Coupled Pressure-Temperature Probes for Monitoring Porewater Fluxes in Coastal Sediment

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1. Introduction

- Submarine groundwater discharge (SGD) and porewater exchange is driven by hydraulic gradients between coastal aquifers/sediment and the ocean[1]
- When integrated over the large spatial areas of exchange, SGD flux can be comparable in magnitude to coastal riverine discharge[2]
- SGD delivers contaminants to the ocean, including nitrogen and heavy metals
- Ocean-aquifer interactions vary in magnitude and direction due to hydraulic oscillations associated with wave and tidal action (Fig. 1)

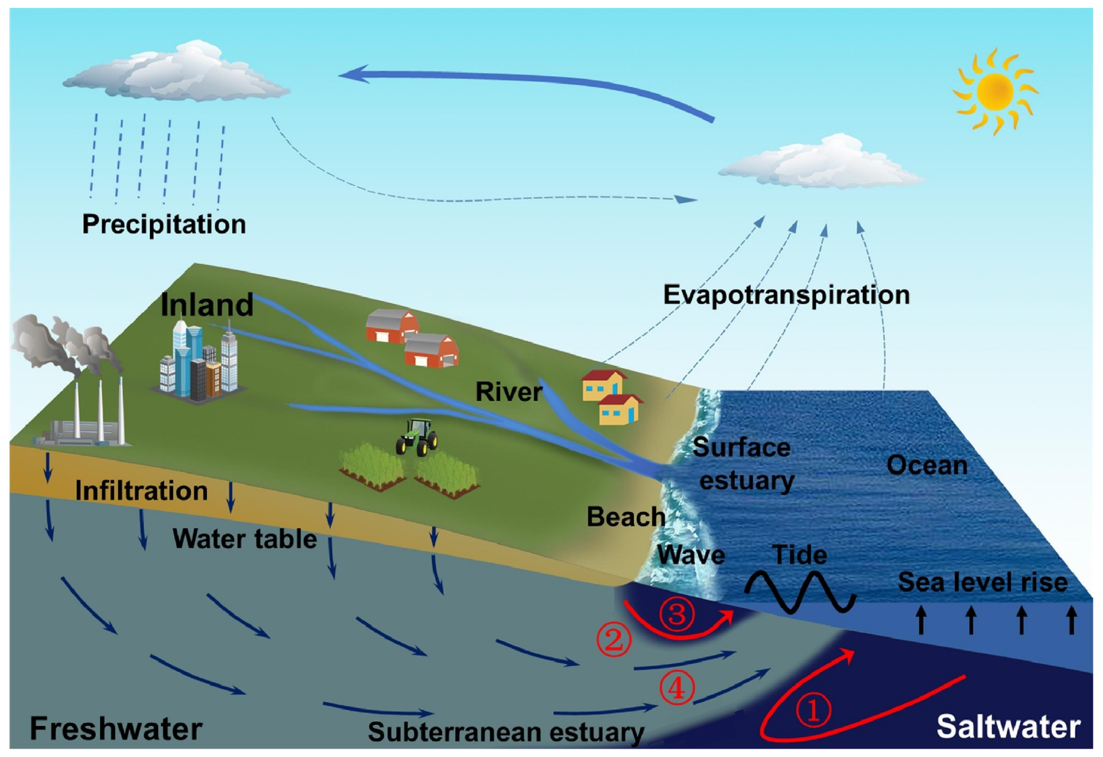

Figure 1: Conceptual model of ocean-aquifer interactions, including: (1) density-driven circulation, (2) tidal pumping, (3) wave pumping and (4) fresh SGD (modified from Robinson et al.[1])

2. Methods and Theory: Heat as a Groundwater Tracer

- When groundwater flows, it advects heat, disturbing subsurface temperatures
- The thermal effects of groundwater flow enable heat to be used as a groundwater tracer
- Multi-depth temperature sensors in sediment (Fig. 2, left) can reveal how periodic temperature signals propagate into the subsurface
- The thermal sine wave is lagged and damped with depth (Fig. 2d,e), but the precise signal transfer is influenced by the direction and magnitude of groundwater flow

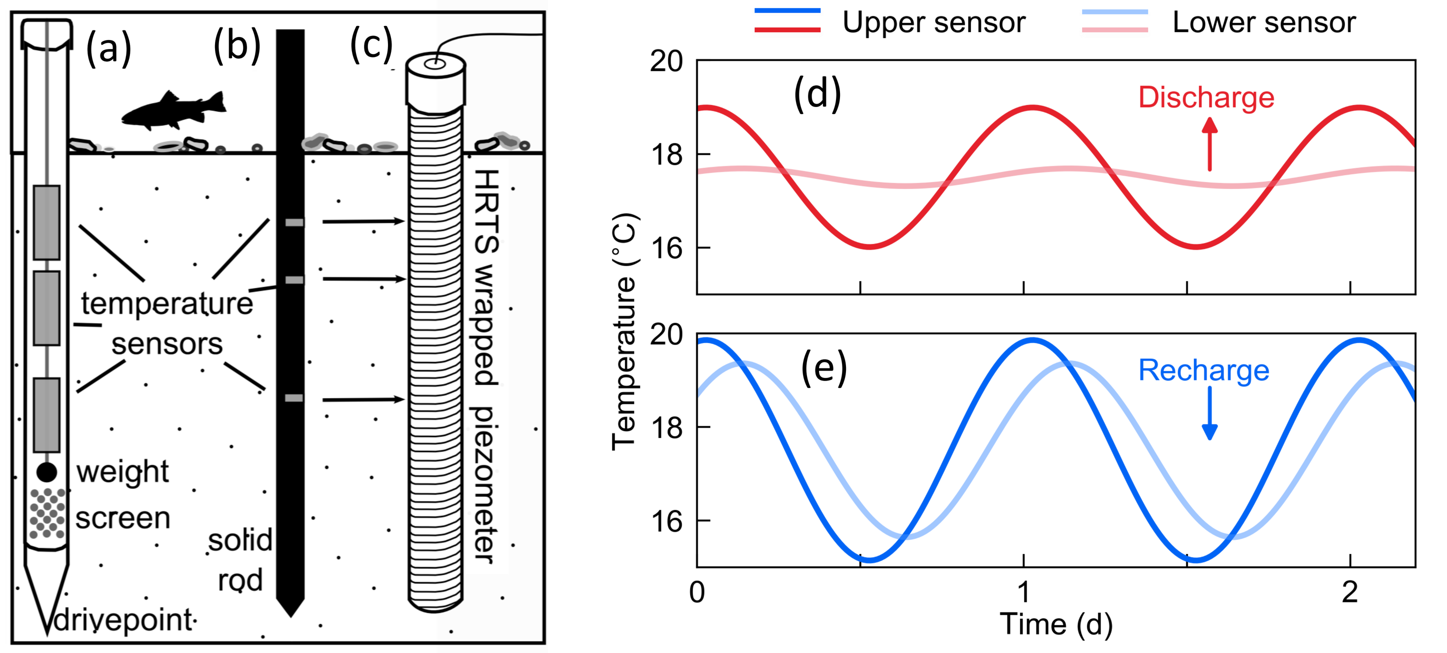

Figure 2: Past setups for temperature monitoring: (a) drive-point piezometer with temperature sensors on a cable, (b) sensors embedded in a rod, or (c) high-resolution temperature sensing (HRTS) approaches (modified from Irvine et al.[3]). Under discharge conditions (d) the signal decays more than under (e) recharge conditions (modified from Kurylyk and Irvine[4]).

- **Governing partial differential equation:** 1D, transient conduction-advection eq.

$$\lambda_{app}\frac{\partial^2 T}{\partial z^2} - q c_w \rho_w \frac{\partial T}{\partial z} = c\rho\frac{\partial T}{\partial t}$$

- **Boundary condition:** Periodic surface temperature

$$T(z=0,t) = T_m + A\sin\left(\frac{2\pi t}{p} - \phi\right)$$

- **Analytical solution:** Signal damping and lagging, where *d* and *L* depend on the Darcy flux[5]

Damping — Phase shift (lag)

$$T(z,t) = T_m + A\underbrace{\exp(-dz)}_{\text{Damping}}\sin\left(\frac{2\pi t}{p} - \phi - \underbrace{Lz}_{\text{Phase shift (lag)}}\right)$$

3. Field Site & Challenges in Coastal Settings

- While heat has been frequently applied as a groundwater tracer in inland studies, it has seldom been applied in tidal settings
- The tidal oscillations in surface water depth (Fig. 3b) drives oscillations in the temperature and groundwater flux magnitude or even direction
- While some analytical approaches can yield estimates of time-varying fluxes, the equations do not explicitly allow for a sinusoidal Darcy flux (see *q* in the governing PDE)
- A YSI sonde was installed in a tidal creek (Fig. 3b) in Sage Lot Pond[6], Waquoit Bay (MA, Fig. 3a), and iButton thermal loggers were installed in the adjacent salt marsh (Fig. 4)
- Data show periodic water depth in the creek and tidal impacts on creek thermal signals (Fig. 3b) and lagging and damping of the subsurface thermal signals in the marsh (Fig. 4)

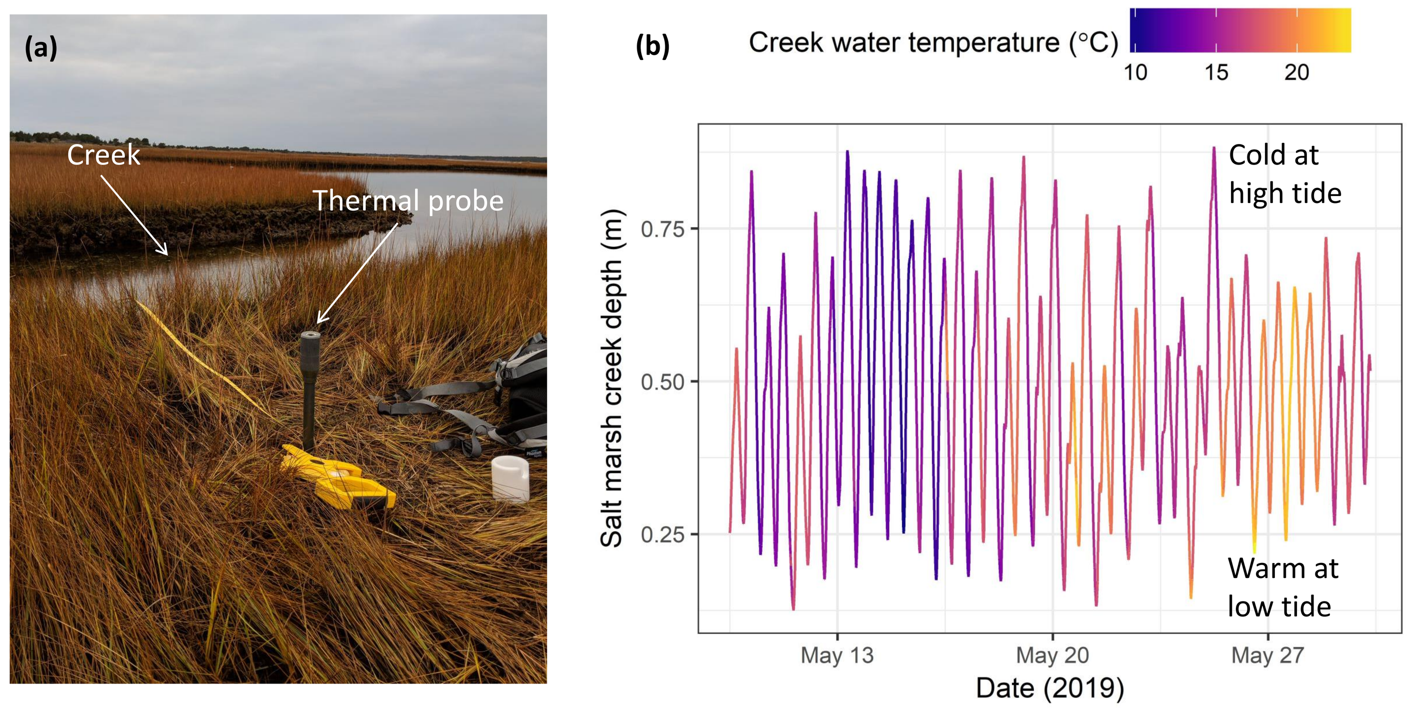

Figure 3: (a) Photograph of the Sage Lot Pond study site with the creek and thermal probe shown. (b) Water levels (vertical axis) and water temperatures (color) in the salt marsh creek

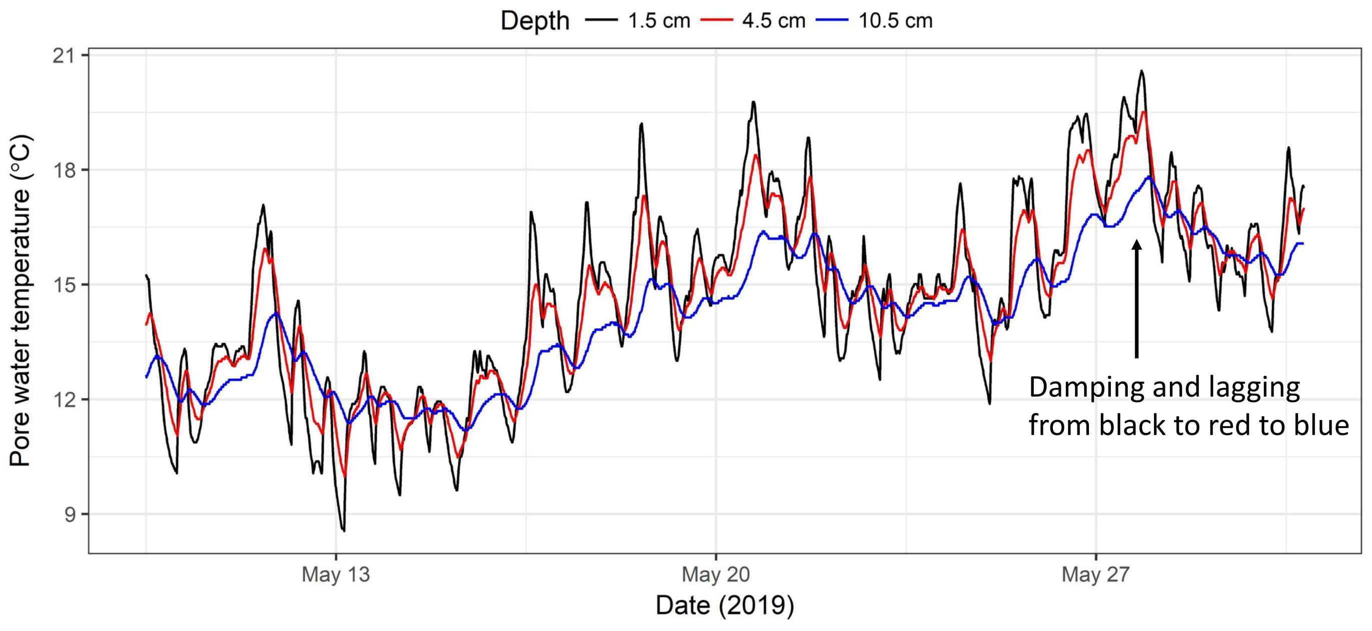

Figure 4: Multi-depth porewater temperatures recorded in Sage Lot Pond in May 2019

4. Modeling Analysis

- The temperature time series from Sage Lot Pond were analyzed in VFLUX2[7], which uses dynamic harmonic regression to determine the lagging and damping of signals
- Different analytical approaches reveal the Darcy fluxes based on the lagging and damping
- The inferred fluxes (Fig. 5) do not exhibit clear tidal oscillations
- Fluxes estimated from the different methods varied in terms of flux magnitude and even direction (Fig. 5a vs. 5b)
- More information on the magnitude and timing of the hydraulic gradient oscillations is needed to limit equifinality

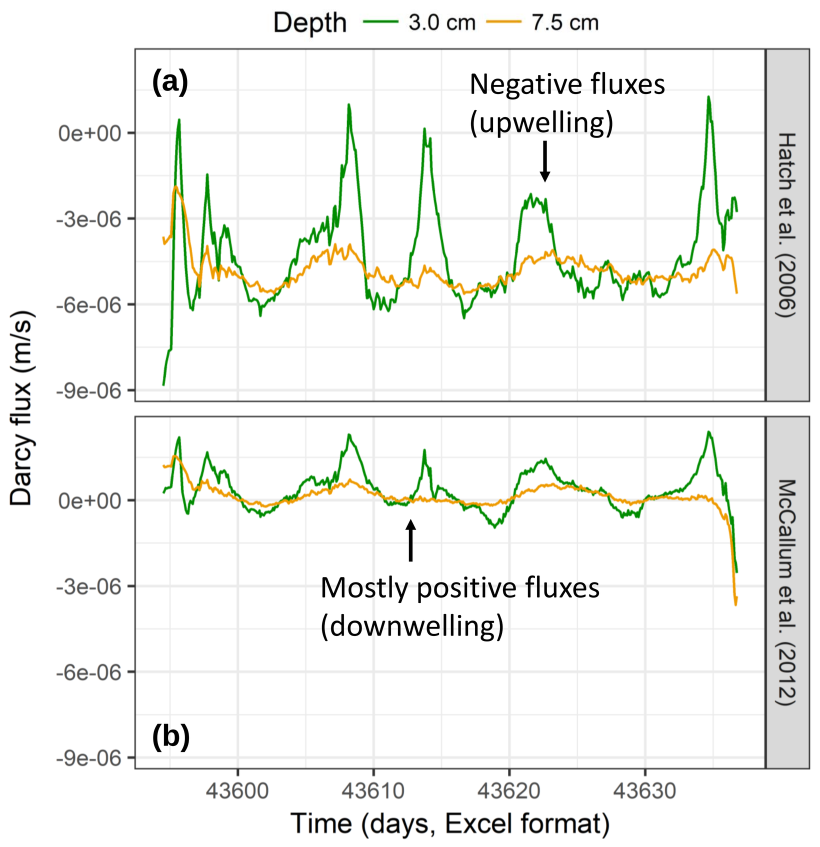

Figure 5: Inferred time series of Darcy fluxes yielded by the VFLUX2 model[7] using the Hatch et al.[8] and McCallum et al.[9] approaches to analyze the multi-depth temperature time series (Fig. 4) from Sage Lot Pond, MA.

5. Sensor Probe Design

- A novel, inexpensive sensor is proposed that monitors porewater pressure, temperature and conductivity at different depths
- Pressure readings reveal the period and magnitude of the tidal fluctuations and thus the hydraulic gradient, while conductivity data indicates whether SGD is fresh or saline
- Also, the Darcy flux inferred from the thermal data can be used to yield the hydraulic conductivity from the pressure data through Darcy's Law
- The design (Fig. 6) incorporates an array of sensors and a programmed microcontroller to record and store the data on a micro SD card

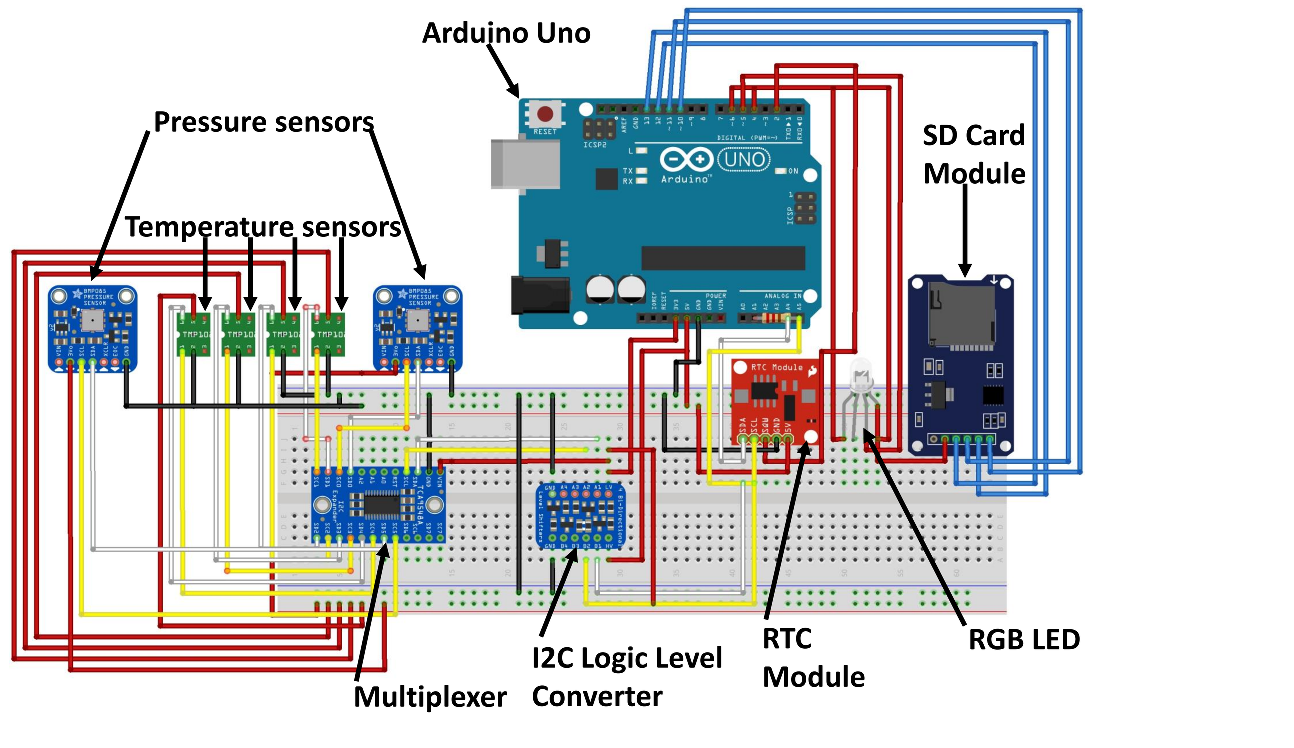

Figure 6: Virtual schematic and wiring diagram representing the present data logging system with temperature and pressure sensor locations and connections. Conductivity sensors are not yet incorporated.

- The initial sensor setup is being tested in the laboratory for code performance and sensor operations
- Fig. 7 displays the vertical sensor array and probe installation for field deployment

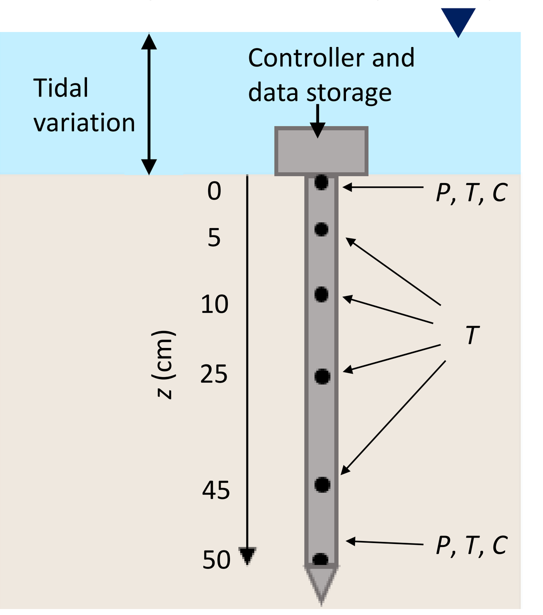

Figure 7: Cartoon of the probe installed in coastal sediment where water level fluctuates due to tidal influences. Variables *T*, *P*, and *C* represent temperature, pressure and conductivity sensors, respectively, and *z* represents the depth from the upper boundary of the subsurface.

6. Conclusions and Future Plans

- Groundwater discharge and porewater exchange is important for coastal biogeochemistry and ecosystem health, but its quantification is challenging
- An inexpensive but powerful sensor probe is being developed to reveal the timing and amplitude of groundwater flux response to tidal forcing and determine if SGD is fresh
- Next steps include finishing the housing unit for the sensors, deploying the probe to collect data in a mega-tidal setting (Bay of Fundy, Nova Scotia), and modifying VFLUX2

7. Acknowledgements and References

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