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Heat as a tracer to quantify processes and properties in the vadose zone: A review

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ABSTRACT

Soil moisture and temperature are some of the most important controls for a wide variety of geochemical and ecological processes in the vadose zone (VZ). Soil moisture is highly variable both spatially and temporally. The development of methods to measure it on various scales has been the subject of much activity. Recently, geoscientists have been increasingly interested in measuring temperature as a proxy for hydrologic properties and parameters, including soil moisture. Here, we discuss the motivation, primary concepts, equipment, and fundamental thermal and hydraulic models related to heat and water transport in variably saturated porous media. A large variety of methods for heat tracing, including both passive and active-heating methodologies, are detailed. Heat tracing methods offer the capacity to measure soil moisture on a scale from ~1 cm up to several km using temperature, a parameter whose measurement in VZ studies is often required anyway due to its effect on many subsurface processes. Furthermore, heat-tracing methods are not affected by high salinity pore water that can limit electromagnetic soil moisture methods. We also review coupled thermo-hydro VZ modelling software and VZ thermal regime studies and identify several knowledge gaps. With the intention to serve as an introduction to VZ heat-tracing, this review consolidates recent advances and outlines potential themes for future research.

Contents

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1. Introduction

Moisture content and temperature act as strong controls on a wide variety of ecological and geochemical processes. Consequently, both are of great interest to researchers investigating the vadose zone (also known as the unsaturated zone). Although moisture in the vadose zone (VZ) represents only ~0.05% of the global freshwater balance (Dingman, 2002), variable saturation occurs in ~87% of the global land cover (Latham et al., 2014). Temporal and spatial variations of soil moisture have pronounced effects on ecology. Anthropogenic and climatic effects on hydrological conditions can affect soil moisture distributions and consequently natural ecosystems or crops. Similarly, many chemical and physical processes are dependent on temperature, often non-linearly. Because accurate knowledge of soil moisture and, in many cases, temperature is crucial for studies and applications in agronomy (e.g., Brandt, 1992; Bolten et al., 2010), geochemistry (e.g., Rousseau et al., 2004; Robinson et al., 2009), and hydrogeology (e.g., Vereecken et al., 2010; Stewart et al., 2013), the thermodynamics of the vadose zone and, specifically, the use of temperature to quantify moisture content are of interest to a broad and interdisciplinary audience.

The importance of soil moisture and its various measurement methods have been discussed in depth by many (e.g., Stafford, 1988; Blöschl and Sivapalan, 1995; Mahmood, 1996; Western et al., 2002; Vereecken et al., 2008; Robinson et al., 2008). Vereecken et al. (2008) presented a review of the value of soil moisture measurements on field and catchment scales, while Robinson et al. (2008) reviewed watershed-scale (defined as 0.1–80 km^2) soil moisture measurement methods. Different research and management questions require soil moisture information on a wide variety of temporal and spatial scales, ranging from minute-duration and centimetre scale to a yearly, 10,000 km^2 scale. Because no single method is suitable for all applications, it is important to choose an appropriate approach.

The most direct and conceptually simple of the many methods for soil moisture measurement is the thermogravimetric measurement, wherein a sediment sample is weighed before and after oven drying to determine the weight that is lost due to evaporation. However, this necessitates disturbance of the sediments and delivers only a point-in-space and point-in-time measurement. All other methods involve some form of indirect measurement of water content. For instance, the relatively large neutron scattering cross-section of hydrogen atoms in water molecules can be exploited to infer moisture content. Invasive mobile neutron probes containing a radiation source and detector have been widely used to measure soil moisture (Bell, 1987; Chanasyk and Naeth, 1996), although their usage is generally subject to regulation. More recently, neutrons originating from collisions with cosmic rays have been used to measure soil moisture integrated on the ~100 m scale (Zreda et al., 2008), most notably in the COSMOS network (Zreda et al., 2012; Rosolem et al., 2013; Franz et al., 2013). Ground penetrating radar (Daniels et al., 1988; Huisman et al., 2003; Lunt et al., 2005) represents another set of methodologies for measuring soil moisture on the >1 m scale. The method exploits the soil moisture dependence of dielectric permittivity, which affects the phase and amplitude of reflected and transmitted electromagnetic waves. Time-domain reflectometry (TDR) and transmissometry (TDT) probes (Robinson et al., 2003; Vereecken et al., 2008) use the reflected or transmitted signals, which depend on soil dielectric properties, from electromagnetic pulses to infer soil moisture and are useful for small-scale measurements. Ground-reflected global positioning satellite (GPS) signals have also been used as soil moisture proxies for the top ~5 cm of the subsurface (e.g., Larson et al., 2008; Chew et al., 2014). Finally, the *Soil Moisture and Ocean Salinity* (SMOS) (Kerr et al., 2001) and *Soil Moisture Active Passive* (SMAP) (Entekhabi et al., 2010) missions have mapped soil moisture globally to ~35 km and ~10 km resolution, respectively, using interferometry and taking advantage of the moisture-dependence of microwave emissivity. All methods, with exception of direct weighing of samples, capitalise upon the quantifiable effects that moisture content has on the transmission of atomic particles, electromagnetic waves or, in the case of this review, thermal energy.

All methods have caveats and limitations in their applicability. Electromagnetic methods, for example, are effected by salinity, which can limit applications in coastal zones or dryland regions of high salinity, while neutron probes require on-board radioactive material. Temperature offers the advantage of being an extremely robust parameter that is easily measured with high precision and resolution. Furthermore, temperature measurements are often required for other analyses. The thermal methods discussed in this review extend soil moisture measurement capabilities to smaller spatial and temporal scales.

Since the publication of foundational studies (e.g. Constantz et al., 2003a), heat-tracing has seen rapid uptake by researchers interested in surface water-groundwater (SW-GW) exchange and other hydrogeological processes. Reviews on heat-as-a-tracer for groundwater flow and SW-GW exchange (Anderson, 2005; Constantz, 2008; Rau et al., 2014), as well as a review of deep subsurface flow geothermal heat-tracing (Saar, 2011), have provided in-depth summaries of progress made in heat-tracing methods and applications, albeit only for saturated conditions.

Vadose zone heat-tracing has seen rapid growth in published research over the past decade. This article seeks to provide the first review of this accelerating domain of research. Firstly, details of the relevant physics are presented. Variable saturation introduces another level of non-linear complexity into the equations that govern heat transport in porous media. While some of the physics describing heat and moisture transport can be described analytically, other parameters, most notably thermal conductivity, require empirical models. Secondly, we present a comprehensive review of methods applicable to heat-tracing in the VZ. This includes a discussion of both active heating and passive methods. Thirdly, we discuss thermal regime studies that have been carried out in the variably saturated subsurface. Fourthly, a brief overview of the temperature measurement methods used in heat-tracing is offered, much of which is equally applicable to the saturated zone with simplifications. We also review numerical studies of heat transport in the variably saturated subsurface and associated software packages. Finally, the current knowledge gaps and areas for future research in VZ heat-tracing are outlined.

2. Water and heat transport in the vadose zone

While much research has been dedicated to the mechanics and deformation of porous materials and their coupling with thermal and fluid flow processes (e.g., Schrefler, 2002; Stephansson et al., 2004), in the context of heat-tracing in unsaturated conditions, we consider only the physics of water flow and heat transport. Additionally, heat tracing research to date has primarily considered unfrozen conditions due to the complexities involved with frozen water expansion and the thermodynamics of water freezing and thawing. Thus, the absence of pore ice is assumed throughout. The mathematical symbols used throughout this section are listed in Table 1 for ease of reference.

2.1. Water flow in unsaturated conditions

The fundamentals of water behaviour in the vadose zone have been well documented by many (e.g., Bear, 1979; Stephens, 1995; Domenico and Schwartz, 1998; Tindall et al., 1999). For certain aspects, analytical expressions can describe idealised behaviour; for others, empirical expressions have been developed. Here, we present equations of particular importance for heat-tracing in variably saturated conditions. *Richards*' equation (Richards, 1931), presented here in its mixed form (Celia et al., 1990), describes water transport in variably saturated conditions:

$$\frac{\partial\theta}{\partial t} - \nabla\cdot\left(K_e(H_p)\nabla H_p\right) - \frac{\partial K_e}{\partial z} = 0 \qquad (1)$$