WATS 6900 – Ecohydraulics
WEEK 13: Stream Temperature and Gross Primary Production

UtahState University
DEPARTMENT OF WATERSHED SCIENCES

JOE WHEATON

NICK BOUWES

Fish – Habitat Relationships

Fish Habitat

Physical Habitat

- Valley Setting
- Channel Morphology
- Substrate Composition
- Cover

Stream Temperature

Stream Productivity

- Fish Food
- Availability and
- Transfer of Energy

BIOENERGETICS MODELING OF TROUT GROWTH

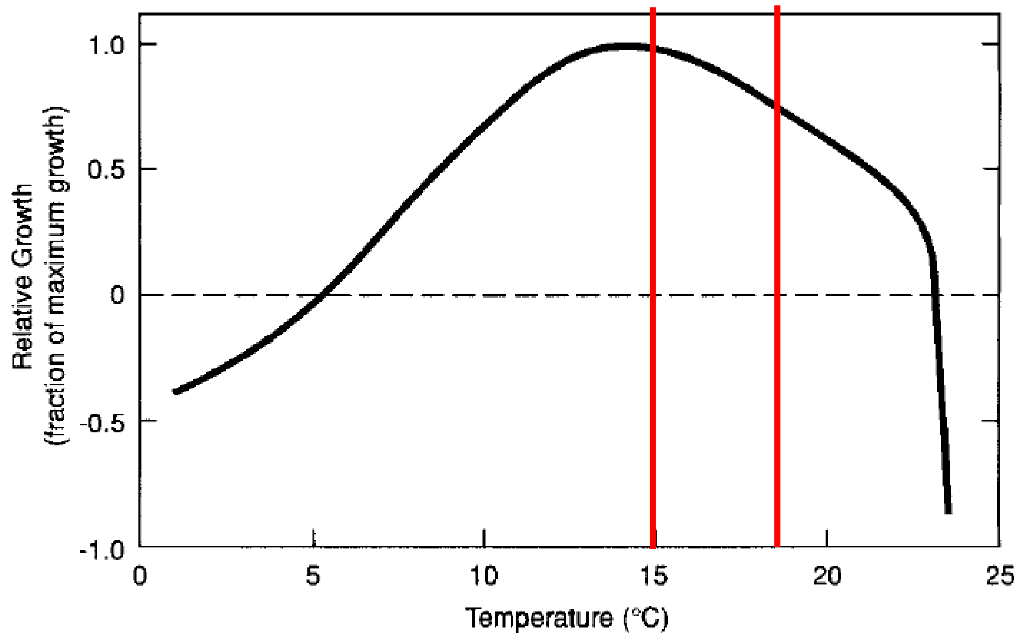
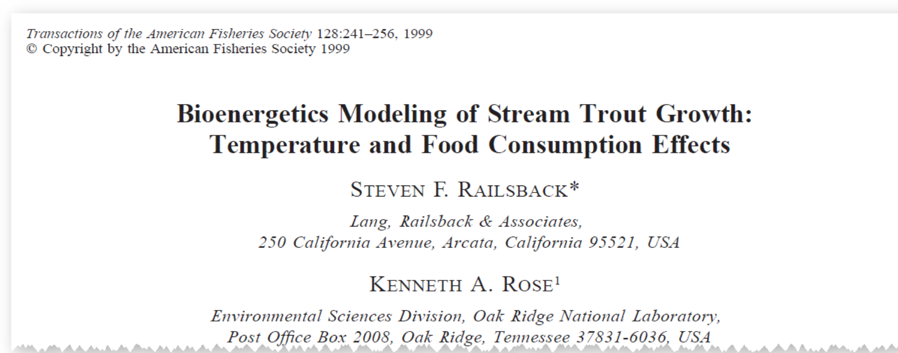


FIGURE 1.—Approximate dependence of modeled rainbow trout growth on temperature, assuming food consumption (P) has a constant value of 0.4. The y-axis is growth rate as proportion of growth at the optimal temperature. Potential growth rates also depend on fish size, but they are generally high between 10°C and 22°C; actual growth is highly dependant on the value of P.



Transactions of the American Fisheries Society 128:241–256, 1999

Bioenergetics Modeling of Stream Trout Growth: Temperature and Food Consumption Effects

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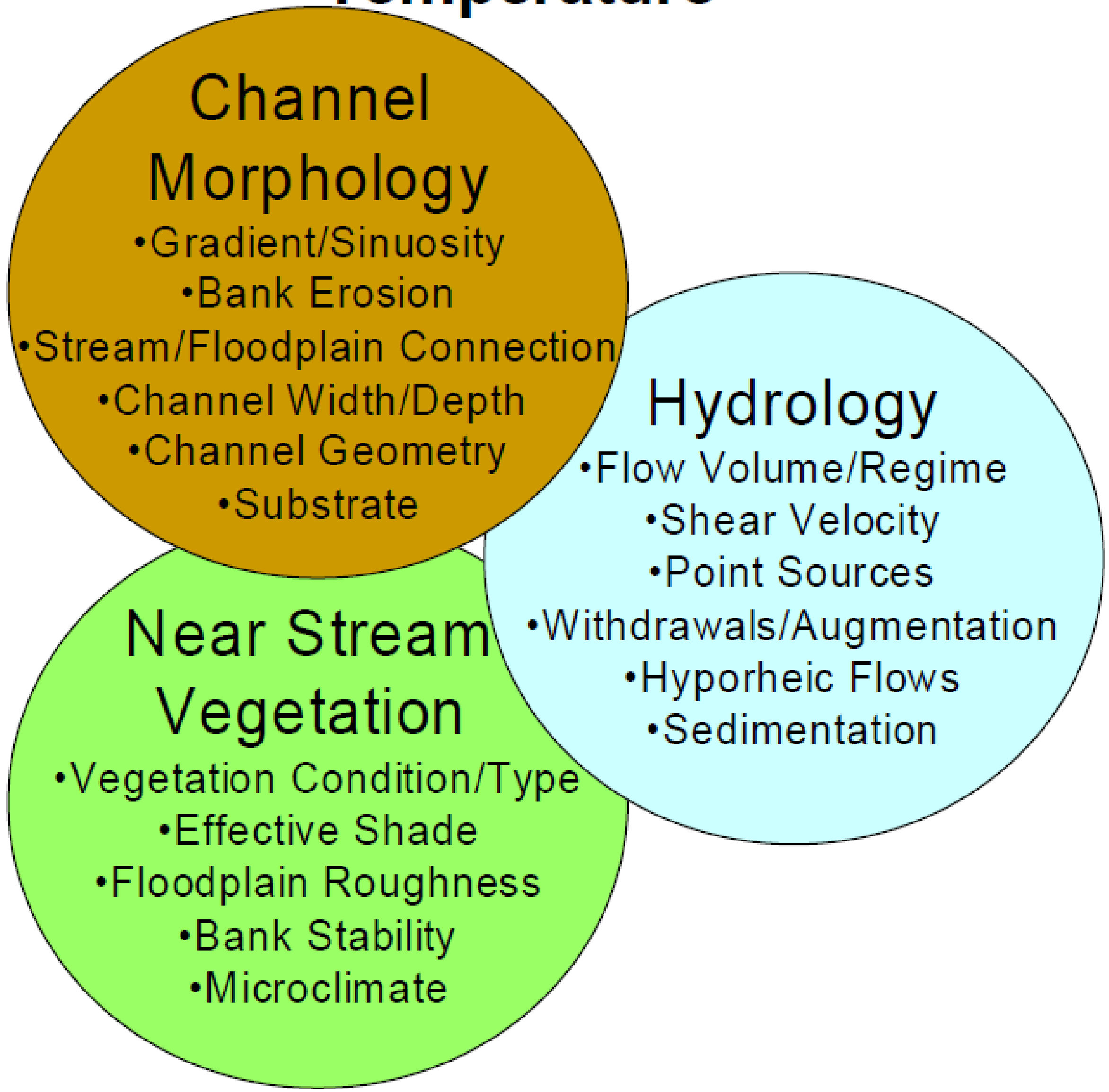
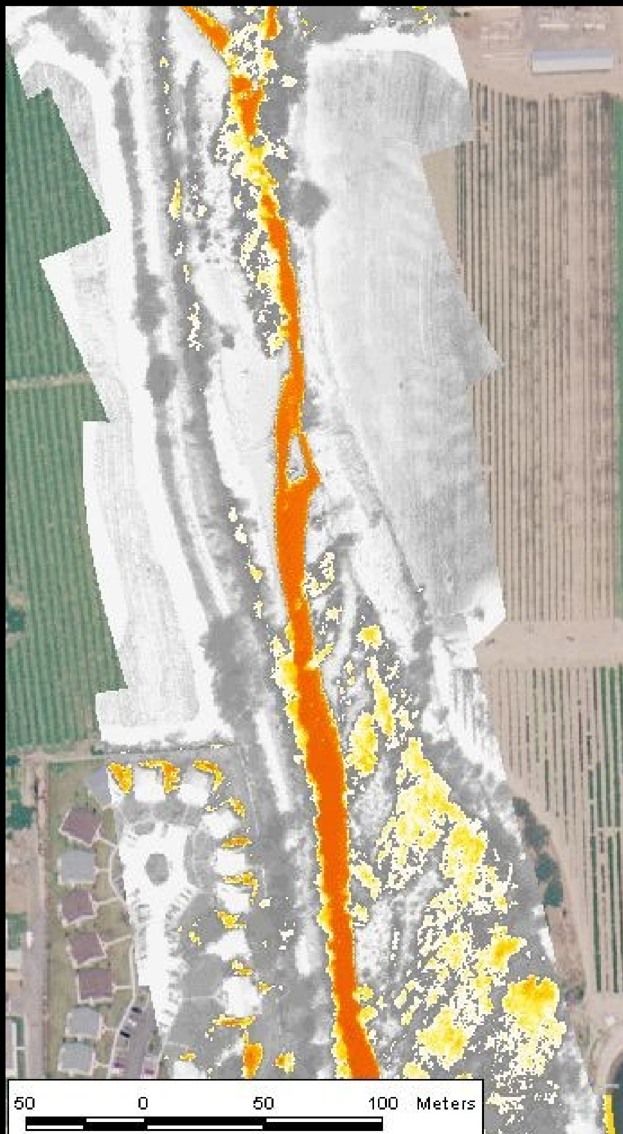
Post Office Box 2008, Oak Ridge, Tennessee 37831-6036, USA

Factors that Affect Stream Temperature



(Many of these parameters are interrelated)

Thermal Infrared (TIR) System



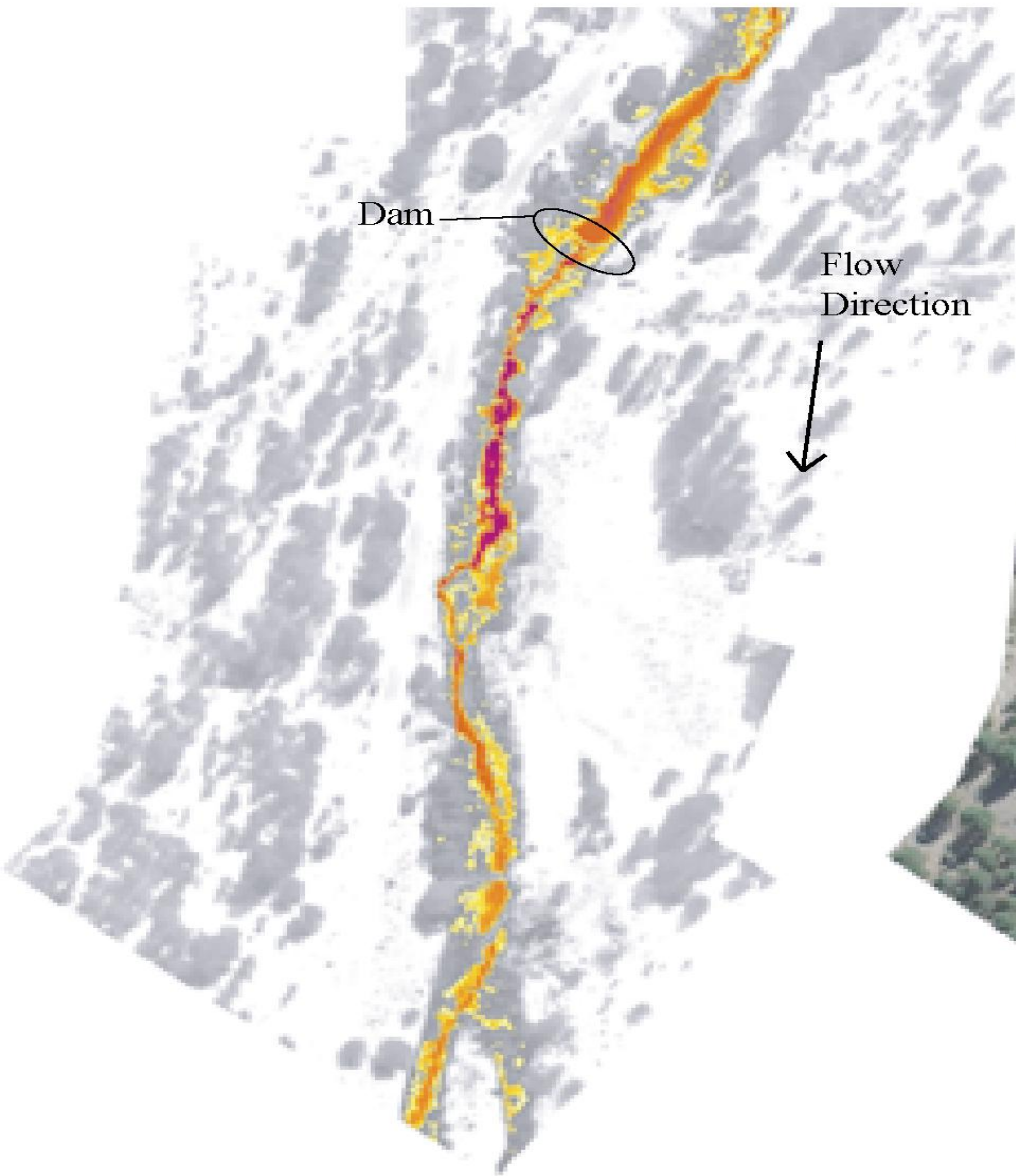
Sequence of Overlapping Images

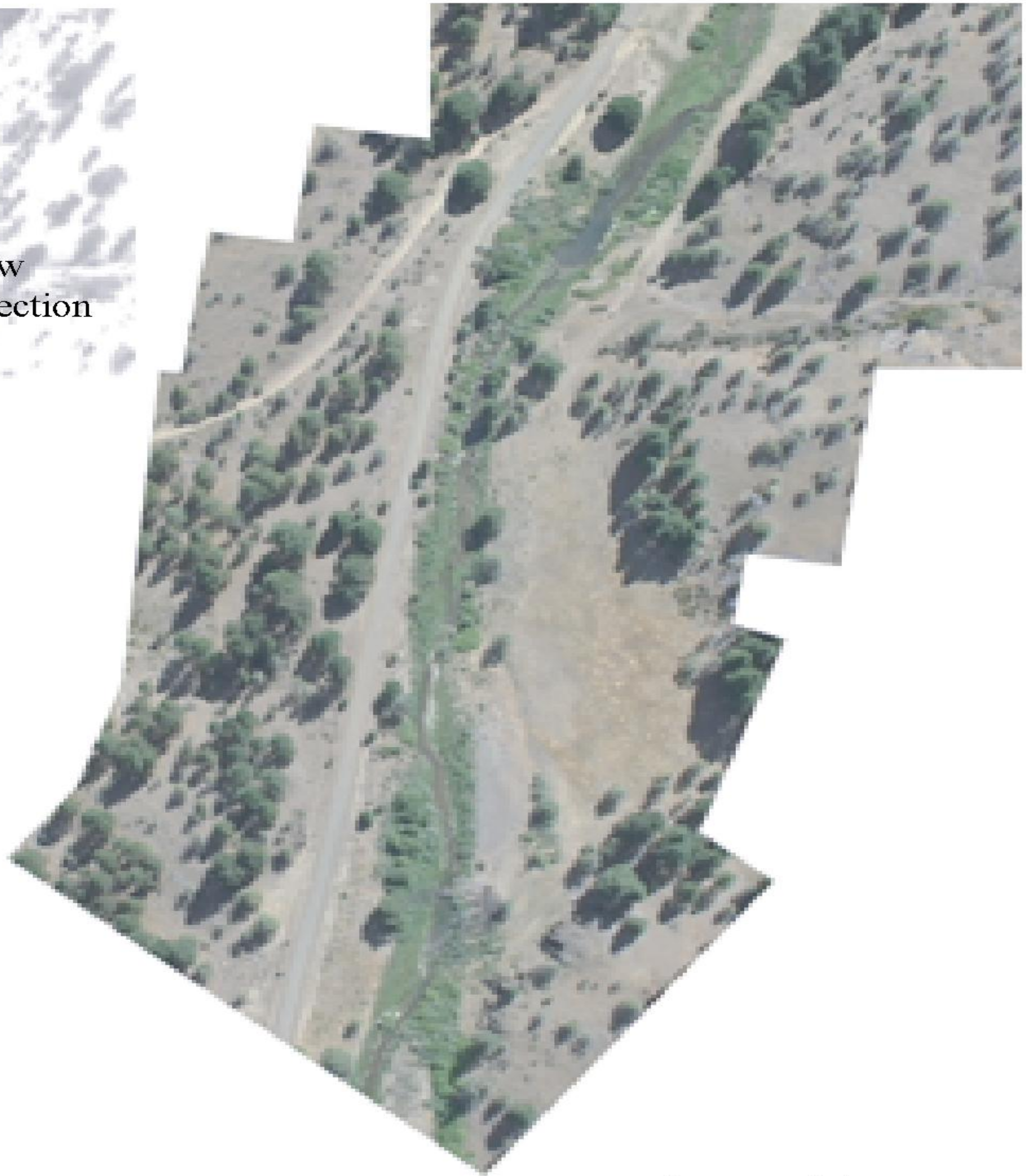
Pixel Size: 0.5 – 1.5 meters

Ground Footprint: 100 - 400 meters

Local Variability – Cause?

August 15, 2003
22.3°C -> 19.4°C



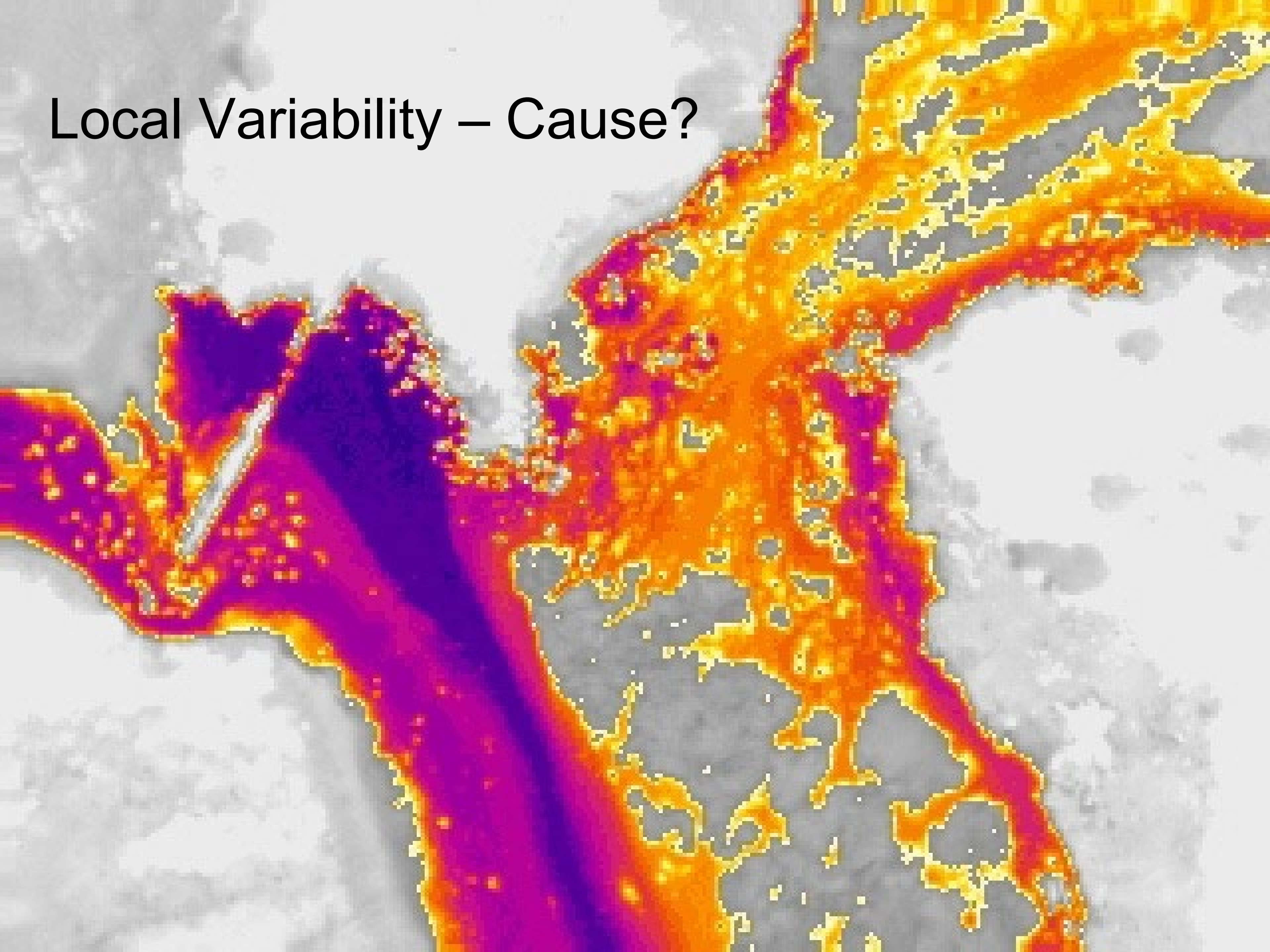


TIR Image Temperature Scale (deg C)

frames: sfjd0993-0998

Hyporheic exchange caused by a push-up dam

Local Variability – Cause?



Cold Water Augmentation from a large spring

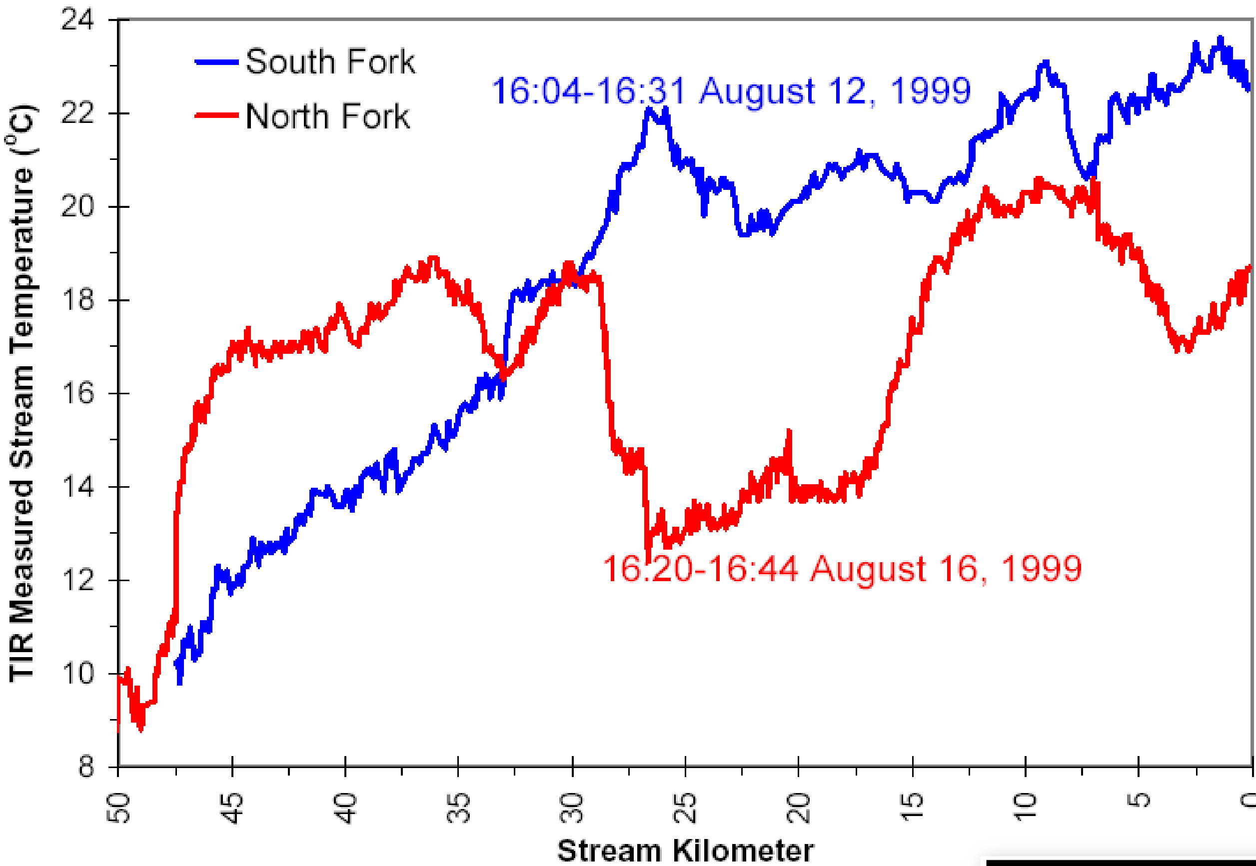


FIGURE 1.1
TIR Sampled Stream Temperature Patterns for the North and South Fork Sprague River

Analytical Methods for Dynamic Open Channel Heat and Mass Transfer

Methodology for the Heat Source Model Version 7.0

Prepared by:

Matthew Boyd & Brian Kasper

water temperature α heat energy/water volume

water temperature change
as a function of heat exchange per unit volume

$$\Delta T_w \propto \frac{\Delta \text{Heat}}{\text{Volume}}$$

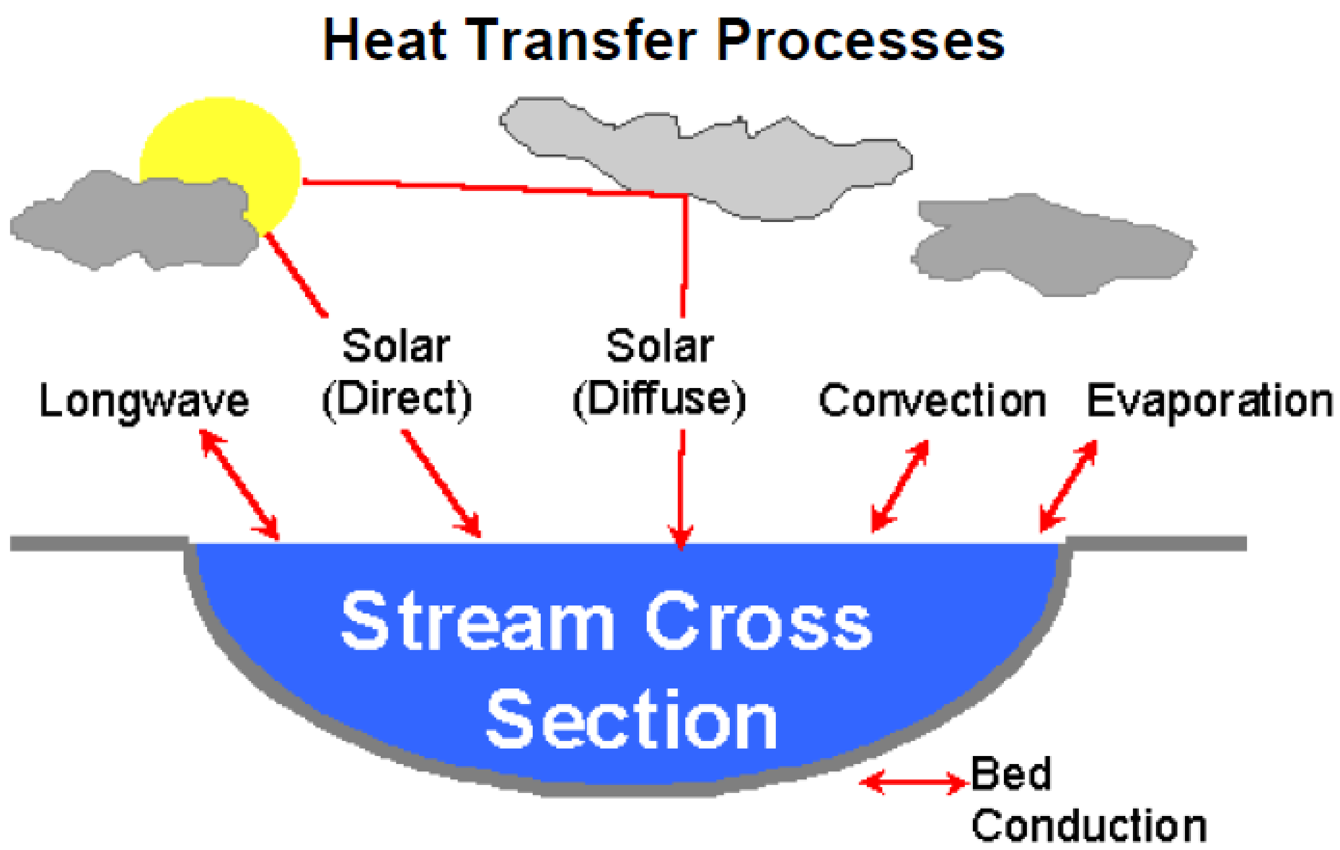
or for a stream

water temperature α heat load/discharge

water temperature α heat transfer/mass transfer

Heat Transfer

Any heat added or taken away from the system

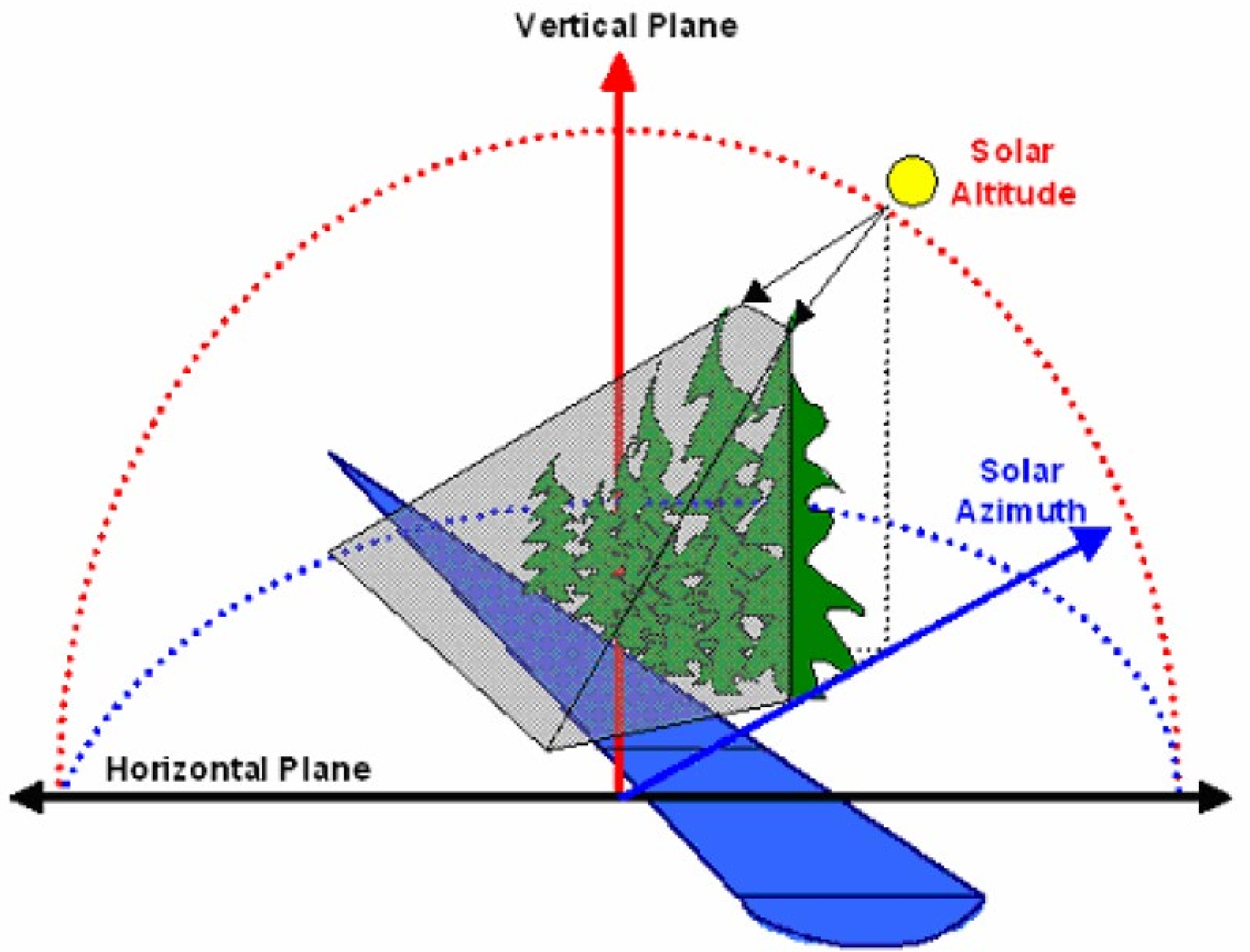


Net Heat Energy Continuity,

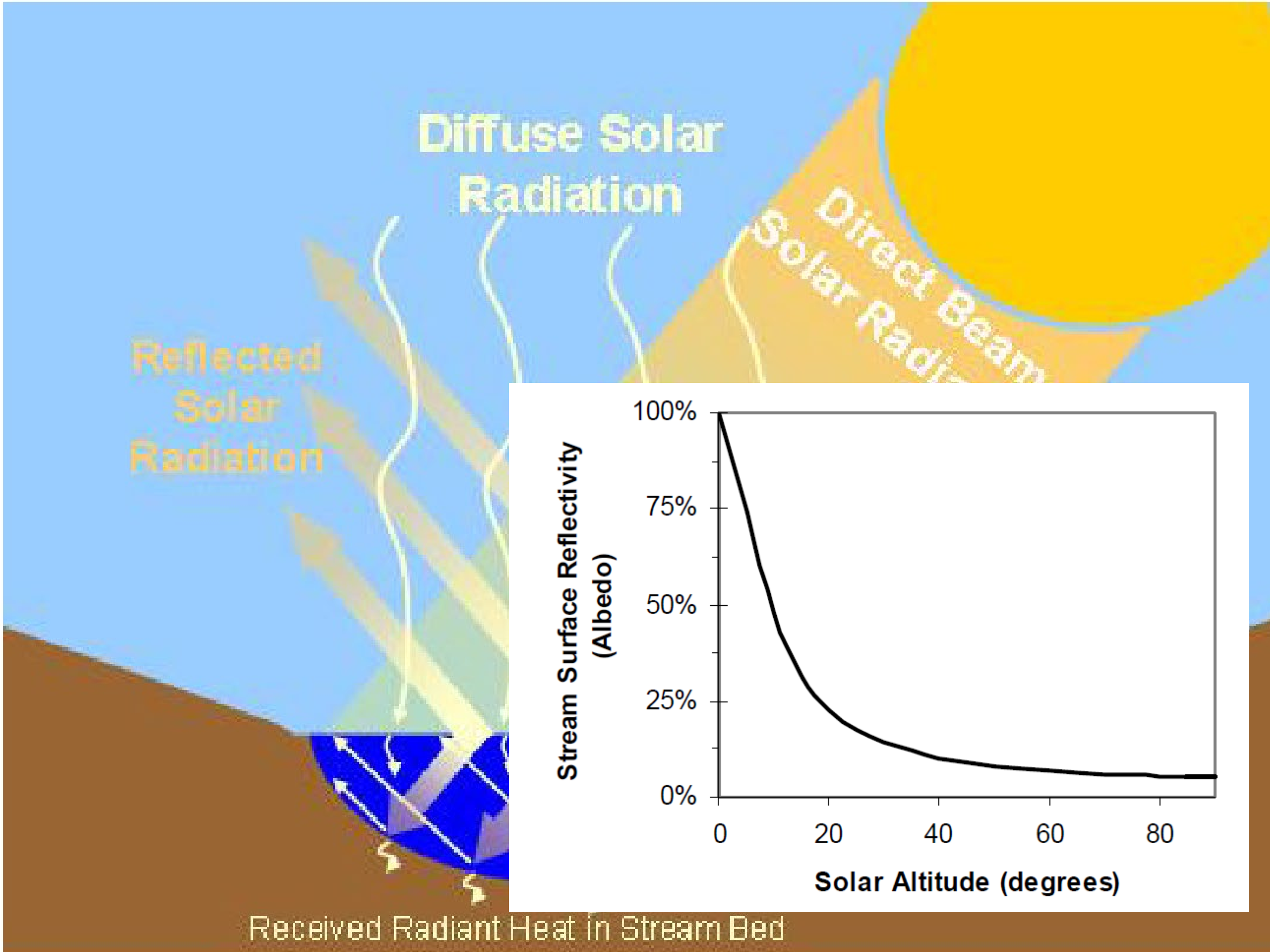
$$\Phi_{\text{total}} = \Phi_{\text{solar}} + \Phi_{\text{longwave}} + \Phi_{\text{evaporation}} + \Phi_{\text{convection}} + \Phi_{\text{streambed}}$$

The ultimate source of terrestrial and atmospheric heat energy is solar radiation (images from SOHO telescope and Apollo 17 mission).

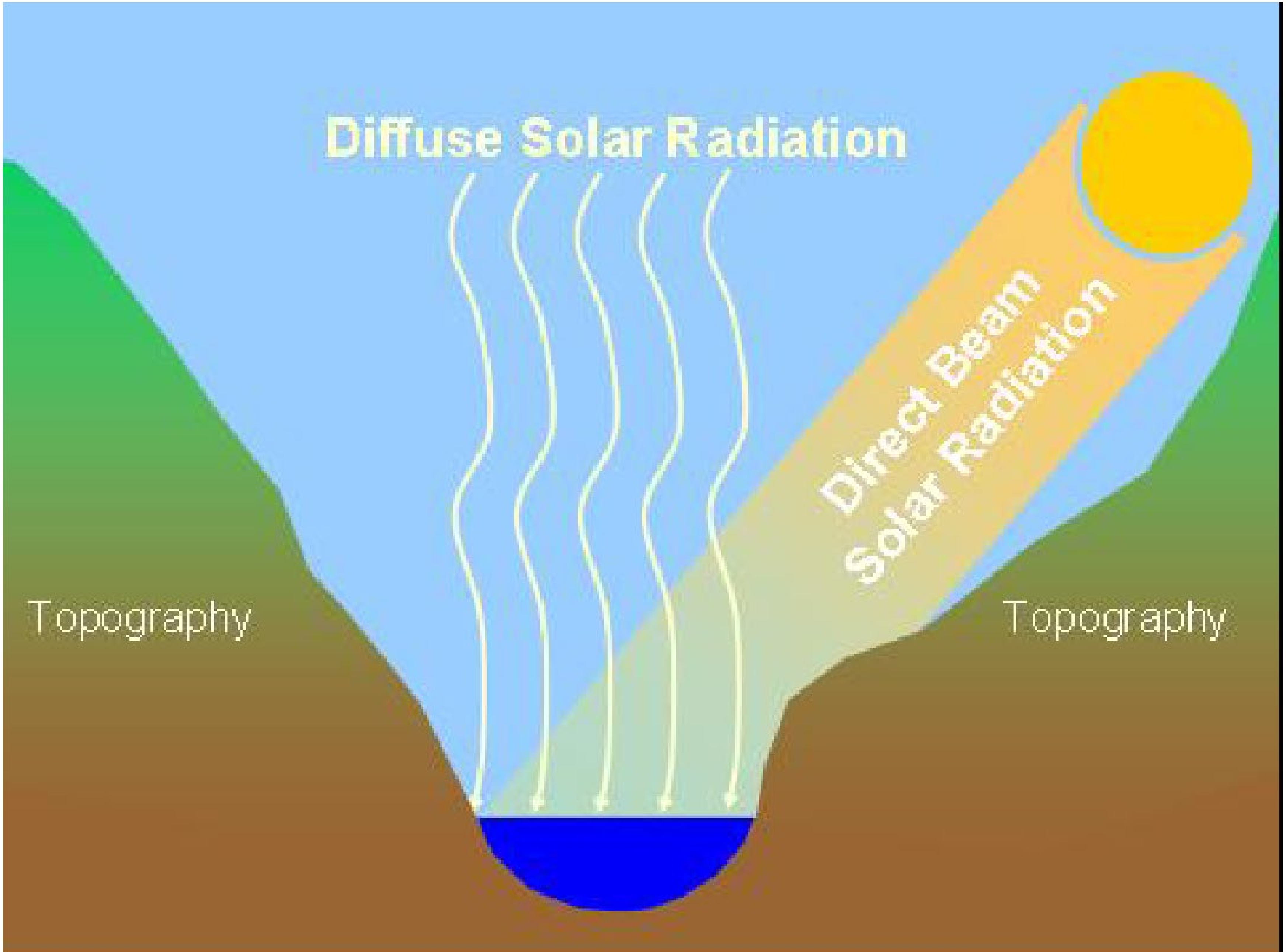
Solar altitude and azimuth



Angle of incidence, solar reflection



Topographic shading



Effective shade from land cover

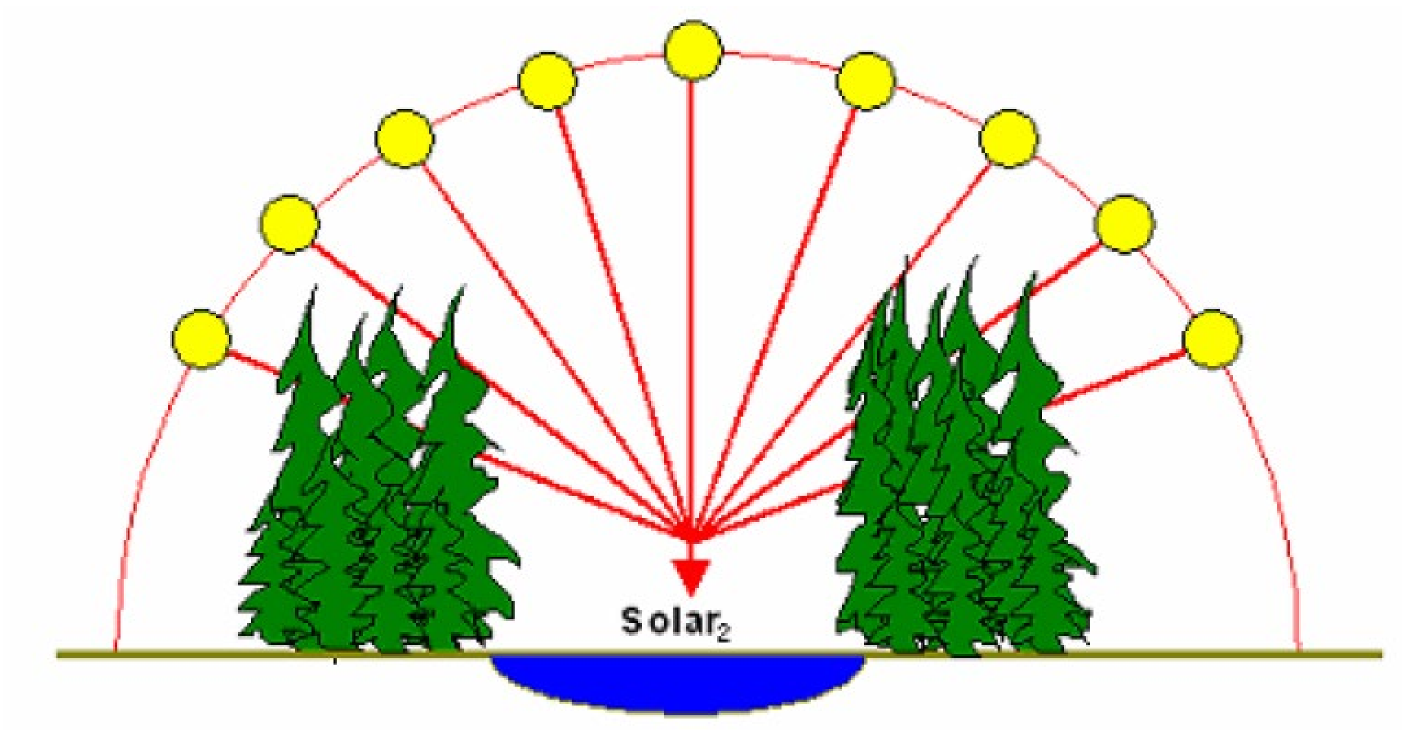


Table 1.1

Factors that Influence Stream Surface Shade

	Blue – Not Influenced by Land Management
	Red - Influenced by Land Management
Season/Time:	Date/Time
Stream Morphology:	Aspect, Channel Width, Incision
Geographic Position:	Latitude, Longitude, Topography
Land Cover:	Near Stream Land cover Height, Width, Density
Solar Position:	Solar Altitude, Solar Azimuth

Poor shade results from near stream vegetation removal and is compounded by channel morphology response to near stream vegetation removal (Vey Meadow, Grande Ronde River, Oregon)

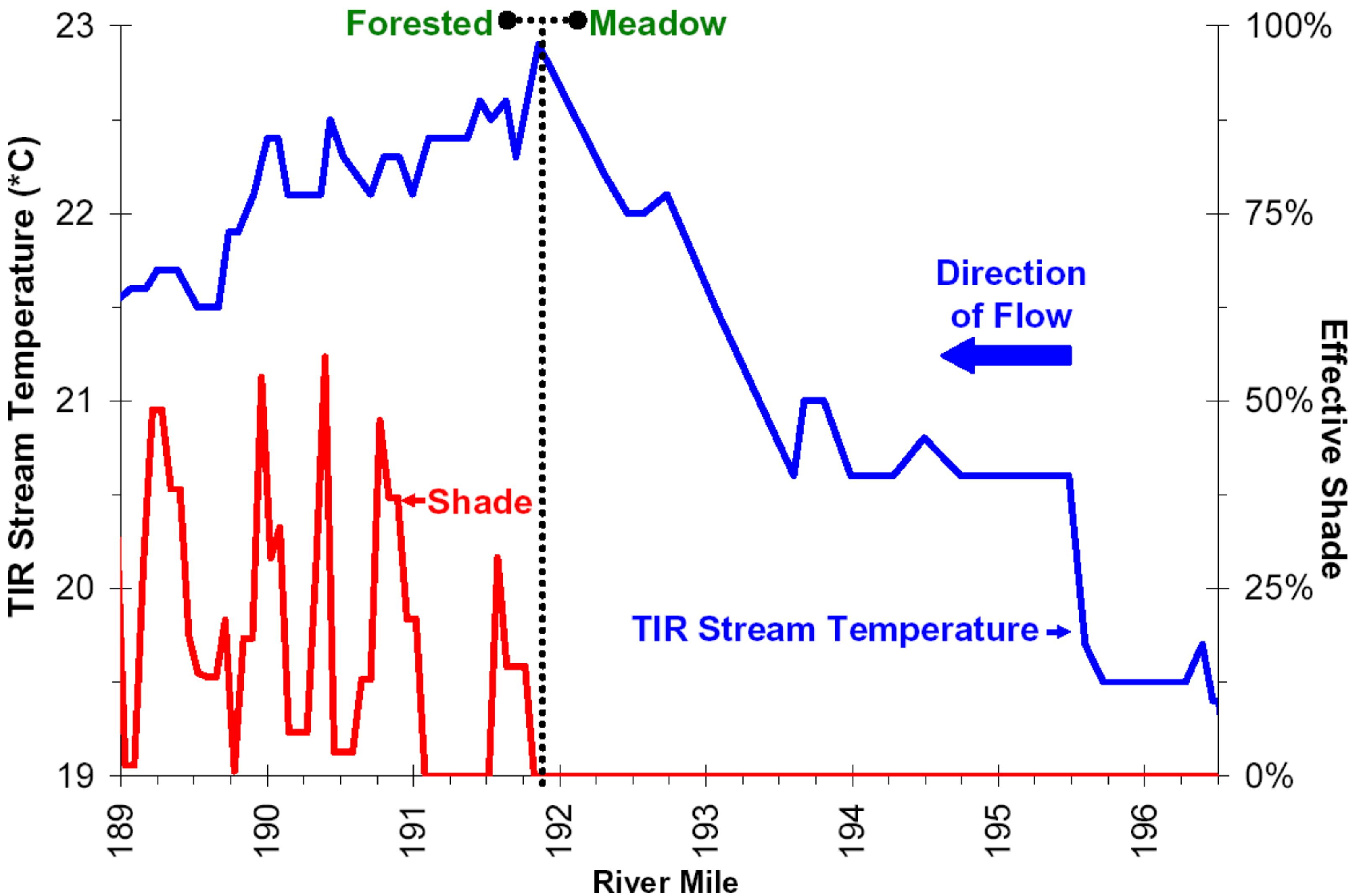


FIGURE 1.4
TIR derive stream temperature data and effective shade modeling indicate that 3°C stream heating corresponds to reduced shade distributions. Reduced rates of stream heating are apparent in the shaded (forested) downstream reach (Vey Meadow, Grande Ronde River, Oregon).

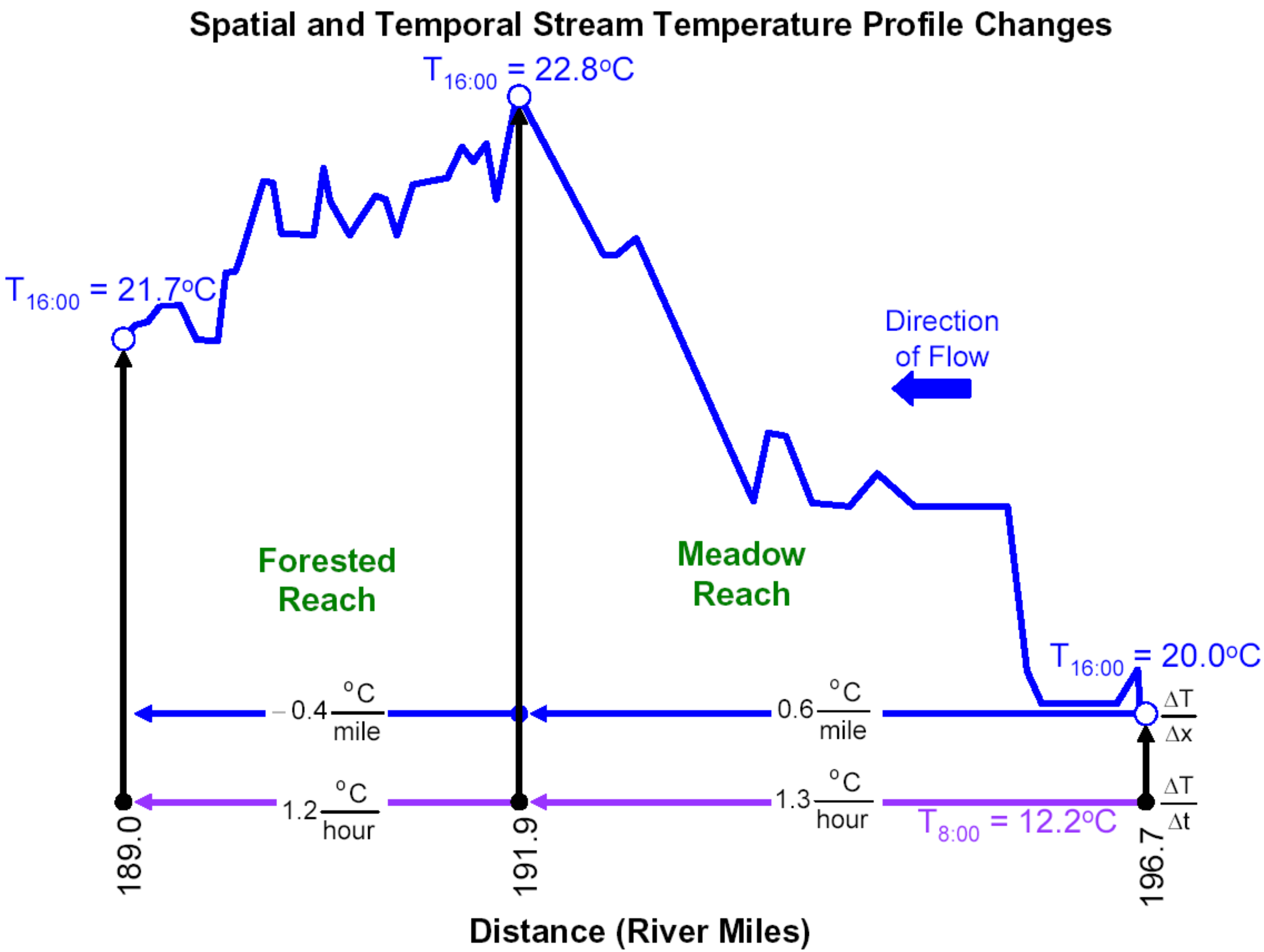
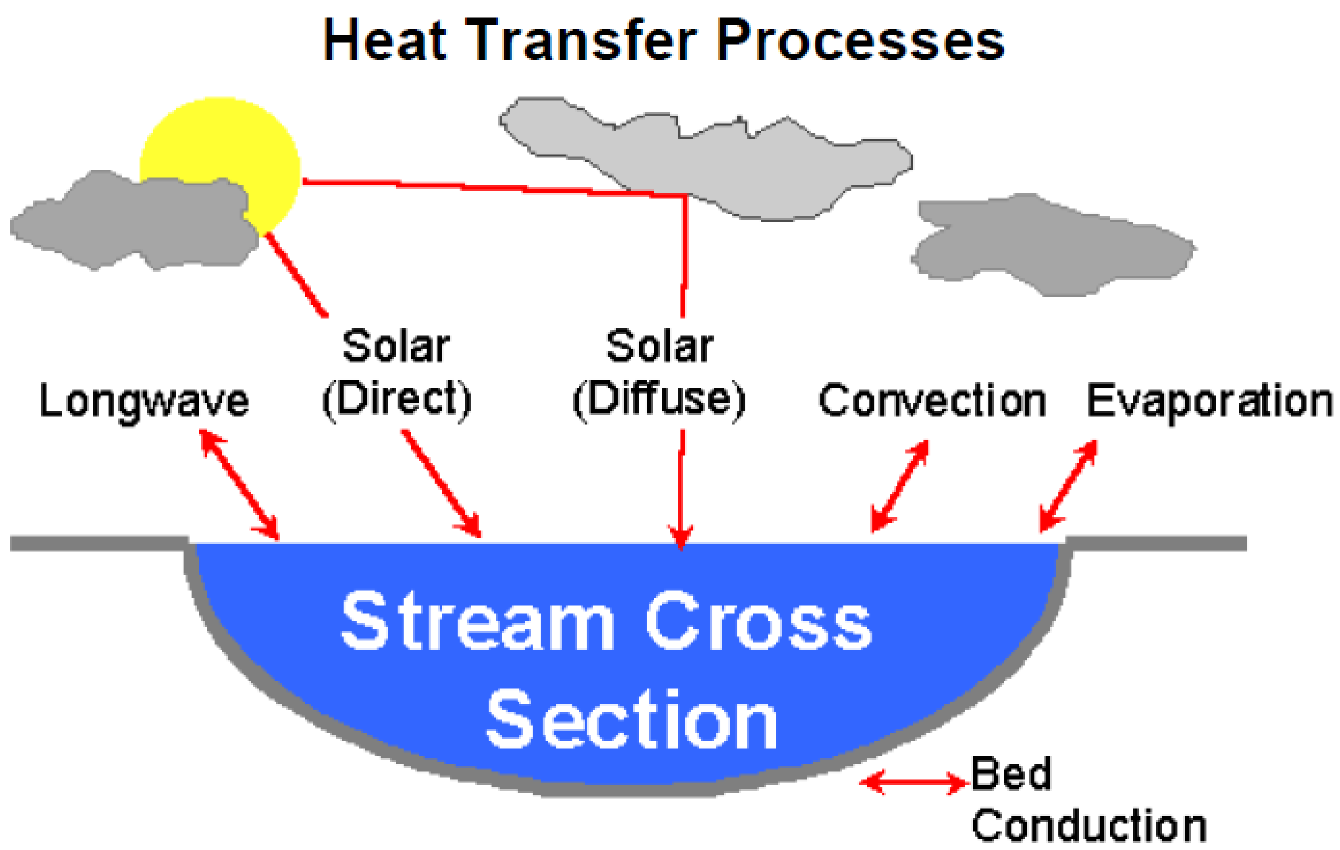
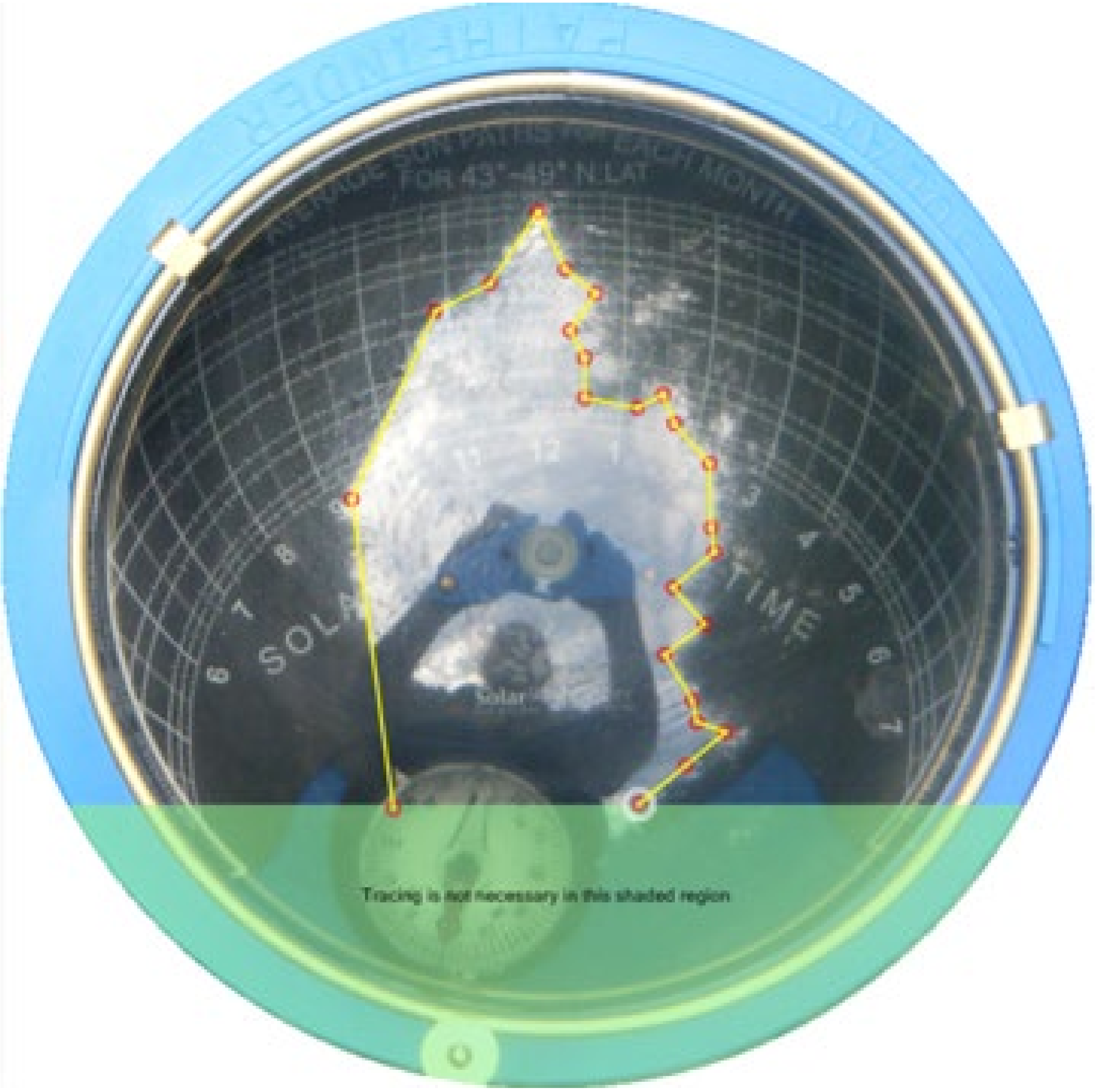


FIGURE 1.5
Rates of temperature change over time and distance (Vey Meadow, Grande Ronde River, Oregon).

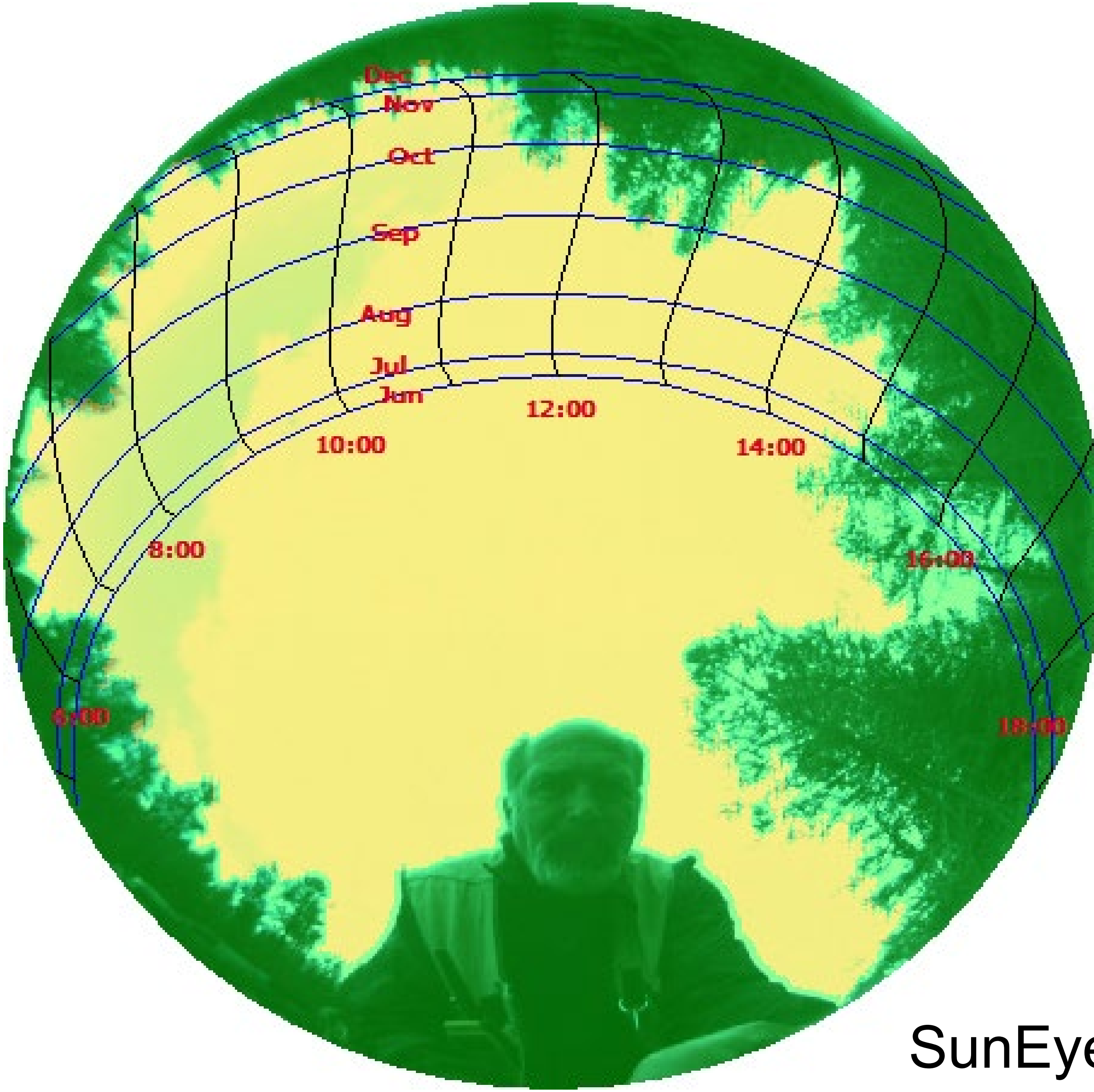


Net Heat Energy Continuity,

$$\Phi_{\text{total}} = \Phi_{\text{solar}} + \Phi_{\text{longwave}} + \Phi_{\text{evaporation}} + \Phi_{\text{convection}} + \Phi_{\text{streambed}}$$



Solar PathFinder

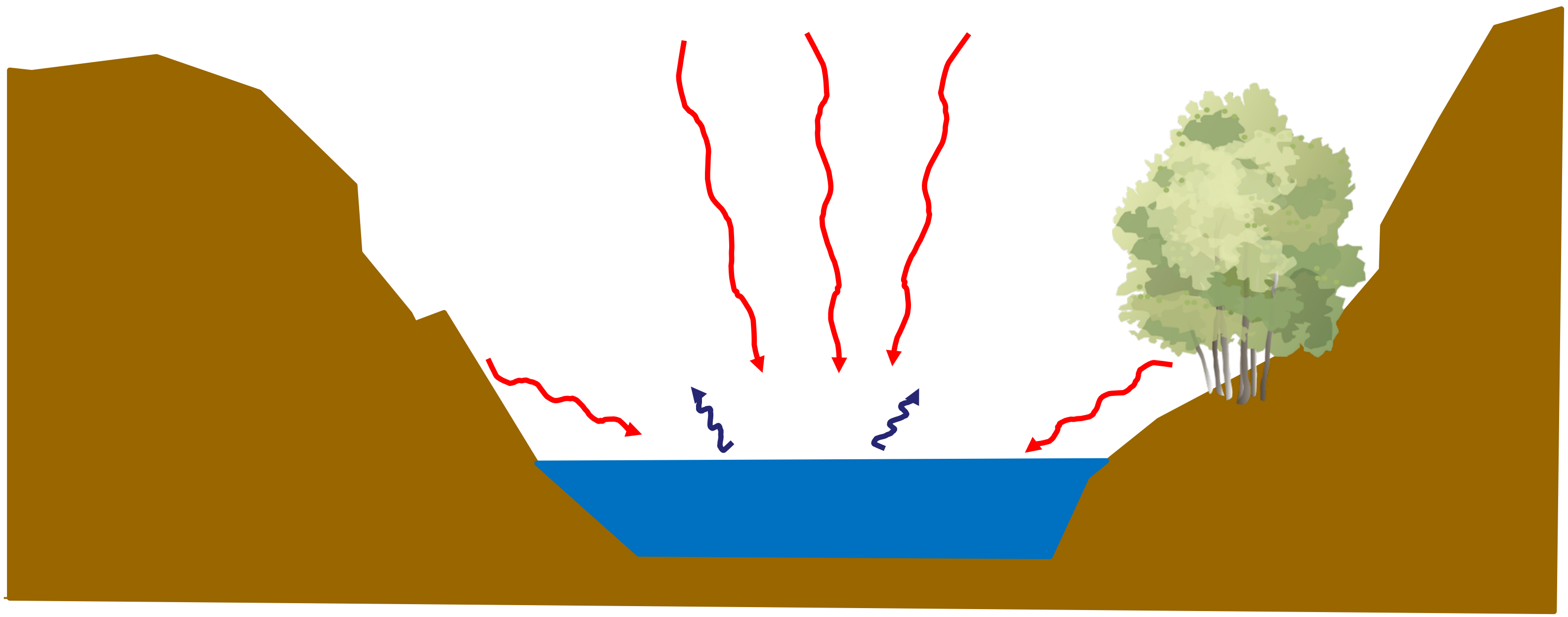


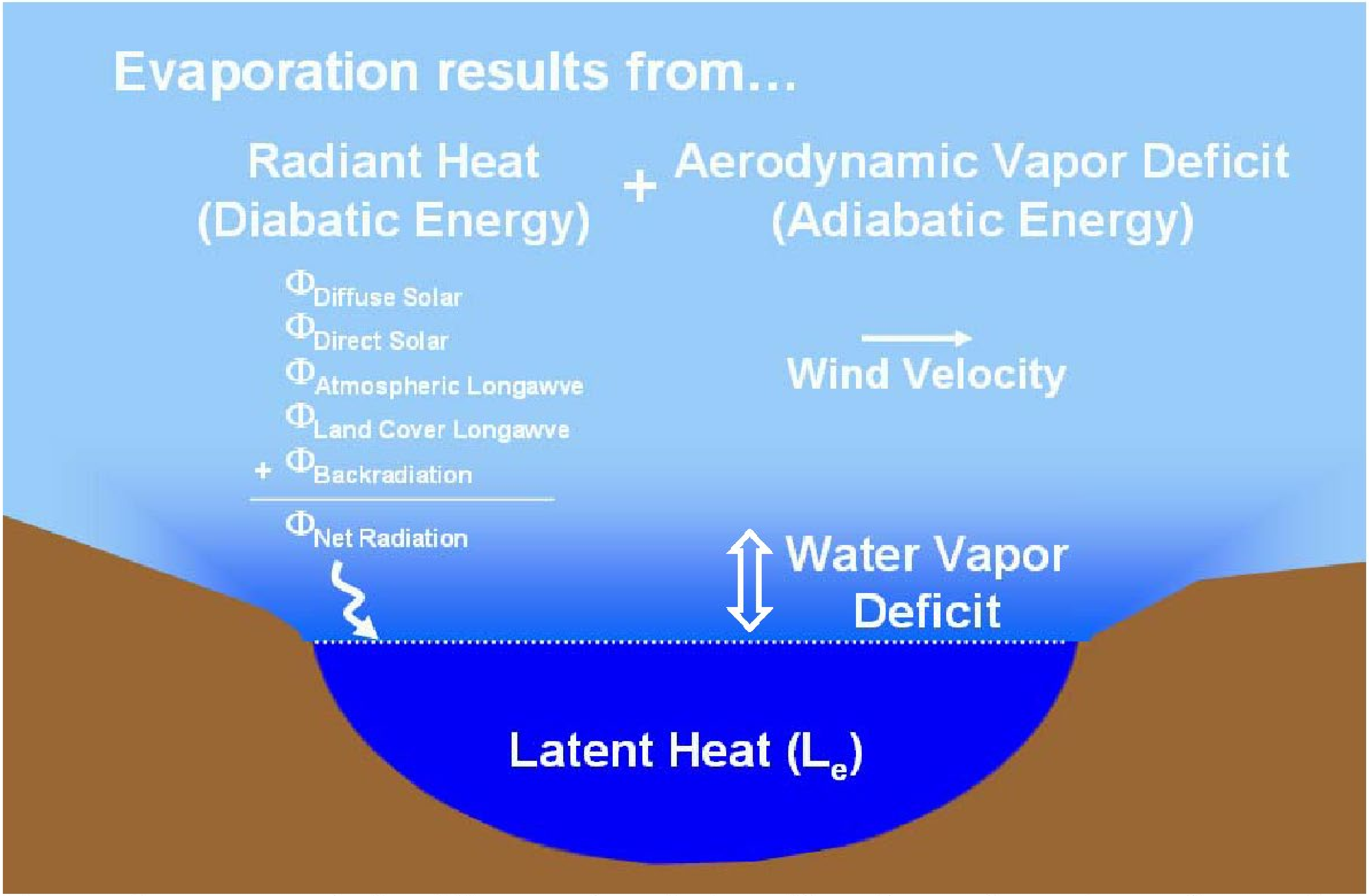
SunEye

Longwave Thermal Radiation

$$\Phi_{\text{longwave}} = \Phi_{LW}^{A} + \Phi_{LW}^{LC} + \Phi_{LW}^{S}$$

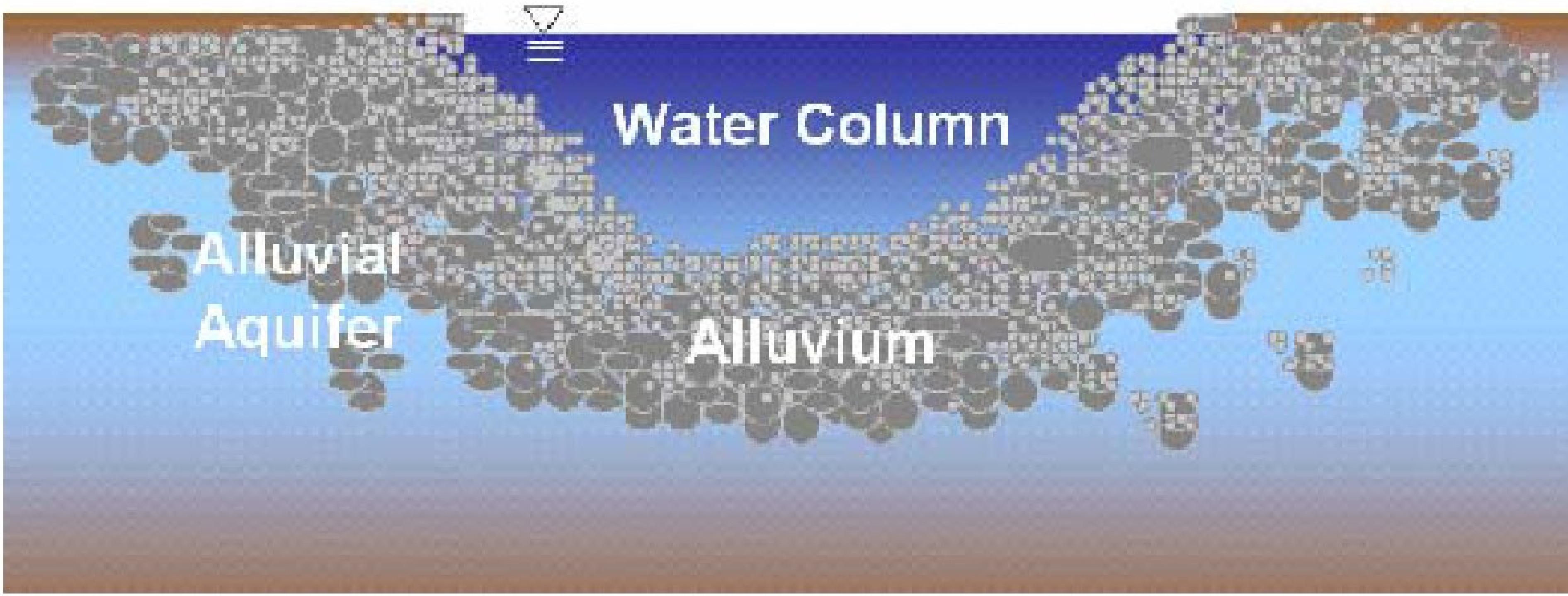
Atmosphere Land Cover Back (stream)





Evaporation represents the difference in enthalpy of the air near the water surface and the ambient air. Evaporation raises the total energy content of the air near the evaporating surface representing a heat loss to the water column.

Substrate conductive flux



Heat exchange between alluvium and the water column acts as a heat buffer with the stream and does so as a function of particle size, embeddedness and channel geometry.

Mass Transfer

instream mixing and any volume added or taken away

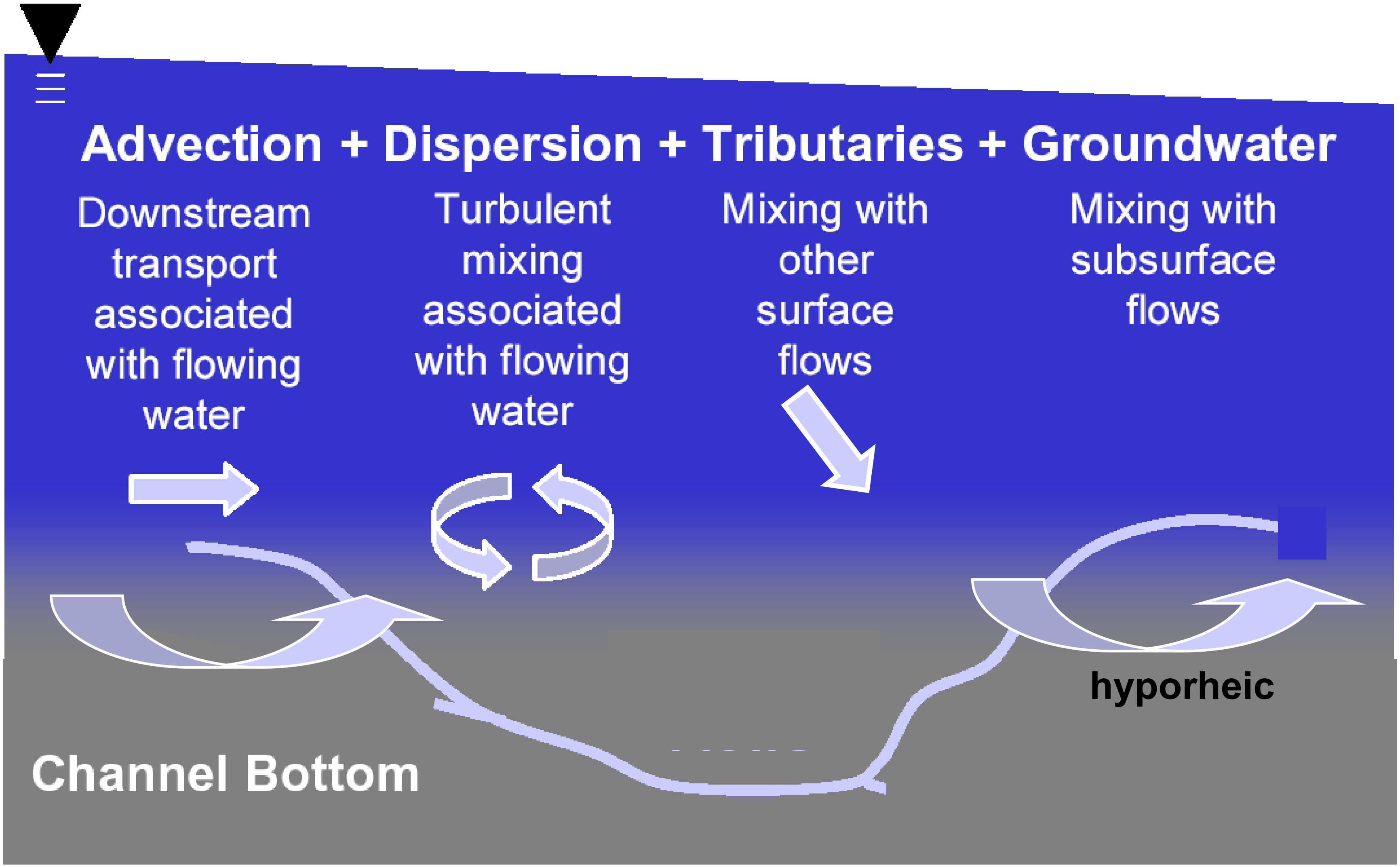


FIGURE 3.1
Mass Transfer Processes: Advection, Dispersion, and Mixing

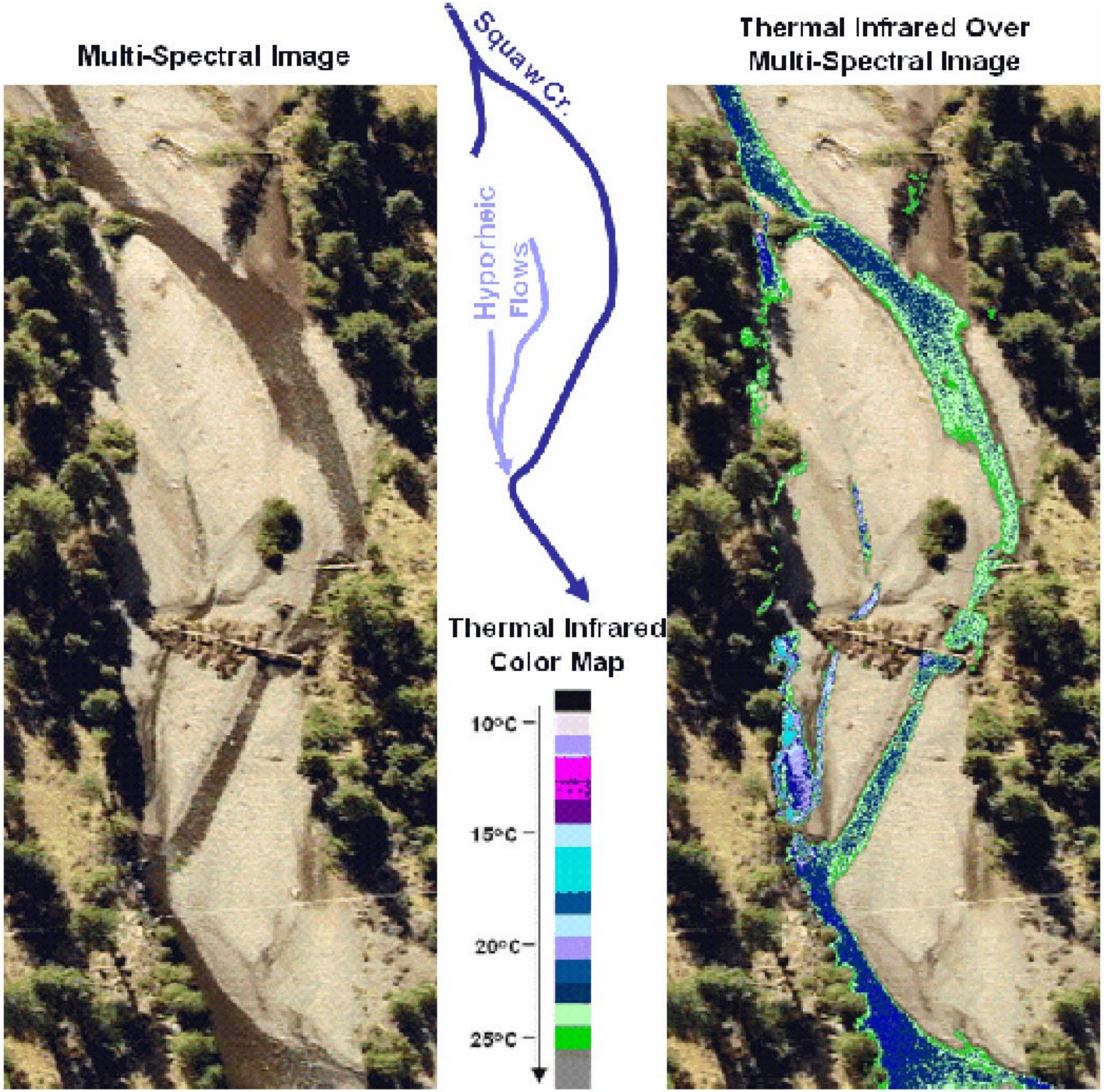


FIGURE 3.12
Hyporheic flows through stream bar substrate (Squaw Creek, Oregon)

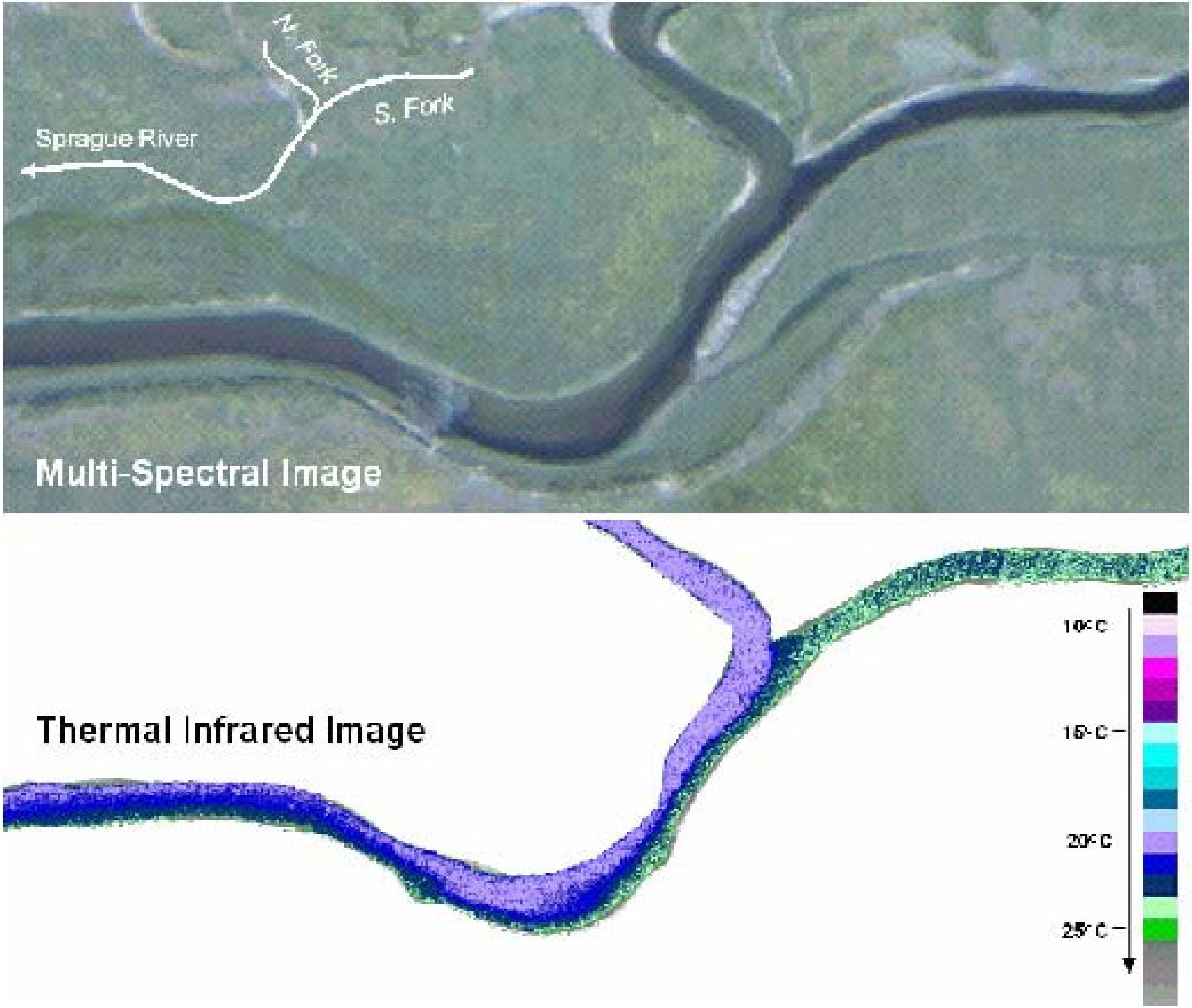


FIGURE 3.7
Example of mixing at a confluence (North and South Forks of the Sprague River, Oregon)

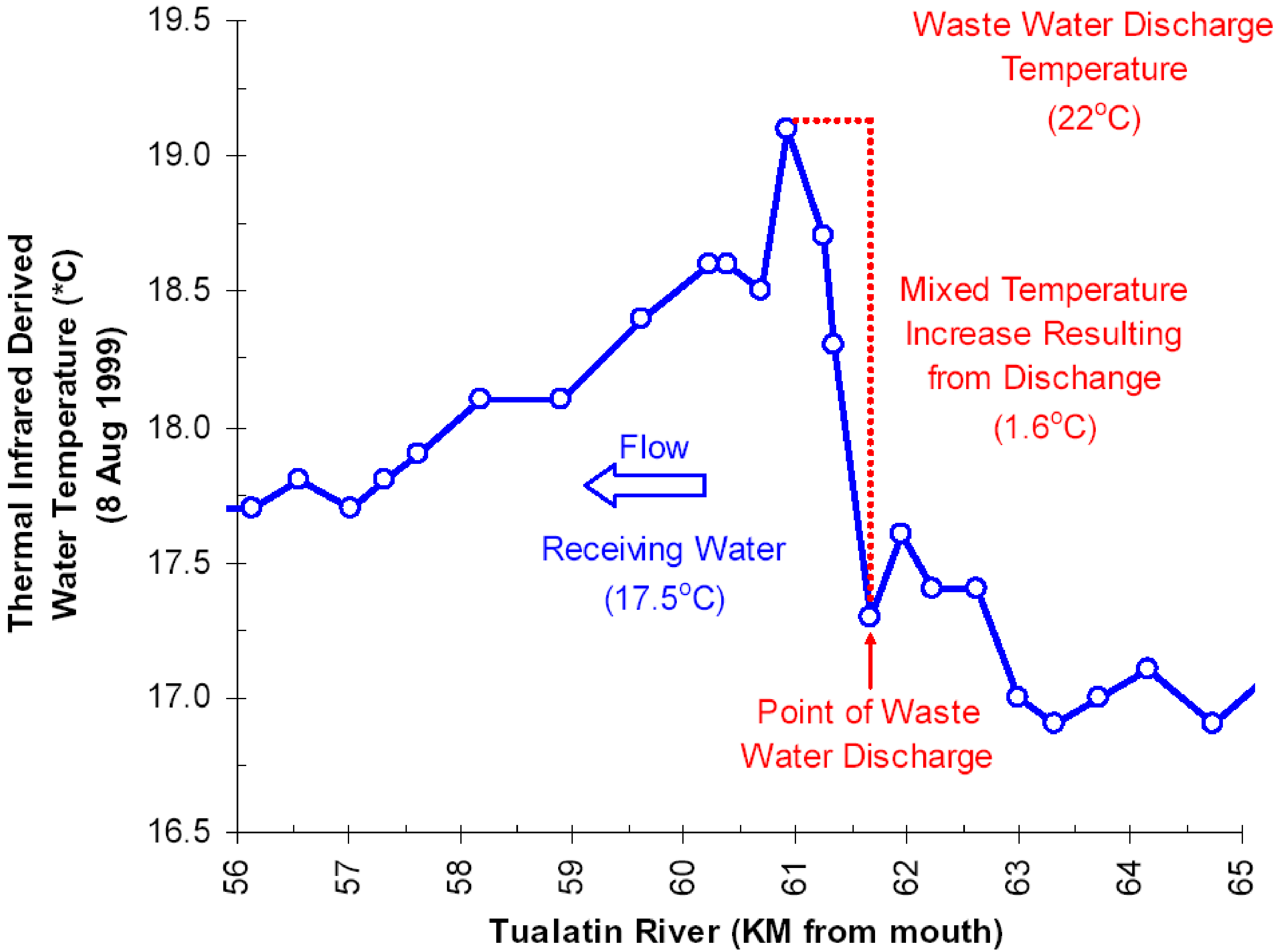


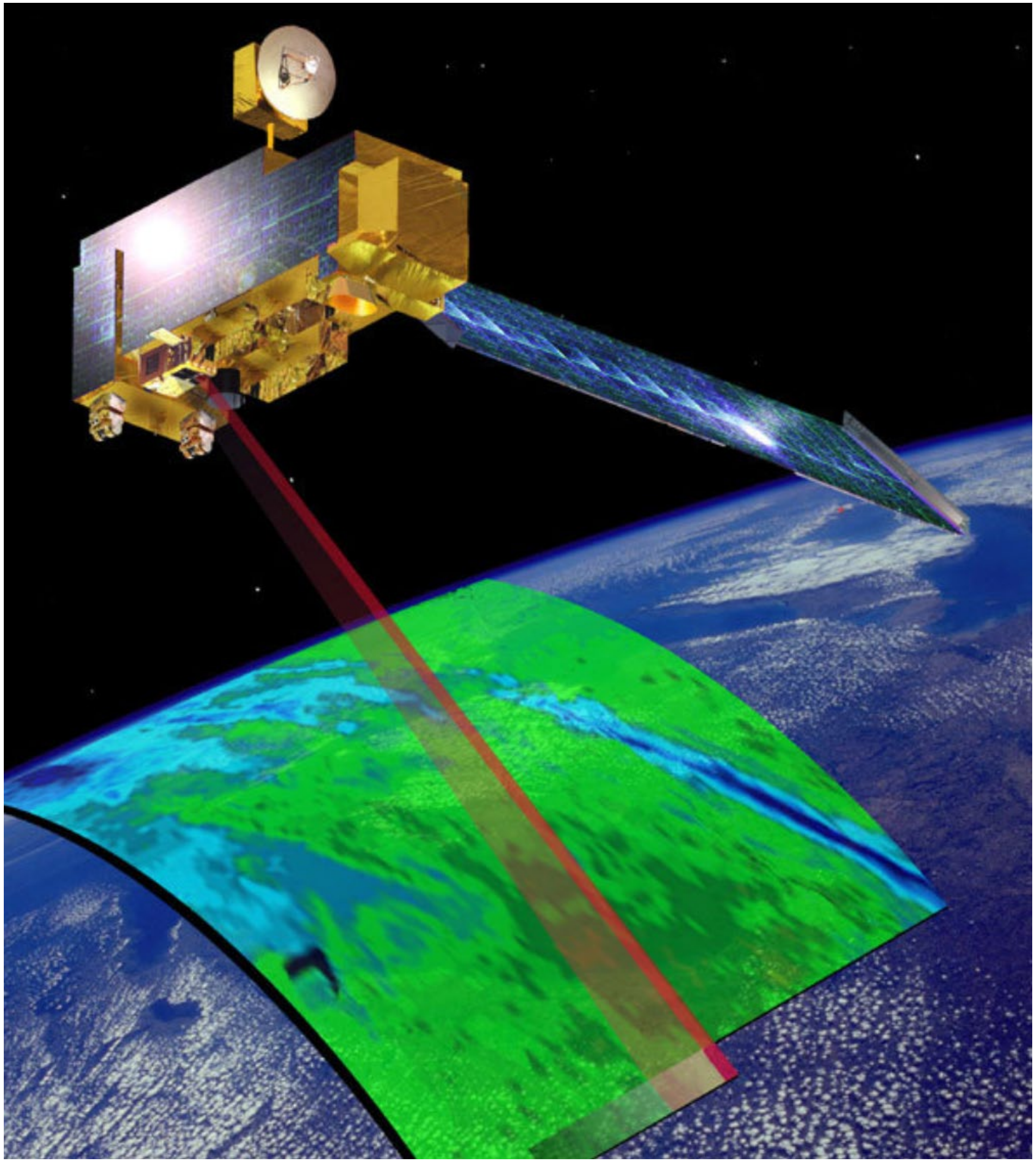
FIGURE 1.6
Measured TIR data indicates a 1.6°C increase in water temperature after complete mix (Tualatin River, Oregon).

Temperature Models

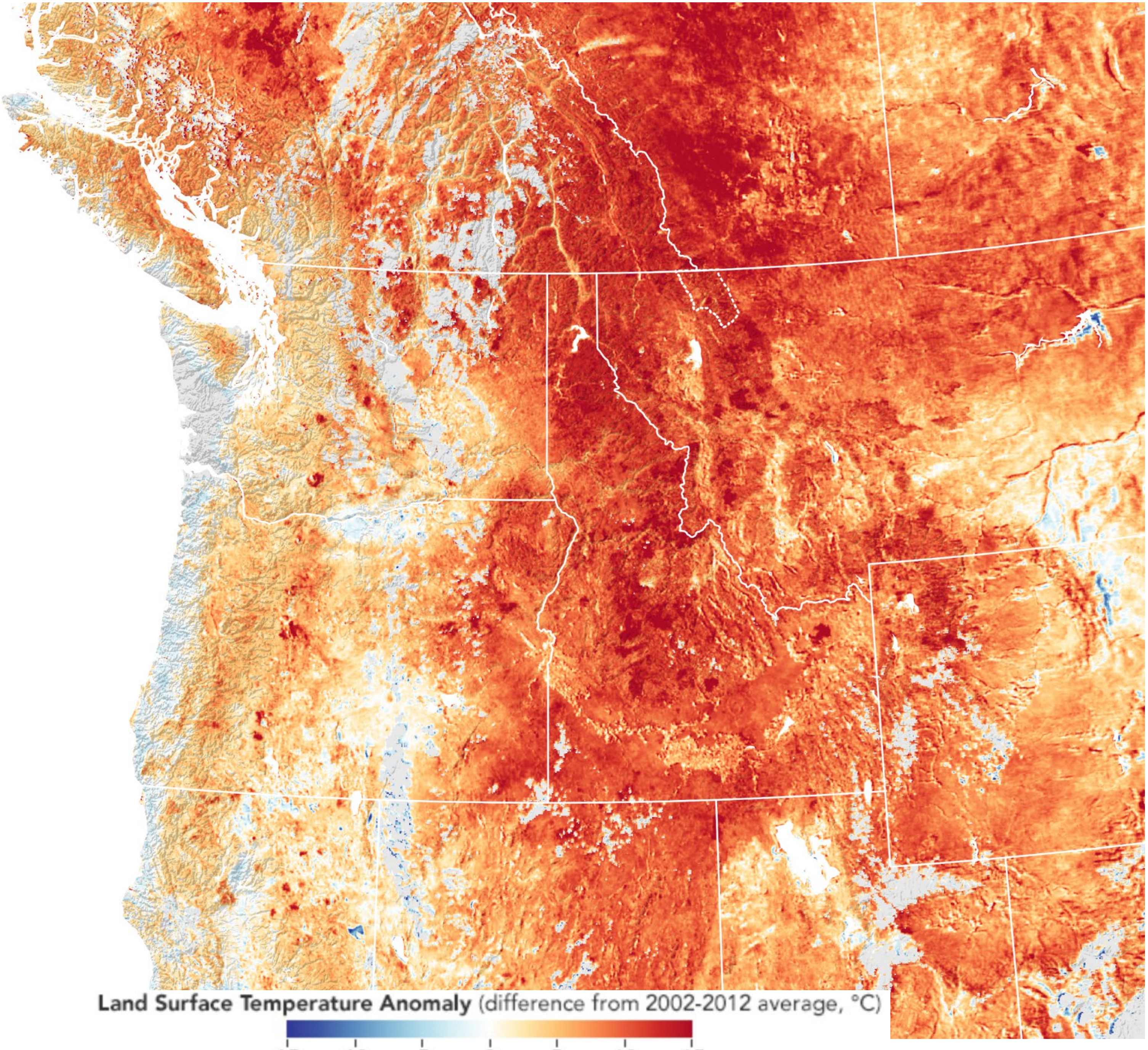
1. Empirical (remote sensing)
2. Empirical (spatial autocorrelative)
3. Mechanistic

MODIS

(Moderate Resolution Imaging Spectroradiometer)

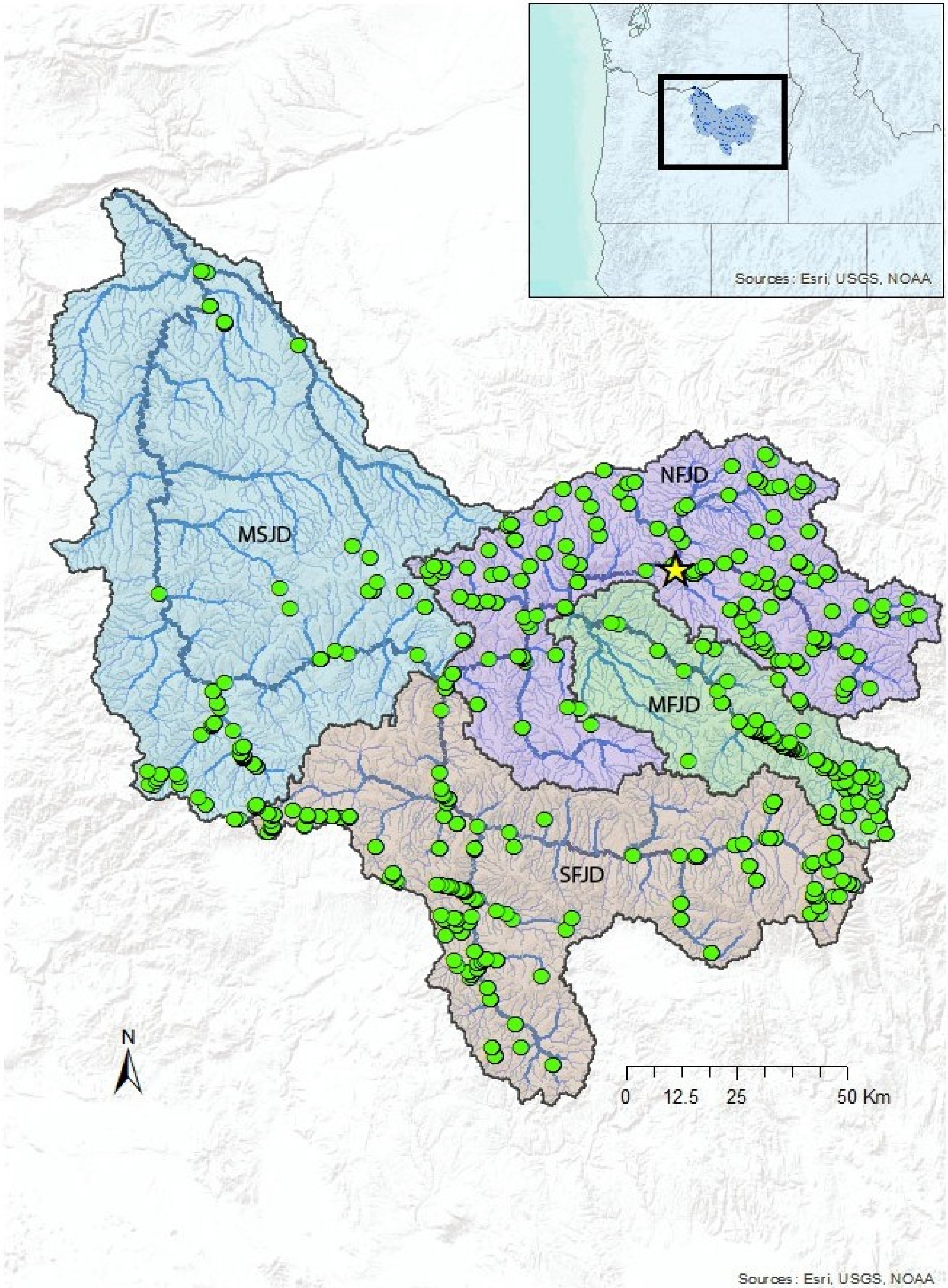


- Instrument aboard Terra and Aqua Satellites
- View entire earth surface every 1-2d
- 36 spectral bands
- Spatial resolution 250-1000 m



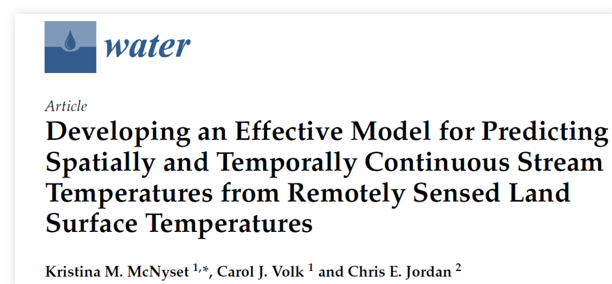
MODIS

Land surface temperatures (1 km^2)



Temperature logger data

- John Day Basin
- 2000-2009
- 510 sites
- 79,790 logger days


water

Article

Developing an Effective Model for Predicting Spatially and Temporally Continuous Stream Temperatures from Remotely Sensed Land Surface Temperatures

Kristina M. McNyset [1,*], Carol J. Volk [1] and Chris E. Jordan [2]

Water **2015**, *7*, 6827–6846; doi:10.3390/w7126660

Approach: correlation between temperature loggers and LST

"… Land Surface Temperature (LST) …. is a measure of thermal conditions at the Earth's surface. These conditions are influenced by air temperature, climate, surface geology, vegetation, elevation, and physiography, among other factors, and these are the same factors that influence the temporal and spatial variation of temperature in many stream systems."

McNyset et al. 2015

LST vs temp logger correlations

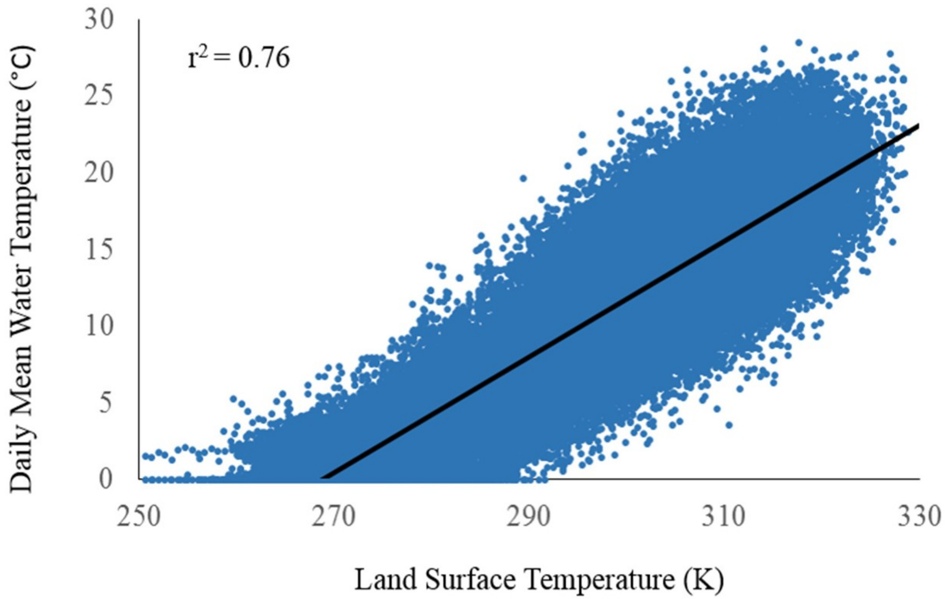


Figure 5. Relationship between Daily Mean Water Temperature (˚C) and Land Surface Temperature (K) for all sites, 2000–2009 in the John Day River basin. The black line and r^2 are from a simple linear regression (DMWT ~ LST).

Table 3. Model comparison of global models built including all sites across all years, those including year and season terms, and those split into two datasets based on the highest DMWT across each year ("Spring" and "Fall"). "Year" models are the mean metrics for models built on each year's data (including a seasonal split).

Model	Fixed Effects	RMSE	r^2
Global	DMWT ~ LST	2.74	0.76
Global	DMWT ~ LST + year	2.85	0.77
Global	DMWT ~ LST + year + season	2.85	0.77
Global	DMWT ~ LST + LST^2 + Elev	2.83	0.77
Spring	DMWT ~ LST + LST^2 + Elev + JulDay	2.63	0.82
Fall	DMWT ~ LST + LST^2 + Elev + JulDay	2.33	0.82
Year	DMWT ~ LST + LST^2 + Elev + JulDay	2.24	0.83

McNyset et al. 2015

Global vs Site-specific correlations

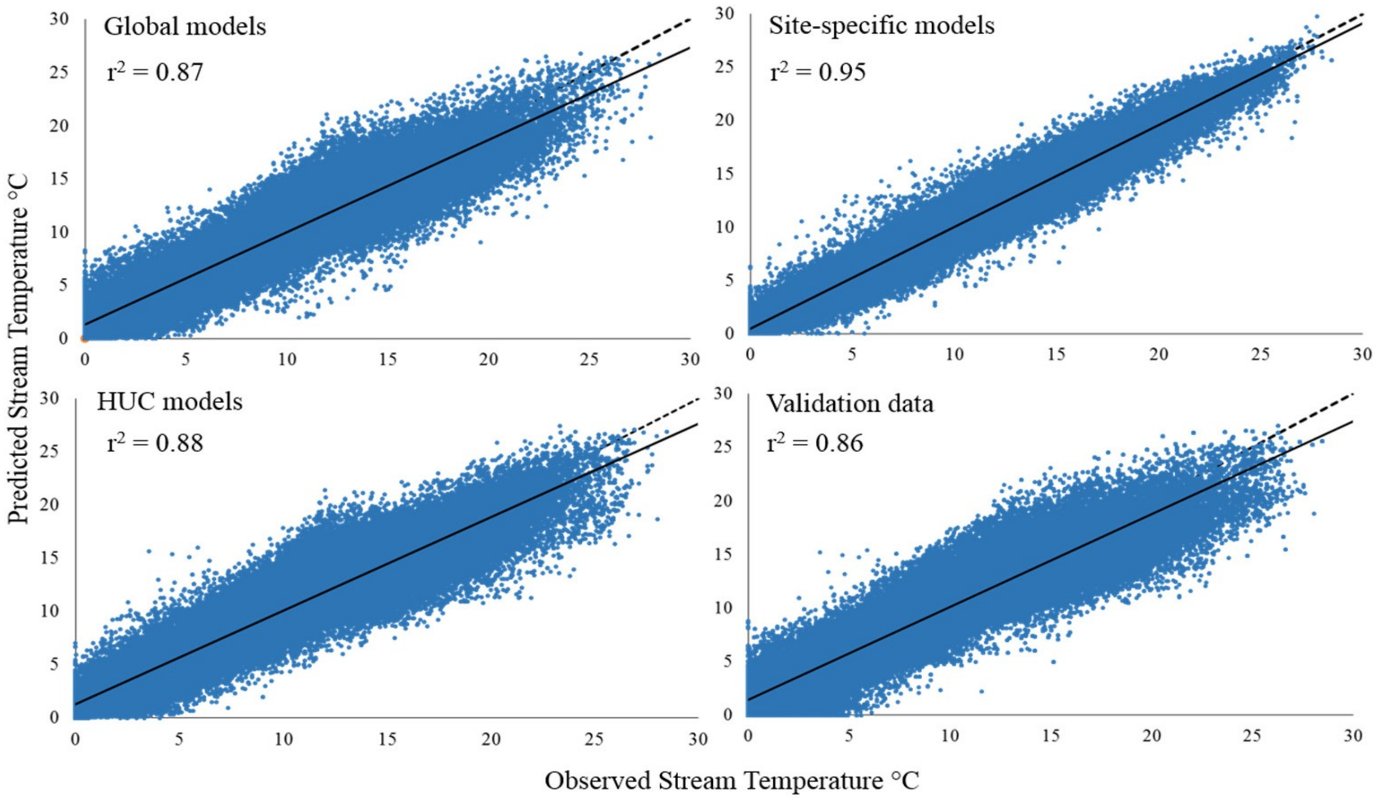


Figure 7. Stream temperature predicted from the global, site-specific, and HUC models for 2000–2009 *vs.* the observed values. The validation data plot is the jackknife-by-site, leave-one-out validation data for all years *vs.* the predicted temperatures for those sites from the global models for each year. The solid black line is the simple linear regression between the predicted and observed temperatures (with r^2 for that relationship). The dashed line is the one-to-one relationship.

McNyset et al. 2015

Captures temporal variability

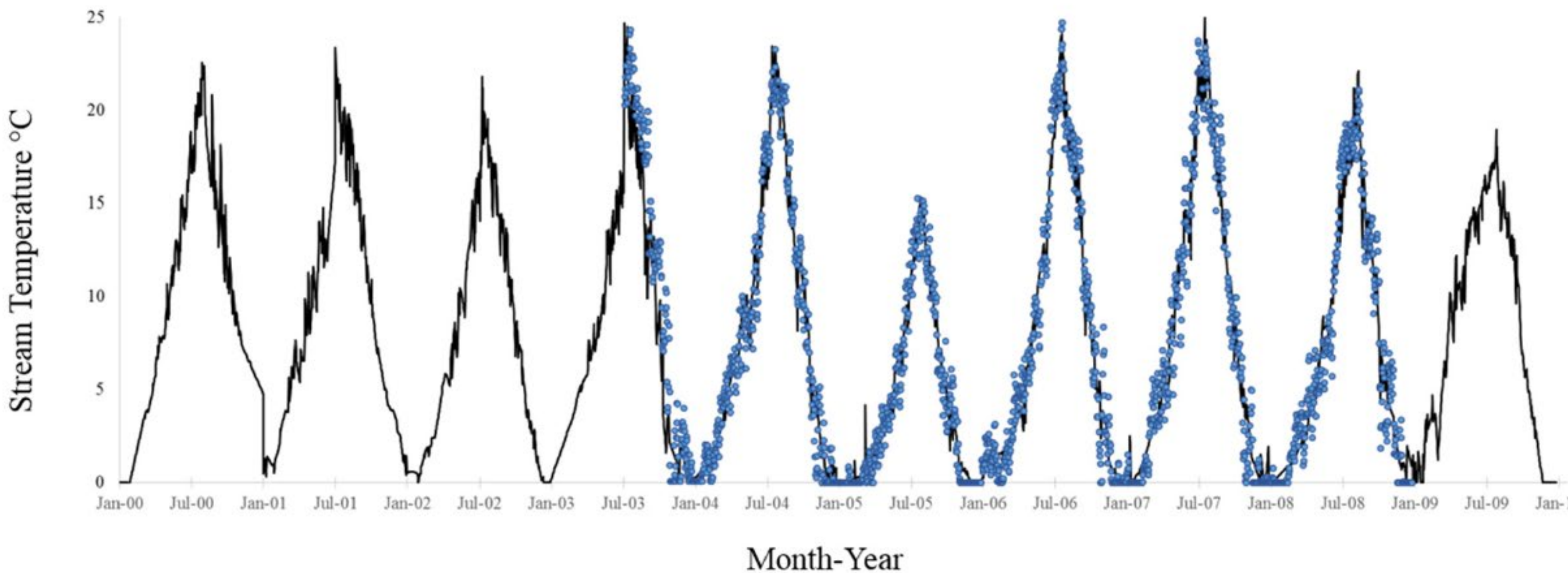


Figure 8. Example of observed and predicted daily mean stream temperature from one site across 10 years (2000–2009). The site is located on the North Fork John Day River above the confluence with Camas Creek. Blue dots are observed daily mean stream temperature and the gray line is estimated daily stream temperature from site-specific models in years where data are available, and the black line is from HUC-based models.

Site-specific factors (e.g. springs) can be important

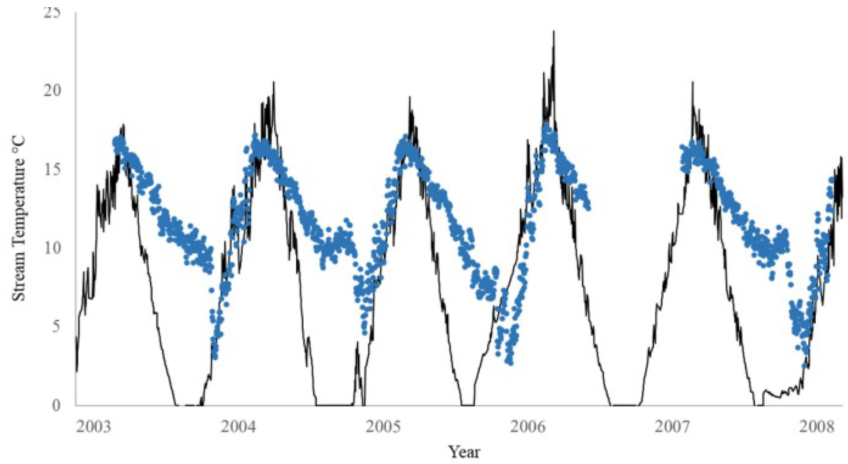


Figure 11. Observed (**blue dots**) and estimated (**black lines**) daily mean stream temperature from a site in the Middle Fork John Day River near Phipps Meadow. Estimated stream temperature is from models built using all the data for the HUC 4 encompassing the Middle Fork.

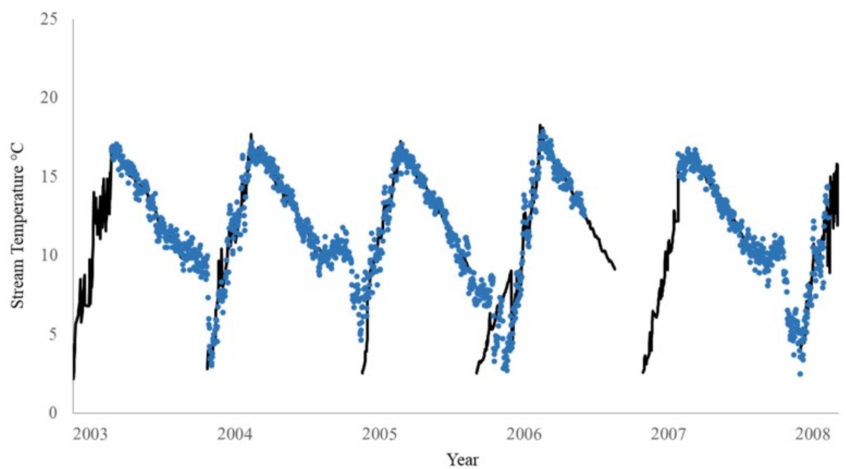


Figure 12. Observed (**blue dots**) and estimated (**black lines**) daily mean stream temperature from a site in the Middle Fork John Day River near Phipps Meadow. Estimated stream temperature is from models built using site-specific data.

How many temp logger do you need?

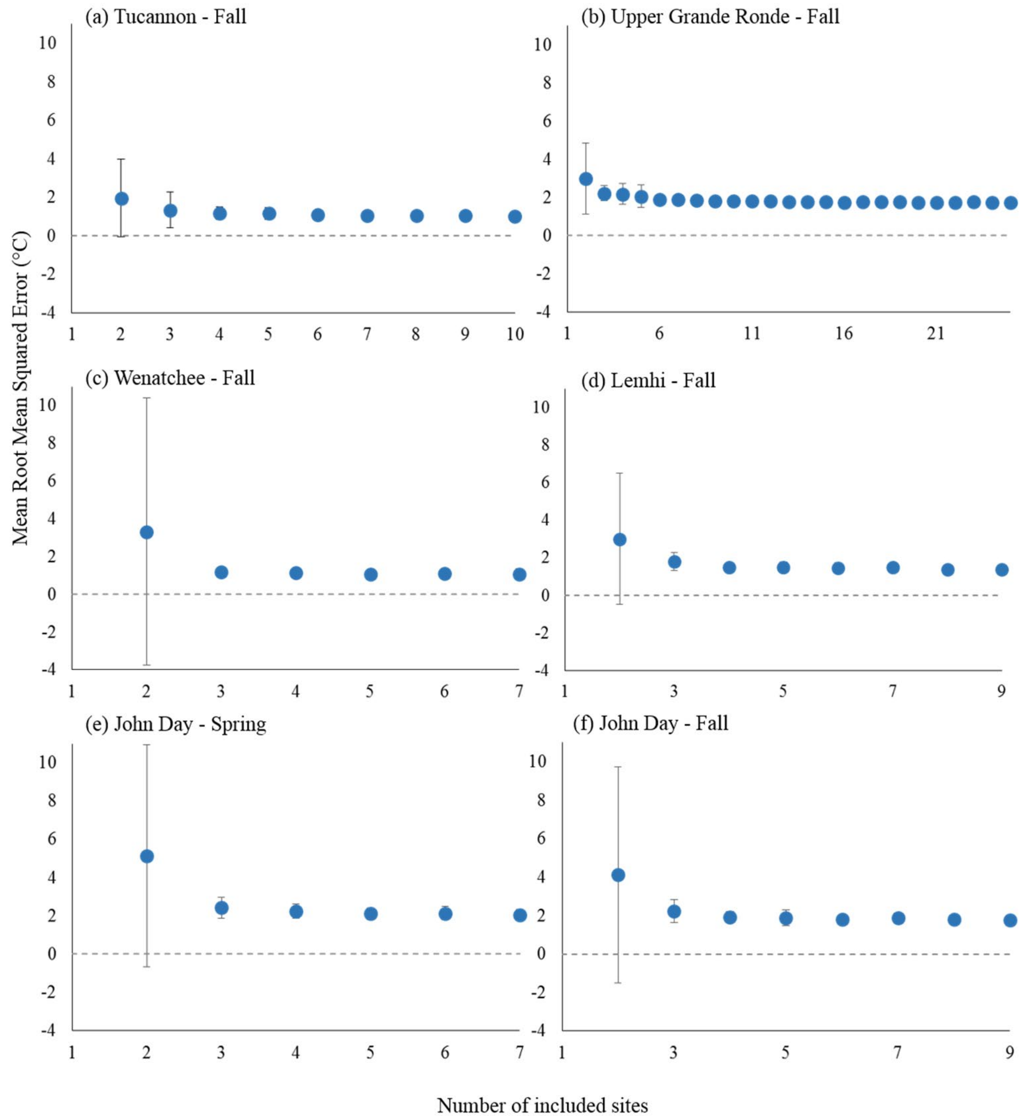
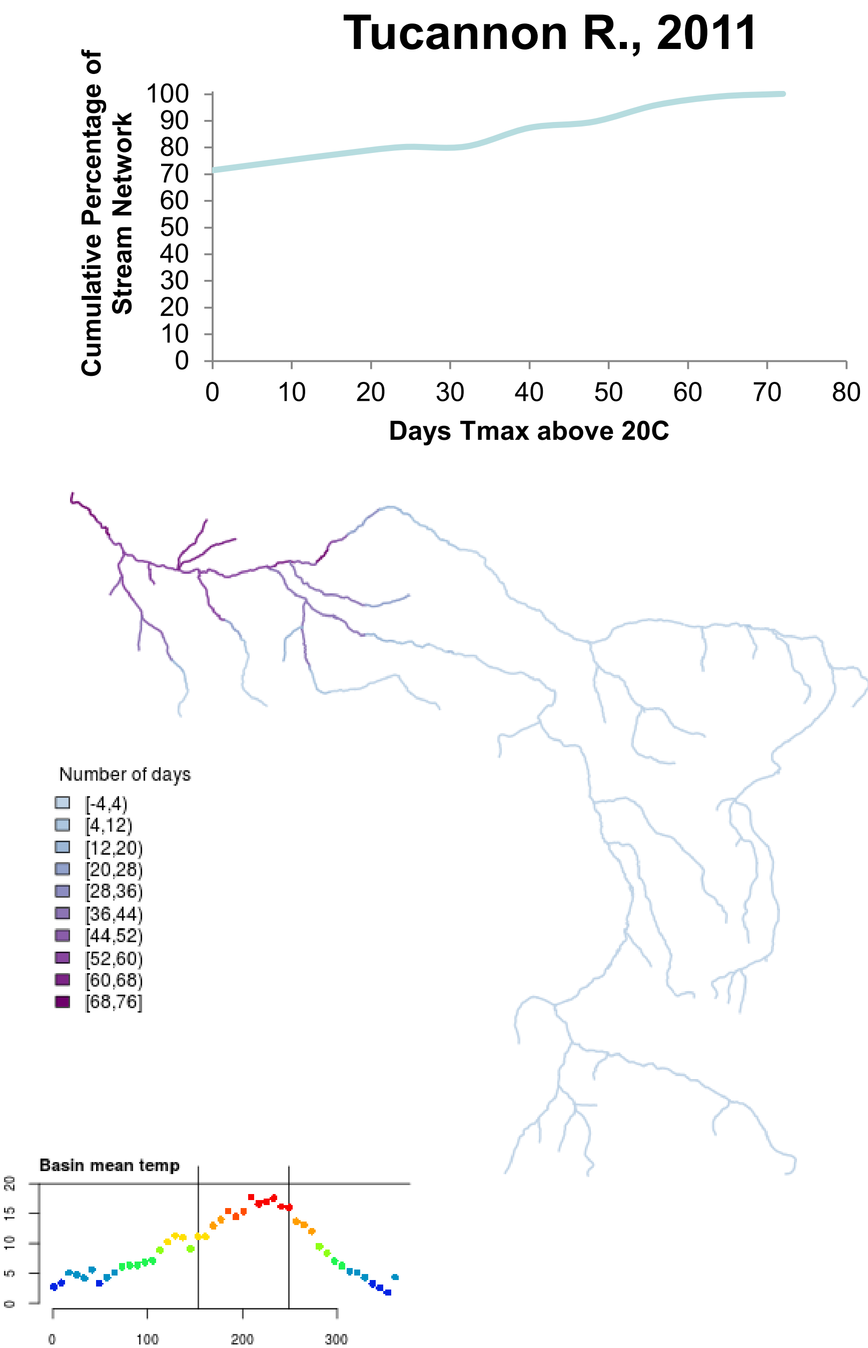
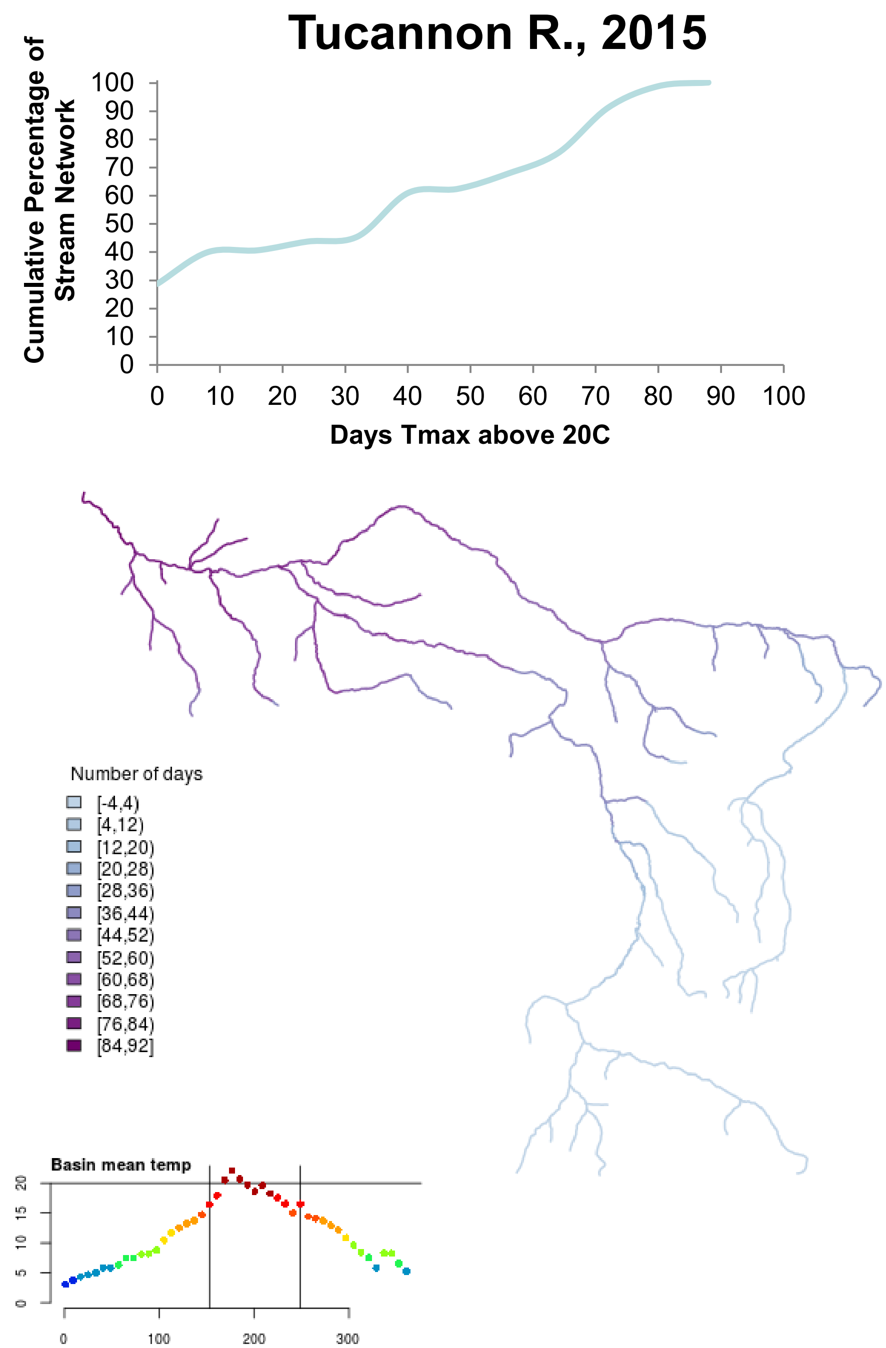


Figure 10. Sensitivity analysis mean root mean squared errors (and standard deviation of those means) from the N-i site jackknife for all basins. Mean Root Mean Squared Errors on the Y-axis, and the number of included sites on the X-axis for all graphs. "Spring" indicates data from the first half of the year (and "Fall" the second half) as determined by the peak mean temperature across the year. (**a**) Tucannon River basin; (**b**) Upper Grande Ronde River basin; (**c**) Wenatchee River basin; (**d**) Lemhi River basin; (**e**,**f**) John Day River basin.


Tucannon R., 2011
Cumulative Percentage of Stream Network
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
Days Tmax above 20C
Number of days
[-4,4)
[4,12)
[12,20)
[20,28)
[28,36)
[36,44)
[44,52)
[52,60)
[60,68)
[68,76]
Basin mean temp
20
15
10
5
0
0
100
200
300


Tucannon R., 2015
Cumulative Percentage of Stream Network
100
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60
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30
40
50
60
70
80
90
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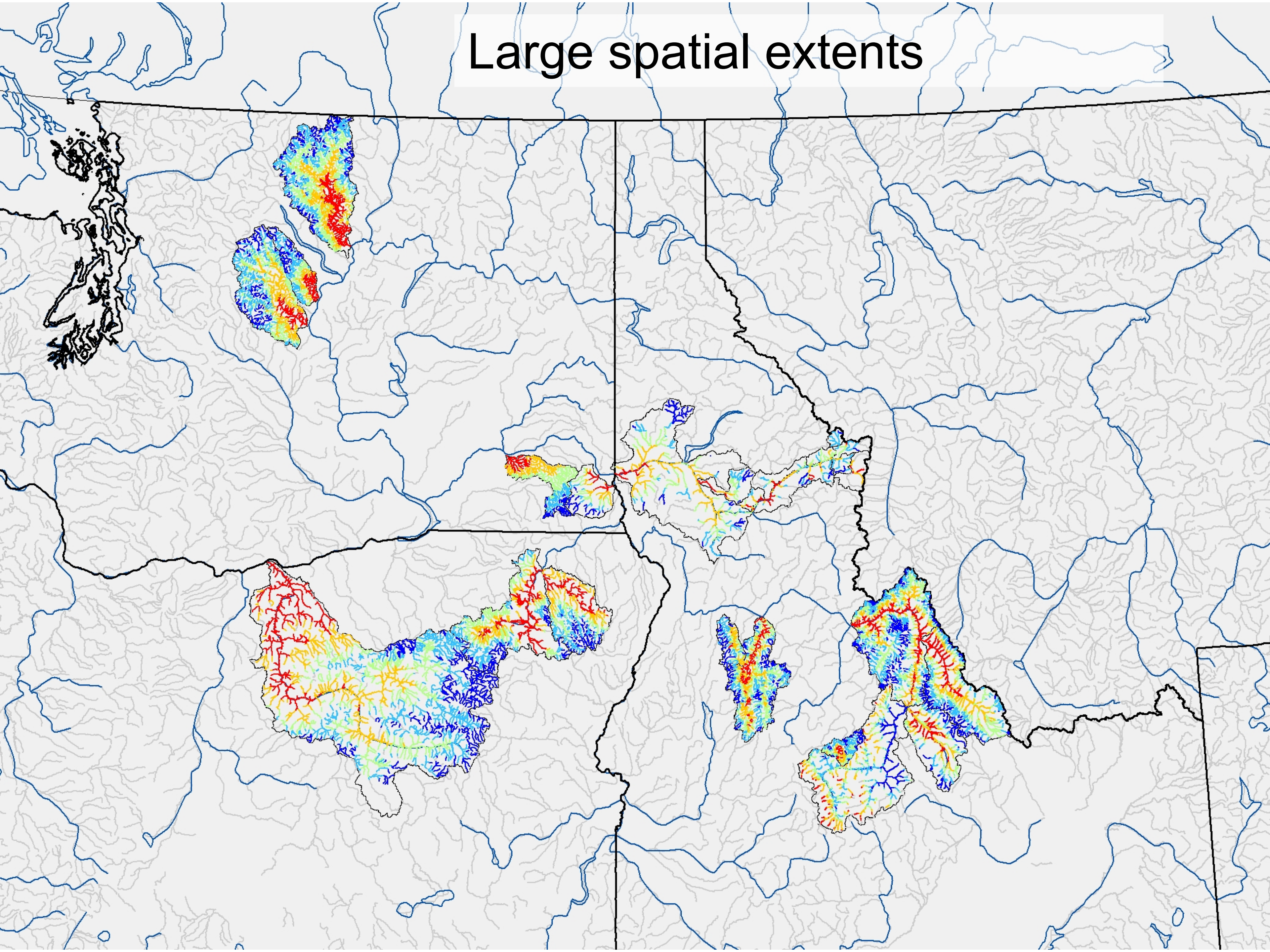
Days Tmax above 20C
Number of days
[-4,4)
[4,12)
[12,20)
[20,28)
[28,36)
[36,44)
[44,52)
[52,60)
[60,68)
[68,76)
[76,84)
[84,92]
Basin mean temp
20
15
10
5
0
0
100
200
300

Large spatial extents



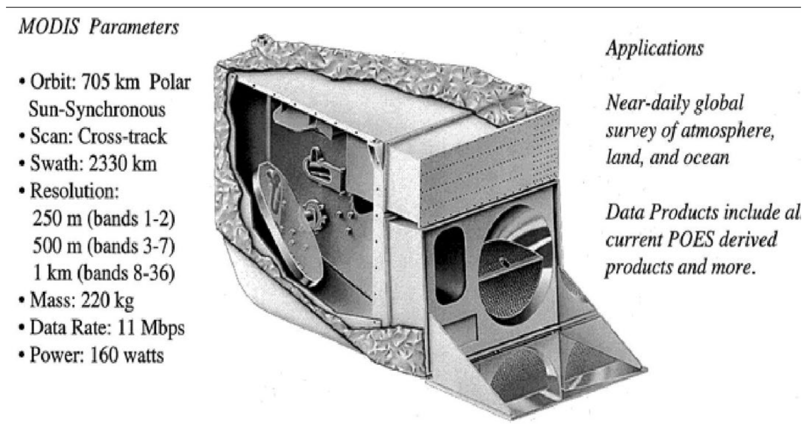
MODIS correlation approach

Pros-

- Relatively straight forward
- Large spatial scales & year round estimates (assuming temp loggers available)

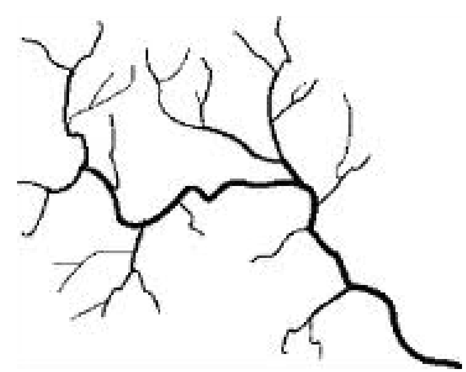
Cons-

- Projections not currently possible (e.g. management scenarios, climate change)
- Must have data loggers in the network
- Can miss important smaller scale drivers



Spatial Autocorrelation

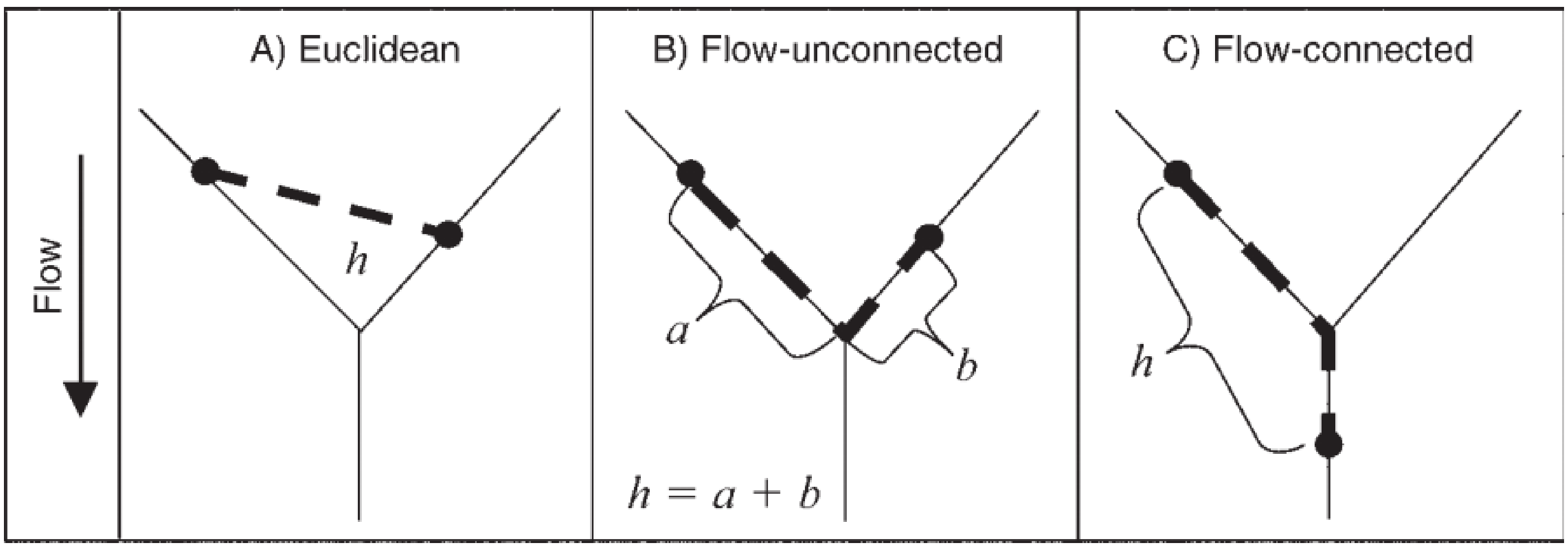
- **Spatial Autocorrelation (SAC):** degree to which observations are independent of one another
  - General Rule: observations that are closer to each other are more similar that those that are farther apart
  - Environmental factors and species specific adaptations can dictate spatial structure
    - Temperature
    - Spawning densities/location
  - Sites kilometers apart may demonstrate SAC
  - Incorporate into models: Isolate spatial structure, focus on habitat



Spatial Stream Network (SSN)

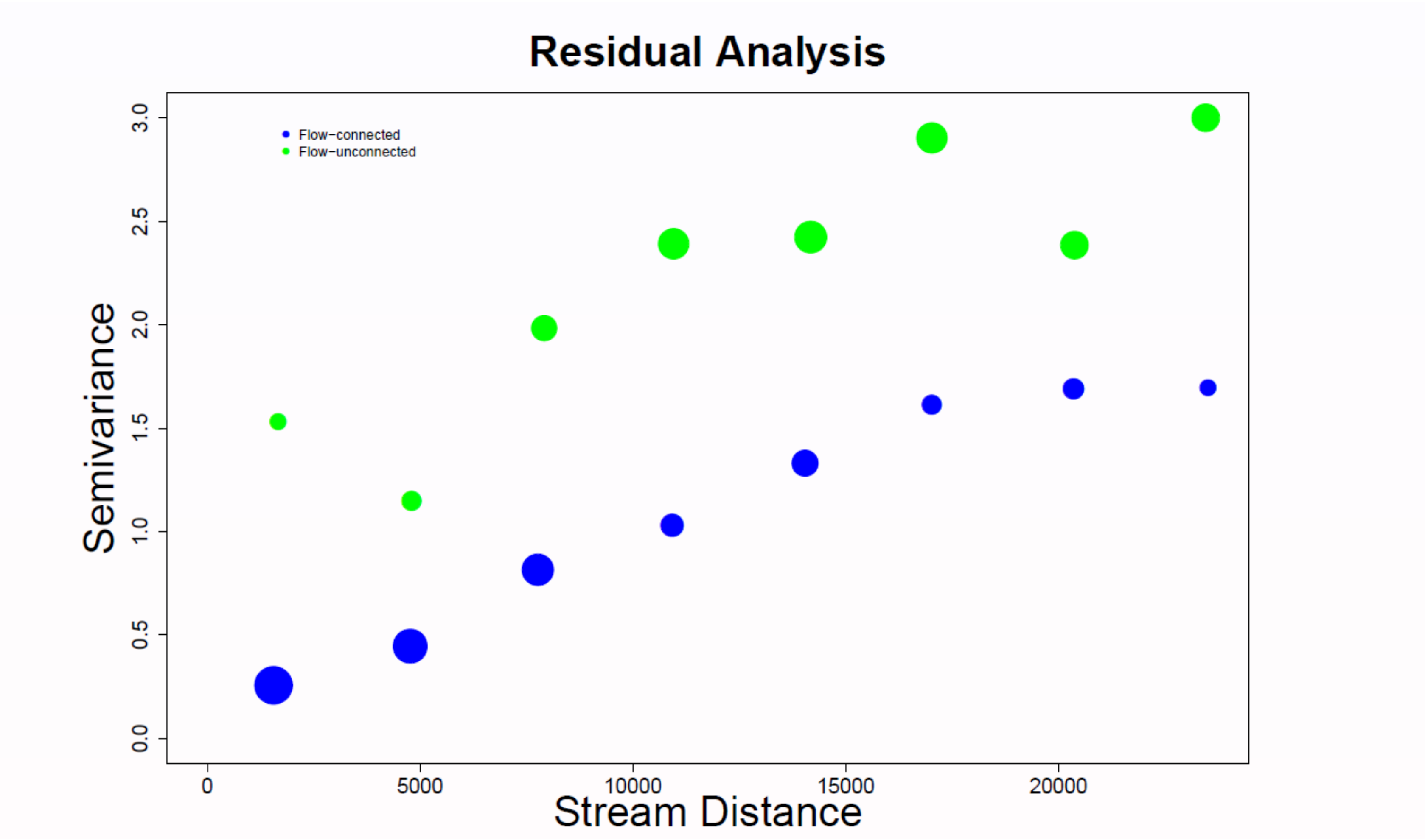
Streams operate differently than terrestrial systems:

- Directional
- Branching network
- Hydrologic distances not Euclidean



Peterson and Ver Hoef , 2010

Semivariogram



NorWeST

Dan Isaak et al.

Figure 1. Locations of stream temperature data that were used to develop temperature models and scenarios in the western U.S. Letters and white boundaries denote 23 processing units used to partition the data and fit individual models.

- >100 resource groups
- >220,000,000 temp recordings
- >22,700 stream sites

AGU PUBLICATIONS

Water Resources Research

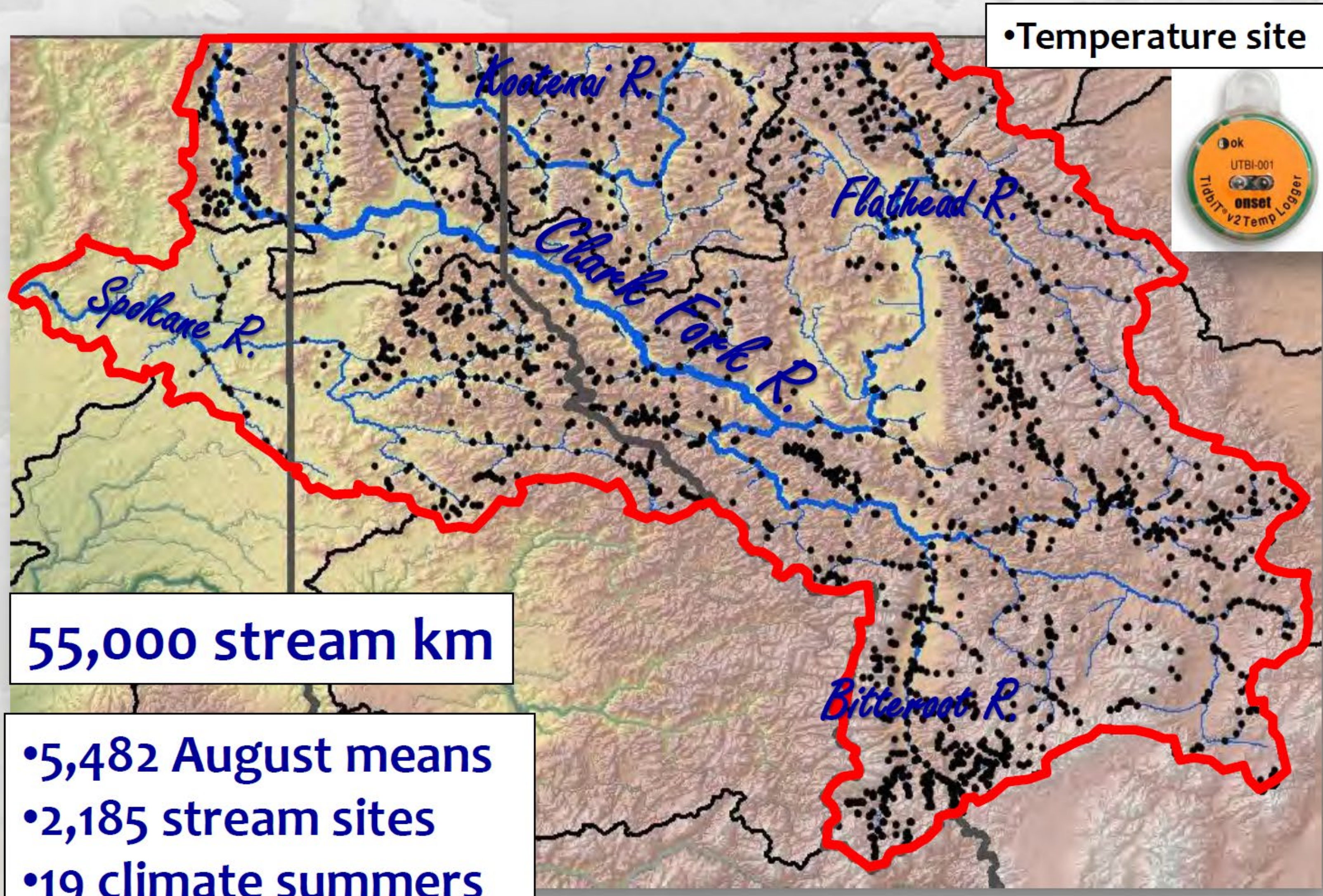
The NorWeST Summer Stream Temperature Model and Scenarios for the Western U.S.: A Crowd-Sourced Database and New Geospatial Tools Foster a User Community and Predict Broad Climate Warming of Rivers and Streams

Daniel J. Isaak[1], Seth J. Wenger[2], Erin E. Peterson[3], Jay M. Ver Hoef[4], David E. Nagel[1], Charles H. Luce[1], Steven W. Hostetler[5], Jason B. Dunham[6], Brett B. Roper[7], Sherry P. Wollrab[1], Gwynne L. Chandler[1], Dona L. Horan[1], and Sharon Parkes-Payne[1]

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017WR020969

Example: SpoKoot River Basins

Data extracted from NorWeST



55,000 stream km

- 5,482 August means
- 2,185 stream sites
- 19 climate summers

SpoKoot River Temp Model

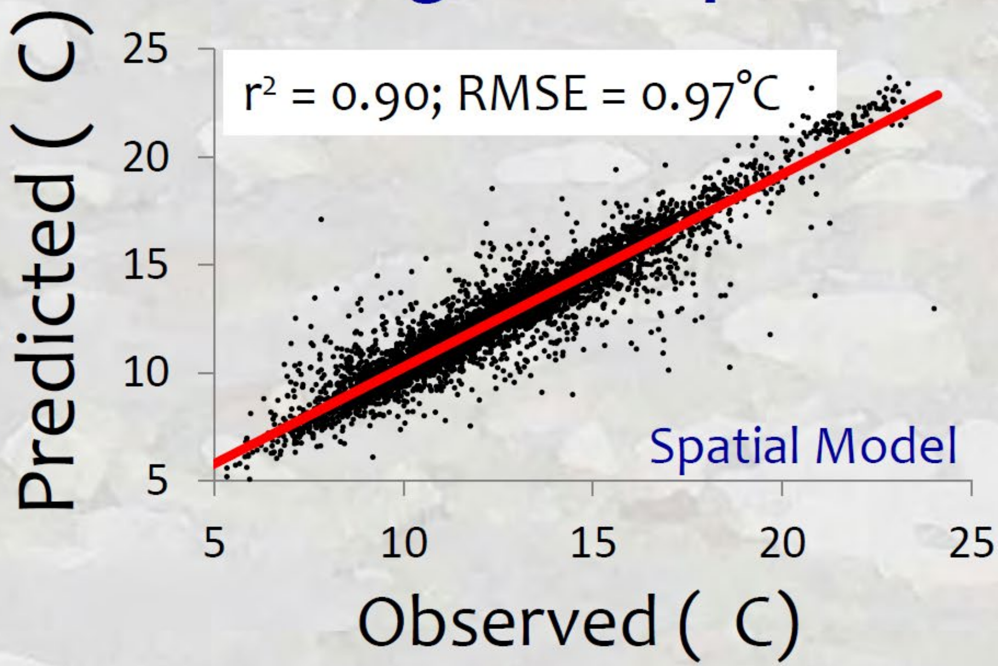
n = 5,482

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 (km²)

9. Discharge (m³/s)
   USGS gage data
10. Air Temperature (°C)
    RegCM3 NCEP reanalysis
    Hostetler et al. 2011

Mean August Temperature



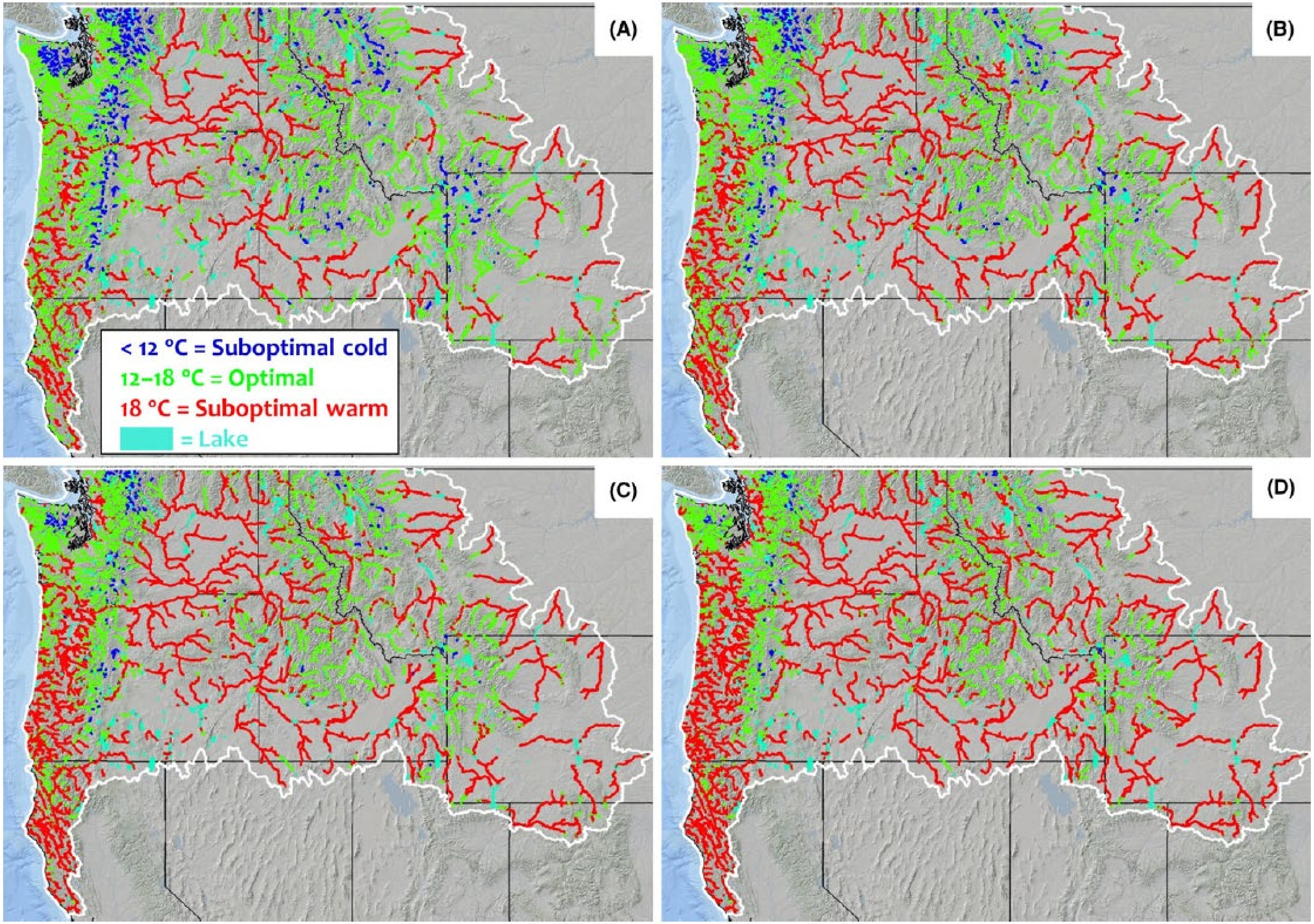


FIGURE 8. Rivers classified by thermal suitability for Brown Trout and Rainbow Trout under scenarios of mean August temperatures that represent (**A**) baseline conditions for 1993–2011, (**B**) +1.0°C, (**C**) +2.0°C, and (**D**) +3.0°C. Supplement G contains high-resolution images of the figure panels, including versions based on different color palettes.

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Global Warming of Salmon and Trout Rivers in the Northwestern U.S.: Road to Ruin or Path Through Purgatory?

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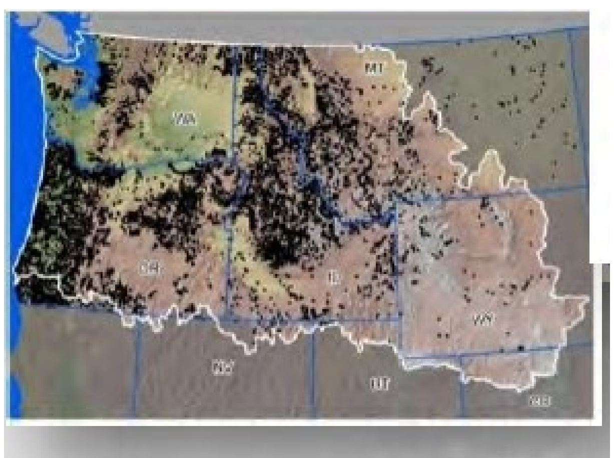
SSN/SAC multiple regression approach

Pros-

- Remove auto-correlation to reveal more accurate and relevant controlling factors
- Large spatial scales (logger information needed but large database likely has this covered in western US)
- Moderate ability to predict

Cons-

- Projections not currently possible for many management scenarios
- Can miss important smaller scale drivers
- Limited temporal information (mainly for mean August temperature)
- SSN requires a fair amount of GIS prep and statistical analysis



NorWeST Stream Temp

Analytical Methods for Dynamic Open Channel Heat and Mass Transfer

Methodology for the Heat Source Model Version 7.0

A general setup stepwise procedure can be summarized as follows:

Step 1. Complete data fields (text boxes) found in the 'General Inputs' tab from the 'Main Menu'

Step 2. Setup the spatial data worksheets from the 'Data Sheets' tab

Step 3. Setup the temporal data worksheet from the 'Continuous Data' tab

Step 4. Setup the flow data worksheet from the 'Mass Transfer Data' tab

Step 5. Assign physical attributes to land cover classifications

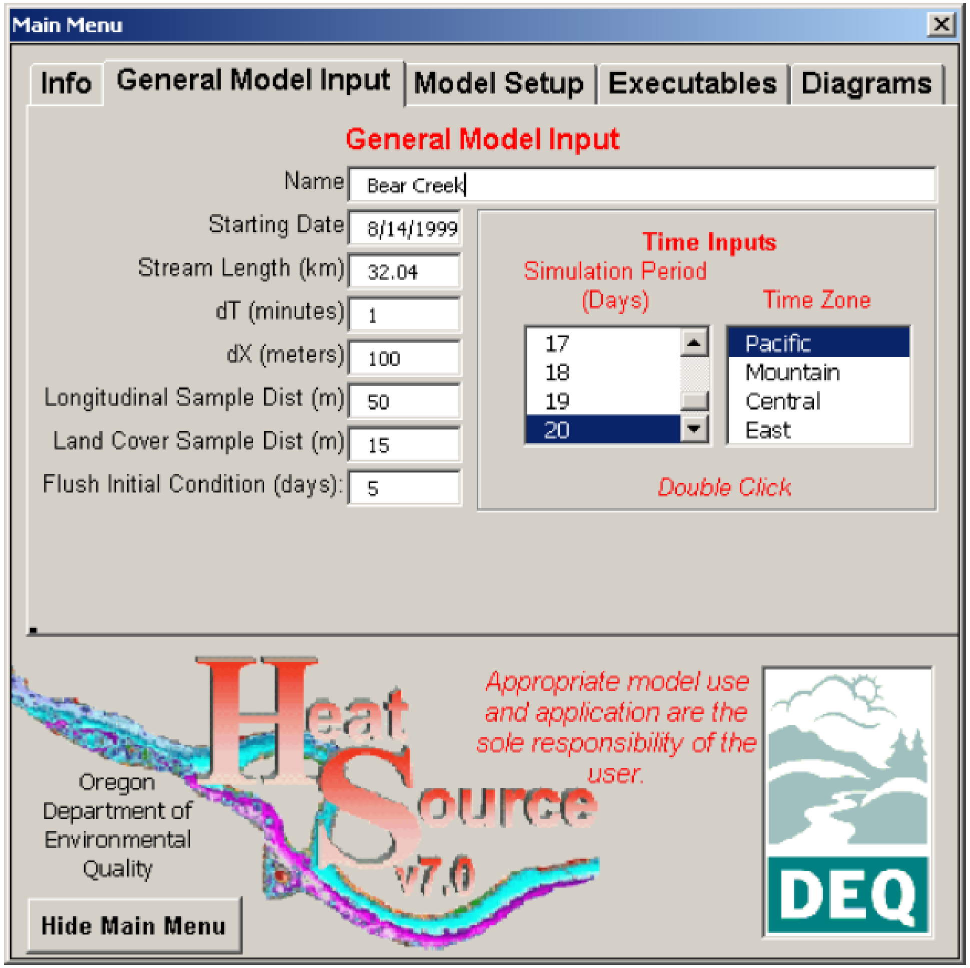
- ⇒ Enter codes and associated physical attribute information into the 'Land Cover Codes' worksheet
- ⇒ Run 'Vegematic' to assign height, density and overhang information to sampled land cover classifications

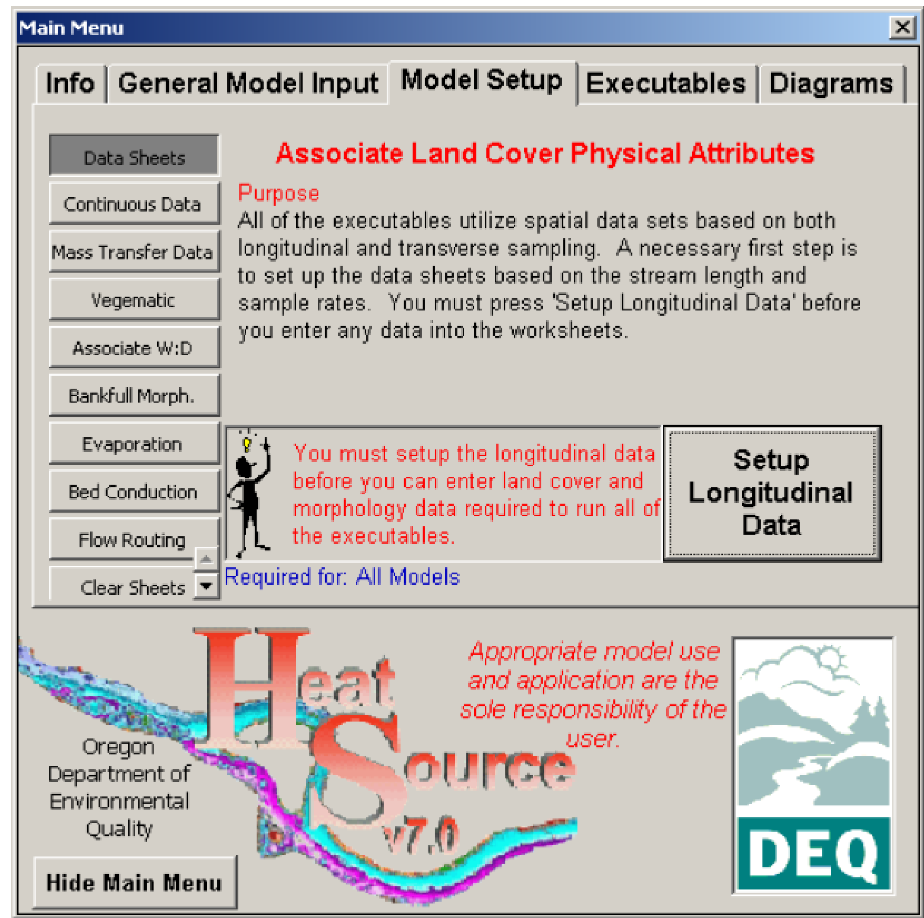
Step 6. Enter morphology input data

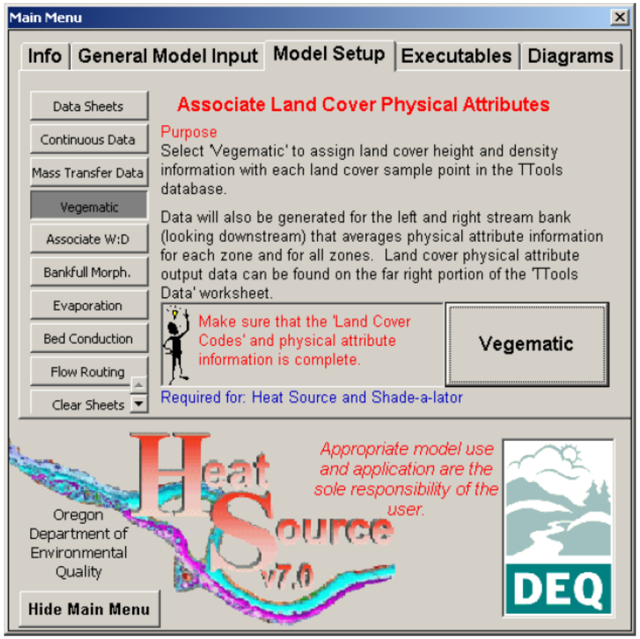
- ⇒ Either enter or assign W:D based on Rosgen Level I information under the 'Associate W:D' tab
- ⇒ Calculate the bankfull morphology under the 'Bankfull Morph.' tab.

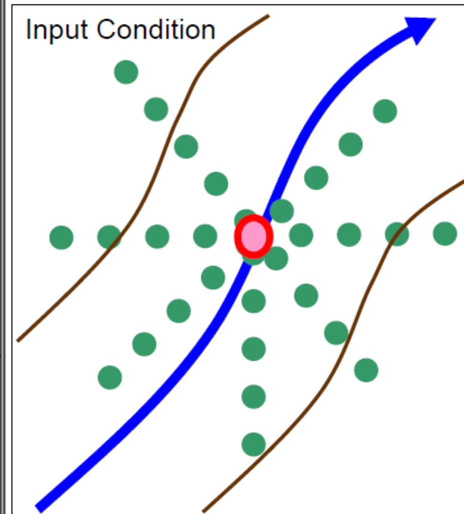
Step 7. Select evaporation rate model and 'a' and 'b' constants under the 'Evaporation' tab

Step 8. Select dynamic flow routing method under the 'Flow Routing' tab


Main Menu
Info
General Model Input
Model Setup
Executables
Diagrams
General Model Input
Name
Bear Creek
Starting Date
8/14/1999
Stream Length (km)
32.04
dT (minutes)
1
dX (meters)
100
Longitudinal Sample Dist (m)
50
Land Cover Sample Dist (m)
15
Flush Initial Condition (days):
5
Time Inputs
Simulation Period (Days)
Time Zone
17
18
19
20
Pacific
Mountain
Central
East
Double Click
Appropriate model use and application are the sole responsibility of the user.
Oregon Department of Environmental Quality
Heat Source v7.0
DEQ
Hide Main Menu


Main Menu
Info
General Model Input
Model Setup
Executables
Diagrams
Data Sheets
Continuous Data
Mass Transfer Data
Vegematic
Associate W:D
Bankfull Morph.
Evaporation
Bed Conduction
Flow Routing
Clear Sheets
Associate Land Cover Physical Attributes
Purpose
All of the executables utilize spatial data sets based on both longitudinal and transverse sampling. A necessary first step is to set up the data sheets based on the stream length and sample rates. You must press 'Setup Longitudinal Data' before you enter any data into the worksheets.
You must setup the longitudinal data before you can enter land cover and morphology data required to run all of the executables.
Setup Longitudinal Data
Required for: All Models
Appropriate model use and application are the sole responsibility of the user.
Oregon Department of Environmental Quality
Heat Source v7.0
DEQ
Hide Main Menu





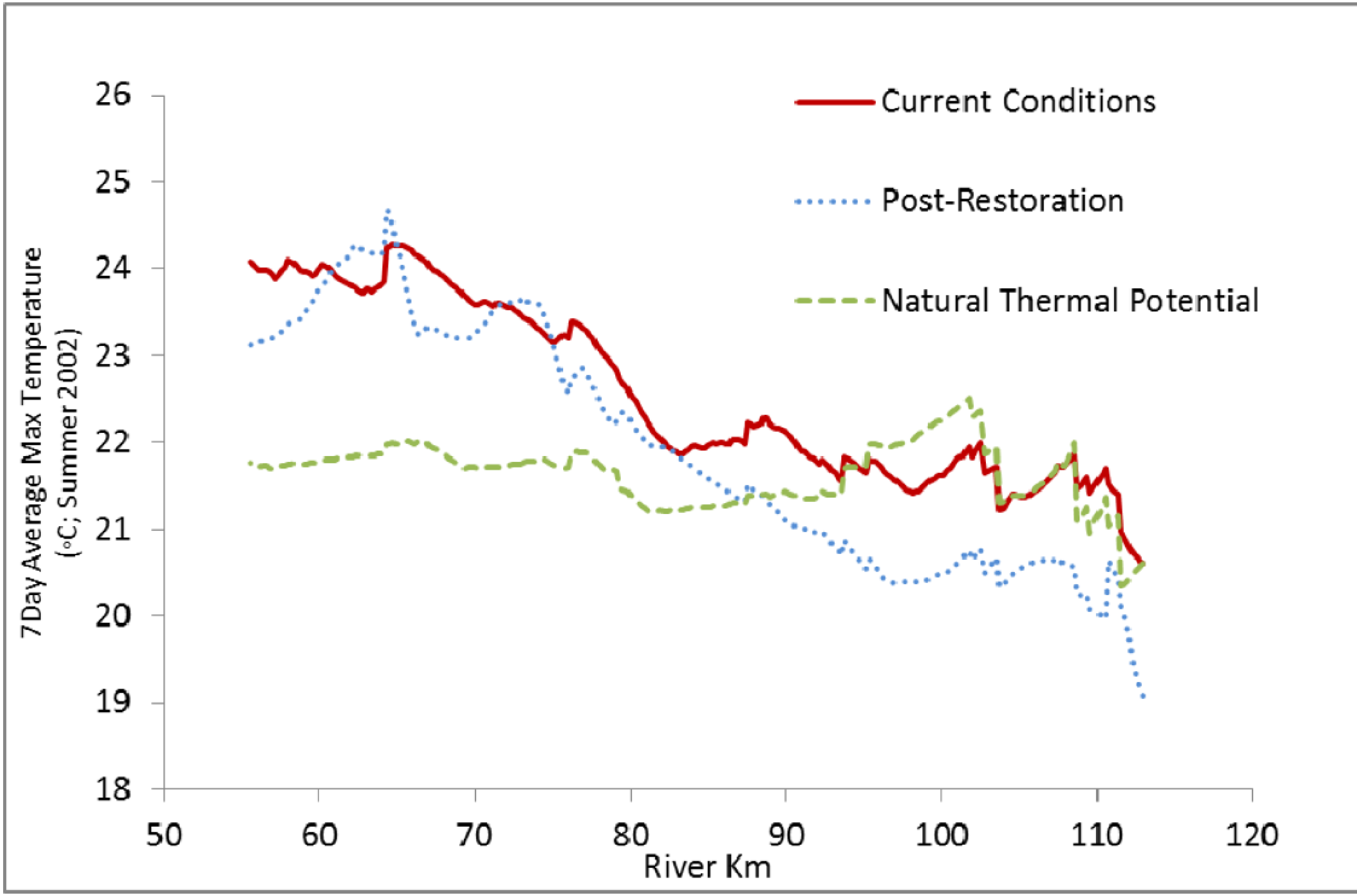
Code	Riparian Feature Description	Height (m)	Density (%)
301	Water	0.0	0%
3011	River Bottom - Floodplain	0.0	0%
302	Pastures/Cultivated Field/Lawn	0.0	0%
3025	Young Orchard	3.0	75%
303	Mature Orchard	12.2	75%
304	Barren - Rock	0.0	0%
305	Barren - Embankment	0.0	0%
306	Barren - Campground/Park	0.0	0%
307	Barren - Gravel Pit	0.0	0%
308	Barren - Clearcut	0.0	0%
309	Clearcut, below 50% dense regeneration	4.6	25%
321	Lumber Yard	0.0	0%
400	Barren - Road	0.0	0%
401	Barren - Forest Road	0.0	0%
402	Barren - Railroad	0.0	0%
403	Barren - Ag. Road	0.0	0%
500	Large Mixed Conifer/Hardwood (>75% Canopy)	24.4	75%
501	Small Mixed Conifer/Hardwood (>75% Canopy)	12.2	75%
550	Large Mixed Conifer/Hardwood (>25% Canopy)	24.4	25%
551	Small Mixed Conifer/Hardwood (>25% Canopy)	12.2	25%
600	Large Hardwood	22.9	75%
601	Small Hardwood	12.2	75%
650	Large Hardwood	22.9	25%
651	Small Hardwood	12.2	25%
700	Large Conifer	27.4	75%
701	Small Conifer	12.2	75%
750	Large Conifer	27.4	25%
751	Small Conifer	12.2	25%
800	Shrubs	4.6	75%
850	Shrubs	4.6	25%
900	Grasses	1.0	75%
3248	Developed – Residential buildings	6.1	100%
3249	Developed – Industrial buildings	9.1	100%
3252	Dam	0.0	0%
3253	Pipeline	0.0	0%
3254	WWTP	0.0	0%

Heat Source: Stream position and channel width

FIGURE 5.3
Digitized Stream Position Polyline and Segmented Stream Data Nodes Point Layer Segmented at 50 meter Interval (Mapped at 1: 5,000 Scale)

Digitized Channel Edges and Stream Data Nodes (Williamson River, Oregon)

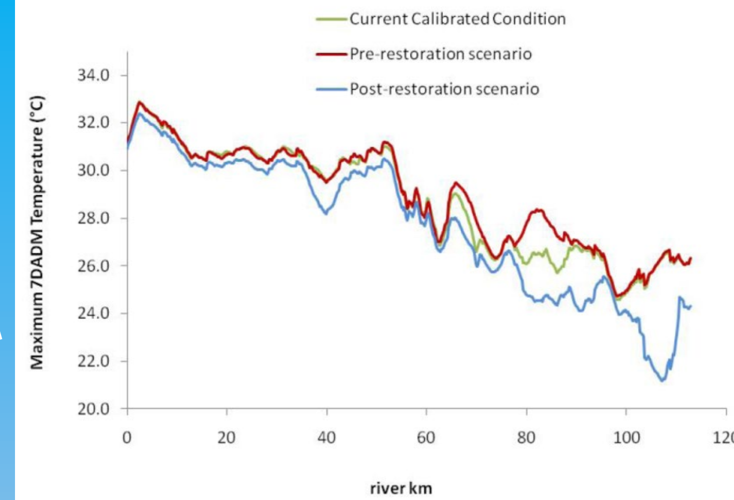
Temperature under proposed scenario



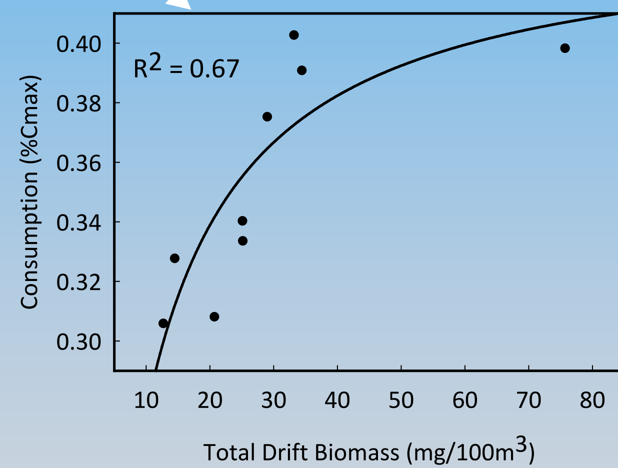
Heat Source calculates longitudinal profiles of temperature under different scenarios

CHaMP Surveys

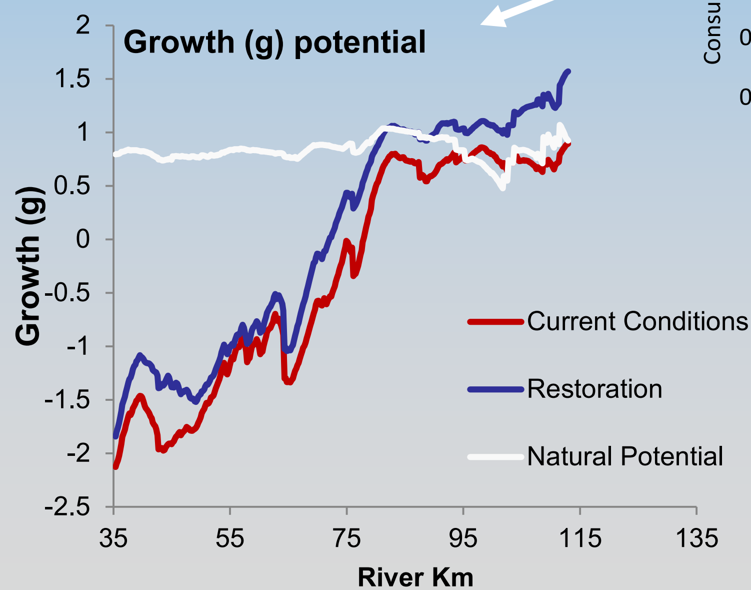
Thermal experience
Drift biomass



Habitat surveys used to calibrate Heat Source and estimate drift biomass

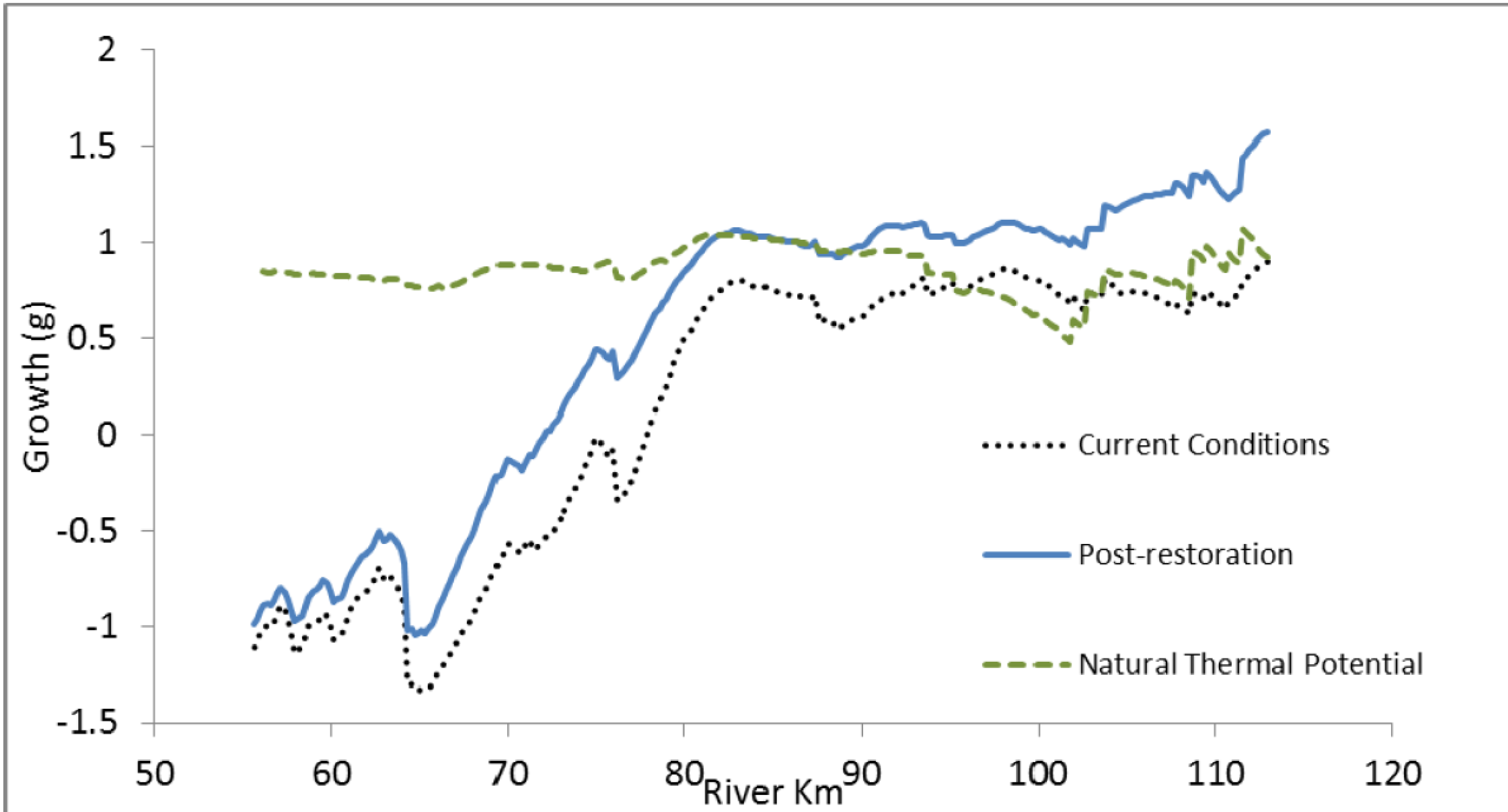


Bioenergetics model translates drift and temperature into growth

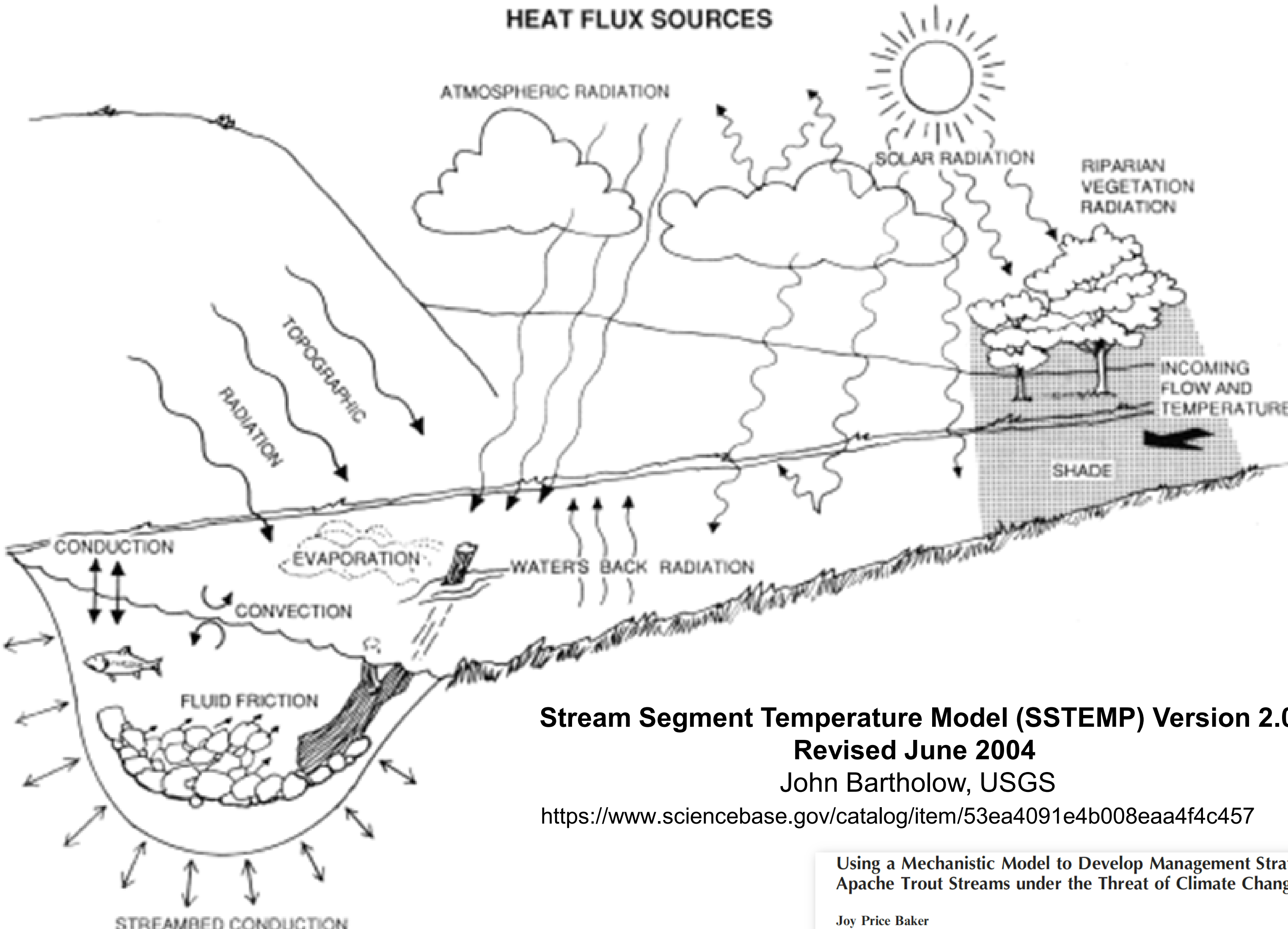


Model growth potential profiles under different scenarios

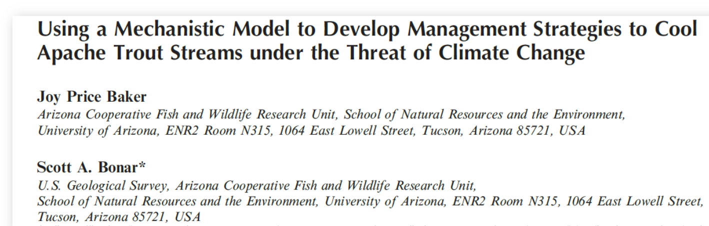
Growth under proposed scenarios



Other temperature models



Stream Segment Temperature Model (SSTEMP) Version 2.0
Revised June 2004
John Bartholow, USGS
https://www.sciencebase.gov/catalog/item/53ea4091e4b008eaa4f4c457



Using a Mechanistic Model to Develop Management Strategies to Cool Apache Trout Streams under the Threat of Climate Change

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North American Journal of Fisheries Management 39:849–867, 2019

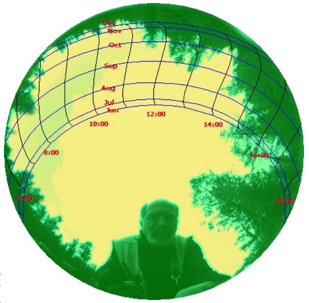
Mechanistic modelling approach

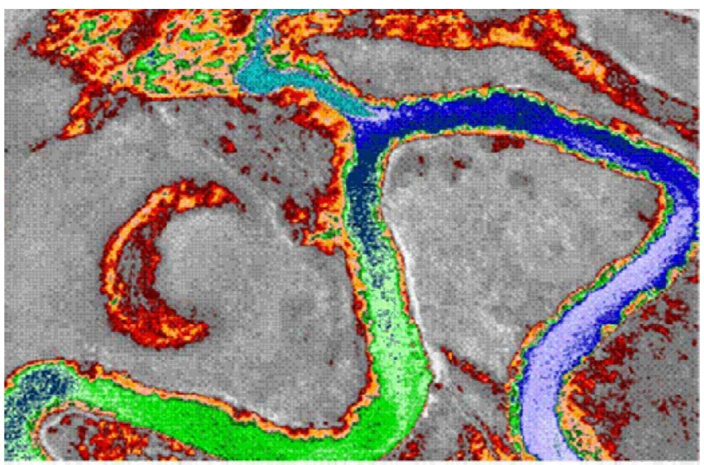
Pros-

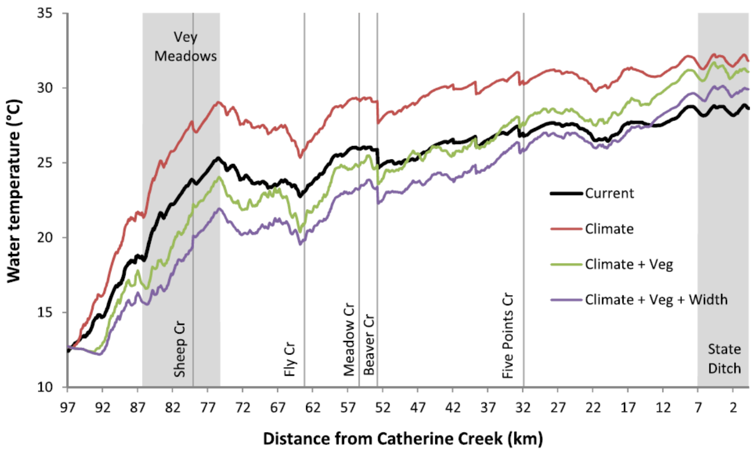
- Can provide very accurate results
- High resolution - can pick up small scale but important influences
- Greater ability to predict
- Can evaluate multiple management and climate scenarios

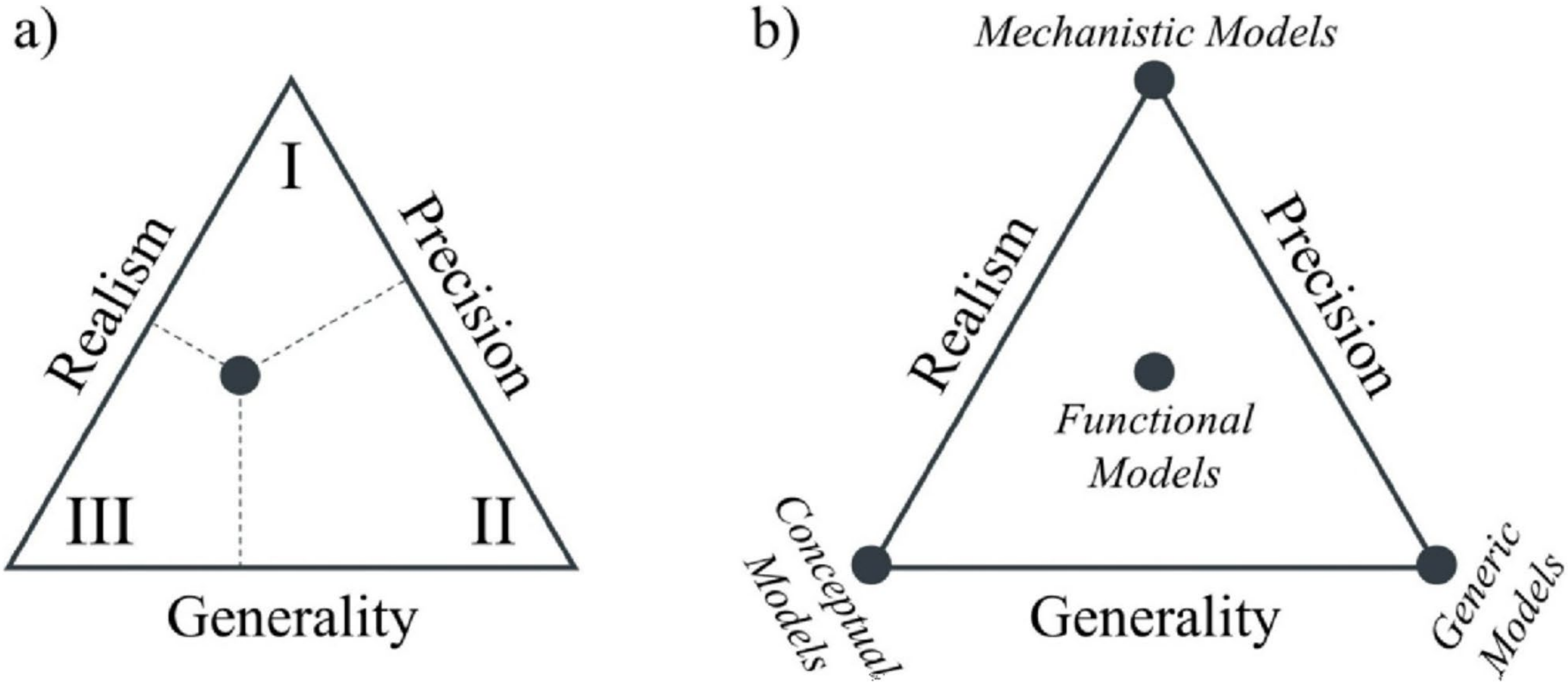
Cons-

- Requires a lot of input information; can be very time consuming to compile
- Limited temporal information (e.g. August temperatures for one year)
- Limited spatial extent (generally used for mainstems)









Levins 1966

From Bullock 2014