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Heat as a tool for studying the movement of ground water near streams

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Circular 1260

This is a bit dated for this rapidly evolving method, but the basic concepts have not changed. We'll start here and then move into some of the many new tools and approaches.

U.S. Department of the Interior
U.S. Geological Survey

Stonestrom & Constantz, 2003

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

2023,

University of Granada

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

# Water Exchange between Streams and Ground Water (Chapter 1)

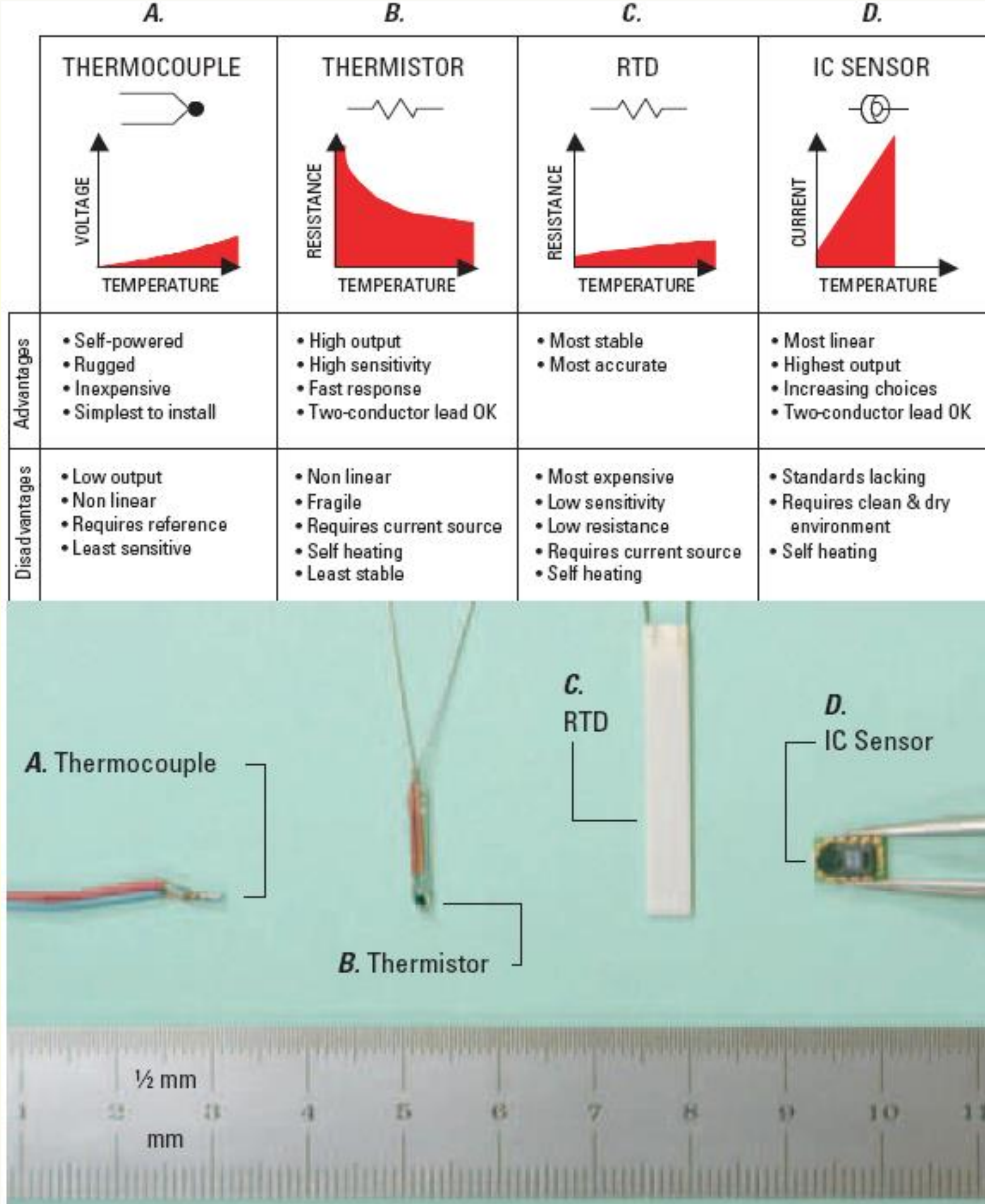
Really? We think we can just measure temperature and get seepage rates? You should be pretty skeptical. It turns out this can work pretty well in some settings if we have a good understanding of several thermal parameters and if flow is primarily vertical.

- The rate at which water moves between streams and ground water is governed by the head gradient across the streambed ($i_V$) and the resistance to flow within the sediments of the streambed ($K_V$).
- Heat is well suited for estimating localized exchanges between ground water and surface water **if** temperature changes near streams are large and rapid.
- These diurnal or seasonal changes need to provide a clear thermal signal that is easily measured.
- Researchers in the early 1900's recognized that heat is transferred along with 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.

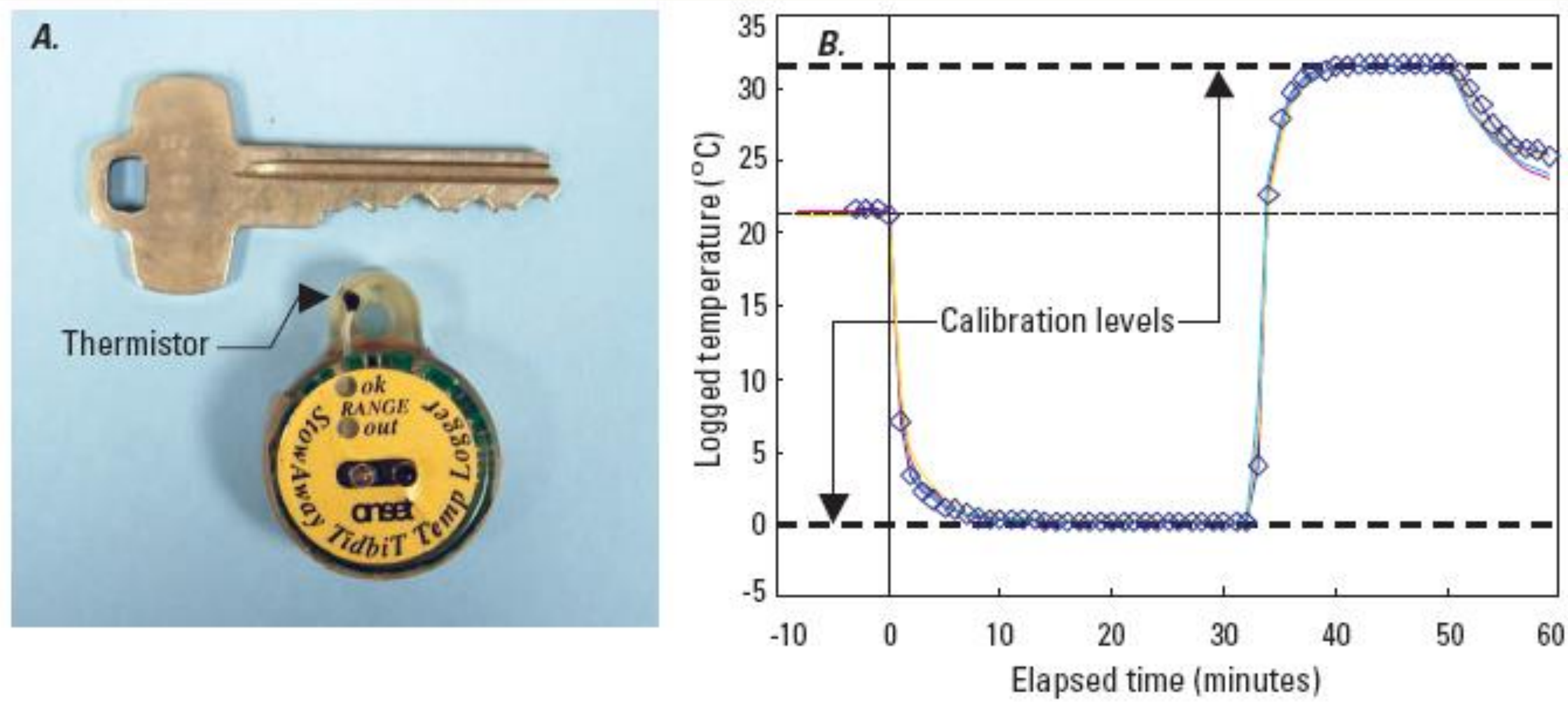
It is this last item that makes measurement of temperature so enticing for groundwater scientists. Temperature is a measurement that we can make very inexpensively and we don't have to give up much accuracy to do so.

# 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.

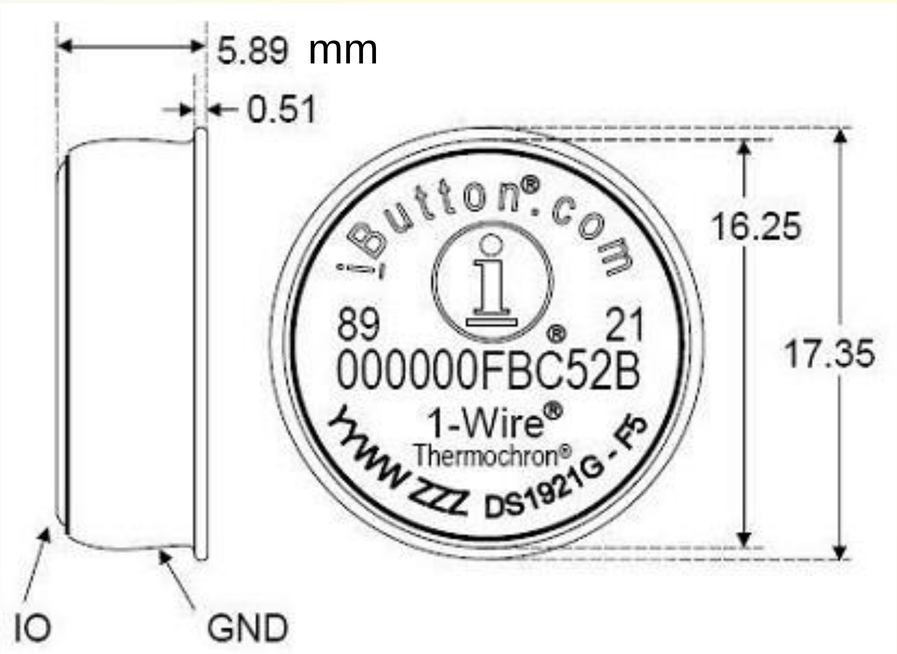



A. Self-contained temperature loggers are about 3 cm in diameter
B. Dynamic response of four self-contained temperature loggers (Figure 2; Appendix A)

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.

# Even smaller

## ~0.1° resolution

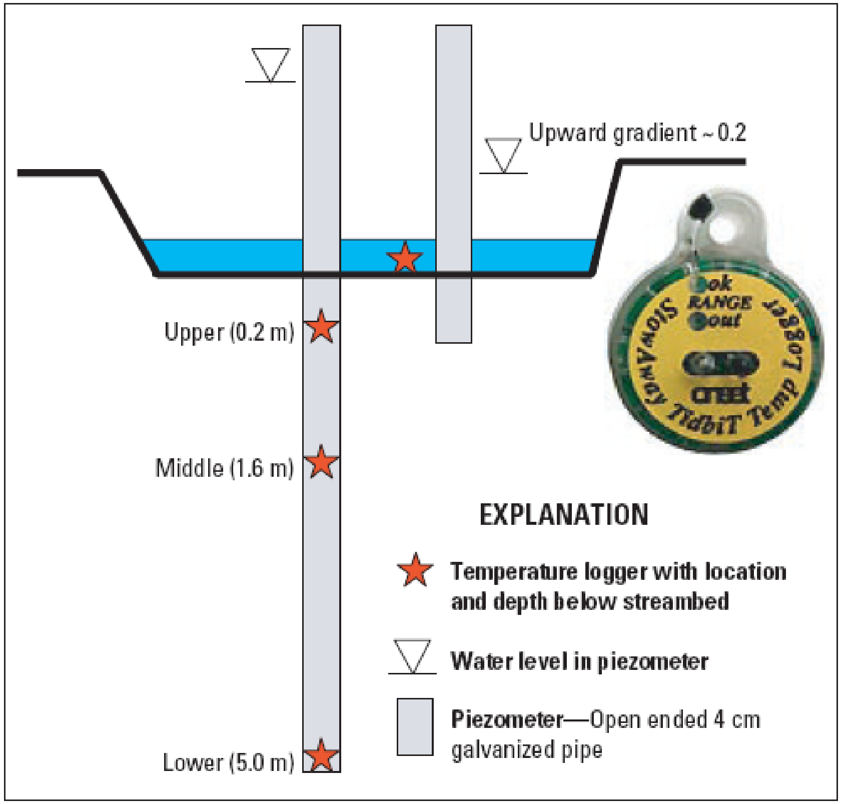



These devices are about 40 to 100 USD each, but they are not waterproof and they are not as reliable. Still, at such a low cost, some studies can afford to deploy two at each location. And they are wonderfully small so they can be lowered into small-diameter monitoring wells.
Newer ones have both better temperature resolution and much larger memory capacity (DS1925L-F5 (**currently $107 USD**). We can also buy waterproof enclosures.

Now only 76 €!


Here we are lowering iButtons into a well. iButtons were dipped in “Plastidip” (silicone also works well) to waterproof them and tied to a fishing line at measured intervals. It is very important to know precisely how far below the sediment-water interface they are located. But look at the streambed. How accurately can we determine just where the sediment-water interface is?

# Installing self contained dataloggers beneath streams




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.

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

Method used in Oregon (Figure 3; Appendix 5)

# Design 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**
- Success in quantifying stream exchange with ground water requires placement of temperature sensors in the "thermally active zone"
- Existence and thickness of the thermally active zone depends on:
  - Hydraulic and thermal properties of sediments
  - Variations of temperature at surface
  - Speed at which water moves through sediments
  - Practical considerations such as scour (a concern in fluvial settings)
- Frequency of data collection needs to provide sufficient data for a good model fit (commonly 15-minute to 30-minute frequency)
- Preliminary modeling can be useful in selecting the placement and frequency of temperature measurements

Courtesy of Rich Niswonger, USGS

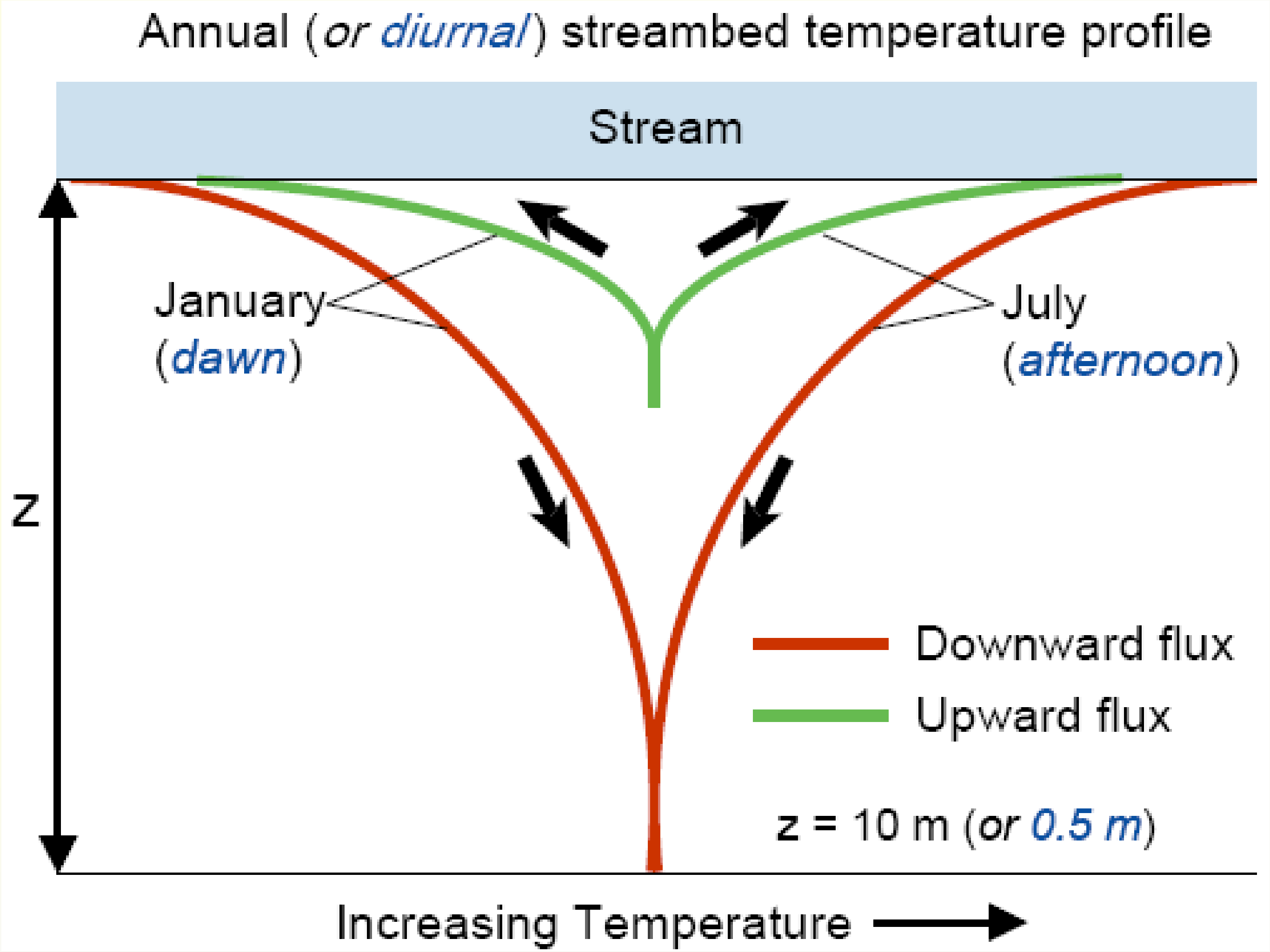
# Design of Temperature Measurements – continued

- The magnitude of daily and annual temperature changes at the surface decreases with depth as the heat wave moves through sediments due to storage and release of energy
- Depth of attenuation (thermally active zone) 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 allows for assessment of heterogeneity and lateral flow
- Placement of replicate or several types of sensors at the same location reduces uncertainty and provides insurance against sensor failure

Courtesy of Rich Niswonger, USGS

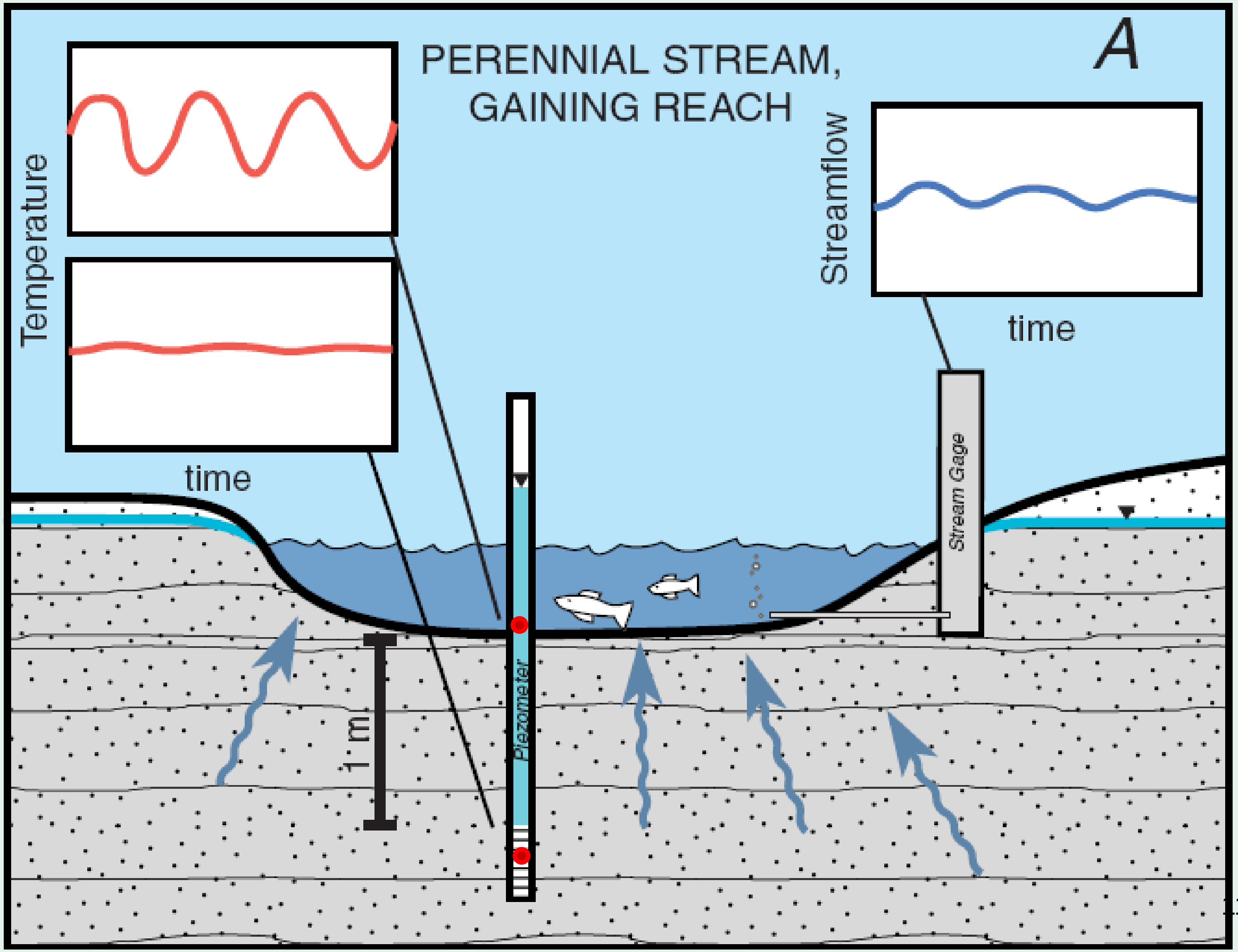
# Example showing annual or diurnal streambed temperature profile (USGS Circular 1260, Figure 3; Chapter 1)

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 and in opposite directions for upward flow.



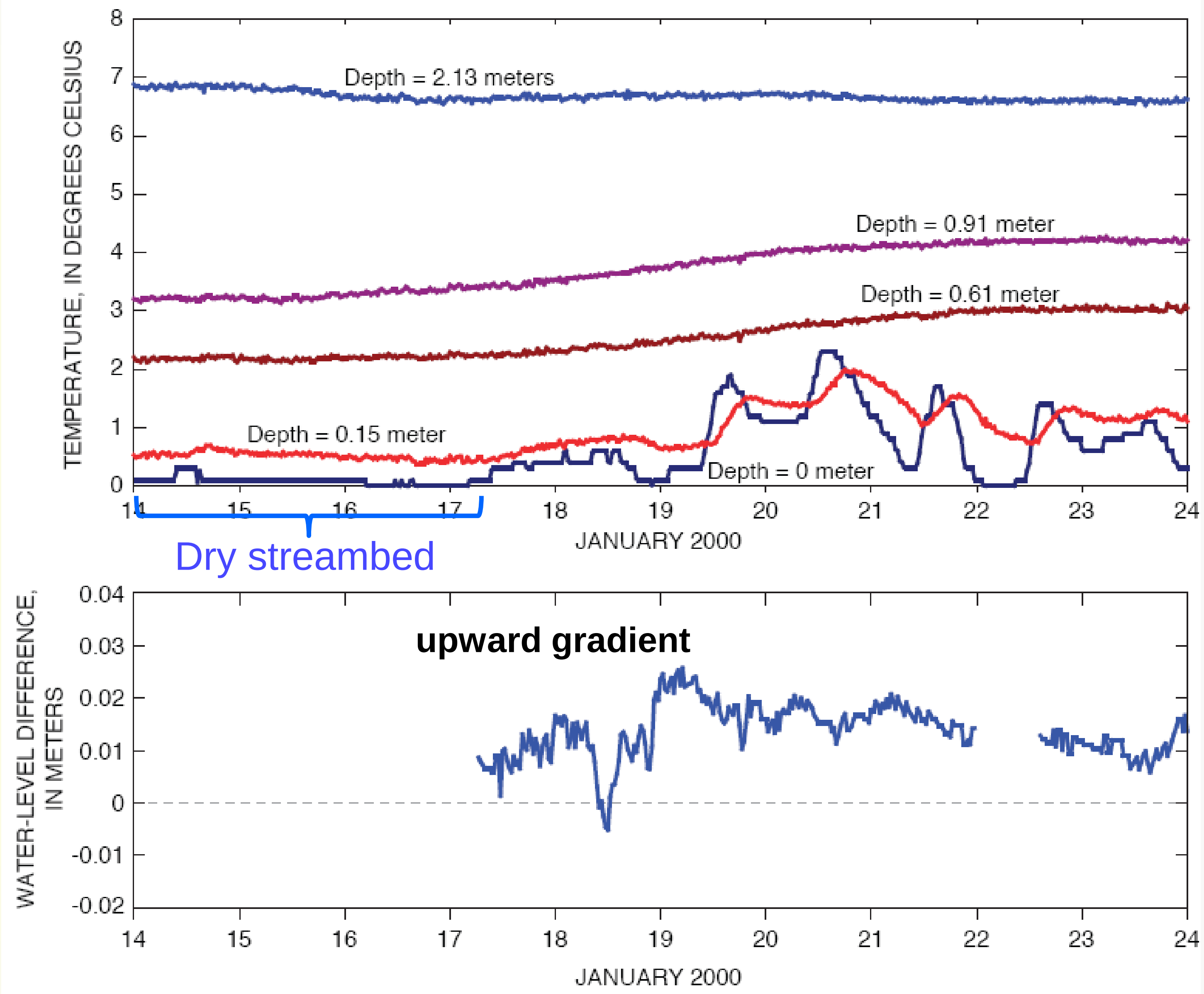
## Example showing expected temperature response when stream is gaining (Figure 1; Chapter 1)

In the next few slides 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 small 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.



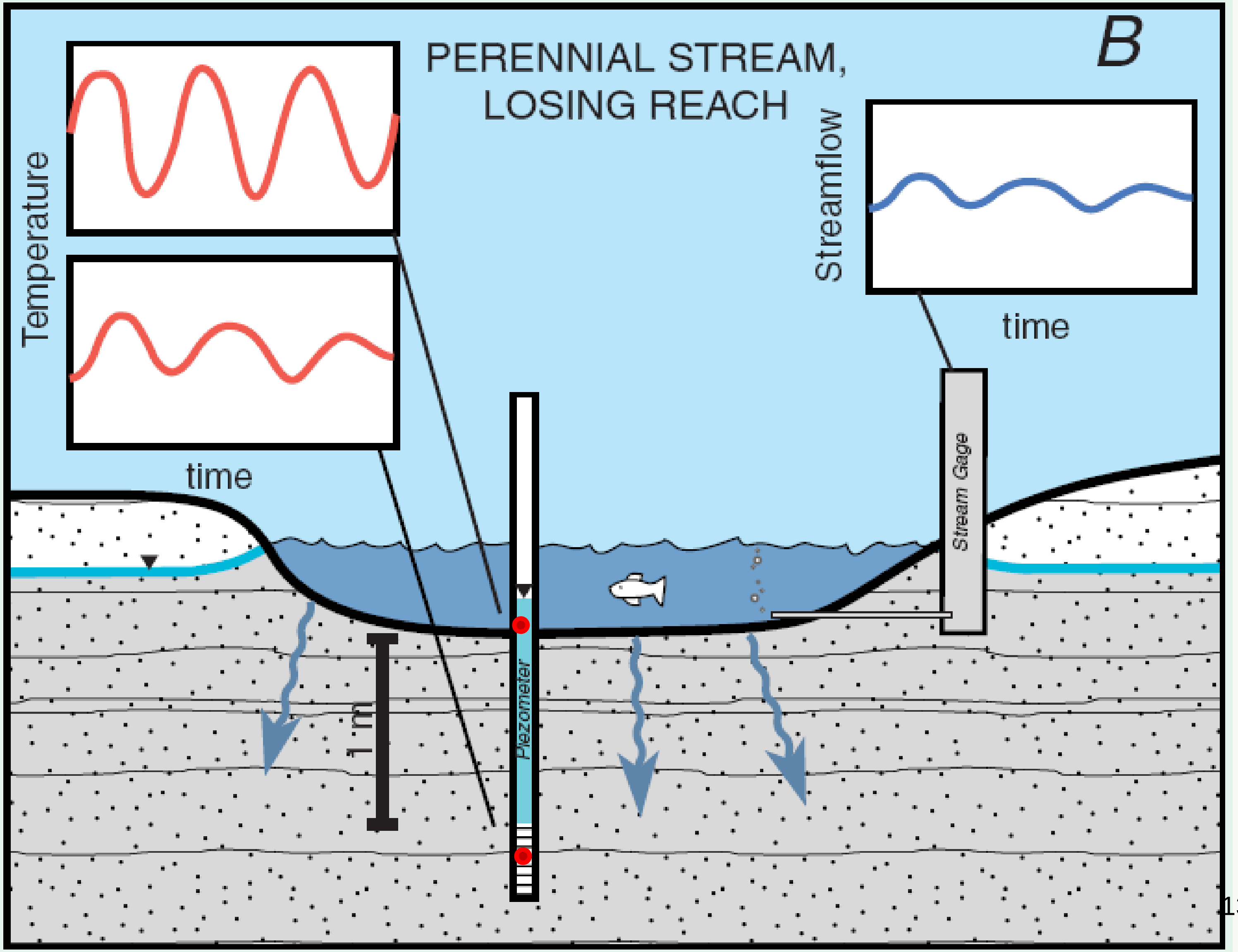
# Diurnal temperature fluctuations when stream is gaining, Trout Creek, Lake Tahoe (Figure 8, Chapter 6)

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 somewhat consistent.

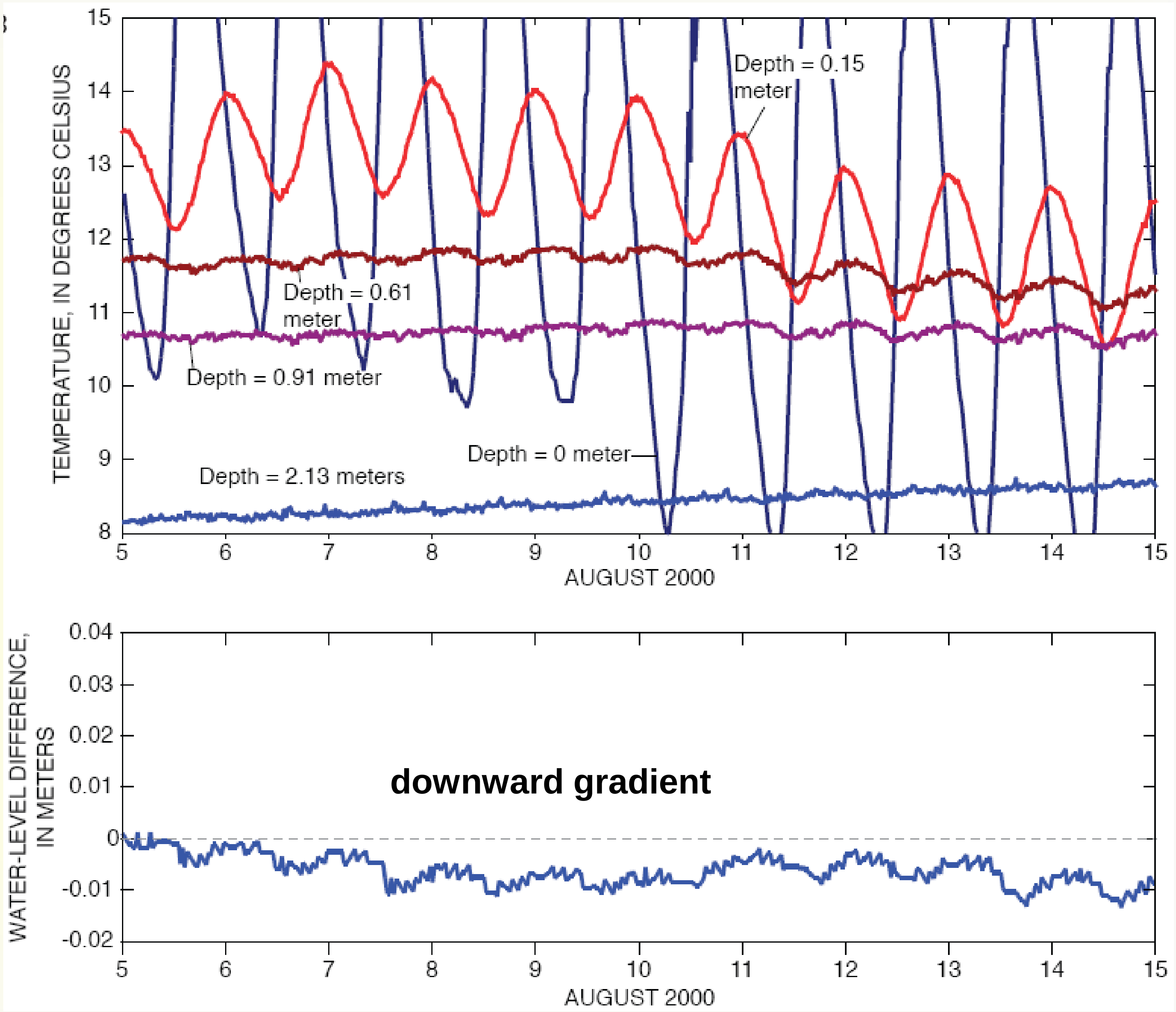


Example showing expected temperature response when stream is losing (Figure 1; Chapter 1)

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.



# 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.

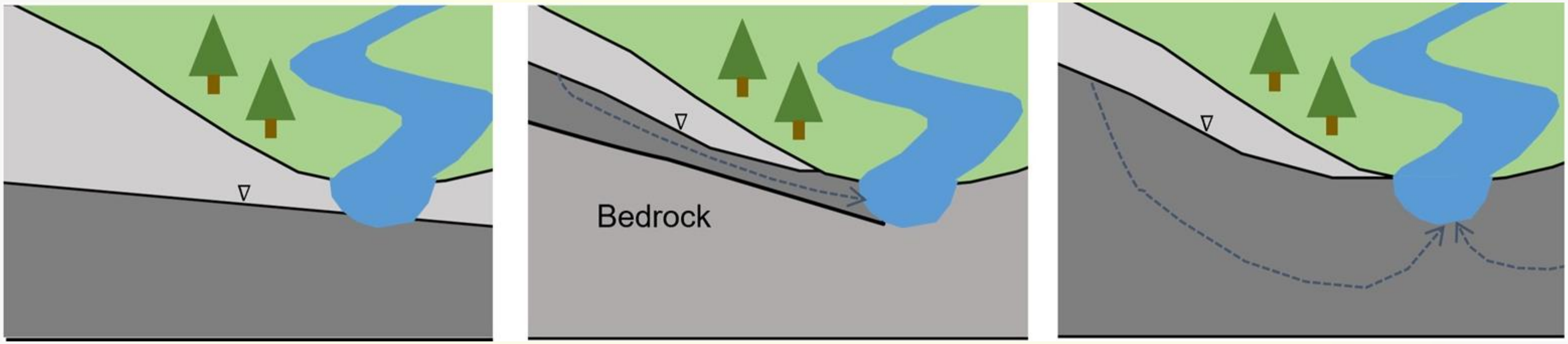
# Trout Creek

## Very scenic place to work but with challenging conditions for measuring temperature or gradients or seepage

We measured seepage in May and had small upward gradients and slow upward seepage. The direction of flow had reversed, likely because the lake level had declined so much. Now, though, the lake level is greatly increased again.

# Use of relative stream and air temperatures to infer GW discharge

- Compare annual air-temperature amplitude with annual stream temperature amplitude
- Deep GW temperature is quite stable.
- Stream temperatures with discharge of deep GW have strong attenuation of annual temperature variability relative to air temperature. But there is no phase shift in annual air temperature relative to annual stream temperature.
- Stream temperatures with discharge of shallow GW have variable attenuation of annual temperature variability relative to air temperature. But there is a substantial phase shift in annual stream temperature relative to annual air temperature.




Danielle Hare has developed an **R shiny** shinyapp called PASTA that can be used to analyze diurnal stream-temperature data relative to air temperature to determine various contributions of groundwater from shallow and/or deep flowpaths based on amplitude attenuation and phase lag.

*Paired Air and Stream Temperature Analysis* **(PASTA)**

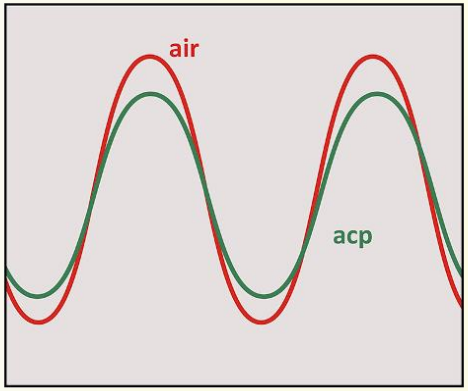
https://cuahsi.shinyapps.io/pasta/



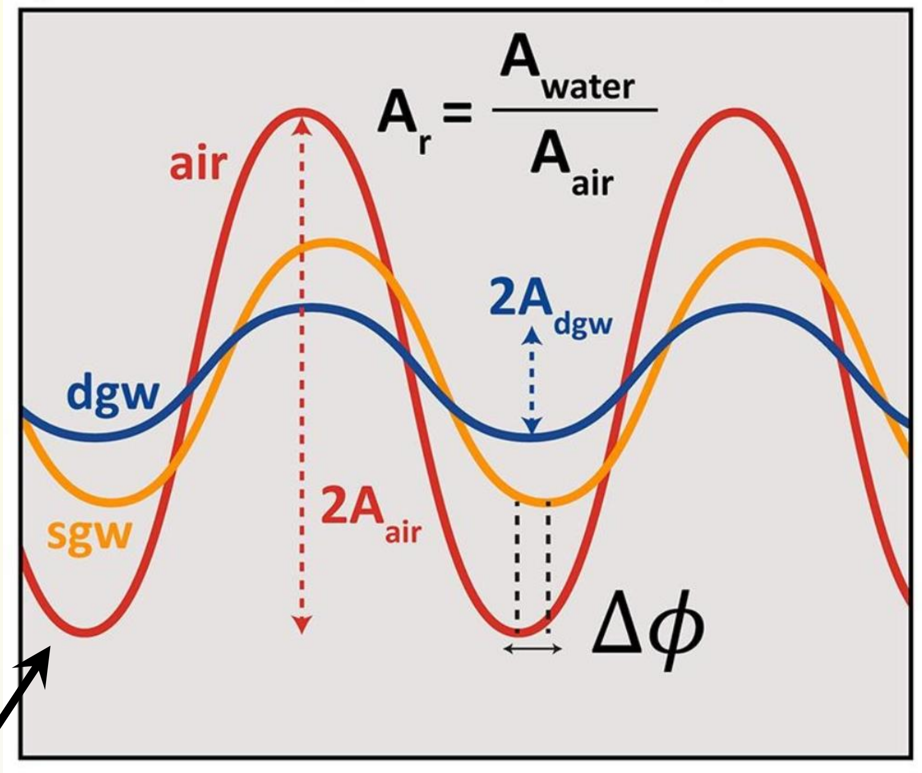
Hare et al., **2023**, *WRR.*

# Use of relative stream and air temperatures to infer GW discharge

- Compare annual air-temperature amplitude with annual stream temperature amplitude
- Deep GW temperature is quite stable.
- Stream temperatures with discharge of deep GW have strong attenuation of annual temperature variability relative to air temperature.  But there is no phase shift in annual air temperature relative to annual stream temperature.
- Stream temperatures with discharge of shallow GW have variable attenuation of annual temperature variability relative to air temperature.  But there is a substantial phase shift in annual stream temperature relative to annual air temperature.



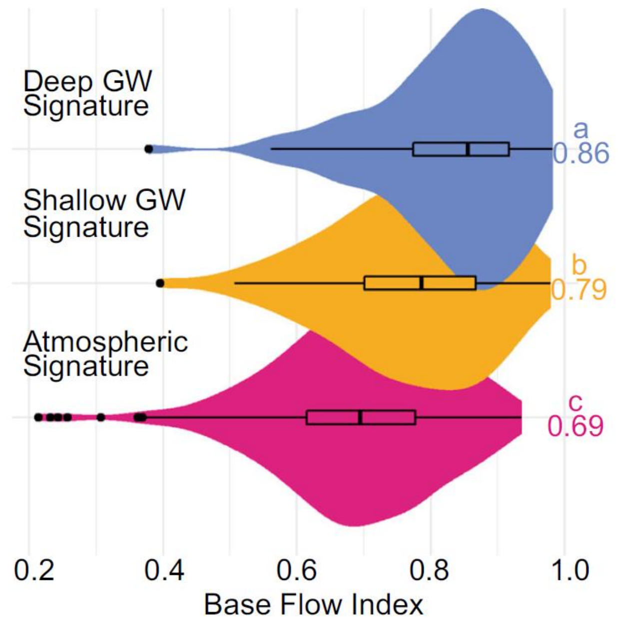

Deep groundwater (>6m DTW) has virtually no annual fluctuation in temperature.  Therefore, discharge of deep groundwater to a stream attenuates the annual stream temperature (blue line) relative to a stream influenced only by air temperature (red line).  Shallow groundwater is influenced somewhat by annual air temperature, but by the time it is discharged to a stream, that temperature signal is shifted relative to the annual air-temperature cycle (orange line).



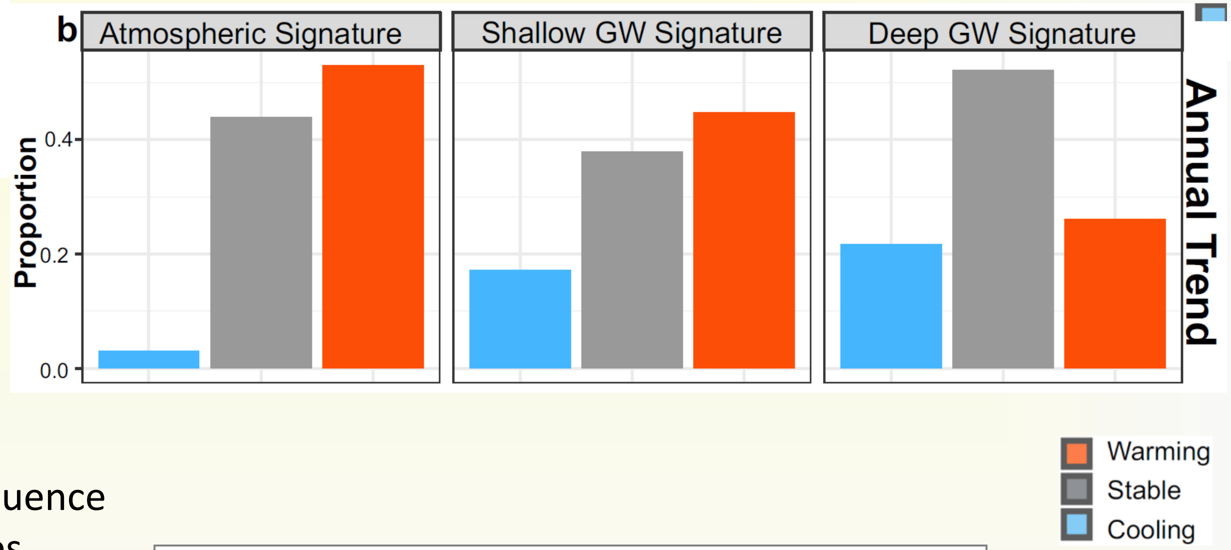

Stream temperature is influenced by these three temperature signals

Rey et al., 2023, *JHydrol.*

# Use of relative stream and GW temperatures to infer GW discharge




Based just on comparison of annual air-temperature and streamwater-temperature data, these violin plots show that deep GW discharge is best related to sites with the largest baseflow index (BFI) values, shallow GW discharge is related to still large but smaller BFI values, and streams dominated by air-temperature are related to smaller values of BFI.




1729 sites

- Major dam influence
- Shallow GW influence
- Deep GW influence
- Atmospheric (no GW) influence

- 40 % of non-dam-influence sites indicated GW influence
- Shallow GW influence showed reduced baseflow and a warming trend

For sites with long-term records, a warming trend is indicated for sites with no GW influence and for sites with shallow GW discharge. Most sites with strong influence from deep GW discharge do not yet indicate warming temperatures.

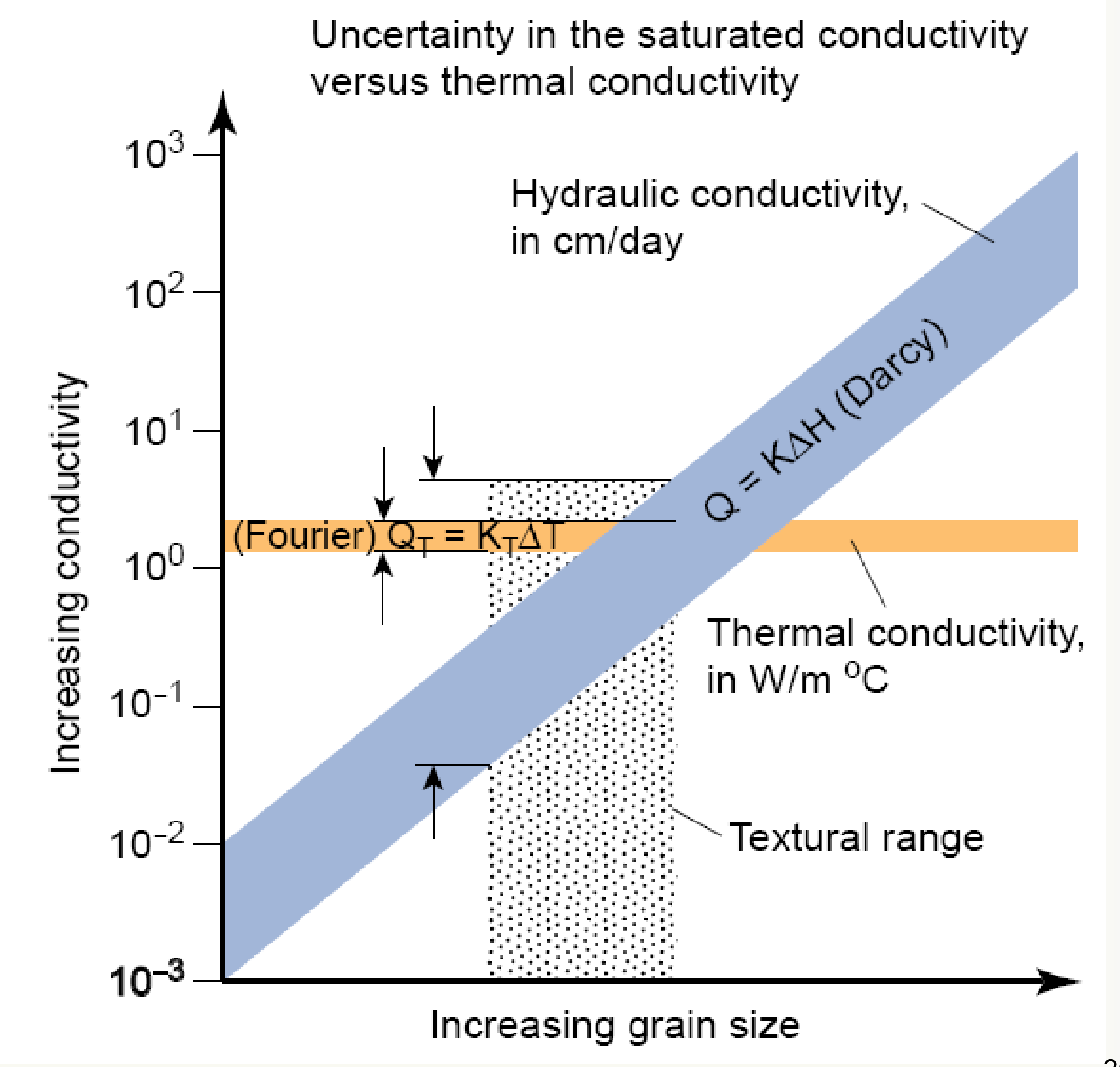
Hare et al., 2021, *Nature Comm.*

# 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)
- We have two equations with two unknowns (hydraulic conductivity and thermal conductivity). Therefore, we need to know both hydraulic and thermal gradients and either hydraulic conductivity or thermal conductivity
- Luckily, thermal conductivity is less uncertain and is not dependent on sediment texture.  We can often provide a good “guess.”

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.

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



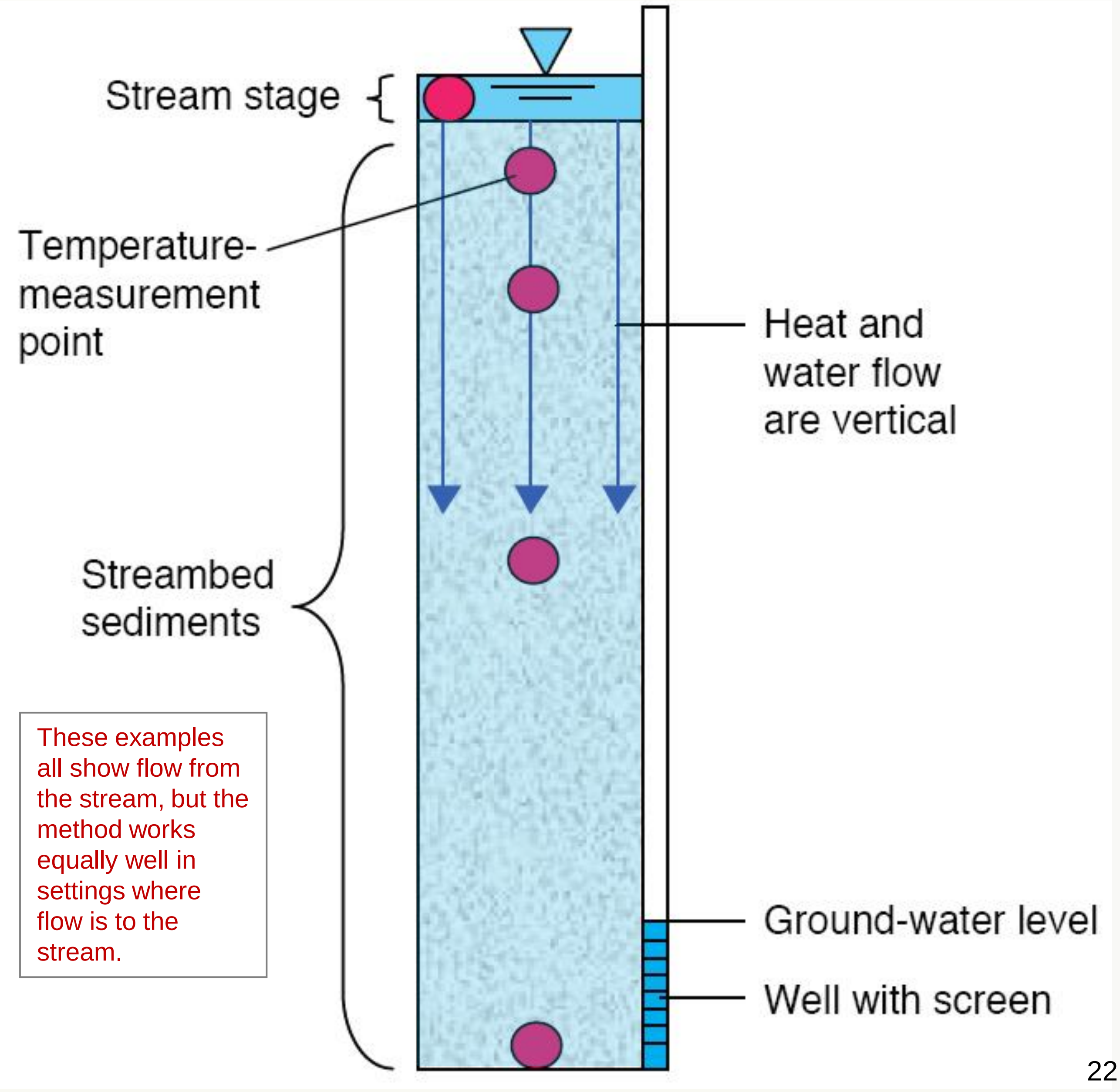

$K_T$ is virtually independent of sediment texture

# 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

There now are several models that are available that can combine these two governing equations for flow of fluid and heat. We will discuss them in greater detail and you'll get a chance to use one with provided field data.

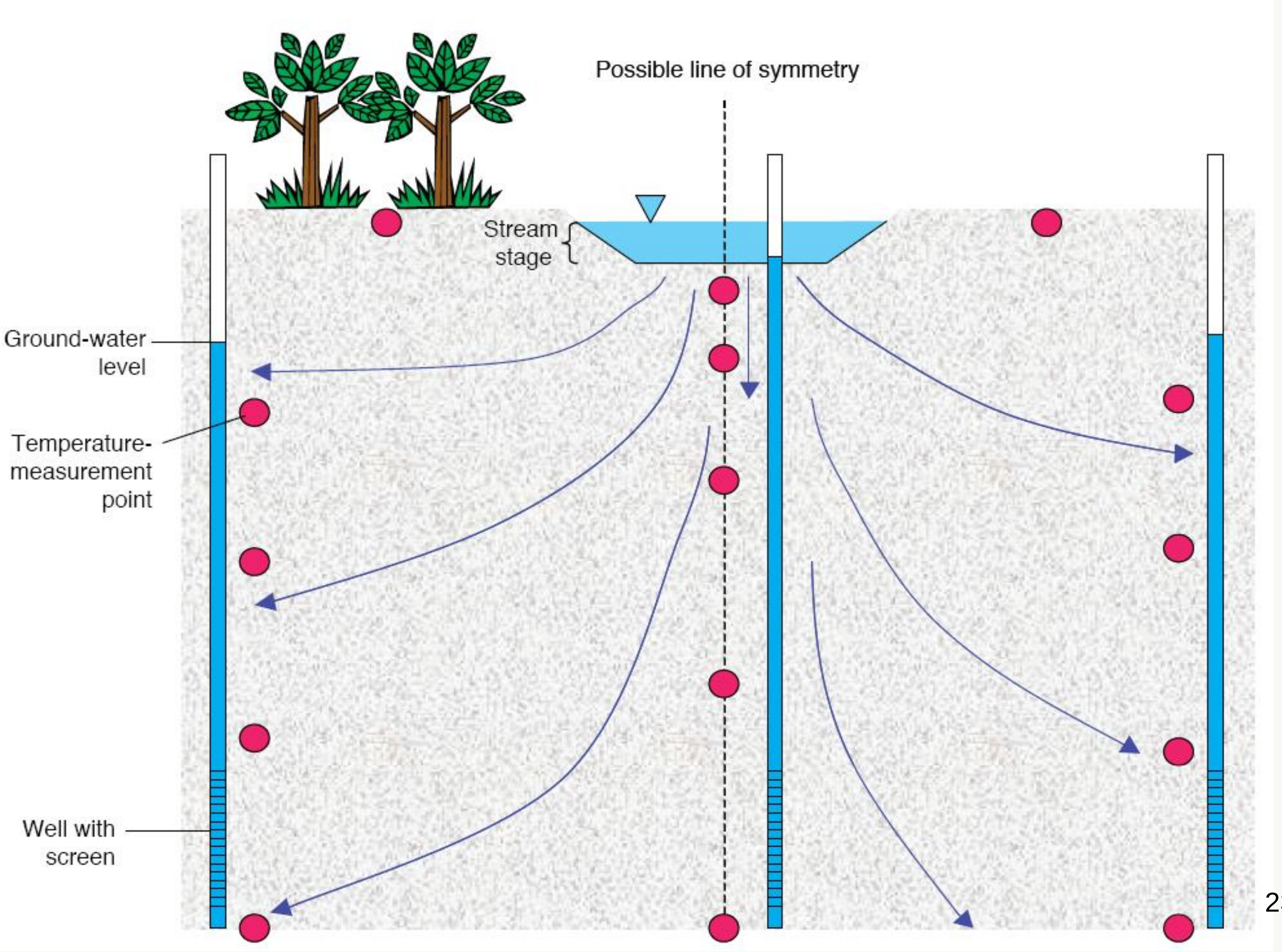
One dimensional model used when water table is some distance below top of streambed (Figure 1; Appendix B)




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. For the 1DTempPro model, we need data from three depths because it uses the top and bottom depths as boundaries.

These examples all show flow from the stream, but the method works equally well in settings where flow is to the stream.

# 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.

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

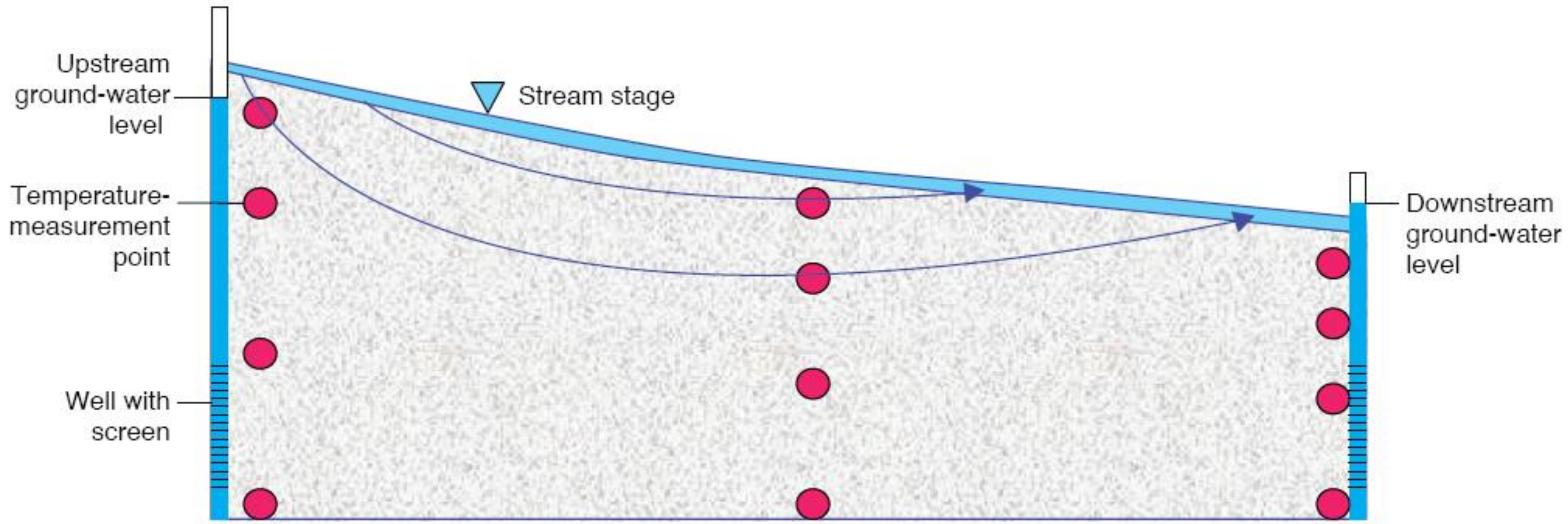



**Figure 3.** Conceptual framework when seepage through the streambed parallels stream profile.

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.

# 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 | $1.1\times10^6$ to $1.3\times10^6$ |
| 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 | $4.2\times10^6$ |
| **Additional parameters for variably saturated flow through fluvial sediments** | | |
| Unsaturated hydraulic conductivity parameters in van Genuchten retention model[5] | | |
| $\alpha$ (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 commonly make an educated guess of the value for thermal conductivity.

# 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.

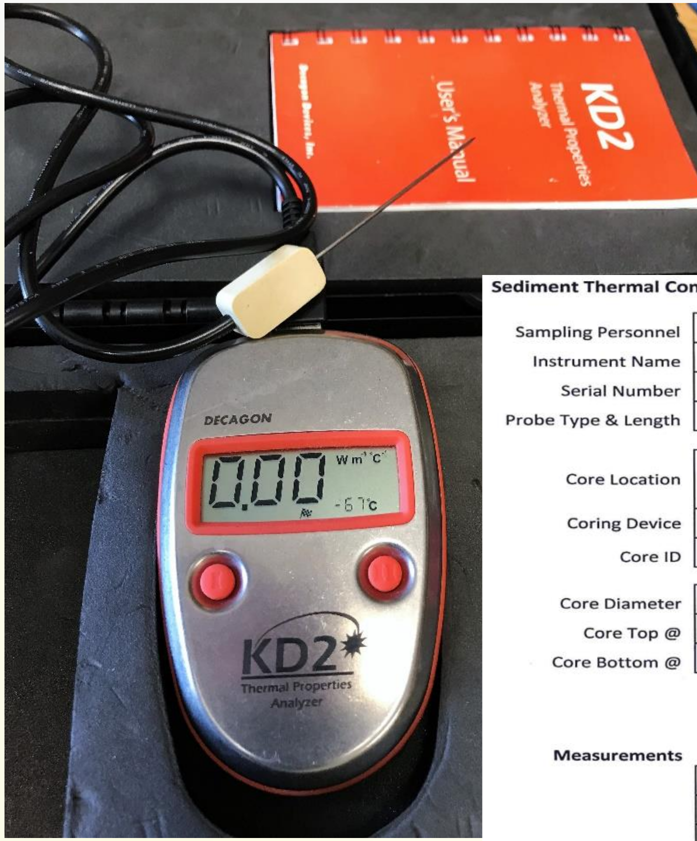
# Thermal Properties of Porous Media (Table 1; Appendix A)

**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.

# Or we can measure $K_T$




The sensor is not that expensive and is easy to use. Simply drill a small hole through the lexan sleeve (core tube) and insert the probe through the hole into the undisturbed sediment. Make sure the drill bit doesn't extend into the sediment, though. Crisco vegetable shortening is used as a calibration material with known $K_T$.

**Sediment Thermal Conductivity Data Sheet**

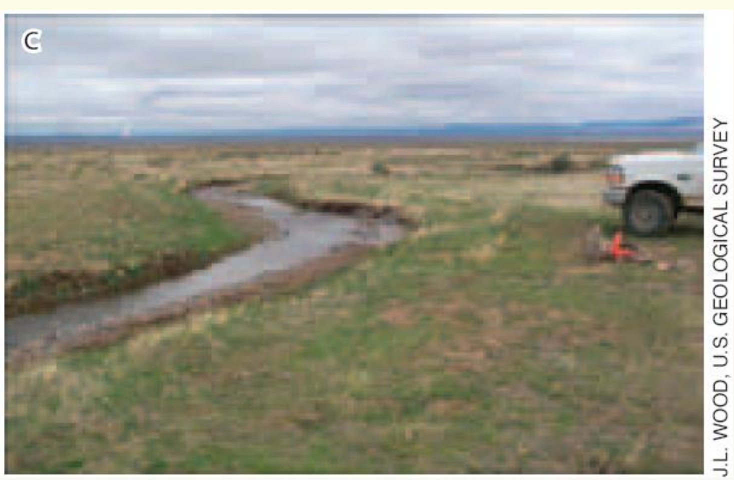
| | |
|---|---|
| Sampling Personnel | D. Rosenberry |
| Instrument Name | Decagon KD2 |
| Serial Number | K1406 |
| Probe Type & Length | KS-1 6-cm |
| Core Location | ESM 2, Shingobee Lake, 6/21/18 |
| Coring Device | Aquatic Research Instruments, Universal Percussion Corer |
| Core ID | ESM 2 |

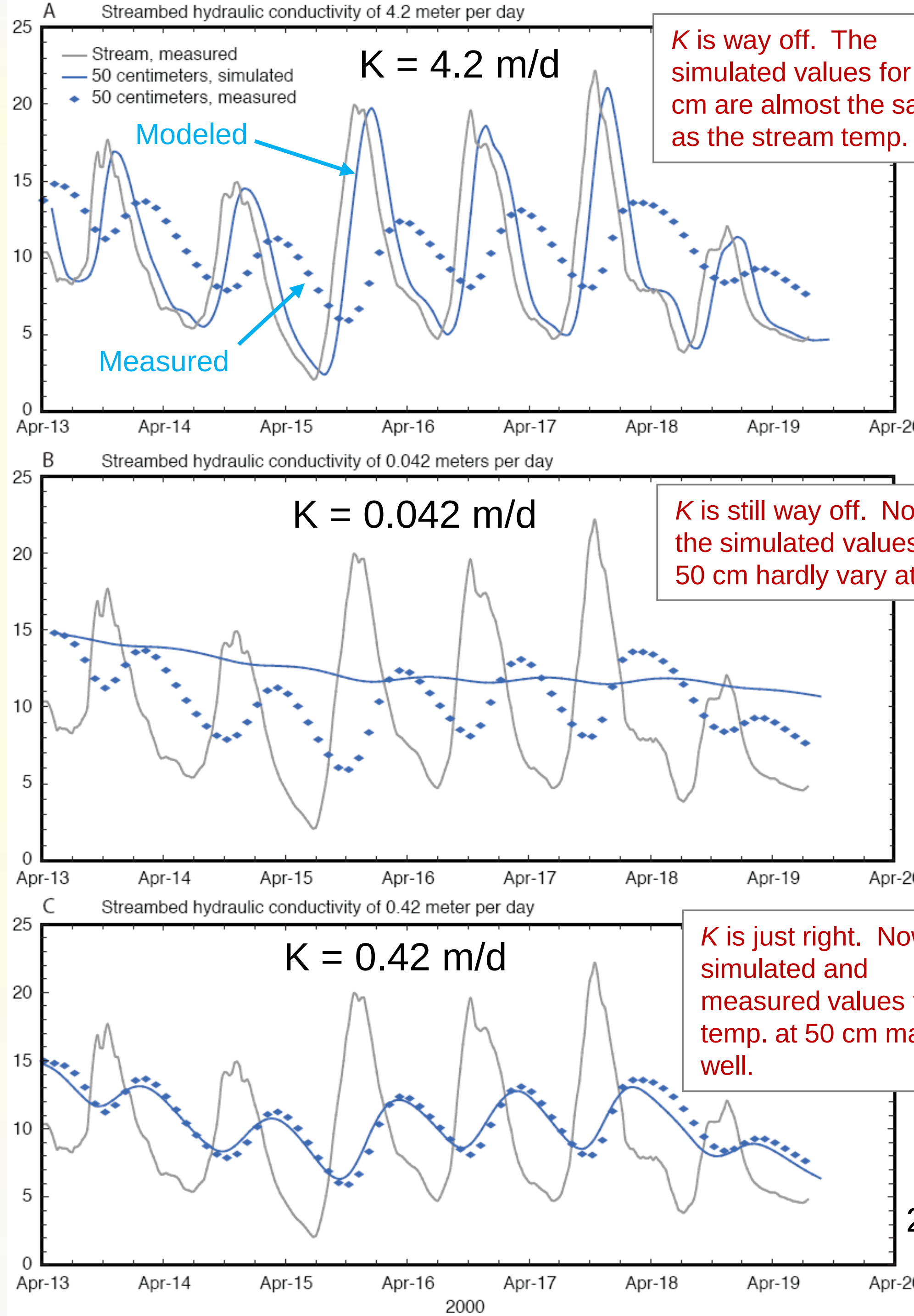
| | | | | |
|---|---|---|---|---|
| Core Diameter | 2.625 | inches / centimeters | Project Name | Shingobee |
| Core Top @ | 0 | inches / centimeters | Date | 7/3/18 |
| Core Bottom @ | 61.5 | inches / centimeters | Shortening Info | Crisco All-Veg., Lakewood CO |

| Measurements | Interval from Top in / cm | Measurement Time HH:MM (military) | Sediment Temperature °C | Thermal Conductivity W / m.°C | Observation Notes |
|---|---|---|---|---|---|
| | 5 | 12:30 | 25.5 | 0.53 | Sed. very loose * |
| | 10 | 12:32 | 25.9 | 0.57 | Loose, fibrous organics |
| | 15 | 12:35 | 25.2 | 1.25 | Trans. to gray med sand |
| | 20 | 12:44 | 25.8 | 1.17 | |
| | 25 | 12:47 | 25.8 | 0.99 | Med. gray sand |
| | 30 | 12:50 | 25.6 | 1.35 | |
| | 35 | 12:52 | 25.5 | 1.43 | |
| | 40 | 12:54 | 25.3 | 1.53 | |
| | 45 | 12:56 | 25.1 | 0.85 | |
| | 50 | 12:58 | 25.0 | 0.80 | White calcareous grains |
| | 55 | 13:01 | 25.0 | 0.84 | Light gray med. sand |
| | 60 | 13:03 | 25.2 | 0.93 | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Reference 1 | Crisco | 12:27 | 24.5 | 0.14 | |
| Replicate | 15 | 12:42 | 25.7 | 1.26 | |
| Duplicate 1 | 25 | 13:06 | 26.5 | 0.83 | |
| Duplicate 2 | 40 | 13:09 | 25.6 | 1.55 | |
| Reference 2 | Crisco | 13:12 | 25.4 | 0.14 | |

# 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

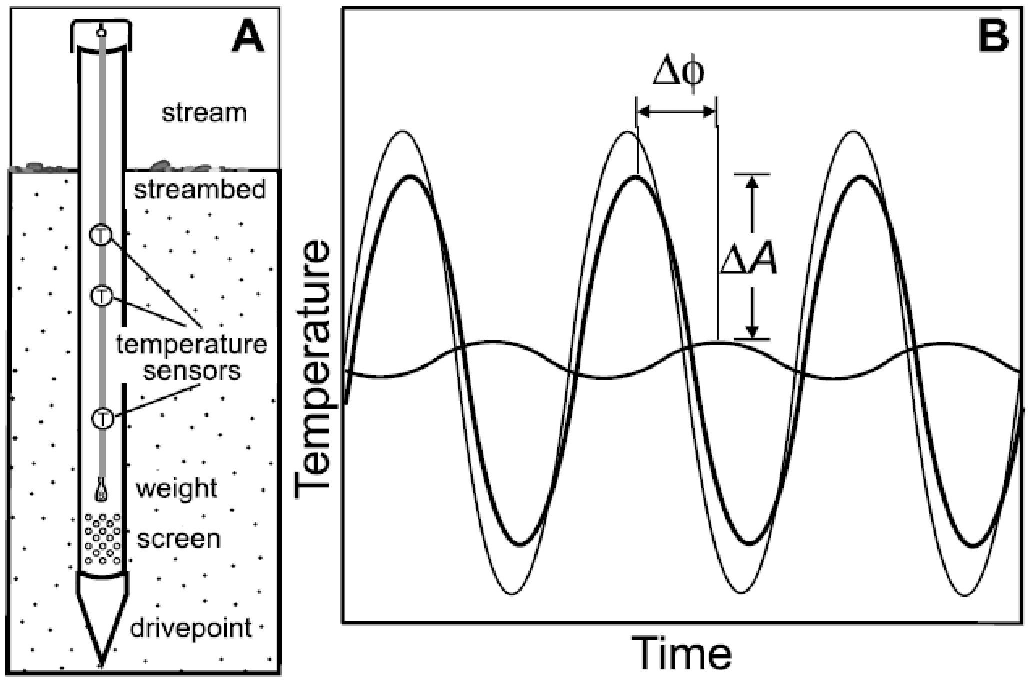



**Figure 1.** Diagrams illustrating acquisition of streambed temperature records and basis for new analytical method. (a) Streambed piezometer with temperature sensors at various depths. (b) Temperature versus time records showing reduction in amplitude ($\Delta A$) and shift in phase ($\Delta\phi$)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

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

$A_r$ = amplitude ratio

$\Delta z$ = spacing between measurement points

$\kappa_e$ = effective thermal diffusivity

$\alpha$ is related to $\kappa e$, $\nu$, and frequency of temperature variations

$\nu$ = 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 ($\nu_{Ar}$ and $\nu_{\Delta\phi}$ respectively):

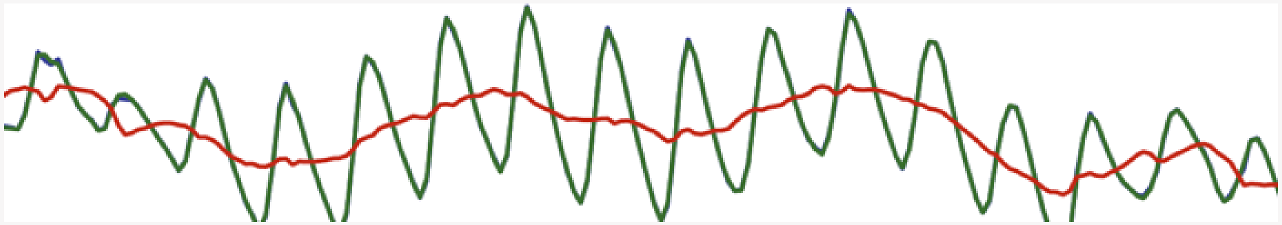
$$\nu_{Ar} = \frac{2\kappa_e}{\Delta z}\ln A_r + \sqrt{\frac{\alpha + \nu^2}{2}} \quad (6a)$$

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

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.

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 or https://www.hydroshare.org/resource/4df337867d314620bd87b27c6732e6fe/

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

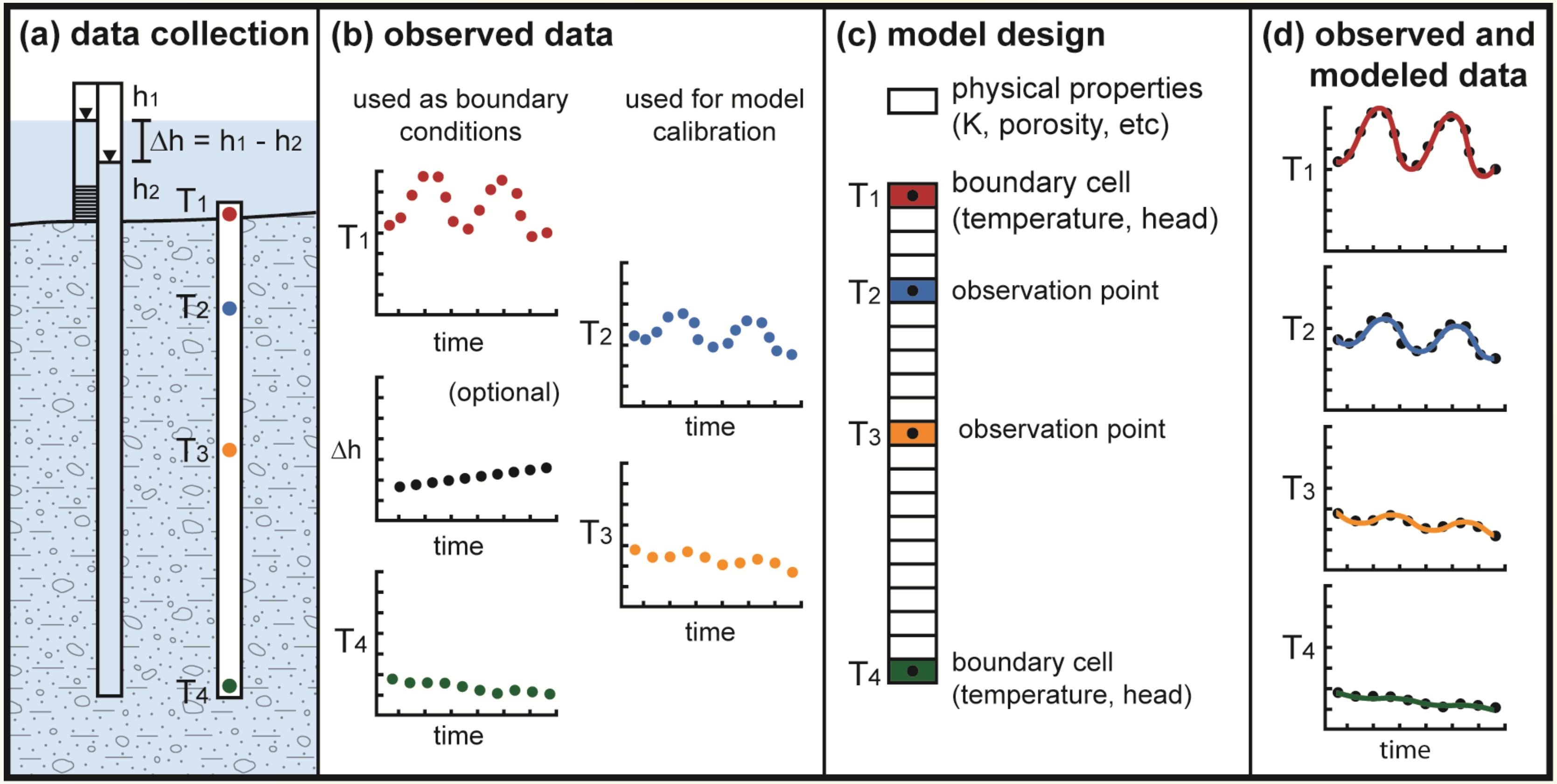
VFLUX can now deal with non-vertical flow. It calculates the vertical component of flux.

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.

Irvine et al. (2017) goes into more detail about using multiple analytical methods and refined thermal diffusivity.

# 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

We will use Version 2 of this model

https://code.usgs.gov/water/espd/hgb/1dtemppro

# 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

# And now a new approach that combines 1DTempPro with VFLUX

Water Resources Research

RESEARCH ARTICLE
10.1029/2021WR030443

**Key Points:**
- Recursive filtering applied to heat tracing enables real-time estimation of groundwater/surface-water exchange
- Recursive filtering and smoothing applied to heat tracing improve estimation of groundwater/surface-water exchange
- Recursive filtering applied to heat tracing allows quantification of uncertainty in groundwater/surface water exchange estimates

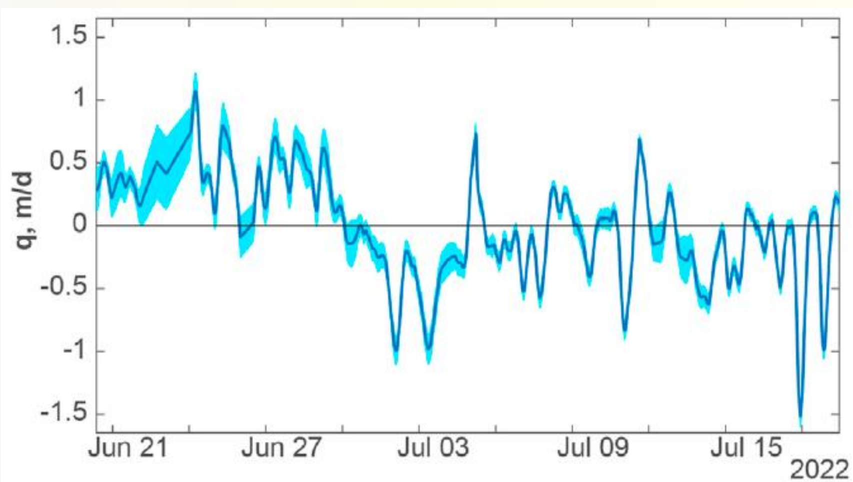
## Application of Recursive Estimation to Heat Tracing for Groundwater/Surface-Water Exchange

W. Anderson McAliley[1,2], Frederick D. Day-Lewis[3], David Rey[4], Martin A. Briggs[5], Allen M. Shapiro[6], and Dale Werkema[7]

[1]Student Contractor to the U.S. Geological Survey, Golden, CO, USA, [2]Now at U.S. Geological Survey, Water Mission Area, Golden, CO, USA, [3]Pacific Northwest National Laboratory, Earth Systems Science Division, Environmental Subsurface Science Group, Richland, WA, USA, [4]U.S. Geological Survey, Water Mission Area, Denver Federal Center, Denver, CO, USA, [5]U.S. Geological Survey, Water Mission Area, Storrs, CT, USA, [6]U.S. Geological Survey, Water Mission Area, Reston, VA, USA, [7]Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Pacific Ecological Systems Division, Pacific Coast Ecology Branch, Newport, OR, USA

This approach combines aspects of 1DTempPro and VFLUX to provide better estimates where fluxes are changing rapidly with time. The ERTSS option is also more robust where there is strong upward GW discharge that washes out the temperature signal. The next slide shows how much upward flow can wash out the temperature signal.

**E**xtended **R**auch-**T**ung-**S**triebel **S**moother

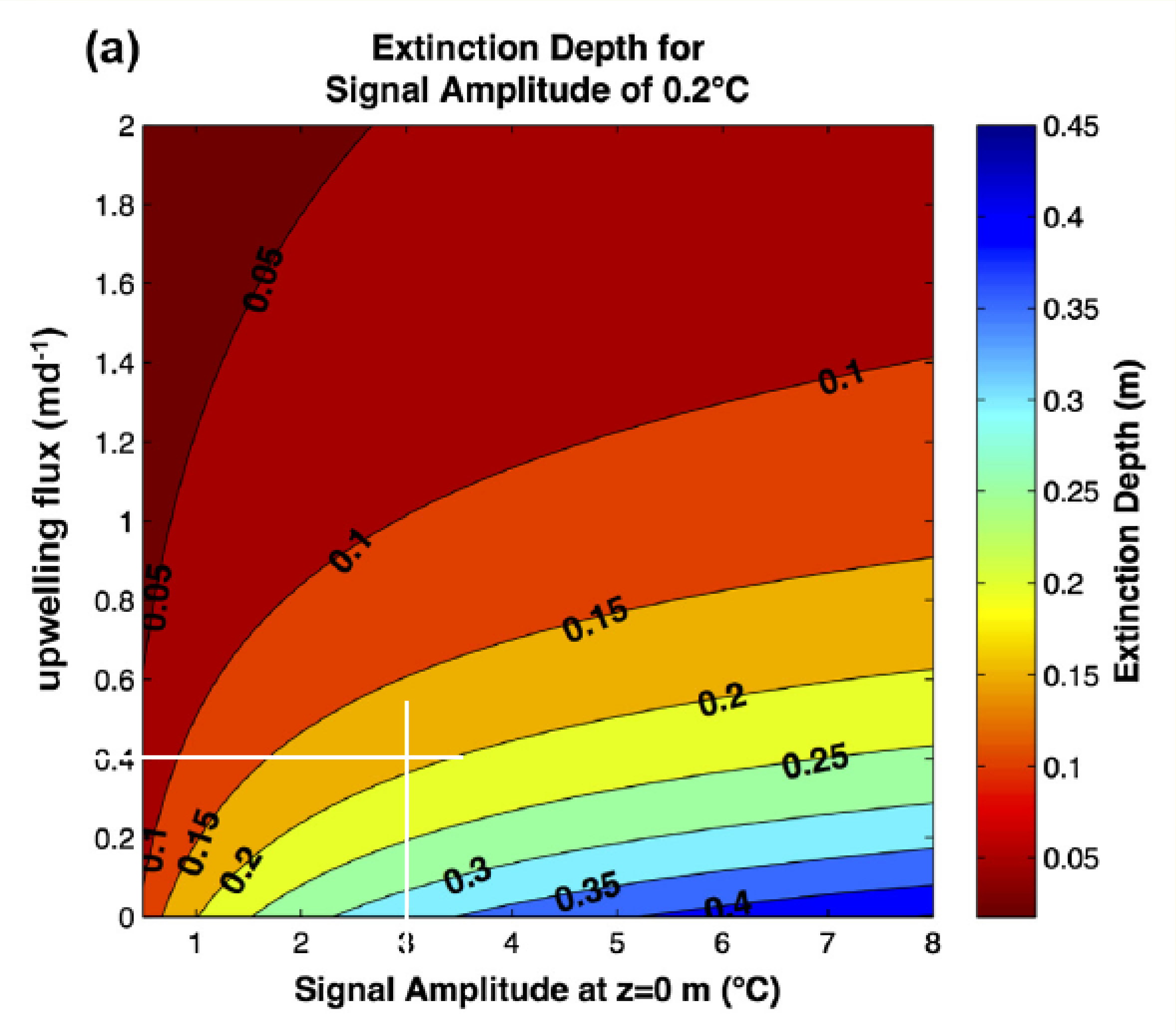



"Our approach therefore can be viewed as a hybrid
between calibration of rigorous process models (e.g., *1DTempPro*) and digital signal processing (e.g., *VFLUX*)"

- Better computational efficiency
- Better resolution of abrupt changes in GW discharge
- Can better handle time-varying boundary conditions
- Provides uncertainty bounds for estimated fluxes

McAliley et al., 2022, *WRR*

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.

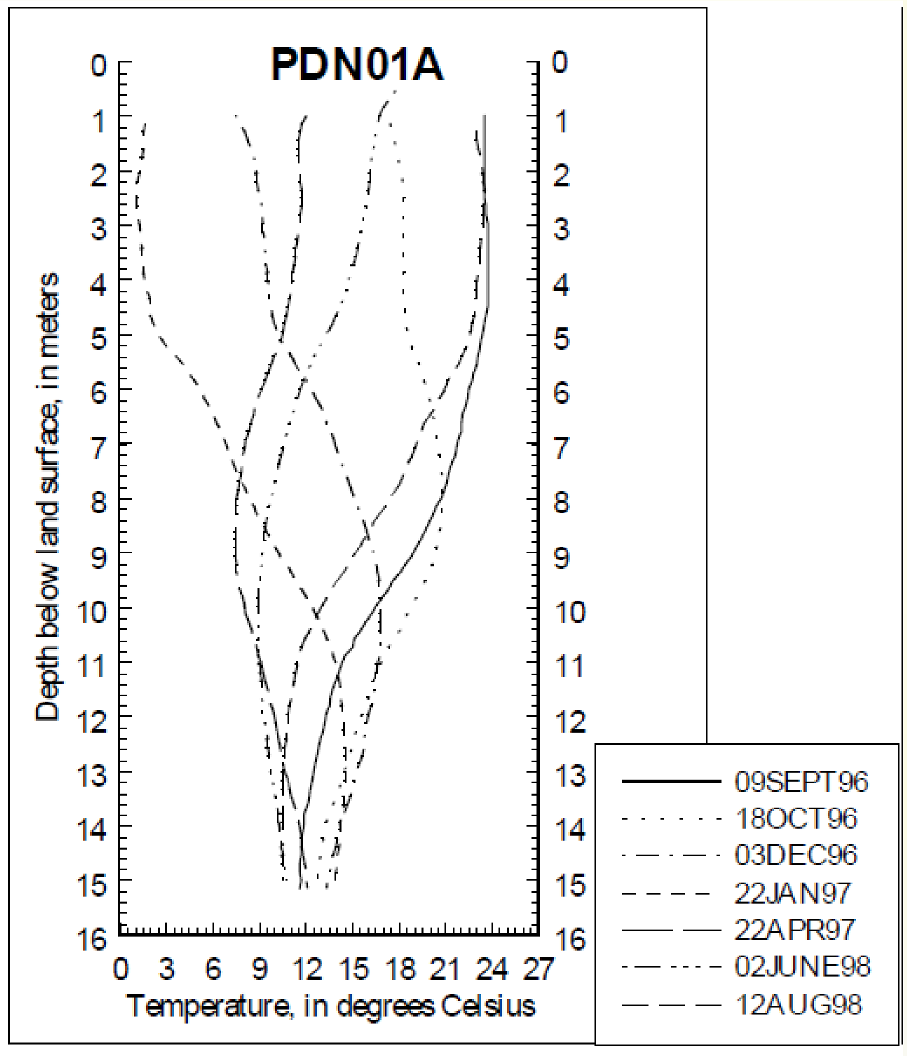
This plot will vary with sediment properties, such as thermal conductivity, porosity, sediment heat capacity, etc.

**The thermally active zone can be quite shallow (or thin) for diurnal applications where fast upward seepage occurs.**

**Briggs et al., 2014, J. Hydrology**

Rio Grande Basin– Issues related to aquifer recharge from Rio Grande River, NM

**Or the thermally active zone can be very thick on an annual scale and where downward seepage is fast.**




**Bartolino and Niswonter, 1999, USGS WRIR**

Irvine et al., 2017, GW-1 – Excellent review paper with lots of the latest thinking on expanding the capability of this tool.

**Table 2**
**Examples of Commonly Used Temperature Sensors/Data Loggers with Their Resolution, Temperature Range, Data Storage Capacity and Dimensions (as of May 2016)**

| Manufacturer, Sensor, Model | Sensor Resolution (°C) | *T* Range (°C) | Data Storage Capacity (Samples) | Height x Width (mm) |
|---|---|---|---|---|
| Onset® HOBO® Water Temperature Pro v2 | 0.02 | −40 to 70 | 42,000 | 114 × 30 |
| Onset® TidbiT v2 | 0.02 | −20 to 70 | 42,000 | 17 × 41 |
| Thermochron® iButton DS1922L | 0.5/ 0.0625 | −40 to 85 | 8192/4096 | 6.4 × 17.4 |
| Alpha Mac Inc. iBWetland 22 L | 0.5/0.0625 | −40 to 85 | 8192/4096 | 7.5 × 20 |
| Vemco Minilog-II-T | 0.01 | −10 to 40 | 1,000,000 | 98 × 23 |
| UIT temperature lances (m welt- und Ingenieurtechnik GmbH, Germany) | 0.04/0.004 | −20 to 50 | [1] | $660^2$ × 31 |

[1]Storage capacity is 512mb, to store output from eight sensors.
[2]20 mm minimum sensor spacing.

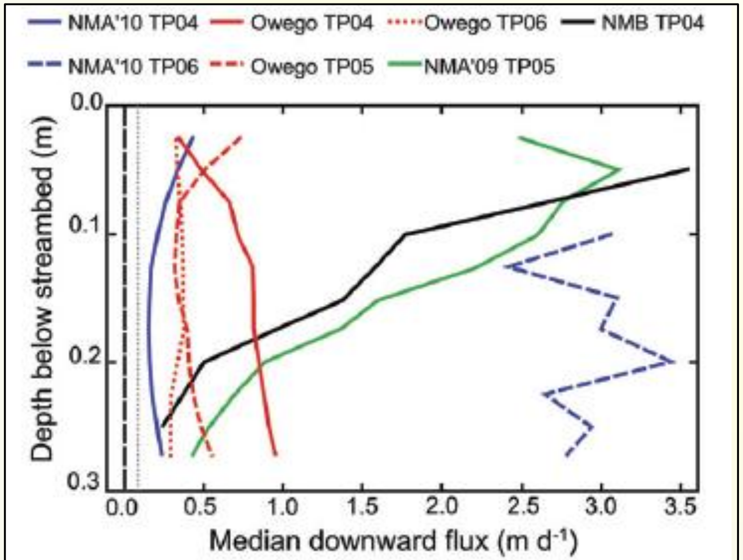



**Figure 7.** Median *q* with depth plots from stream restoration sites at Nilemile and Owego Creeks in Central New York State. Modified from Gordon et al. (2013).

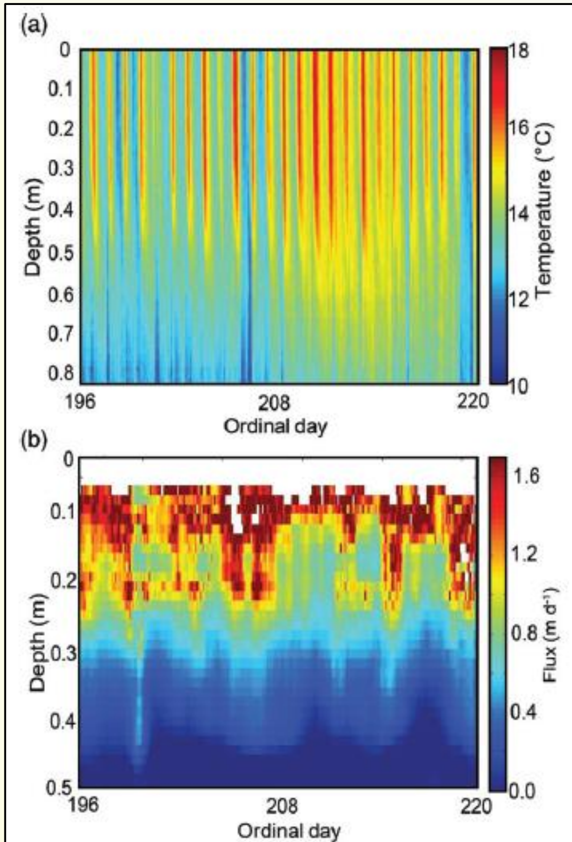
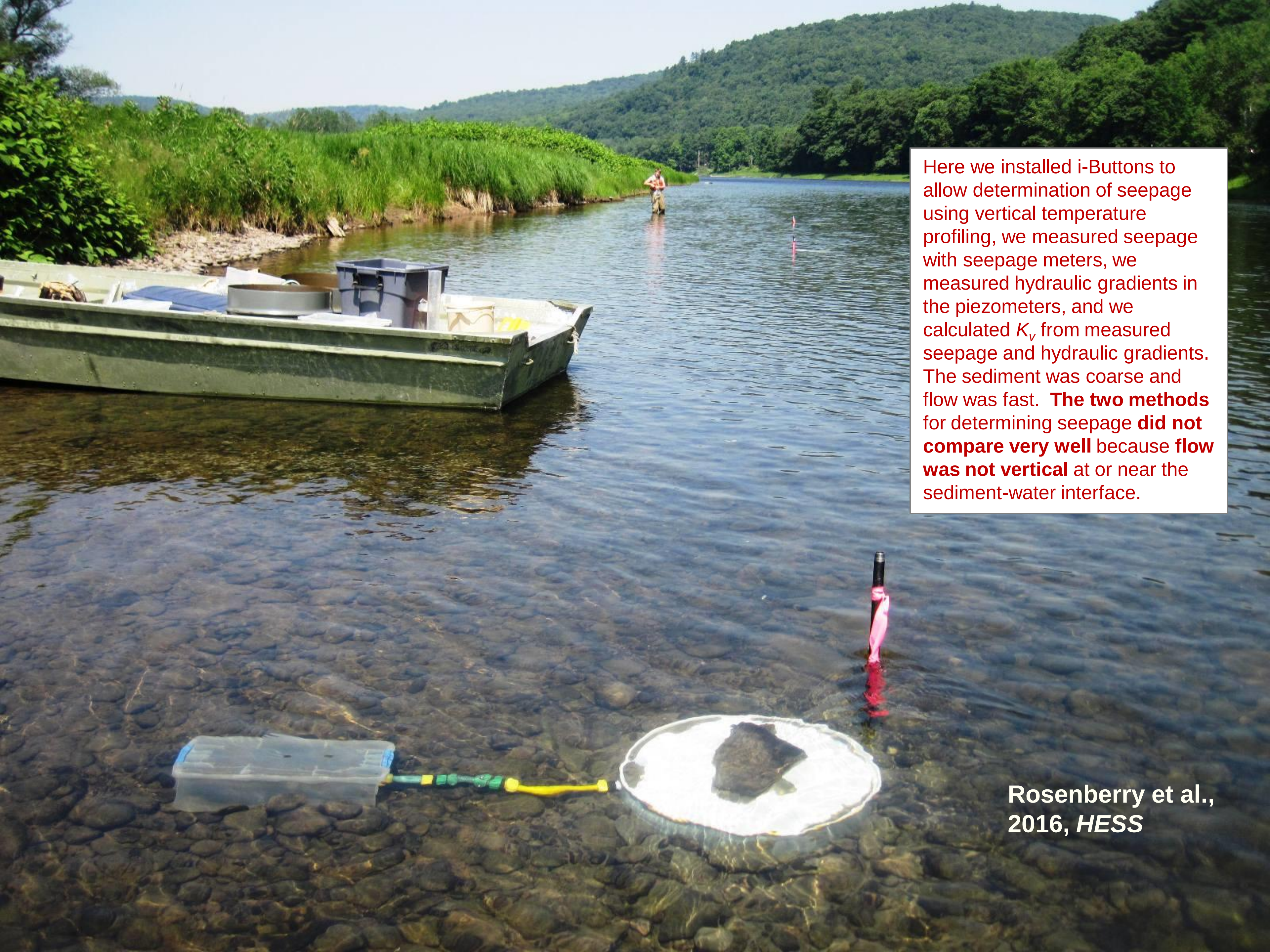
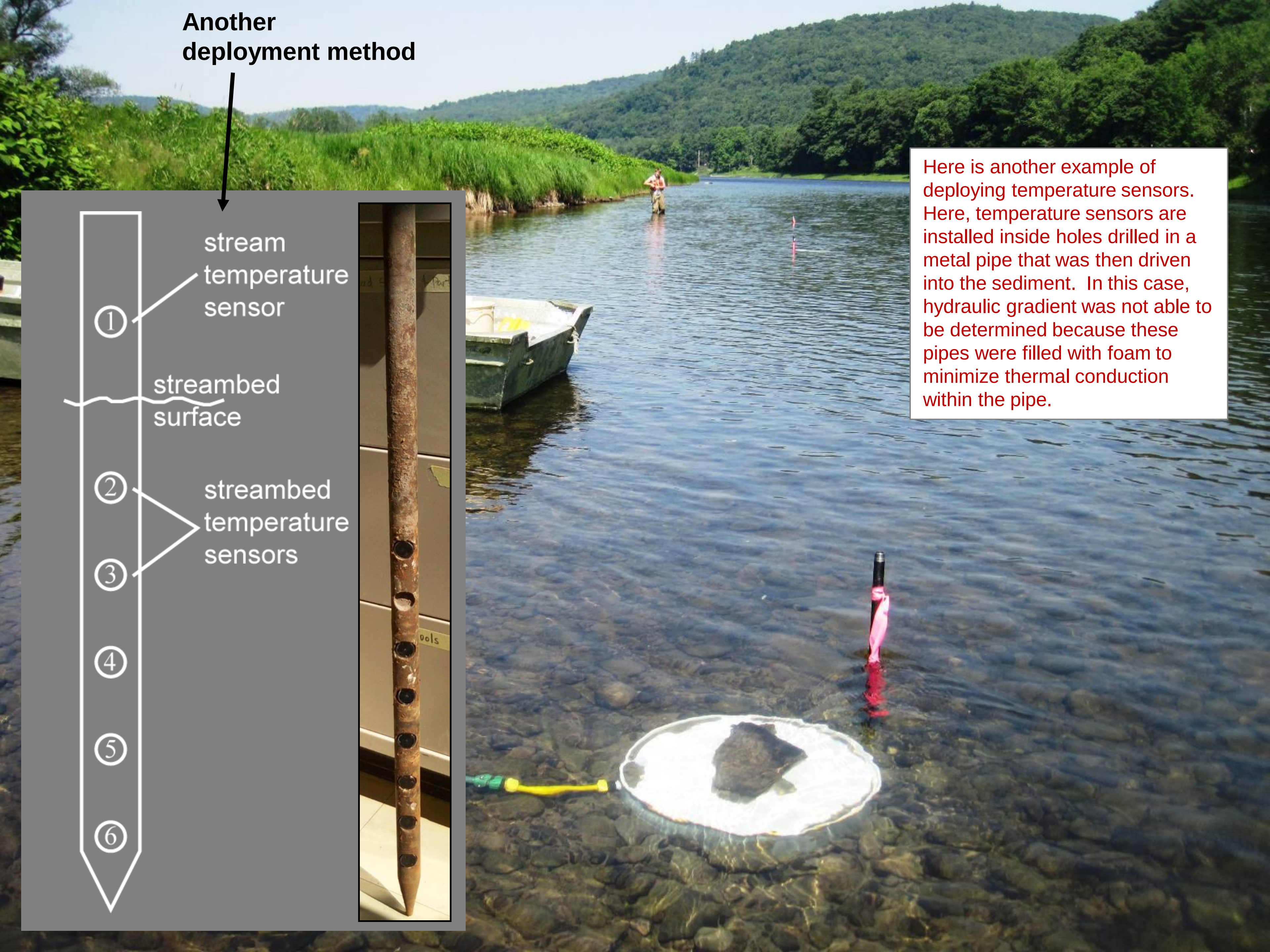
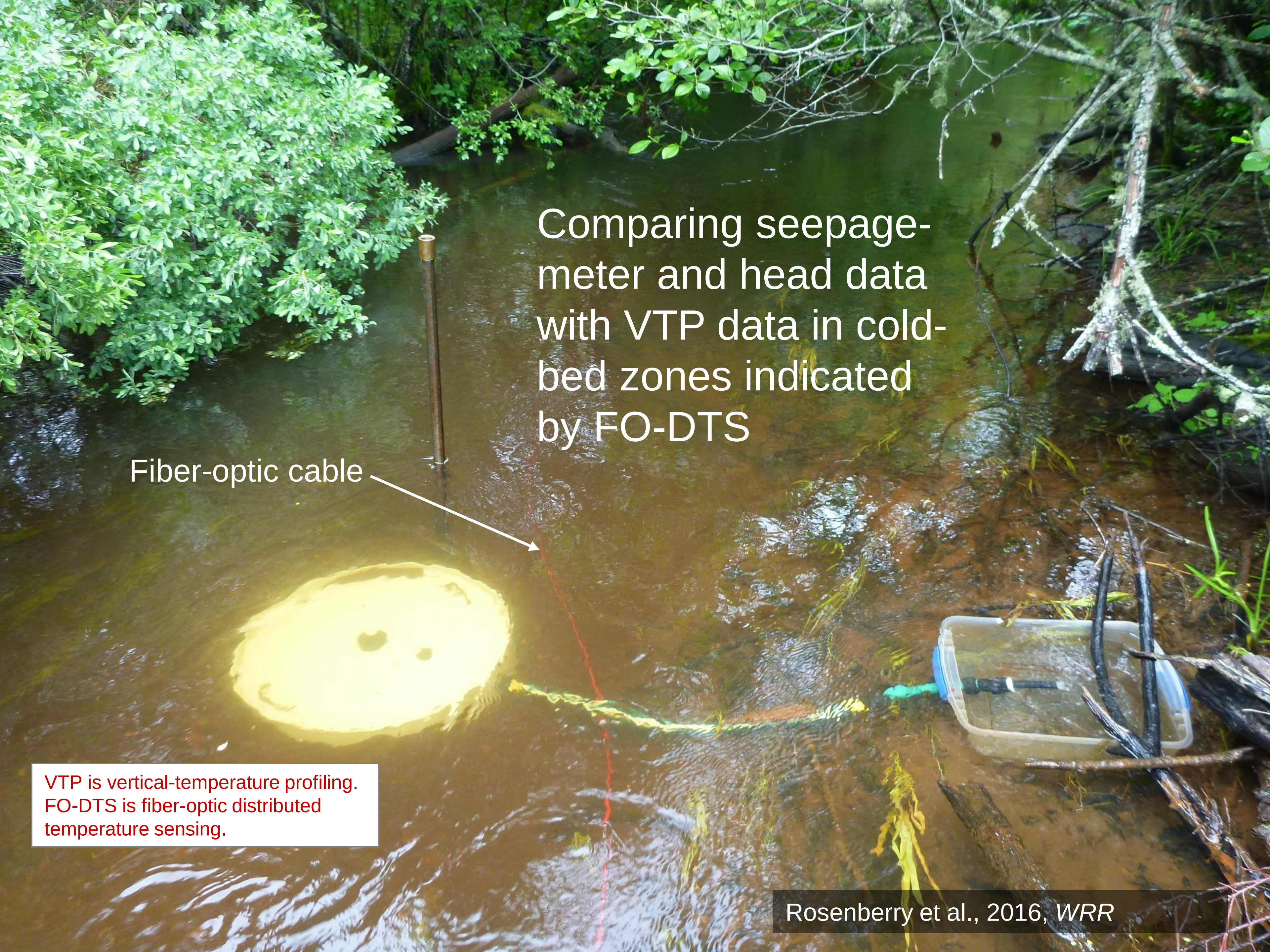
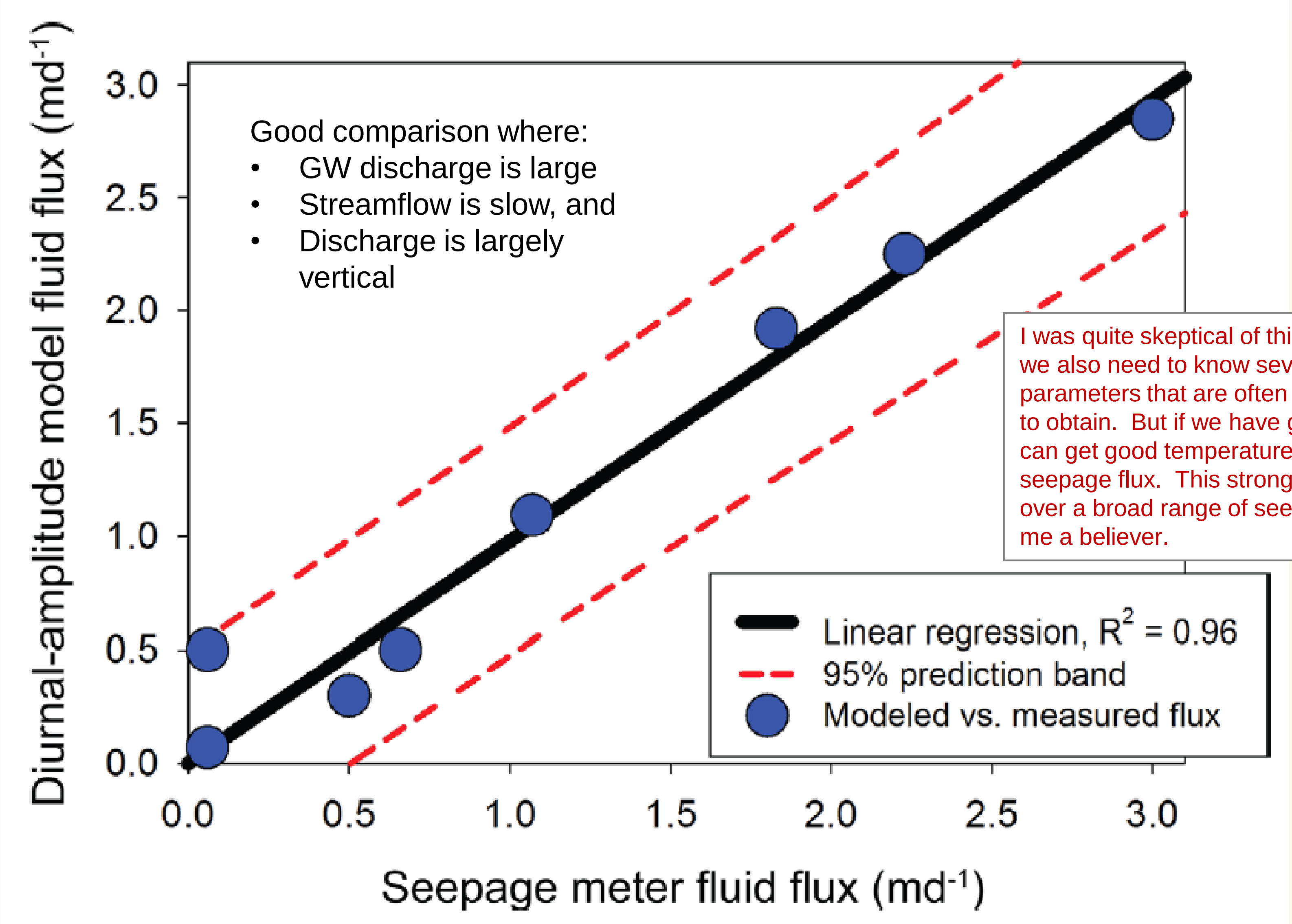



Figure 8. (a) Raw HRTS streambed temperature data (1.4 cm spatial resolution, 20 min temporal resolution) collected over 1 month in a zone of strong but shallow downwelling above a beaver dam. (b) The amplitude-ratio between various depth signals from (a) was used to model downward vertical fluid flux over time between the depths of 0 and 0.5 m. Note the transition to "zero" vertical flux with depth has been interpreted as a transition to pure horizontal flow, as is expected in shallow hyporheic flow cells (modified from Briggs et al. 2012).


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. The sediment was coarse and flow was fast. **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***

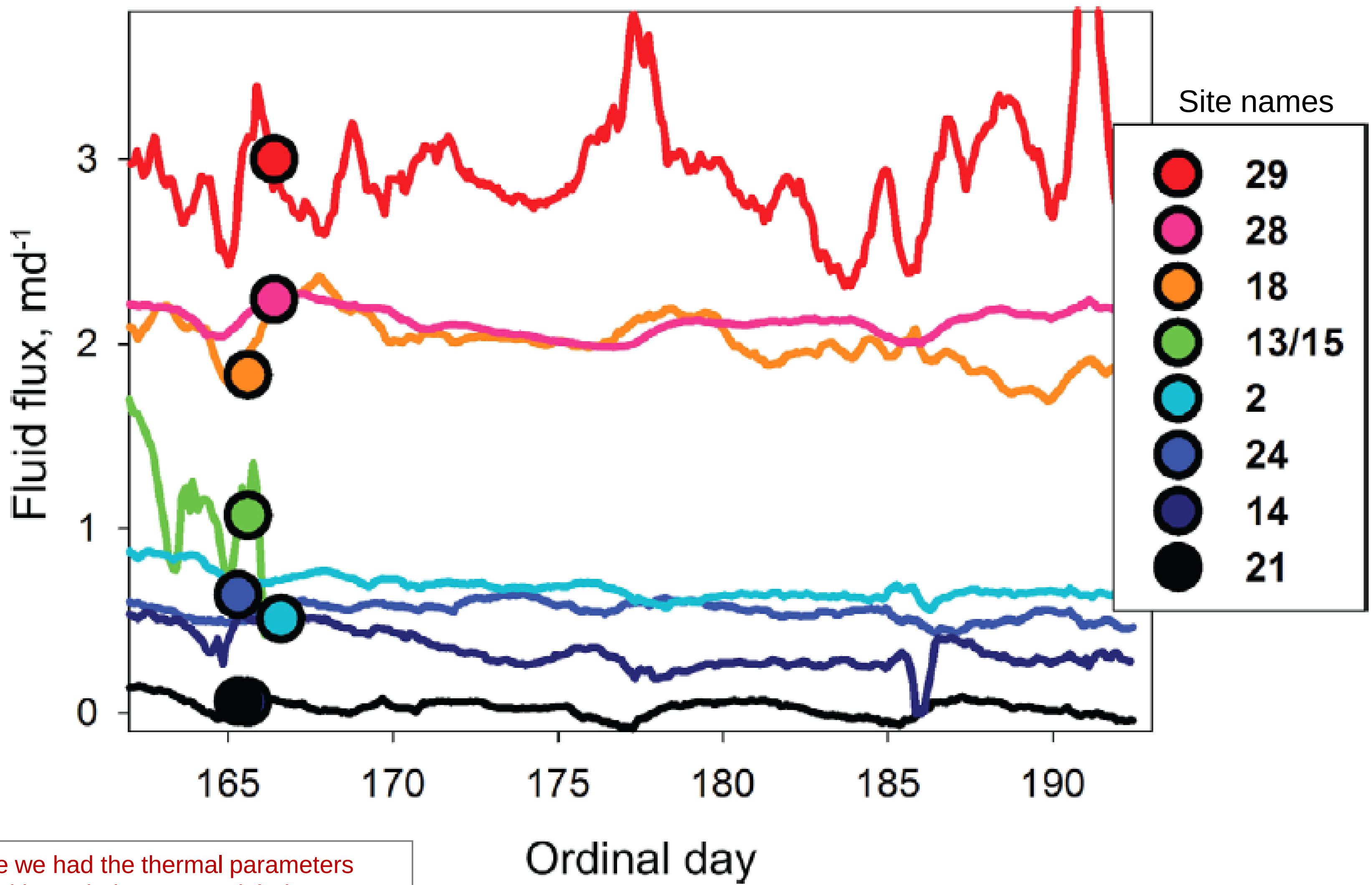

Another deployment method
stream temperature sensor
streambed surface
streambed temperature sensors
1
2
3
4
5
6
Here is another example of deploying temperature sensors. Here, temperature sensors are installed inside holes drilled in a metal pipe that was then driven into the sediment. In this case, 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
VTP is vertical-temperature profiling.
FO-DTS is fiber-optic distributed temperature sensing.
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. This strong linear relation over a broad range of seepage rates made me a believer.

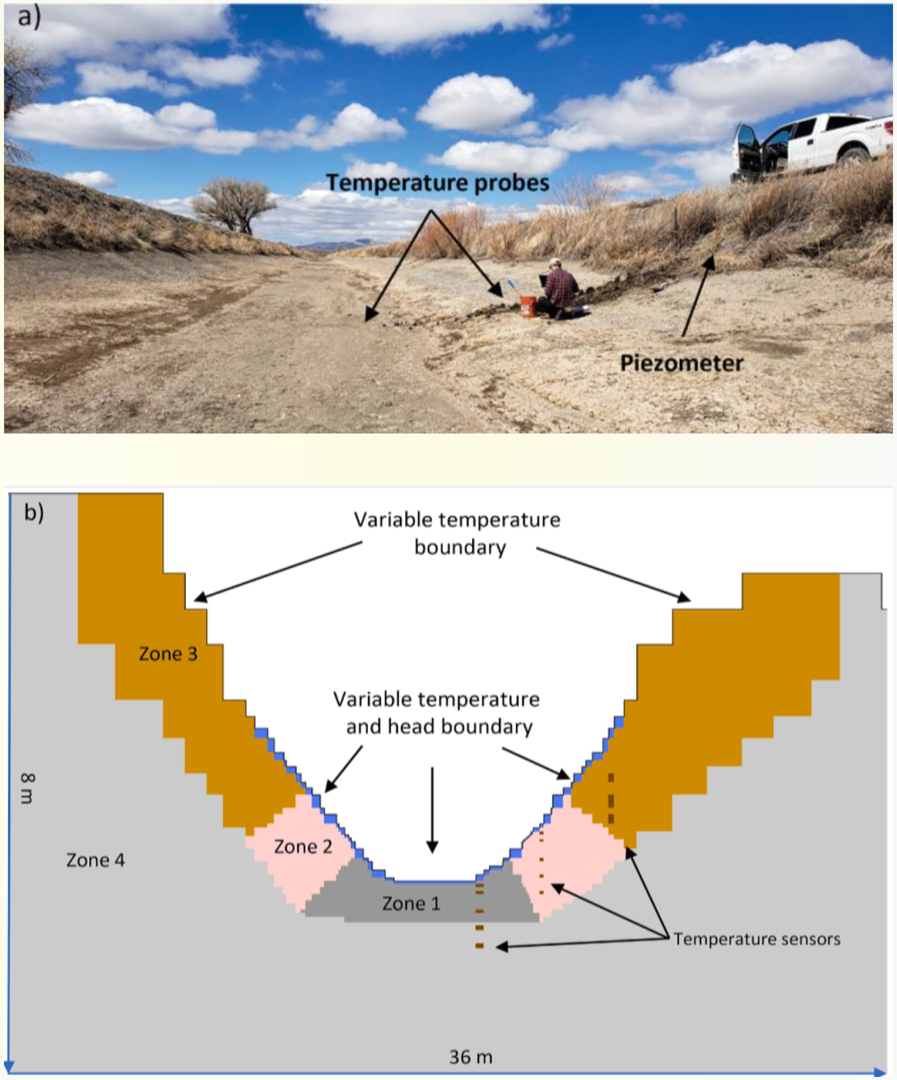
Rosenberry et al., 2016, *WRR*




Once we had the thermal parameters dialed in such that our modeled seepage values matched measured seepage, we could then automate the model fits over time and calculate temporal variability in seepage.

Rosenberry et al., 2016, *WRR*

# Vertical temperature profiling to determine loss from acequias


Sensors placed at depths of 0, 0.1, 0.2, 0.5, 0.75, and 1 m

Unsaturated beneath the acequia

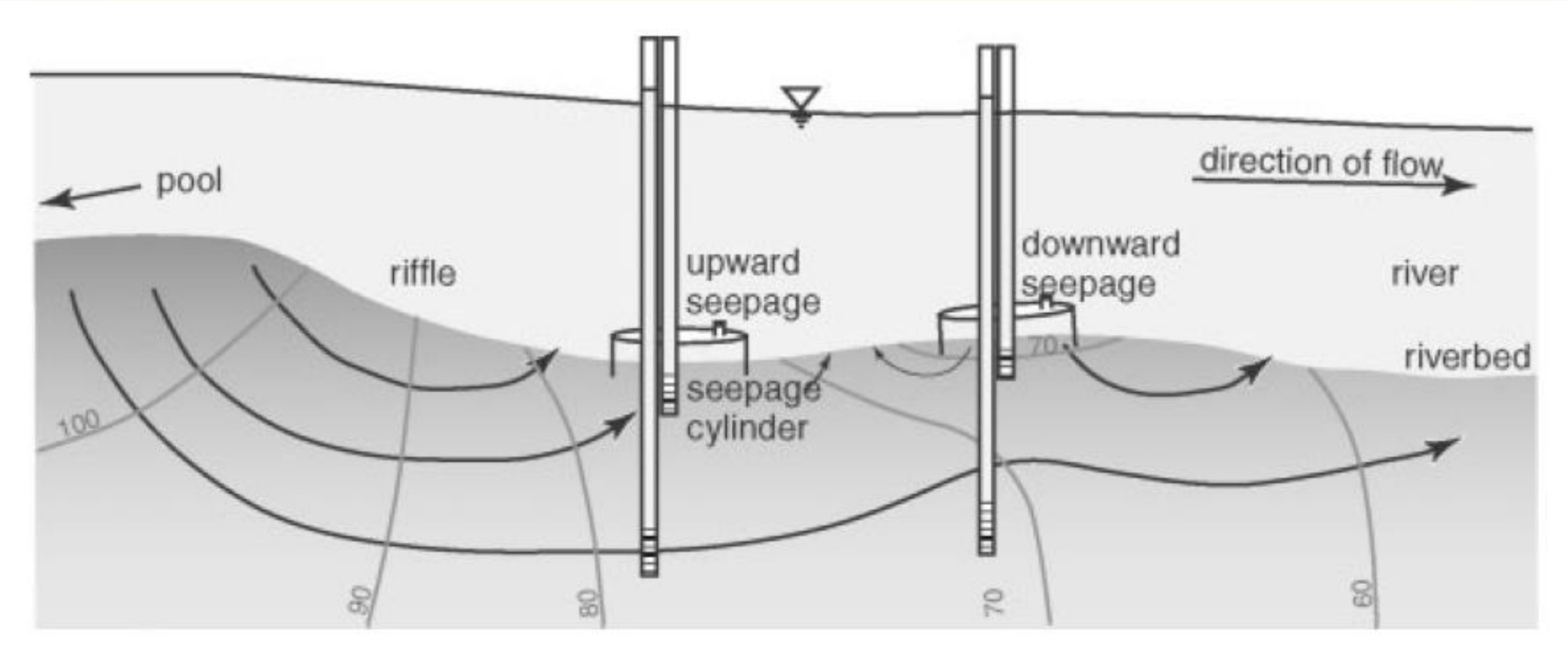
Seepage ranged from 1 to 37 cm/d and averaged 9 cm/d

Seepage losses were 37 to 41 percent of flow in acequia

They used vertical temperature profiling with the USGS numerical model VS2DHI to calculate seepage at 19 cross sections along the acequia. The model adjusted for temperature-driven variability in water viscosity and results indicated **substantial seasonal variability** in seepage loss related to temperature of the surface water.

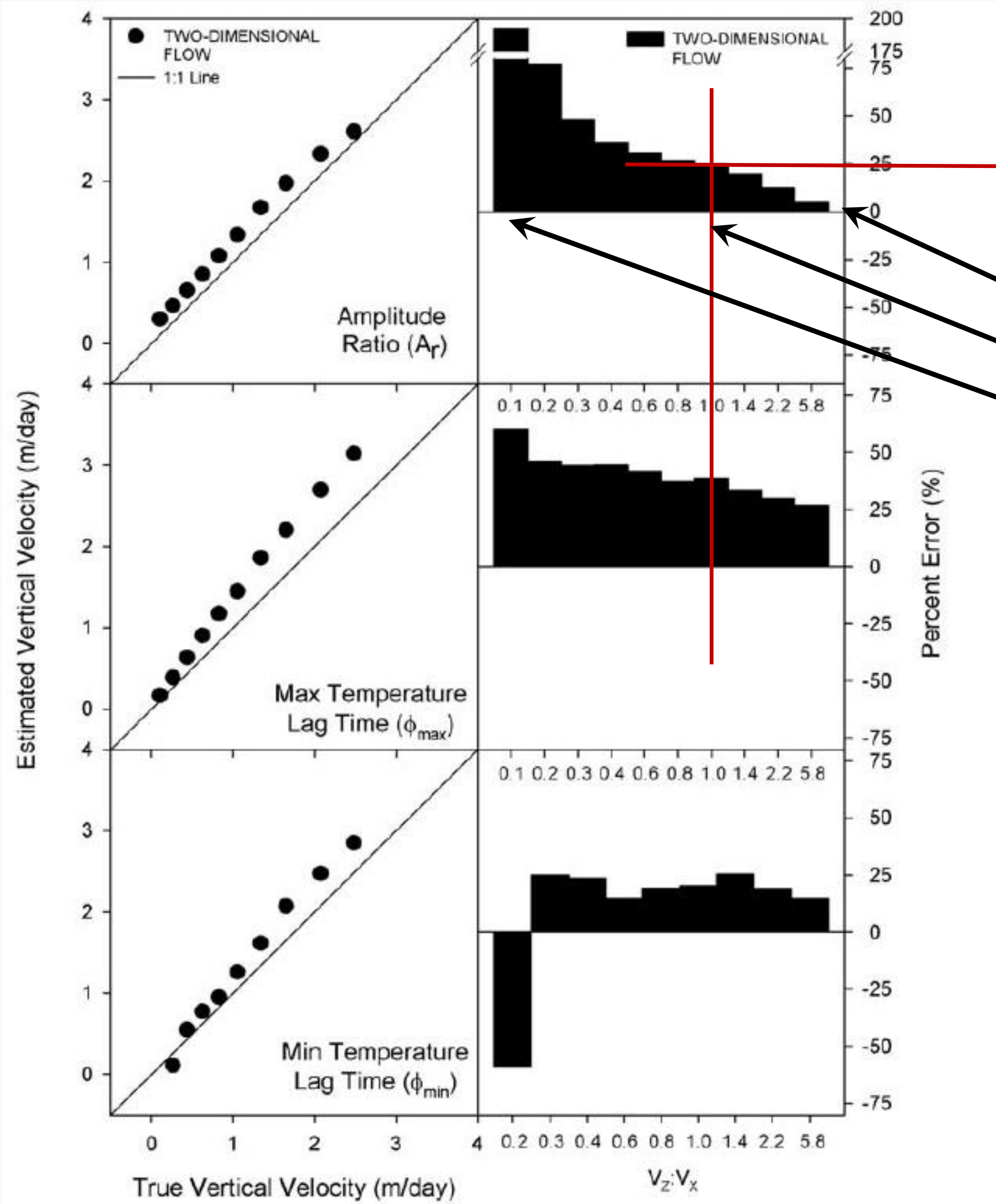
Naranjo et al., 2023, *JHydrol*

# Flow is often not vertical, particularly in hyporheic settings




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?




Errors become large as $V_z/V_x$ decreases

Close to vertical

45 degrees

Almost horizontal

Amplitude ratio (top plot) generally gives smaller errors.

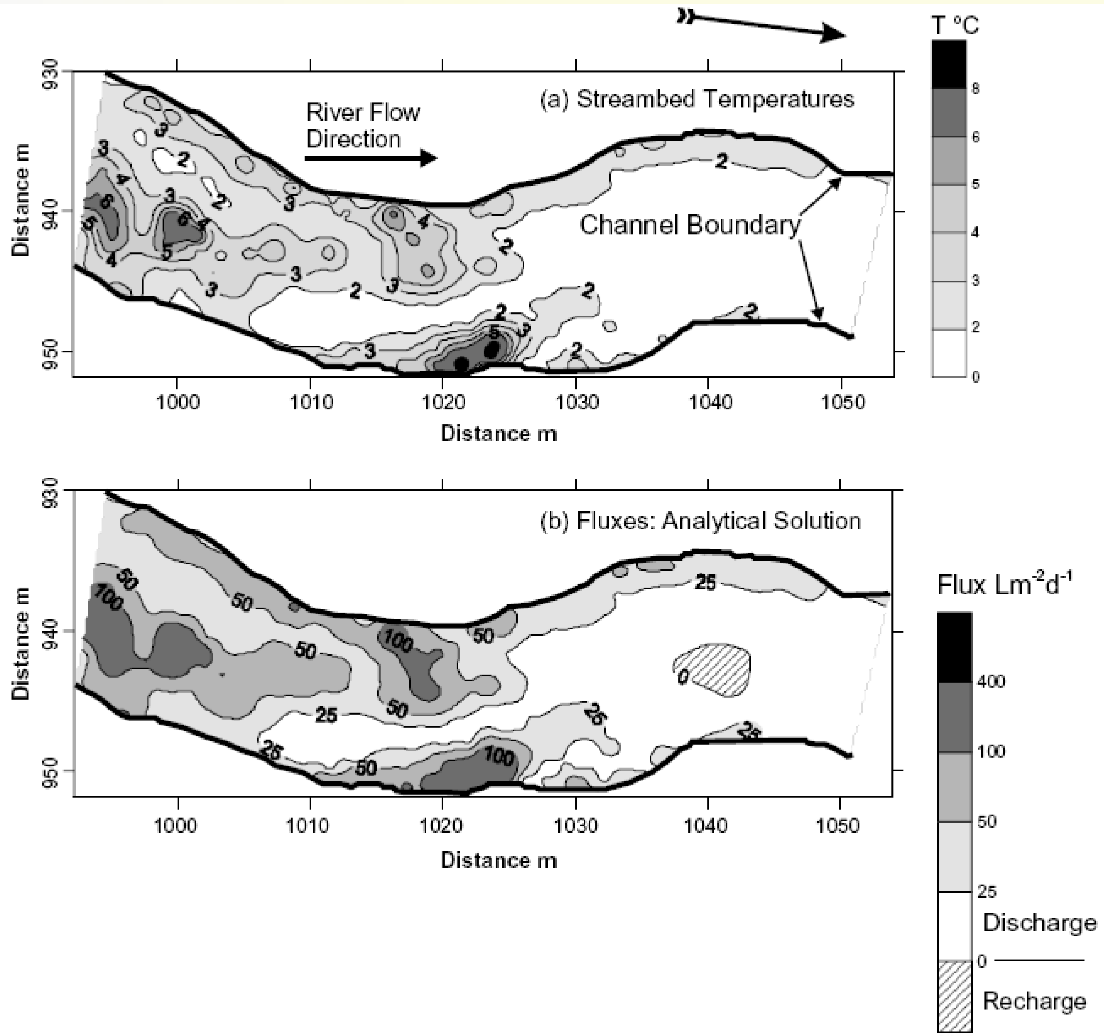
Errors can be pretty large when flow is not vertical. These simulations give us an idea of just how large. For flow at 45 degrees or less from vertical, the amplitude ratio method generates errors less than about 25 percent.

Lautz, 2010, *WRR*

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

$\kappa_{fs}$ = thermal conductivity

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

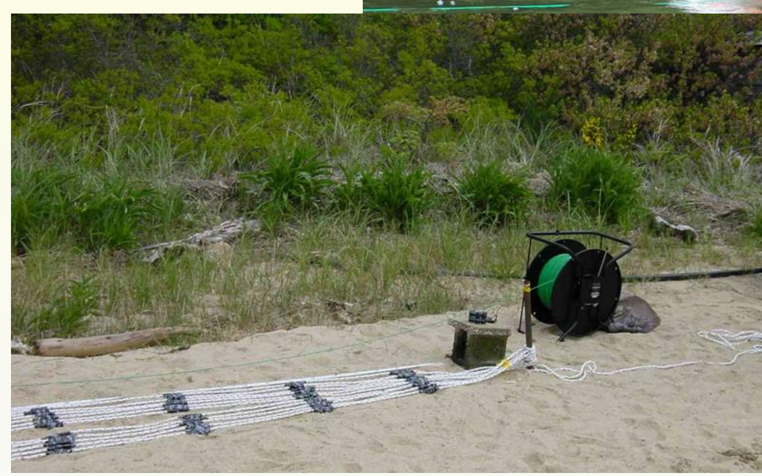
$z$ = depth beneath the sediment-water interface

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 everywhere the same at that depth, all we need to do is map the temperature at the bed surface. Then, using the above equation, we can map $q$.

# Fiber Optic – Distributed temperature system (FO-DTS)

Here's an efficient way to 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*

# 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.

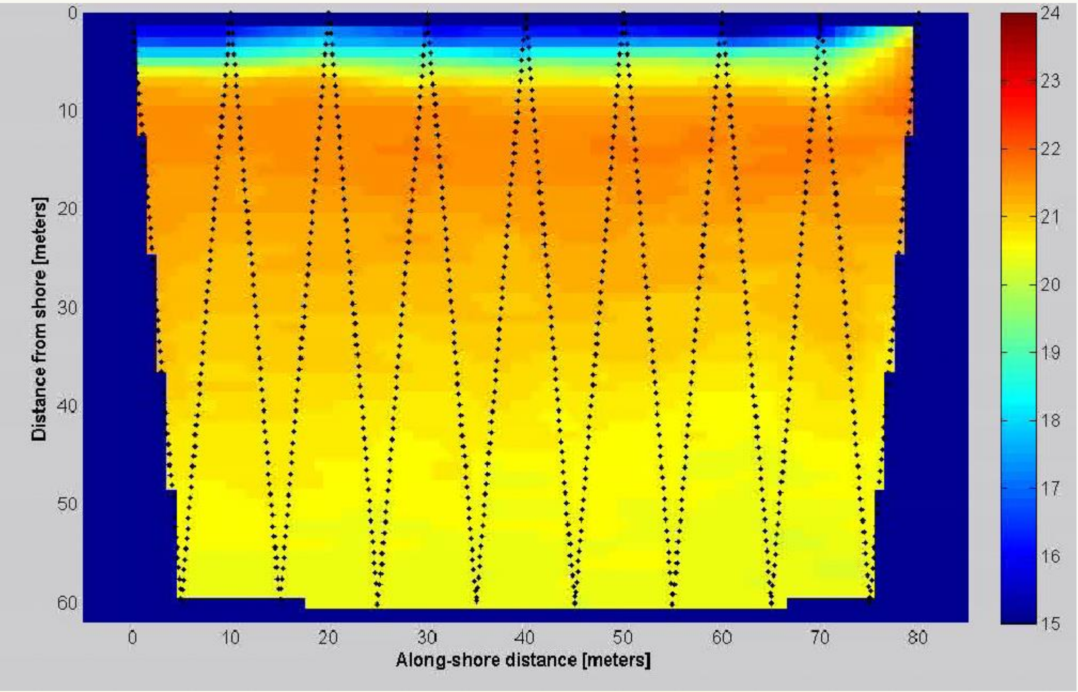


USGS
science for a changing world

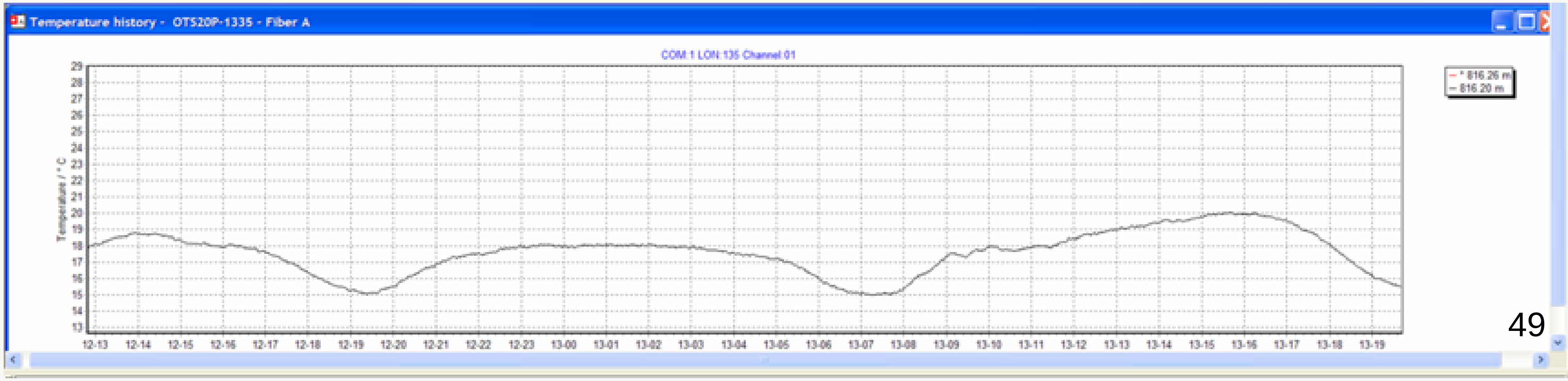
# Great spatial resolution

## GW discharge occurs primarily within 5 m of shore

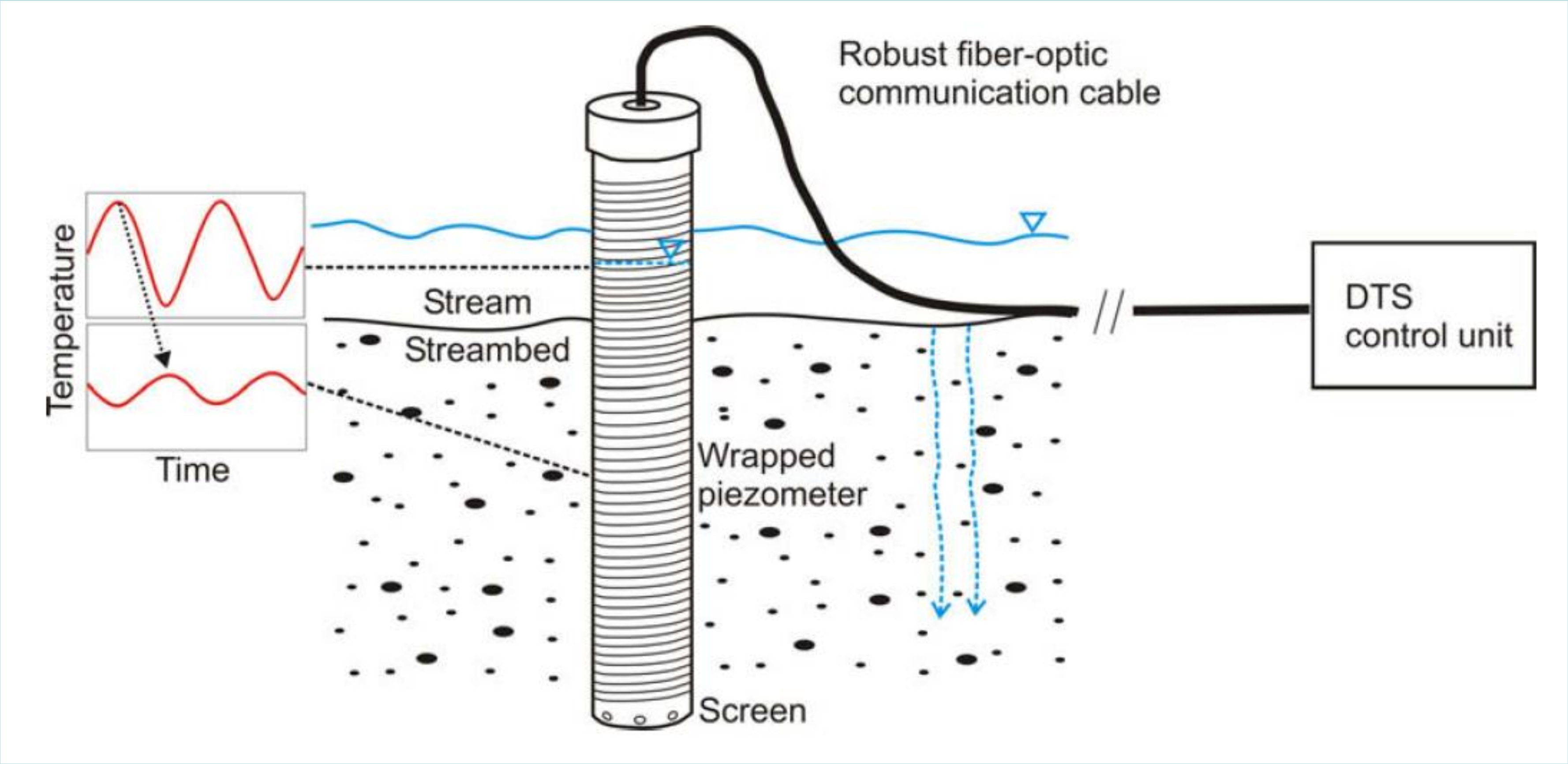
Here blue indicates cold water. These data indicate GW discharge was greatest within 5 m of the shoreline. The bottom graph shows that temperature changes with the tide, indicating that GW discharge also is changing in response to tides.




## Temp vs. time: (1m from shore)



# 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 use of technology that was developed for an entirely different purpose.

Vogt et al., 2010, *JHydrol*.

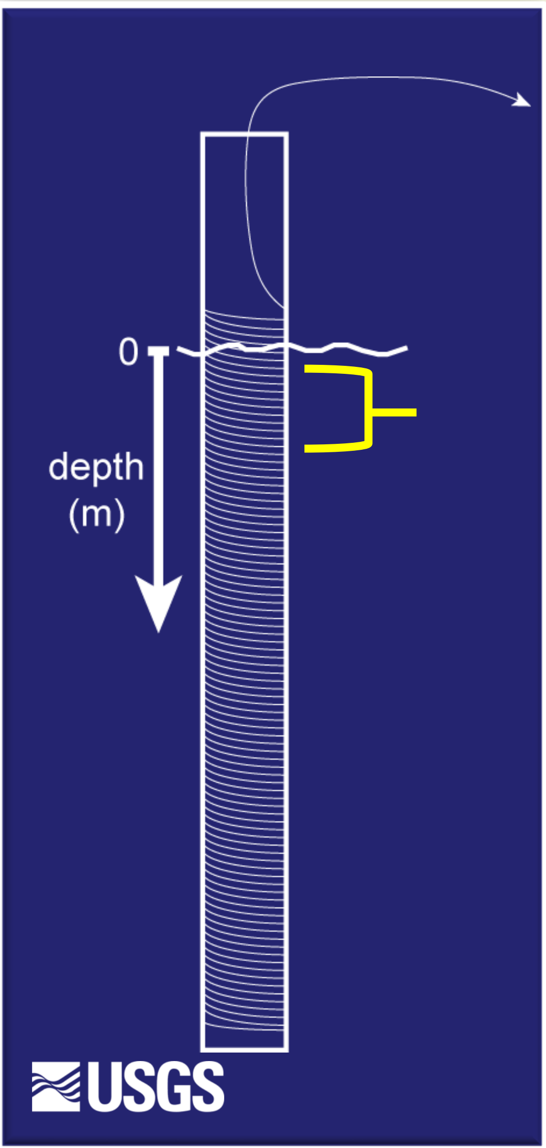
# Wrapped fiber-optic cable to give vertical temperature resolution of 1.4 cm

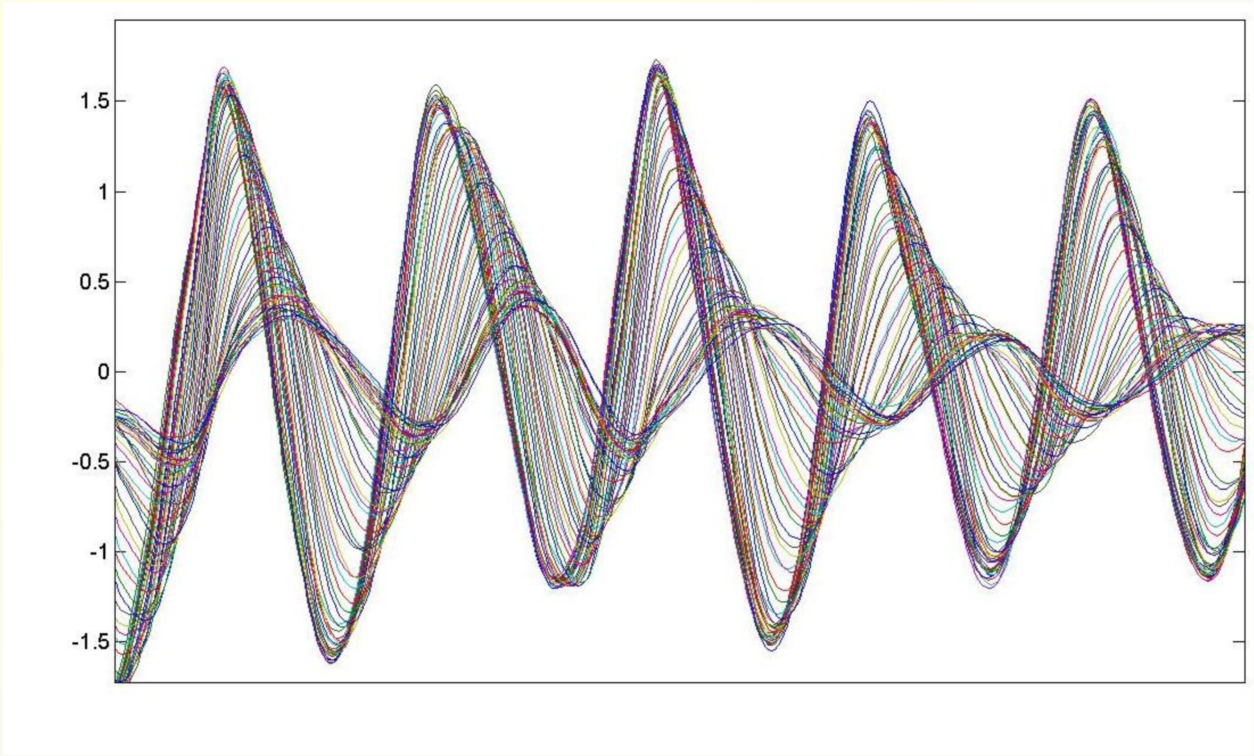
This is Marty Briggs' design. Those silver pipes to the right are actually wrapped with fiber-optic cable just as you can see in the close-up above. The pipes are installed in holes drilled in the sediment bed with the auger connected to a gasoline-powered drill.

# HRTS Installation

Briggs et al., 2013,
*ES&T*

# Applications: High Spatial Resolution




Briggs et al., 2012, WRR

The Briggs et al. design gets a temperature value every 1.4 cm vertical depth increment.

# 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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