | 0 |
| C | 0 | 13 | 0 | 0 |
| D | 0 | 0 | 0 | 0 |

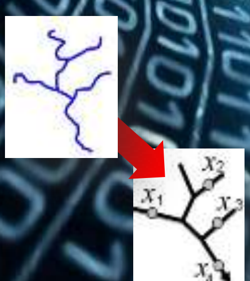
Distance matrix

**Maximum sample size ~ n < 10,000**

**-inversion of n x n matrix**

# A BIG DATA challenge



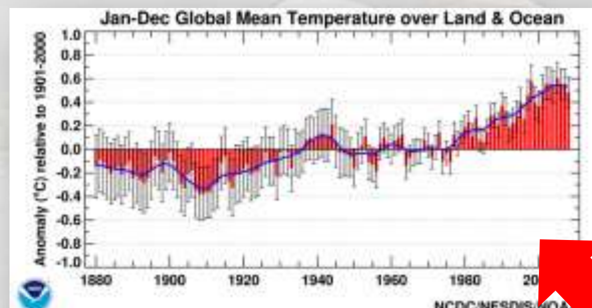


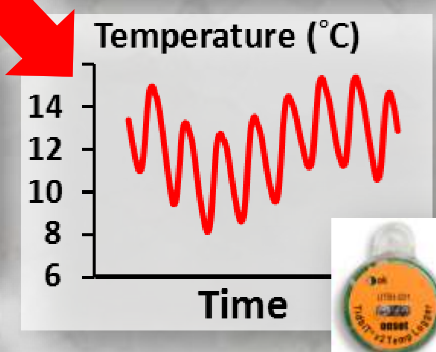
**BIG DATA = BIG INFORMATION?**

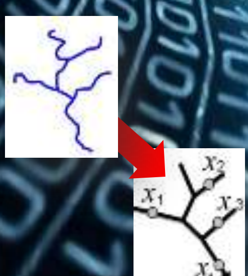
# The NorWeST Stream Temperature Database, Model, & Climate Scenarios


Dan Isaak, Seth Wenger[1], Erin Peterson[2], Jay Ver Hoef[3] Charlie Luce, Steve Hostetler[4], Jason Dunham[4], Jeff Kershner[4], Brett Roper, Dave Nagel, Dona Horan, Gwynne Chandler, Sharon Parkes, Sherry Wollrab, Collete Breshares, Neal Bernklu

U.S. Forest Service
[1]Trout Unlimited
[2]CSIRO
[3]NOAA
[4]USGS

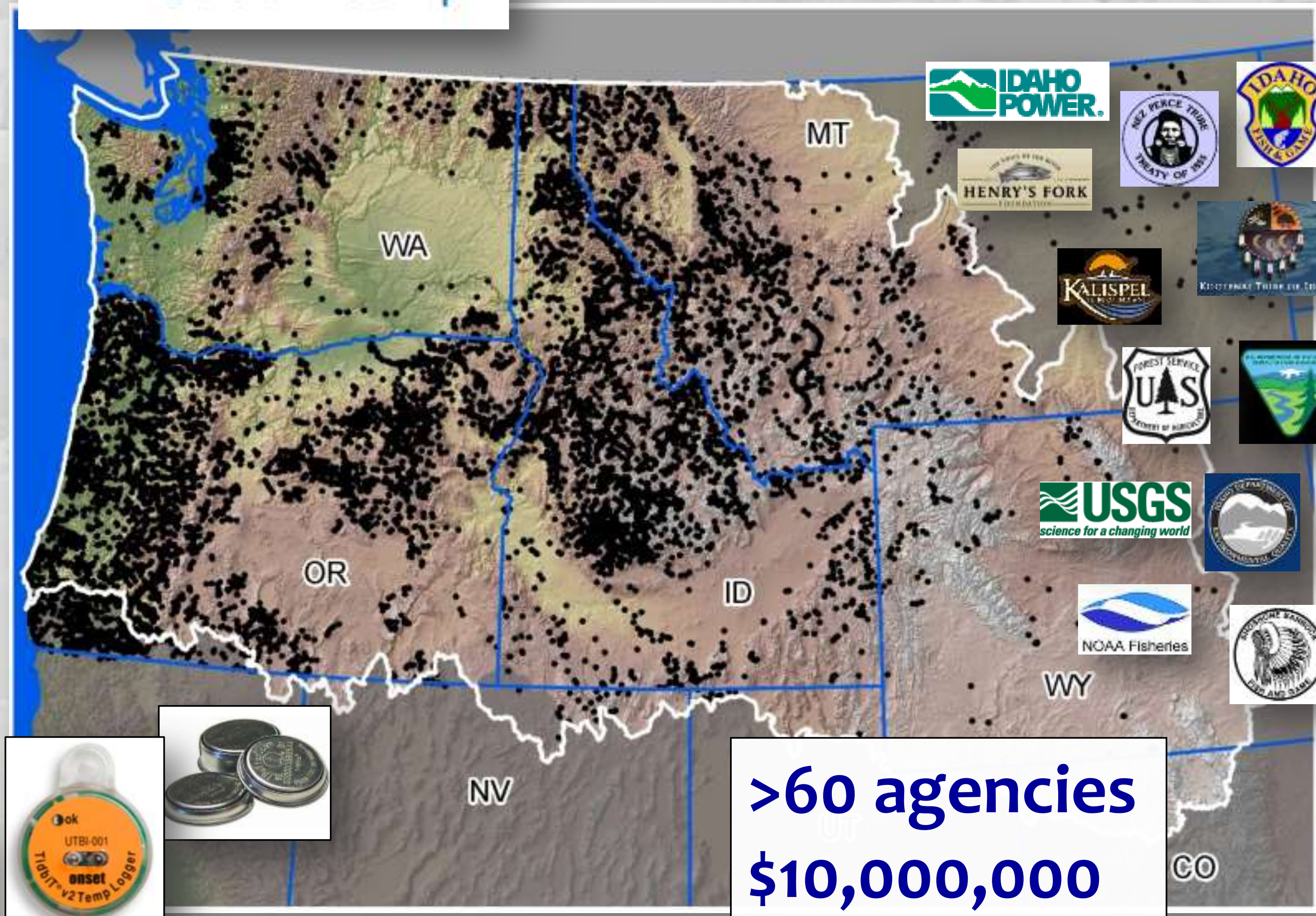



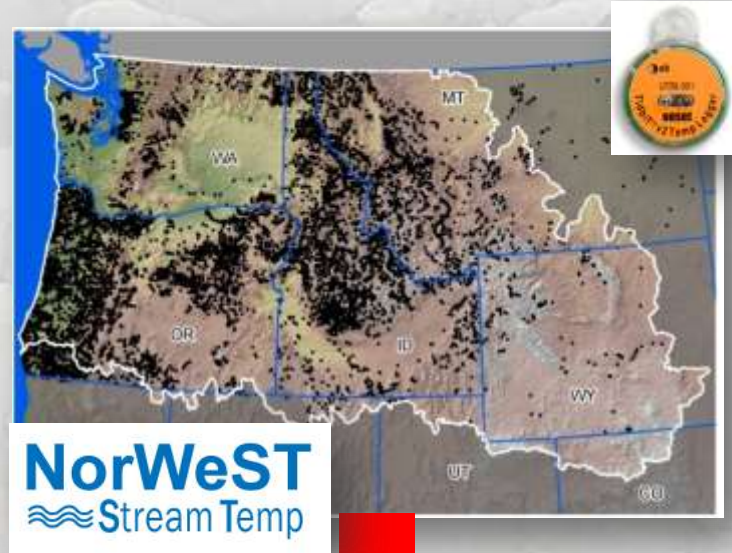
# NorWeST Stream Temp

**>45,000,000 hourly records**
**>15,000 unique stream sites**

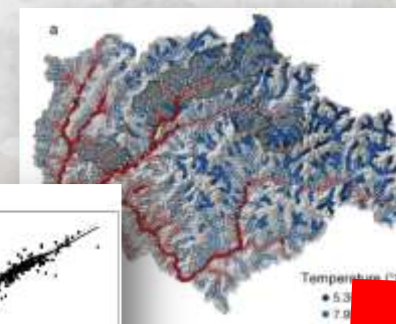


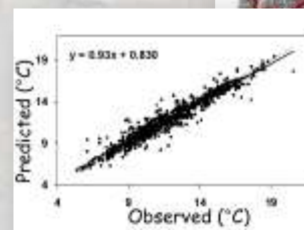

**>60 agencies**
**$10,000,000**


# Regional Temperature Model

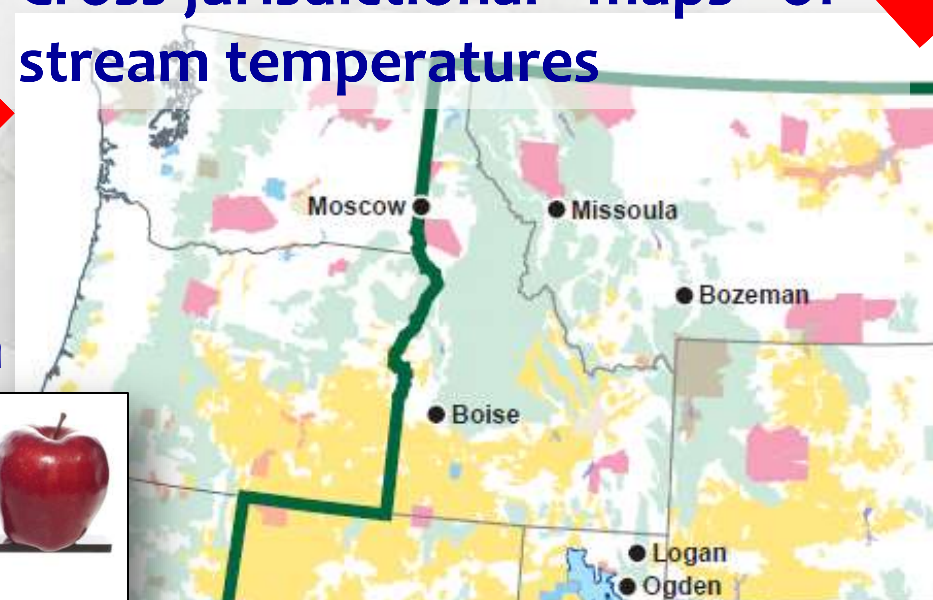



**Spatial stream models**

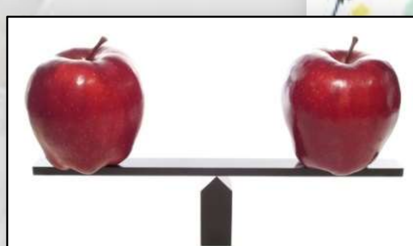


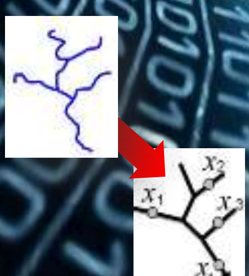



**Cross-jurisdictional "maps" of stream temperatures**

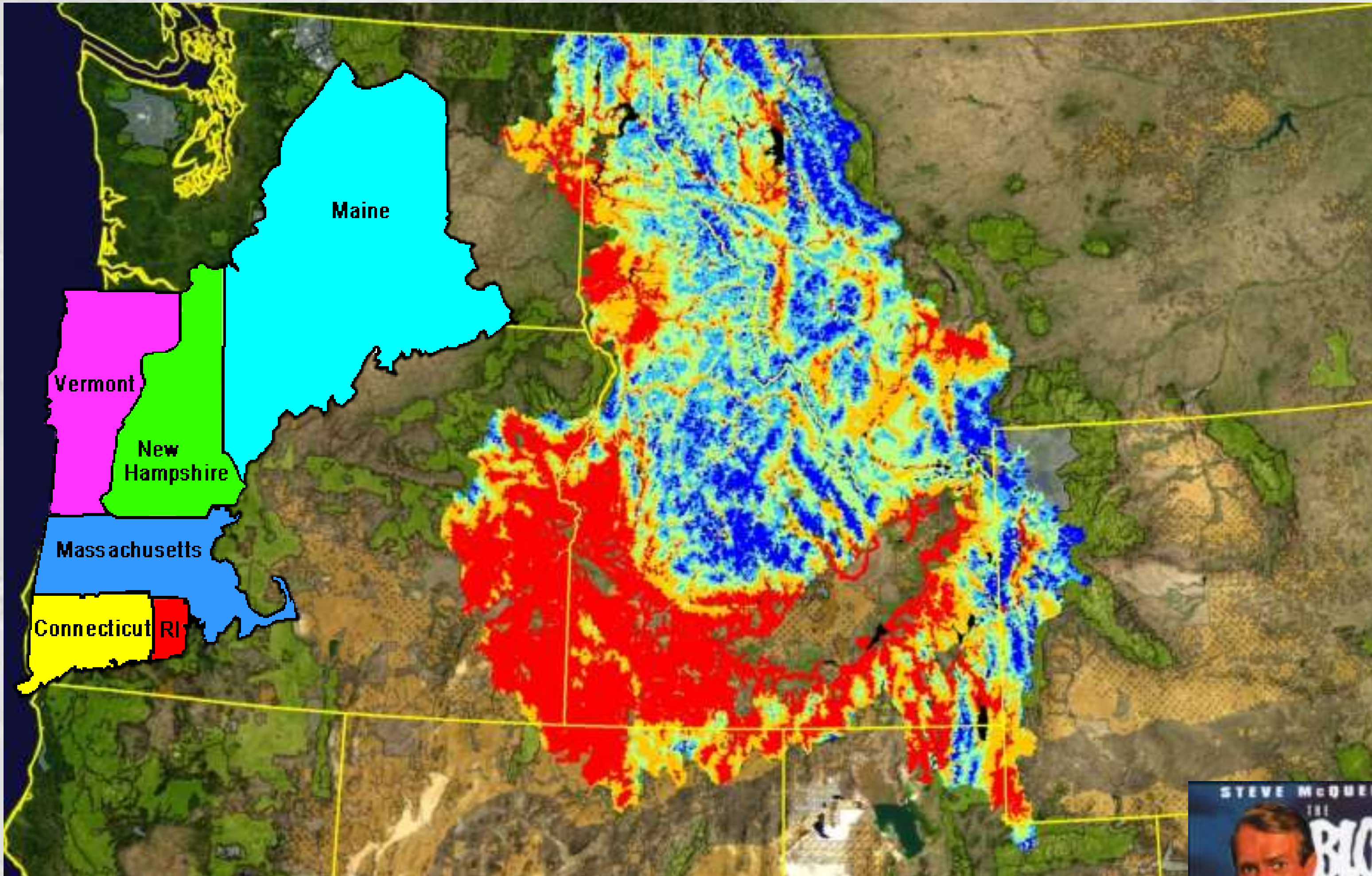


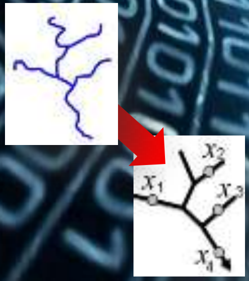

**Consistent planning across 500,000 stream kilometers**





# Stream Thermalscape so Far…

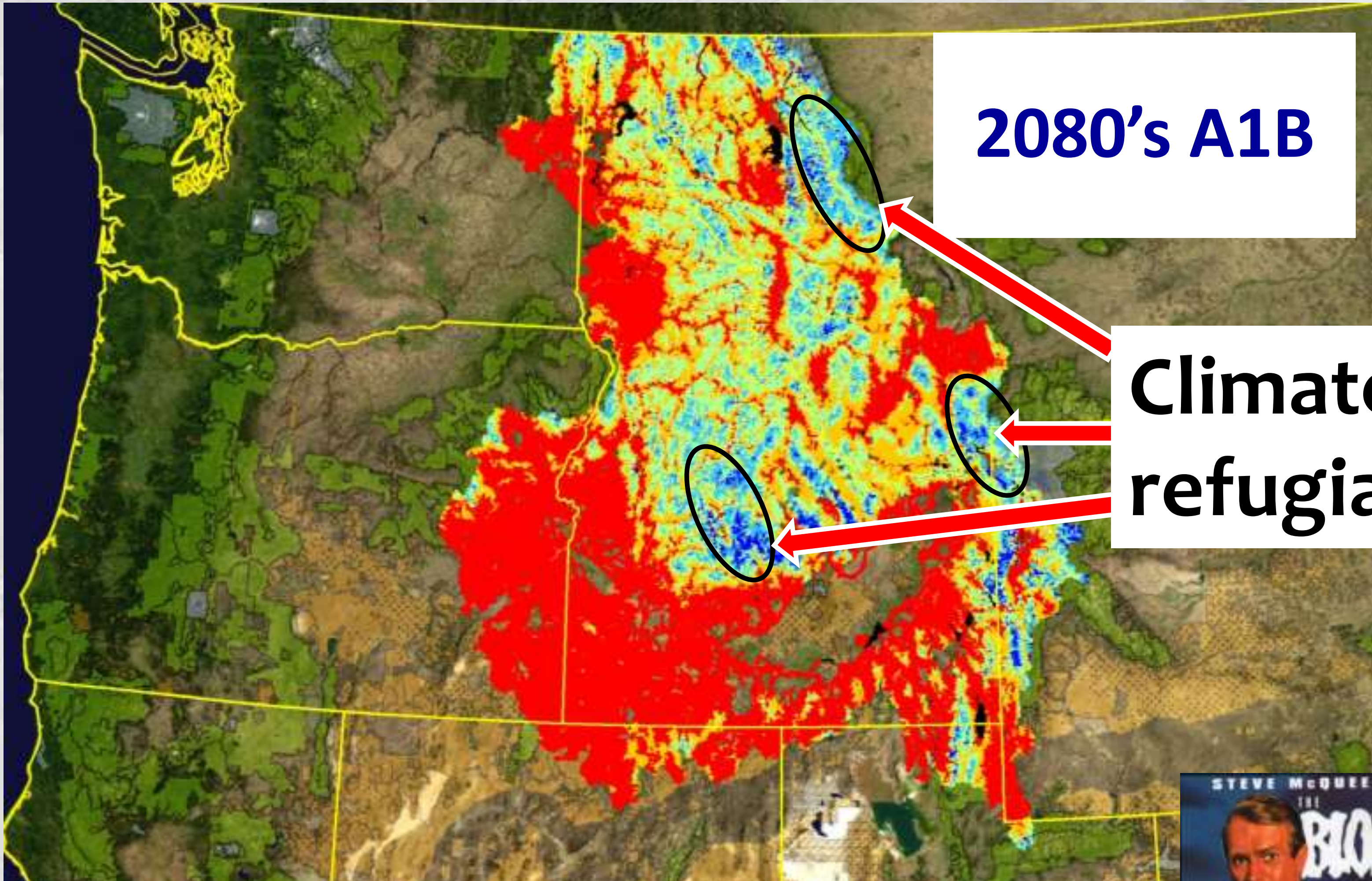


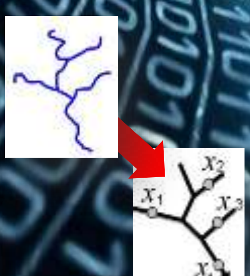




## The BLOB… it just keeps growing…

- 234,000 stream kilometers of thermal ooze
- 20,072 summers of data swallowed

# BLOB Space, but BLOB time too…



## The BLOB… it just keeps growing…

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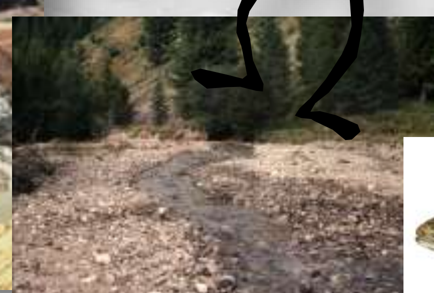
- 20,072 summers of data swallowed

# Climate-Smart Prioritization of Habitat Restoration


## Lots of things we can do…

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



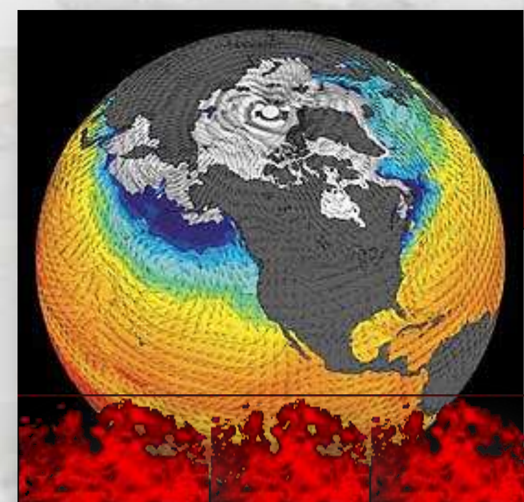





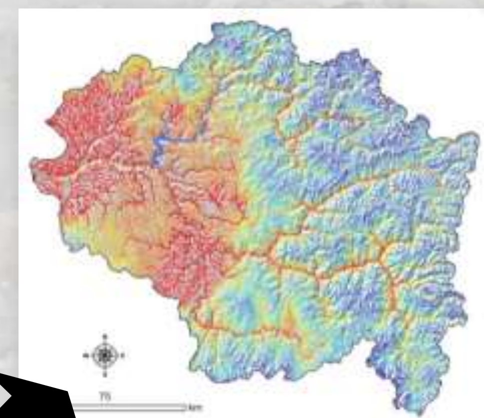

**… but where to do them?**

# Network Models Facilitate Climate Downscaling (& Measurement Upscaling)

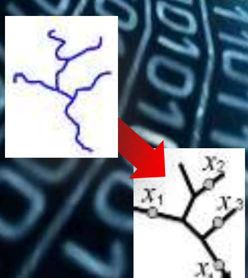
## Global climate model



## River network

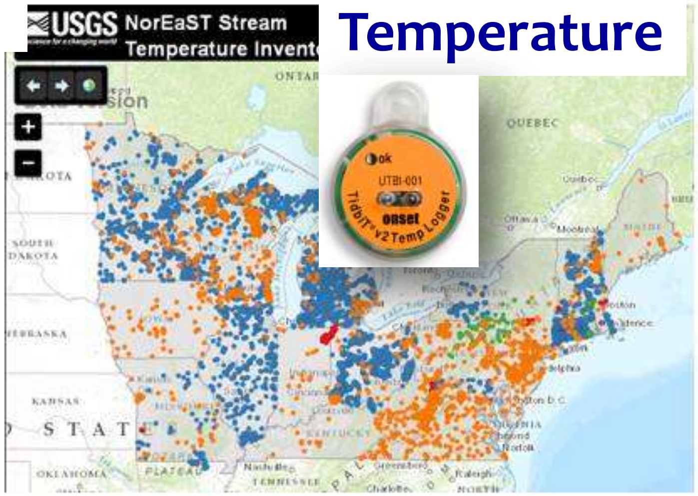


## Stream reach / site

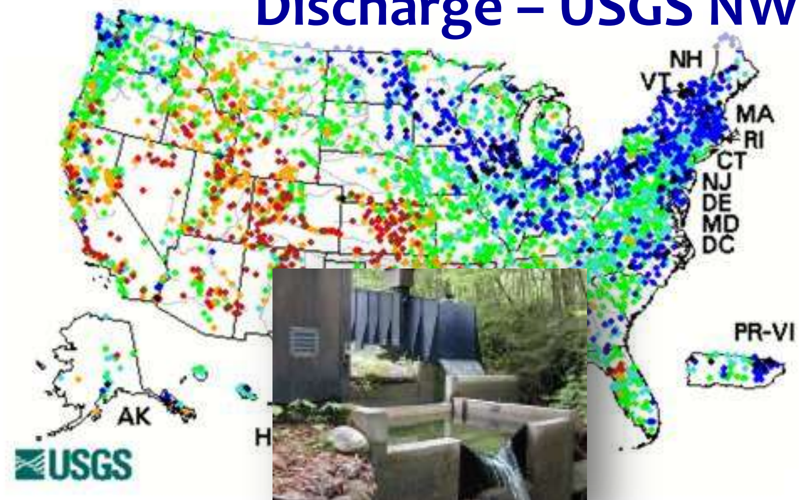


# Spatial Models are Powerful Data Mining Tools

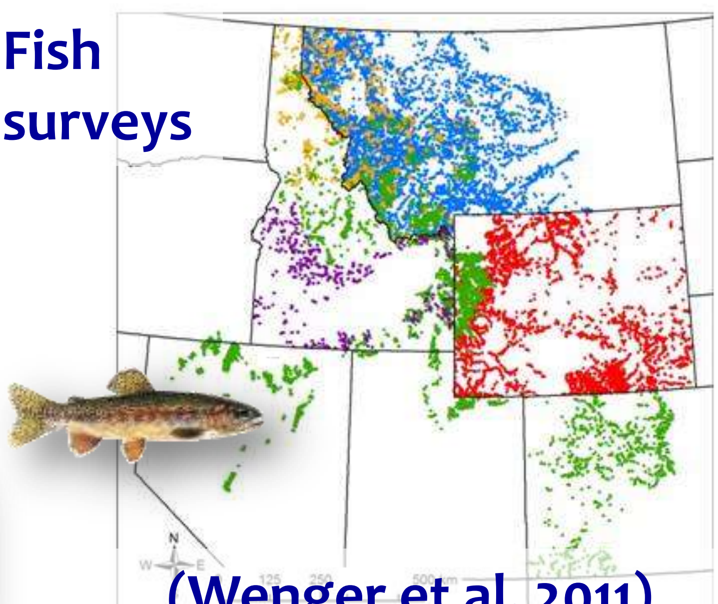
Temperature




Discharge – USGS NWIS

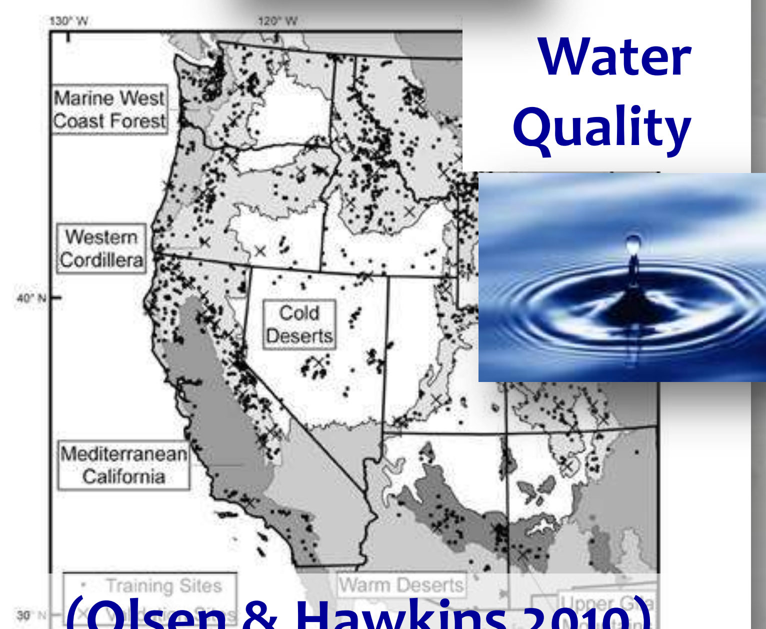



Fish surveys

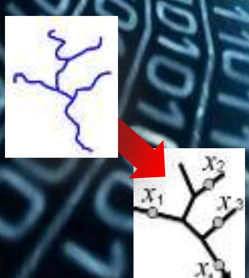


(Wenger et al. 2011)

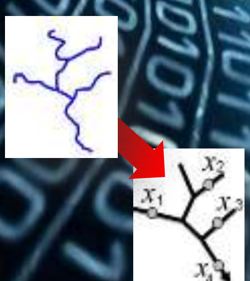
Water Quality




(Olsen & Hawkins 2010)



# Spatial Models are Powerful Data Mining Tools

# The National Stream Internet Project

## An analytical framework for creating new information from old data on stream networks

Dan Isaak, Erin Peterson, Dave Nagel, Jay Ver Hoef, Jeff Kershner

FOREST SERVICE U S DEPARTMENT OF AGRICULTURE

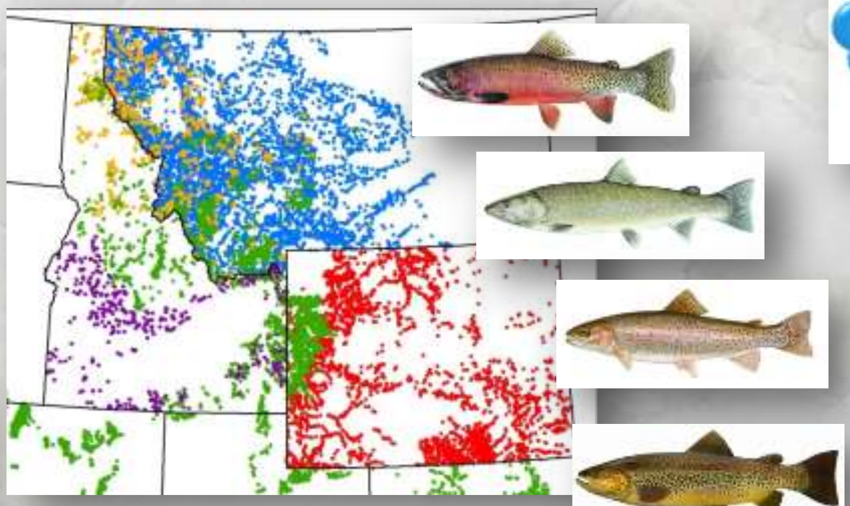
CSIRO

NOAA

USGS science for a changing world

**BIG DATA =**

**BIG POSSIBILITIES**

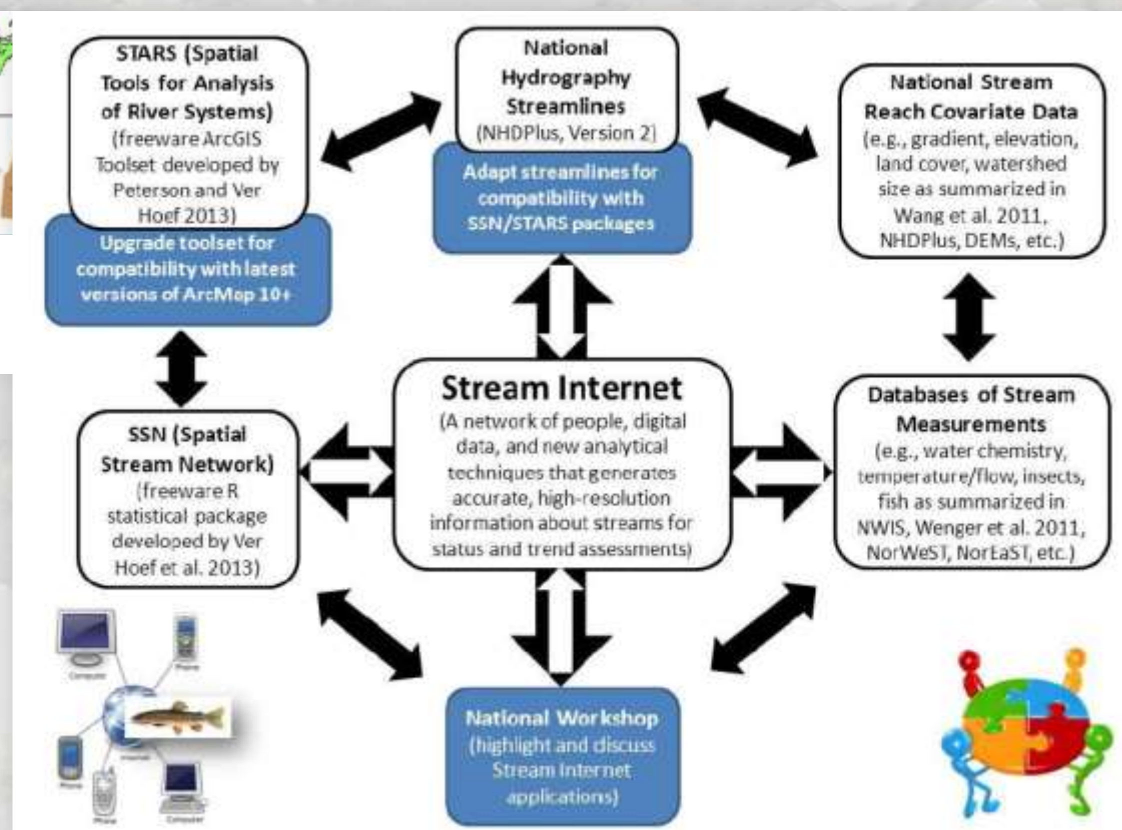



LANDSCAPE CONSERVATION COOPERATIVES

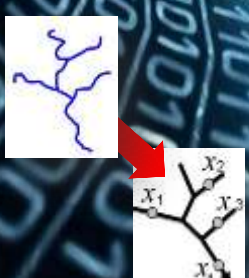
# Stream Internet Project Objectives

1) Develop compatibility between spatial stream analysis tools and national hydrography layer (USGS NHDPlus, v2)
2) Update STARS stream analysis tools to ArcGIS 10.2
3) Host national workshop in 2015 to engage key researchers & leaders from aquatic programs (i.e., power-users)

LANDSCAPE
CONSERVATION
COOPERATIVES

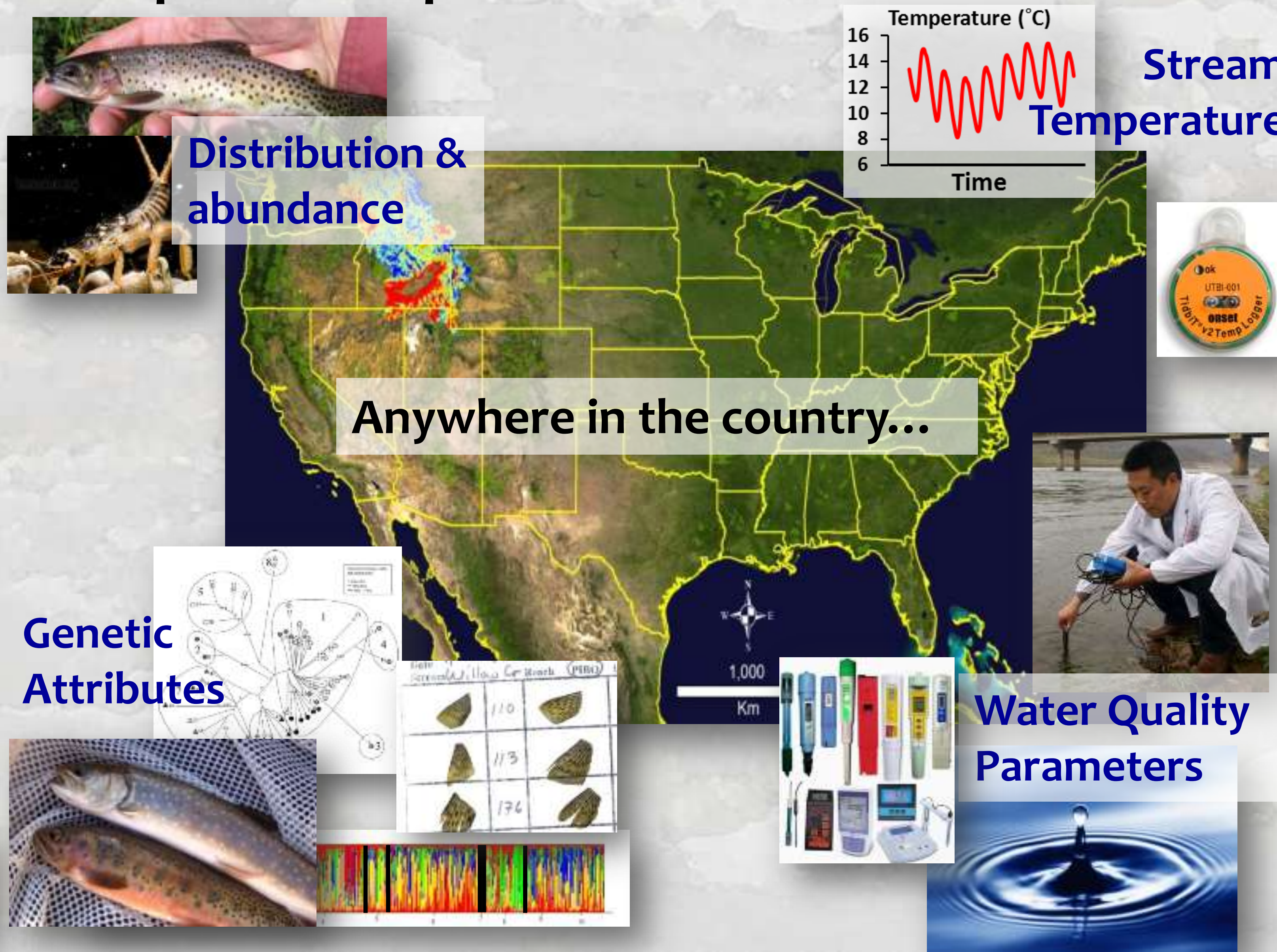


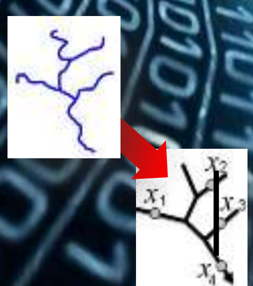

Projects like NorWeST done routinely & incentives for database aggregation



# Then it’s just 3 easy steps

## Step 1. Develop a Stream Database…

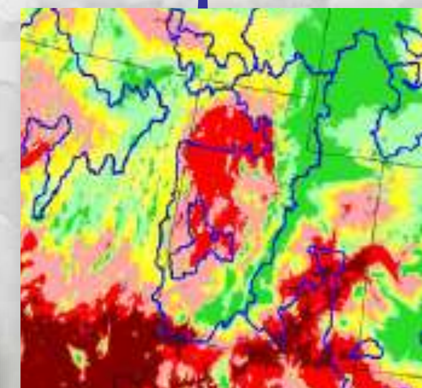


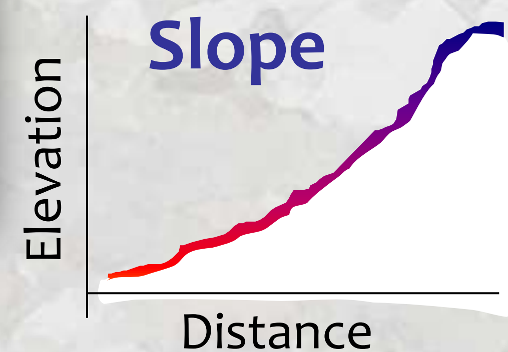
# Step 2. Link to Covariate Predictors

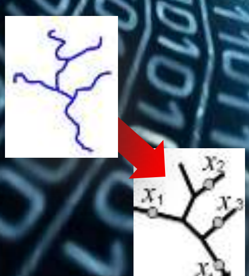
## 100’s are Available (NHDPlus, NLCD, DEMs… )


Precipitation





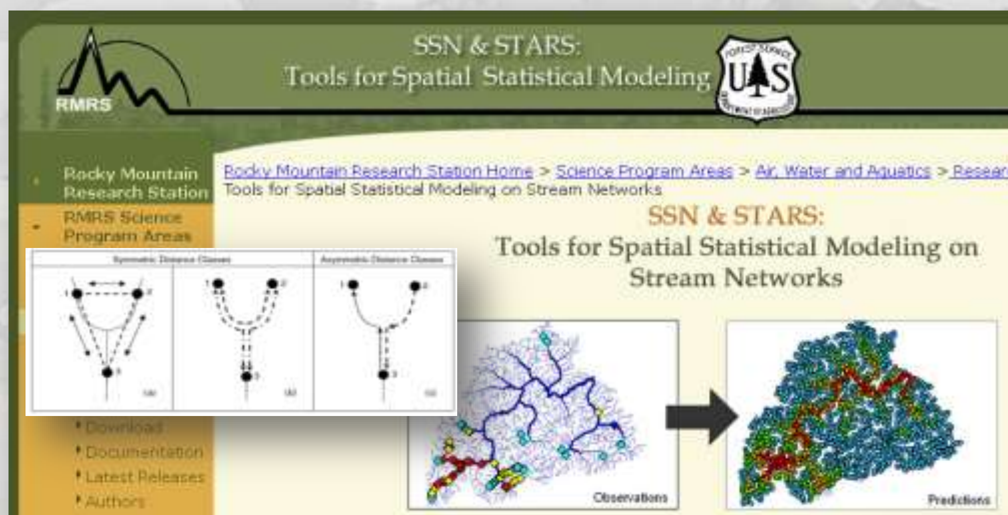


Wang et al. 2011. A Hierarchical Spatial Framework and Database for the National River Fish Habitat Condition Assessment. *Fisheries* **36**:436-449.

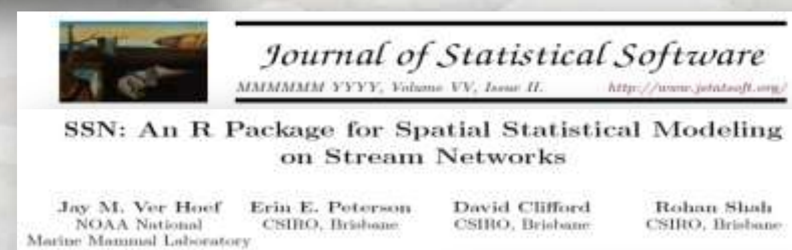
# Step 3. Stream Statistical Analysis

## SSN/STARS Website – Free Software




- Software
- Example Datasets
- Documentation

**Spatial Stream Networks (SSN) Package for R**

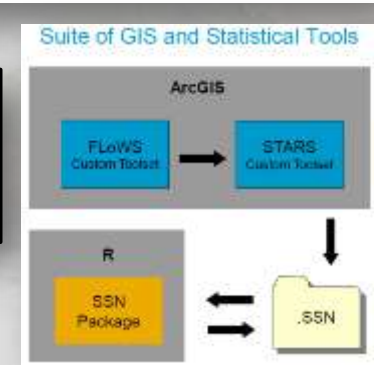


*Journal of Statistical Software*

MMMMMM YYYY, Volume VV, Issue II. http://www.jstatsoft.org/

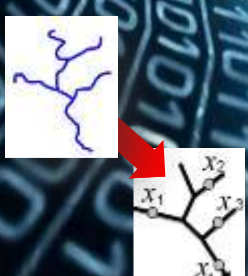
**SSN: An R Package for Spatial Statistical Modeling on Stream Networks**

Jay M. Ver Hoef, NOAA National Marine Mammal Laboratory
Erin E. Peterson, CSIRO, Brisbane
David Clifford, CSIRO, Brisbane
Rohan Shah, CSIRO, Brisbane




**A Moving Average Approach for Spatial Statistical Models of Stream Networks**

Jay M. Ver Hoef and Erin E. Peterson



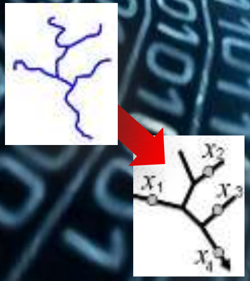
**STARS: An ArcGIS toolset used to calculate the spatial data needed to fit spatial statistical models to stream network data**

# An InterNet Happens Because of Users

## Rapidly Developing at Grassroots Level

**>11,000 Visits to SSN/STARS website in first year**

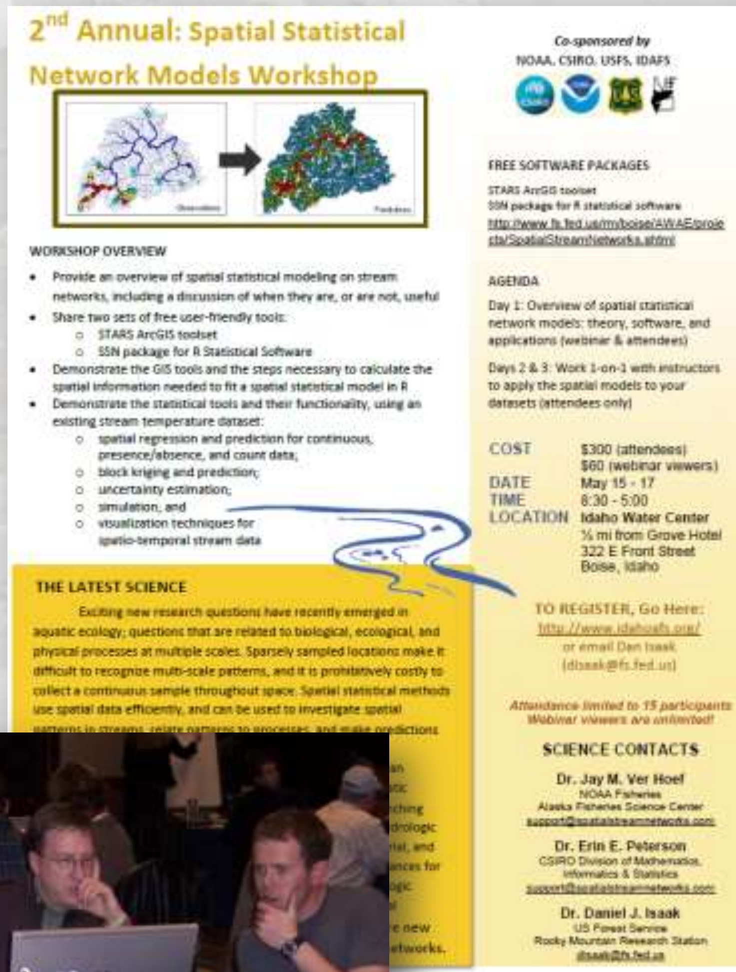
**>300 software downloads**


Locations of visits to SSN/STARS website in last month

# 2nd Annual Training Workshop in Boise

## May 15 – 17, prior to Joint Aquatic Sciences meeting in Portland



## 2nd Annual: Spatial Statistical Network Models Workshop

Co-sponsored by
NOAA, CSIRO, USFS, IDAFS

WORKSHOP OVERVIEW

- Provide an overview of spatial statistical modeling on stream networks, including a discussion of when they are, or are not, useful
- Share two sets of free user-friendly tools:
  - STARS ArcGIS toolset
  - SSN package for R Statistical Software
- Demonstrate the GIS tools and the steps necessary to calculate the spatial information needed to fit a spatial statistical model in R
- Demonstrate the statistical tools and their functionality, using an existing stream temperature dataset:
  - spatial regression and prediction for continuous, presence/absence, and count data;
  - block kriging and prediction;
  - uncertainty estimation;
  - simulation; and
  - visualization techniques for spatio-temporal stream data

THE LATEST SCIENCE

Exciting new research questions have recently emerged in aquatic ecology; questions that are related to biological, ecological, and physical processes at multiple scales. Sparsely sampled locations make it difficult to recognize multi-scale patterns, and it is prohibitively costly to collect a continuous sample throughout space. Spatial statistical methods use spatial data efficiently, and can be used to investigate spatial patterns in streams, relate patterns to processes, and make predictions ... new ... networks.

FREE SOFTWARE PACKAGES

STARS ArcGIS toolset
SSN package for R statistical software
http://www.fs.fed.us/rm/boise/AWAE/projects/SpatialStreamNetworks.shtml

AGENDA

Day 1: Overview of spatial statistical network models: theory, software, and applications (webinar & attendees)

Days 2 & 3: Work 1-on-1 with instructors to apply the spatial models to your datasets (attendees only)

| | |
|---|---|
| COST | $300 (attendees)<br>$60 (webinar viewers) |
| DATE | May 15 - 17 |
| TIME | 8:30 - 5:00 |
| LOCATION | Idaho Water Center<br>½ mi from Grove Hotel<br>322 E Front Street<br>Boise, Idaho |

TO REGISTER, Go Here:
http://www.idahoafs.org/
or email Dan Isaak
(disaak@fs.fed.us)

*Attendance limited to 15 participants*
*Webinar viewers are unlimited!*

SCIENCE CONTACTS

Dr. Jay M. Ver Hoef
NOAA Fisheries
Alaska Fisheries Science Center
support@spatialstreamnetworks.com

Dr. Erin E. Peterson
CSIRO Division of Mathematics, Informatics & Statistics
support@spatialstreamnetworks.com

Dr. Daniel J. Isaak
US Forest Service
Rocky Mountain Research Station
disaak@fs.fed.us

## Idaho Water Center

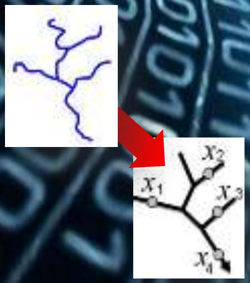
## 3 day workshop

1st day: overview of spatial stream models (webinar)

2nd/3rd days: work 1-on-1 with Jay/Erin to model your data

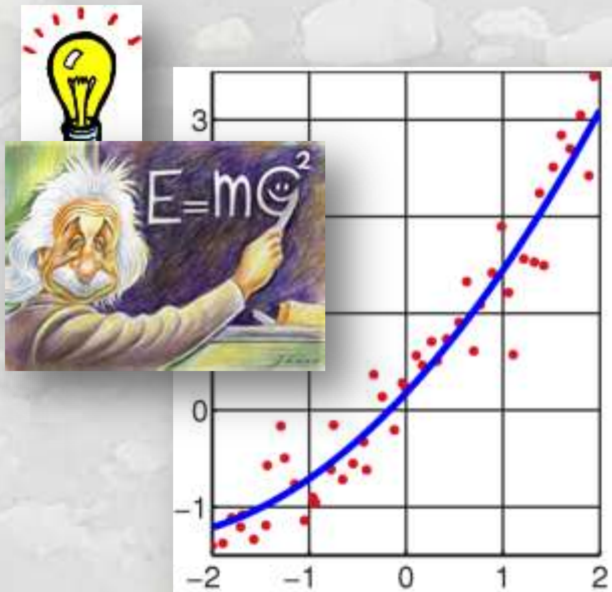
Attendees (15 people); 1st day webinar viewers (unlimited)

**If Interested, contact Dan Isaak (disaak@fs.fed.us) or go to the SSN/STARS website for registration details**

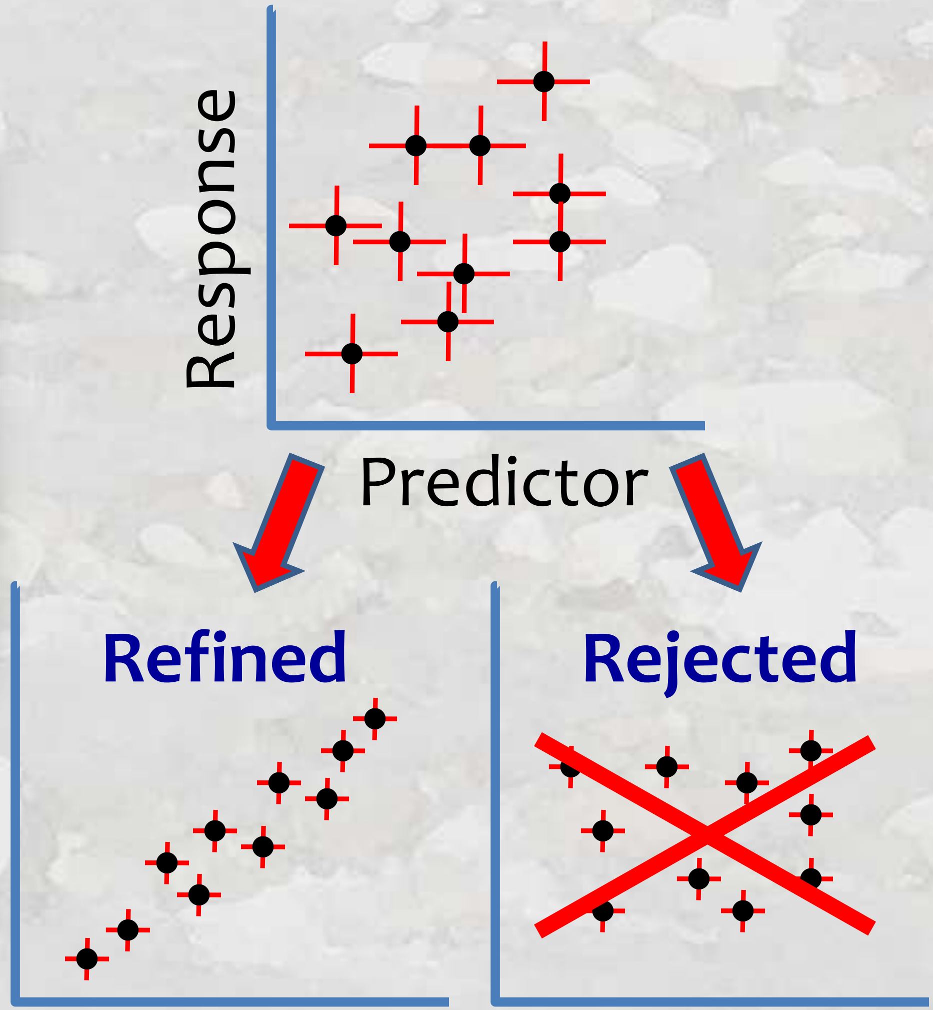


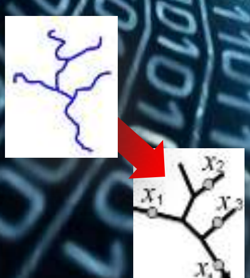
# Better Understanding & Prediction for Streams

## New relationships described



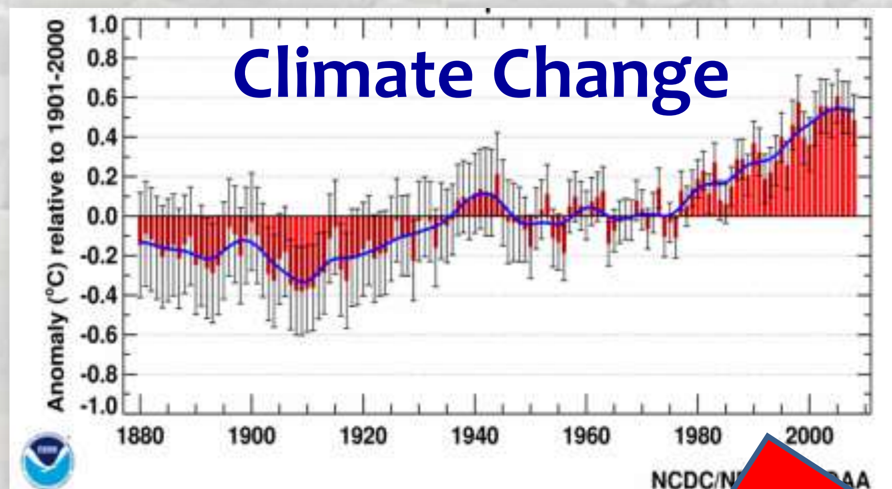

## Old relationships tested



# More Pressure, Fewer Resources

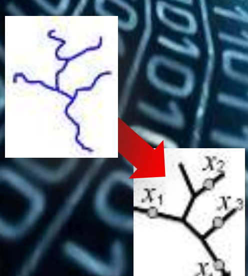
Climate Change




Urbanization & Population Growth

Shrinking Budgets

Need to do more with less



# More With Less, but What If… It was Massively More?