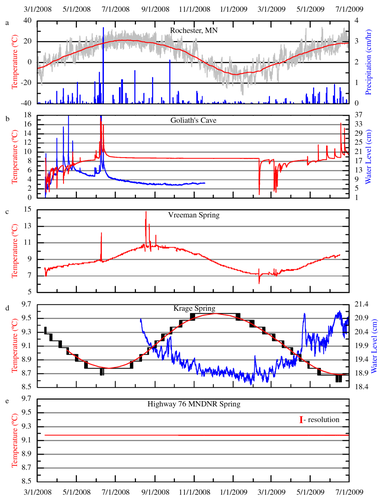
Water temperatures and heat transport in karst: a review of recent advances

M.D. Covington[1,2] and A.J. Luhmann[3]

1. Karst Research Institute ZRC SAZU, Slovenia, 2. University of Arkansas, Department of Geosciences (starting 2012),
3. University of Minnesota – Twin Cities, Department of Earth Sciences

Observed temperature patterns at karst springs



Surface air temperature and precipitation

Pattern 1: Short-term, event-scale temperature variations during recharge events

Pattern 2: Seasonal temperature variations that are *in phase* with surface temperatures

Pattern 3: Seasonal temperature variations that are *out of phase* with surface temperatures

Pattern 4: Stable temperatures

Figure 1. The four types of temperature patterns observed at 25 springs and cave streams in Minnesota. From Luhmann et al. (2011).

Physical Interpretation of Thermal Patterns at Karst Springs

Ineffective heat exchange (localized recharge) | Effective heat exchange (distributed recharge)

Event-scale input variability | Seasonal input variability | Changing rock temperature | Constant rock temperature

Event-scale variations (Pattern 1) | **In phase seasonal variations (Pattern 2)** | **Out of phase seasonal variations (Pattern 3)** | **Stable temperatures (Pattern 4)**

Luhmann et al. (2011)

Mechanisms for heat exchange

Conduction and convection

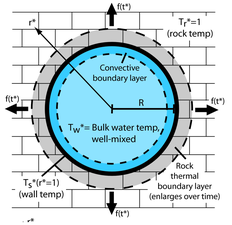
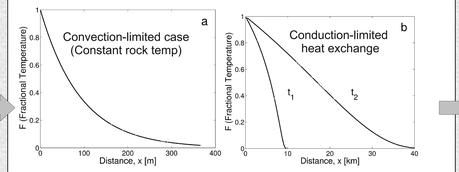


Figure 2. Heat passes from the bulk water through a convective boundary layer and then conducts into the surrounding rock. From Covington et al. (WRR, in press).

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



Scale of meters | Scale of kilometers

Figure 3. Longitudinal temperature profiles for the (a) convection-limited and (b) conduction-limited solutions. The conductive solution is shown for one flow-through time (t_1) and five flow-through times (t_2). Note that the conductive solution allows significantly deeper penetration of temperature pulses (x axis in km). The conduction-limited solution also changes with time. From Covington et al. (WRR, in press).

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

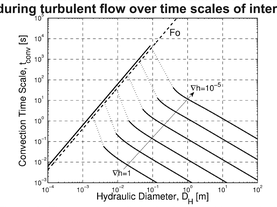


Figure 4. The convection-limited solution holds at early times during a temperature pulse when the rock wall temperature has barely changed. The conduction-limited solution applies at late times when the rock wall has had time to reach the water temperature. The time scale (y-axis) for the validity of these solutions can be derived analytically. The convection-limited solution only holds for very short times for typical karst conduit parameters. Each line is a choice of head gradient (Δh). From Covington et al. (WRR, in press).

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

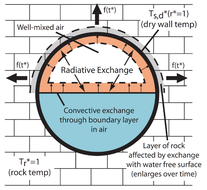
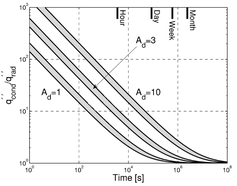


Figure 5. Covington et al. (WRR, in press).

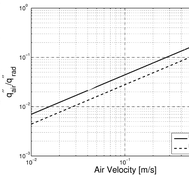
Relative Importance of Radiation



Covington et al. (WRR, in press).

Figure 6. 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_g. At short time scales (hours) radiative flux is small in comparison to the water-rock flux. Dry conduit heat fluxes approach wetted conduit heat fluxes by day to week time scales, showing that radiative effects can be quite important.

Relative Importance of Air-Convection



Covington et al. (WRR, in press).

Figure 7. 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. Near entrances, air-convective effects may be more important.

How far do thermal pulses propagate?

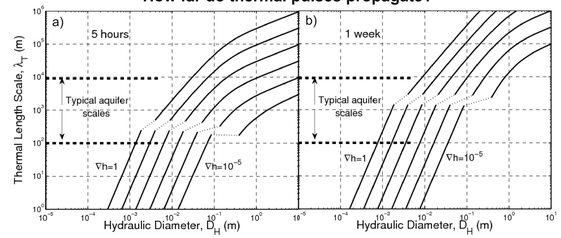


Figure 9. Analytically-derived thermal length scales for pulses with time scales of (a) 5 hours and (b) 1 week. Thermal pulses propagate farther with longer duration inputs as more rock surrounding the flow path changes temperature. Each line is a choice of head gradient (Δh). From Covington et al. (JGR-ES, in review).

Inverse modeling using a multi-tracer experiment: the future?

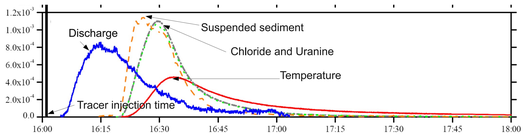


Figure 10. Normalized tracer breakthrough curves observed at Freiheit Spring during a multi-tracer experiment. Tracers were injected into a nearby sinkhole. From Luhmann et al. (J. Hydrol., in review).

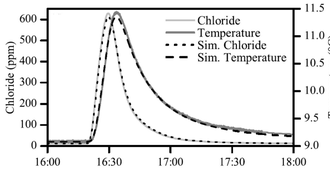
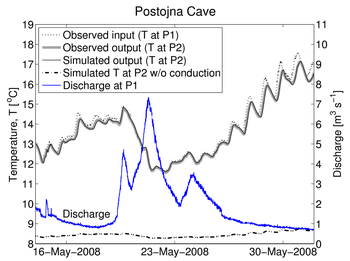
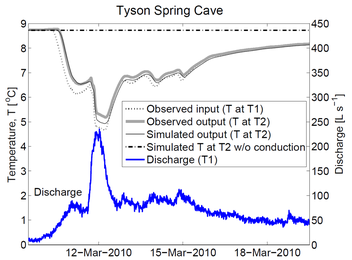


Figure 11. Chloride and temperature breakthrough curves were simulated using an advection-dispersion and heat transport model. The conservative chloride tracer allowed calculation of the percentage of tracer water at all times. Using this information within the model, the conduit diameter was adjusted until the model temperature curve matched the observation. From Luhmann et al. (J. Hydrol., in review).

Validation of the heat transport model by simulation of observed stream temperature in two cave streams with known conduit geometry.

Figure 8. We use 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. From Covington et al. (WRR, in press).





Acknowledgments: A review such as this would not be possible without the help of many people. In particular, we would like to acknowledge our co-authors on the four papers listed below, all of whom contributed to the work presented here. Additionally, we thank John Ackermann and the Minnesota Cave Preserve for access to Tyson Spring Cave. MDC was supported during this work by an NSF Earth Sciences Postdoctoral Fellowship and an NSF International Research Fellowship. AJL acknowledges support from a Doctoral Dissertation Fellowship from the University of Minnesota Graduate School. Partial funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).

References:

Covington, M.D., A.J. Luhmann, F. Gabrovšek, M.O. Saar, and C.M. Wicks, Mechanisms for heat exchange between water and rock in karst conduits, *Water Resour. Res.*, in press.

Covington, M.D., A.J. Luhmann, C.M. Wicks, and M.O. Saar, Process length scales and longitudinal damping in karst conduits, *J. Geophys. Res.*, in review.

Luhmann, A.J., M.D. Covington, S.C. Alexander, S. Chai, B. Schwartz, J. Groten, and E.C. Alexander Jr., Comparing natural and artificial tracers in karst and using them to estimate flow path geometry, *J. Hydrol.*, in review.

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), Classification of thermal patterns at karst springs and cave streams, *Ground Water*, 49, 3, 324-335.