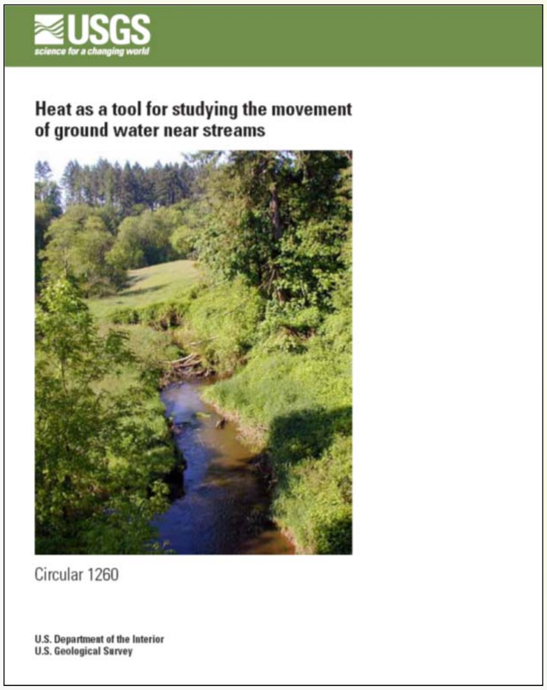


Heat as a Tool for Studying the Movement of Ground Water near Streams

June 27 – July 1, 2016,
University of Copenhagen

Masaki Hayashi, University of Calgary, Calgary, Alberta, Canada

Donald Rosenberry, U.S. Geological Survey, Denver, Colorado, USA

Information primarily from USGS Circular 1260 or from Jim Constantz, Rich Niswonger, or Marty Briggs, USGS

1

Water Exchange between Streams and Ground Water (Chapter 1)

- The rate at which water moves between streams and ground water is governed by the head gradient across the streambed and the resistance to flow within the sediments of the streambed.
- Heat is well suited for delineating localized exchanges between ground water and surface water.
- Temperature changes near streams are often large and rapid.
- These changes provide a clear thermal signal that is easily measured.
- Researchers in the early 1900's recognized that heat is transferred in the movement of water through porous media.
- In the 1950's and 60's researchers developed analytical equations to estimate the rate of water movement.
- Recent advancements in temperature measurement and computational technologies have enabled the economical and routine application of heat to estimate water flow across streambeds.

It is this last item that makes measurement of temperature so enticing for groundwater scientists. Temperature is a measurement that we can make very inexpensively and we don't have to give up much accuracy to do so.

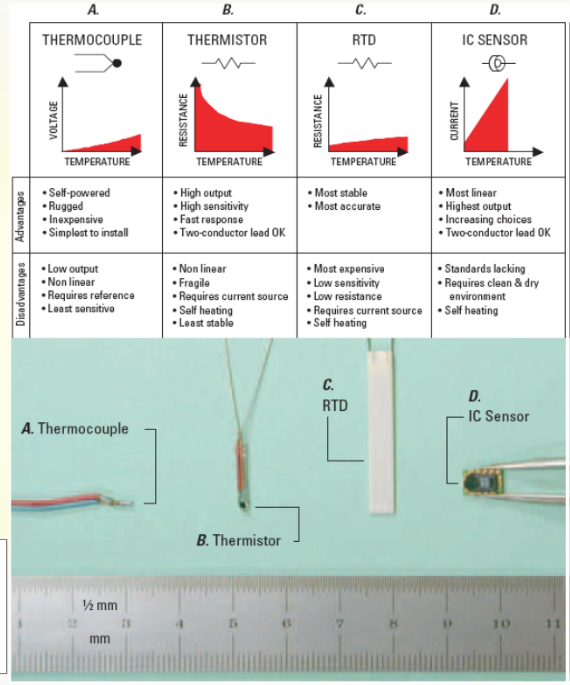
2

Common Electronic Temperature Sensors (Figure 1; Appendix A)

•RTD usually platinum or nickel. Resistance directly related to temperature. More expensive but very stable.

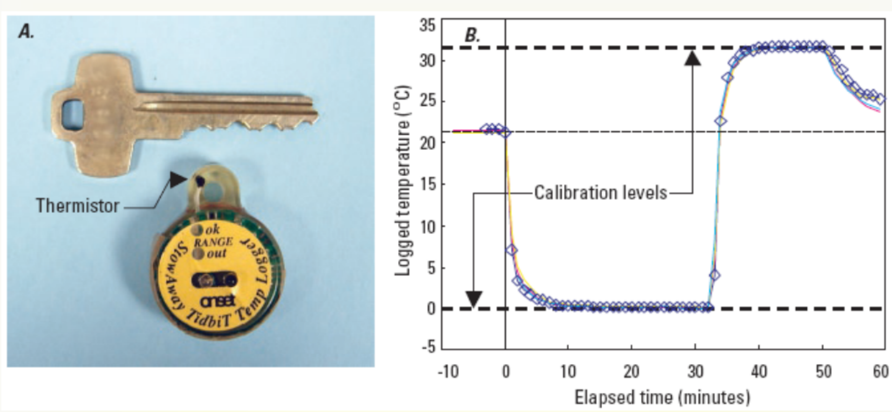
•Thermistor resistance inversely related to temperature. Non-linear. Drift more than RTD.

•Thermocouples create a current when junctions of two dissimilar metals are at different temperatures. Thermocouples are very inexpensive but may drift.



Thermocouples are very cheap, but they can provide biased output if we are not careful to prevent that. Thermistors give a non-linear response to temperature, but polynomial equations can correct for that. They are also quite inexpensive, are very durable, and are the most common type of temperature sensor.

3



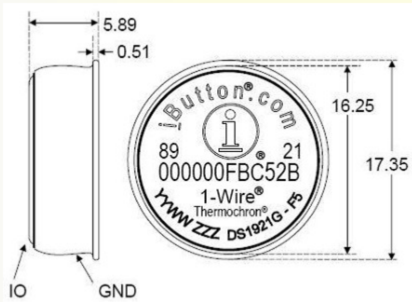
A. Self-contained temperature loggers is about 3 cm in diameter and
B. Dynamic response of four self-contained temperature loggers
(Figure 2; Appendix A)

Here is a commercially available thermistor that can be submerged in water. It also includes a datalogger that collects and stores data from the sensor. This device, and others like it, are now commonly used in GW-SW studies.

4

Even smaller

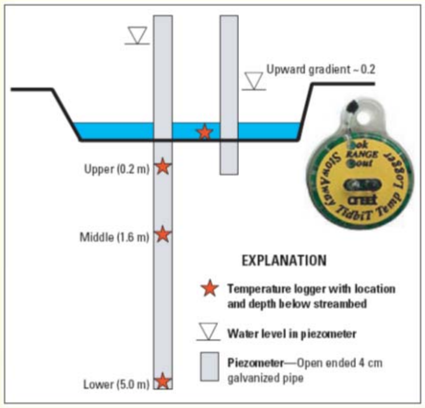
~0.1° resolution



These devices area about $30 each, but they are not waterproof and they are not as reliable either. Still, at such a low cost some studies can afford to deploy two at each location. And they are wonderfully small so they can be lowered into small-diameter monitoring wells.

5

Installing self contained dataloggers beneath streams



Self contained datalogger installed in streambed (Figure 4; Chapter 5)

Temperature sensors are placed at one or several depths beneath the bed of a surface-water body, in this case a stream. The guy on the right in the photo is Jim Constantz.

Method used in Oregon (Figure 3; Appendix 5)

7

Design of Temperature Measurements

- Success in quantifying stream exchange with ground water depends on the placement of temperature sensors.
- Placement of temperature sensors depend on:
  - Hydraulic and thermal properties of sediments
  - Climatic conditions– temperature at surface
  - Speed that water moves through sediments
  - Practical considerations such as scour
- Frequency of data collection
- Preliminary modeling can be useful in selecting the placement and frequency of temperature measurements
- **Transmission of heat is affected by water flow and thus the flow can be estimated by the departure of temperatures from a purely conductive pattern**

Courtesy of Rich Niswonger, USGS

8

Design of Temperature Measurements

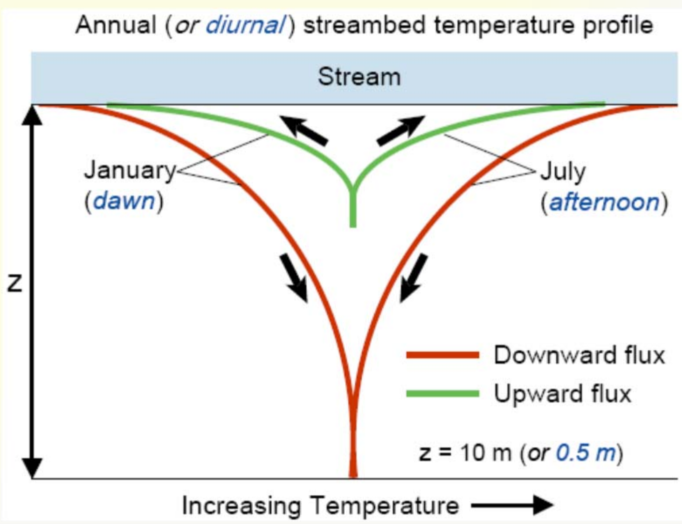
- Daily and annual temperature fluctuations at land surface generally follow a periodic pattern
- Magnitude of the periodic temperature change decreases with depth as the heat wave moves through sediments due to storage and release of energy
- Depth of attenuation in a wet sand, for example, was
  - 0.14 m for daily fluctuations
  - 2.7 m for annual fluctuations
- Sensors should be placed in the thermally active zone
- Sensors can be placed at uniform depth intervals or exponentially increasing depth intervals
- Placement of several sensor arrays allow for assessment of heterogeneity and lateral flow
- Placement of several types of sensors at same location reduce uncertainty and provide insurance against sensor failure

Courtesy of Rich Niswonger, USGS

9

Example showing annual or diurnal streambed temperature profile (Figure 3; Chapter 1)

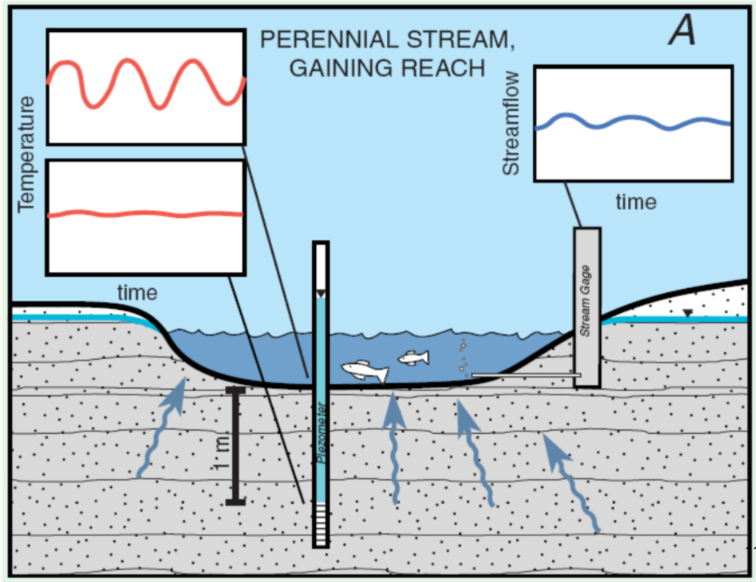
The thermally active zone is the depth above which temperature changes either daily or seasonally. The thermally active zone is much deeper if flow is downward than if flow is upward because conduction and advection are acting in the same direction for downward flow.



10

Example showing expected temperature response when stream is gaining (Figure 1; Chapter 1)

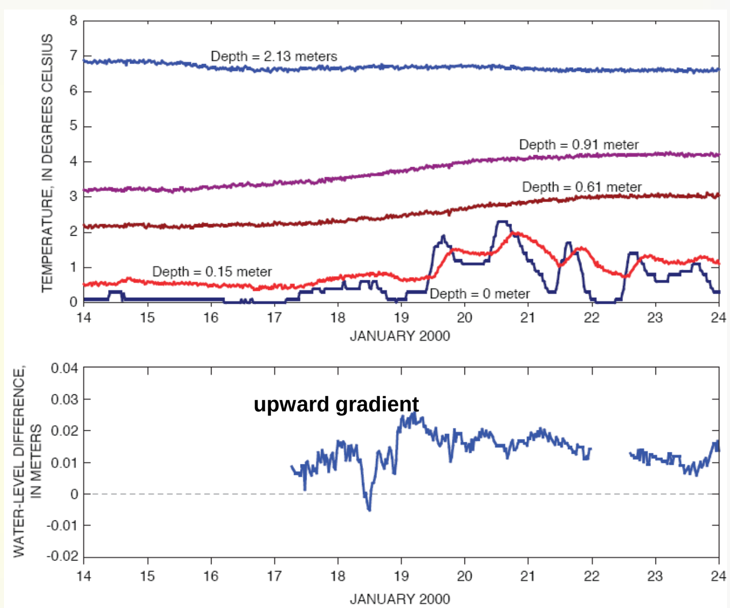
In the next few pages you will see several examples of the types of diurnal responses we see for several types of exchange between GW and SW. In this first response we have GW discharging to SW. There is a smalll diurnal change in streamflow. There is a small diurnal change in temperature of surface water. There is an almost imperceptible change in GW temperature. This is because upward flow associated with GW discharge to the stream is compressing the thermally active zone.



11

Diurnal temperature fluctuations when stream is gaining, Trout Creek, Lake Tahoe (Figure 8, Chapter 6)

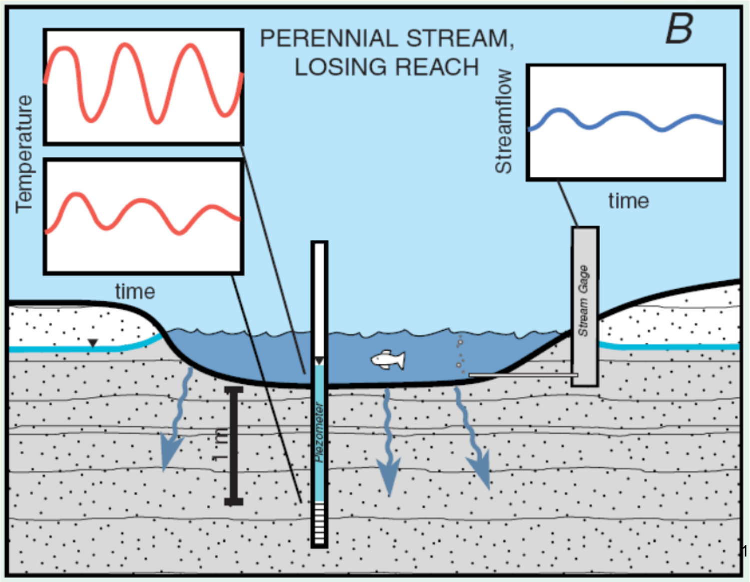
At this site only the thermistor at 15 cm beneath the bed was sensing a diurnal change in temperature. The thermally active zone was shallow indeed. A well in the streambed was showing that upward hydraulic gradient was pretty consistent.



12

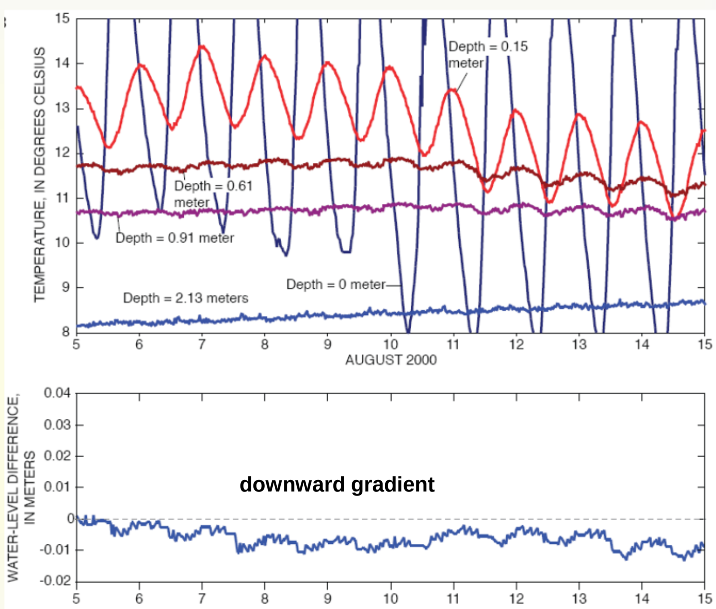
Example showing expected temperature response when stream is losing (Figure 1; Chapter 1)

With downward flow from SW to GW we have a stronger diurnal signal in the bed sediments. Downward flow of surface water is advecting diurnal changes in SW temperature deeper into the bed sediments than when GW is discharging to SW.



13

Diurnal temperature fluctuations when stream is losing water, Trout Creek, Lake Tahoe (Figure 8, Chapter 6)



Wow. Here the diurnal variability in SW is huge; the stream must be pretty shallow to have such a large surface-water diurnal response. Diurnal signals are detected at 15, 61, and even slightly at 91 cm beneath the bed. Note that the hydraulic gradient is always downward.

14

Estimating Flow Rates Across Streambed

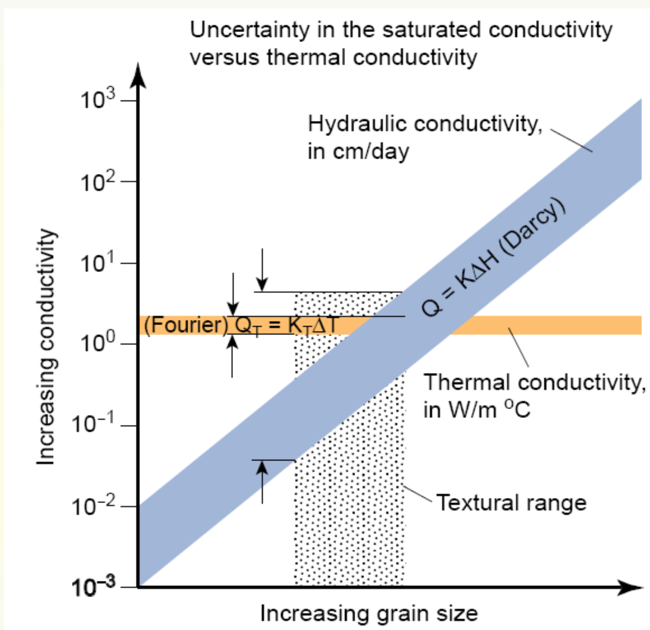
- Fluid flow is governed by Darcy's Law (product of hydraulic conductivity and hydraulic gradient)
- Conductive heat flow is governed by Fourier's Law (product of thermal conductivity and temperature gradient)
- Because we have two unknowns (hydraulic conductivity and thermal conductivity) we need to know hydraulic and thermal gradients
- Luckily thermal conductivity is less uncertain and is not dependent on texture.

This is the logic associated with this method. It's actually quite simple and can work very well if we have a good diurnal response in surface water.

15

Example showing uncertainty of hydraulic conductivity and thermal conductivity of sediments (Figure 2; Chapter 1)

K_T is virtually independent of sediment texture



16

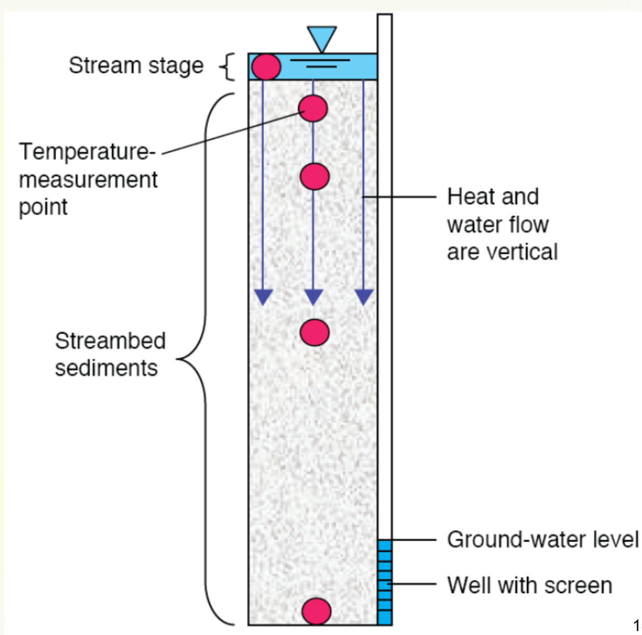
Modeling to Estimate Streambed Seepage and Hydraulic Conductivity

- Numerical models developed by Voss and Kipp (1987; SUTRA) and Healy and Ronan (1996; VS2DH) solve the equations governing flow of water and heat through sediments
- Models can be used for both gaining and losing streams
- Conceptual frameworks vary depending on the particular problem to be solved

The model you saw earlier where we modeled GW discharge either to the break in slope or to the thalweg is VS2DT (T indicates transport). That is the transport equivalent to VS2DH, which is modified to solve for advection-dispersion to simulate heat (H) flow. Both models are very user friendly.

17

One dimensional model used when water table is some distance below top of streambed (Figure 1; Appendix B)

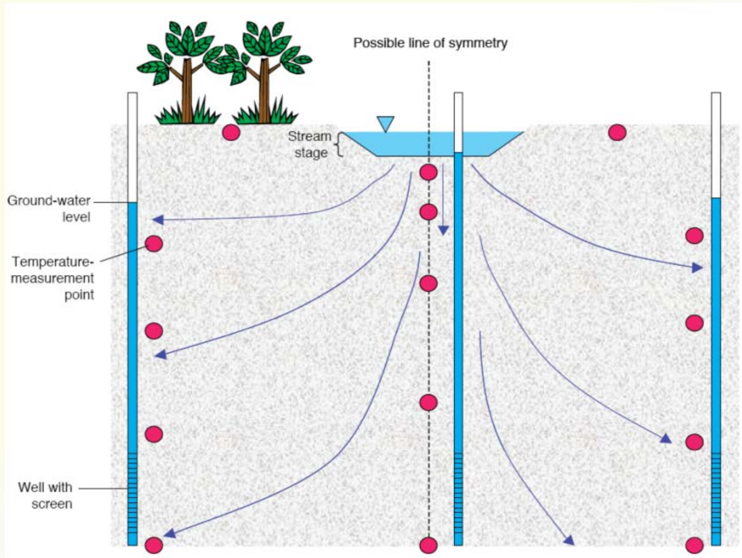


In a 1-d simulation we assume only vertical flow. We need temperature at the streambed and at least one depth below the bed, stream stage, and head at the well screen, to feed the model. Additional temperature sensors at other depths will give us a better idea of variation of *K* with depth beneath the streambed.

18

Two-dimensional model used when lateral flow away from stream is important (Figure 2; Appendix B)

If we have data at several locations we can set up a 2-d simulation. This is just about as easy to set up as a 1-d model.



19

Two-dimensional model used when lateral flow along stream is important (Figure 3; Appendix B)

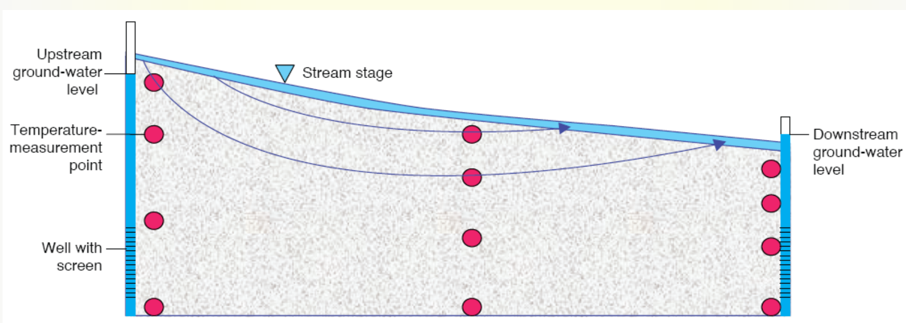


Figure 3. Conceptual framework when seepage through the streambed parallels stream profile.

We can also set up a model to look at GW-SW exchange along a river reach instead of along a cross section across a river.

20

Parameters used for VS2DH (Table 1; Appendix B)

Table 1. Parameters used in VS2DH to model heat as a tracer through fluvial sediments

Parameter	Sensitivity	Range in values
Parameters for saturated flow through fluvial sediments		
Saturated hydraulic conductivity[1] (m/s)	High	10^{-7} to 10^{0}
Horizontal and vertical hydraulic conductivity ratio[1]	High	3 to 100
Porosity[1] (m^3/m^3)	Moderate	0.25 to 0.5
Dispersivity[2] (m)	Moderate	0.01 to 1
Heat capacity of dry sediments[3] (J/m^3 °C)	Moderate	1.1×10^6 to 1.3×10^6
Thermal conductivity of saturated sediments (W/m °C)[3]	Moderate	1.4 to 2.2
Heat capacity of water at 20 °C [4] (J/m^3 °C)	Low	4.2×10^6
Additional parameters for variably saturated flow through fluvial sediments		
Unsaturated hydraulic conductivity parameters in van Genuchten retention model[5]		
α (per meter)	Moderate	1 to 500
n (dimensionless exponent)	Moderate	1.1 to 2.8
Thermal conductivity at residual water content[3] (W/m °C)	Moderate	0.18 to 0.26
Residual water content[5] (m^3/m^3)	Low	0.00 to 0.10

Rarely larger than 0.1

The model is most sensitive to *K* and anisotropy, and not as sensitive to thermal conductivity. That's a good thing because we make an educated guess of the value for thermal conductivity.

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Thermal Properties of Individual Phases (Table 1; Appendix A)

Table 1A. Thermal properties of selected materials -- Individual phases

Individual phase	Density (10^6 g/m^3)	Volumetric heat capacity (10^6 J/m^3 °C)	Thermal conductivity (W/m °C)	Thermal diffusivity (10^{-6} m^2/s)
Air[1]	0.001	0.001	0.024	19.
Liquid water[1]	1.0	4.2	0.60	0.14
Ice[2]	0.9	1.9	2.2	1.2
Quartz[3]	2.7	1.9	8.4	4.3
Average, soil minerals[3]	2.7	1.9	2.9	1.5
Average, clay minerals[4]	2.7	2.0	2.9	1.5
Average, soil organic matter[3]	1.3	2.5	0.25	0.10

If you don't know the actual values for your modeled setting you can use the values listed above as good approximate values.

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Thermal Properties of Porous Media (Table 1; Appendix A)

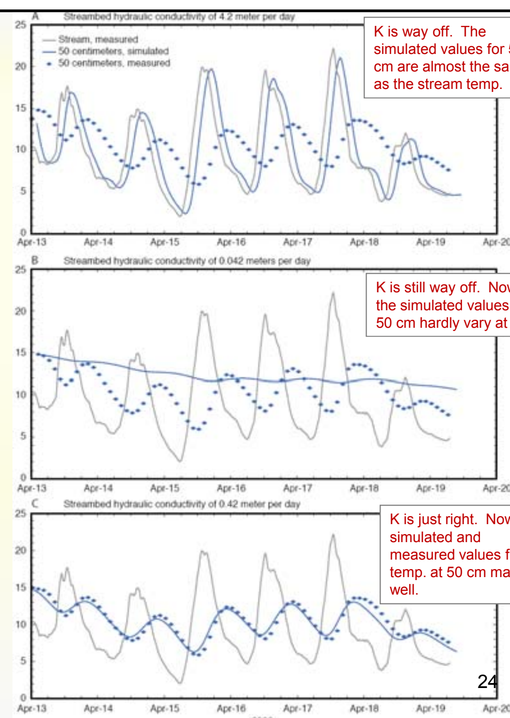
Table 1B. Thermal properties of selected materials -- Porous media

Porous medium	Bulk Density (10^6 g/m^3)	Porosity (V_{pores}/V_{bulk})	(Liquid) Water content	Volumetric heat capacity (10^6 J/m^3 °C)	Thermal conductivity (W/m °C)	Thermal diffusivity (10^{-6} m^2/s)
Tottori sand[5]	1.83	0.31	saturated	2.6	2.2	0.85
Clarion sandy loam[6]	1.38	0.48	saturated	3.2	1.8	0.55
Harps clay loam[6]	1.21	0.54	saturated	3.2	1.4	0.42
Sandfly Creek sand[7]	1.50	0.43	dry	1.3	0.25	0.18
Yolo silt loam[8]	1.30	0.51	dry	1.1	0.26	0.23
Clarinda clay[7]	1.16	0.56	dry	1.2	0.18	0.15
Snow[9]	0.46	0.50	dry	1.0	0.71	0.68
Snow[9]	0.18	0.80	dry	0.4	0.13	0.36
Snow[9]	0.05	0.95	dry	0.1	0.06	0.60

Another handy table for approximate values for model input.

Sensitivity of Hydraulic Conductivity to Measured Temperature Profile Assuming Vertical Flow Beneath Trout Creek, Nev. (Figure 6; Appendix B)

Once we get reasonable parameters for the model, we adjust *K* until the simulated temperature values match the measured temperature values. The examples shown here give you an idea of how sensitive the model is to *K*.



K is way off. The simulated values for 50 cm are almost the same as the stream temp.

K is still way off. Now the simulated values for 50 cm hardly vary at all.

K is just right. Now the simulated and measured values for temp. at 50 cm match well.

Hatch et al., 2006, *WRR*, Quantifying surface water–groundwater interactions using time series analysis of streambed thermal records: Method development

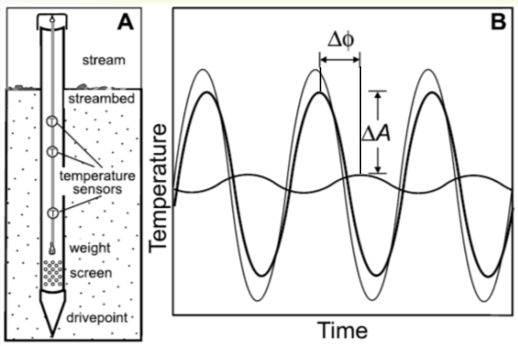


Figure 1. Diagrams illustrating acquisition of streambed temperature records and basis for new analytical method. (a) Streambed piezometer with temperature sensors at various depths. (b) Temperature versus time records showing reduction in amplitude (ΔA) and shift in phase ($\Delta\phi$) with greater depth.

$$A_r = \exp\left\{\frac{\Delta z}{2\kappa_e}\left(v - \sqrt{\frac{\alpha + v^2}{2}}\right)\right\}$$

A_r = amplitude ratio

Δz = spacing between measurement points

κ_e = effective thermal diffusivity

α is related to κe, v, and frequency of temperature variations

v = rate of penetration of the thermal front

Equations (4b) and (5b) are rearranged to solve for the velocity of a thermal front as a function of amplitude and phase relations (v_{Ar} and $v_{\Delta\phi}$ respectively):

$$v_{Ar} = \frac{2\kappa_e}{\Delta z}\ln A_r + \sqrt{\frac{\alpha + v^2}{2}} \tag{6a}$$

$$v_{\Delta\phi} = \sqrt{\alpha - 2\left(\frac{\Delta\phi 4\pi\kappa_e}{P\Delta z}\right)^2} \tag{6b}$$

There are other ways to do this too. Here we can make use of either amplitude ratio or phase shift of the diurnal signals to determine *q*. **In general, amplitude ratio provides better results than phase shift (Briggs et al., 2014).**

Masaki can add information regarding making the necessary Fourier transform of the data if you are interested.

25

Home Research Teaching People Facilities Publications Vita VFLUX

VFLUX (Now VFLUX2) Irvine et al, 2015, *JHydrol*.

Vertical Fluid Heat Transfer Solver (VFlu[H]X Solver)

Please cite as:

Gordon, RP, LK Lautz, MA Briggs, JM McKenzie. 2012. Automated calculation of vertical pore-water flux from field temperature time series using the VFLUX method and computer program. Journal of Hydrology, 420-421:142-158. Internet: http://hydrology.syr.edu/Lautz_Group/VFLUX.html.

VFLUX is a program that calculates one-dimensional vertical fluid flow (seepage flux) through saturated porous media, using heat transport equations. It uses temperature time series data measured by multiple temperature sensors in a vertical profile in order to calculate flux at specific times and depths. VFLUX is written as a MATLAB toolbox, a set of functions that run in the MATLAB environment. More information can be found in the VFLUX Documentation, and in the following publication:

Gordon, RP, LK Lautz, MA Briggs, JM McKenzie. 2012. Automated calculation of vertical pore-water flux from field temperature time series using the VFLUX method and computer program. Journal of Hydrology, 420-421:142-158. [abstract]

VFLUX ~~1.2.4~~ may be downloaded using the following link. The zip file contains the MATLAB code, documentation describing the functionality of VFLUX and a sample data set.

Download: vflux1.2.3.zip

The current (2015) version is 2.0.0 and is available at http://hydrology.syr.edu/vflux.html

A new MATLAB code has been developed to greatly simplify use of this analysis procedure.

VFLUX can now deal with non-vertical flow. It calculates the vertical component of flux.

Version 2.0.0 can solve for the combined amplitude ratio and phase lag methods

The word on the street is that model developers are considering writing another version using Python for people who do not have access to Matlab.

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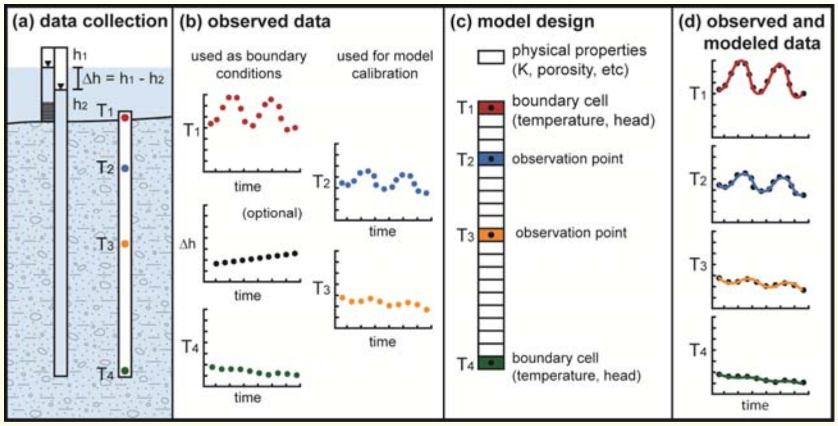
The 1DTempPro graphical user interface



If we think we have vertical flow, this numerical model works well and is very easy to use. We will be using this in an exercise later.

Voytek et al., 2014, *Ground Water*

Koch et al., 2015, *Ground Water* – IDTempPro V2

http://water.usgs.gov/ogw/bgas/1dtemppro/

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Comparison of Software

- 1DTempPro
  - Numerical model (Runs USGS model VS2DH)
  - Requires 3+ thermal time series
  - Can simulate non-ideal time series- no need to filter
  - Control over fitting process
  - Single flux across model
  - Determine K with head data
  - Fewer model assumptions
  - New version includes automatic parameter estimation

- VFLUX
  - Multiple analytical models
  - Estimated flux between 2 thermal time series (window)
  - Filter non-ideal time series to extract diurnal signals
  - Automated fitting
  - Variable flux over depth and time
  - Built in error and sensitivity analysis

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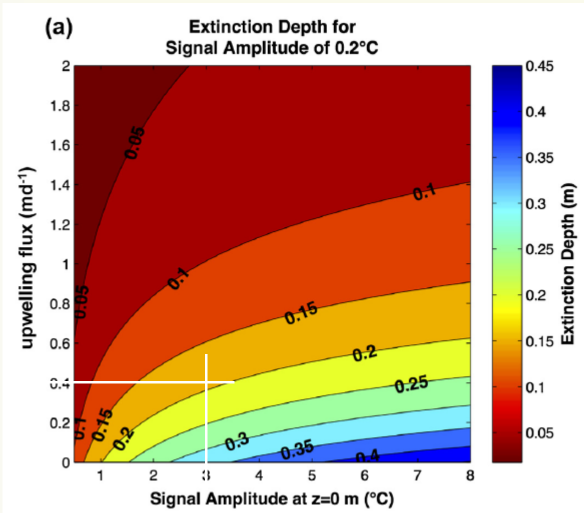
This method may not work well for higher-velocity upward flows



The extinction depth is the depth where diurnal signal is smaller than the resolution of the temperature sensor. When that happens the amplitude ratio cannot be used to determine vertical flow.

For example, for an upward seepage rate of 40 cm/day, if the diurnal temperature variation at the sediment-water interface is 3 degrees C, the extinction depth is about 20 cm.

This means that all the diurnal temperature variability occurs in the top 20 cm. Placing thermistors below 20 cm depth will not be useful.

This plot will vary with sediment properties, such as thermal conductivity, porosity, sediment heat capacity, etc.

Briggs et al., 2014, J. Hydrology

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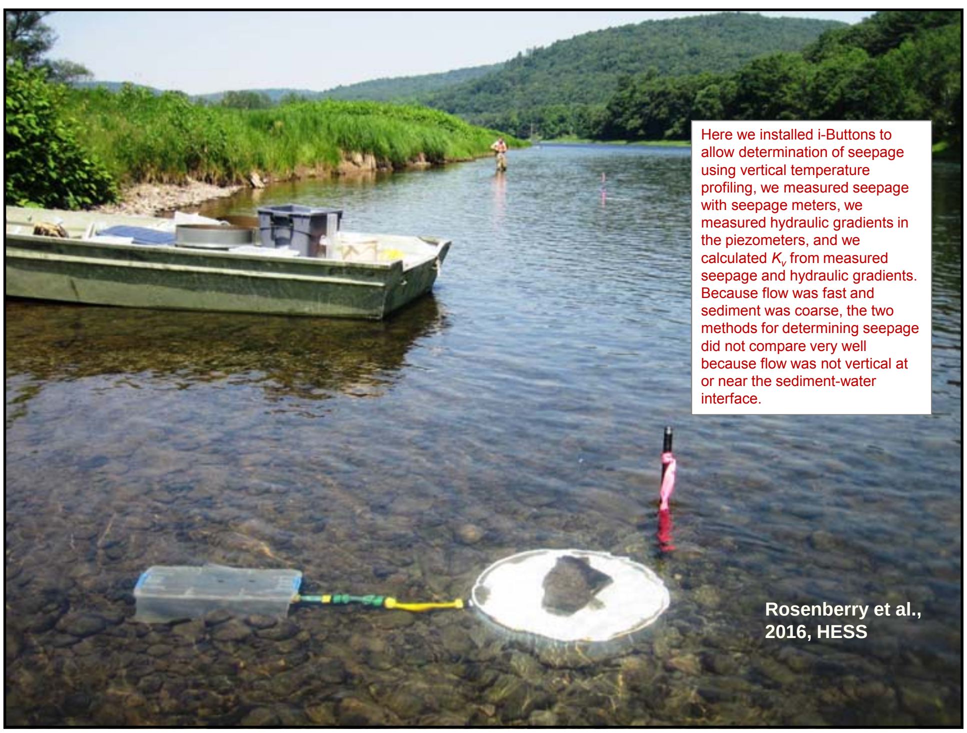
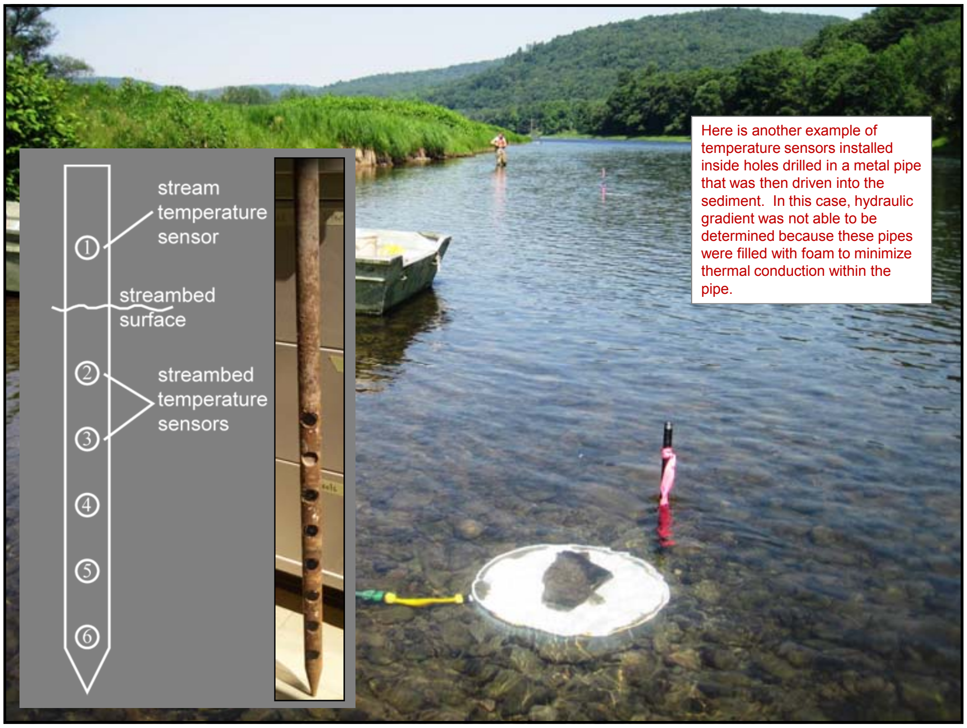
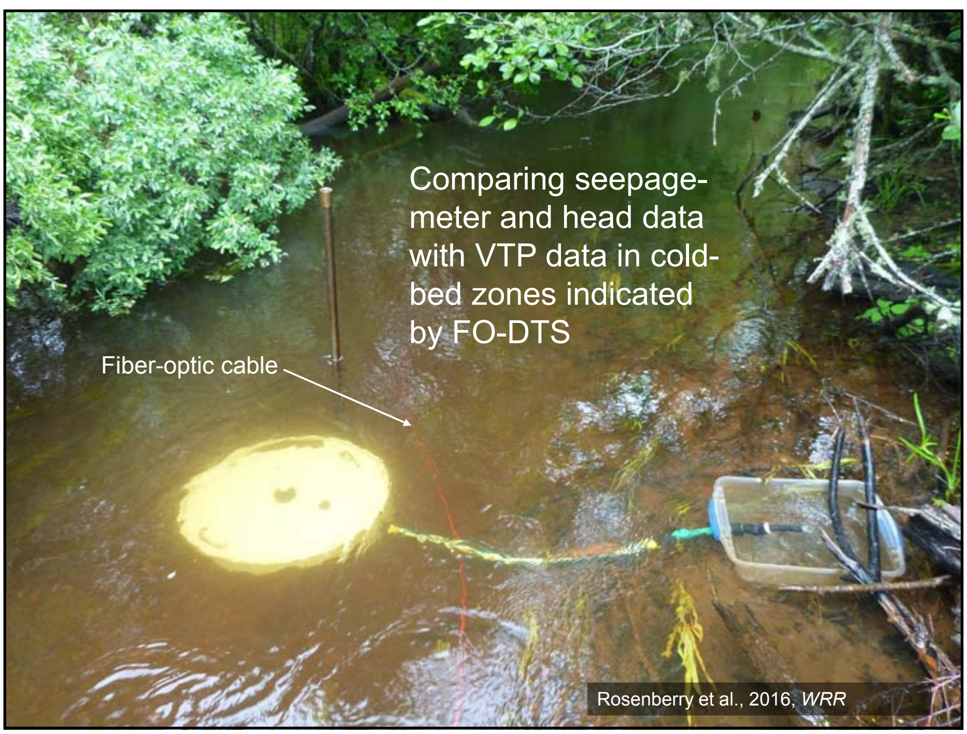


Here we installed i-Buttons to allow determination of seepage using vertical temperature profiling, we measured seepage with seepage meters, we measured hydraulic gradients in the piezometers, and we calculated K_v from measured seepage and hydraulic gradients. Because flow was fast and sediment was coarse, the two methods for determining seepage did not compare very well because flow was not vertical at or near the sediment-water interface.

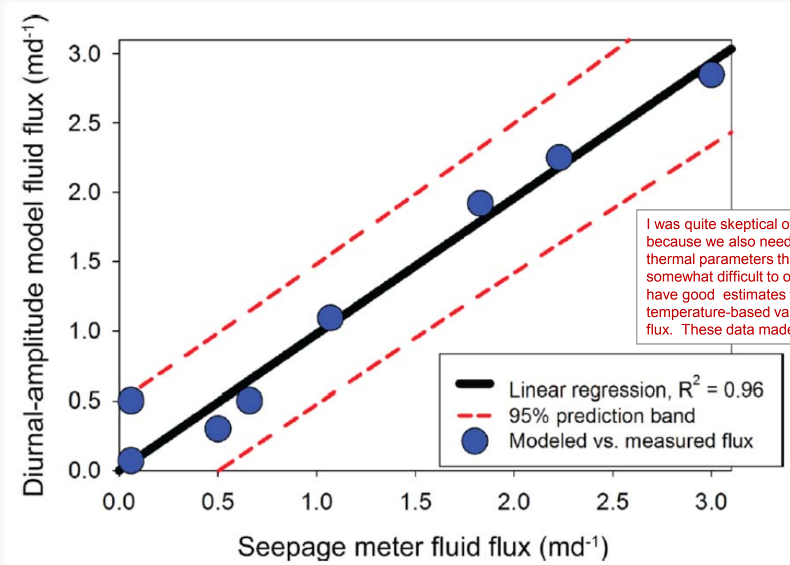
Rosenberry et al., 2016, HESS



stream
temperature
sensor
streambed
surface
streambed
temperature
sensors
1
2
3
4
5
6
Here is another example of temperature sensors installed inside holes drilled in a metal pipe that was then driven into the sediment. In this case, hydraulic gradient was not able to be determined because these pipes were filled with foam to minimize thermal conduction within the pipe.



Comparing seepage-meter and head data with VTP data in cold-bed zones indicated by FO-DTS
Fiber-optic cable
Rosenberry et al., 2016, *WRR*



I was quite skeptical of this method because we also need to know several thermal parameters that are often somewhat difficult to obtain. But if we have good estimates we can get good temperature-based values for seepage flux. These data made me a believer.

Rosenberry et al., 2016, *WRR*

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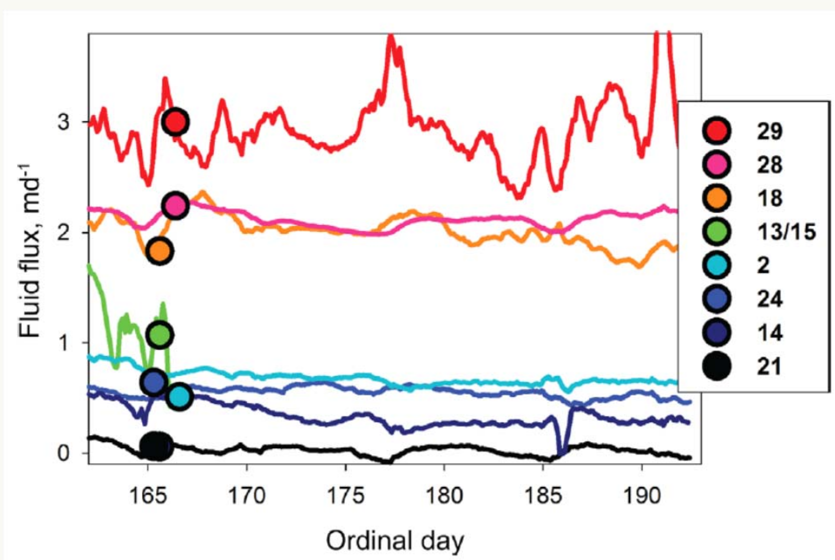

Rosenberry et al., 2016, *WRR*

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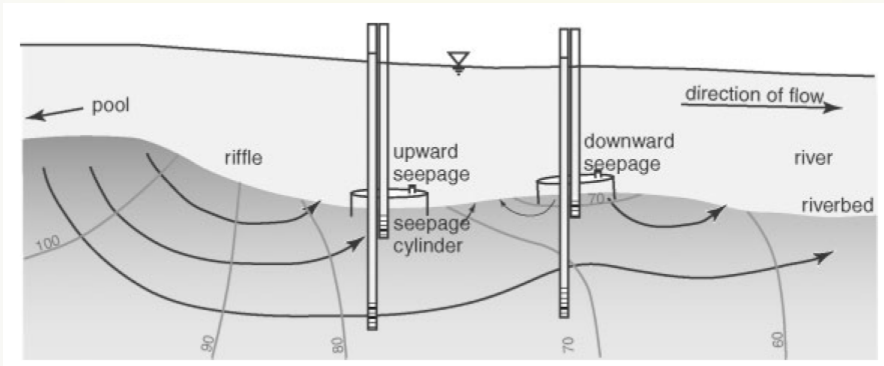
Flow is often not vertical in hyporheic settings in particular



Rosenberry & Pitlick, 2009, *HP*

Use of a 1-D model assumes exchange is vertical. But exchange in hyporheic settings commonly is not vertical. What is the problem associated with violating the assumption of vertical flow?

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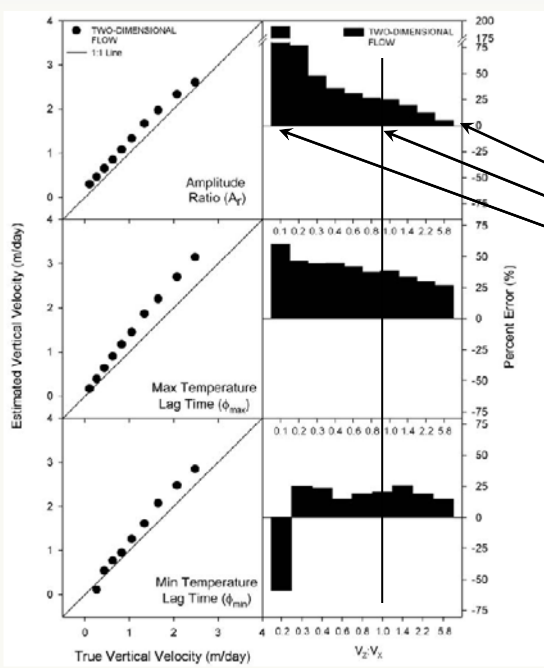


Errors become large as V_z/V_x decreases

Close to vertical
45 degrees
Almost horizontal

Amplitude ratio (top plot) generally gives smaller errors.

Errors can be pretty large when flow is not vertical. These simulations give us an idea of just how large. For flow at 45 degrees or less from vertical, the amplitude ratio method generates errors less than about 25 percent.

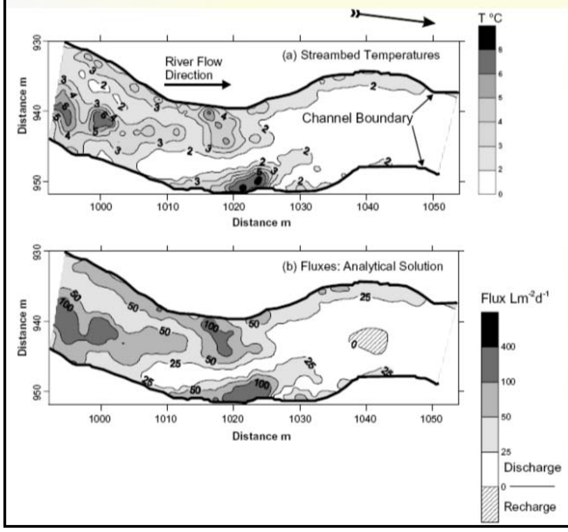
Lautz, 2010, *WRR*

36

Schmidt et al., 2007, *JHydrol.*, Evaluation and field-scale application of an analytical method to quantify groundwater discharge using mapped streambed temperatures

Used the Turcotte and Schubert (1982) analytical solution to the one-dimensional steady-state heat-diffusion–advection equation

$$q_z = -\frac{K_{fs}}{\rho_f c_f z} \ln \frac{T(z) - T_L}{T_0 - T_L}$$



q_z = Seepage velocity

$T(z)$ = streambed temperature at depth z

T_L = fixed temperature at bottom of aquifer

T_0 = temperature at depth 0

κ_{fs} = thermal conductivity

$\rho_f c_f$ = volumetric heat capacity of the fluid

z = depth beneath the sediment-water interface

Here's another clever way to calculate seepage across the bed of a stream. If we assume temperature at some depth beneath the streambed is all the same at that depth, all we need to do is map the temperature at the bed surface and then using the above equation we can map *q*.

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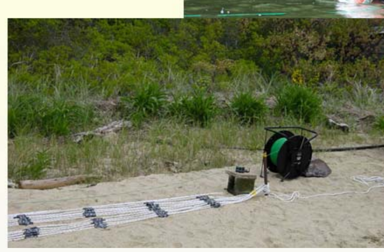
Fiber Optic – Distributed temperature system (FO-DTS)

And here's an exciting new way we can map temperature on the bed. We can place this cable on the bed and it will give us the temperature of the bed every meter or so along the cable. And we can also get this temperature every few minutes. And we can get this temperature very accurately.

- High spatial resolution (~0.5 to 1 m)
- High precision (0.01 deg C)
- Large scale (10's of km possible)
- Continuous measurement (in time and space)
- Continuous data download (no retrieval/disturbance)
- Long-term installation possible



Day-Lewis, 2006, *TLE*
Selker et al., 2006, *WRR*

USGS

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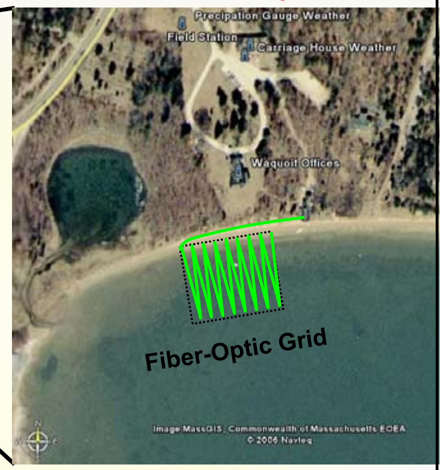
Waquoit Bay, Cape Cod, MA

FO-DTS Study Area



- DTS Cable zig-zags over a 80-m by 60-m area
- As configured:
  - Spatial resolution along cable = ~1 m
  - Temporal resolution = ~1 min
  - Thermal resolution = 0.1 deg C

This method was used to determine where GW was discharging to a portion of Waquoit Bay in Massachusetts in the northeastern USA.

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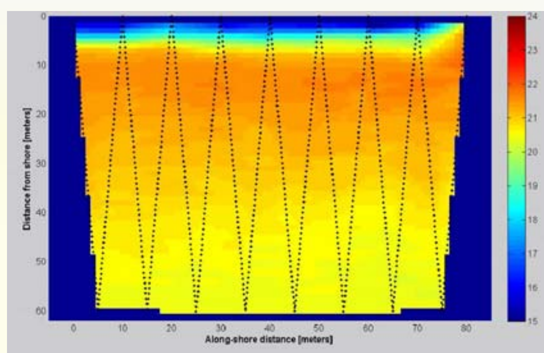
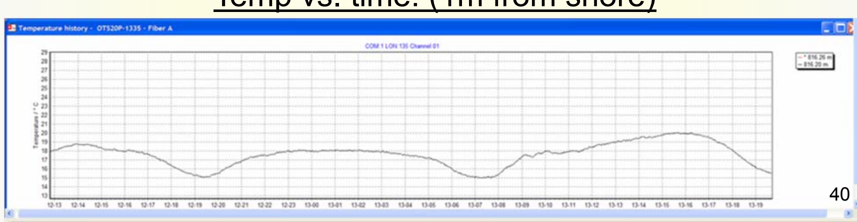
Great spatial resolution

GW discharge occurs primarily within 5 m of shore

Here blue indicates cold water. These data indicate GW discharge was greatest within 5 m of the shoreline. The bottom graph shows that temperature changes with the tide, indicating that GW discharge also is changing in response to tides.



Temp vs. time: (1m from shore)



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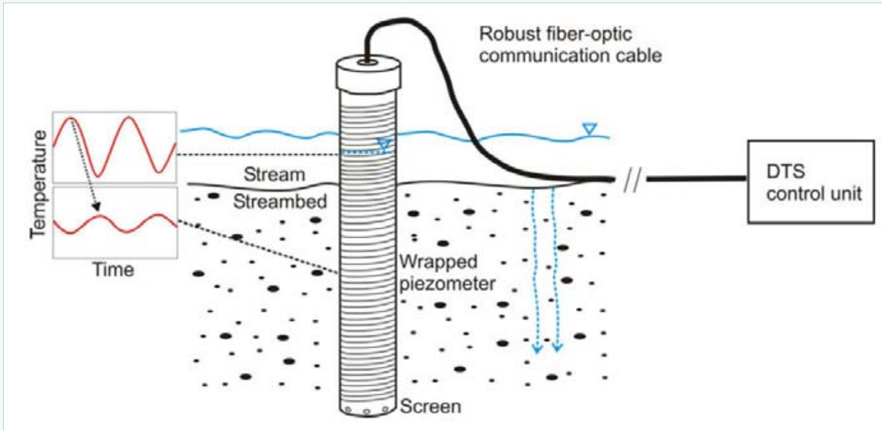
Clever use of DTS



Remember when we talked about measuring temperature at multiple depths below the bed? That allows us to get a better idea of K at various depths beneath the bed. With this method we can get temperature at every cm beneath the bed. Imagine the unprecedented level of detail with which we can determine K when we make use of these data! This is a really exciting new use of technology.

Vogt et al., 2010, JHydrol.

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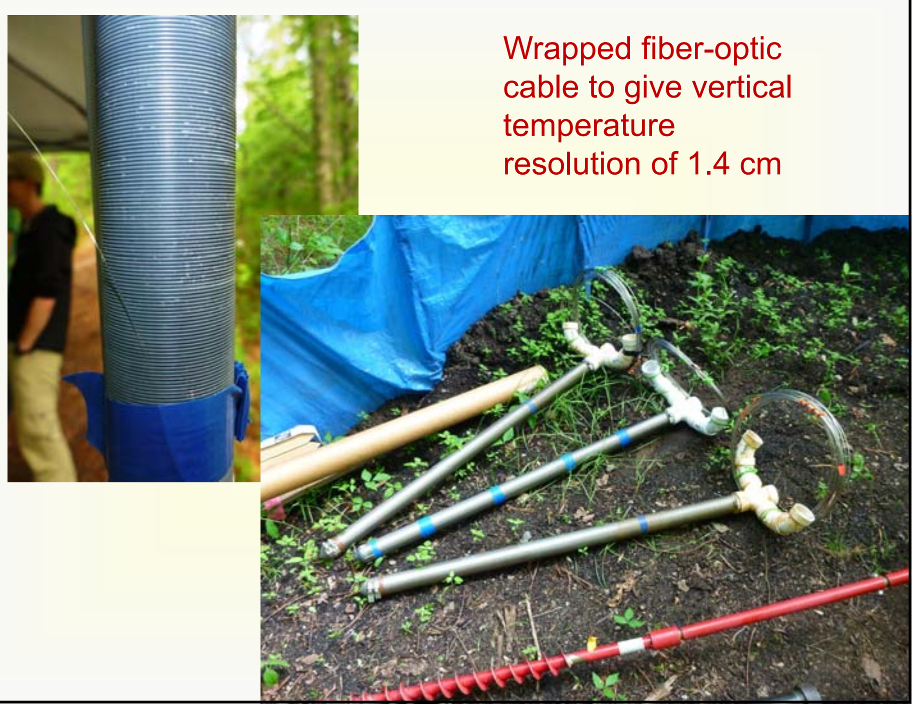
Wrapped fiber-optic cable to give vertical temperature resolution of 1.4 cm



HRTS Installation

Briggs et al., 2013, ES&T

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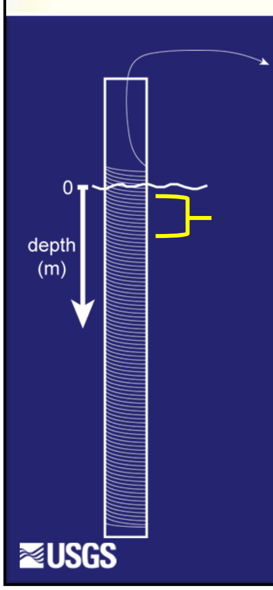
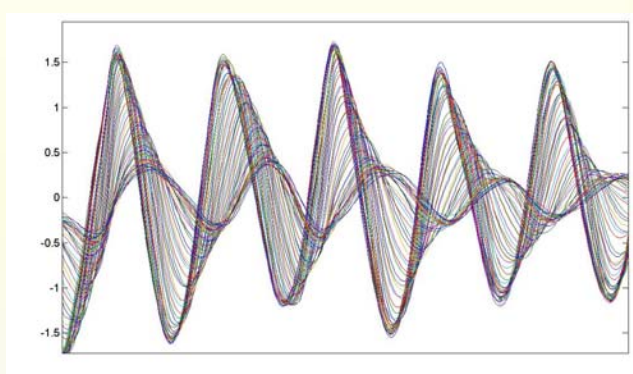
Applications: High Spatial Resolution





The Briggs et al. design gets a temperature value every 2.4cm vertical depth increment.

Briggs et al., 2012, WRR

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Summary

- Temperature profiles beneath streams is a relatively inexpensive method that can be used to estimate the seepage rate across the streambed and the hydraulic conductivity of the streambed
- Although streambed temperatures can be used to estimate duration of flow in intermittent and ephemeral channels, the interpretation of the data may require extensive analyses.

We will try this ourselves using 1DTempPro

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