Thermal transport in heterogeneous groundwater systems: Dynamics and flow estimation

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Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any other university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Coauthorship

This PhD thesis was produced as a series of journal publications in leading international scientific journals. Chapters 2 - 4 were written as independent journal papers. At the time this thesis was completed, one journal paper (chapter 3) was published, one was accepted and in the final stages of copy editing (chapter 2), and another (chapter 4) was undergoing revision and is expected to be published in due course.

I am the first author on all journal publications and was responsible for leading and conducting the majority of research contained in them, including the final writeup and publication of the research.

The papers in this thesis have benefitted from ongoing advice and input of my supervisors, coauthors and the peer review process. I acknowledge their valuable advice and important contributions.

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Summary

The use of water temperature as a tracer to infer rates of fluid flow, and determine subsurface properties has gained popularity in recent years, with review articles on heat as a tracer to infer groundwater–surface water exchange (Anderson 2005; Constantz 2008; Rau et al. 2014), heat as a tracer in hydrogeology (Anderson 2005), and the use of heat as a tracer for deep groundwater processes (Saar 2011). Heat is a popular tracer because both natural variations in water temperature (e.g. diurnal temperatures in streambed materials), or applied (e.g. input temperature can be monitored in aquifer storage and recovery systems) temperatures can be analysed. Other benefits of temperature measurements include the fact that water temperature can be measured without the need for laboratory analysis, and it can be collected quickly and easily from point measurements, to the use of Distributed Temperature Sensors to record temperature both temporally and spatially. With the increase in popularity in the use of temperature in hydrogeology, an understanding of the influence of aquifer heterogeneity on thermal transport in groundwater is required.

Anderson (2005) highlights that a revival of the use of temperature measurements in hydrogeology has been promoted by the availability of inexpensive temperature data loggers, and increased availability of numerical codes to simulate joint water flow and thermal transport. Temperature measurements could be useful in a range of contexts, as thermal transport occurs on a range of spatial scales, and is involved in a number of processes. With heterogeneity of porous media also occurring from the pore scale to the basin scale, the understanding of how heterogeneity influences thermal transport is vital to understand where the use of heat may be useful to understand groundwater systems, and to identify any limitations to its use. This body of work addresses the influence of aquifer heterogeneity on the transport of heat in porous media on scales from the kilometre scale down to the centimetre scale, and across a range of processes. Specifically, this work investigates: 1) the influence of aquifer heterogeneity on the potential for thermal free convection, 2) the influence of aquifer heterogeneity on the interpretation of applied heat and solute groundwater tracers, and 3) the influence of streambed heterogeneity on the use of temperature time series to infer groundwater–surface water exchange.

The first part of this study investigates the potential for thermal free convection in the Yarragadee aquifer in the Perth metropolitan area in Western Australia. It does so by utilising a stratigraphic forward model of the aquifer, which provides a realistic, and plausible heterogeneous structure of the aquifer, something that is lacking in existing investigations of the influence of aquifer heterogeneity on the potential for free convection. The key question was whether the inclusion of heterogeneity in simulations of coupled heat and water flow would prevent the occurrence of free convection. We show that the influence of heterogeneity may not be sufficient to prevent the occurrence of thermal free convection, and identify regions where convection is most likely. This study provides further evidence for the presence of thermal free convection in the Perth metropolitan area, which will assist in the search for low temperature geothermal energy sources in Western Australia.

The second part of this study investigates the influence of aquifer heterogeneity on the interpretation of applied solute and heat tracers to determine pore water velocity in heterogeneous aquifers. It does so through the use of numerical simulations of groundwater flow, solute and heat transport in synthetic heterogeneous aquifers. Aquifer heterogeneity is represented using geostatistical properties that span the range found across highly instrumented sites such as the Borden, Cape Cod and the MADE sites. The goal was to identify any benefits or drawbacks of the use of applied heat or solute tracers. We show that interpretations of a heat tracer yielded the lowest variance in estimates of velocity. This means that estimates of velocities inferred from heat tracers will be closer to the mean velocity, which may be a key benefit. The higher variance in estimates of velocity from interpretation of the solute tracer may provide more insight about aquifer heterogeneity.

The final part of this study investigates the influence of streambed heterogeneity on the Hatch et al. (2006) analytical solutions that use temperature time series to determine groundwater– surface water interactions. It does so through the use of numerical models which generate synthetic temperature time series data, which are used to estimate vertical fluxes. The benefits of this approach is that the analytical models can be tested where fluxes are known. We show that generally, the Hatch et al. (2006) equations perform fairly well for losing streams. We show that failure of the Amplitude Ratio method, and large variations in estimated fluxes over small distances from the Phase Shift method can be attributed to streambed heterogeneity. This research demonstrates that even when the assumption of 1D and homogeneous flow is violated, that the Hatch et al. (2006) equations perform well, and can provide detailed understanding of fluxes in heterogeneous streambeds.

Following Anderson's (2005) review, temperature measurements are becoming a more widely used tool in hydrogeology, including contexts ranging from groundwater–surface water interaction, to the identifying the location of fractures. With the use of temperature measurements on the increase in hydrogeology, it is important to understand the influence of heterogeneity in porous media on thermal transport and the estimation of flow rates from water temperature.

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