INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

Australian National Chapter

NSW Branch

2010 Seminar Series

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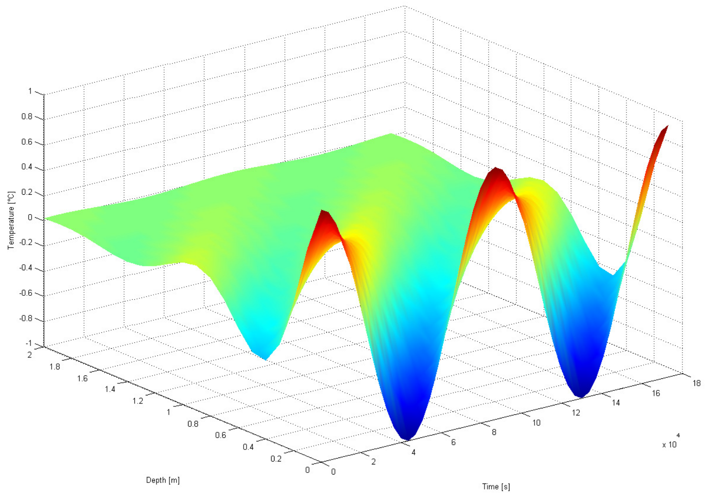
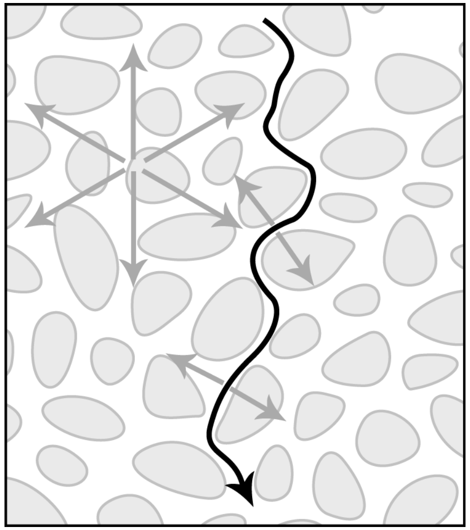
Analytical methods that use natural heat as a tracer to quantify surface water–groundwater exchange, evaluated using field temperature records

Gabriel Rau, Dr. Martin Andersen, Andrew McCallum, Prof. Ian Acworth



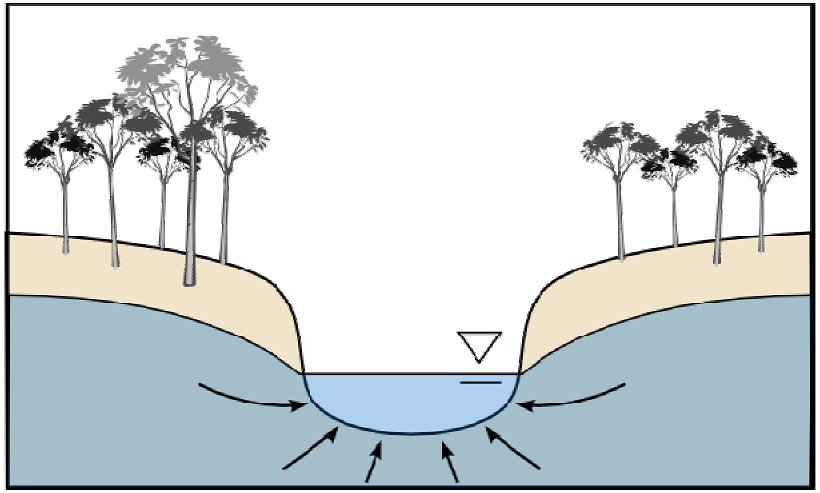


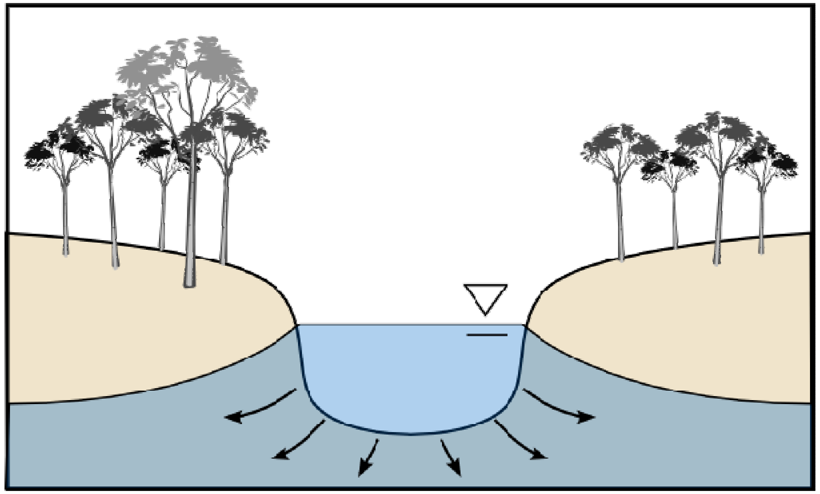
IAH NSW Meeting – 9 Feb 2010 – Sydney

UNSW - School of Civil and Environmental Engineering
Water Research Laboratory

CONNECTED WATERS

Stream Aquifer Water Exchange





Main Interactions

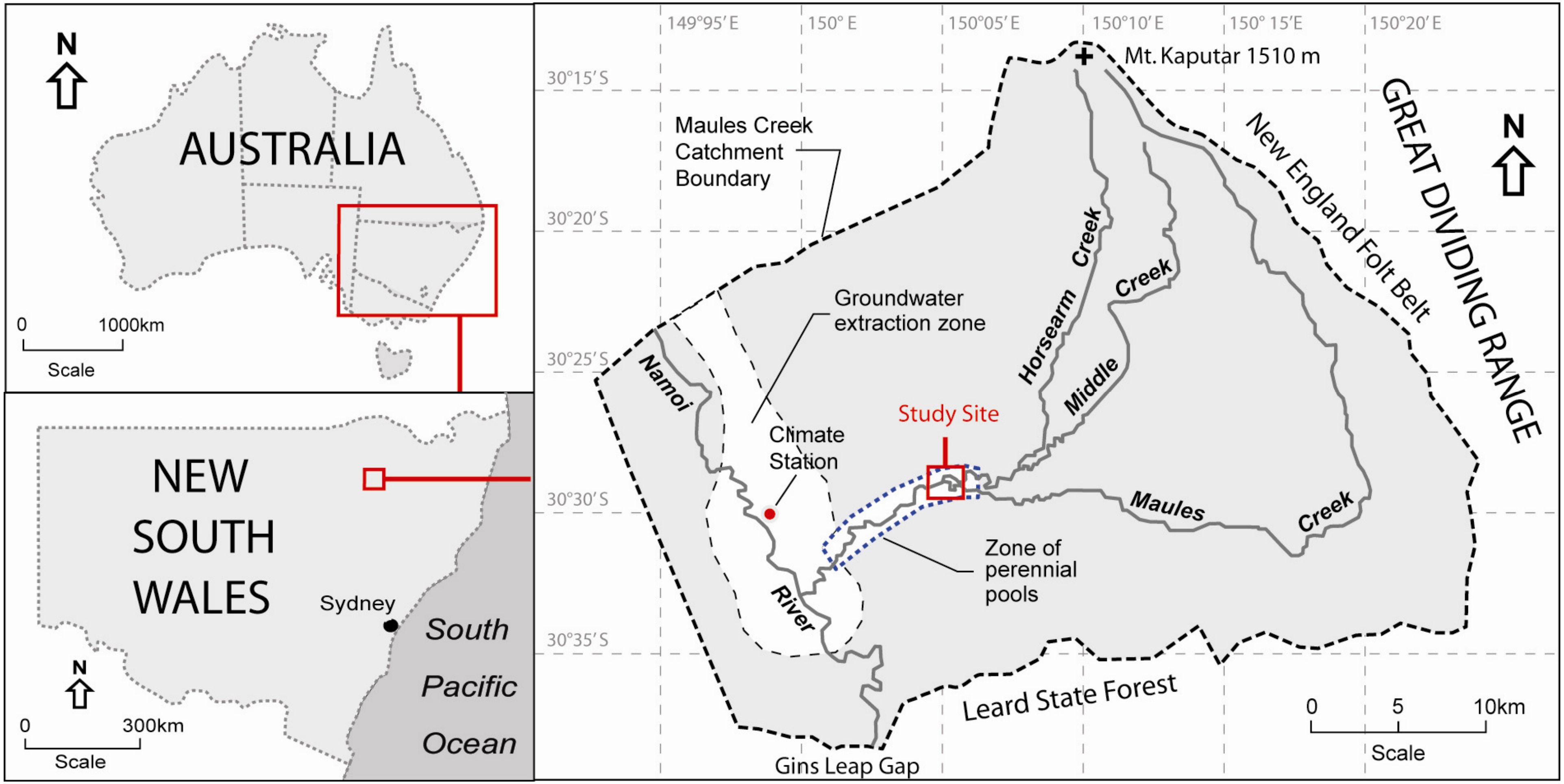
- Groundwater discharge into stream (e.g. baseflow)
- Stream discharge into aquifer (recharge)

Hyporheic Zone

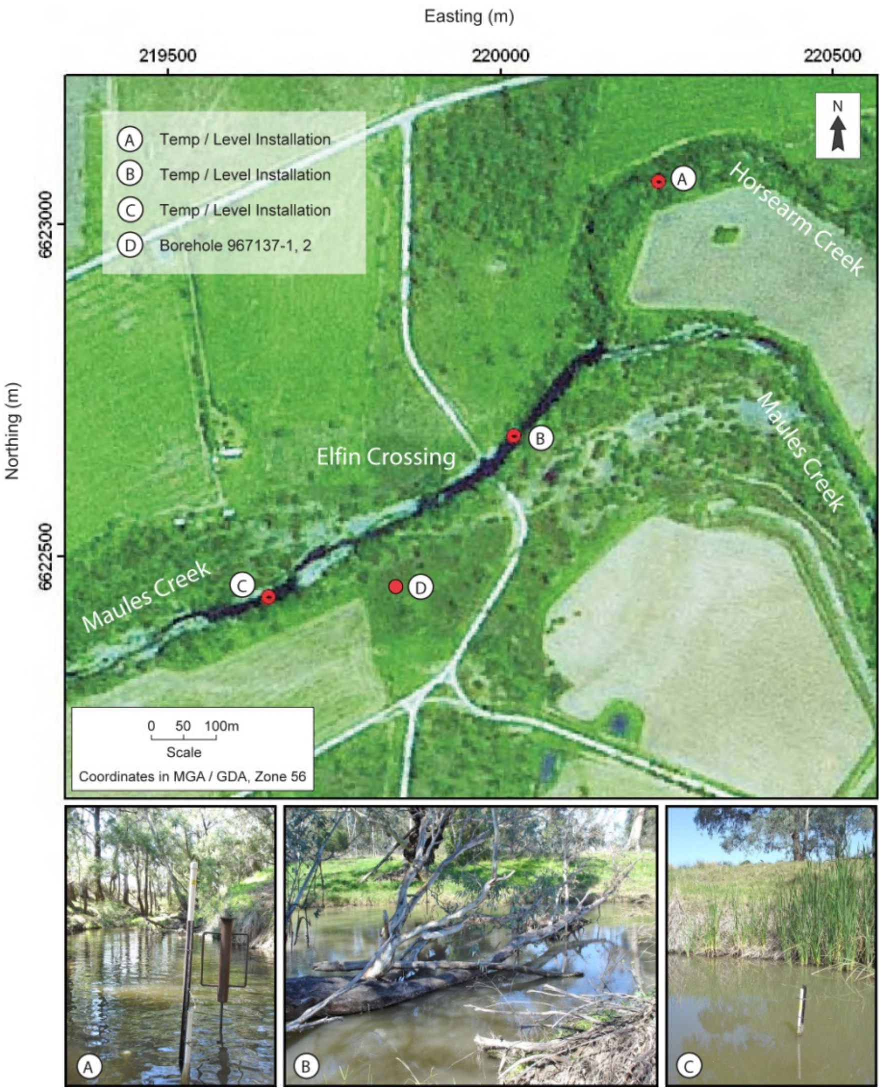
- Interface between surface and groundwater
- Water passes through this area
- Flow affects water quality

What is the flow rate?

Location of Field Site in Australia



Field Installations at Maules Creek



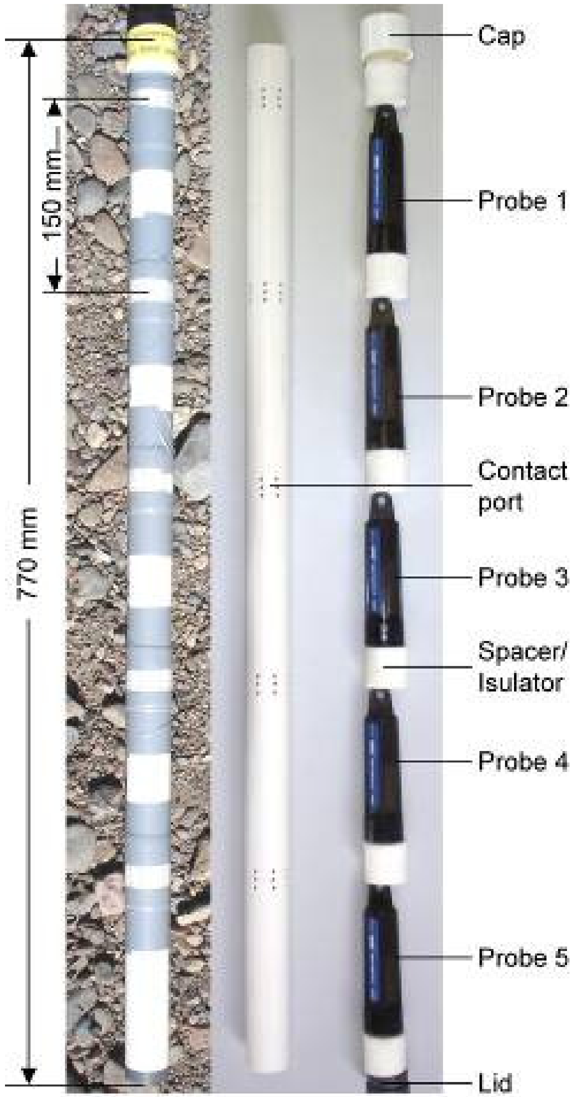
Temperature Installations

- Apparently stagnant perennial pools
- Arrays installed at 3 locations
- Period: September & October 2007

Water Level Installations

- Monitoring of surface water levels
- Streambed water level logging

Field Equipment



Multilevel Temperature Array

- Contact ports at 5 different depths
- 5 self-contained temperature loggers

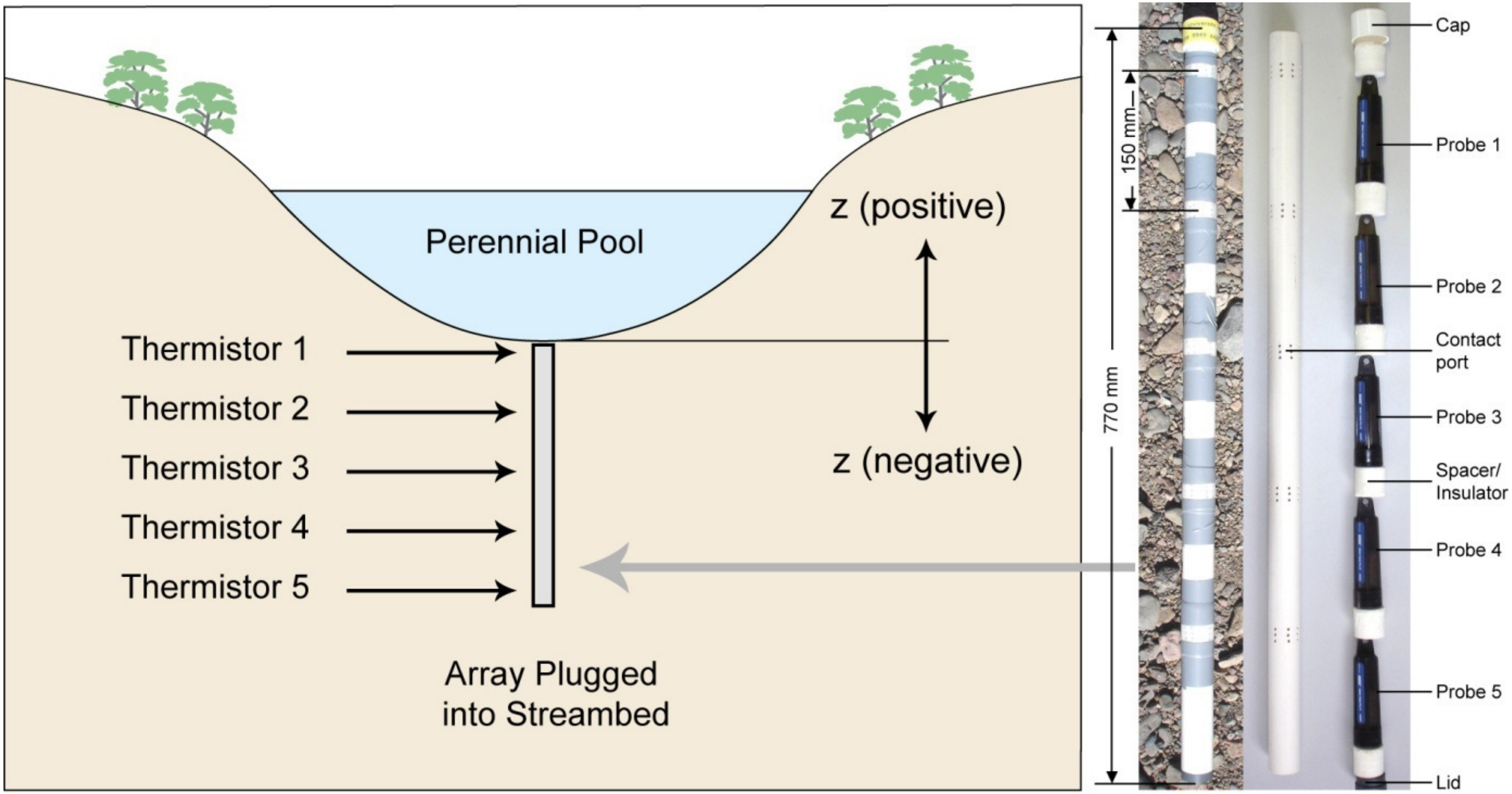
Surface Water Levels

- Automated measurement at 3 locations

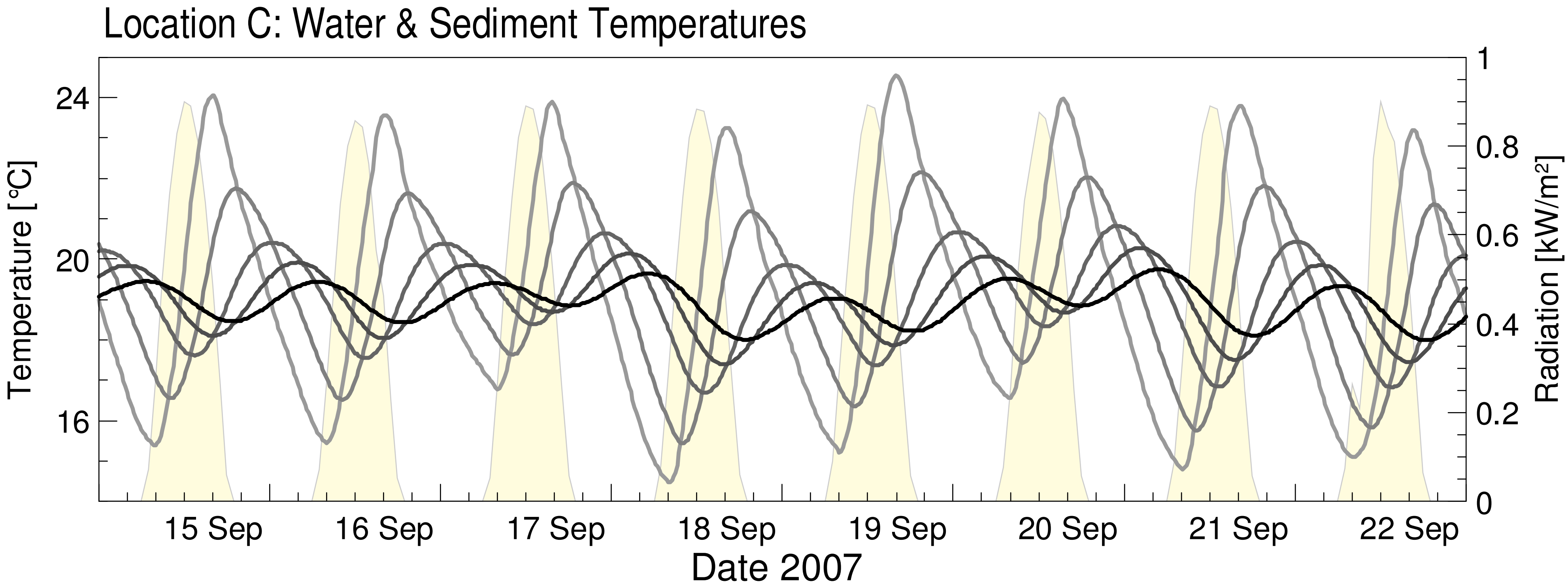
Piezometers

- Streambed depth of approx. 0.76 m
- Automated measurement

Sketch of Installation



Streambed Thermal Response



Multilevel Streambed Temperatures

- Driven by solar radiation
- Dominant diurnal temperature signature & noise
- Features: Amplitude Damping & Phase Shift with depth!

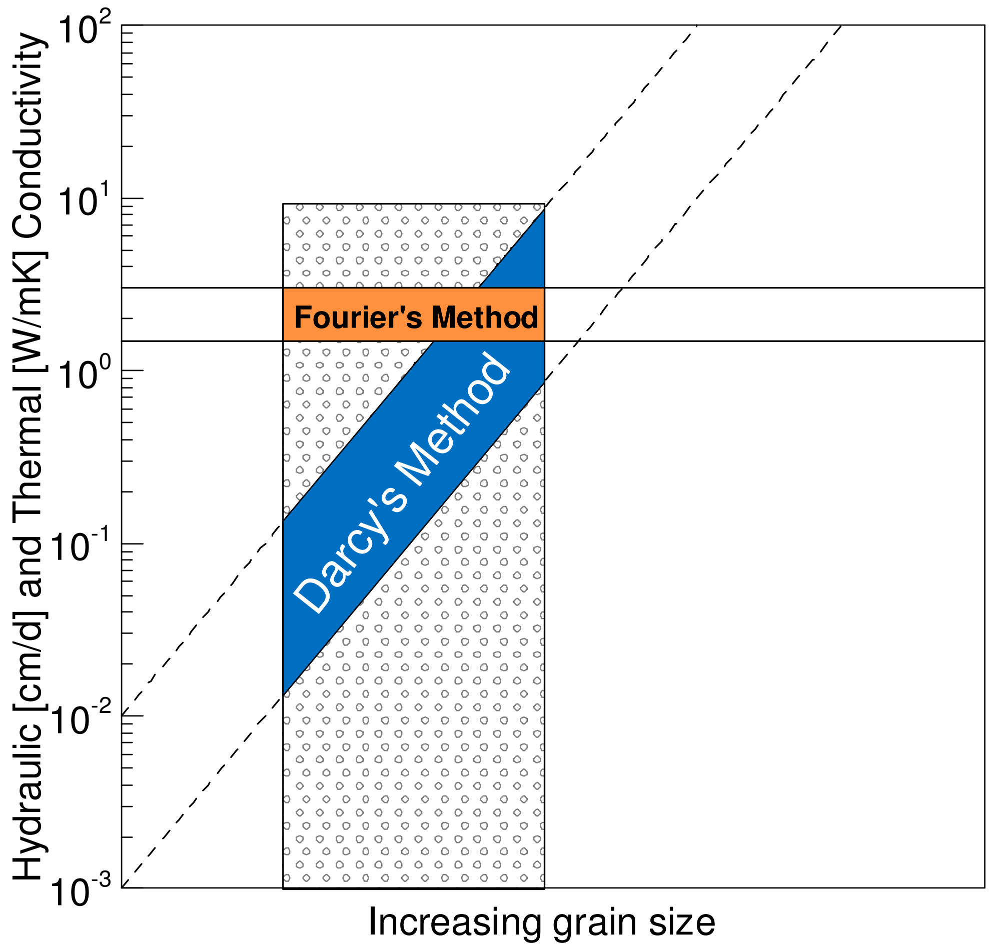
Darcy vs Fourier

Fourier's Method

- Fluid carries heat as it flows
- Temperature: measureable state variable
- Properties are hardly a function of sediment texture

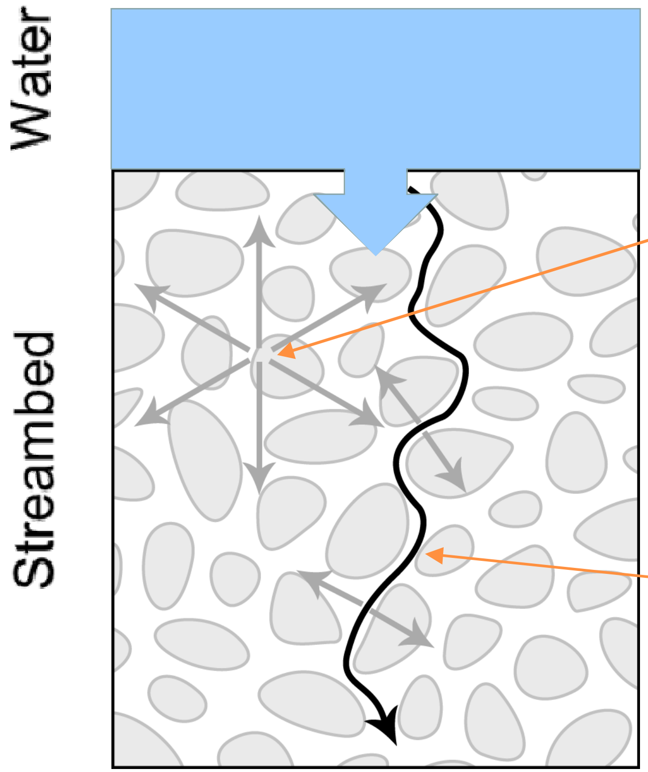
Darcy's Method

- Pressure difference: only a potential for flow
- Hydraulic conductivity averages liquid properties
- Variables are highly dependent on sediment texture



Adapted from *Blasch et al. 2007*

Mathematical Foundation



conduction — Rate of Change — convection

$$\frac{\lambda_e}{\rho \cdot c}\nabla^2 T - \frac{\rho_f \cdot c_f}{\rho \cdot c}\nabla(T\vec{v}) = \frac{\partial T}{\partial t}$$

(Stallman 1963)

Convective Conductive **Heat Transport Equation** (HTE)

- Heat transport in porous media with **two phases**
- The two phases are **volume averaged**

Analytical Solutions

Two 1D analytical solutions to HTE

Forward Method (Silliman et al., 1995)

- Calculates the sediment response as function of **vertical (!) flow velocity**
- **Iteration required** to calculate water flow velocity
- Requires steady-state conditions – Average flow value!

Quasi-Transient Method (Stallman, 1965; Hatch et al., 2006; Keery et al., 2007)

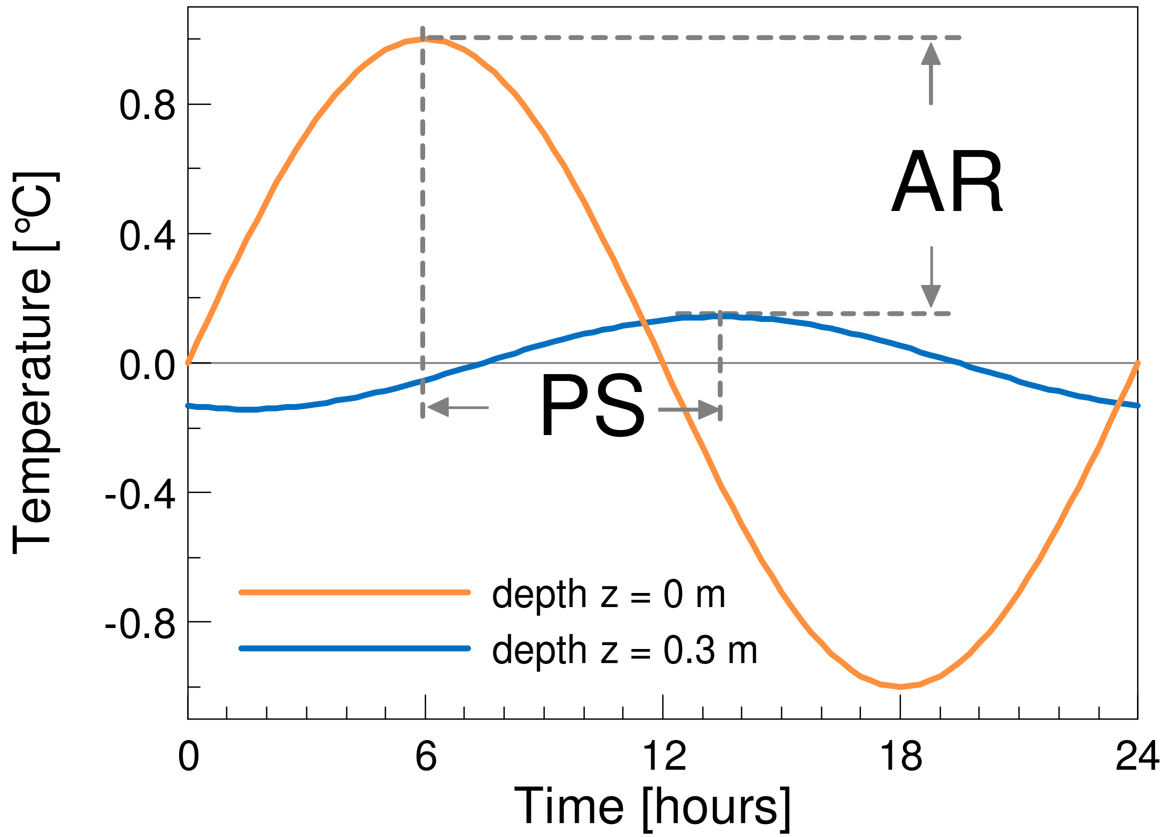
- Uses **amplitude ratio** and **phase shift** to calculate **vertical (!) water flow**
- Mathematically independent solutions
- Requires **sophisticated signal processing**
- Offers **two daily values for water flow**

Transient Solutions

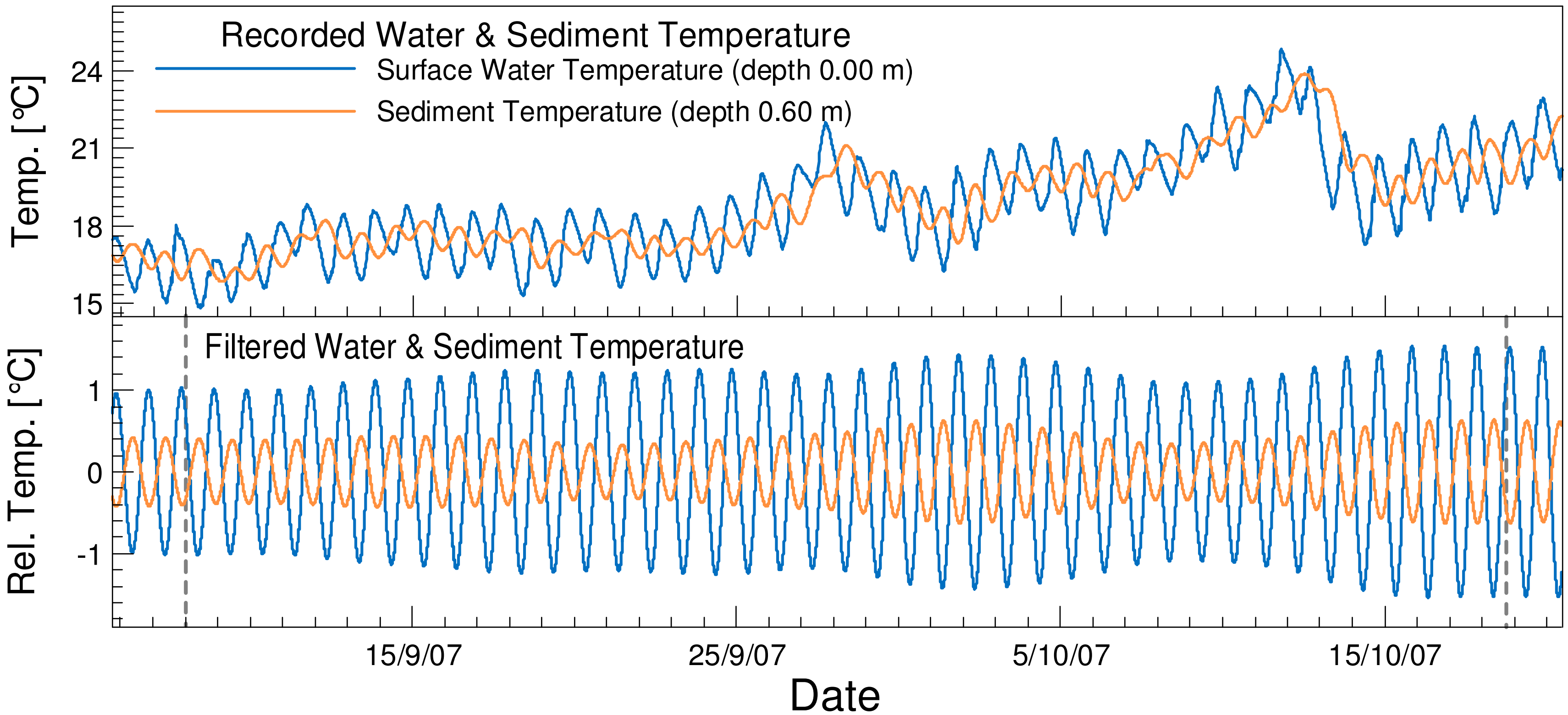
Two independent solutions (Hatch et al., 2006)

Amplitude Ratio (AR)

Phase Shift (PS)



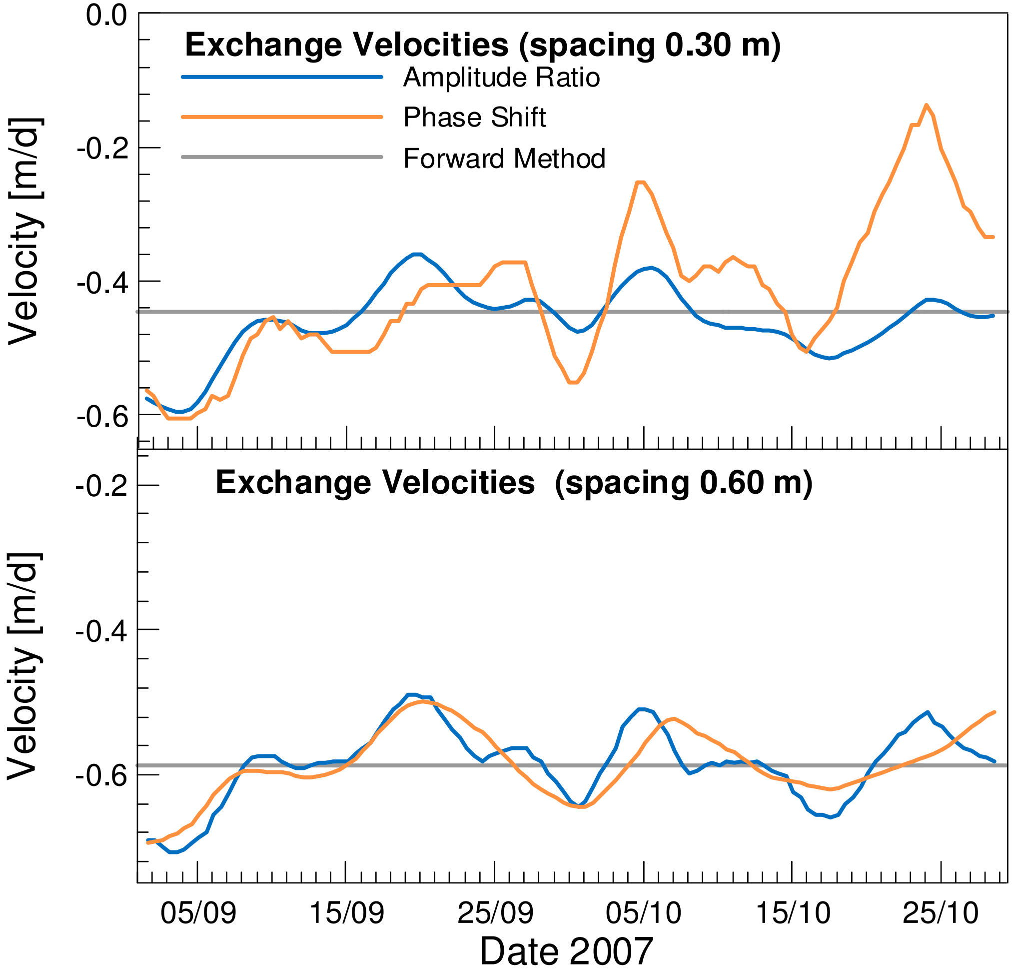
Signal Processing



Window Filtering (Hatch et al. 2006)

- Using a band pass filter with 0.9 < f < 1.1 (two-pass, Tukey window)
- Reveals diurnal fluctuations in compliance with sinusoids
- Suitable for peak picking and flow calculation

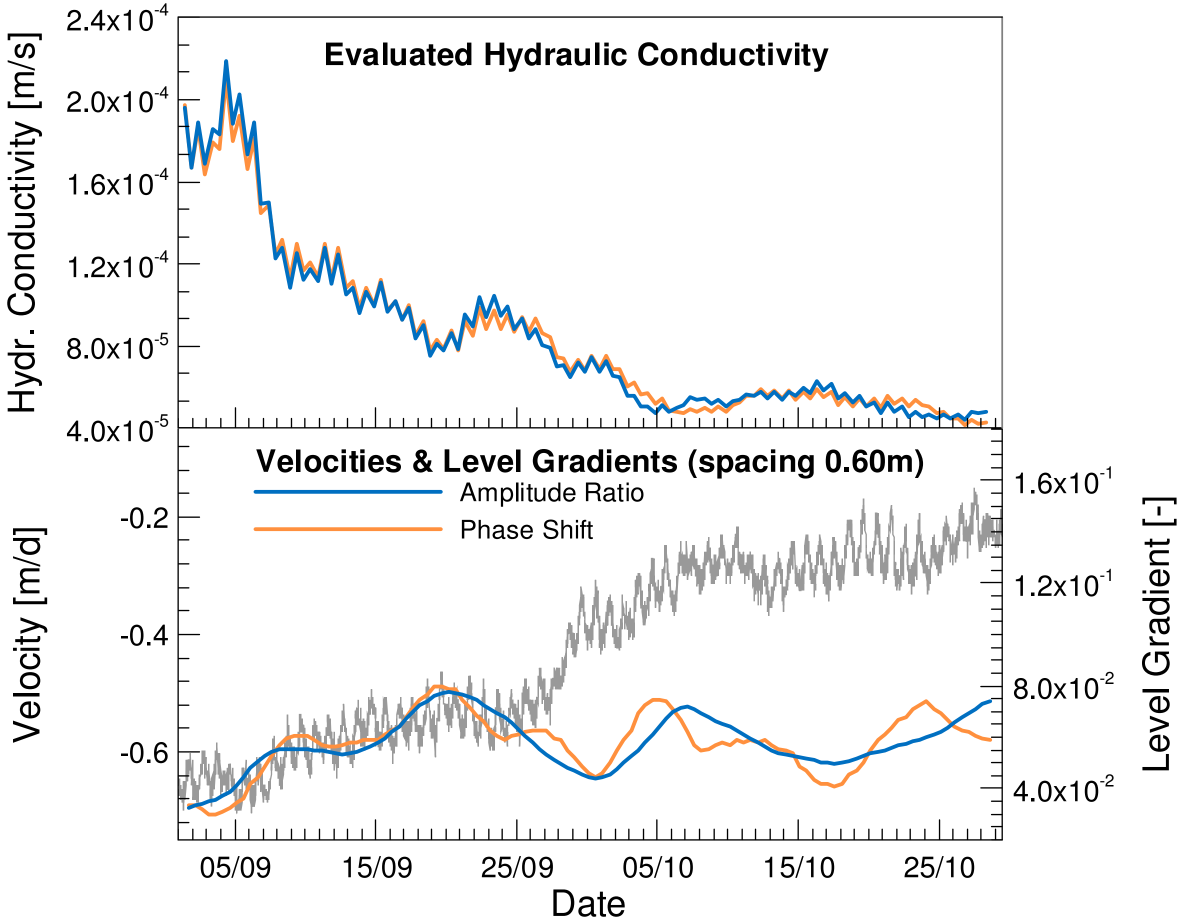
Seepage Results



Vertical Flow Velocities

- Losing water to the sediment
- velocity results between -0.4 m/d and -0.6 m/d
- Pairs show similar fluctuations and similar long term trend
- Forward modelling averages the transient results
- Amplitude ratio and phase shift solutions diverge slightly

Combination of Darcy & Fourier



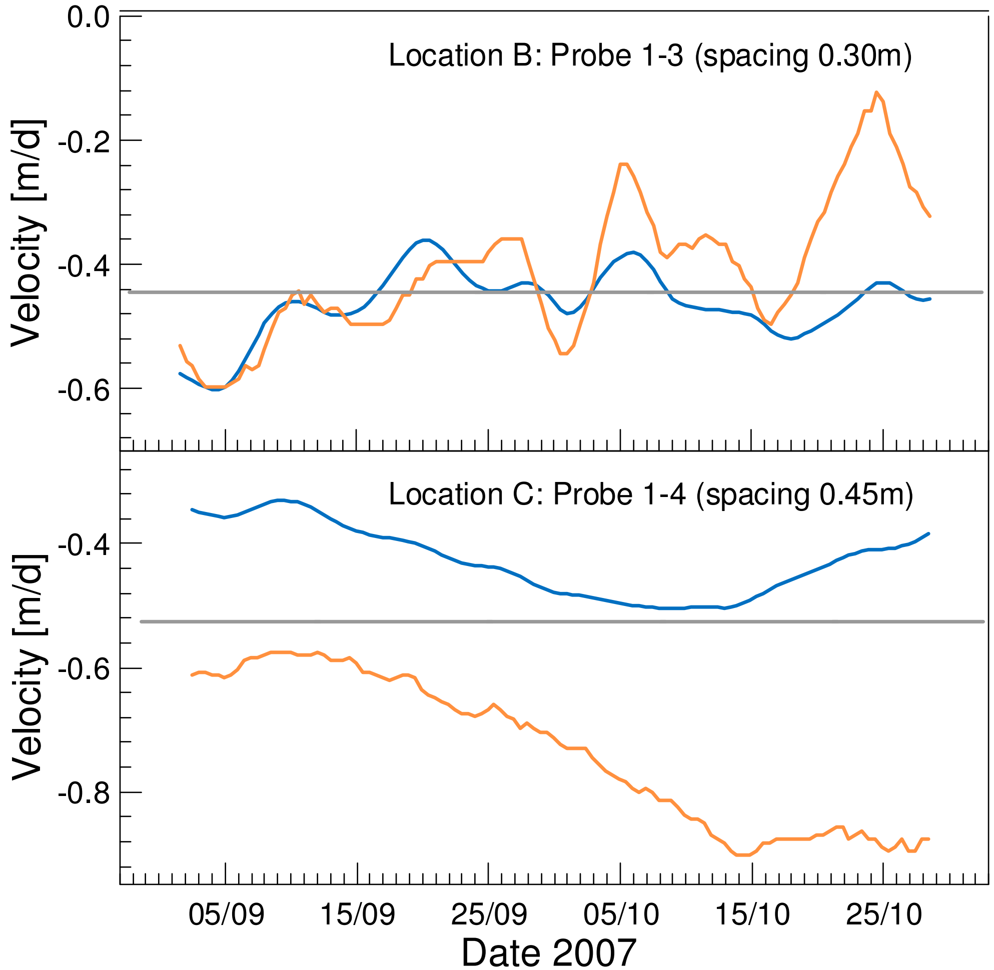
Hydraulic Conductivity

- Evaluated from heat derived velocities and water levels
- Level gradient increased
- Velocities remained constant

Interpretation?

- Time dependent Hydraulic Conductivity?
- Streambed Clogging (colmation)?

Artifacts in Results



Vertical Flow Velocities

- Dynamic flow velocities
- Amplitude ratio (AR) and phase shift (PS) solutions exhibit deviating results
- Pairs show similar fluctuations and similar long term trend

How robust are results?

Potential Errors 1

Streambed Instrumentation

- **Important for applications**:
  Temperature measurement requires direct contact to sediment for equilibration !!!
  Heat penetration through PVC pipe could introduce response delays
  (Cardenas, in press)

- **Accuracy:**
  Not important! Filtered for (TM), disappears in initial condition (FM)

- **Resolution:**
  Very important! The higher, the better: improves robustness of method

- **Response time:**
  Influences the phase shift response

Unresolved: The tool design has not yet been tested in the laboratory

Potential Errors 2

Sediment Thermal Properties

- **Porosity**, **density**, **specific heat capacity**, **solid conductivity**
- Usually well constrained values
- Do not explain the large deviations in flow velocity
- Impossible origin for deviations:
  One location shows reasonable fit of AR and PS results

Does not explain the large deviations in flow velocity !

Unresolved: what is the impact of streambed heterogeneity?

Potential Errors 3

Data Processing

- **Limitation:** sinusoidal fluctuations are required
- **Filtering:** Very difficult to quantify effect! It was found to be approx. 2%, but more testing necessary
- **Up-sampling:** Possible because signal complies with predictable sinusoid

Does not explain the large deviations in flow velocity !

Potential Errors 4

Fluid Properties

- Water **viscosity** and **density** are temperature dependent
- Change of hydraulic conductivity possible by 18% during investigation
- **Contradiction**: Streambed shows colmation (clogging) despite warming

Does not explain the large deviations in flow velocity !

Potential Errors 5

Thermal Dispersivity

- Responsible for enhanced propagation of thermal front
- **Thermal dispersivity** used analogue to **solute dispersivity**
- Used to compensate for mismatch between two signals (FM)
- Is the only parameter (with the current model) that can explain the deviation

Unresolved: Parameter values for materials are totally unknown

Potential Errors 6

Underlying Mathematics and Dimensionality

- **1D equation for Multi-D flow phenomenon:** restriction to purely vertical flow !

- **Incorrect Equation**:
  Heat transport is a two phase transport problem (conduction through fluid AND solid) but is described using a single phase equation

- All parameters are **volume averaged** to pretend single phase transport

Unresolved:

What about streambed heterogeneity?
What size REV is required for this assumption?
Is the volume average model sufficient for any shallow hydrogeological systems?

Conclusion

Research Outcome

- Reasonable flow results proved that the alluvial system features active flow
- Hydraulic conductivity can change significantly over time !
- Heat in combination with head offers improved understanding of system process
- **Hypothesis**: Deviation in AR and PS result from impact of horizontal flow !
- Detailed uncertainty analysis necessary (e.g. Monte Carlo)
- Reliability of the method must be established

Journal Publication:

Rau G., Andersen M.S., McCallum A. & Acworth R.I. (accepted): Analytical methods that use natural heat as a tracer to quantify surface water-groundwater exchange, evaluated using field temperature records, Hydrogeology Journal.

The Future …

Potential Applications or Benefits

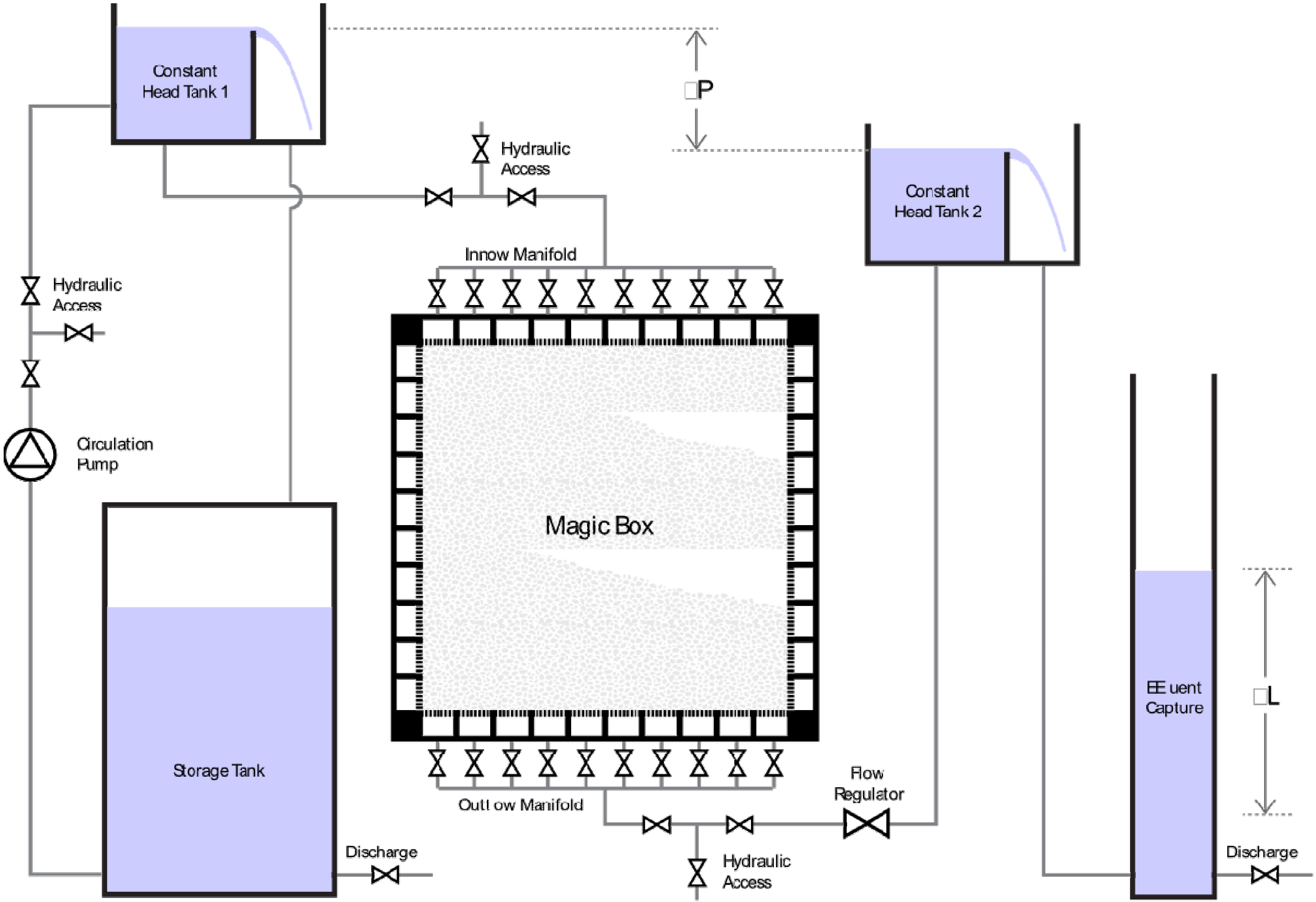
- Enhance process understanding of interactions between SW and GW on a spatial and temporal scale
- Quantify losses from surface storage and transport structures (e.g. dams and irrigation channels)
- Quantify river losses and river gains
- Provide real data for modelling SW-GW interactions
- Close the gap between hydrological and hydrogeological modelling
- Consider water as a single resource, thus improve water budget calculations towards a more sustainable goal

Laboratory Experiment

PhD Project

Funding: NPSI & CRDC
Duration: 3 years
Location: WRL (Manly Vale)

Laboratory Experiment



Thank you for your attention!

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