Modeling Streambed Heating in Shallow Streams

Dr. Robert Annear

Department of Civil and Environmental Engineering

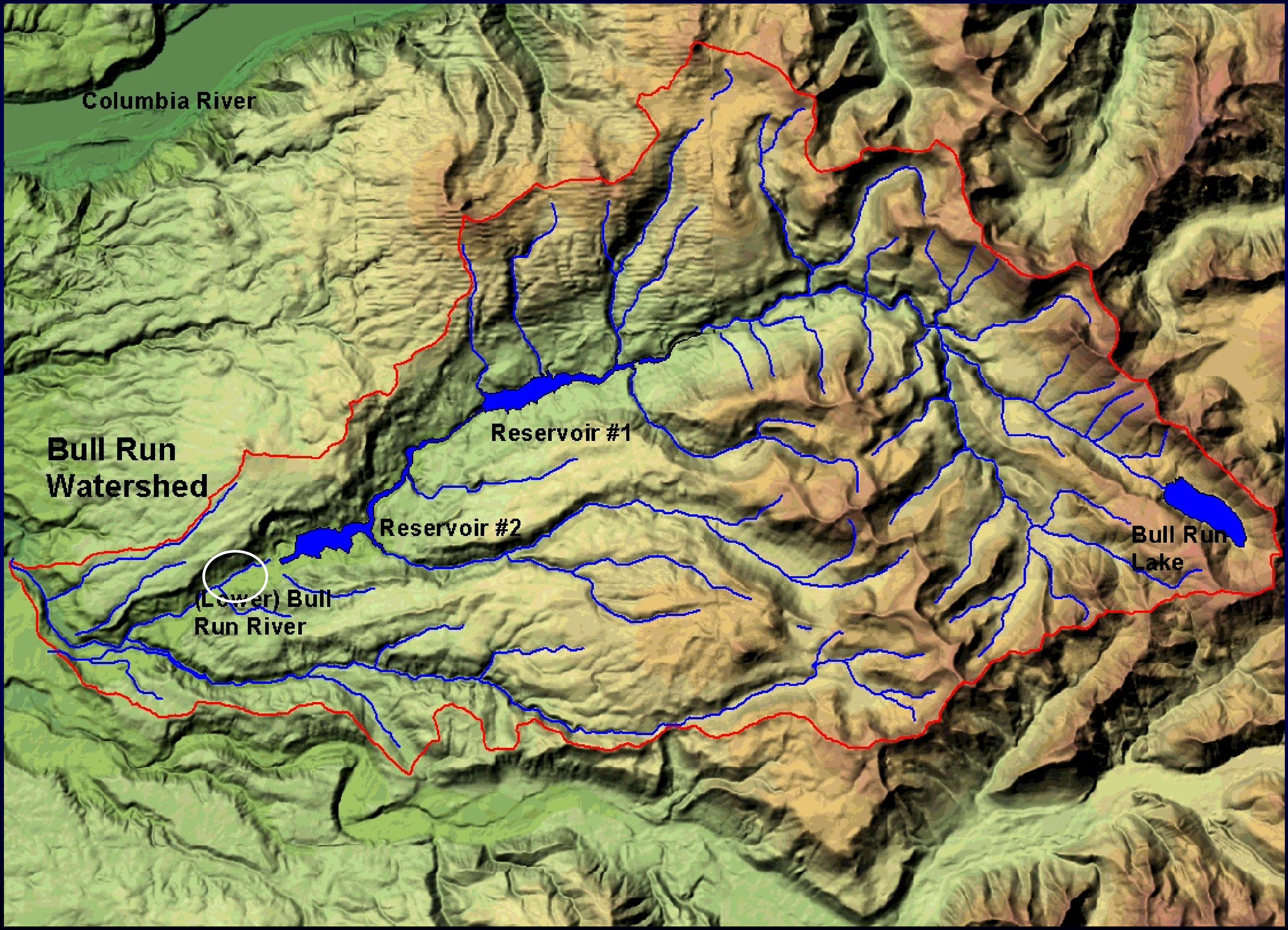
Portland State University

Outline

- Background
- Field Study
- Laboratory Experiments
- Streambed Model
    - Development
    - Calibration
    - Verification
    - Sensitivity Analyses
- Summary and Conclusions

Background

Bull Run Watershed



Background

Bull Run Water Quality Issues

• Meet water supply demands

• Meet fish habitat objectives downstream of the reservoirs in the Bull Run River (principally temperature)

March 1998: Steelhead listed as threatened under the ESA
March 1999: Spring Chinook listed as threatened under the ESA

• Temperatures in Lower Bull Run River violate the State of Oregon’s standard that the 7-day moving average of the daily maximum temperature should not exceed 17.8 ^{o}C

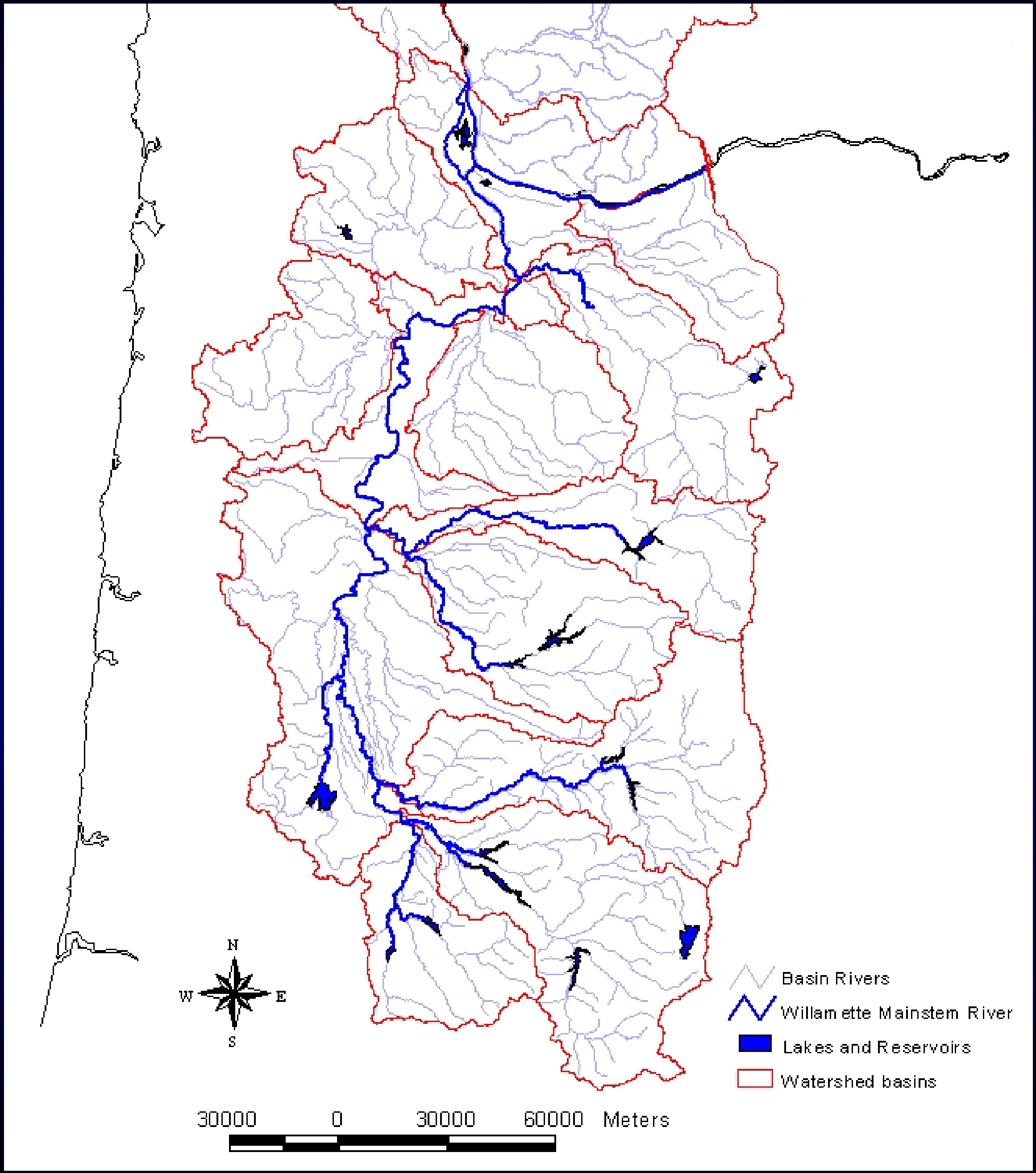
Background

Willamette River Main stem

OR DEQ Temperature TMDL development

781 river km

More accurate model for load allocations



Background

Water Quality Model
CE-QUAL-W2 Version 3.1

•River Basin Reservoir Model
2-D longitudinal-vertical

•Physically based, theoretically sound

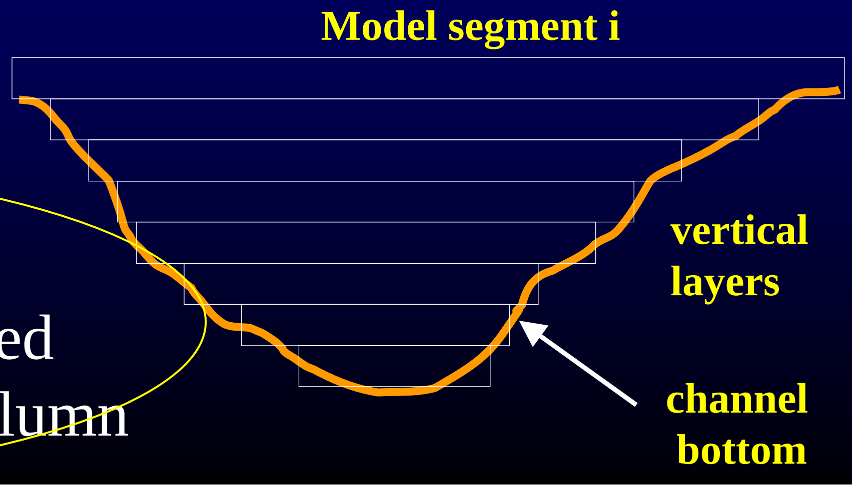
•Capable of modeling reservoir-stratified flow and open-channel river flow

• Fixed streambed temperature

• Fixed rate of heat lost to streambed that is re-radiated back to water column

Data necessary for the model:

- geometry of the system
- meteorological conditions
- inflow flow and temperature/quality



Background

Research Objectives

Examine the influence of streambed heating on water temperatures and incorporate a dynamic streambed heating algorithm in the CE-QUAL-W2 Version 3.12.

- Monitor streambed temperatures in the Lower Bull Run River and environmental factors influencing the heat budget.
- Conduct laboratory experiments to demonstrate heating processes.
- Develop a streambed heating model for incorporation in W2.
- Calibrate the model and run sensitivity analyses to determine the impact of streambed heating.
- Review clear-sky solar radiation models and with data.

Flow and Temperature Monitoring

Field Study

Stream temperature
with replicate monitoring

Streambed temperature
monitoring, cobble

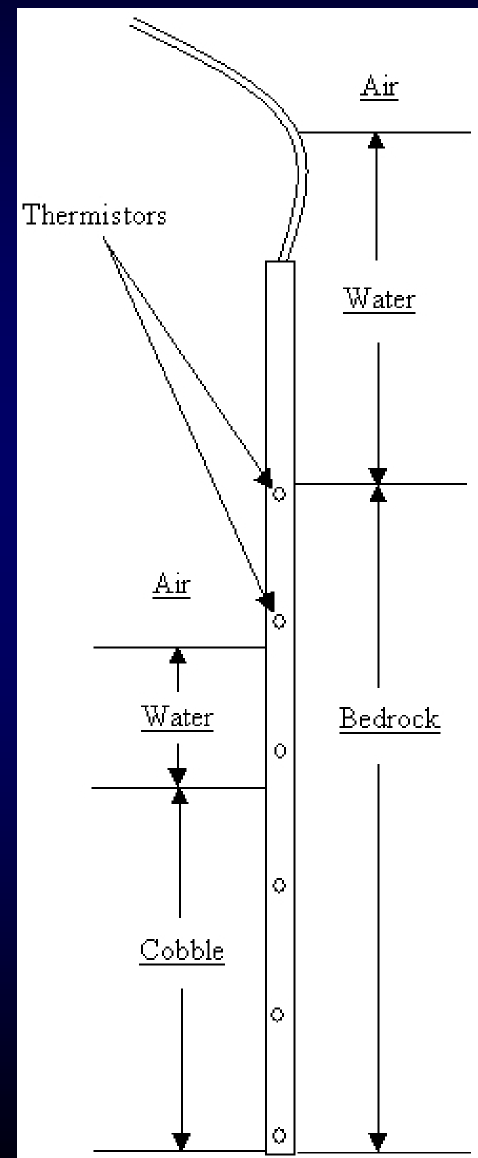
Flow, water level
and water temperature

Streambed temperature
monitoring, bedrock

Field Study

Streambed Temperature Monitoring

Probes 1 to 3

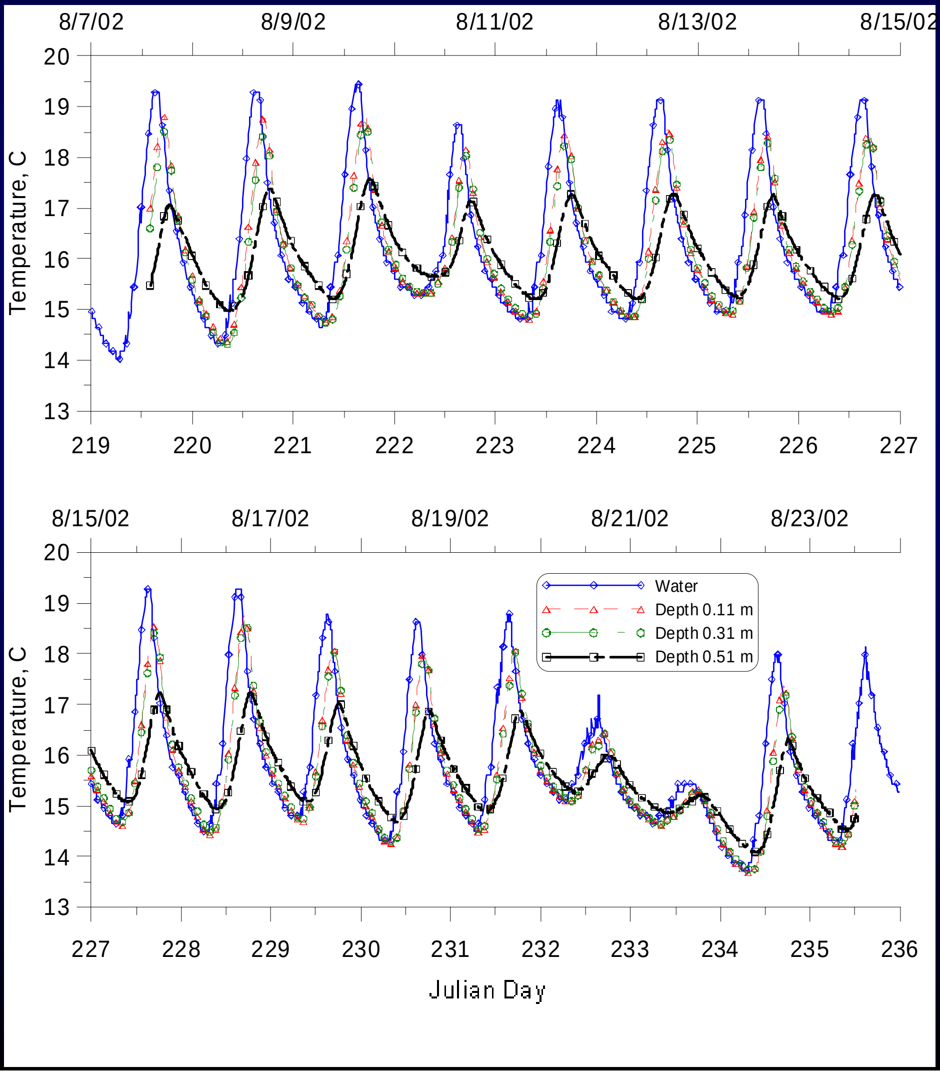


Probe 4
and 5

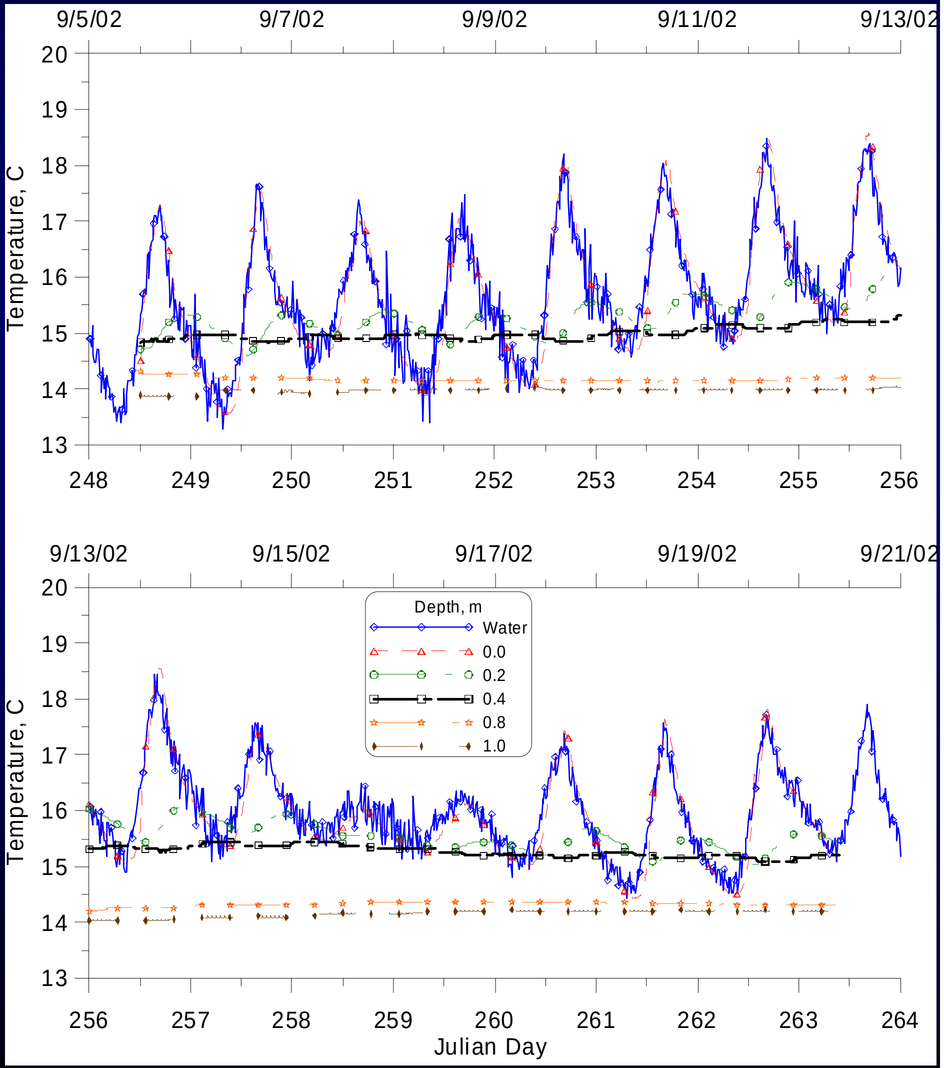
Streambed Temperature

Field Study

Probe 1
Cobble Substrate

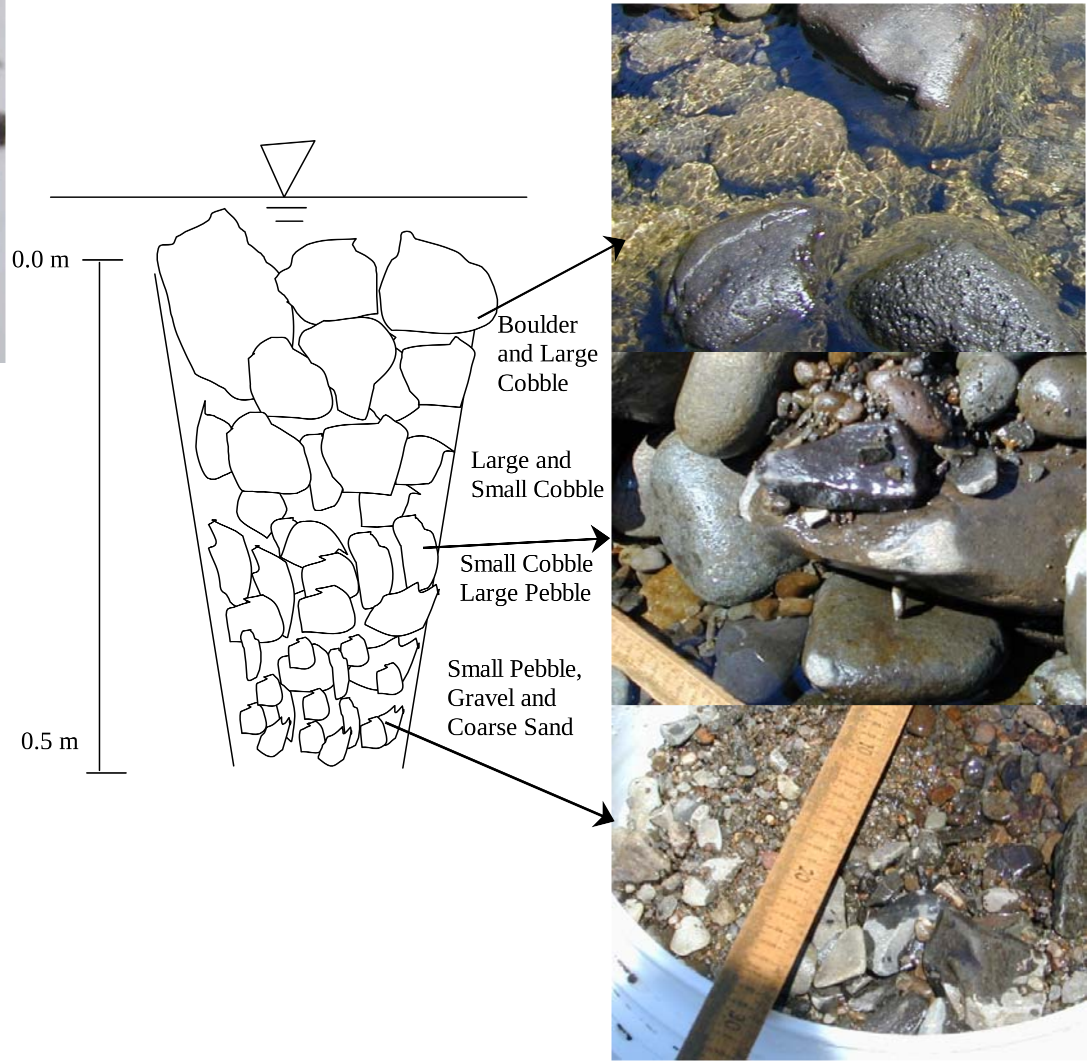


Probe 5
Bedrock Substrate



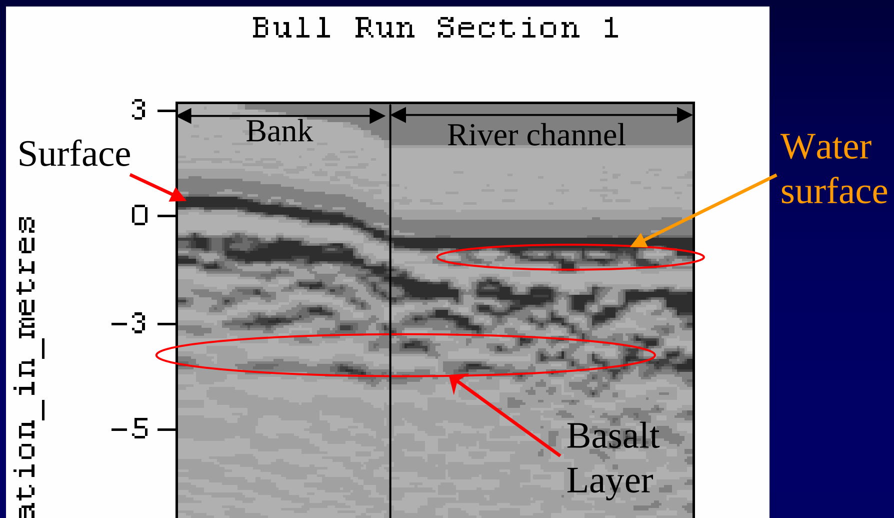
Field Study

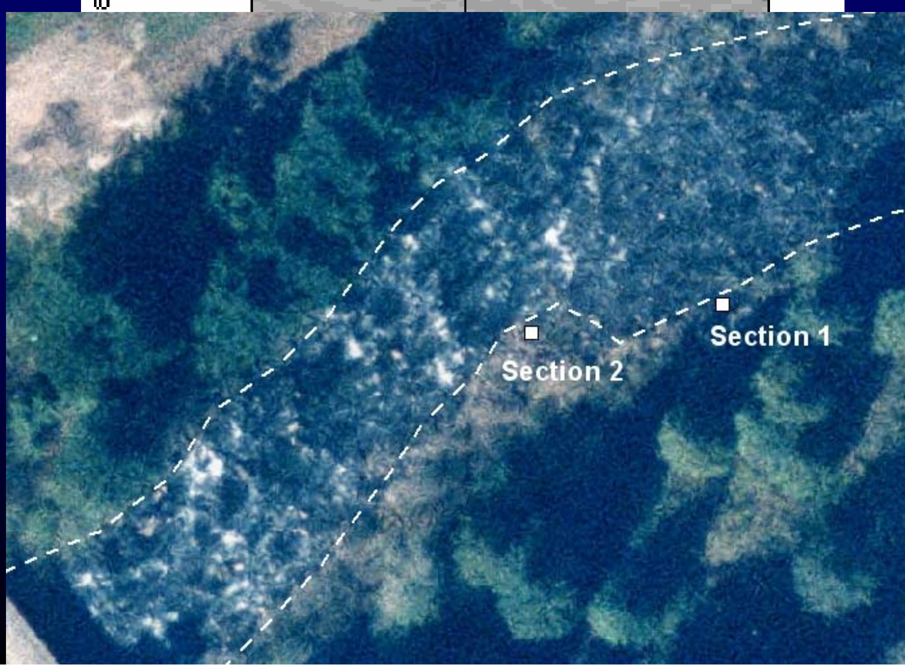
Streambed Geology

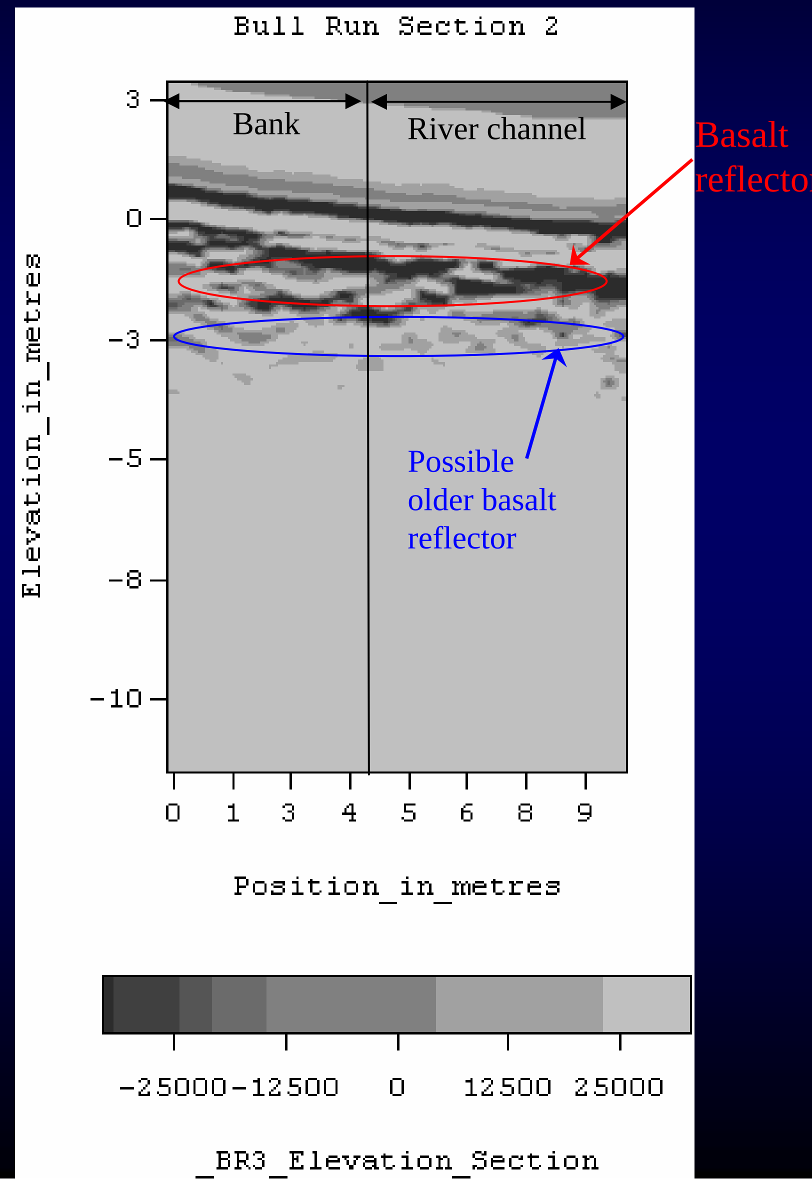


Field Study

Streambed Geology
Ground Penetrating Radar







Field Study

Substrate Dye Study

Monitoring sites

Dye Monitoring Site	Dist. Downstream, m
A	7.6
B	32.9
C	0.3

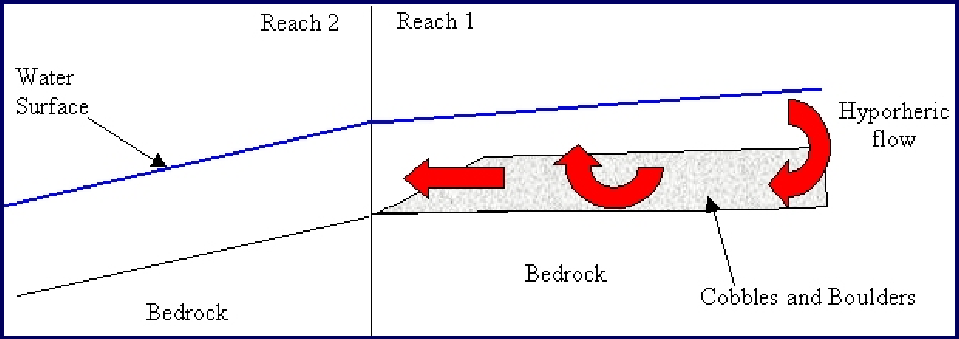
Field Study

Additional Field Data

Meteorological Data

Water Level Data

Flow Measurements



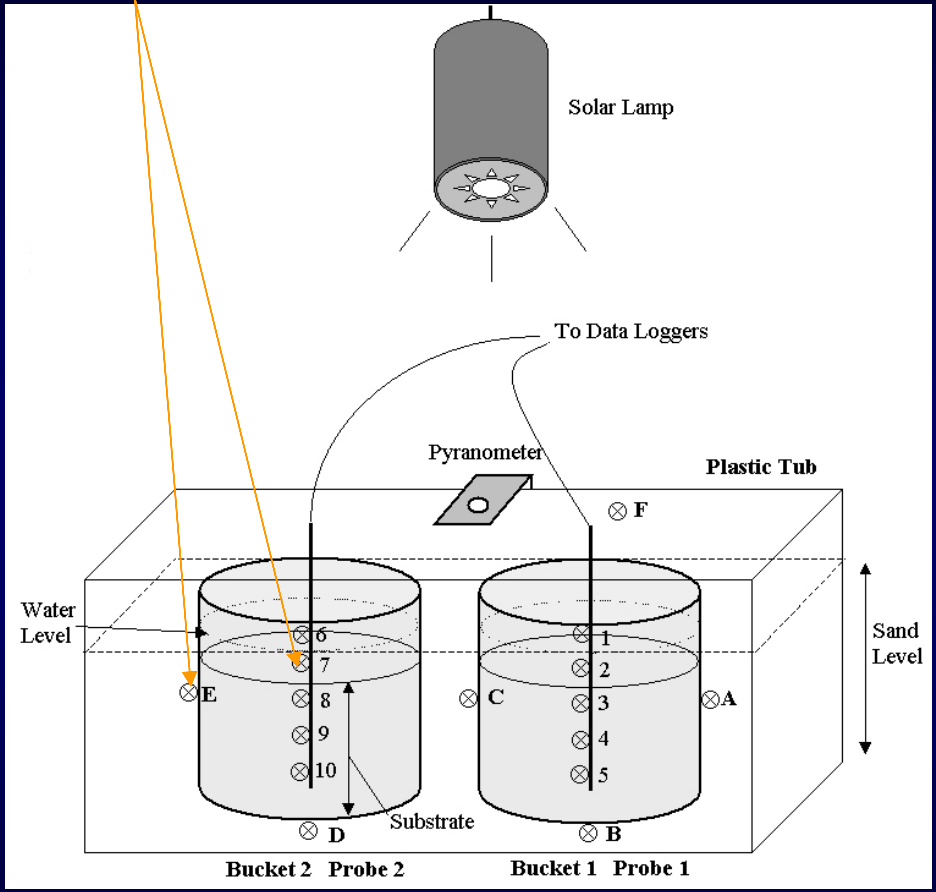
Vegetation Characteristics
- Offset from channel
- Height

Light Attenuation
- Light data at several depths
- Light data reflecting off bottom

Laboratory Experiments

Experimental Lab Work

Thermistors



Lamp Data Loggers

Three Experiments:

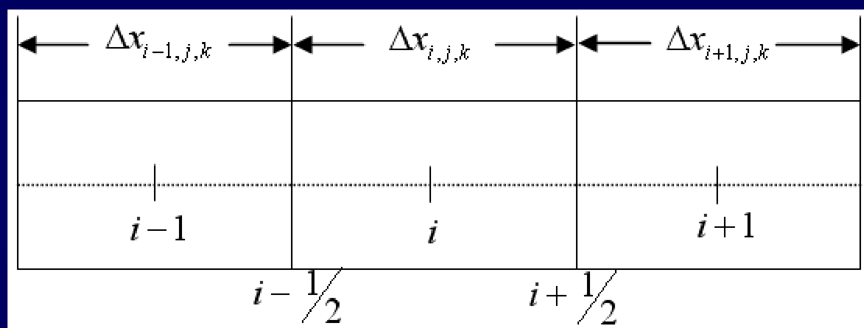
1. Sand vs. Gravel
2. Sand vs. Sand and Gravel Mixture
3. White Surface Concrete vs. Black Surface Concrete

Streambed Model, Development

3-D heat transfer governing equation

Cartesian Coordinate System

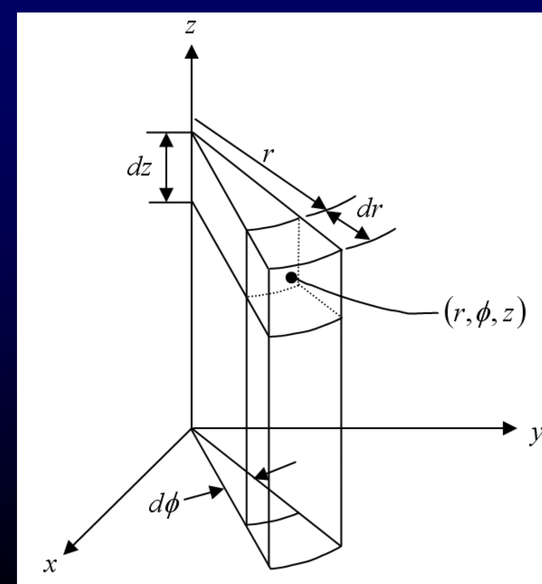
$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\beta_x\left(\frac{\partial T}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(\beta_y\left(\frac{\partial T}{\partial y}\right)\right) + \frac{\partial}{\partial z}\left(\beta_z\left(\frac{\partial T}{\partial z}\right)\right)$$



Explicit finite difference numerical scheme

Cylindrical Coordinate System

$$\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\beta_r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(\beta_\phi\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(\beta_z\frac{\partial T}{\partial z}\right)$$



Streambed Model, Development

Surface Boundary Condition

$$h\left.\frac{\partial T}{\partial z}\right|_{z=0} - \beta\left.\frac{\partial T}{\partial z}\right|_{z=0} = \frac{\varphi_{at}}{\rho_s c_{ps}} - D_z\left.\frac{\partial T}{\partial z}\right|_{z=0}$$

$$\frac{2\beta}{\Delta z}\left(T_{\text{int}} - T_{i,j,k}\right) = \frac{\varphi_{at}}{\rho_s c_{ps}} + \frac{D_z}{\delta_w}\left(T_w - T_{\text{int}}\right)$$

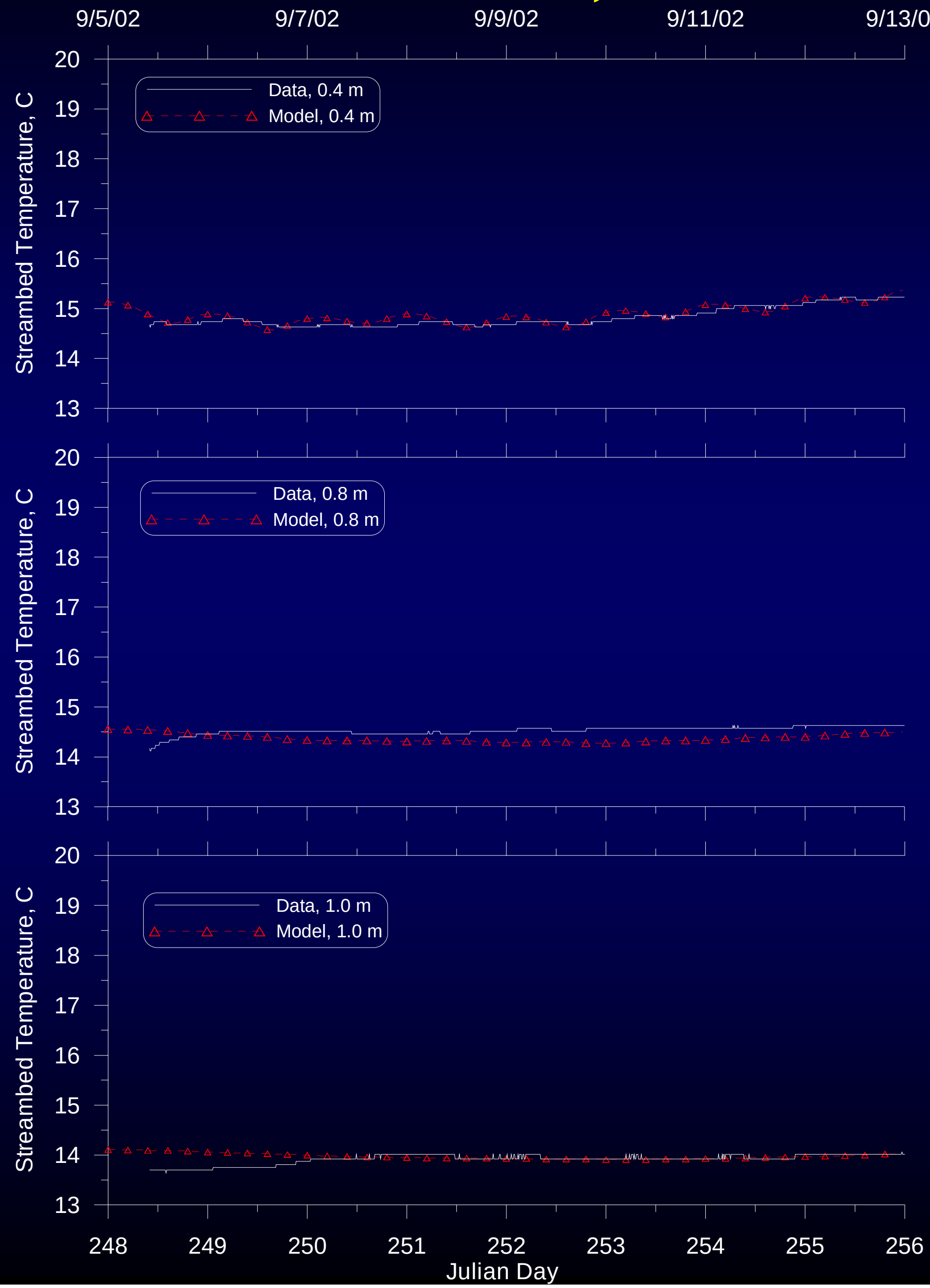
Bottom and Side Boundary Condition

$T_b = \text{constant}$ Cartesian Coordinate System

$T_b = T_b(t)$ Cylindrical Coordinate System

Streambed Model, Calibration

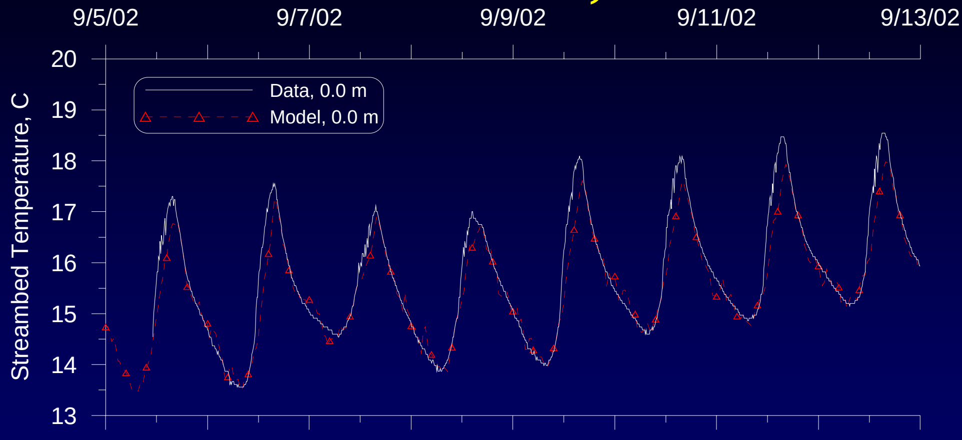
Bedrock Substrate
Probe 4, Shaded



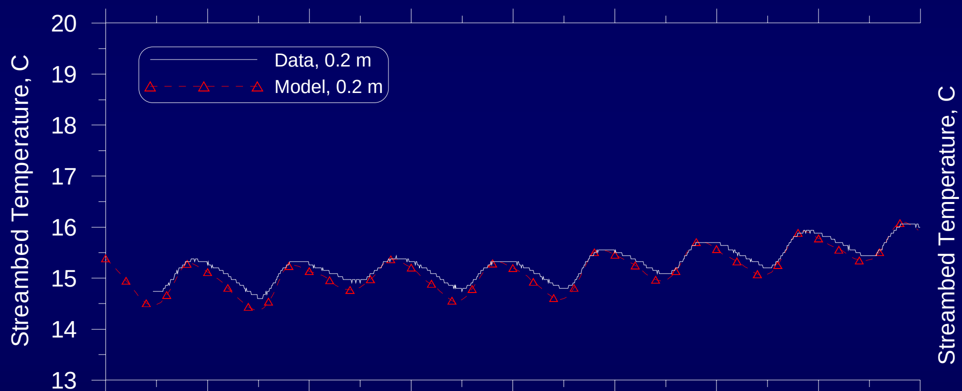
Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.4	1,231	0.05	0.09	0.10
0.8	2,155	-0.14	0.15	0.17
1.0	2,155	0.01	0.08	0.12

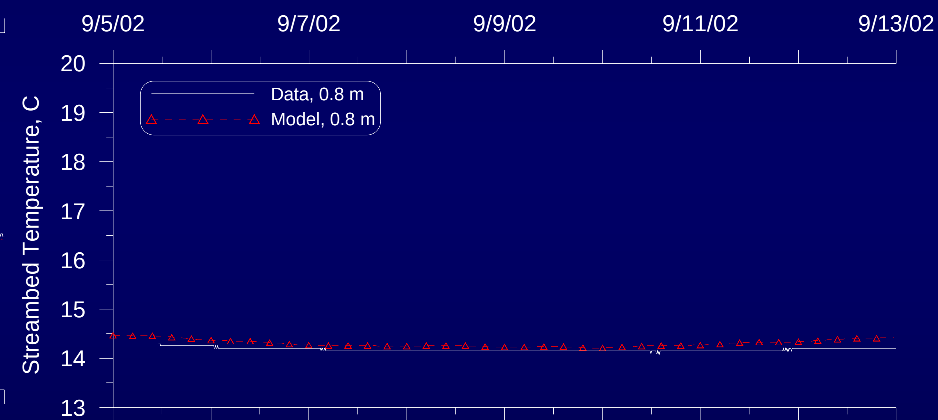
Streambed Model, Calibration

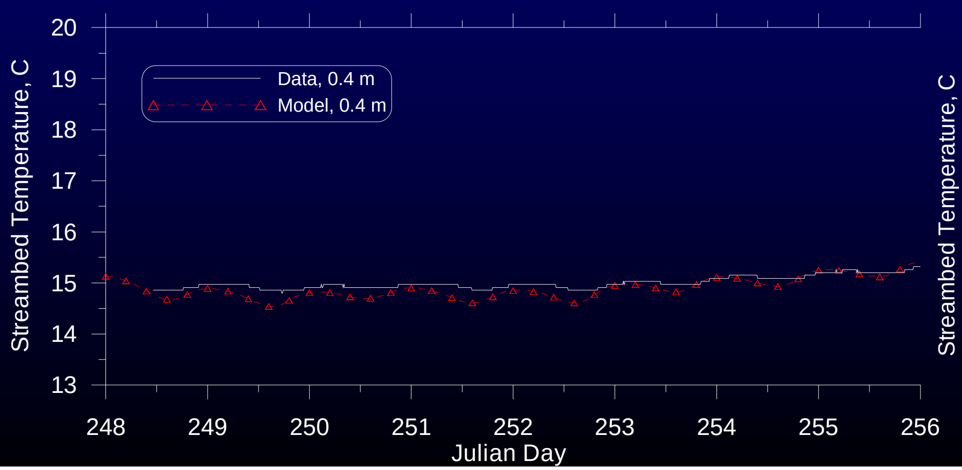
Bedrock Substrate
Probe 5, Sunny

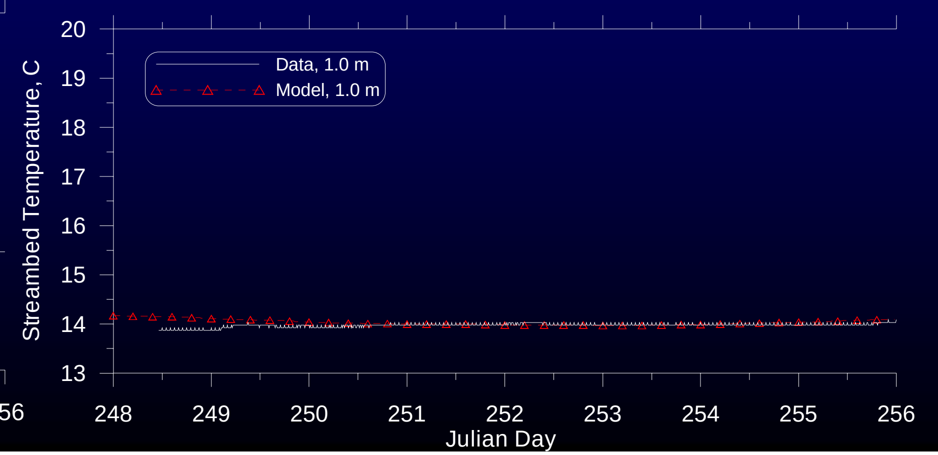


Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.0	2151	-0.10	0.19	0.31
0.2	2151	-0.06	0.10	0.13
0.4	2151	-0.10	0.11	0.13
0.8	2151	0.18	0.18	0.19
1.0	2151	0.03	0.05	0.07





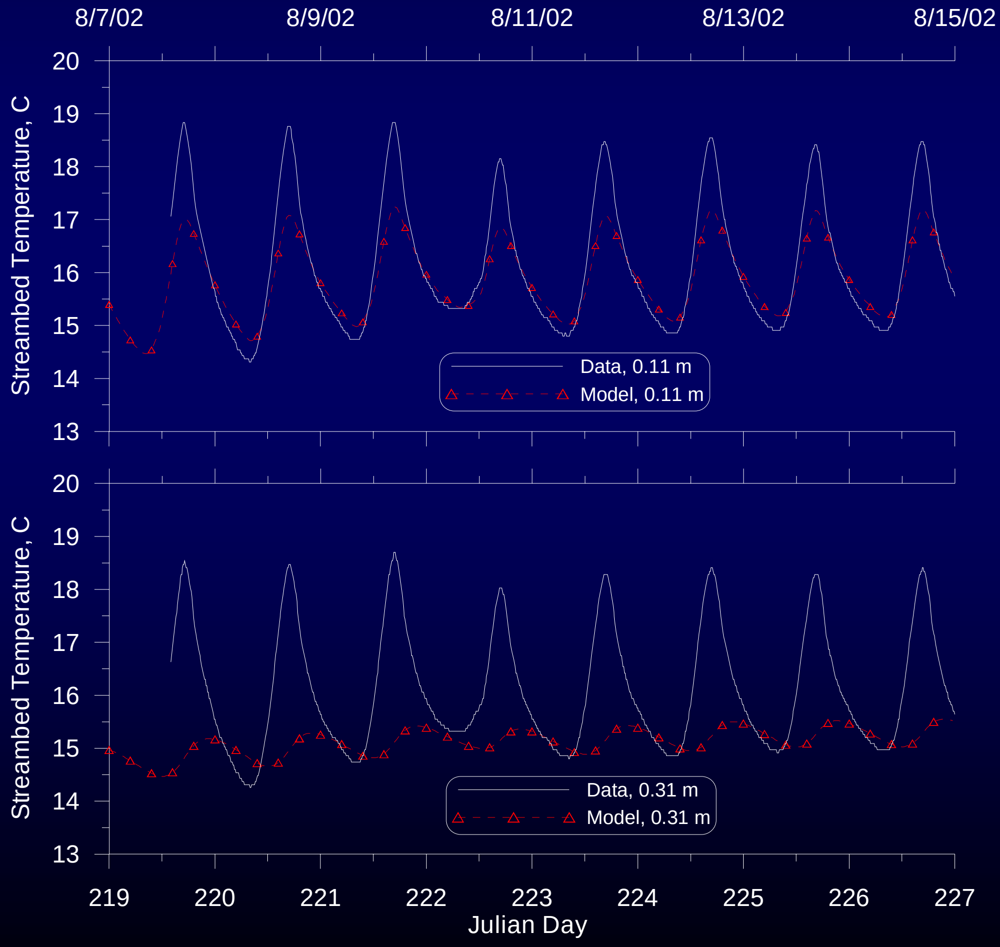




Streambed Model, Calibration

Cobble Substrate Probe 1

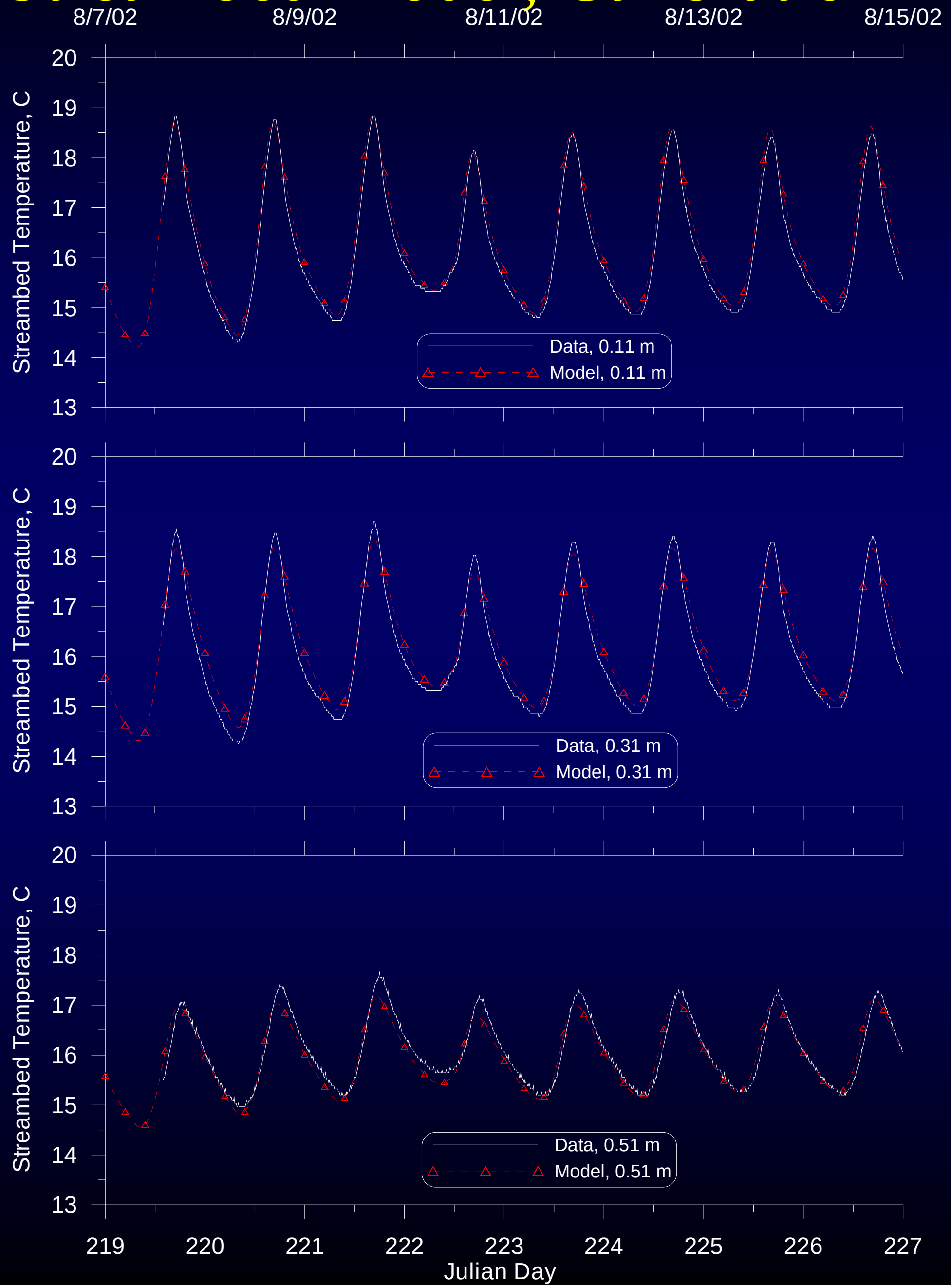
Depth, m	Density, kg/m^3	Specific Heat, kJ/kg^{o}C	Thermal Diffusivity, m^2/s	Fraction of Rock	Fraction of Water	Increase in Thermal Diffusivity
0.00 to 0.23	1960	2150.8	9.17E-07	75%	25%	0%
0.23 to 0.37	2088	1878.9	1.02E-06	85%	15%	0%
0.37 to 0.72	2280	1471.0	1.23E-06	100%	0%	5%
0.72 to 20.0	2280	1471.0	1.41E-06	100%	0%	20%



Depth, m	Fraction of water temperature used
0.00 to 0.23	0.10%
0.23 to 0.37	0.10%
0.37 to 0.52	0.10%
0.52 to 0.87	0.00%
0.87 to 20.0	0.00%

Streambed Model, Calibration

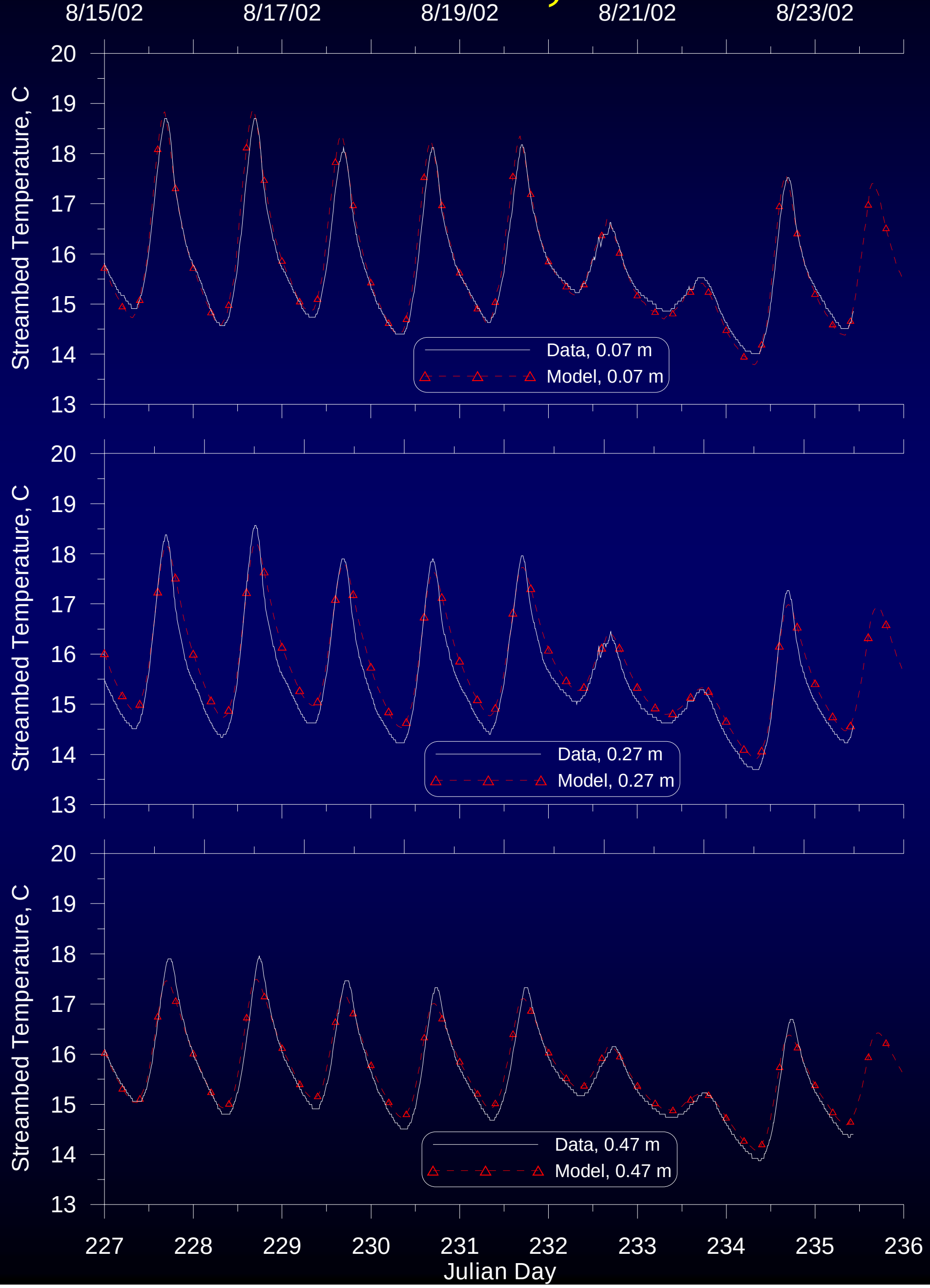
Cobble Substrate
Probe 1



Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.11	3128	0.23	0.23	0.25
0.31	3128	0.21	0.24	0.27
0.51	3128	0.04	0.14	0.18

Streambed Model, Calibration

Cobble Substrate
Probe 2



Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.07	2277	0.16	0.22	0.29
0.27	2277	0.23	0.28	0.33
0.47	2277	-0.23	0.37	0.51

Streambed Model, Verification

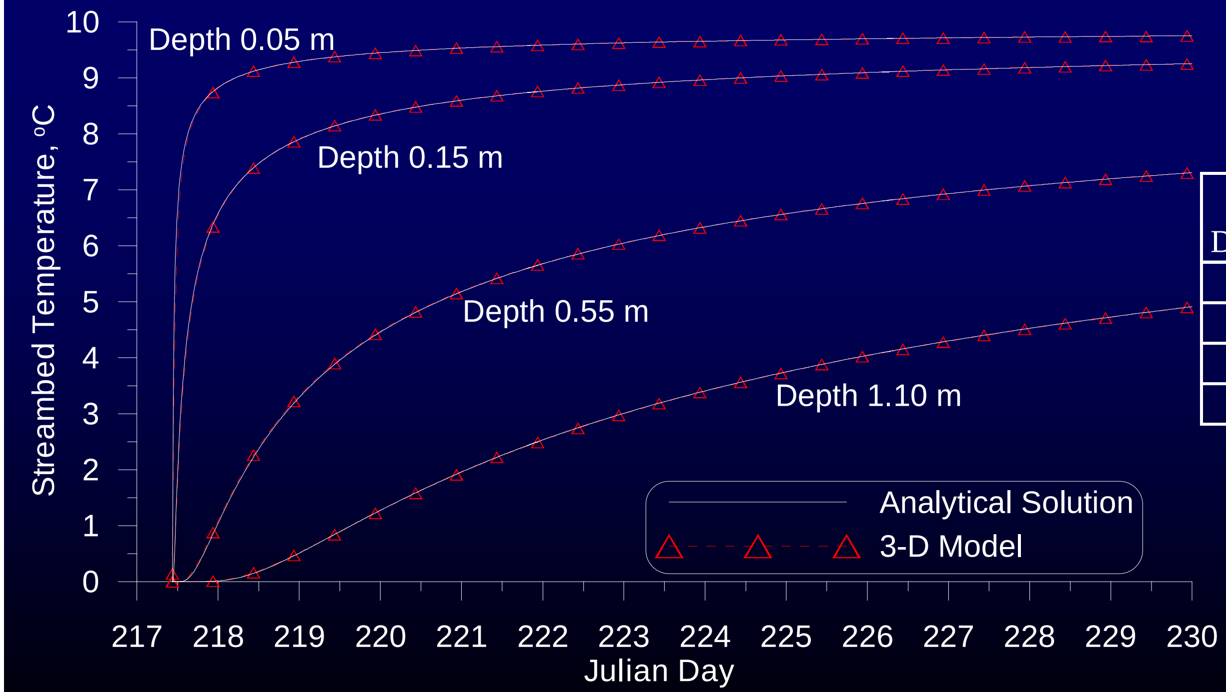
Analytical Solution
Simple Case

- A semi-infinite solid
- Initial and BCs temperature: 0.0 ^oC
- No solar radiation
- Water temperature constant: 10.0 ^oC

(Incropera and De Witt, 1990)

$$\frac{\partial T}{\partial t} = \beta \frac{\partial^2 T}{\partial z^2}$$

$$T = T_o erfc\left(\frac{z}{\sqrt{4\beta t}}\right)$$

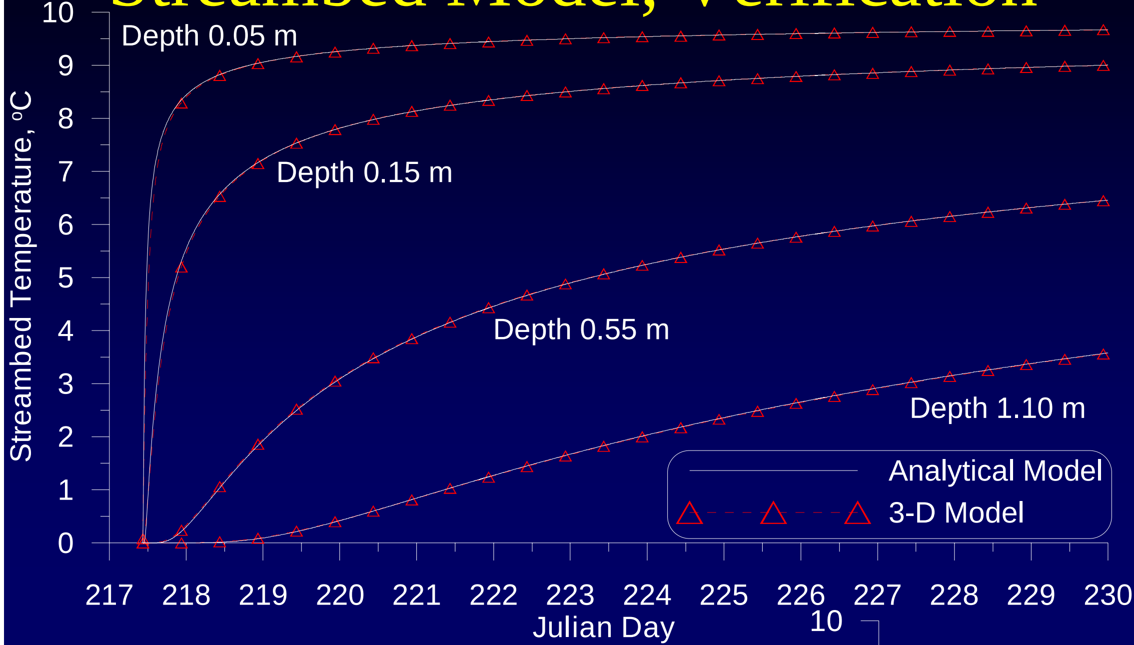


100% rock

Depth, m	Number of Comparisons	ME, ^oC	AME, ^oC	RMS, ^oC
0.05	3733	-0.01	0.01	0.07
0.15	3733	0.00	0.01	0.03
0.55	3733	0.01	0.01	0.01
1.10	3733	0.00	0.01	0.01

Streambed Model, Verification

Analytical Solution
Simple Case

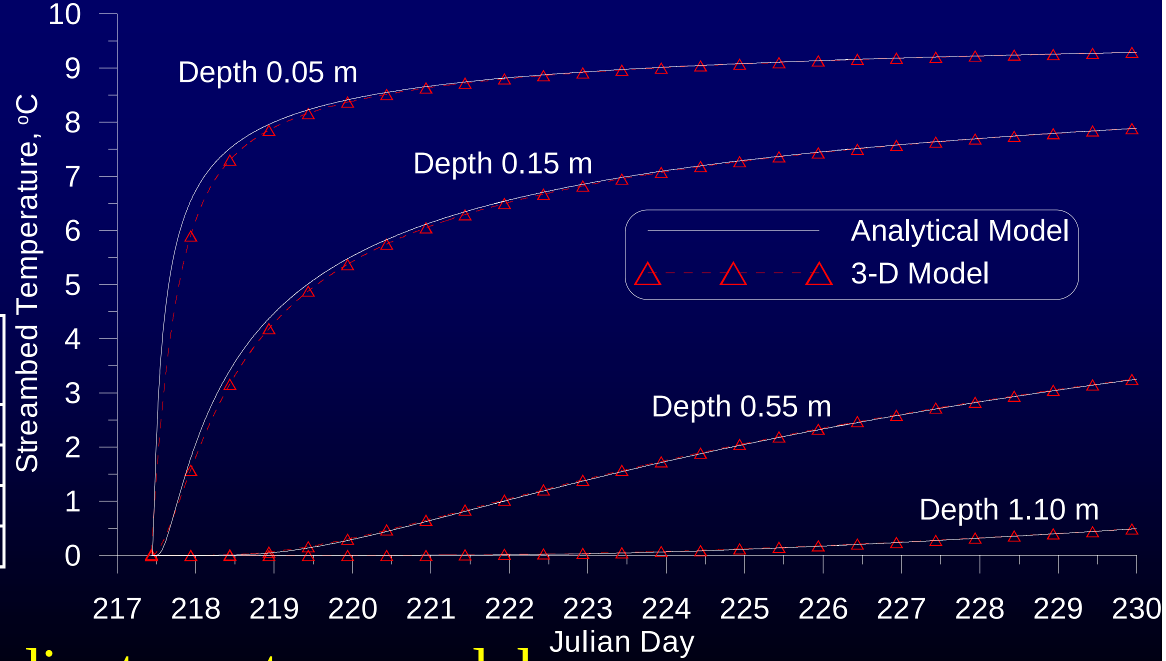


50% rock, 50% water

Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.05	3733	-0.01	0.01	0.09
0.15	3733	-0.01	0.01	0.04
0.55	3733	0.01	0.01	0.01
1.10	3733	-0.01	0.01	0.01

100% water

Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.05	3733	-0.07	0.07	0.21
0.15	3733	-0.05	0.05	0.09
0.55	3733	0.02	0.02	0.02
1.10	3733	0.00	0.01	0.01



Repeated for cylindrical coordinate system model

Streambed Model, Verification

Analytical Solution
Bedrock

$$\frac{\partial T}{\partial t} + \alpha \frac{\partial T}{\partial z} = \beta \frac{\partial^2 T}{\partial z^2}$$

(Silliman et al., 1995)

$$\Delta T = \frac{\Delta T_w}{2}[erfc\{(z_1 - \alpha t)/2\sqrt{\beta t}\} + \exp\{\alpha z_1/\beta\} erfc\{(z_1 + \alpha t)/2\sqrt{\beta t}\}]$$

Analytical

Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.0	2151	-0.11	0.19	0.29
0.2	2151	-0.08	0.69	0.84
0.4	2151	-0.21	0.74	0.90
0.8	2151	-0.02	0.66	0.84
1.0	2151	-0.13	0.67	0.84

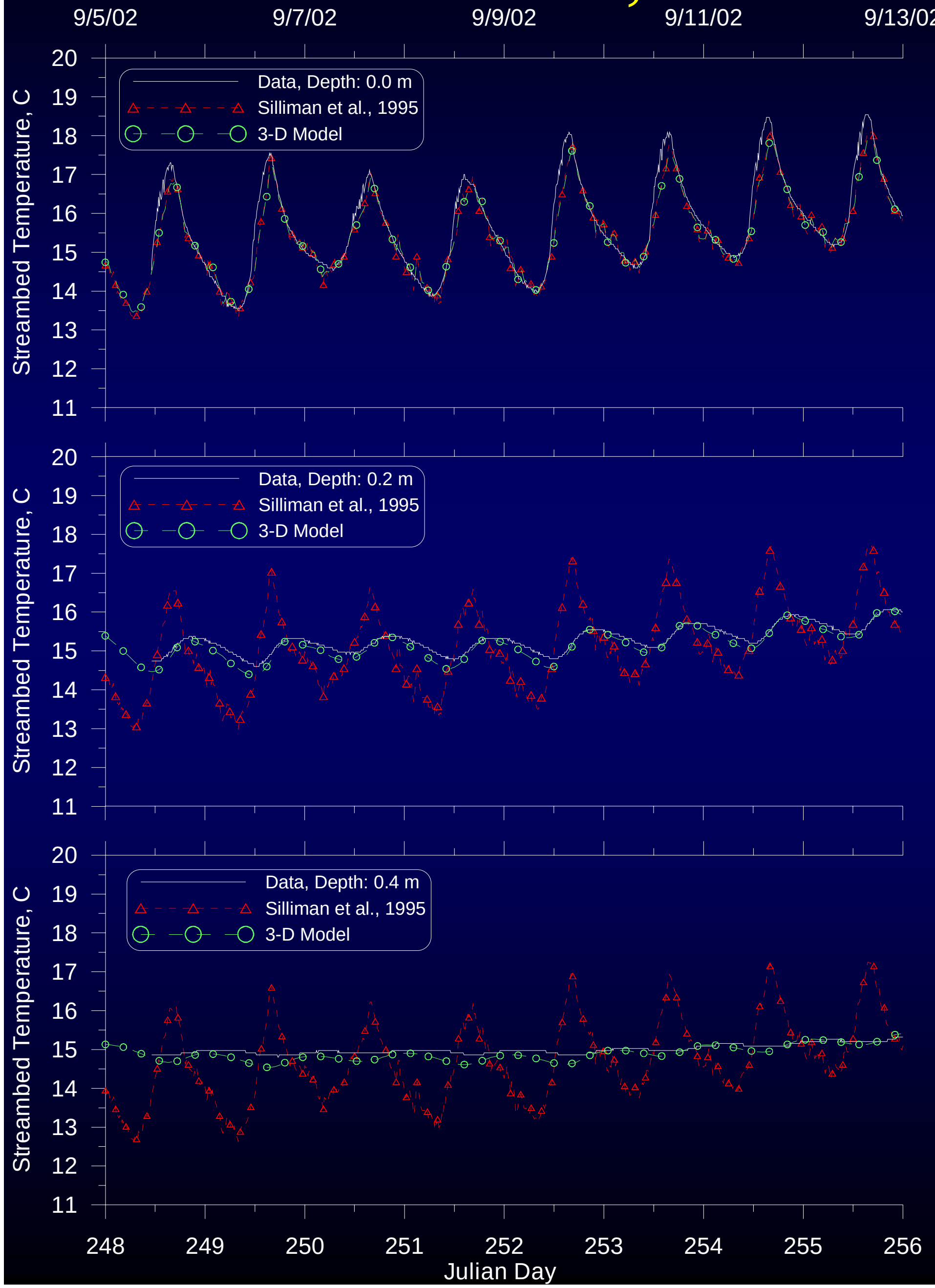
Model does not include solar radiation

3-D model

Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.0	2151	-0.10	0.19	0.31
0.2	2151	-0.06	0.10	0.13
0.4	2151	-0.10	0.11	0.13
0.8	2151	0.18	0.18	0.19
1.0	2151	0.03	0.05	0.07

Streambed Model, Verification

Analytical Solution
Bedrock



Streambed Model, Verification

1-D Model
Bedrock

Governing Equation: $\frac{\partial T}{\partial t} = \beta \frac{\partial^2 T}{\partial z^2}$

Bottom BC: $q = -\beta \frac{\partial T}{\partial z}\bigg|_{z=bottom} = 0$

Surface BC: $-\beta \frac{\partial T}{\partial z}\bigg|_{z=0} = h \frac{\partial T}{\partial z}\bigg|_{z=0}$

(Sinokrot and Stefan, 1993 and Incropera and De Witt, 1990)

1-D model

Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.0	2151	-0.18	0.21	0.33
0.2	2151	-0.14	0.18	0.22
0.4	2151	-0.18	0.19	0.22
0.8	2151	0.09	0.10	0.13
1.0	2151	-0.03	0.06	0.08

Model does not include solar radiation

3-D model

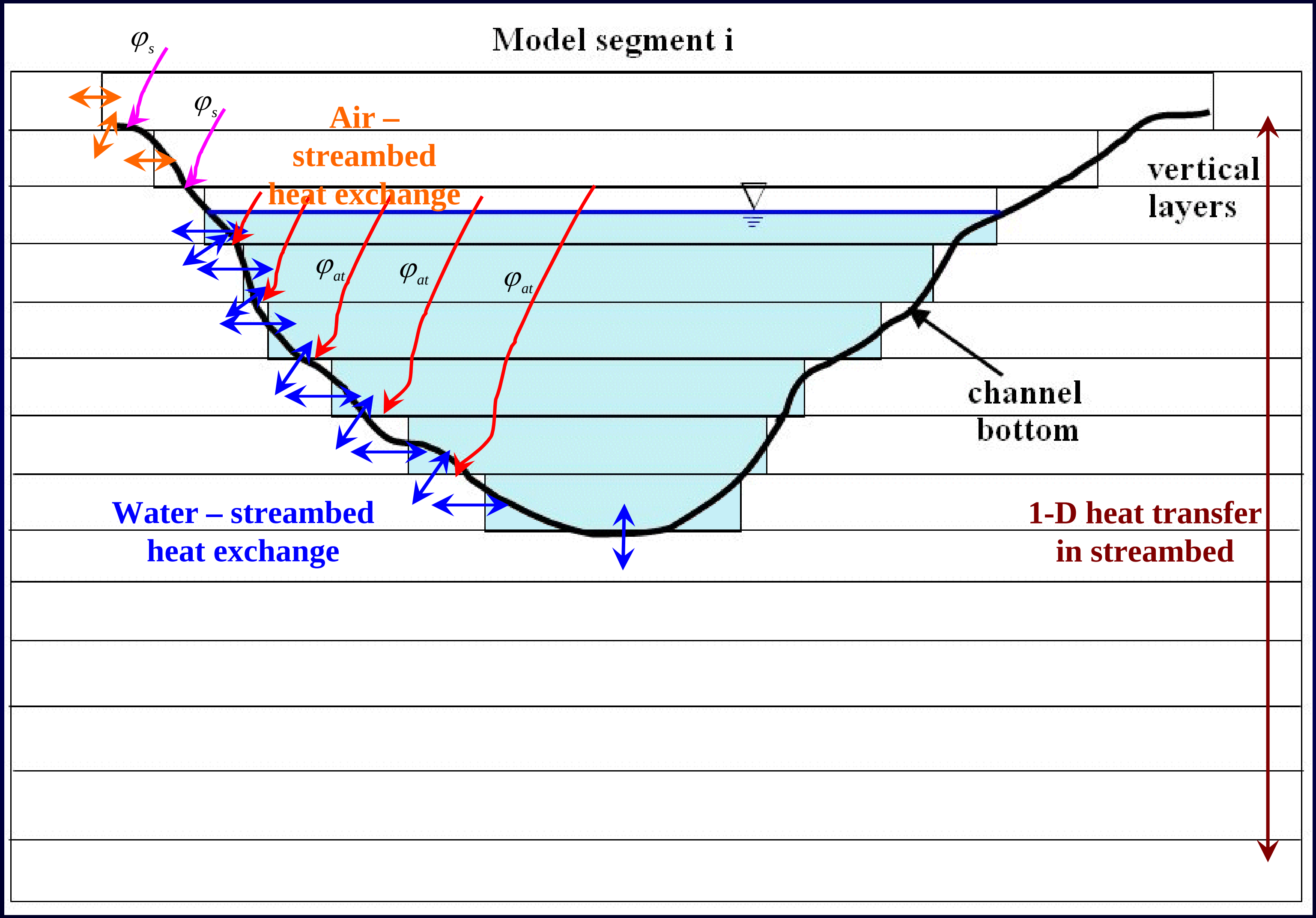
Depth, m	Number of Comparisons	ME, °C	AME, °C	RMS, °C
0.0	2151	-0.10	0.19	0.31
0.2	2151	-0.06	0.10	0.13
0.4	2151	-0.10	0.11	0.13
0.8	2151	0.18	0.18	0.19
1.0	2151	0.03	0.05	0.07

Streambed Model, Verification

1-D Model Bedrock

Streambed Model

Implementation in CE-QUAL-W2



Vertical Temperature Gradient >> Horizontal Temperature Gradient
Implemented in CE-QUAL-W2 as a 1-D model.

Streambed Model, Sensitivity Analysis

Implementation in CE-QUAL-W2

Sensitivity to Flow Rates

Flow, ft^3/s	Flow, m^3/s	Volume-Weighted Water Temperature with No Streambed Heating Model, °C	Volume-Weighted Water Temperature with Streambed Heating Model, °C	Volume-Weighted Water Temperature Difference, °C
55	1.56	16.10	16.07	-0.03
40	1.13	16.13	16.12	-0.01
30	0.85	16.10	16.12	0.03
20	0.57	16.09	16.12	0.03
10	0.28	15.95	16.02	0.07

← Not much difference

Substrate	Flow, ft^3/s	Flow, m^3/s	RM 4.88		RM 0.33	
			Temporal Average Difference in Water Temperature (WT) with Streambed Heating Model - No Streambed Heating Model			
			Daily Minimum WT, °C	Daily Maximum WT, °C	Daily Minimum WT, °C	Daily Maximum WT, °C
100% Bedrock	55	1.56	0.09	-0.24	0.10	-0.19
	40	1.13	0.08	-0.13	0.09	-0.12
	30	0.85	0.13	-0.17	0.27	-0.06
	20	0.57	0.16	-0.14	0.28	0.06
	10	0.28	0.24	-0.14	0.03	0.24

Decreasing Flow ↓

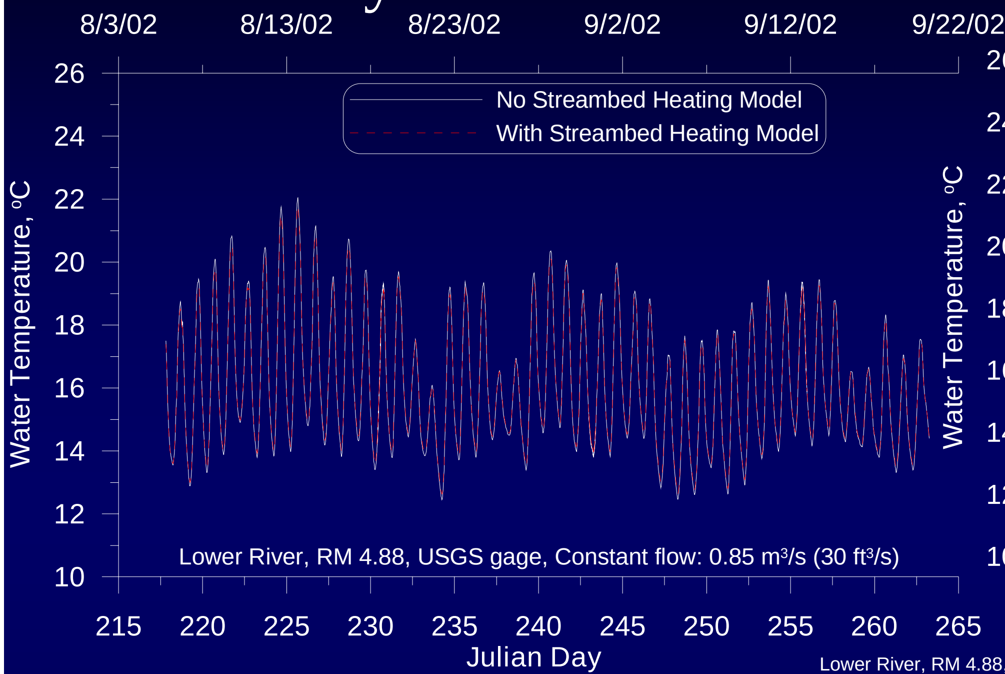
Increasing Temp. Diff. in Daily Min.

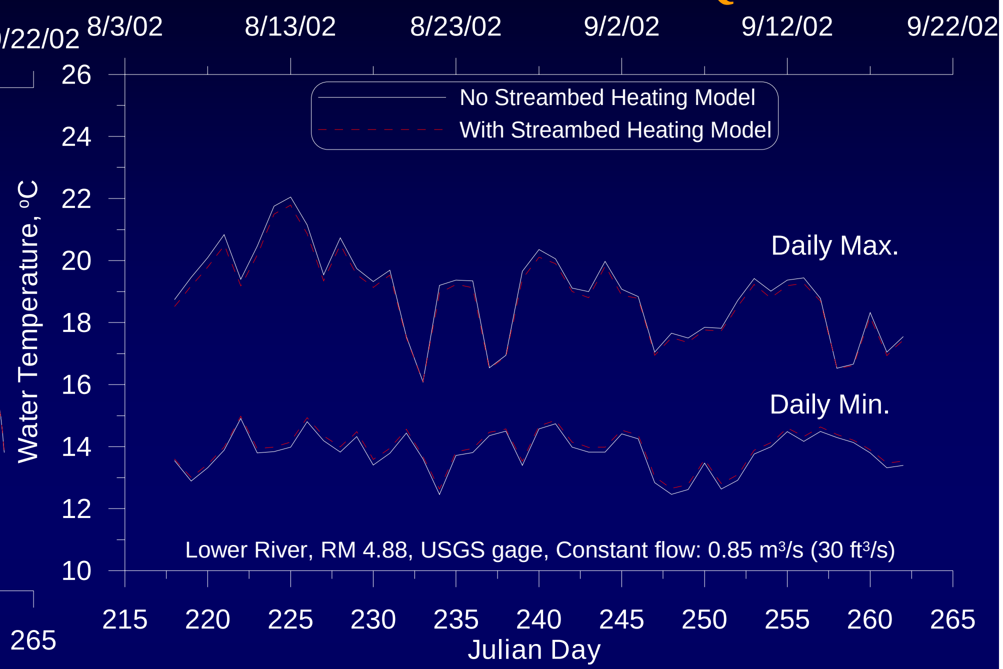
Decreasing Temp. Diff. in Daily Max.

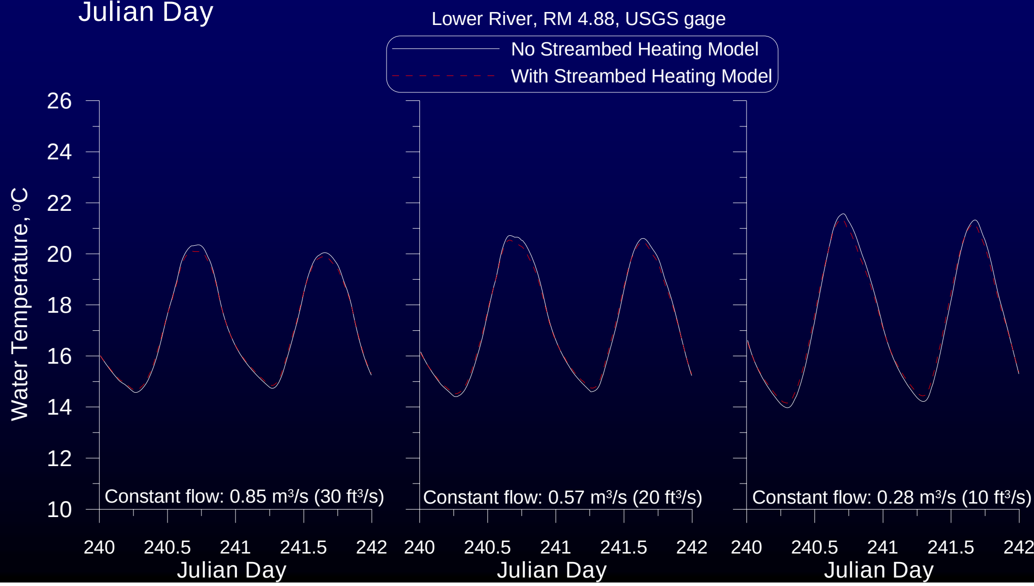
Streambed Model, Sensitivity Analysis

Implementation in CE-QUAL-W2

Sensitivity to Flow Rates







Streambed Model, Sensitivity Analysis

Implementation in CE-QUAL-W2

Sensitivity to Substrate Types

River Substrate	Flow, ft^3/s	Flow, m^3/s	RM 4.88: Temporal Average Difference in Water Temperature (WT) with Streambed Heating Model - No Streambed Heating Model			RM 0.33: Temporal Average Difference in Water Temperature (WT) with Streambed Heating Model - No Streambed Heating Model		
			Daily Minimum WT, °C	Daily Maximum WT, °C	Substrate at RM 4.88	Daily Minimum WT, °C	Daily Maximum WT, °C	Substrate at RM 0.33
100% bedrock	30	0.85	0.13	-0.17	Bedrock	0.27	-0.06	Bedrock
	20	0.57	0.16	-0.14		0.28	0.06	
	10	0.28	0.24	-0.14		0.03	0.24	
75% bedrock, 25% cobble	30	0.85	0.03	0.02	Bedrock	0.16	0.09	Cobble
	20	0.57	0.02	0.05		0.24	0.13	
	10	0.28	0.02	0.08		0.17	0.19	
50% bedrock, 50% cobble	30	0.85	0.03	0.02	Bedrock	0.16	0.09	Cobble
	20	0.57	0.02	0.05		0.24	0.13	
	10	0.28	0.02	0.08		0.17	0.19	
25% bedrock, 75% cobble	30	0.85	0.03	0.02	Cobble	0.16	0.09	Bedrock
	20	0.57	0.02	0.05		0.24	0.13	
	10	0.28	0.02	0.08		0.17	0.19	
100% cobble	30	0.85	0.03	0.02	Cobble	0.16	0.09	Cobble
	20	0.57	0.02	0.05		0.24	0.13	
	10	0.28	0.02	0.08		0.17	0.19	

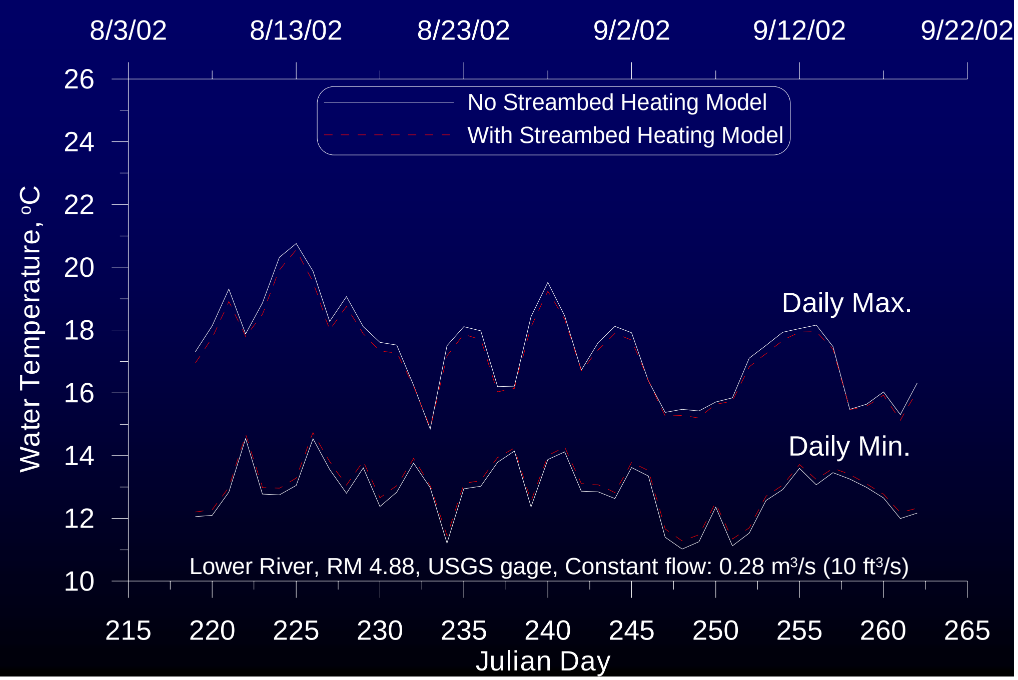
Streambed Model, Sensitivity Analysis

Implementation in CE-QUAL-W2

Sensitivity to Dynamic Shading

Substrate	Vegetative and Topographic Shade	Flow, ft^3/s	Flow, m^3/s	RM 4.88		RM 0.33	
				Temporal Average Difference in Water Temperature (WT) with Streambed Heating Model - No Streambed Heating Model			
				Daily Minimum WT, °C	Daily Maximum WT, °C	Daily Minimum WT, °C	Daily Maximum WT, °C
100% Bedrock	No	30	0.85	0.13	-0.17	0.27	-0.06
		20	0.57	0.16	-0.14	0.28	0.06
		10	0.28	0.24	-0.14	0.03	0.24
100% Bedrock	Yes	30	0.85	0.10	-0.19	0.10	-0.17
		20	0.57	0.12	-0.20	0.01	0.05
		10	0.28	0.18	-0.20	-0.03	0.05

Daily minimum and maximum water temperature with dynamic shading



Stream characteristics when Streambed Heating may be important

- The river is exposed to a lot of direct sunlight with limited vegetative and topographic shade.
- The channel morphology and flow rates allow for wide-open channels with shallow depths in summer.
- The light extinction allows solar radiation to penetrate the water column and reach the streambed.
- The substrate types are dominated by bedrock and consolidated cobble.
- The low river flow season corresponds to dry summer periods with a lot of solar radiation and higher air temperatures.

Summary and Conclusions

- Field and laboratory studies demonstrated vertical and horizontal temperature gradients.
- Light extinction data revealed a large fraction (66%) of the solar radiation reaches the streambed.
- A 3-D streambed heating model was successfully developed and calibrated to field and lab data.
- A higher resolution grid is necessary near the surface to capture higher temperature gradients. A coarser grid near the bottom BC would be acceptable.
- The 3-D model compared well for a simple case analytical solution and a 1-D model and performed better than the analytical when calibrated to field data.

Summary and Conclusions

- Implementation of the streambed model in CE-QUAL-W2 showed:
  daily minimum temperatures increased and
  daily maximum temperatures decreased.
- Increased flow rates decreased the impacts from streambed heating but resulted in larger heat fluxes.
- The largest impacts occurred with bedrock substrate.
- Increased shade decreased solar radiation and the impact of streambed heating.
- MBH solar radiation model compared well with data, 4 calibration parameters
- EPA solar model compared well with data, no calibration parameters

Acknowledgements

Rich Miller, Toni Pennington, Miguel Estrada, Mark Sytsma

Kazu Sonoda, Alan Yeakley, Sharon Stanton, Robert Tinnen, David Percy

Curt Peterson, Spencer Slominski, Mike McKillip, Steve Speer

Chris Berger, Kyle Muramatsu, Vanessa Wells

Stan Cioeta, Doug Bloem, and Jeff Leighton: City of Portland, Water Bureau

My Advisor: Scott Wells

My Committee: Scott Wells, Curt Peterson, William Fish, Roy Koch, and Alan Yeakley

Verena Winter

The field and lab work were partially funded by a grant from the U.S. Geological Survey and the Institute for Water and Watersheds at Oregon State University.

http://www.cee.pdx.edu/w2/