Water temperatures in cave streams and karst springs

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Abstract: Stream temperature is an important water quality parameter and can have strong influences on aquatic biota. A variety of models have been proposed to simulate water temperatures in karst conduits; however, many of the assumptions of these models have not been validated using field data or examined in detail using heat transport theory. We examine the conditions necessary for the validity of each of these assumptions, and determine the mechanisms that control heat exchange under a variety of conditions. To explore these questions we employ analytical solutions, record stream temperatures in multiple locations along cave streams in Tyson Spring Cave, Minnesota, USA and Postojna Cave, Slovenia, and simulate the observed temperatures with a numerical model using realistic geometrical parameters for the conduits. We conclude that, in most cases, conductive heat transport limits overall heat exchange rates, and therefore cannot be neglected. However, radiative exchange and convective exchange through the air can also play a role in conduits with open channels. Additionally, we discuss the types of temperature patterns that are typically observed in caves and karst springs and explain these patterns using the theoretical framework developed above.

Model of Heat Transport

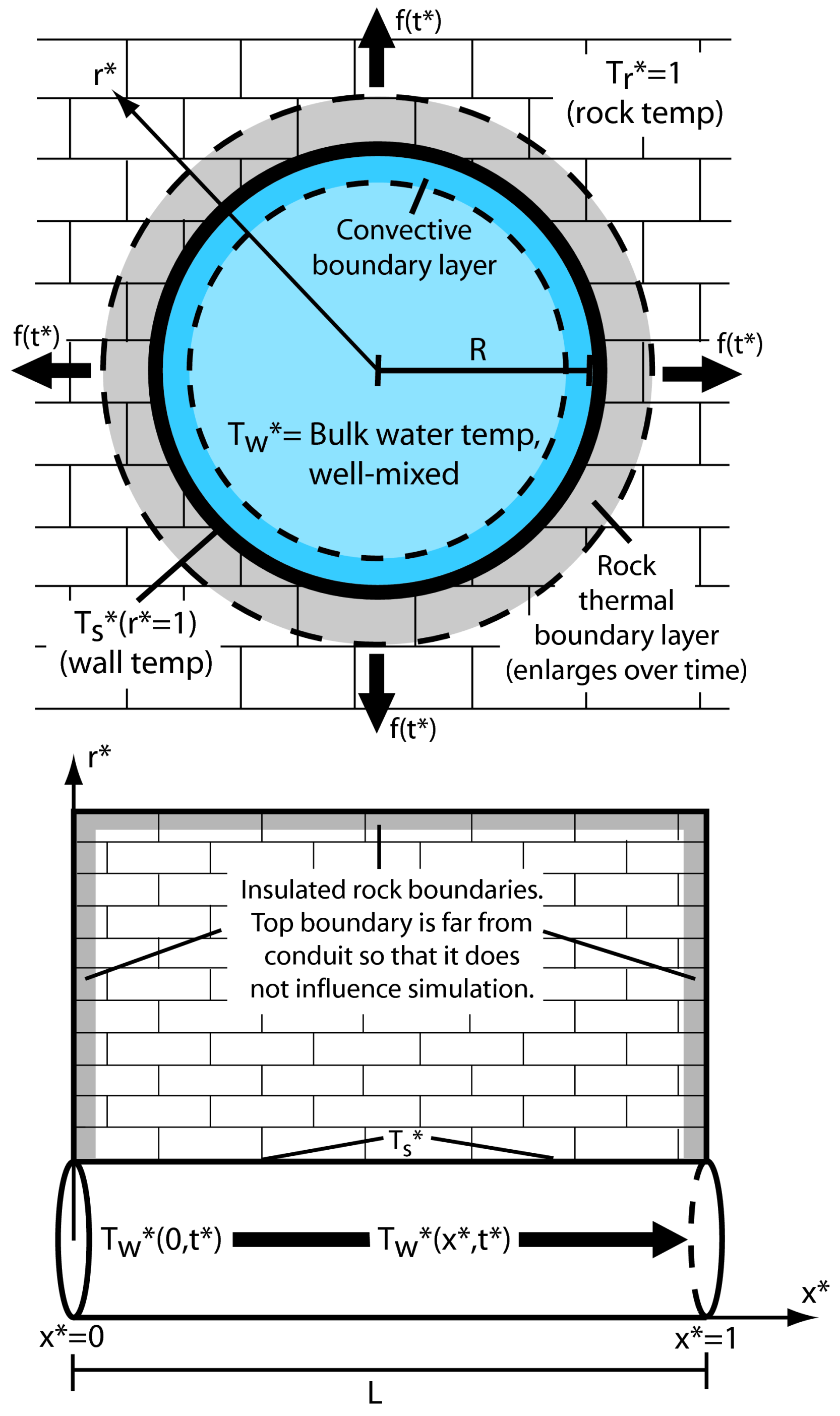


Figure 1. Heat passes from the bulk water through a convective boundary layer and then conducts into the surrounding rock. As time increases, the volume of rock that changes temperature enlarges. Some previous models of karst heat exchange have assumed that heat exchange is limited by convective rates (constant wall rock temperature), whereas models of surface stream temperatures typically assume that the streambed is at the water temperature such that heat exchange is limited by conduction (model from Covington et al., in review).

Previous models have sometimes assumed that heat exchange is limited either by convective rates within the water or conductive rates within the rock. However, these assumptions produce dramatically different results!

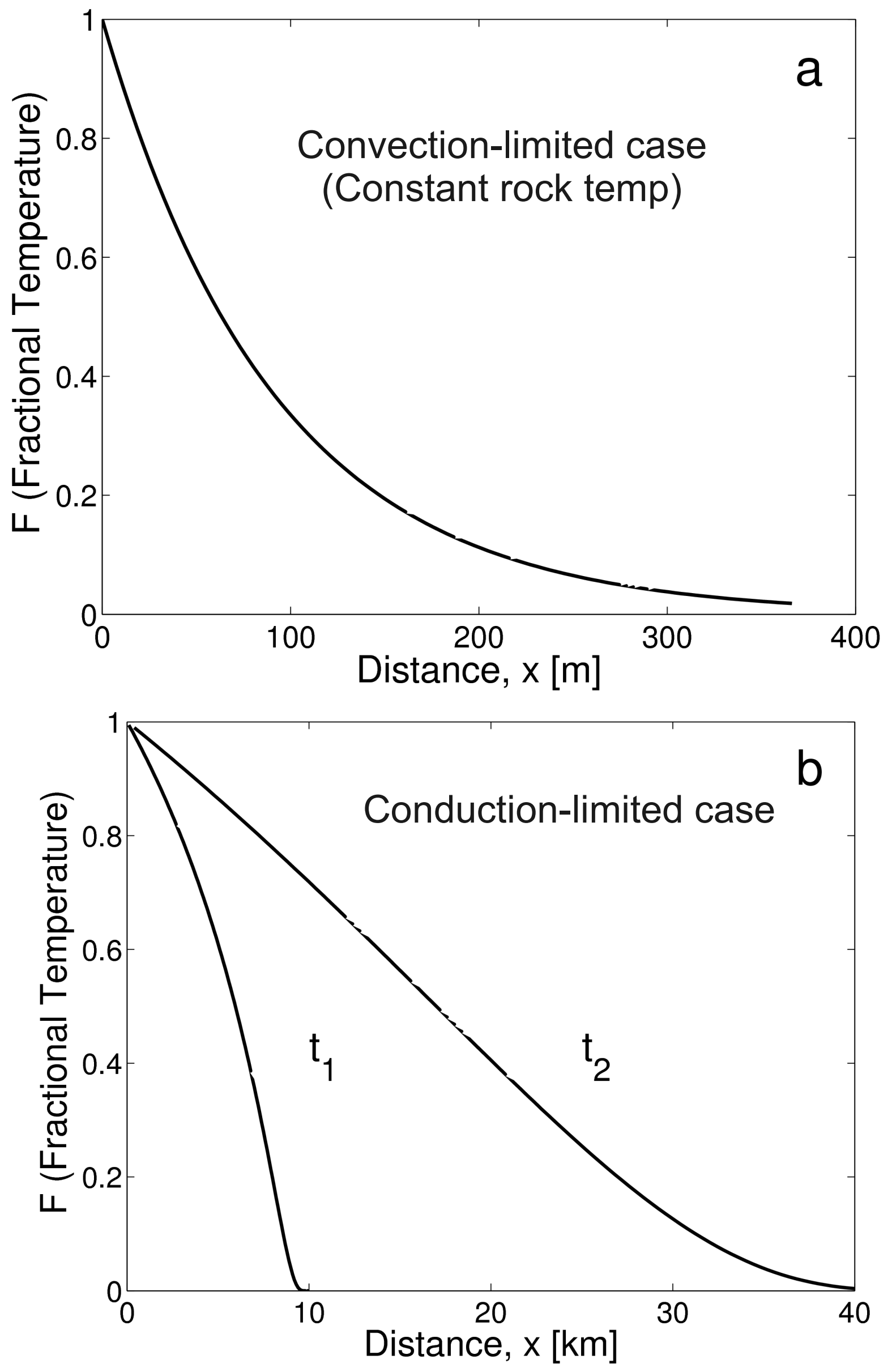


Figure 2. Longitudinal temperature profiles for the convection-limited (a) and conduction-limited (b) solutions. The conductive solution is shown for one flow-through time (t1) and five flow-through times (t2). Note that the conductive solution allows significantly deeper penetration of temperature pulses (x axis in km). The conduction-limited solution also changes with time.

The convection-limited solution almost never holds during turbulent flow over time scales of interest.

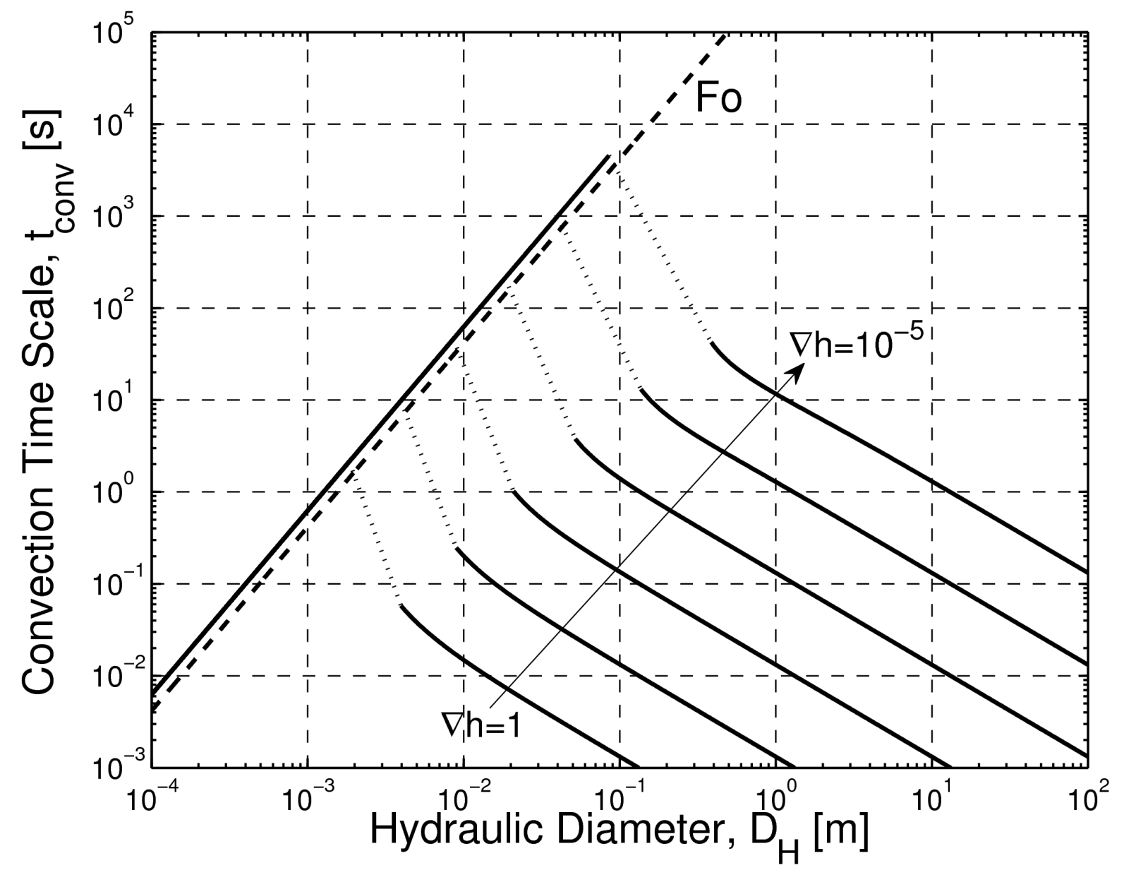
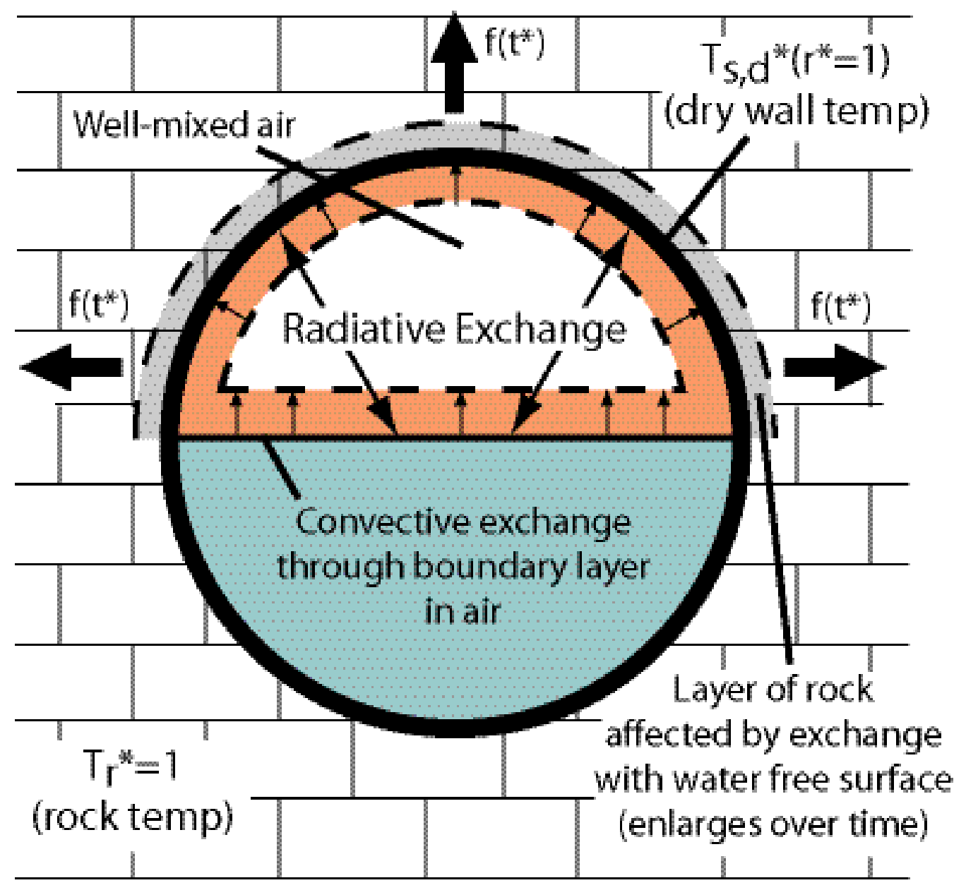


Figure 3. The convection-limited solution should hold at early times during a temperature pulse when the rock wall temperature has barely changed. The conduction-limited solution will apply for late times when the rock wall has had time to reach the water temperature. However, the time scale (y-axis) for the validity of these solutions can be derived analytically, and the convection-limited solution only holds for very short times for typical karst conduit parameters.

Additional processes occur in open channel conduits that have not been considered in previous models (radiation and air-convection).



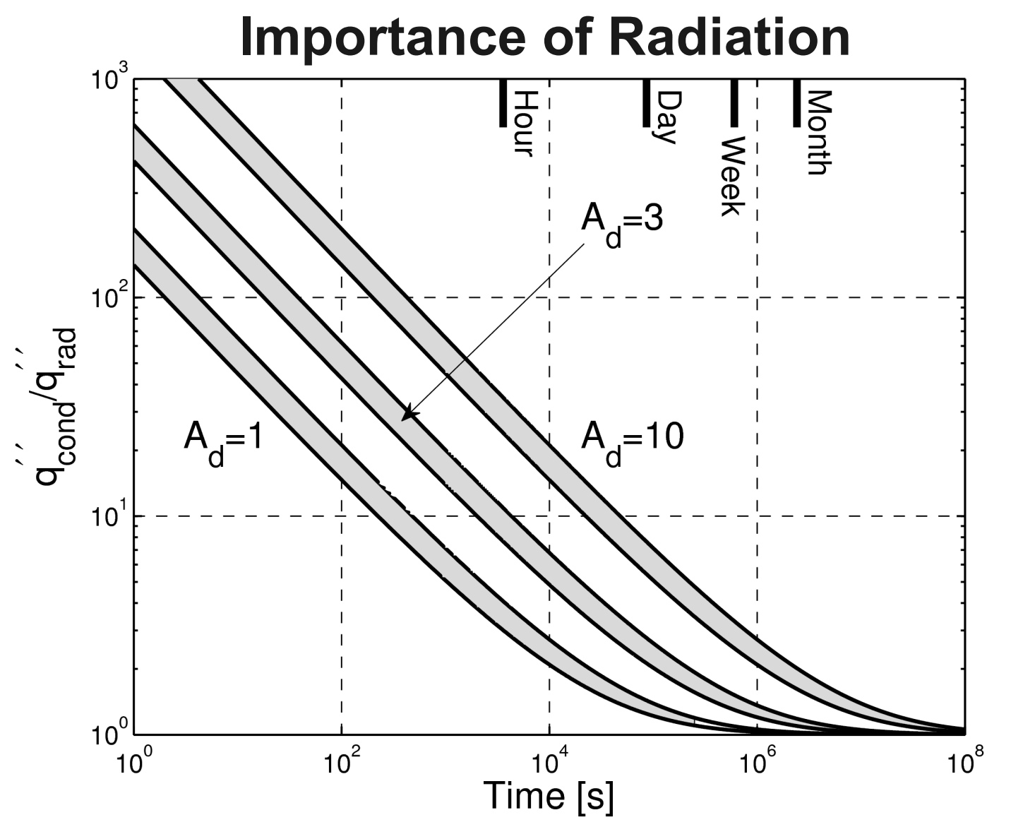


Figure 5. The ratio of heat flux at the water-rock boundary, q''_{cond}, to the radiative heat flux into the dry conduit wall, q''_{rad}, as a function of time for three choices of the ratio between surface areas of dry rock and the water free surface, A_d. At short time scales (hours) radiative flux is small in comparison to the water-rock flux. By day to week time scales, wetted conduit and dry conduit heat fluxes are approximately equal, showing that radiative effects can be quite important.

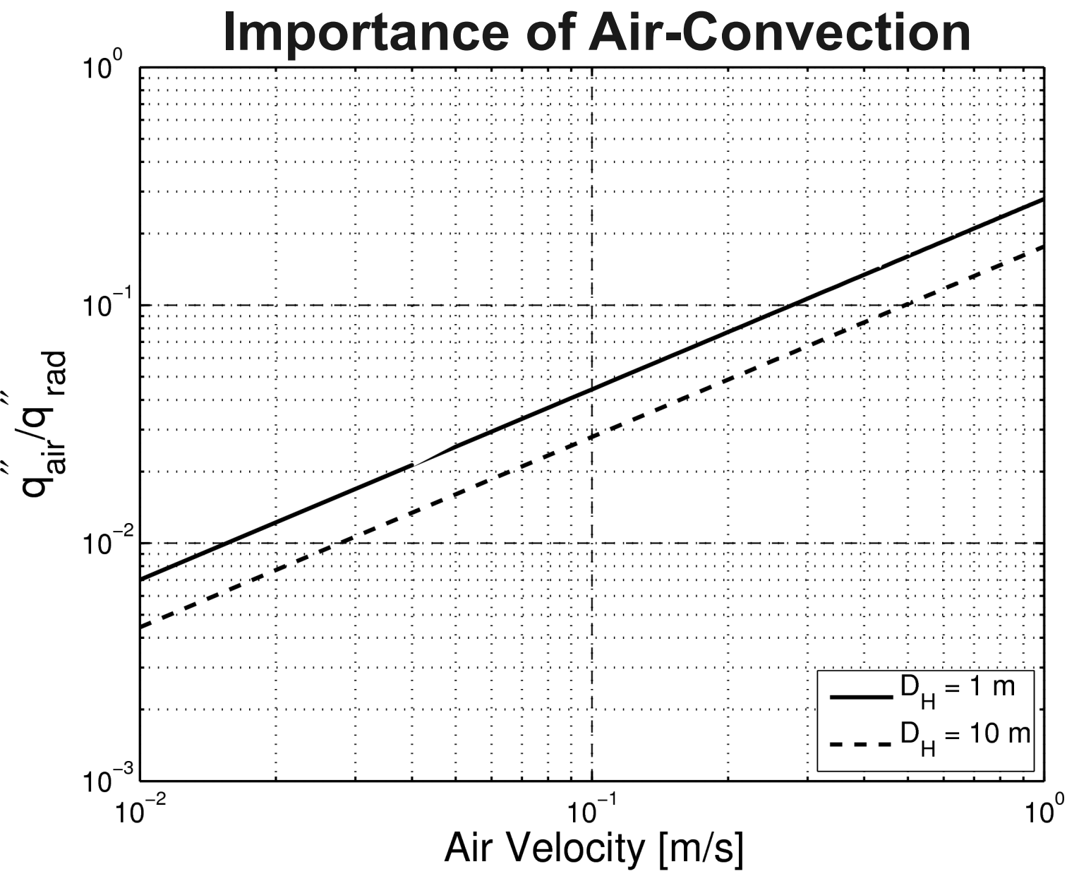


Figure 6. The ratio of air-convective, q''_{air}, to radiative, q''_{rad}, heat fluxes as a function of air flow velocity for two choices of air-filled hydraulic diameter. For typical air velocities of 0.1 m s^{-1}, air-convective heat exchange is negligible. These results apply for exchange within conduits that are far from entrances, which can possibly produce stronger air-convective effects.

Computer simulations of stream temperatures in two cave streams in Slovenia and Minnesota, USA.

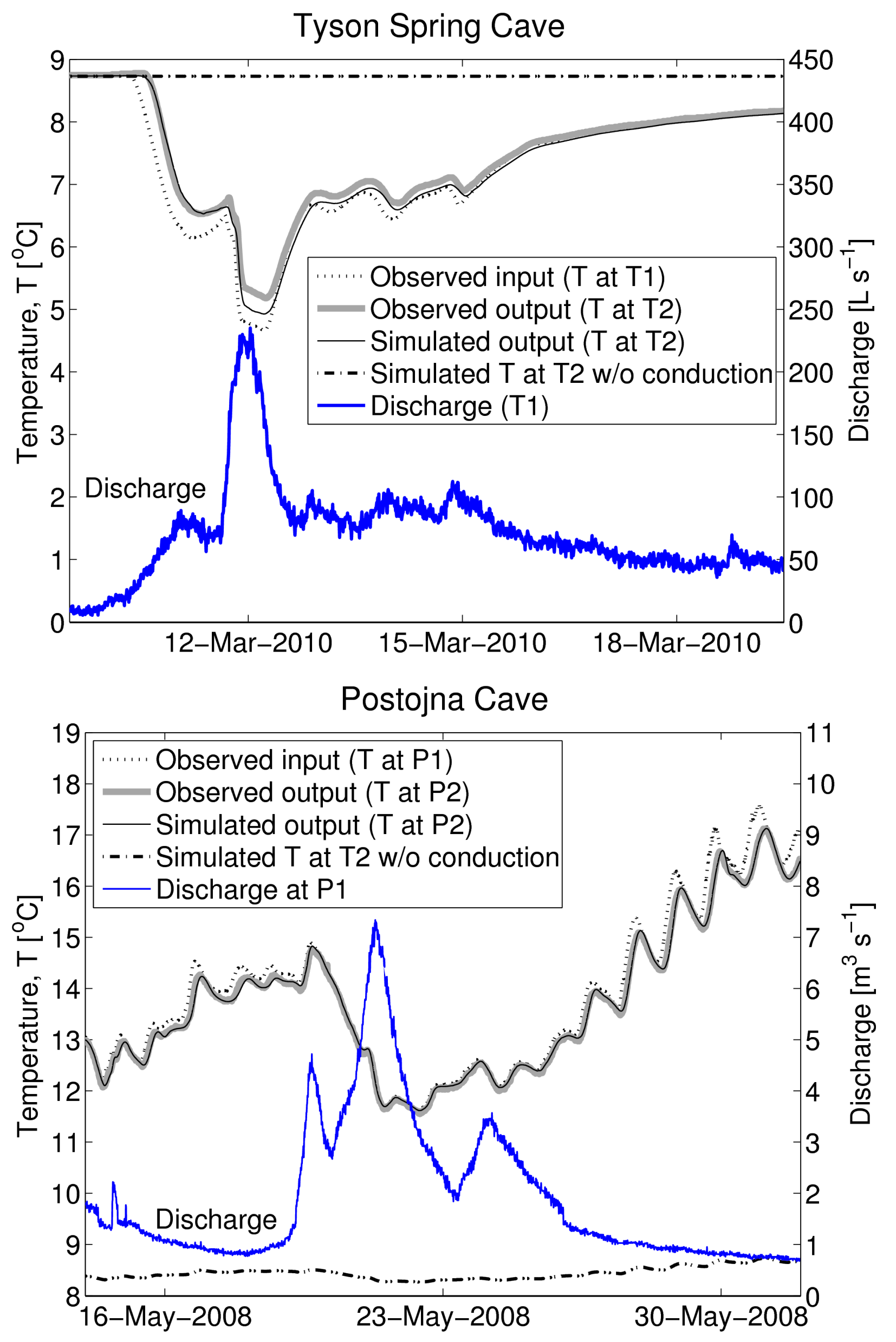


Figure 7. We used our mathematical model of heat exchange in karst conduits to simulate stream temperatures at downstream data loggers using upstream data logger temperatures, discharges, and realistic conduit diameters as inputs to the model. The model includes rock conduction and radiative exchange. For comparison, the dash-dot lines depict the solutions that were obtained for the convection-limited assumption. In both cases, the complete solution performs well, whereas the convection-limited solution significantly overpredicts thermal damping.

Temperature Patterns at Karst Springs

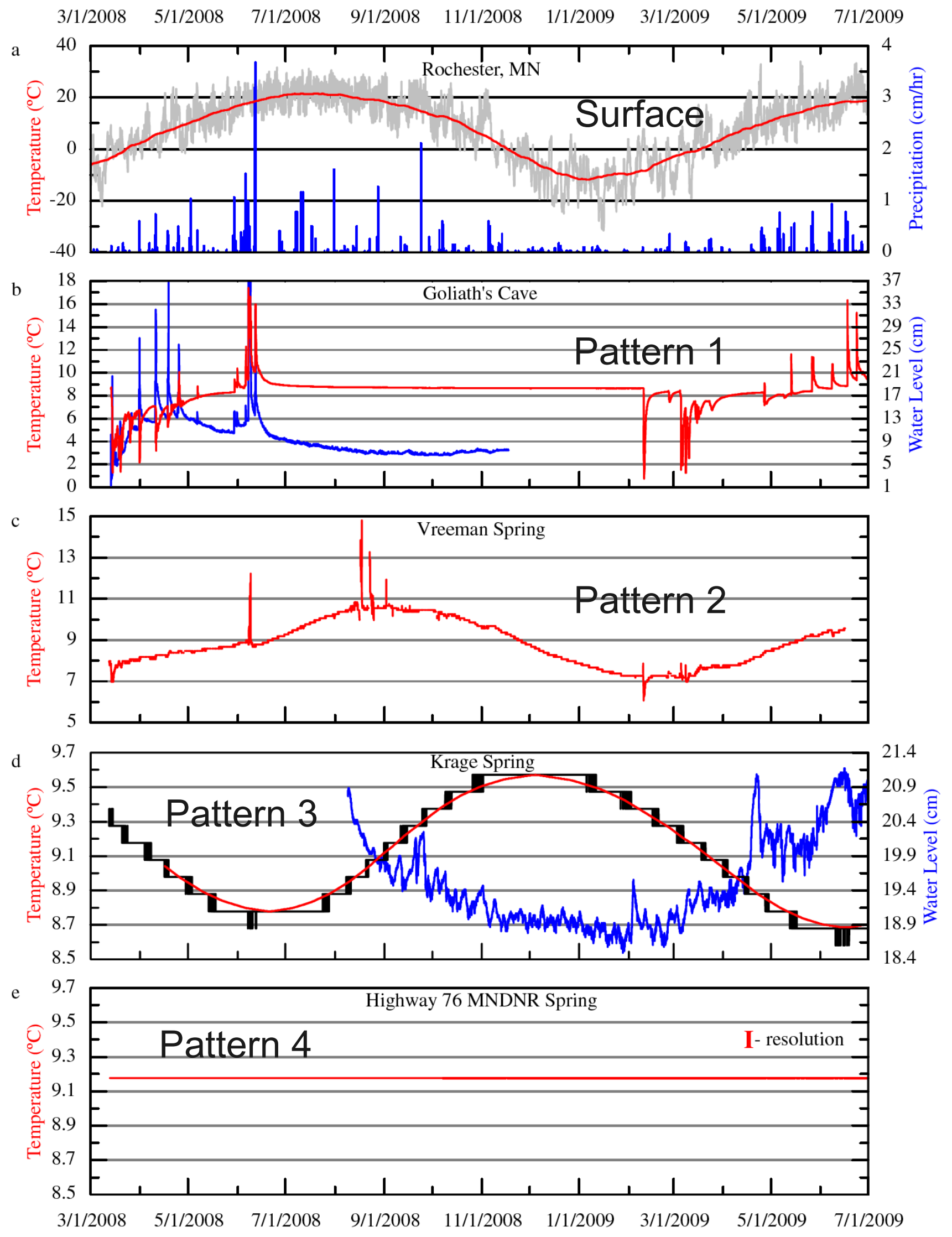
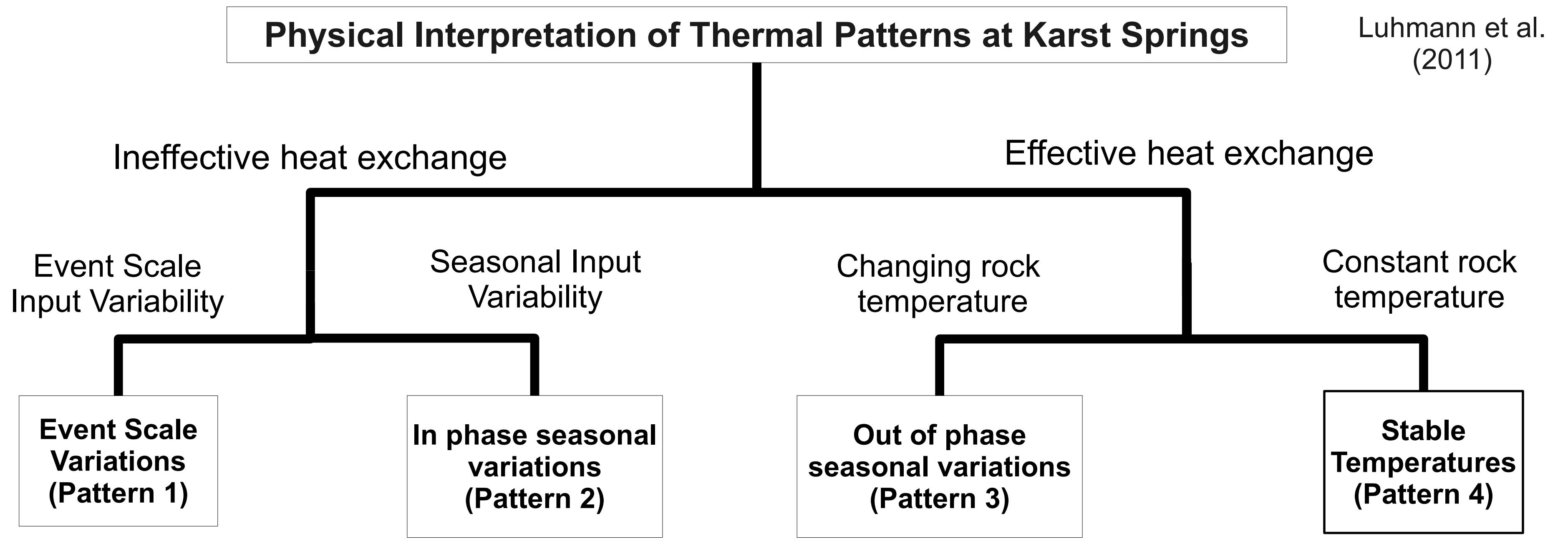


Figure 8. Example of the four types of temperature patterns observed at 25 springs and caves that were monitored in Minnesota as well as surface climate data. (a) Surface temperature and precipitation at Rochester, Minnesota, (b) temperature and water level of a stream running through Goliath's Cave, (c) temperature of Vreeman Spring, (d) temperature and water level of Krage Spring, and (e) temperature of Highway 76 MNDNR Spring. Hourly surface temperature data in gray in (a) were smoothed with a two-month running average shown in red. Temperature data in black in (d) were smoothed with a 10-week running average shown in red. Note the changes in temperature scales: 0° C to 18° C in (b), 5° C to 15° C in (c), and 8.5° C to 9.7° C in (d) and (e). From Luhmann et al. (2011).



Physical Interpretation of Thermal Patterns at Karst Springs

Luhmann et al. (2011)

Ineffective heat exchange

- Event Scale Input Variability
  - **Event Scale Variations (Pattern 1)**
- Seasonal Input Variability
  - **In phase seasonal variations (Pattern 2)**

Effective heat exchange

- Changing rock temperature
  - **Out of phase seasonal variations (Pattern 3)**
- Constant rock temperature
  - **Stable Temperatures (Pattern 4)**

References:

Covington, M.D., A.J. Luhmann, F. Gabrovšek, M.O. Saar, and C.M. Wicks, in review, *Water Resources Research.*

Luhmann, A.J., M.D. Covington, A.J. Peters, S.C. Alexander, C.T. Anger, J.A. Green, A.C. Runkel, and E.C. Alexander Jr. (2011). *Ground Water*, 49, 3, 324-335.