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Interactive comment on "Thermal damping and retardation in karst conduits" *by* A. J. Luhmann et al.

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Below you will find our responses (in plain text) to the comments from Referee R. T. Green (in bold text). We thank R. T. Green for his time and effort in helping us to improve our manuscript.

The subject paper builds on a sequence of recent papers that explore heat flow through karst media. The mathematical development builds on work by Hauns et al. (2001) and Covington et al. (2009, 2011, 2012) using data from a field-scale experiment described in Luhmann et al. (2012). Much of the mathematical model in the subject paper is introduced in the Hauns et al. (2001) paper and further developed in the Covington et al. (2009, 2011, 2012) papers and the dissertation

by Luhmann (2011). The subject paper clearly describes the governing equations. The authors then discuss at length analytical and numerical solutions to the advection-dispersion equation to evaluate thermal damping and retardation for cylindrical and planar geometries chosen for representing karst solution features.

The authors solve the equations for a sinusoidal signal chosen to represent the pulse of heated and tagged water injected into a sinkhole during the field-scale experiment. The authors make simplifying assumptions when solving these equations. Although solving the equations without making these assumptions would be challenging, there is some question whether these assumptions are appropriate. Of concern is the assumption of constant velocity. In particular, the temperature of the water input into the cylindrical or planar conduit is represented as sinusoidal but flow is constant (Eq. 34).

Derivations of relatively simple analytical solutions require simplifications, one of which is the constant velocity assumption. It is possible that this assumption will introduce too much uncertainty and limit the applicability of the damping and retardation analytical solutions in some field scenarios. However, a conduit fed by a sinking stream will have periods of relatively constant velocity between recharge events even while there are diurnal variations in water temperature. In this case, the analytical solutions are directly applicable to field settings, at least in terms of the constant velocity assumption. We noted that interpretation of damping and retardation data is most easily accomplished in these systems when flow-through time is relatively constant. Still, it is possible that the analytical solutions provide useful results, even when the assumptions are not valid. Velocity was not constant during our field experiments at Freiheit Spring. In Luhmann et al. (2012), the best fitting numerical simulation of the thermal pulse from the first experiment incorporated a flow path with a hydraulic diameter of 7 cm in planar coordinates, and the numerical simulations incorporated the variations in velocity. If we assume that velocity was constant and use the average flow-through time in the conduit, then the average of the two estimates of hydraulic diameter using both the damping and retardation data is 6.5 cm.

The field-scale experiment was described in a separate paper by Luhmann et al. (2012) which described how a volume of 13,000 L of water was heated and spiked with tracers, then injected into a sinkhole in 3-1/2 minutes. The temperature of the injected water was not reported, but groundwater temperatures at the spring discharge located at a distance of 95 m increased by a maximum of about 2.5°C. This input is consistent with the assumption of sinusoidal temperature at the upstream boundary, but violates the assumption of constant velocity in Eq. (34) thereby raising a question whether the numerical solution is valid. The solution may be valid if velocity is assumed constant during the injection of the pulse, however this assumption is not noted. Given the description of discharge in Fig 3a in Luhmann et al. (2012), however, this assumption does not appear to be supported.

The manuscript includes data from two field-scale experiments. The first experiment was described in Luhmann et al. (2012), and the publication includes the temperature of the injected water (24.1°C). The second experiment was conducted at the same site three days later, and data from this experiment is described for the first time in this manuscript. The temperature of the injected water was included in Fig. 6 (21.5°C), but we will also include this temperature in the text to prevent any confusion. In Luhmann et al. (2012), we concluded that the pressure pulse, which indicated full pipe flow conditions, suggests that the flow path's cross-sectional area was likely constant. Therefore, the variation in discharge corresponds to a variation in velocity during both field experiments. We acknowledge that variations in velocity will cause uncertainty in Eqs. (36), (37), and (38). However, even with this uncertainty, we note that estimates of hydraulic diameter using Eqs. (36) and (38) are comparable to and bound the estimate in Luhmann et al. (2012) from heat transport simulations that include variations in velocity.

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When discussing the results, the authors introduce time-averaged or reference flow velocity (Eq. 37) when establishing the terms for agreement in thermal transmission between planar and cylindrical heat transport and determine a correction factor is needed. The correction term is dependent on the time-average flow velocity. Later on, the authors comment that scatter in the cylindrical solution at relatively slow velocities may be due to numerical scatter. This correction factor in the solution for planar flow may be needed to overcome the assumption of constant velocity.

It is unlikely that there is a simple correction factor that would provide agreement between constant and variable velocity scenarios. Even if there were, such a correction factor would be different from the correction factor given in Eq. (37).

The authors discuss the implications of assuming constant velocity in Section 6.3.2 and evaluate the impact of this assumption by comparing numerical simulations with and without constant velocity. The comparisons suggest that thermal retardation is affected by a maximum of 30 % occurred when the ratio of recharge duration to flow-through time is decreased (Table 3). In other words, the discrepancy is increased for systems in which the duration of recharge is small relative to the velocity and the spatial distance between the locations of recharge and discharge (i.e., flow-through time).

The relationship in retardation variability between constant and variable velocity simulations is complex. Variability in thermal retardation between constant and variable velocity simulations increased for most of the sets as the ratio of recharge duration to flow-through time decreased. However, the set that had the lowest recharge duration to flow-through time ratio had the second lowest retardation variability between constant and variable velocity simulations.

The authors further elaborate on the qualifying assumptions in Sections 8.1 and 8.2 (Limitations). They note that velocity only occurs twice in the final solution,

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Eq. (36) and (38), and that it is included as the flow-through time (L/V). The Limitations section (8.1) provides minimal discussion on the ramifications when assuming constant velocity.

We will add some additional discussion on the limitations of the constant velocity assumption, noting that this assumption may introduce too much uncertainty in some field settings.

It would be informative for the authors to expand on the assumption of constant velocity. It is obvious that the severity of the assumption of constant velocity is dependent on spatial scale, introducing more uncertainty and inaccuracy when the flow-through time becomes relatively large. Providing a graph of how uncertainty or inaccuracy increases with flow-through time would be instructive. Partial data for such a graph is already provided in Table 3. Additional data could be provided with limited additional comparisons similar to those used to create the data in Table 3. Such a graph would provide readers a better sense on when the assumption of constant velocity relative to travel time inherent in the assessment become too large as to be unacceptable.

Of the five simulation sets in Table 3, the one with the largest flow-through time had the second lowest variability in thermal retardation. Therefore, the constant velocity assumption does not necessarily introduce more uncertainty and inaccuracy when the flow-through time becomes relatively large. Because of this, it is difficult to generalize when the constant velocity assumption introduces large errors.

Would it be possible to report the temperature of the water that is input? This could possibly allow evaluation of the energy budget. It would be necessary to assume the thermal properties of the host rock and make assumptions on the constitutive relations of heat transfer, but insight on thermal damping and retardation could be gained by such an assessment.

We will add the temperature of the water input from the second field experiment

(21.5°C) to the text, although it was already included in Fig. 6. The temperature of the input from the first field experiment (24.1°C) was included in Luhmann et al. (2012). We have already included the thermal retardation data from both field experiments in the current manuscript. Our calculation of damping from the first field experiment is detailed in Luhmann et al. (2012), but we do not calculate damping from either pulse of the second field experiment because no samples were analyzed for chloride and there was more thermal variability in the spring water before the second field experiment, both of which increase uncertainty in a damping calculation.

An evaluation of the energy budget from the first study was provided in Luhmann et al. (2012), where we calculated a lower heat recovery than either dye or salt recovery over the first two hours of the experiment. This lower heat recovery occurred because of the damping of the thermal signal, where some of the heat was transferred into the rock surrounding the flow path. We also noted that heat from the heated rock was later transferred to subsequent water that flowed along the flow path, since water temperature at the spring remained higher than its background after experiment water no longer reached the spring. There is more uncertainty in the evaluation of the energy budget from the second experiment because of the reasons noted above which introduce uncertainty in the damping calculation.

In summary, the paper is well organized and well written. It relies heavily on the series of papers leading up to it (Covington et al., 2009, 2011, 2012; Luhmann, 2011; Luhmann et al., 2012). This is not to imply that the paper does not make a substantive contribution, it does, but by relying on this proven path, a lot of the developmental work regarding the theory was well established. I would ask that the authors examine the concern that velocity may not be assumed to be constant and to consider exploring the energy balance. Evaluating the energy balance could provide insights on energy transport and thermal damping. This latter suggestion might be best left to a subsequent publication.

Please see our responses above regarding the constant velocity assumption and the energy balance.

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