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Tomographic inversion of active thermal tracer experiments to characterize aquifer heterogeneity

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The tomographical approach has been established as an efficient and robust way to characterize spatial heterogeneity of hydraulic aquifer properties. It has been successfully applied on pressure signals and solute tracers, but only little experience is available using heat tracer signals in a tomographic setup. The advantage of using a heat tracer is that temperature can be easily monitored with good temporal and spatial resolution and it provides information directly about the heat transport in the subsurface. In this study, we consider active injection of warm water into a shallow groundwater well. The concept is tested on a virtual aquifer implemented in a numerical model. The thermal evolution in the system after repeated injection at different depth levels is monitored though a tomographical observation setup. This delivers thermal tracer travel times for each combination of injection (source) and observation points (receivers). The combined inversion of all source-receiver travel times is formulated and efficiently solved as an eikonal problem. The result of the eikonal inversion is a cross section through the aquifer of mean tracer velocity and of inverted flow paths. By assuming that the heat transport is dominated by advection, a hydraulic diffusivity map can be calculated from the velocity map, similar to solute tracer tomography, introducing one new variable, which is known as the thermal retardation factor. This assumption is crucial for the inversion procedure, and it also reflects that our main interest is in the detection of preferential flow paths, where thermal diffusion plays only a minor role. For this purpose, early time diagnostics are used instead of, for example, the mean breakthrough time at the receivers. To characterize the reliability of the results, the null-space energy map is calculated based on the inverted advection flow paths. First results of the heat tracer inversion approach are comparable to those from other hydrogeological tomography methods, demonstrating the effectiveness of the new method. Our main interest is to determine the application window, where the method efficiently captures aquifer heterogeneity in different environments and it can be applied in practice. This is limited by the relative importance of advection and diffusion, the size of the examined system, and the degree of hydraulic heterogeneity.