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Application limits of the interpretation of near-surface temperature time series to assess groundwater recharge

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SUMMARY

The main objective of this study was to test the application limits of a groundwater recharge assessment technique based on the inversion of a vertical one-dimensional numerical model of advective–conductive heat transport, using temperature time series at three different depths (1, 3, 5 m) in the unsaturated zone. For this purpose, several synthetic hourly datasets of subsurface temperatures, representing various weather, ground cover, and soil texture conditions, thus covering a wide range of groundwater recharge values, were produced with the vertical one-dimensional coupled heat and moisture transport simulator SHAW (Simultaneous Heat and Water model). Estimates of the vertical flux of water in the soil were then retrieved from these realistic temperature profiles using a simple one-dimensional numerical simulator of advective and conductive heat transport in the unsaturated zone that was developed as part of this study. The water flux was assumed constant on a weekly, monthly, semiannual, and annual basis. From these vertical water flux estimates, annual (potential) groundwater recharge rates were then computed and results were compared to those calculated previously with SHAW to assess the accuracy of the method. Results showed that, under ideal conditions, it would be possible to estimate annual recharge rates that are above 200 mm/y, with an acceptable error of less than 20%. These "ideal" conditions include the resolution of the water flux on a weekly basis, error-free temperature measurements below the soil freezing zone, and model parameter values (thermal conductivity and heat capacity of the soil) known *a priori* with no uncertainty. However, this work demonstrates that the accuracy of the method is highly sensitive to the uncertainty of the input model parameters of the numerical model used to carry out the inversion and to measurement errors of temperature time series. For the conditions represented in this study, these findings suggest that, despite the best modeling and field instrumentation practices, heat-based techniques for the assessment of diffuse groundwater recharge rates are likely not well suited for real field conditions, but could still represent a viable approach for applications carried out in engineered materials and under controlled conditions.

1. Introduction

1.1. Background

It has long been recognized in the field of hydrogeology that water flowing in the soil carries sensible heat affecting subsurface temperatures (Anderson, 2005; Healy, 2010; Rau et al., 2014). Therefore, hydrogeologists have been interested since the 1960s in using heat as a tracer to monitor qualitatively and quantitatively the movement of groundwater (e.g. Suzuki, 1960; Stallman, 1963, 1965; Bredehoeft and Papadopulos, 1965). Heat is an attractive tracer for groundwater studies because soil temperature has a natural dynamic signal that can be measured accurately, cheaply, and at high frequencies (Stonestrom and Blasch, 2003). Arrays of sensors can be easily deployed, with minimal soil disturbance, to monitor temperature at various depths below the ground surface. Moreover, unlike methods based on chemical and isotopic tracers, no sample of water or soil is required (Healy, 2010).

Assessment of the vertical flow of groundwater by the analysis of transient subsurface temperature measurements was introduced by Suzuki (1960) and Stallman (1963, 1965). They estimated the downward flow of water in irrigated rice paddy fields by fitting an analytical solution of the transient vertical one-dimensional (1Dz) advective–conductive heat transport equation in homogeneous soils to near-surface temperature measurements. Several

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years later, Taniguchi (1993) calculated the steady upward and downward flow of groundwater in a shallow irrigated aquifer in Japan using transient vertical temperature profiles measured in boreholes, with a method based on the analytical solution of Stallman (1965). These results were later validated by Vandenbohede and Lebbe (2010a) who used inverse numerical modeling to estimate the vertical flow of water with the dataset published by Taniguchi (1993). All the aforementioned studies used transient near-surface (0–15 m) temperature measurements to estimate the steady vertical flow of water in the saturated zone and involved irrigated conditions at the ground surface. Stallman's approach has also been extensively and successfully employed in the last decades to assess interactions beneath streams and large bodies of water (e.g. Lapham, 1989; Silliman et al., 1995; Stonestrom and Constantz, 2003; Baskaran et al., 2009). In contrast, studies on the use of heat for the estimation of the vertical flow of water in the context of natural diffuse recharge are very scarce. Diffuse recharge is defined by Healy (2010) as "recharge that is distributed over large areas in response to precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table".

Published studies on this topic include the work of Taniguchi (1994) who used the method he had published the previous year (Taniguchi, 1993) to estimate the steady vertical flow of water in the saturated zone from vertical temperature profiles measured in 10 observation wells located in a sandy aquifer in the Nara Basin, Japan. Tabbagh et al. (1999) estimated steady percolation rates in the vadose zone on an annual basis, from transient temperature time series measured in the upper first meter of soil at weather stations located in metropolitan and northern France, with a method based on the analytical solution of Stallman (1965). Koo and Kim (2008) fitted a numerical heat transport model to temperature time series measured in the unsaturated zone of a site located in Korea, by optimizing the value of two lumped parameters of the heat transport equation on a seasonal basis. However, no quantification of recharge was achieved in their study, as only the lumped parameters were estimated (one of which included the vertical water flux).

1.2. Rationale and objectives

One of the main issues that is common to most of the studies using heat as a tracer to estimate groundwater recharge is the difficulty to properly assess the uncertainty associated to the estimated values. This topic was addressed by Vandenbohede and Lebbe (2010a,b) for applications to the saturated zone and its relevance was stressed by Rau et al. (2014). The uncertainty of seepage fluxes estimated beneath streams with a heat-based approach has also been studied (e.g. Shanafield et al., 2011; Soto-López et al., 2011). However, no substantial work has been carried out to validate the application and assess the uncertainty of heat-based methods in the vadose zone in a context of natural diffuse recharge, moreover for a climate involving snow and seasonally frozen ground.

Estimation of the vertical flow of water with a heat-based approach in a shallow unsaturated zone is complex. In contrast to the saturated zone, water fluxes in the near-surface vadose zone can be very irregular over time, being strongly related to short time-scale precipitation events. Furthermore, thermal properties of unsaturated sediments vary over time, following the fluctuations of their moisture content (Farouki, 1981). The application of the method becomes even more complex for cold environments, due to the combined effect of the snow cover insulation during winter and the annual cycle of freezing and thawing of the soil, which involve large latent heat effects. These elements play a significant role in heat transfer within the near-surface soil and cause asymmetrical annual subsurface temperature cycles, which make the use of analytical models difficult (Williams and Smith, 1991). For these reasons, Gosselin et al. (2011) suggested that the assessment of the vertical flow of water from temperature time series in the unsaturated zone should be carried out through the inversion of a numerical model of heat transport over periods that match the expected recharge pattern.

The purpose of the present work was to use synthetic data to test and assess the accuracy of the above approach for the estimation of annual groundwater recharge rates. For this purpose, several long-term (20 years) synthetic hourly datasets of subsurface temperatures, representative of a range of weather under cool humid climate, ground covers, and soil texture conditions, were generated with the coupled simulator of heat and water transport SHAW (Simultaneous Heat and Water). Annual groundwater recharge rates were inferred from these synthetic datasets and compared with the "true" values simulated with SHAW. The influence of input model parameter uncertainty and of subsurface temperature measurement errors on the accuracy of the method was also assessed with a sensitivity analysis.

A unique aspect of this study is that the method was tested for conditions beyond the traditional assumption of quasi steady-state water flux. Contributions of this work include a better definition of the applicability limits of the heat-based approach for the unsaturated zone and of the magnitude of the uncertainty on predicted annual groundwater recharge values that can be expected in real-life applications. Furthermore, this paper presents a functional and simple inverse numerical simulator of heat transport for the unsaturated zone that was validated against the more complex and proven numerical simulator SHAW.

2. Materials and methods

2.1. Overview of the methodology

The methodology that was followed to assess the uncertainty of annual groundwater recharge rates derived from temperature time series is illustrated in Fig. 1 and briefly summarized below.

First, the coupled numerical simulator of heat and moisture transport SHAW (Simultaneous Heat and Water, version 3.0; Flerchinger and Saxton, 1987; Flerchinger et al., 1996) was used to produce 12 synthetic datasets of hourly subsurface temperatures. This was done using, as inputs, two different weather datasets (daily precipitation, wind speed, relative humidity, air temperature, and solar radiation), two ground covers (bare soil and short grass), and three soil textures (sand, loamy sand, and sandy loam). Annual (potential) groundwater recharge rates were computed from the hourly water flux simulated with SHAW (q_{SHAW}) at the bottom of the soil profile. A wide range of realistic recharge values that can occur under a cool humid climate were thus obtained. A detailed description of the models developed with SHAW to produce the synthetic datasets is presented in Section 2.2.

The basic idea was then to use these realistic simulated temperatures as synthetic measurements to retrieve groundwater recharge values through the inversion of a simple numerical model and to compare the recharge estimates with those computed previously with SHAW. For this purpose, a simple vertical one-dimensional numerical simulator of advective and conductive heat transport in the unsaturated zone was developed as part of this study. A detailed description of this numerical simulator, hereafter referred to as *HeatFlow1Dz*, is presented in Section 2.3.

The temperature time series simulated at the depths of 1 and 5 m below the ground surface with SHAW were first used as synthetic measurements to constrain (with Dirichlet conditions) a