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Estimating groundwater recharge from time series measurements of subsurface temperature

Min-Ho Koo, Yongje Kim*

Dept. of Geoenvironmental Sciences, Kongju National Univ., Kongju, Chungnam 314-701, Korea
**Korea Institute of Geoscience and Mineral Resources, Daejeon, 305-350, Korea (e-mail: koo@kongju.ac.kr)*

Abstract

Efforts for better understanding of the interaction between groundwater recharge and thermal regime of the subsurface medium is gaining momentum for its diverse applications in water resources. A numerical model is developed to simulate temperature variations of the subsurface under time varying groundwater recharge. The model utilizes MacCormack scheme for finite difference approximation of the partial differential equation describing the conductive and advective heat transport. For the estimation of recharge rate, optimization of the model is realized by searching for the unknown parameters which minimize the root-mean-square error between simulated and measured temperatures. Simulation results for 22-year time series data of temperature measurements reveal that the proposed model can accurately simulate subsurface temperature variations resulting from the redistribution of the heat due to the movement of water and it can also estimate temporal variations of recharge. Seasonal variations of recharge and a linear relationship between precipitation and recharge are clearly reflected in the simulated results.

Key words: groundwater recharge, heat transport, subsurface temperature

1. Introduction

Instantaneous or seasonal changes of soil temperature at the surface are transferred into the subsurface mainly by conduction. During the precipitation period, the heat is also transported by the advection process driven by the movement of water through the subsurface medium. This process makes the convection velocity to play a significant role in controlling the thermal stability of the subsurface. Thus, it is interesting to investigate the response of the subsurface thermal regime to the movement of water resulting from the precipitation which is a time variant hydrologic process.

Several analytical models, which commonly solve the heat transfer equation incorporating advection as well as conduction, are developed for estimating groundwater recharge (Stallman, 1965; Bredehoeft and Papadopulos, 1965; Taniguchi, 1993; Tabbagh et al., 1999). However, these approaches are restricted to either steady state conditions with simplified boundary conditions or transient conditions with an assumption of sinusoidal temperature fluctuations. The assumption of sinusoidal or harmonic fluctuation can be best arrived in real life situations only with diurnal and annual periods of temperature oscillations, and thus these approaches can not simulate the short time recharge events resulting from the precipitation storms. The other critical limitation in these approaches is that they have considered a steady movement of water, which is not going to happen in real life conditions. Due to temporal variability of precipitation, which is very high especially in the monsoon region, groundwater recharge is also a time variant process and thus the approaches or models should account for transient behavior of recharge.

The objective of this paper is to develop a numerical model to simulate the subsurface temperature under time varying groundwater recharge. The study is aimed to reveal seasonal variations of recharge rates by simulating time series data of soil temperatures measured in a region under monsoon climates.

2. Model development

When precipitation occurs on the land surface, a part of the precipitation infiltrates and percolates down through the unsaturated zone. The movement of water results in the heat transfer through the convective process, which leads to the redistribution of heat within the subsurface and altering the subsurface temperature. Assuming that conduction and advection are the dominant processes of heat transport in the shallow vadose zone, the governing equation can be expressed as:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} - \beta \frac{\partial T}{\partial z} \tag{1}$$

$$\beta = \frac{\rho_w c_w q_w}{\rho c} \tag{2}$$

where ρ, c, and α are the density, the specific heat, and the thermal diffusivity of the bulk medium, ρ_w and c_w are the density and the specific heat of water, and q_w is the flux of water.

A numerical model is developed to estimate the flux of water and the thermal diffusivity from the subsurface temperature measurements. The developed model simulates temperature variations of the subsurface by solving Eq. (1) using the MacCormack scheme which is a two-step predictor-corrector finite difference method. By repeating the simulation, optimization of the model is realized by searching for two parameters α and β which minimize the root-mean-square error (RMSE) between simulated and measured temperatures. A simple sequential search is used for the optimization process.

3. Simulation results and discussion

The developed model is applied to 22-year (1981-2002) time series data of soil temperatures measured at the Chuncheon synoptic station. Based on the amount of precipitation, the data is divided into 66 time series segments which consist of monsoon, pre-monsoon, and post-monsoon periods. The model parameters α and β are assumed to be constant during the period of each segment, and they are estimated by the optimization procedure.

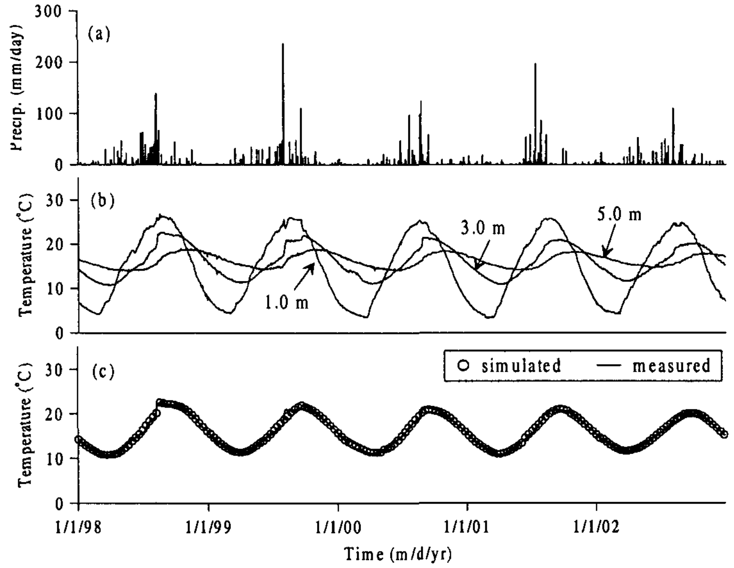

Fig. 1. Time series data of (a) daily precipitation and (b) soil temperature at three depths measured at the Chuncheon synoptic station and (c) simulated and measured temperature.

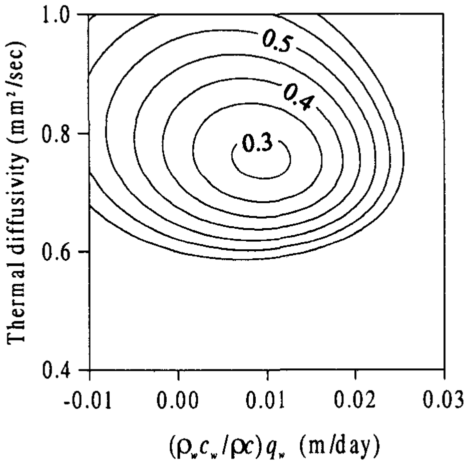

Fig. 2. Sensitivity of the RMSE over a range of two known parameters.

Fig. 1 shows the measured data of daily precipitation and temperature at the three prove levels during 5-year period and variations of simulated and measured temperature. The temperatures at 1m and 5m are used for boundary conditions of the simulation, and the optimal values of α and β are searched by minimizing the RMSE between simulated and measured temperatures at 3m depth. Fig. 2 shows that the RMSE is sensitive to both α and β, and thus illustrates that the model is capable of quantifying those parameters.

Fig. 3 shows variations of the estimated parameters in response to precipitation. During the monsoon period, a linear relationship between precipitation and recharge is clearly demonstrated in the simulation results. During the dry period of the pre-monsoon and post-monsoon, negative values of water flow are observed in the simulation results. The most likely possibility is that, if the net amount is considered, the persistent and upward water flux driven by evapotranspiration would exceed the sporadic and downward water flux by precipitation in the dry period. A similar result is also observed in estimates of the thermal diffusivity. Increase of the thermal diffusivity during the monsoon period can be attributed to increase of the volumetric water content in the vadose zone.

This paper describes that the numerical model can estimate the transient behavior of groundwater recharge caused by the variability of precipitation in the monsoon region. Although the nonconductive heat transfer due to the water flow is not clearly observed in the temperature data, the model can successfully exhibit the temporal variation of water fluxes, provided that the period of simulation is divided into shorter time scales based on the amount of precipitation. Thus, the model is capable of elucidating the hydrogeothermal processes for better precision in simulating real life scenario. These aspects make the model more attractive than the conventional analytical models that are restricted to simplifying conditions of constant percolation rates and sinusoidal temperature variations.

Acknowledgements

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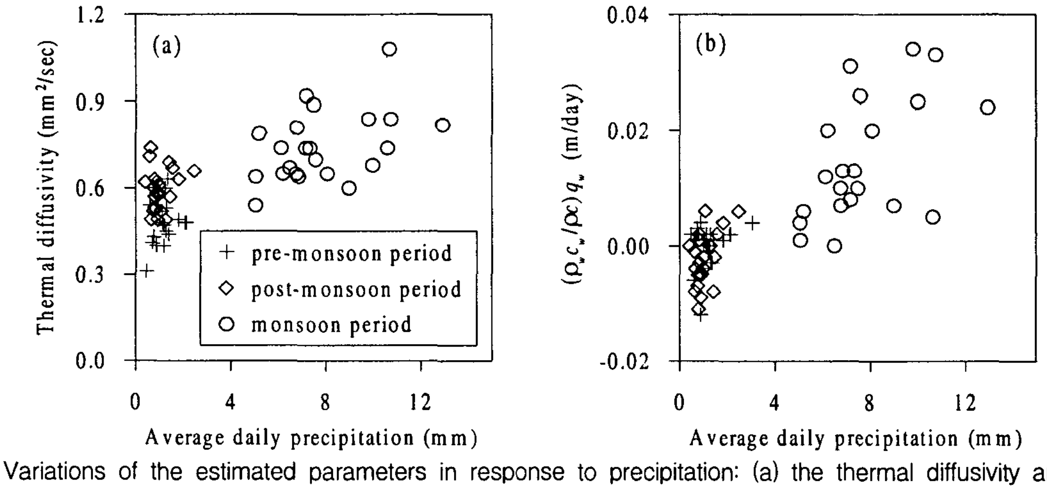

Fig. 3. Variations of the estimated parameters in response to precipitation: (a) the thermal diffusivity and (b) the parameter related to the flux of water.