Earth-Science Reviews 129 (2014) 40–58

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Heat as a tracer to quantify water flow in near-surface sediments

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ARTICLE INFO

Article history:
Received 18 October 2012
Accepted 28 October 2013
Available online 1 December 2013

Keywords:
Heat as a tracer
Conduction heat transport
Convection heat transport
Temperature data
Hydrogeology
Groundwater hydrology

ABSTRACT

The dynamic distribution of thermal conditions present in saturated near-surface sediments have been widely utilised to quantify the flow of water. A rapidly increasing number of papers demonstrate that heat as a tracer is becoming an integral part of the toolbox used to investigate water flow in the environment. We summarise the existing body of research investigating natural and induced heat transport, and analyse the progression in fundamental and natural process understanding through the qualitative and quantitative use of heat as a tracer. Heat transport research in engineering applications partly overlaps with heat tracing research in the earth sciences but is more advanced in the fundamental understanding. Combining the findings from both areas can enhance our knowledge of the heat transport processes and highlight where research is needed. Heat tracing relies upon the mathematical heat transport equation which is subject to certain assumptions that are often neglected. This review reveals that, despite the research efforts to date, the capability of the *Fourier*-model applied to conductive–convective heat transport in water saturated natural materials has not yet been thoroughly tested. However, this is a prerequisite for accurate and meaningful heat transport modelling with the purpose of increasing our understanding of flow processes at different scales. This review reveals several knowledge gaps that impose significant limitations on practical applications of heat as a tracer of water flow. The review can be used as a guide for further research directions on the fundamental as well as the practical aspects of heat transport on various scales from the lab to the field.

Contents

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http://dx.doi.org/10.1016/j.earscirev.2013.10.015

1. Introduction

In this review the transport of heat through unconsolidated water saturated porous materials is investigated with the focus on how to use it as a tracer for water flow in the environment. The theoretical foundation for conductive heat transfer calculations was given by Fourier (1822) based on *Newton's* law of cooling. Mathematical descriptions of the temperature field caused by a moving fluid through porous materials were developed by Schumann (1929) and successfully tested with different porous materials by Furnas (1930). The original heat conduction equation has been subject to comprehensive mathematical exploration including the introduction of a moving heat source (Carslaw and Jaeger, 1959). The first analytical solutions for modelling heat transport under the influence of flowing water in the environmental realm were provided by Suzuki (1960), Stallman (1963, 1965) and Bredehoeft and Papaopulos (1965).

The earth sciences research community did not immediately recognise the potential offered by heat tracing when applied to water saturated near-surface environments. Instead, temperature was mainly considered as a variable that primarily influences the water quality (e. g. Blakey, 1966). Early tracing applications focused on the effect of heat transport across the surface interface on subsurface temperatures (Birman, 1969), heat flow through fractures (Bodvarsson, 1969), the characteristics of temperature depth profiles (Cartwright, 1970; Sorey, 1971), and the horizontal redistribution of geothermal heat (Cartwright, 1971). Somewhat later, Smith and Chapman (1983) comprehensively investigated the characteristics of natural heat flow in the subsurface.

The usefulness of near-surface temperature data as an indicator of natural heat flow were later rediscovered and linked quantitatively to water flow through the soil zone (e. g. Cartwright, 1974; Lee, 1985; Taniguchi, 1993; Taniguchi and Sharma, 1993) and the streambed (e. g. Lapham, 1989; Silliman et al., 1995) using the heat transport model. Increasing research at the earth's surface, streams in particular, was sparked by the recognition that our surface water and groundwater resources are connected and form a single resource (e. g. Winter et al., 1998), and that exchange flows have a crucial impact on the health of our riparian ecosystems (e.g. Brunke and Gonser, 1997; Woessner, 2000; Krause et al., 2011a). The use of natural heat as a tracer has since become popular. Surface water temperature measurements have been used for detecting groundwater discharge zones (e.g. Andersen and Acworth, 2009; Baskaran et al., 2009). Sediment temperature measurements were used for quantifying water fluxes through the saturated porous boundary (e.g. the sediments of any surface water body) (e.g. Stallman, 1965; Lapham, 1989; Hatch et al., 2006). The popularity of heat tracing can be attributed to temperature being a robust parameter that can be measured cheaply and easily by using fully automated devices (Johnson et al., 2005; Kalbus et al., 2006).

Introductions to forced heat convection in subsurface geologic processes are given in Ingebritsen and Sanford (1998) and Domenico and Schwartz (1998). Excellent reviews and summaries on heat as an environmental tracer can be found for groundwater in Anderson (2005), arid zone recharge in (Blasch et al., 2007) and for streambed water exchange in Constantz (2008). Furthermore, advanced heat transport modelling techniques are comprehensively compiled in Nield and Bejan (1992) and Kaviany (1995). These works are specific to their respective research disciplines, such as groundwater or engineering applications. From this it becomes clear that the use of heat as a tracer in the earth sciences overlaps with the application of heat transport in engineering, which has been thoroughly investigated by researchers in the realm of chemical and process engineering. Consequently, additional insights into heat transport modelling can be gained from the literature reporting on engineering research. The overlap between earth sciences and engineering has been explored very little to date. A summary of theoretical and laboratory research from the field of engineering has the potential for informing the use of heat as a tracer in the earth sciences.

Engineering research has mainly focussed on heat transport through beds packed with porous materials (e.g. Green et al., 1964; Metzger et al., 2004). The concept is equivalent to unconsolidated sedimentary material studied in the earth sciences. However, porous packed bed experiments are better suited for fundamental investigations due to the good control over the porous materials, fluid and boundary conditions. The main differences are the pure homogeneous materials with well-defined grain geometries (i.e. glass beads with ideal shapes) in the engineering research versus heterogeneous natural materials with variable grain shapes, sizes and mineralogy in earth sciences research.

In this paper heat as a tracer is reviewed with the aim to (1) compile knowledge about the capability of the differential heat transport equation and its parameters to model conductive–convective heat transport through unconsolidated natural porous materials, (2) summarise advances to date in the development and applicability of methods that quantify water flow from temperature data, and (3) reveal the gaps in our understanding of the heat transport process at different scales. The scope of this review comprises the quantification of heat and water transport in unconsolidated near-surface sediments as well as engineering research employing porous media heat laboratory experiments with the aim of understanding the heat transport model under different hydraulic conditions. This review paper extends the scope of the recent reviews by Anderson (2005) and Constantz (2008) by: (1) including heat transport research from engineering which provides fundamental understanding useful for earth science research; (2) reporting on the significant progress in near-surface heat tracing that has been achieved since Anderson (2005) identified this area as a “recent focus” and is now a rapidly growing area of research; (3) reporting on the outcome from “creative deployment of temperature equipment” that Constantz (2008) envisioned as a future direction for streambed research.

Literature reporting on heat transport in the deeper subsurface is excluded in this review, unless significant contribution to the fundamental understanding of heat transport can be gained. The primary reason for this is the fact that typically groundwater flow velocities decrease with depth from the surface (e.g. Winter et al., 1998) hence convective