Using Temperature Measurements to Map and Quantify Flow across the Sediment/Water Interface

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Outline

• Introduction: The GW/SW Methods Toolbox
• Focus: Heat as a tracer
• 1D vertical profiles for quantitative inference of flux
  – Data collection
  – Analysis
  – Modeling software: 1DTempPro
• Distributed temperature sensing for qualitative mapping of groundwater discharge
  – Data collection
  – Processing/interpretation
  – Visualization/processing software: DTSGUI
• Summary
Introduction: The GW/SW Methods Toolbox

- **Electrical** - resistivity, induced polarization, self potential – surface, waterborne
- **Seismic** – MASW, refraction, reflection, passive seismic/microtremor – surface, waterborne & CHIRP
- **Radar** – reflection & transmission – borehole, surface and waterborne
- **EM** – TDEM, FD inductive EM – surface and waterborne
- **Airborne**: sUAS, FLIR, AEM, etc.
- **Temperature**: Fiber-optic distributed temperature sensing, FLIR camera
Heat as a Tracer: Background

Select history of heat tracing in the U.S.:

- Lewis and Clark, 1804

Which river fork is shortest passage to Rockies

- Thoreau, 1854

Walden pond springs cold in summer/warm in winter

- USGS and others, last ~ 70 yrs

Sensing technology and approaches to determine fluid flux

[Image of Lewis and Clark Expedition stamp]

[Image of Henry David Thoreau]
Heat as a Tracer: Background

Key references:


“…. It appears feasible that temperature measurements can be used for calculating flow velocity and that a combination of head and temperature measurements can be used for calculating aquifer permeability (Stallman, 1963).”

Anderson (2005)
Heat as a Tracer: Background

[Stonestrom and Constantz, USGS Circular 1260, 2003]
Heat as a Tracer: Why?

• Cheap to collect – hardware < $100 per measurement device
• Data collection from multiple platforms, across scale – point probes, DTS, sUAS, etc.
• Cheap to analyze – done by the device; may need external calibration
• Straightforward to interpret qualitatively – cold/warm zones
• Straightforward to model quantitatively and an abundance of tools – Next slides…..
1D Vertical Profiles: Data Collection

A. Conventional 1-D probe with thermistors at discrete depths ➔ Robust, inexpensive, low resolution

B. High resolution distributed sensing system (fiber optic cable) ➔ Expensive, high resolution, ease of calibration

from Gordon et al. 2012
How does this work?

- Propagation of the diurnal (or other) heating and cooling of the streambed depends on vertical GW/SW exchange
- Amplitude and time lag (phase) at a given depth depend on flow direction and rate
- In presence of downward flow, the temperature signal at a given depth has greater amplitude than under upward flow
  - Measure temperature time series at multiple depths
  - Calibrate analytical or numerical models to data to infer discharge rate, q
  - Calculate $K_v$ (if heads are known)
1D Vertical Profiles: Analysis
1D Vertical Profiles: Analysis

- Much less labor-intensive to collect than seepage meter and other direct measurements of fluid flux
- Compares favorably (e.g., $R^2=0.96$) with seepage meters
- Heat is a much easier tracer to work with than solute tracers
- Mature software for data analysis

Figure 6. Groundwater discharge through the streambed directly measured with seepage meters plotted against groundwater discharge inferred from dual signal amplitude based 1D analytical models.

[Rosenberry et al., WRR, 2016]
1D Vertical Profiles: Software

**Assumptions:**
- Saturated, steady-state flow
- 1-dimensional vertical flow

**Capabilities:**
- Inference of specific discharge, $q$, or hydraulic conductivity, $K$ (with heads)
- Non-sinusoidal, non-stationary boundary conditions
- Time-varying discharge
- Layer heterogeneity (any property)
- Automated parameter estimation
- Parameter sensitivity
- Model archiving

![Graph showing temperature profiles over time with various input parameters and simulation settings.](image-url)
Learning Lab
Wednesday 10:30-10:55

1DTempPro
version 2.0

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

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https://pubs.er.usgs.gov/publication/70157483
Distributed Temperature Sensing: Data Collection

- Commercially available for ~2 decades
- Principal markets: Petroleum; Fire Detection; Dam monitoring
- First papers on DTS in hydrologic literature by Selker et al. (2006)
- Raman-based systems:
  - Current precision: +/- 0.01 deg C (~0.1 in practice)
  - Spatial resolution: ~1 m, new instruments report ~10 cm
  - Control units ~$12K – $100K
  - Armored cables ~$4-5/m
Distributed Temperature Sensing: Data Collection

- Control unit transmits laser light
- Optical fiber in cable acts as a "light pipe"
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, Raman)

  - Backscatter is analyzed to estimate temperature and location along the cable
DTS: Processing/Interpretation

Locating contaminated GW gains

- Rich, complex datasets
- Data must be carefully georeferenced & calibrated
- Capitalize on GW/SW contrast
- Used to identify:
  - cold/warm reaches in summer/winter
  - Reaches of low variance
- Amenable to:
  - time-series and spectral analysis
  - Mixing models

[Briggs et al. 2012]
DTS: Processing/Interpretation

Example: Permeable Reactive Barrier

- McCobb et al., 2018, JEM
- Mapping areas of focused discharge
- Processing/visualizing involved GIS
- Labor-intensive to fully capitalize on information provided
DTS: Processing/Interpretation

Example: Hanford, WA

- [Mwakanyamale et al., WRR, 2012, 2013]
- Mapped areas of focused discharge
- Combined discriminant analysis classification and spectral analysis of DTS data
- Trained to sediment thickness from geophysical data (T)
- Results:
  - Classification of high vs. low exchange areas (DA)
  - Provides confidence of the classification (p)
DTS: Software
DTSGUI

- Python-based GUI for data processing, visualization, editing, archiving
- [Domansky et al., accepted pending revision, Groundwater]
DTS: Processing/Interpretation
Example: DTSGUI applied to Quashnet River, Cape Cod
DTS: Processing/Interpretation
Example: DTSGUI applied to Quashnet River, Cape Cod

change in calibration, could trim....

add variance analysis, low indicates GW inflow, regardless of season
DTS: Processing/Interpretation

- Quickly find and download background imagery
- Quickly locate and inspect cold/warm reaches and compare to background imagery
- Quickly calculate and plot summary statistics
- Quickly edit datasets or focus on time periods or sub reaches of interest in large datasets
- Quickly organize data for archiving
- [Domansky et al., accepted pending revision, Groundwater]
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Summary/Take Away

• Heat is an effective and cost-effective tracer for:
  – Qualitative/reconnaissance work
  – Quantitative estimation of fluid flow across the sediment/water interface

• 1D Temperature profiles
  – Effective and cost effective for quantitative estimation of vertical fluxes
  – Mature software available (e.g., 1DTempPro, VFLUX, and others)

• Distributed temperature sensing
  – Effective and cost effective mapping of groundwater discharges (recon)
  – Rich and complex datasets amenable to time-series and spectral analysis and (in some cases) mixing models
  – New software (DTSGU) to facilitate processing, visualization and interpretation

• sUAS data collection has potential to provide additional
  high-resolution and spatially exhaustive
  – Background imagery
  – temperature data
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