Fiber-Optic Distributed Temperature Sensing: Theory and Application to Monitoring Problems

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- USGS Toxic Substances Hydrology Program
- USGS Groundwater Resources Program

OUTLINE

Introduction

- The geophysical toolbox
- Temperature data
- Fiber-optic distributed temperature sensing

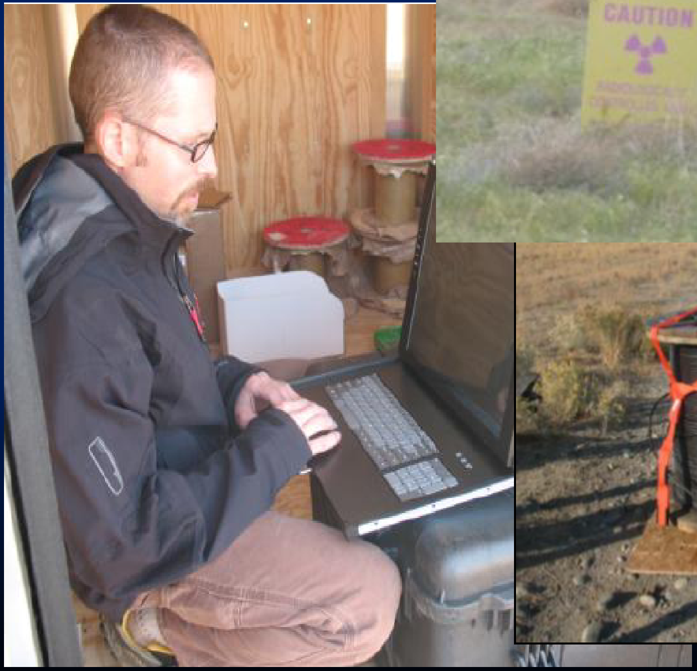
Studies:

(1) Waquoit Bay, MA

(2) Columbia River, Hanford (ERSP)

Potential for application to leak detection

Conclusions & Future Directions

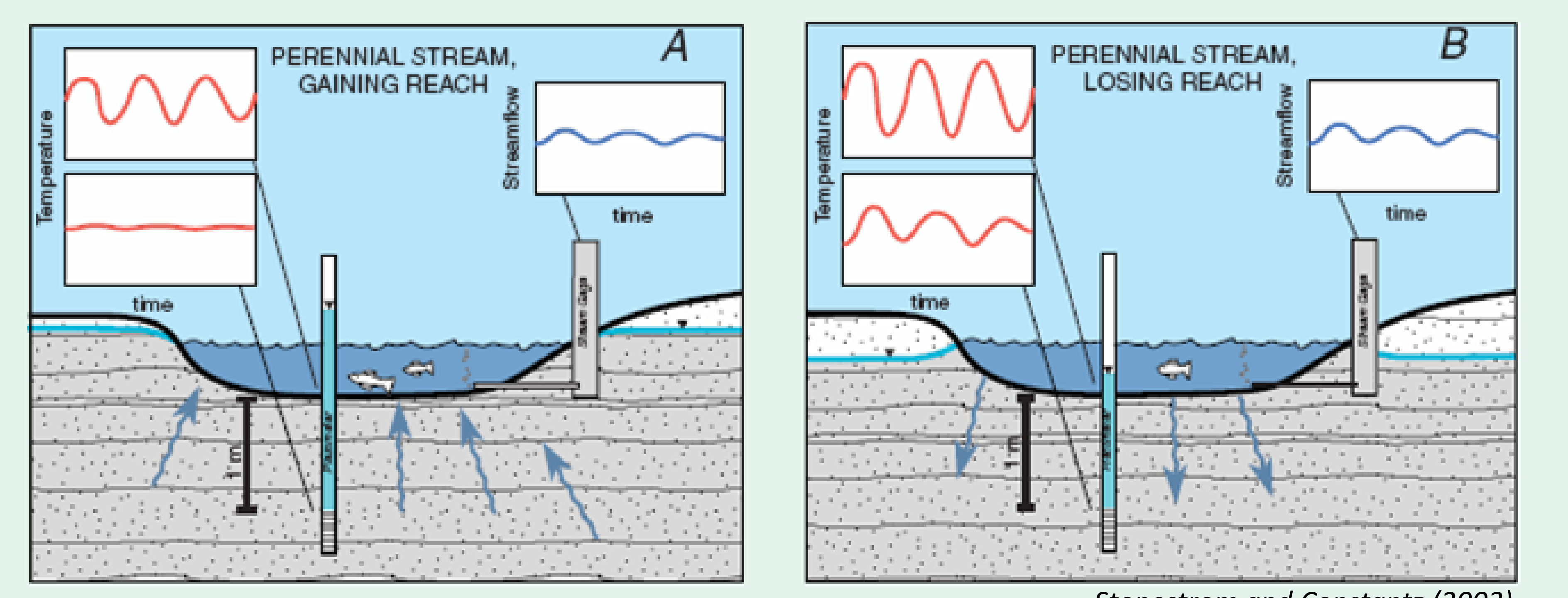


The Hydrogeophysics "Toolbox"

- Electrical - resistivity, induced polarization, self potential
- Seismic – MASW, refraction, reflection, passive seismic/microtremor
- Radar – borehole reflection & transmission, surface reflection
- EM – TDEM, EM Induction
- Gravity – relative, absolute
- Marine: resistivity, chirp seismic, GPR
- Airborne: EM, FLIR, etc.
- Temperature: Fiber-optic distributed temperature sensing

Temperature in the Toolbox

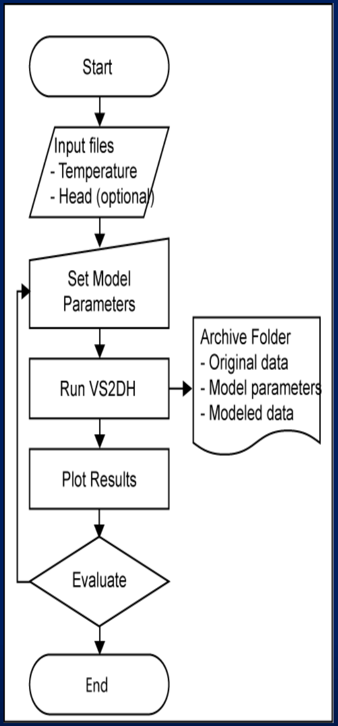
Identifying gaining and losing reaches of streams
Inference of discharge/recharge rates
Inference of aquifer properties (K)

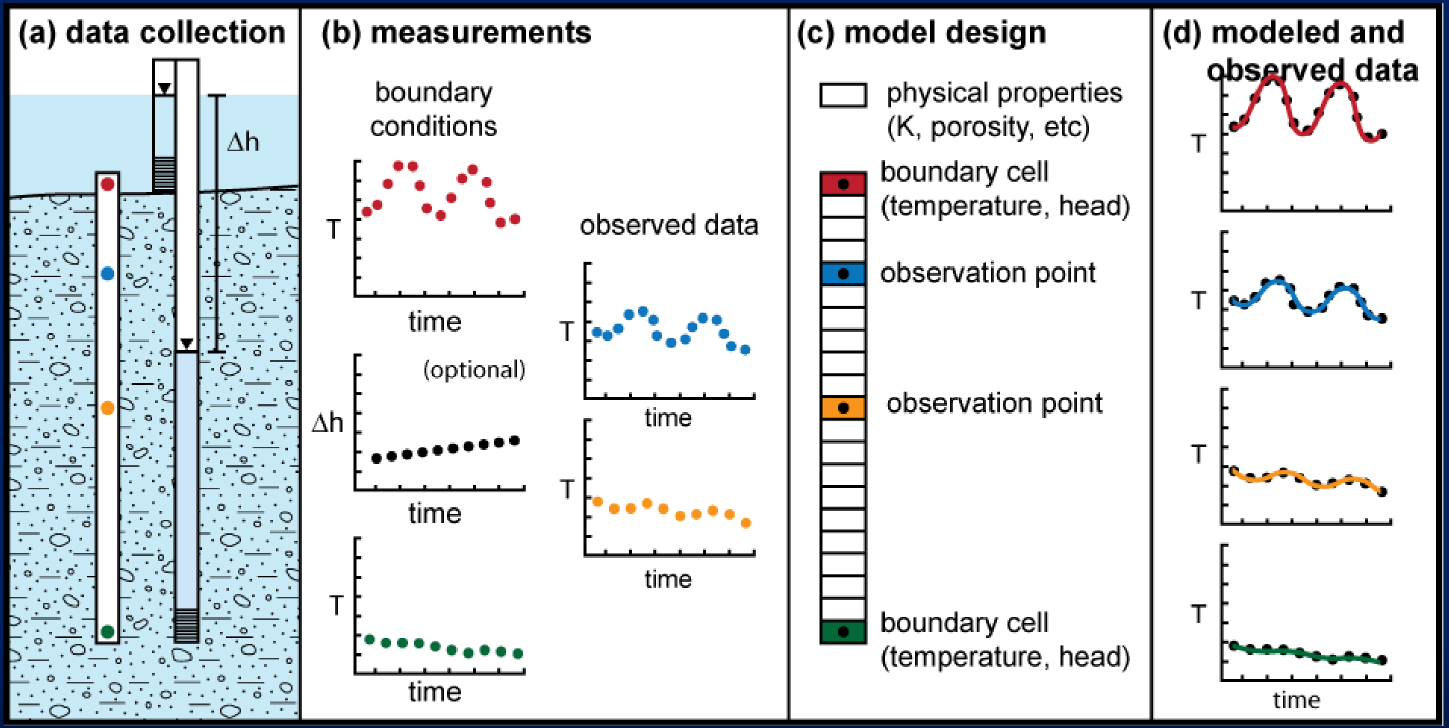


Stonestrom and Constantz (2003)

Temperature Data in Hydrology

Possible to estimate vertical fluid flux from temperature time series at different depths





Voytek et al., *1DTempPro: A tool for analyzing temperature profiles for groundwater/surface-water exchange*, in USGS review

Fiber-Optic DTS (FODTS)

- Commercially available for over a decade
- Principal markets: Petroleum; Fire Detection; Dam monitoring
- Can be installed alongside pipes or inside infrastructure
- USGS demo (20+ sites), 2005-2007
- First papers on technology in hydro literature by Selker et al. (2006)
- Raman-based systems:
  - Current precision: <+/- 0.01 deg C (~0.1 in practice)
  - Spatial resolution: ~1 m (~2 m in practice, new instruments and/or cables report 10 cm)
  - Pricing from ~$15K – $100K

Applications to Leak Detection

Capitalize on:

- Temperature contrast between leaked fluids and native pore water (or surface water)
- Joule-Thomson effect (cooling at leaks in high-P pipelines)
- Change to thermal properties of porous media with saturation
- Strain and/or vibration/sound associated with rupture or leaks

Advantages:

- High spatial resolution
- Permanent installation
- Mature technology for autonomous monitoring & alarms
- Rapid data collection & minimal processing → actionable info.

Limitations:

- Point measurements (not remote sensing)
- Requires temperature contrast or change in thermal properties

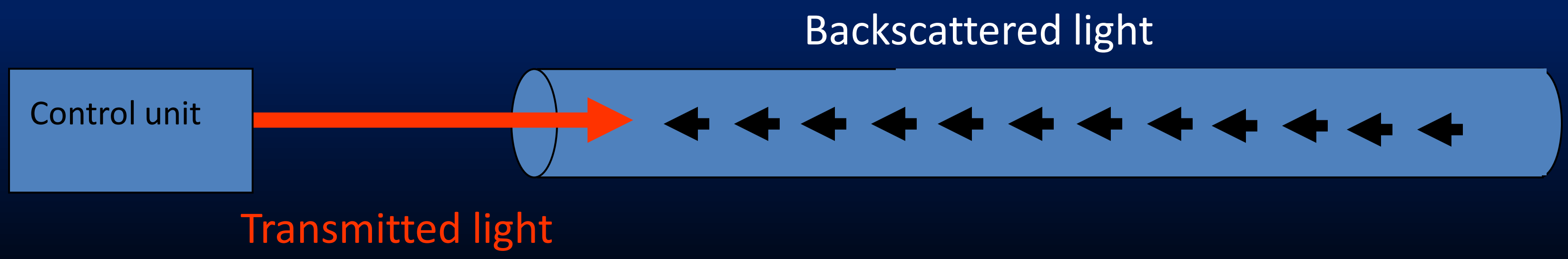
USGS

Stonestrom and Constantz (2003)

Websites for omnisens, sensornet, ap sensing, sensortran, etc. (Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US Government.)

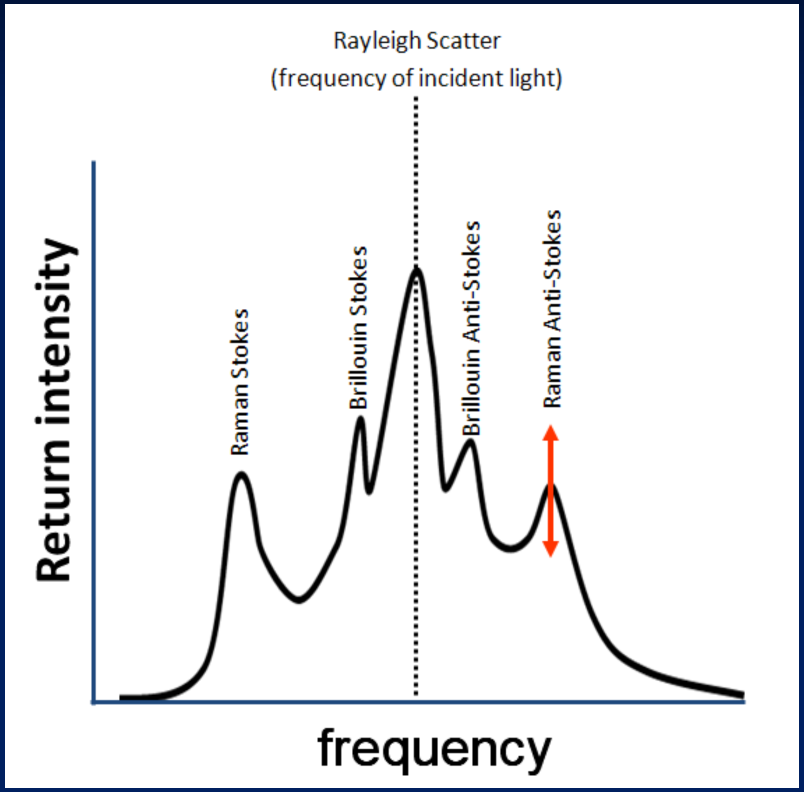
DTS Measurement Physics (1)

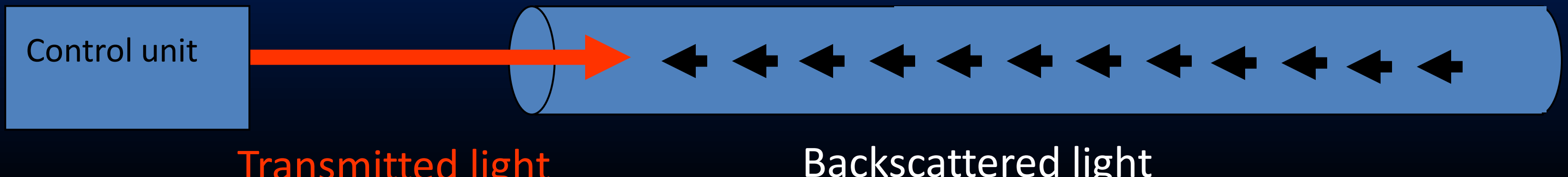
- Control unit transmits laser light down cable
- Cable acts as a "light pipe"
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, **Raman**)
  - *Backscatter spectrum is measured and analyzed to estimate temperature all along the cable*



DTS Measurement Physics (2)

- Control unit transmits laser light down cable
- Cable acts as a “light pipe”
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, **<u>Raman</u>**)
  - *Backscatter is measured and analyzed to estimate temperatures*
  - *OTDR time-of-flight calculation to localize measurements in space*



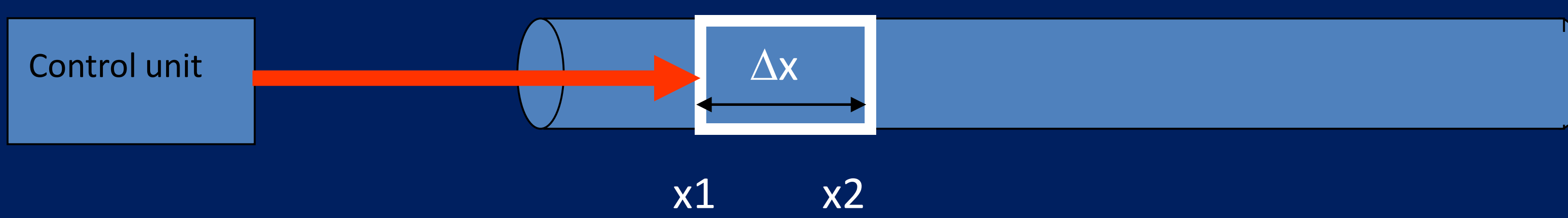


Measurement Physics (3)

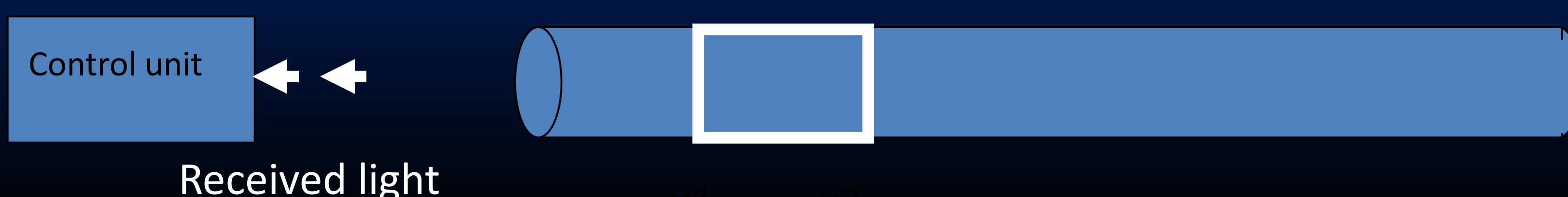
OTDR "time of flight":

– At t=0, laser pulse fires, light travels down glass at constant speed, c:

– Light reaches x1 at c x t1 and x2 at c x t2; best Δx limited by pulse width



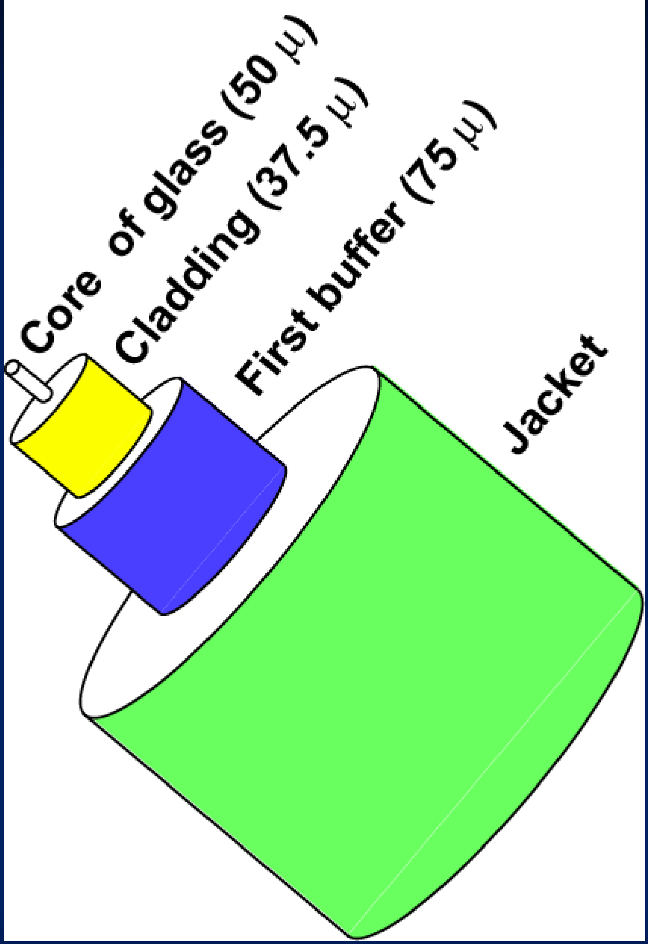
– Can relate backscatter measured over a time window to a spatial interval of the fiber, knowing the speed of light in glass

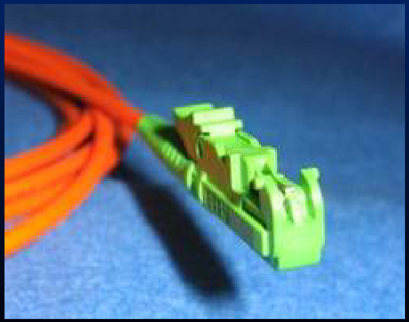


Cable and Fiber (1)

Fiber from inside out:

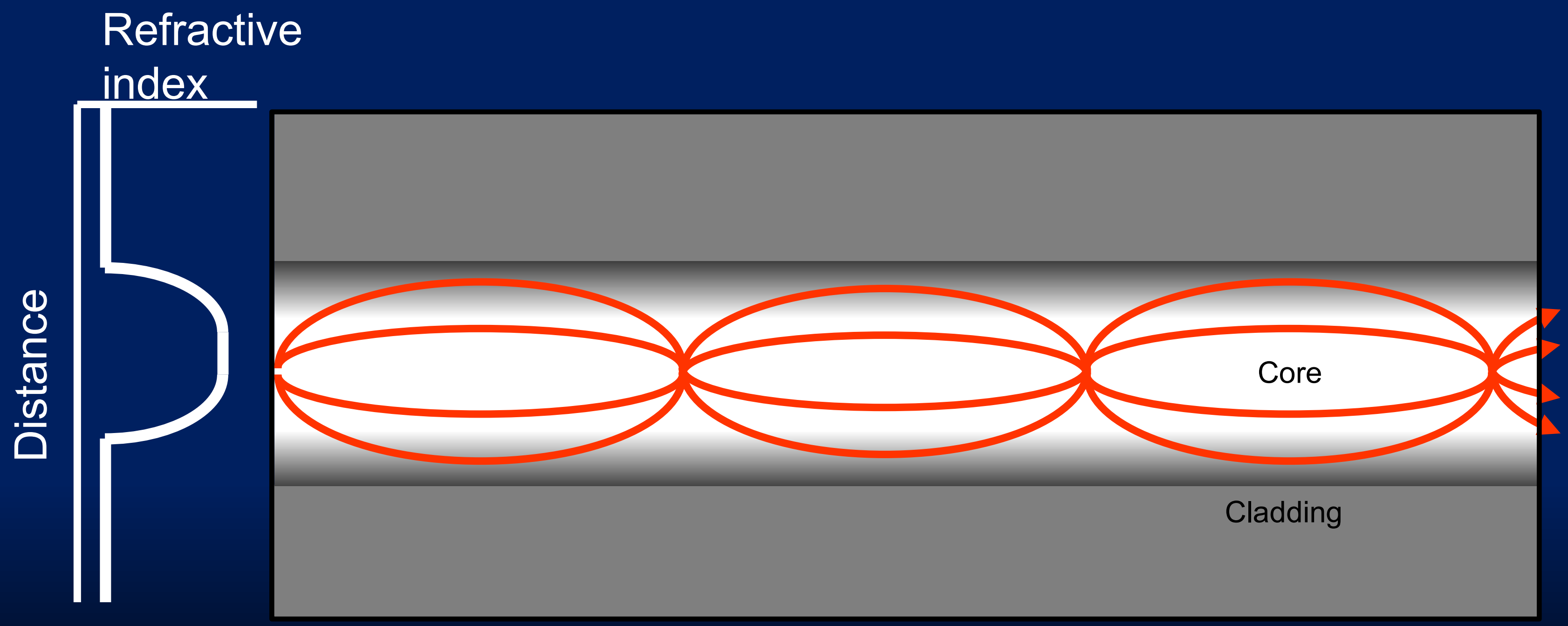
- **Core**: glass, commonly 50- or 62.5-micron diameter multimode for DTS work; index of refraction varies across the cross section
- **Cladding**: 37.5 micron glass with lower index of refraction
- **First buffer**: 75 micron plastic
- **Jacket/Sheathing**: Many options; can be either “loose tube” or “tight”; keeps water out, protects fiber
  - Loose – gel filled, reduces strain on fiber
  - Tight – more common and cheaper





Cable and Fiber (2)

- Multimode, graded index fiber: A light pipe



As light approaches sides of the fiber, it refracts back toward the core

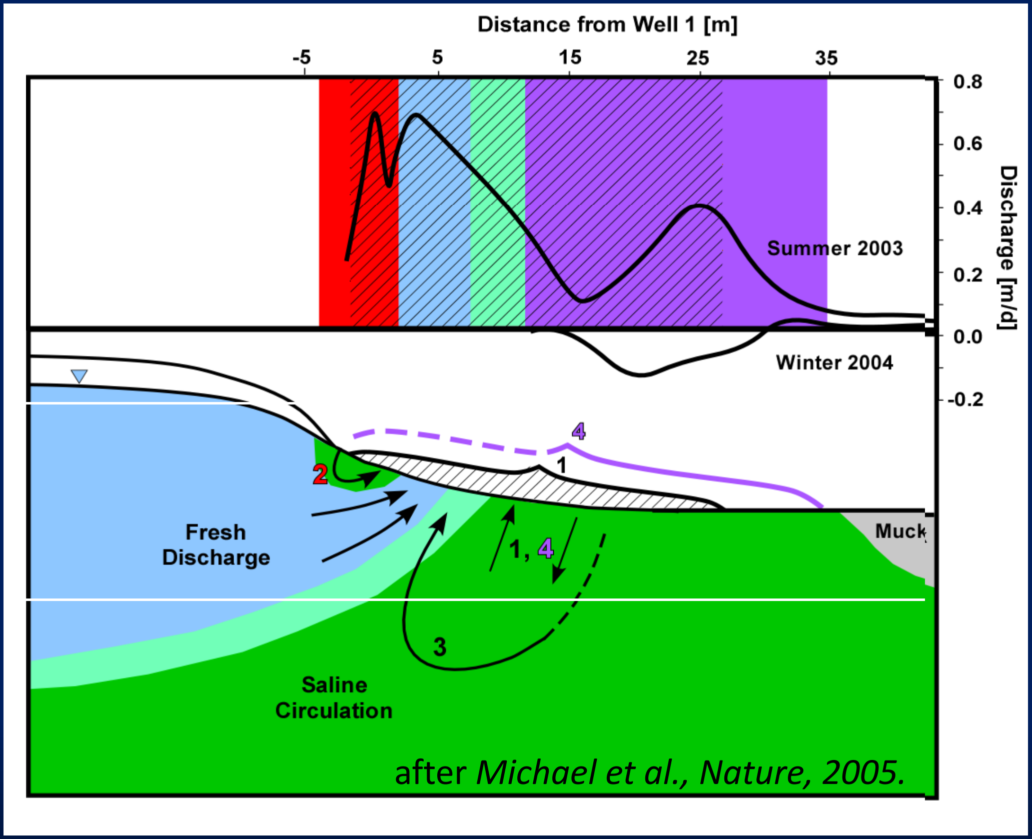
Cable and Fiber (3)

- Cable costs: < $1/m to $50/m depending on the amount of armoring, number and types of fibers, etc.
- Cable weight: 10’s to 100’s of lbs per km depending on armoring
- Major cable manufacturers:
  - AFL, OCC, Brugg

Study 1: Fiber-optic & Resistivity Monitoring of Aquifer-Estuary Interaction, Waquoit Bay, MA

Study 1: Objectives

- Evaluate combination of DTS and fixed-electrode resistivity for characterizing submarine groundwater discharge (SGD) associated with tidal pumping



Zone 1 (cross-hatching) Tidal pumping, extends from the shoreline to approximately 28 m into the bay.

Zone 2: Nearshore circulation due to tides and waves, extends approximately 3 m from the high tide mark.

Zone 3: Dispersive circulation discharges along the bayward edge of the fresh discharge.

Zone 4: Seasonal saline outflow, between 13 and 35 m from shore, but the zone likely extends to the shoreline.

Notes:

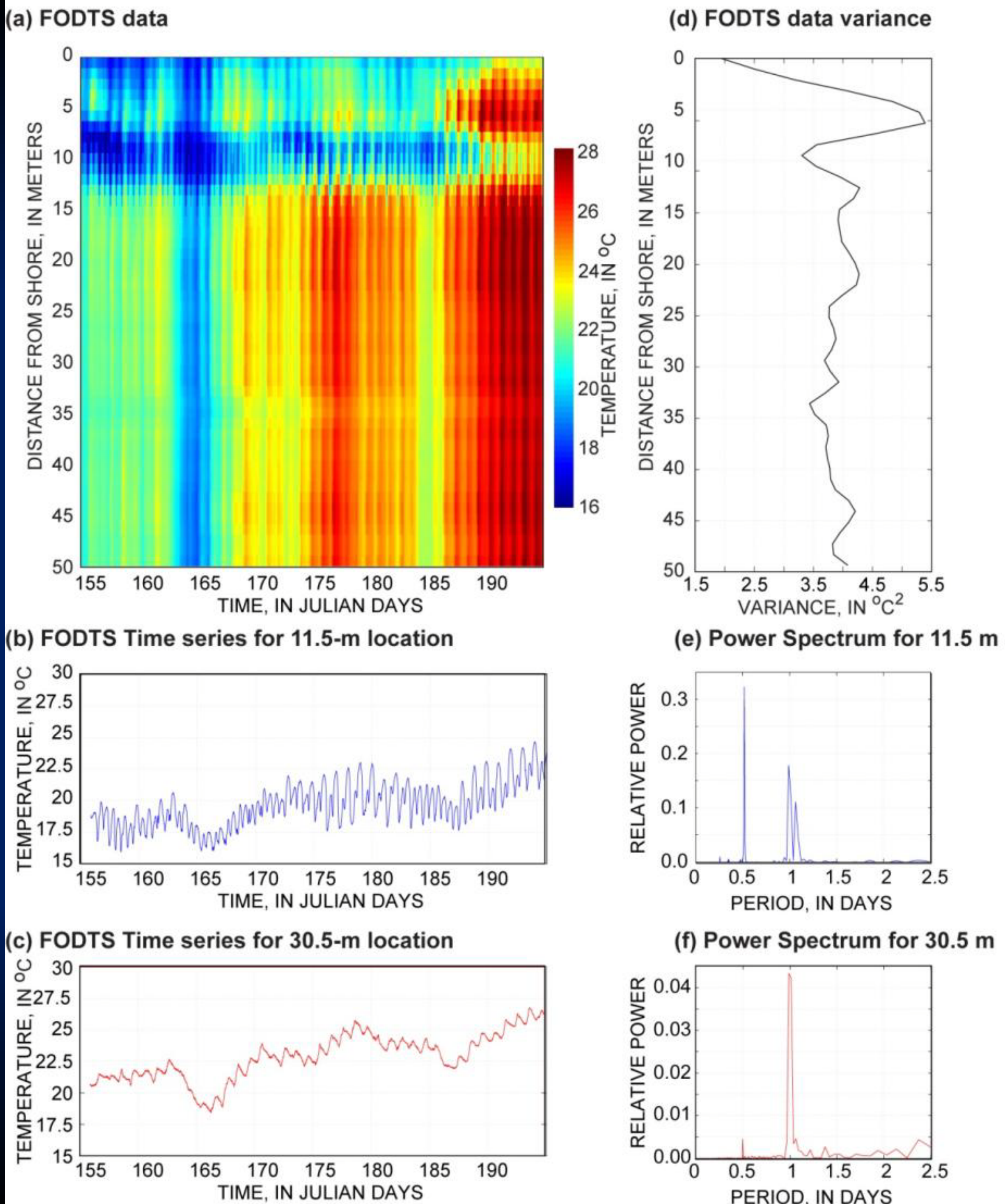
- Expectation: Fresh SGD is cold (summer condition) and electrically resistive
- Groundwater ~11 degrees C

DTS Dataset

- 40 days continuous data (additional data in HJ paper)
- Temperature data show zone of fresh tidal pumping (cold)
- Seepage measurements (not shown) indicate continuous discharge over tidal cycle, enhanced at low tide

- How to look for non-stationary behavior and correlation with other time series?

Henderson et al., GRL, 2009; HJ, 2010



Wavelet Analysis

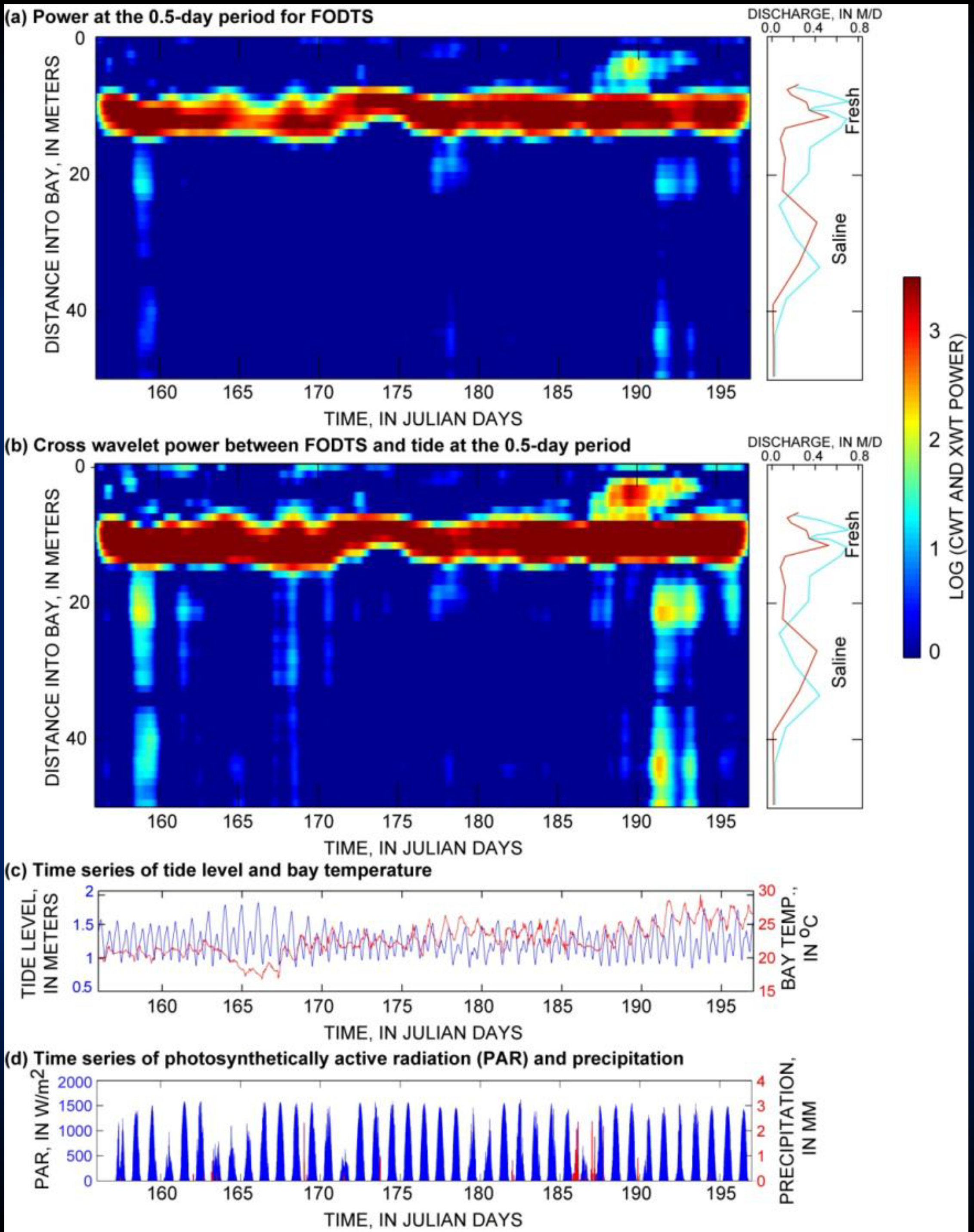
- Continuous wavelet transform (CWT) calculated for all locations

<u>Can provide insight into:</u>

- Frequency content of non-stationary signals
- Large datasets
- Relations between time series
    - Cross wavelet (XWT)
    - Wavelet coherence (WTC)

Note: Slide only summarizes one frequency component (0.5-day)

Henderson et al., GRL, 2009



Study 2: Hanford 300 Area

Contamination legacy: included 241 metric tons of copper, 117 metric tons of florine, 2060 metric tons of nitrate and between 33 and 59 metric tons of uranium.

U [VI] contours

Estimated area of contribution (from borehole projection Frtiz et al., 2007)

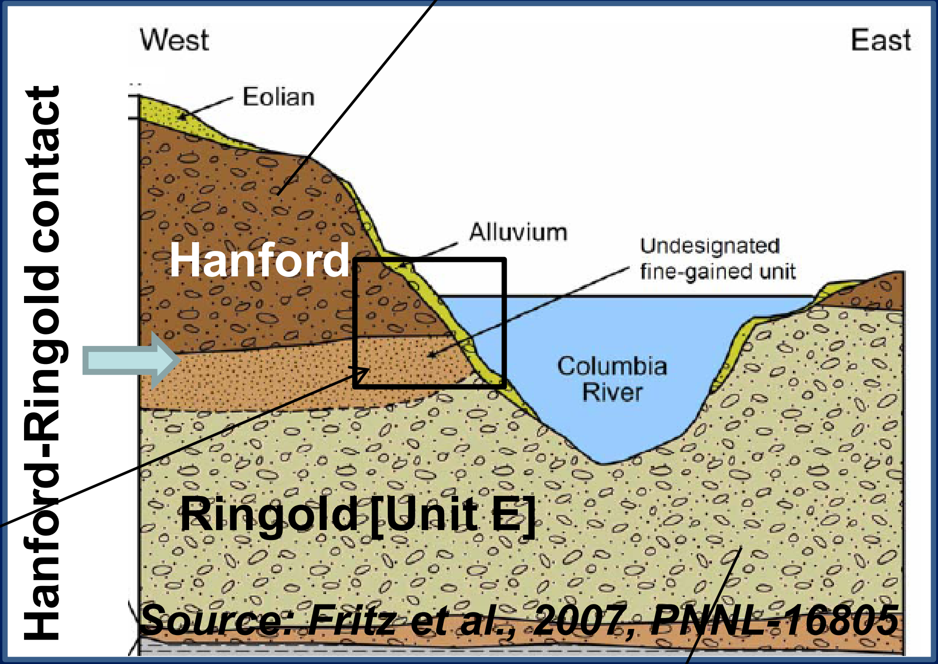
East from the Hanford 300 Area

Spatial and temporal variability in exchange between uranium contaminated groundwater and river water?

Hanford Geology

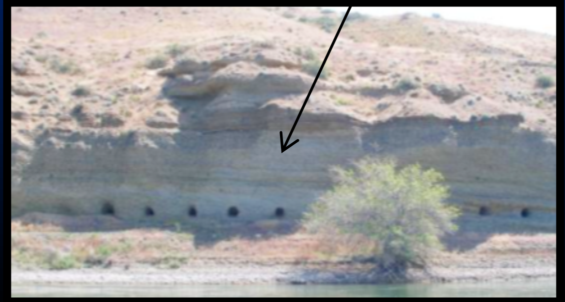
Pebble to boulder size gravels and interbedded sands

- Hanford-Ringold contact: important interface controlling flow/transport
- Intensively studied inland away from the river corridor
- Cobble layer in streambed complicates permeablity measurement and installation of piezometers



Improvements in hydrogeological framework required along corridor of surface-water/groundwater exchange

Highly heterogeneous, granule to cobble size gravels interbedded with fine sand and silt.



Water depths

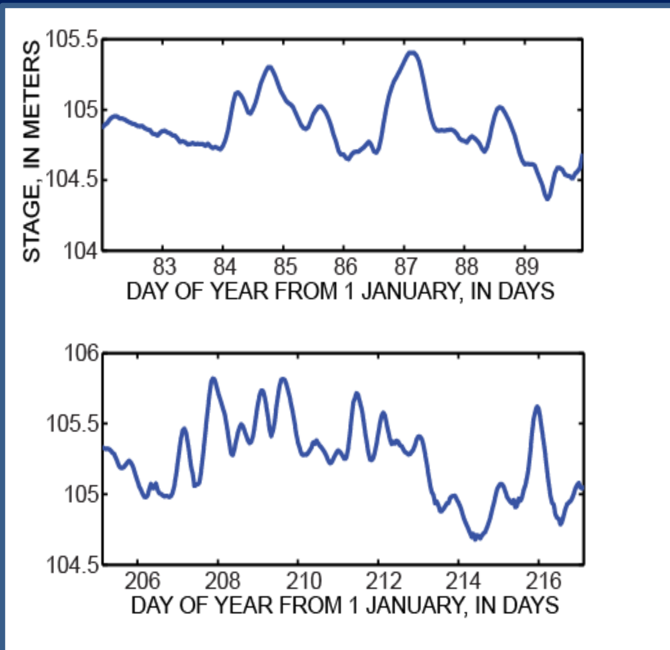
Summary of Field Data Acquisition

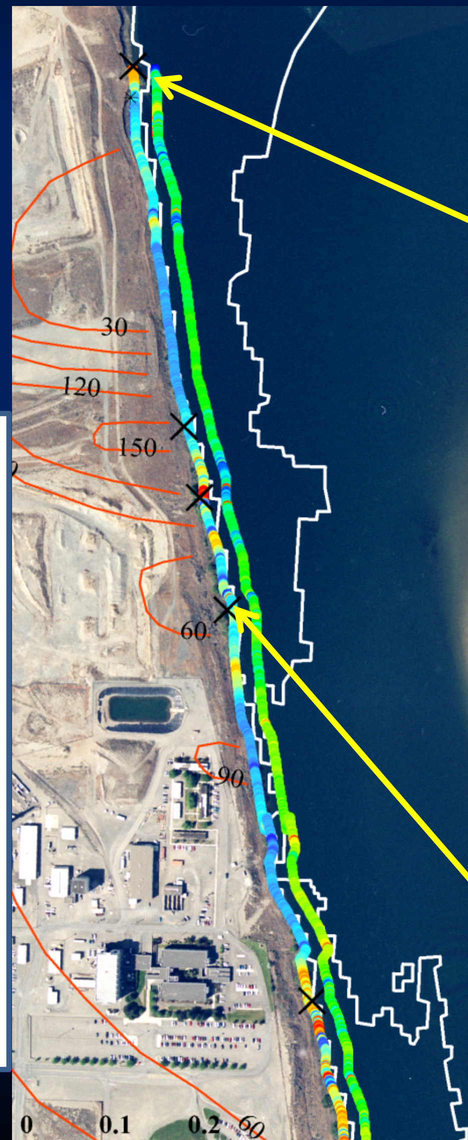
- 30 km of waterborne IP line
- 4.5 km of DTS line, ~1 to 2-m spatial resolution, 5-min interval, ~0.1ºC temperature precision
- Water depths varied from 1-14 m (in channel)
- Focus on near shore where water depth of a few meters only
- *Also waterborne seismic and GPR, land-based res/IP; 1D vertical temp,* ***not reported here***

IP
DTS
Contributing area?

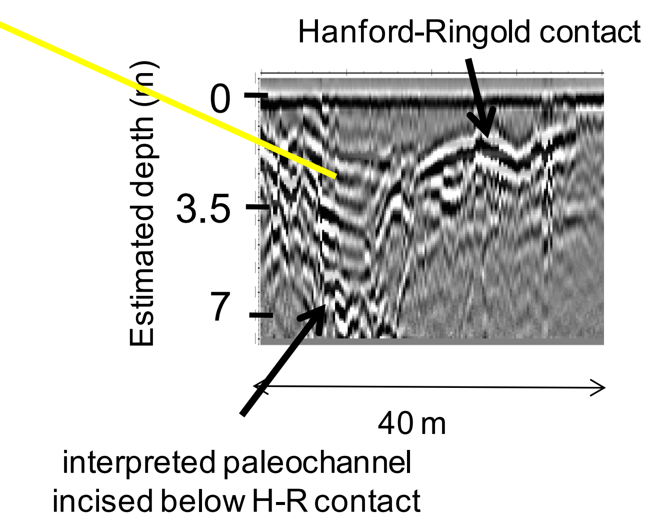
DTS Data Visualization (Winter vs. Summer)

Non-stationary river stage variations driven by seasonal effects and daily dam operations on Columbia River





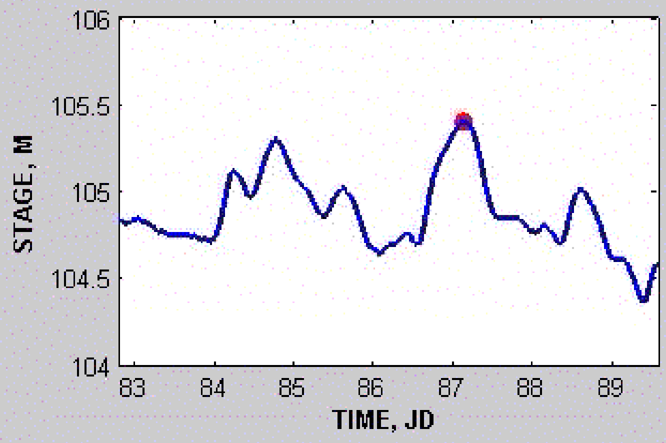
Paleochannels locally eroded beneath Hanford-Ringold contact



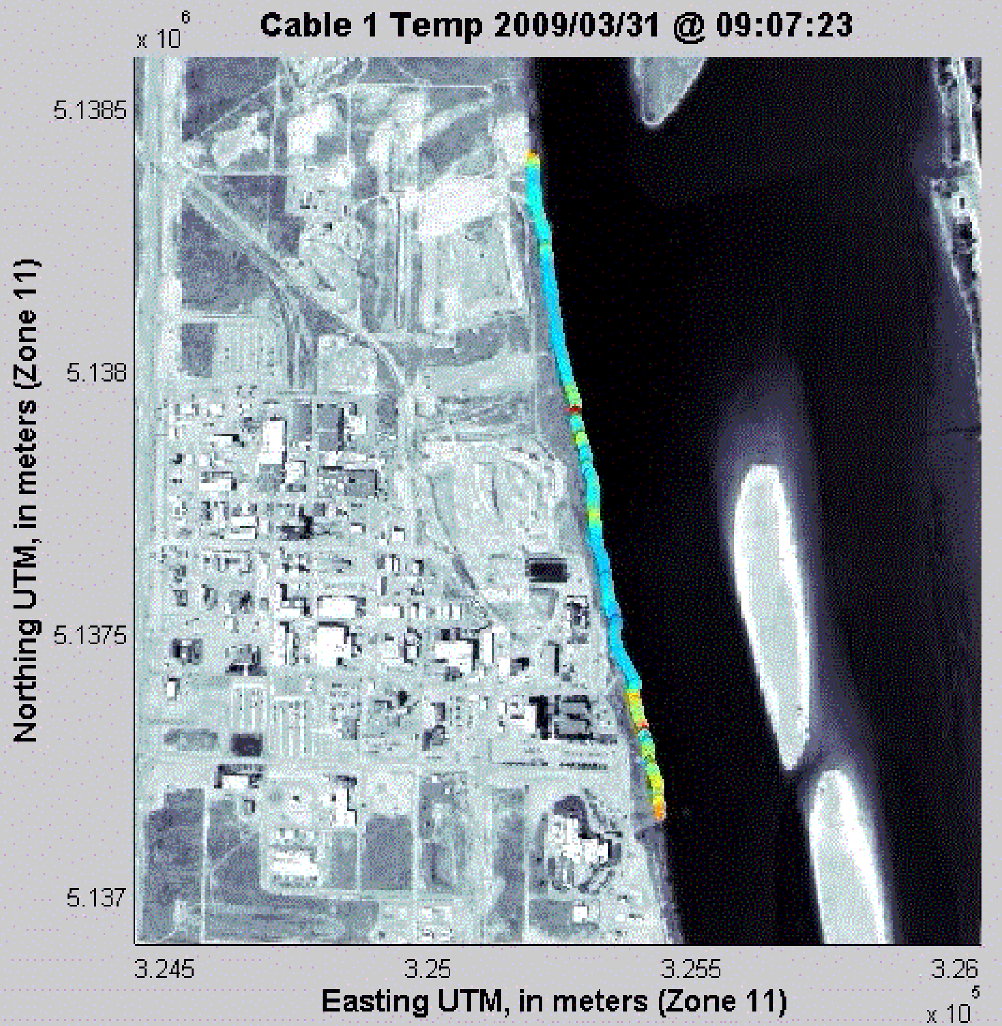
Identified uranium "seeps" (Fritz et al., 2007)

Results: DTS Monitoring of GW/SW Exchange - Winter (March 24-31, 2009)

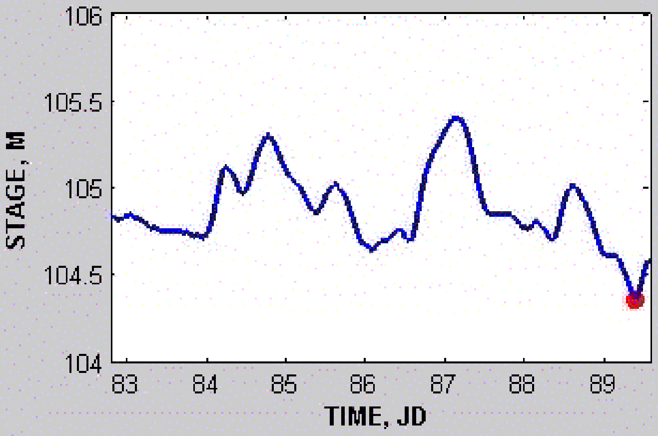
High stage



Results: DTS Monitoring of GW/SW Exchange - Winter (March 24-31, 2009)

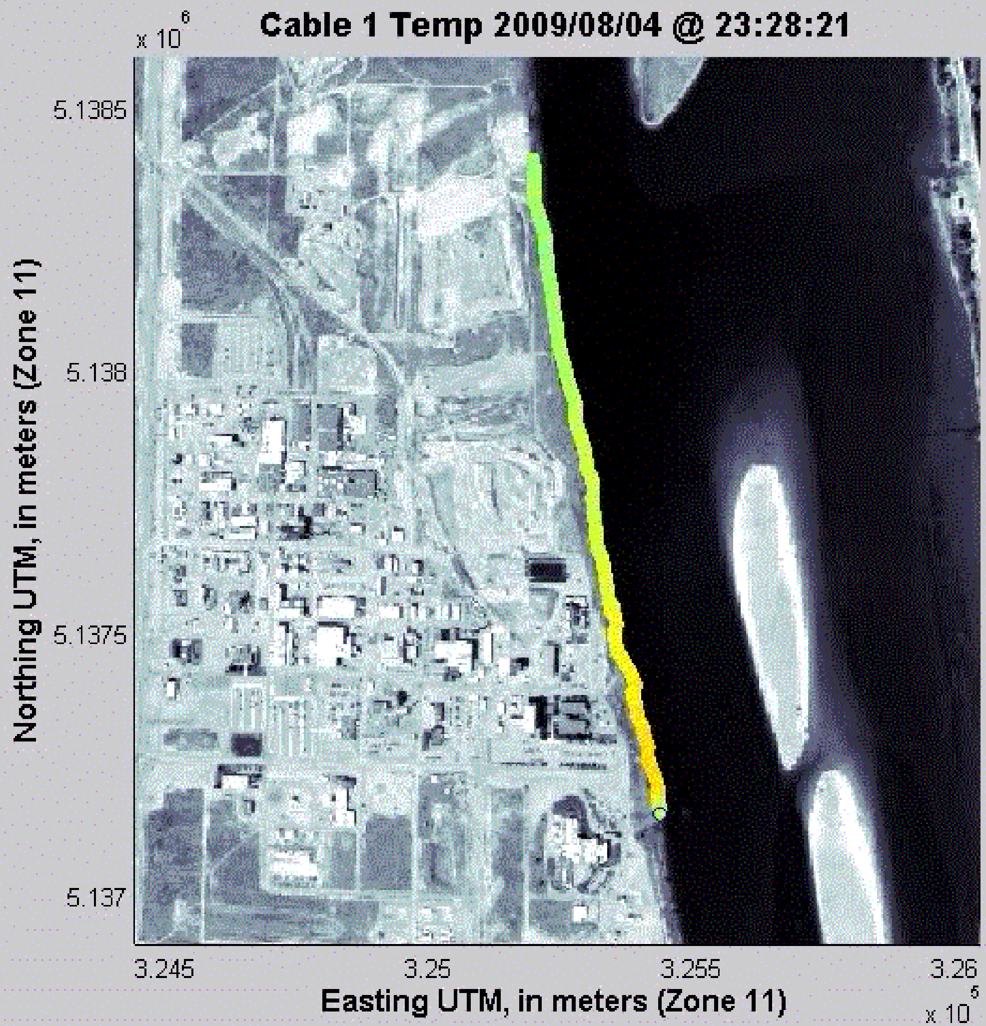


Low stage

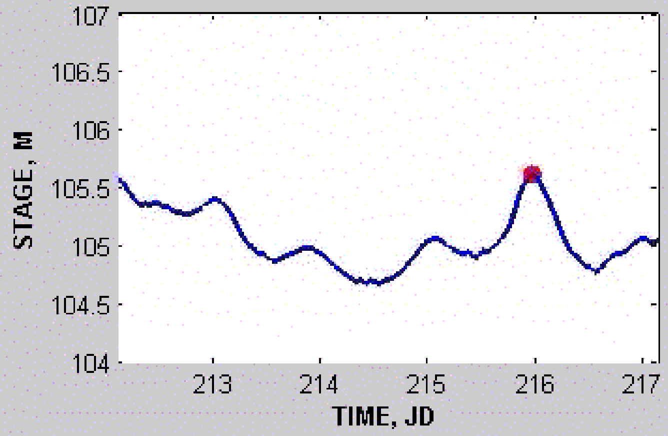


Warm anomalies indicative of focused groundwater discharge

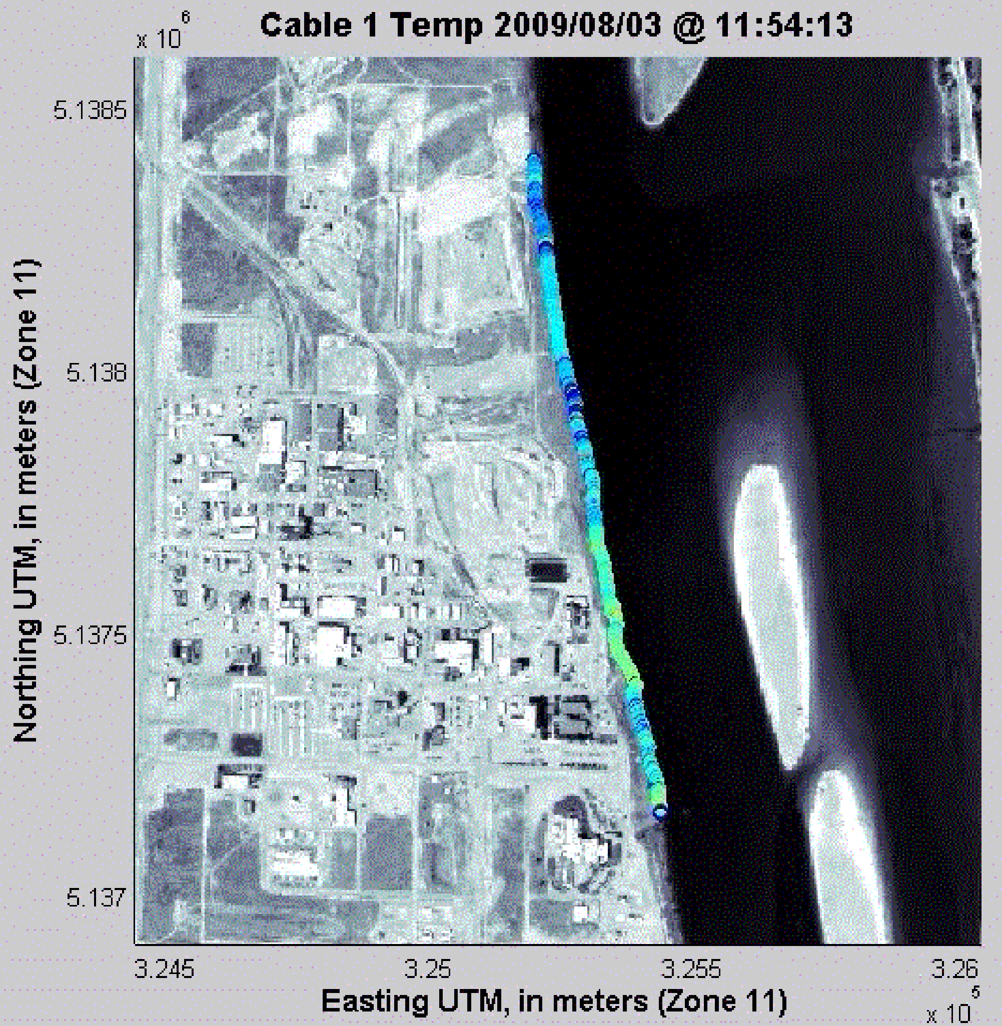
Results: DTS Monitoring of GW/SW Exchange - Summer (August 1-6, 2009)



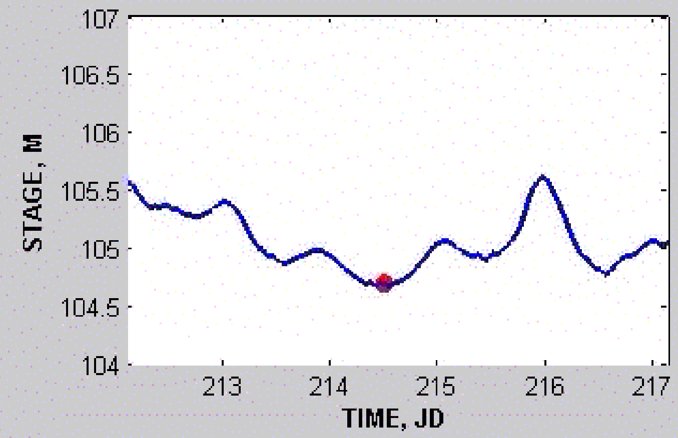
High stage



Results: DTS Monitoring of GW/SW Exchange - Summer (August 1-6, 2009)



Low stage



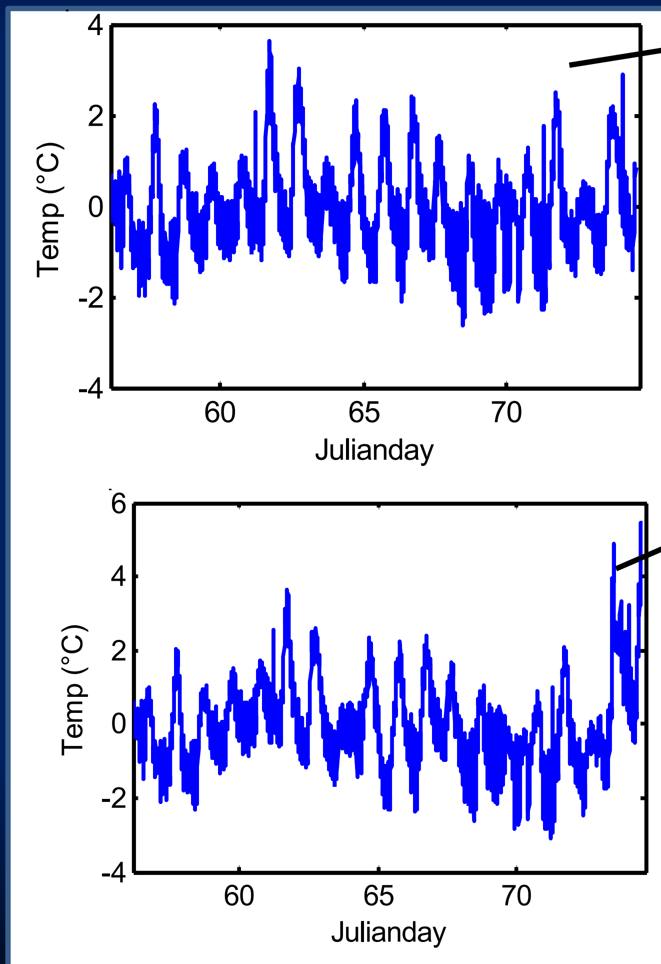
Cold anomalies indicative of focused groundwater discharge

Time-Frequency Analysis

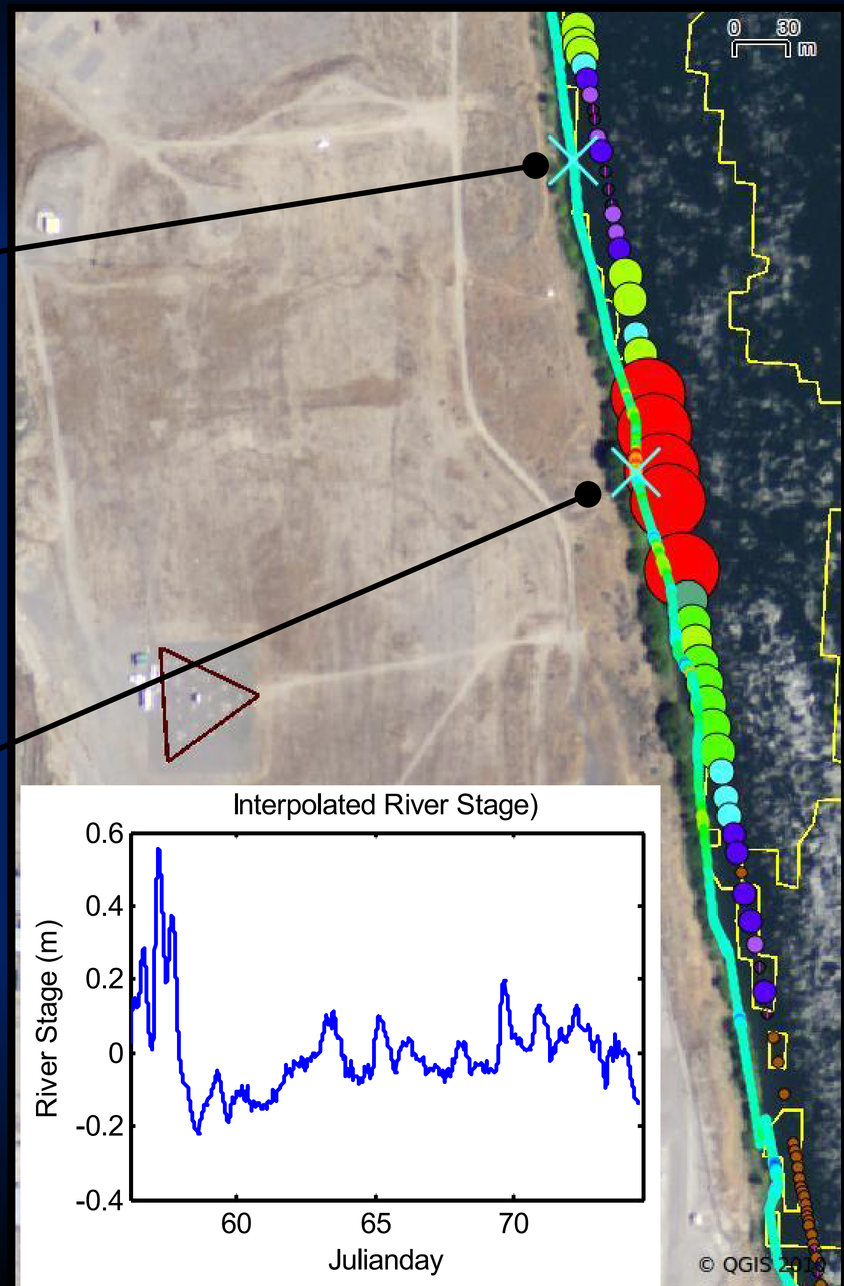
De-trended time series

Non Exchange Area

Focused Exchange Area



Stockwell (S) Transform on selected time series and stage data

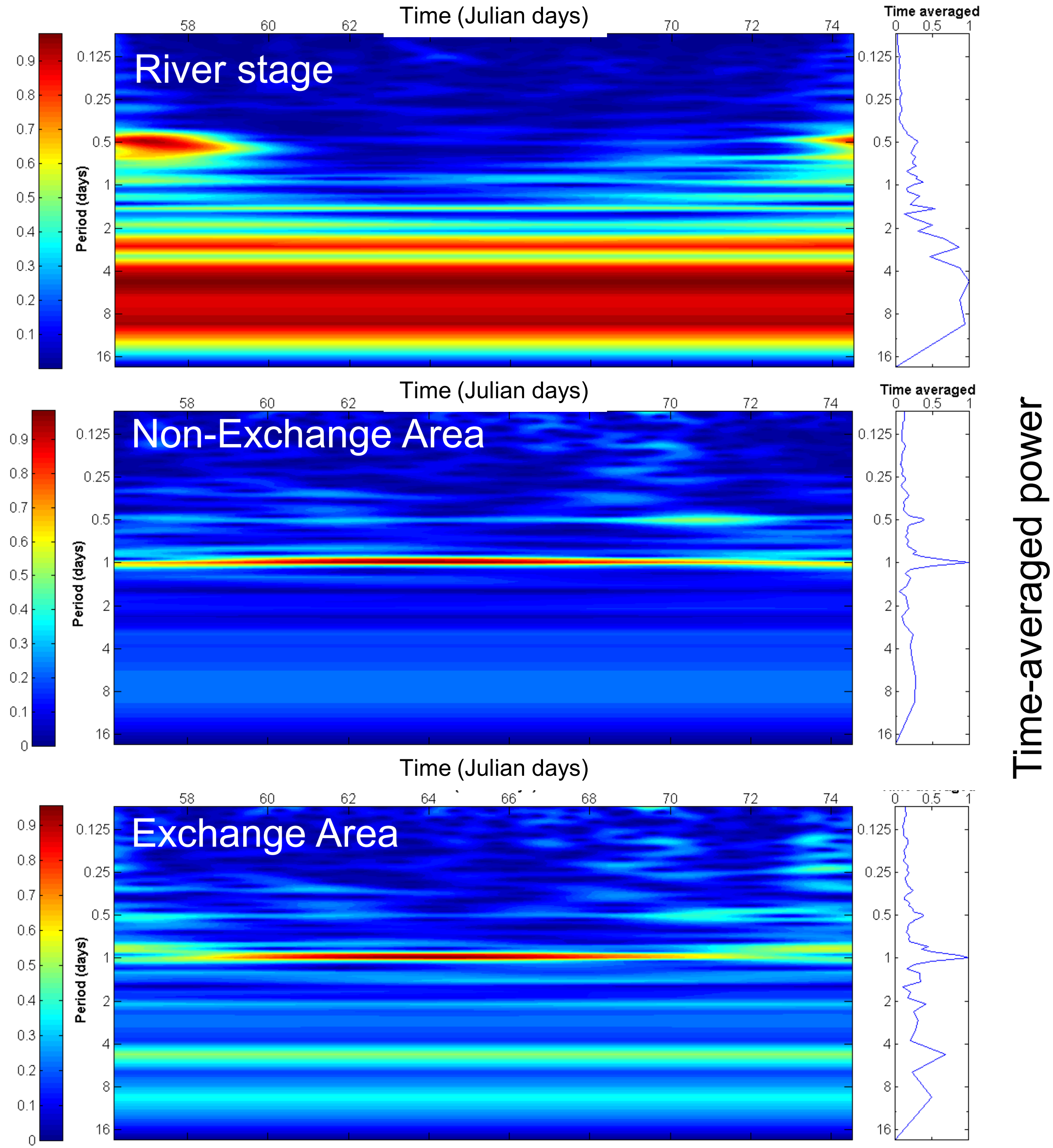


S-Transform Analysis

-Exchange areas contain long periods that are strong signals in stage data

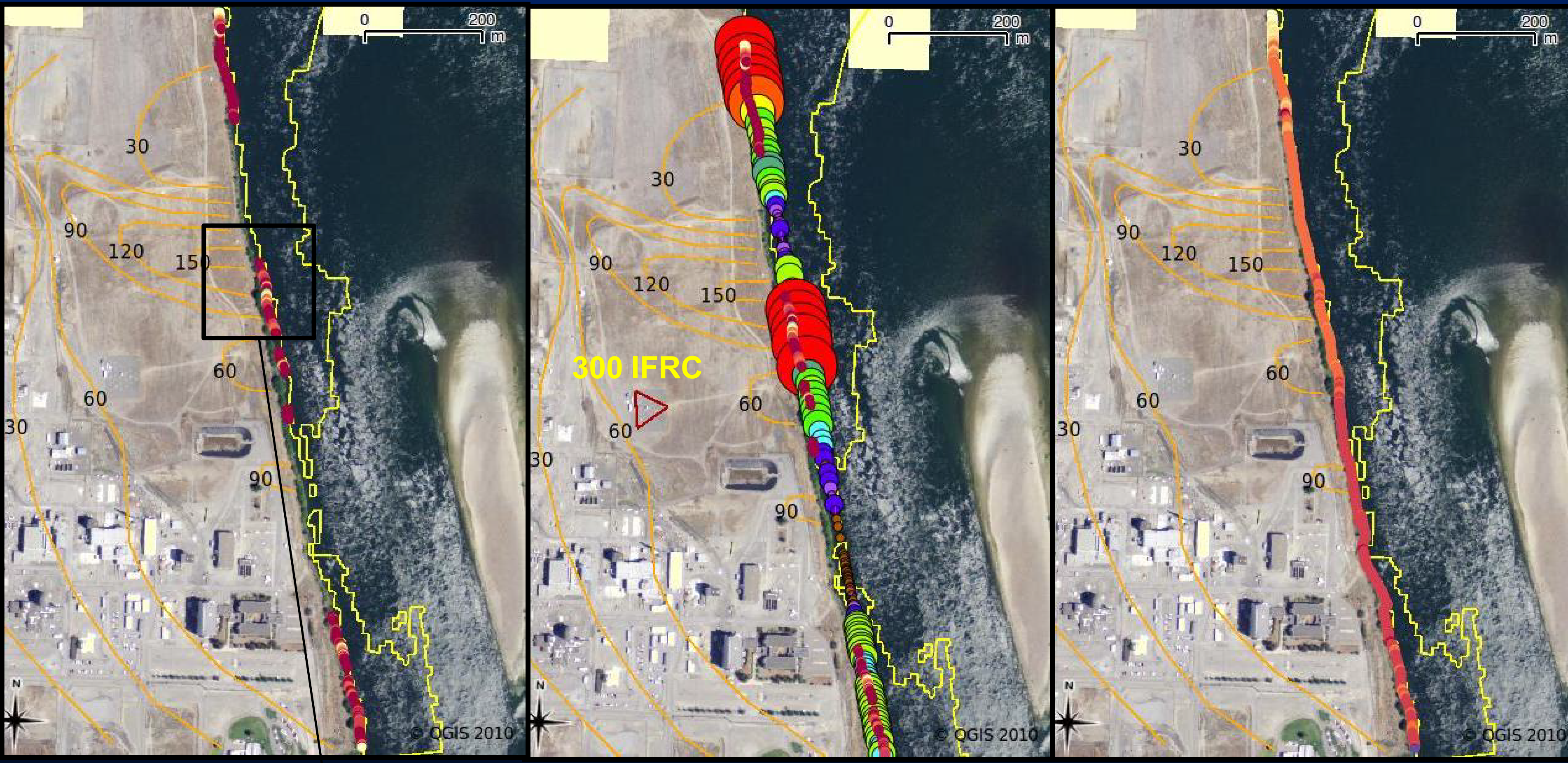
-These periods only weak in non exchange area

-Temperature variations at exchange locations are being driven by stage variations



S-Transform Analysis at Selected Frequencies

4 day period in river stage ⟷ 1 day period (solar heating)

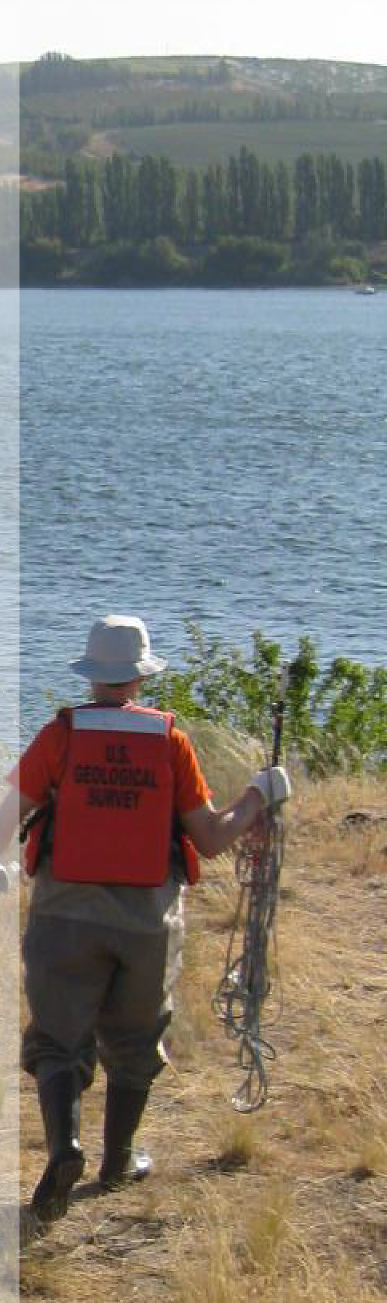


Location of maximum stage forcing

No discrimination

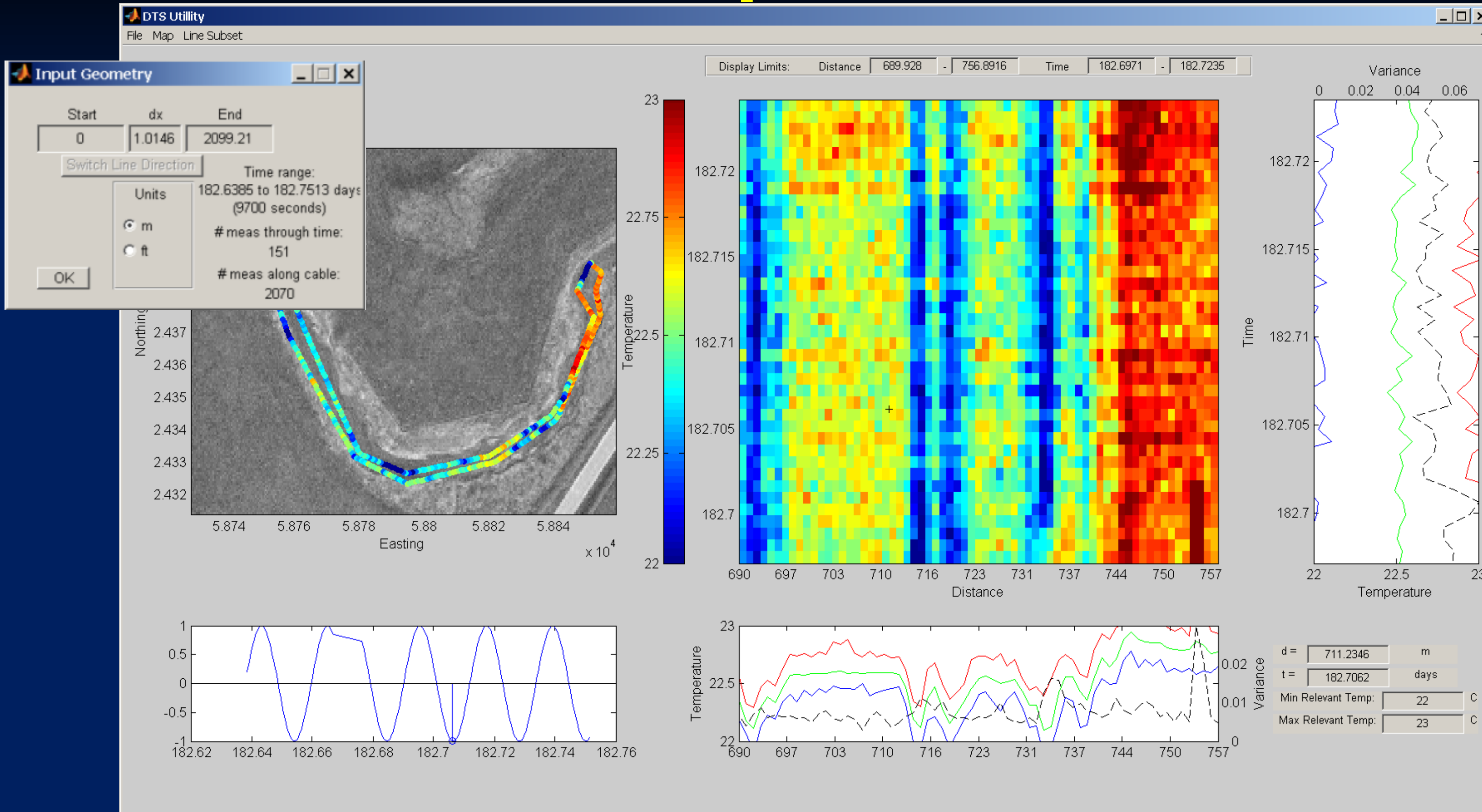
Summary

- FODTS synergistic with other geophysical methods (e.g., electrical results commonly require adjustment for soil temperature)
- High resolution in space and time
- Data amenable to time-series and signal-processing analyses
- Data amenable to numerical simulation (coupled flow and heat-transport)
- Capable of triggering alarm events
- FODTS is low-power, safe; permanent installations are feasible
- Mature COTS technology & software for leak detection



Additional slides

Tools in development: DTSTool GUI



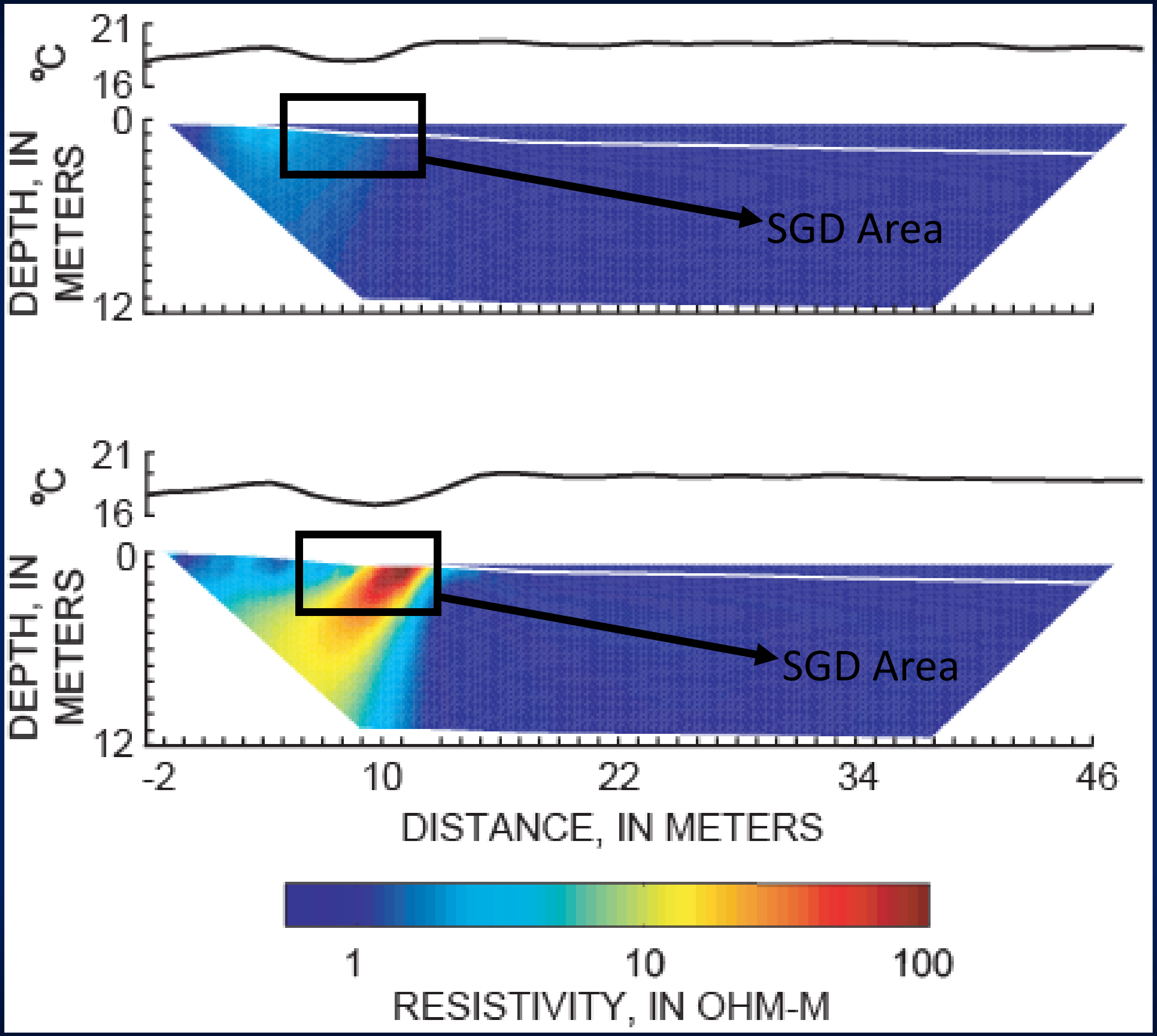
– Import data in Lios, Agilent, Sensortran, and Sensornet format
– Edit to temporal or spatial subsets
– Remove bad data based on value, location, or time interval
– Calculate statistics, e.g., min, max, std deviation, for profiles or time series
– Generate animations and saves to .avi format
– Compare to other time series and calculate cross correlation
– Perform dynamic calibrations to multiple thermistor bath time series

Koch, Elwaseif, Day-Lewis, and Slater, in development

Resistivity Tomography

High-Tide

Low-Tide

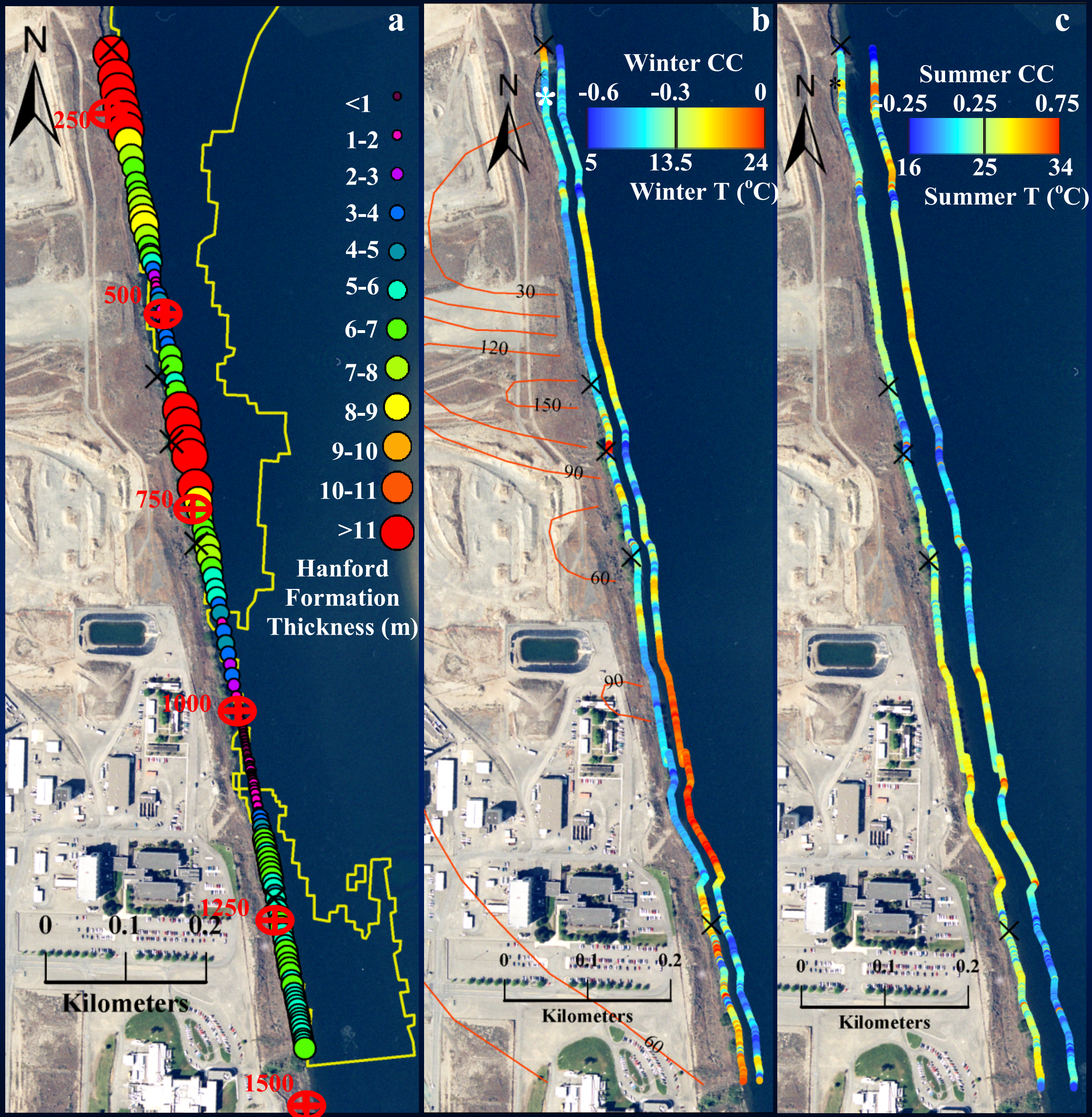


→ Variable resolution in space and time

Henderson et al., Hydrogeology J., 2010

Focused Exchange and Area of Contribution

- IP resolves hydrogeologic framework and provides cross-sectional imaging
- DTS provides high-resolution in space and time
- Temperature anomalies coincide with known uranium seeps, *but there are many additional temperature anomalies/seeps*



Estimated variation in thickness of uranium contributing area from IP

(DTS artificially offset for visualization)