Heat as an aquifer characterization tool and tracer of surface water-groundwater interactions

Audrey Sawyer
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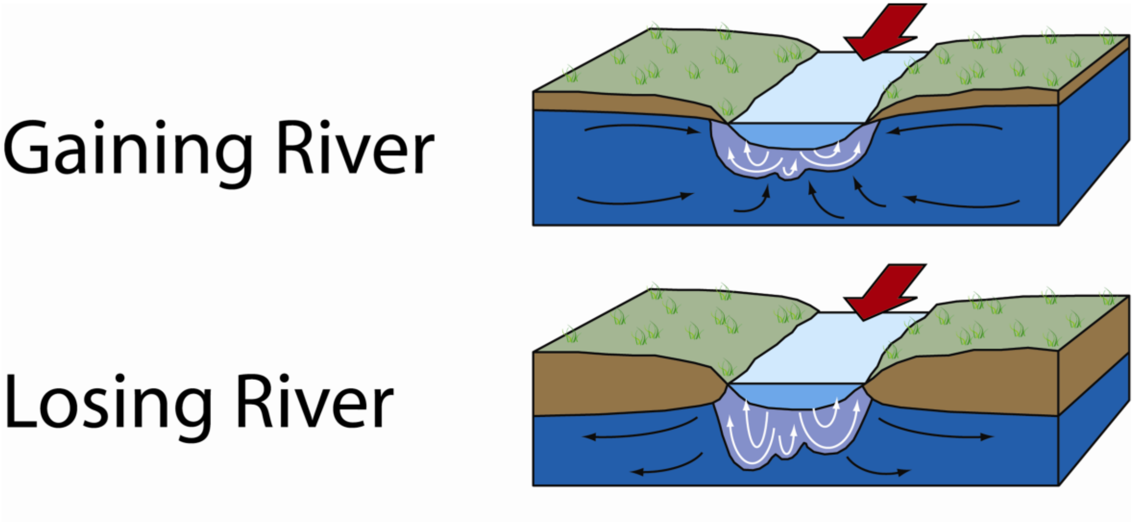
AIPG Short Course, Aquifer Characterization –
Groundwater Behavior in the Subsurface Environment

River-groundwater connections

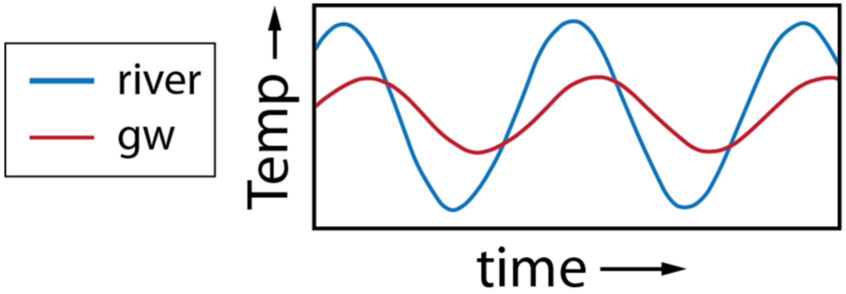


- What is the seepage rate?
- What are the hydraulic properties of the riverbed?

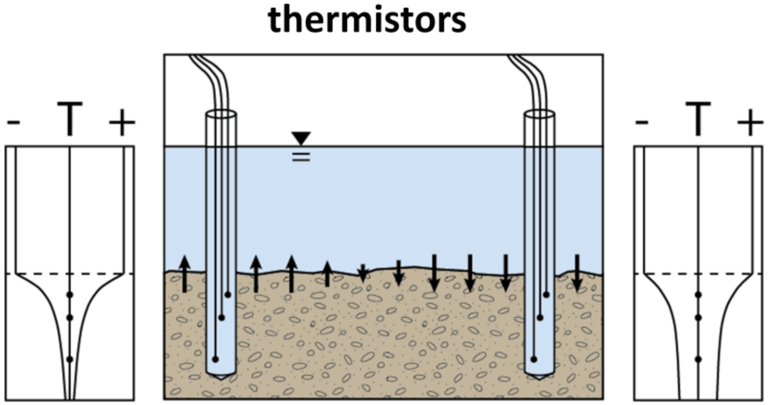
Heat as a tracer

- **Theory:** *temperature signals in riverbeds can be used to determine vertical seepage rates and riverbed conductivity*
- **Tools:** *thermistors and piezometers are cheap and easy to use*
- **Analysis:** *Free software such as ExStream calculates vertical seepage rates, or you can use Excel*
- **Case Study 1:** *River-groundwater exchange created by logs or other stream restoration structures*
- **Case Study 2:** *River-groundwater exchange caused by hydropeaking downstream from a dam*

Theory: vertical seepage, q



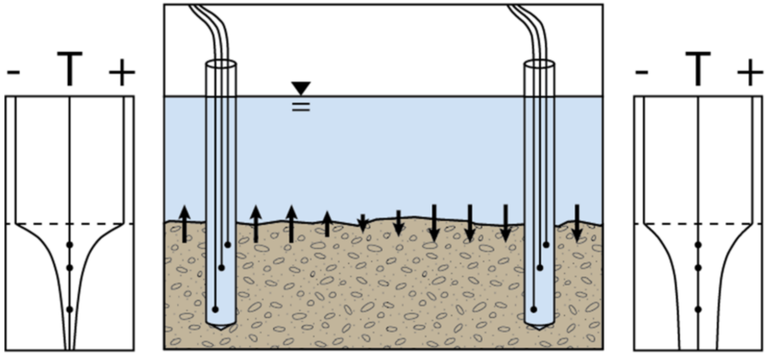
Method requires a periodic temperature signal in surface water



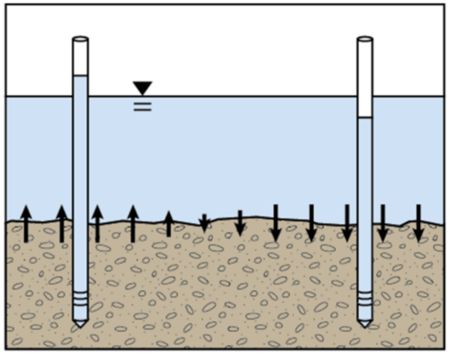
Amplitude Ratio at two depths → q

Theory: streambed hydraulic conductivity, K

thermistors



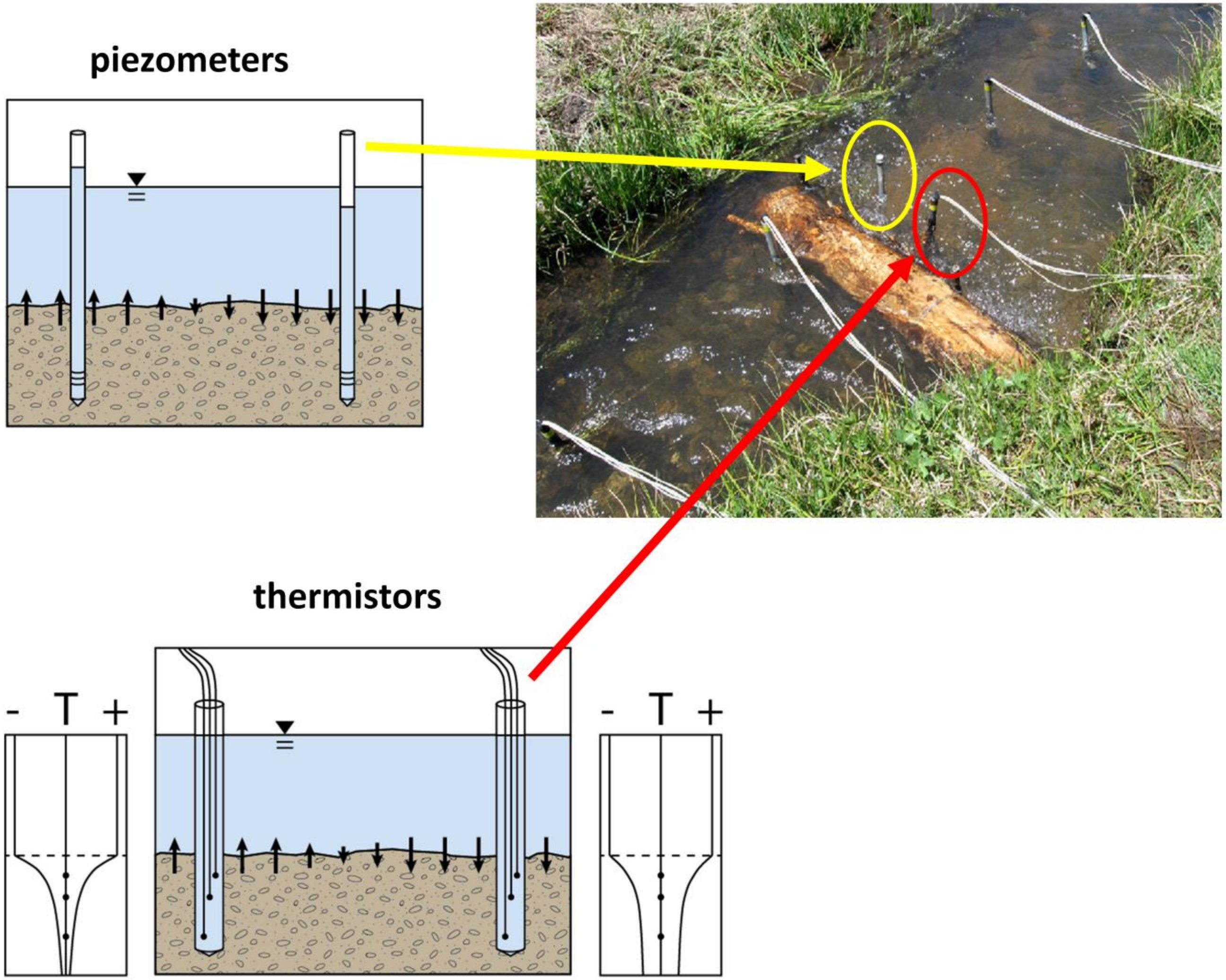
piezometers



Amplitude Ratio at two depths → q

Vertical head gradient → dh/dz

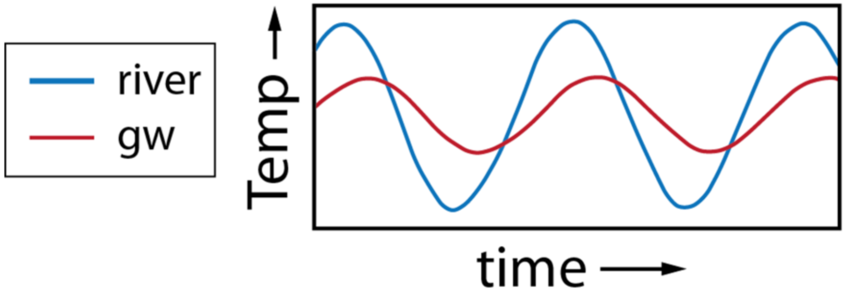
Darcy’s law → K = q/(dh/dz)



piezometers

thermistors

Theory: vertical seepage, q



Amplitude Ratio at two depths → q

Governing equation: 1D heat flow

$$\frac{\partial T}{\partial t} = D_e \frac{\partial^2 T}{\partial t^2} - \frac{q}{\gamma}\frac{\partial T}{\partial z}$$

Analytical solution (Hatch et al., 2006): **(implicit for q)**

$$A_r = \exp\left\{ \frac{\Delta z}{2D_e}\left(\frac{q}{n\gamma} - \sqrt{\frac{\alpha + (q/n\gamma)^2}{2}} \right) \right\},$$

$$\alpha = \sqrt{(q/n\gamma)^4 + (8\pi D_e \omega)^2}$$

De is effective thermal diffusivity
Gamma is the ratio of heat capacity of saturated streambed sediment to heat capacity of water
Omega is frequency (1/d)
q is positive downward

Tools: thermistors, data loggers

Onset TidbiT temperature logger ($133)

- Advantages: internal data loggers (no cables), easy to use and deploy
- Disadvantages: Limited number of measurements, lifetime
- Deployment: drill holes in wooden stakes at desired intervals, epoxy TidbiTs into holes, drive stakes into bed

Tools: thermistors, data loggers

Onset 20’
temperature
cable ($39)

+

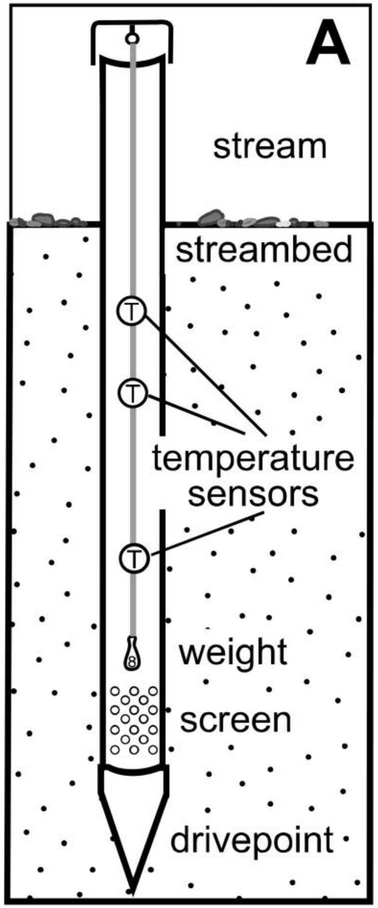
HOBO U12
weatherproof
external data
logger with 4
channels ($249)

- Advantages: Keep using and reusing, extremely reliable
- Disadvantages: Requires external data logger, cables attract unwanted attention from people and wildlife
- Deployment: Drive steel pipe with end cap into streambed and fill with water, secure thermistors to thin rod or dowel at desired intervals and insert in steel pipe, run cables to data logger on stream bank or house data logger in waterproof case

Tools: piezometers (for streambed K)

PVC or steel casing with short screen interval, or tubing with manometer board

Hatch et al. (2006)



Tools: thermal properties (optional)

Decagon Devices KD2 Pro: measures specific heat and thermal conductivity

Analysis

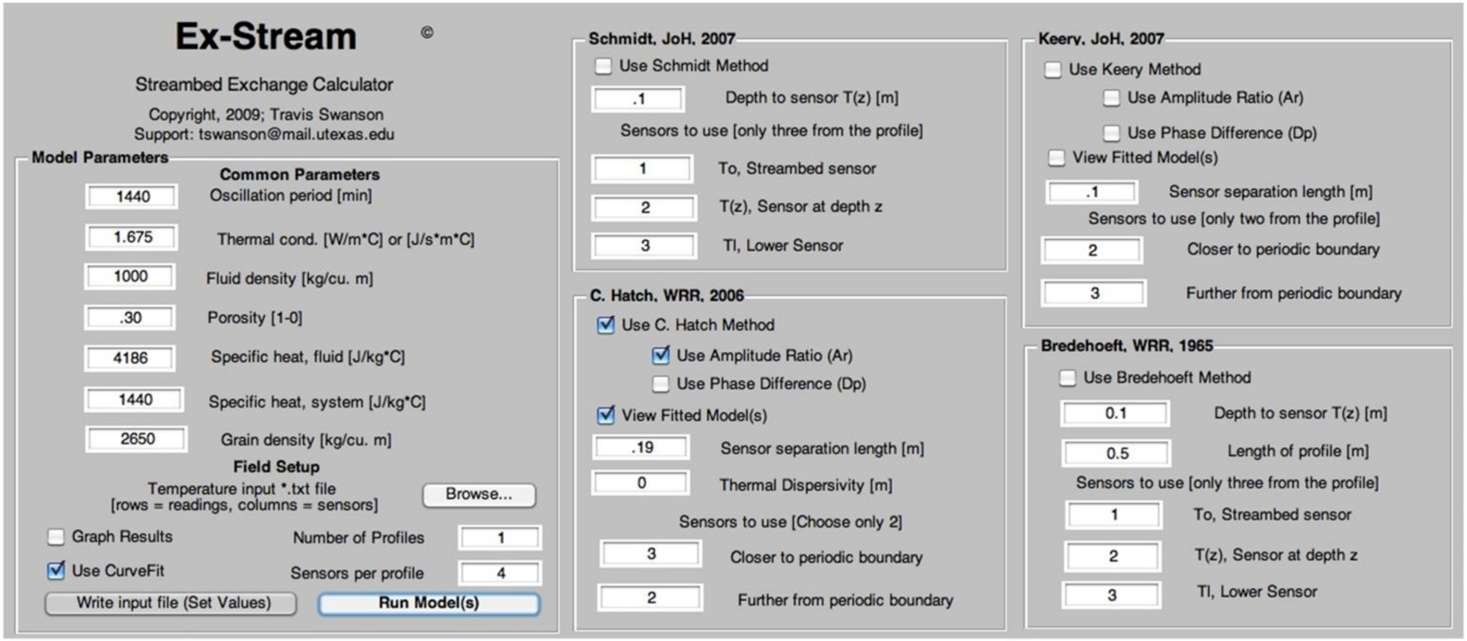
1) Determine amplitude ratio of temperature signals at two depths using method of choice, then solve the implicit equation for q

- Amplitude ratio can be determined visually (less accurate), by fitting data to a sinusoid, or by fourier transform
- Implicit equation can be solved in Excel using GoalSeek or with Matlab/Fortran script

2) Use freeware like ExStream (Swanson et al., 2011) to determine amplitude ratio and solve for q

Either way, you'll need estimates of riverbed thermal properties and porosity, but they don't vary much across geologic materials (choose textbook value)

Analysis: ExStream



Ex-Stream ©

Streambed Exchange Calculator

Copyright, 2009; Travis Swanson
Support: tswanson@mail.utexas.edu

Model Parameters

Common Parameters

1440 Oscillation period [min]
1.675 Thermal cond. [W/m*C] or [J/s*m*C]
1000 Fluid density [kg/cu. m]
.30 Porosity [1-0]
4186 Specific heat, fluid [J/kg*C]
1440 Specific heat, system [J/kg*C]
2650 Grain density [kg/cu. m]

Field Setup

Temperature input *.txt file
[rows = readings, columns = sensors]

☐ Graph Results
☑ Use CurveFit
Number of Profiles 1
Sensors per profile 4

Schmidt, JoH, 2007

☐ Use Schmidt Method
.1 Depth to sensor T(z) [m]
Sensors to use [only three from the profile]
1 To, Streambed sensor
2 T(z), Sensor at depth z
3 Tl, Lower Sensor

C. Hatch, WRR, 2006

☑ Use C. Hatch Method
☑ Use Amplitude Ratio (Ar)
☐ Use Phase Difference (Dp)
☑ View Fitted Model(s)
.19 Sensor separation length [m]
0 Thermal Dispersivity [m]
Sensors to use [Choose only 2]
3 Closer to periodic boundary
2 Further from periodic boundary

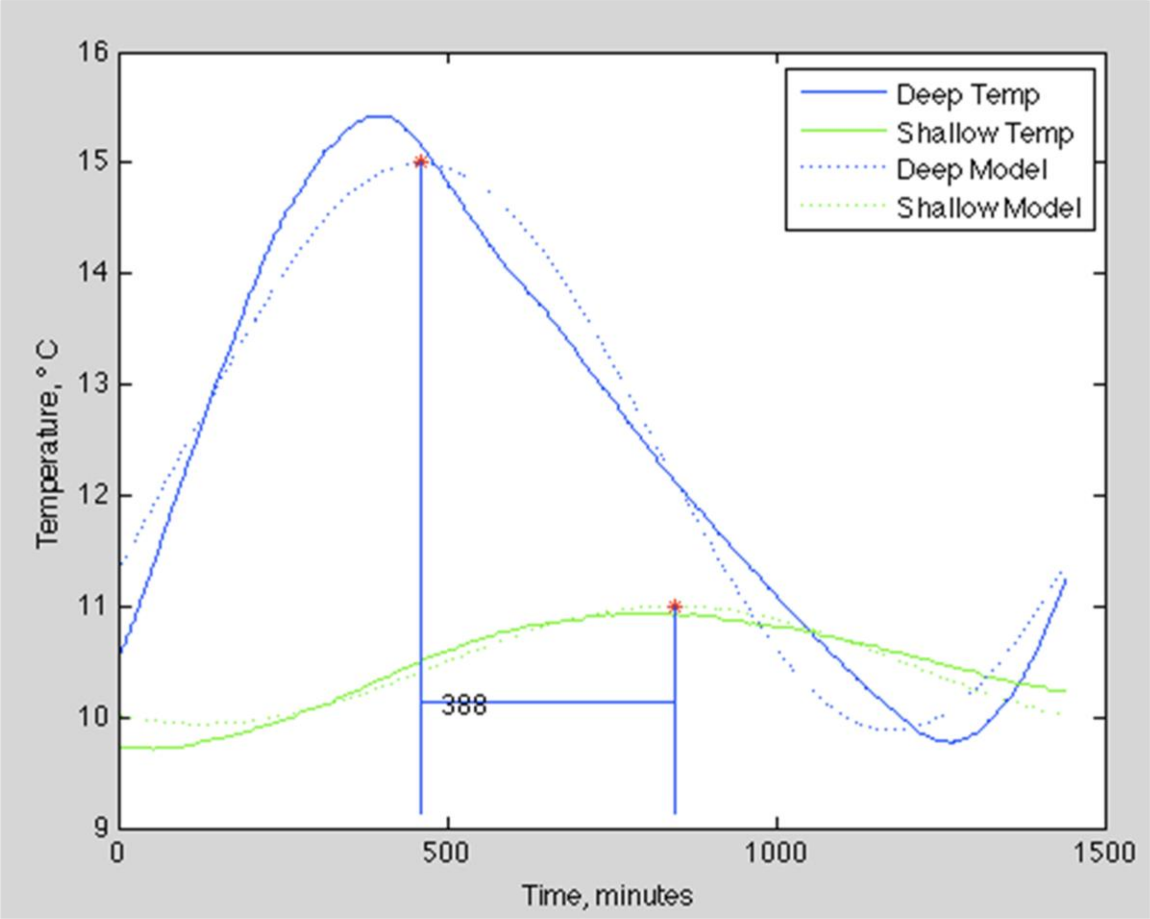
Keery, JoH, 2007

☐ Use Keery Method
☐ Use Amplitude Ratio (Ar)
☐ Use Phase Difference (Dp)
☐ View Fitted Model(s)
.1 Sensor separation length [m]
Sensors to use [only two from the profile]
2 Closer to periodic boundary
3 Further from periodic boundary

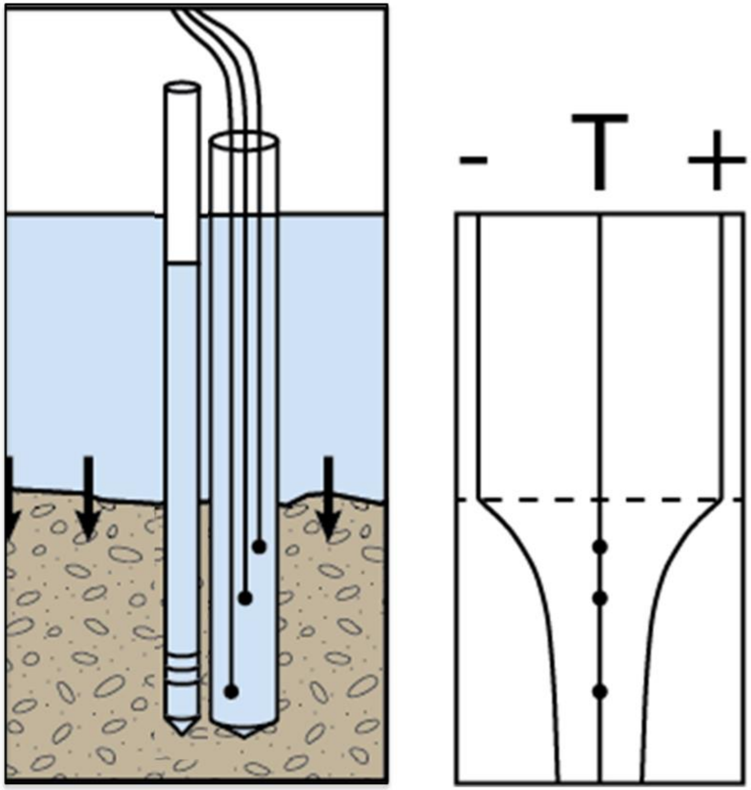
Bredehoeft, WRR, 1965

☐ Use Bredehoeft Method
0.1 Depth to sensor T(z) [m]
0.5 Length of profile [m]
Sensors to use [only three from the profile]
1 To, Streambed sensor
2 T(z), Sensor at depth z
3 Tl, Lower Sensor

Analysis: ExStream



Analysis: estimate K from Darcy's law



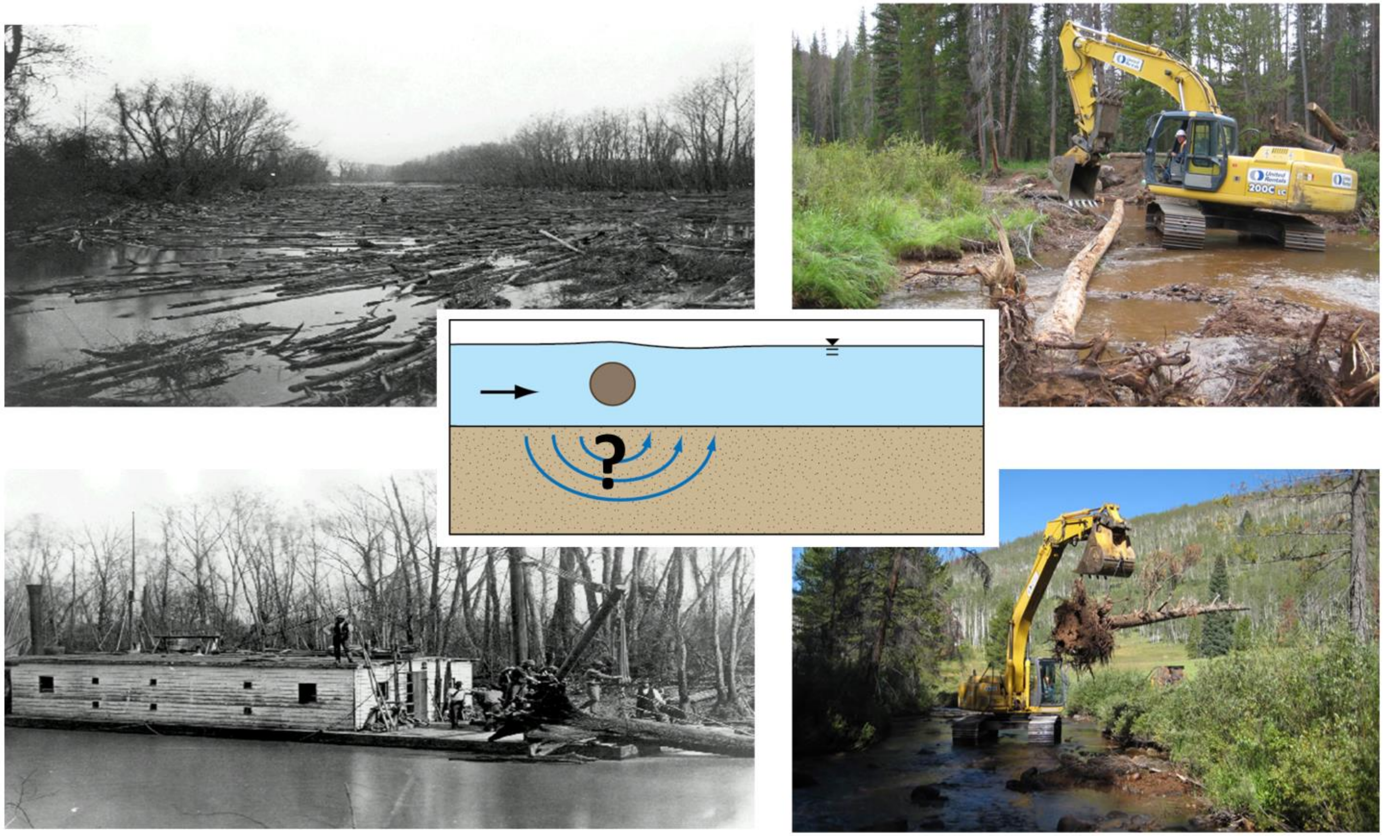
Darcy's law:
K = q/(dh/dz)

- Probably a better estimate of vertical than horizontal K

Case Study 1: river-groundwater exchange due to logs

Shreveport, LA (1873)

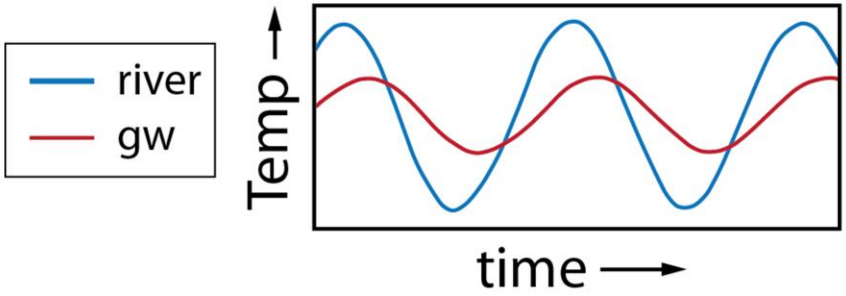
Piney River, Colorado (modern)

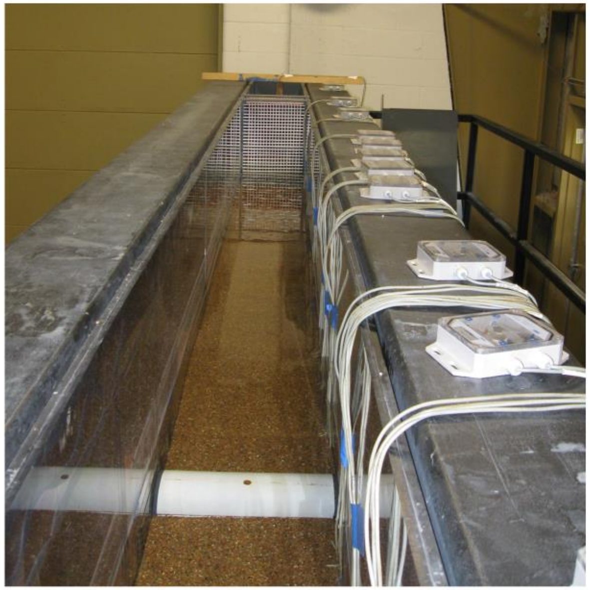


Army Corps of Engineering (http://www.usace.army.mil)

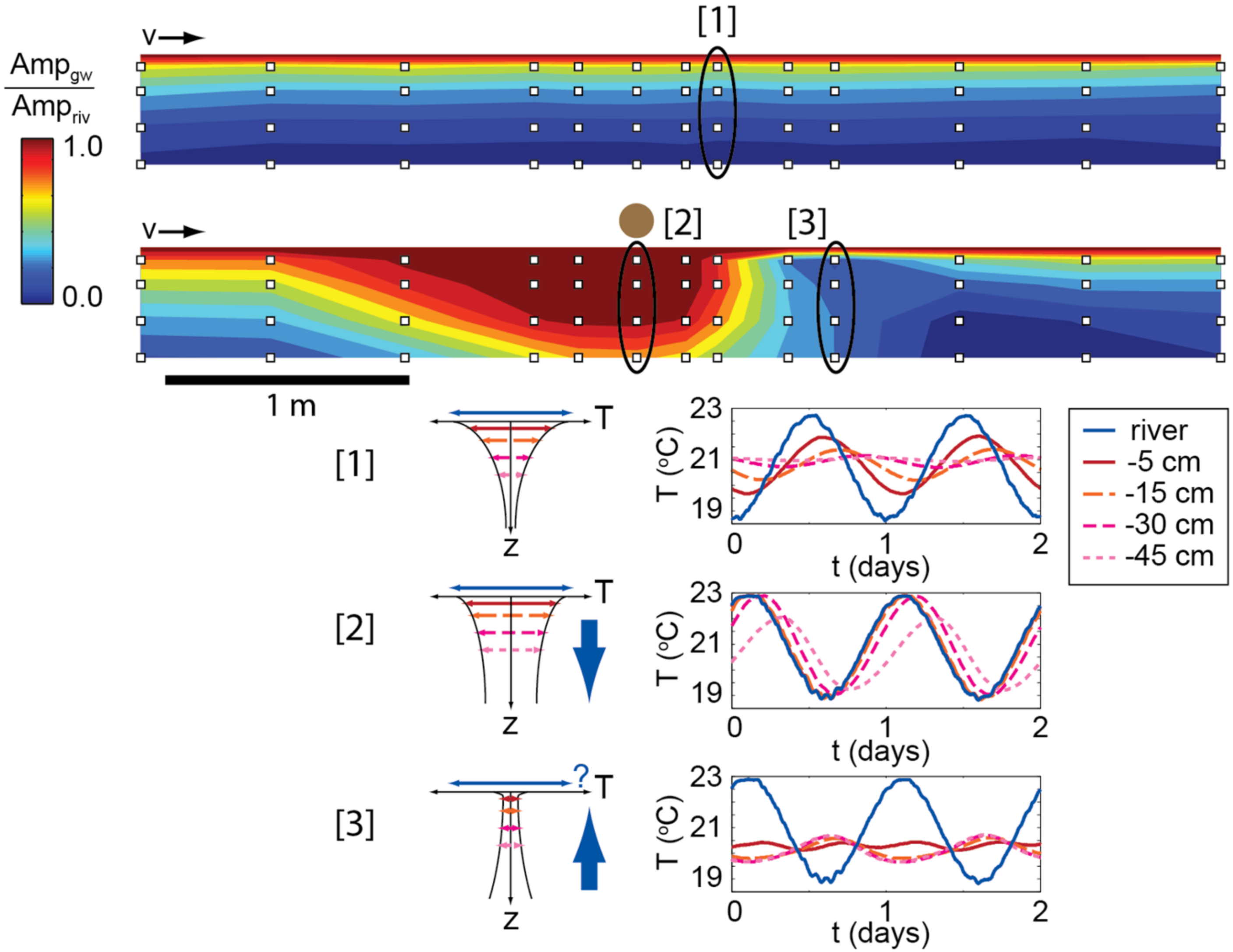
Great raft documented during expedition in 1806 (Red River, LA). Men described it as “an almost impenetrable mass” and dammed the river. Eyewitnesses estimated length to range from 80-150 miles. Army Corps began clearing in 1830’s for navigation.

Temperature studies in flume

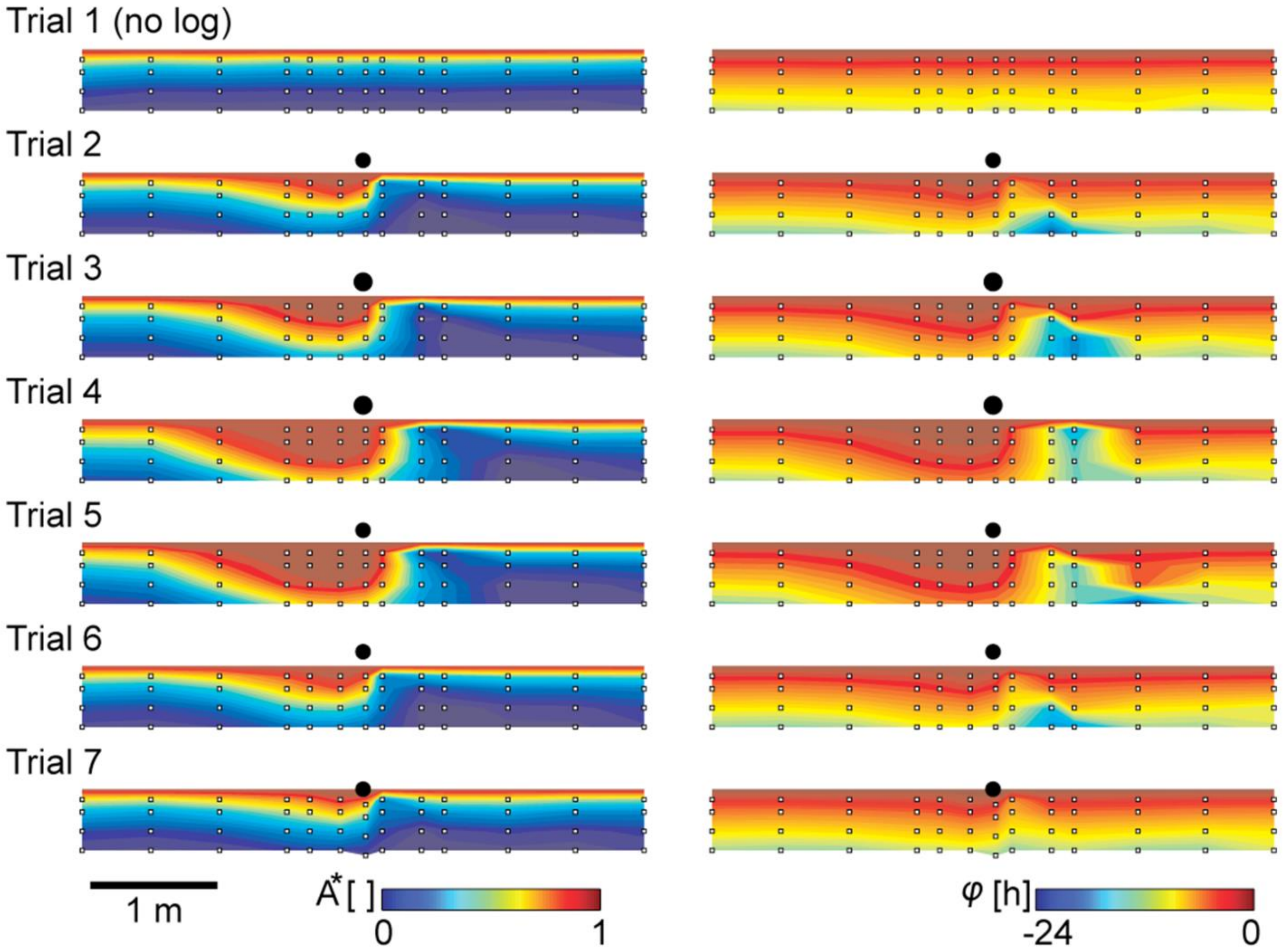




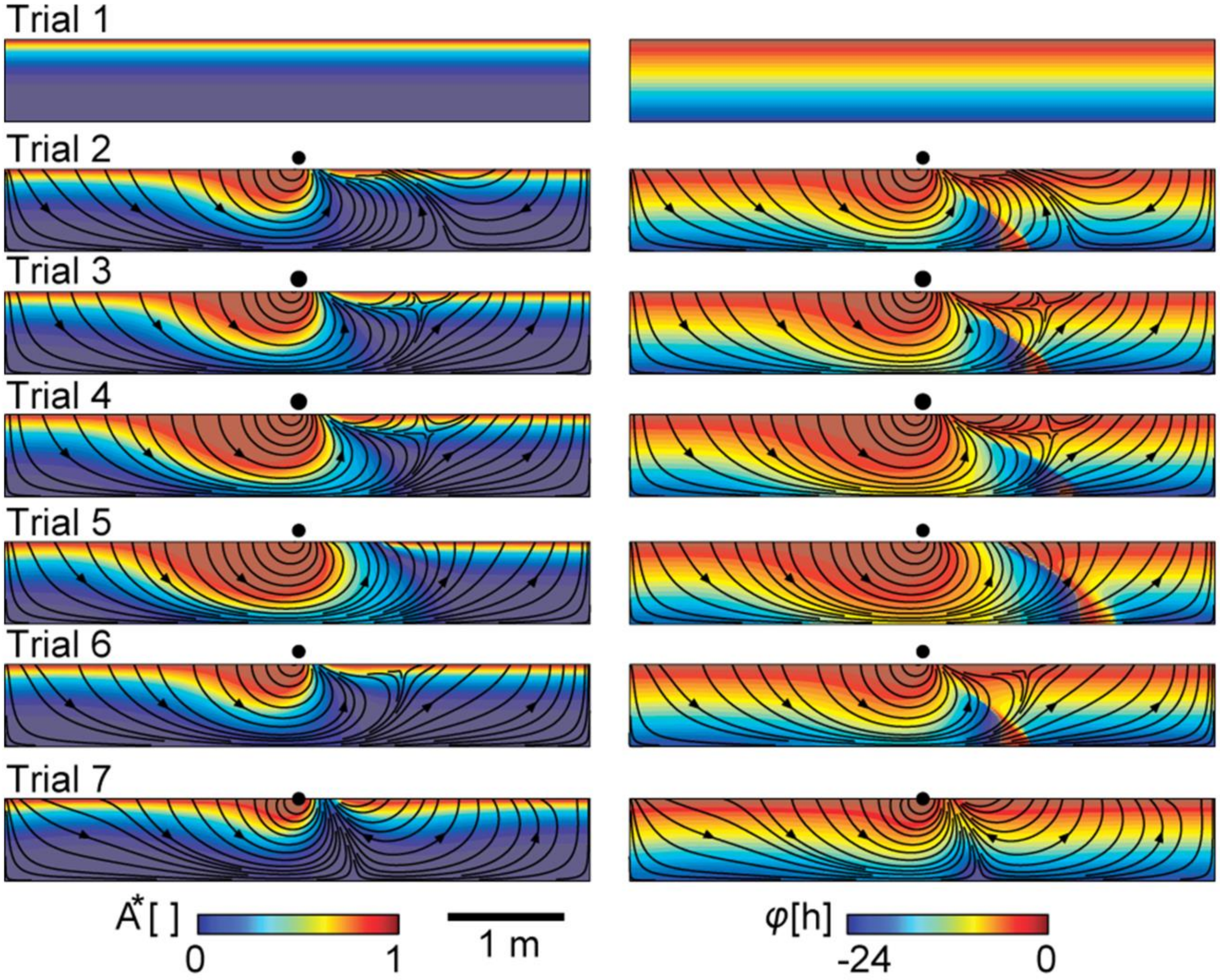
Sawyer, A.H., M.B. Cardenas, J. Buttles (2012), Hyporheic temperature dynamics and heat exchange near channel-spanning logs, Water Resources Research, 48, W01529, doi: 10.1029/2011WR011200.


[1]
v
Amp_gw / Amp_riv
1.0
0.0
[2]
[3]
1 m
[1]
[2]
[3]
T
?
z
T (°C)
23
21
19
0
1
2
t (days)
river
-5 cm
-15 cm
-30 cm
-45 cm

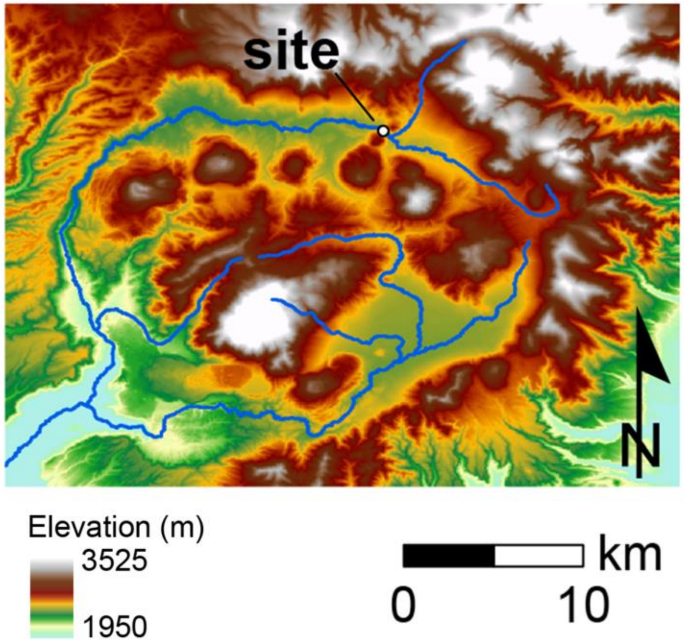
Patterns vary with log size and channel hydraulics



Numerical Simulations



A field test (San Antonio Creek, NM)



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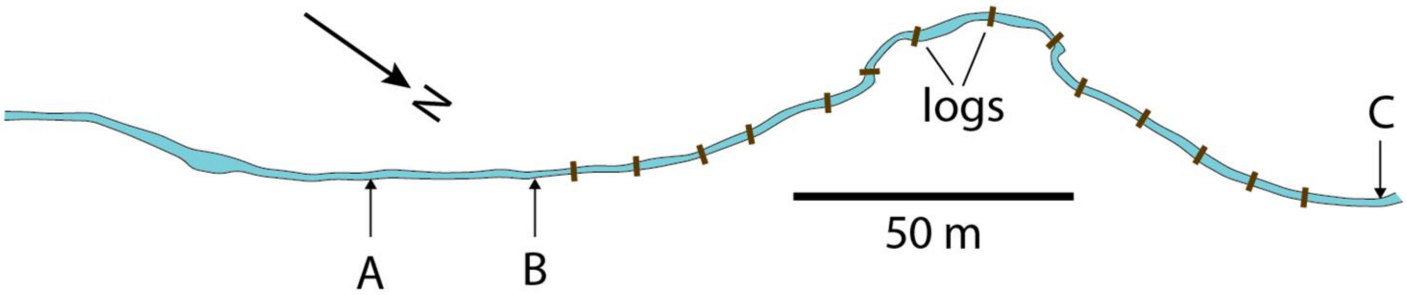
San Antonio River (NM)



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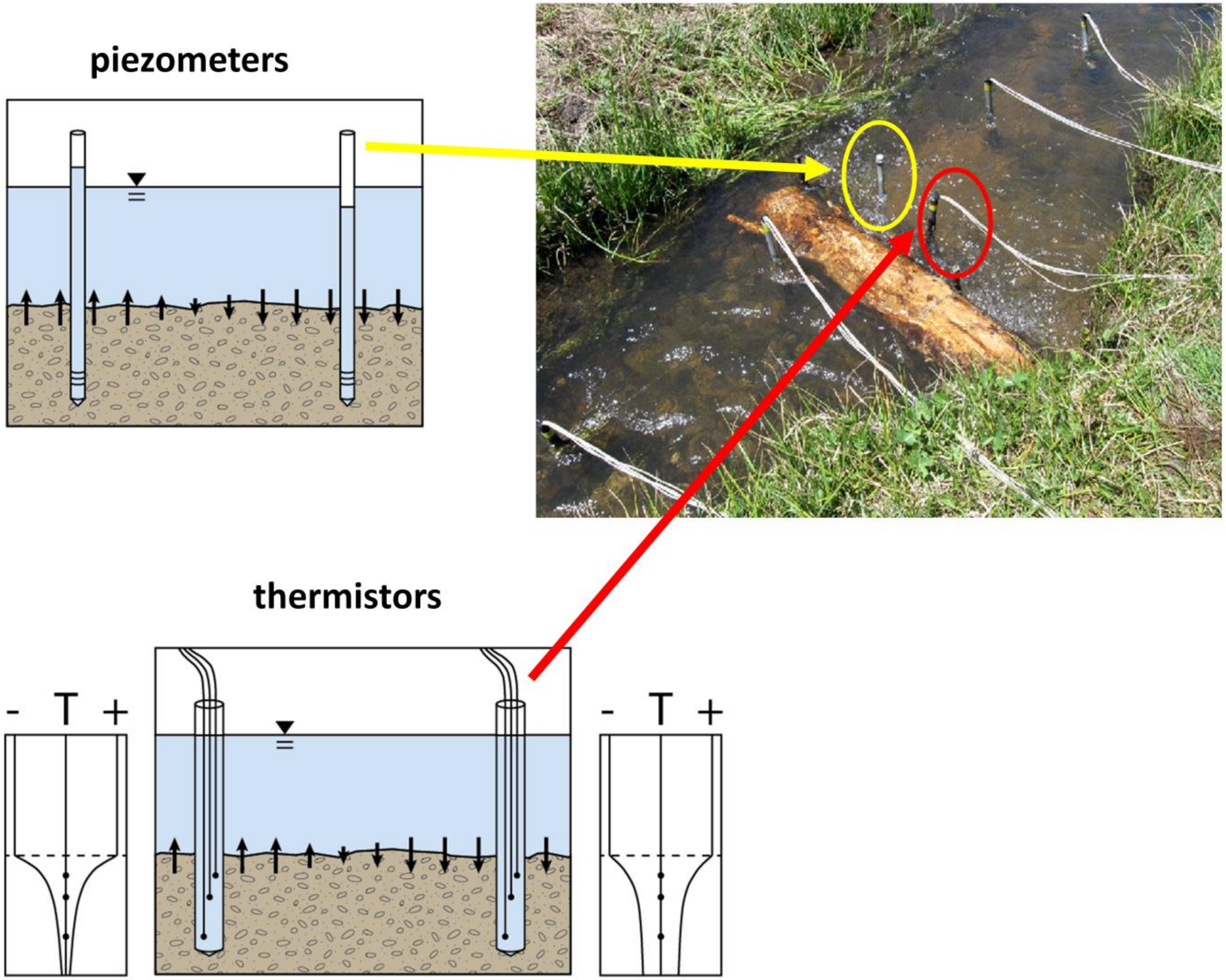


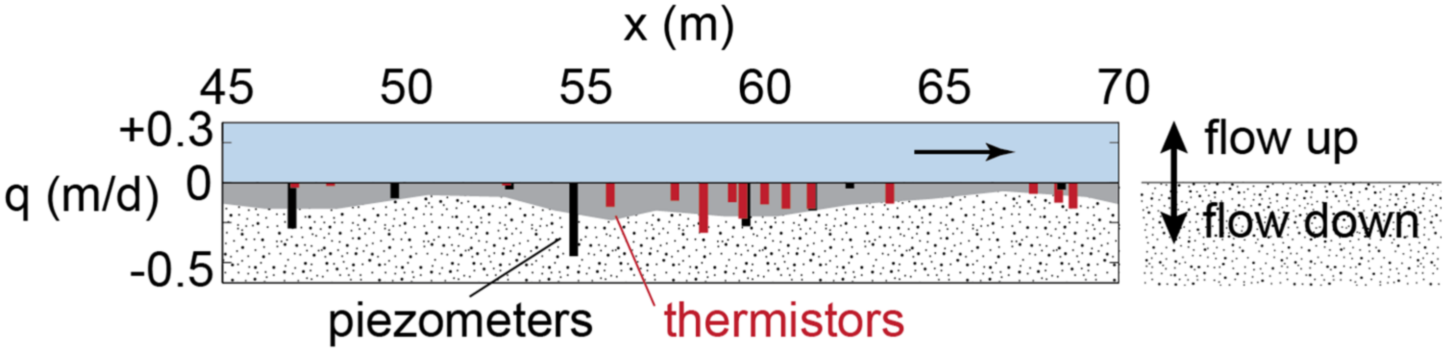
piezometers

thermistors

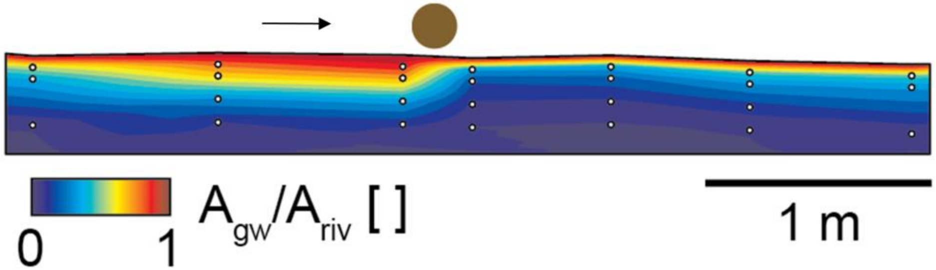
Streambed K estimates

x [m]	K_{therm} [m/d]	K_{slug} [m/d]
17.72	3.5	16
23.72	1.3	7.9
30.32	2.0	4.4

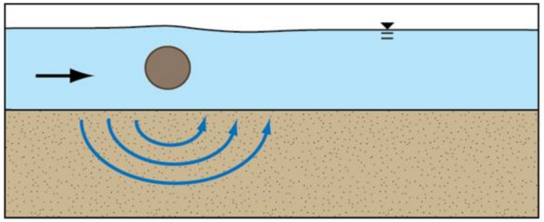
- **K from temperature sensing is ~20-50% of K from slug tests (good agreement)**
- **K_{therm} may be representative of K_v**
- **K_{slug} may representative of K_h**

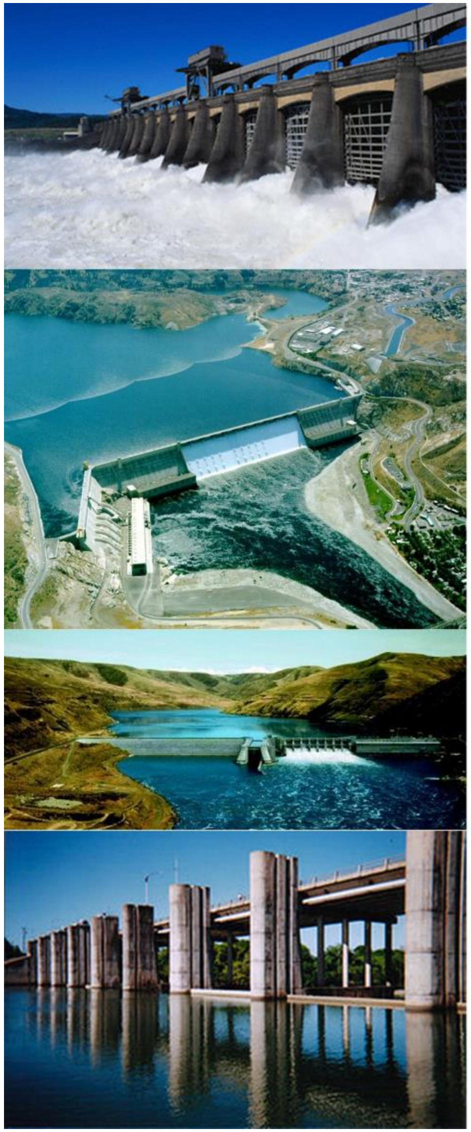

x (m)
45
50
55
60
65
70
+0.3
q (m/d)
0
-0.5
flow up
flow down
piezometers
thermistors

Streambed temperature patterns



- **Logs drive river-groundwater mixing and influence streambed temperature patterns**
- **Here, logs converted ~8% of the streambed to upwelling regions, which may serve as thermal refugia**





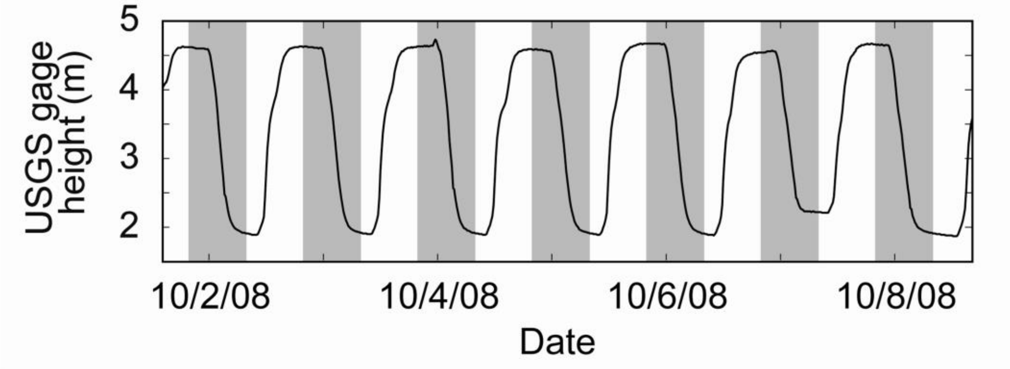
Case Study 2: river-groundwater exchange due to hydropeaking

USA:

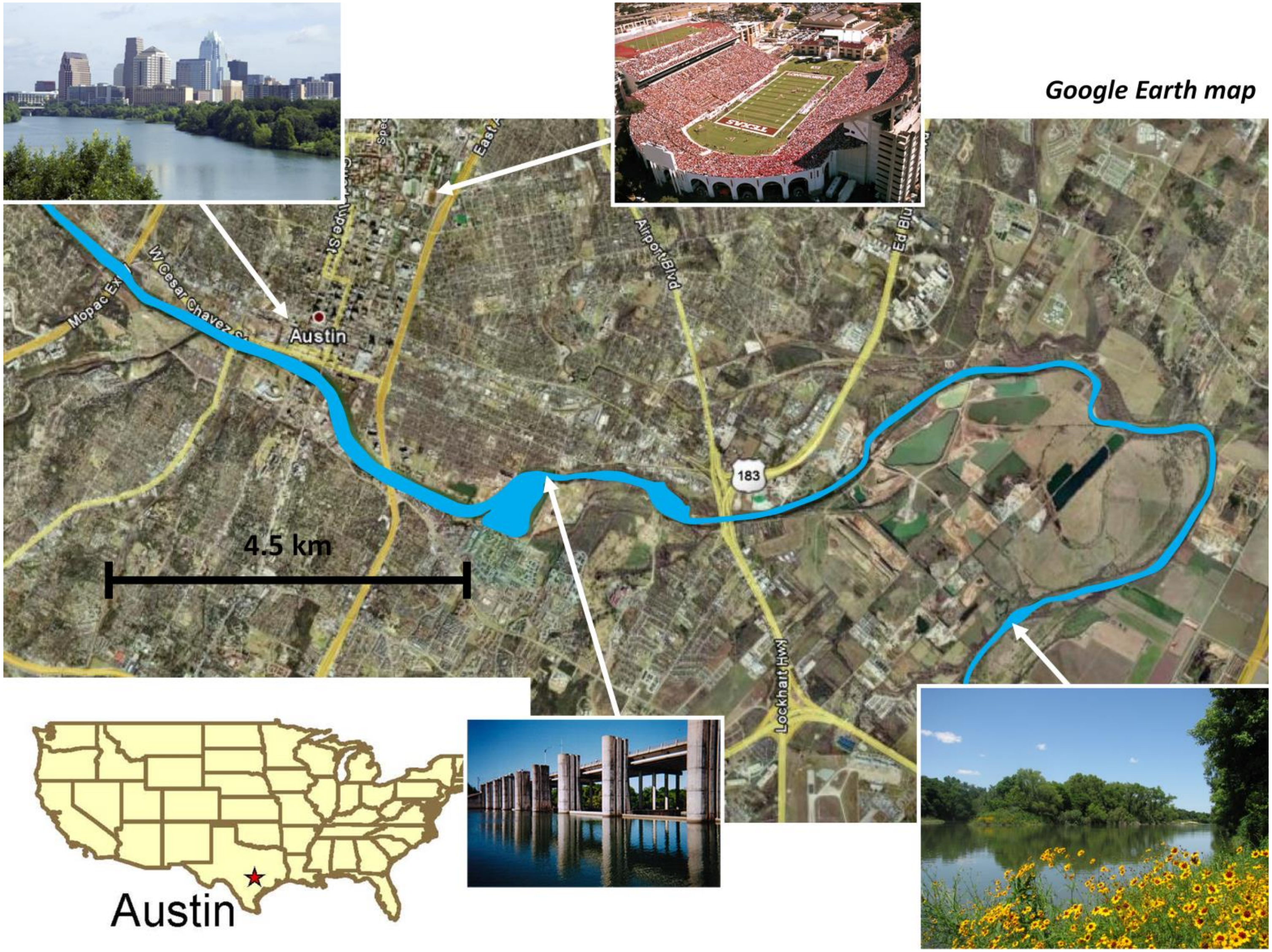
- All watersheds > 2000 sq km have dams (Graff, 1999)
- 10% of power from hydroelectric (www.usgs.gov)

WORLD:

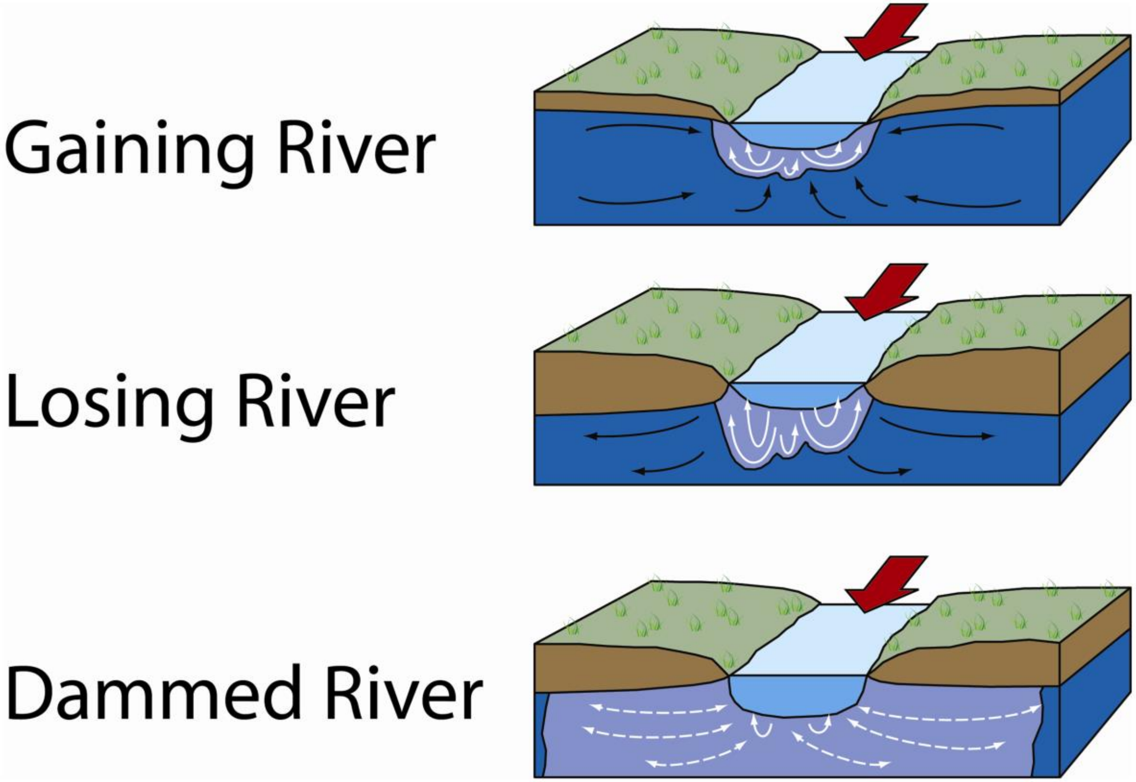
- More than half of large rivers regulated by dams (Nilsson et al., 2005)



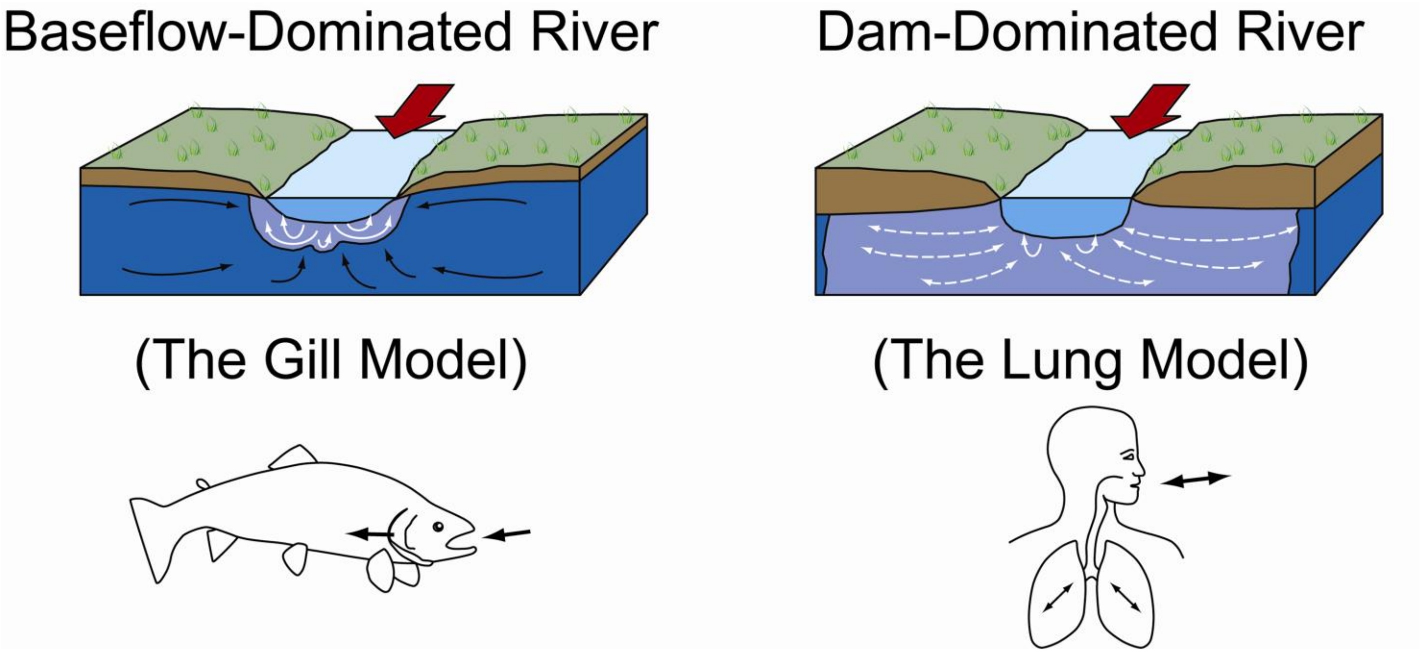
10% of energy produced in US from hydropower


Google Earth map

River-groundwater connections in regulated rivers



River-groundwater connections in regulated rivers



Sawyer, AH, MB Cardenas, A Bomar, and M Mackey (2009), Impact of dam operations on hyporheic exchange in the riparian zone of a regulated river, Hydrological Processes, doi:10.1002/hyp.7324.

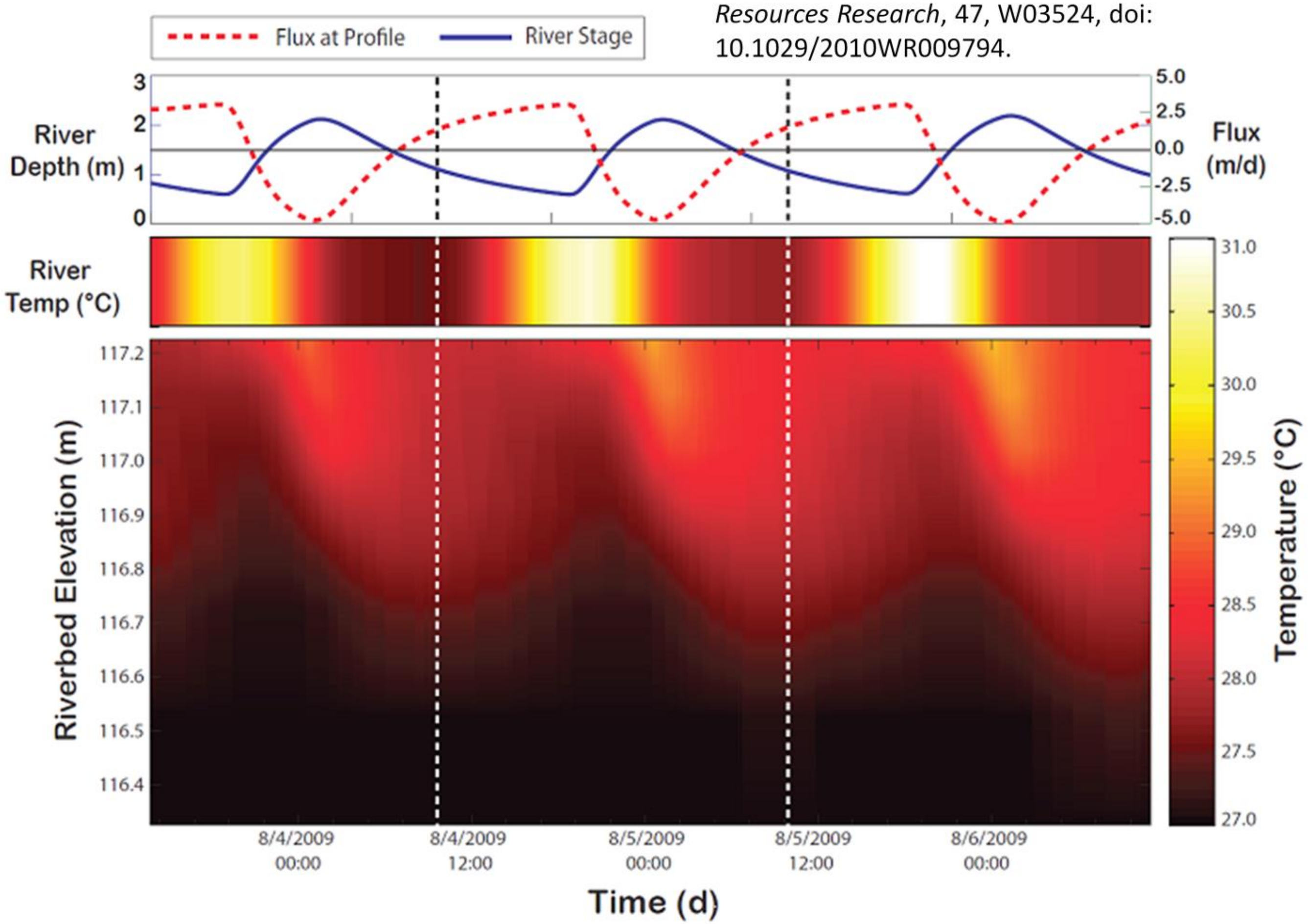
Morning after peak discharge

Afternoon at low discharge

Temperature and pressure monitoring in bed and bank

Temperature dynamics through time

Gerecht, KE, et al. (2011), Dynamics of hyporheic flow and heat transport across a bed-to-bank continuum in a large regulated river, *Water Resources Research*, 47, W03524, doi: 10.1029/2010WR009794.



Summary

- **Theory:** *temperature signals in riverbeds can be used to determine vertical seepage rates and riverbed conductivity*
- **Tools:** *thermistors and piezometers are cheap and easy to use*
- **Analysis:** *Free software such as ExStream calculates vertical seepage rates, or you can use Excel*
- **Case Study 1:** *Logs and restoration structures alter river-groundwater exchange and stabilize streambed temperatures in upwelling zones*
- **Case Study 2:** *Hydropeaking increases river-groundwater exchange and increases depth of themal signal propagation into riverbed*

References

Gerecht, KE, MB Cardenas, AJ Guswa, AH Sawyer, JD Nowinski, and TE Swanson (2011), Dynamics of hyporheic flow and heat transport across a bed-to-bank continuum in a large regulated river, *Water Resources Research*, 47, W03524, doi: 10.1029/2010WR009794.

Hatch, C. E., A. T. Fisher, J. S. Revenaugh, J. Constantz, and C. Ruehl (2006), Quantifying surface water-groundwater interactions using time series analysis of streambed thermal records: Method development, Water Resour. Res., 42, W10410, doi:10.1029/2005WR004787.

Sawyer, AH, MB Cardenas, A Bomar, and M Mackey (2009), Impact of dam operations on hyporheic exchange in the riparian zone of a regulated river, Hydrological Processes, doi:10.1002/hyp.7324.

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Swanson, T. E., and M. B. Cardenas (2011), Ex-Stream: A MATLAB program for calculating fluid flux through sediment-water interfaces based on steady and transient temperature profiles, *Computers & Geosciences*, *37*(10), 1664-1669, doi: 10.1016/j.cageo.2010.12.001.