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ESTIMATING THERMAL PROPERTIES OF UNSATURATED SOILS IN THE MONSOON REGION USING TEMPERATURE MONITORING DATA

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ABSTRACT

A numerical model for estimating both the water flux in the vadose zone and its thermal diffusivity is presented. The model utilizes MacCormack scheme for finite difference approximation of the partial differential equation describing the conductive and advective heat transport. To evaluate the water flux and the thermal diffusivity, the model uses a simple sequential search during the optimization process which minimizes the root-mean-square error between simulated and measured temperatures. The model is applied to 22-year time series data of soil temperatures measured at the Chuncheon synoptic station of Korea. Simulation results reveal that the developed 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 the water flux and the thermal diffusivity of the shallow vadose zone. The impact of moonsoon precipitation on the thermal regime is clearly reflected in the simulated results by illustrating a linear relationship between precipitation and the water flux as well as the thermal diffusivity.

Keywords: soil temperature, vadose zone, heat transport, thermal properties, finite difference method, MacCormack scheme

1. INTRODUCTION

There have been many attempts to analyze concurrent flow of heat and fluid through the subsurface medium to determine thermal properties and water fluxes from the temperature profiles. The subsurface temperature has been used as a tracer for indirect measurement of water movement based on the hypothesis that heat in the subsurface is transported by conduction as well as advection caused by subsurface water movement. The effect of instantaneous or seasonal changes in soil temperature at the surface are reflected in the soil temperature profile and are governed by the heat transport in the subsurface system. The water during the precipitation infiltrates into the soil and percolates through the subsurface medium resulting in the increase of soil moisture in the unsaturated zone and recharge to the aquifers. During the movement of water through the subsurface medium, the heat is also transported by the advection process, and thus the redistribution of heat takes place below the surface. This process makes the advection 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 transient behavior of water flow resulting from the precipitation which is a time variant hydrologic phenomena.

Thus, due to wide potential uses of subsurface thermal data, it has recently generated large interests in researchers. Understanding the interaction between water flow and thermal regime of the subsurface medium has become increasingly important concern for the studies involving quantification of infiltration and groundwater movement (Suzuki, 1960; Cartwright, 1979), groundwater-surface water interactions (Silliman et al., 1995), and quantifying disturbances in thermal regime due to global warming and urbanization (Harris and Chapman, 1995; Taniguchi et al., 1999).

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 and Sharma, 1993). 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 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, vertical water movement in the vadose zone is also a time variant process and thus the approaches or models should account for transient behaviors of thermal properties and water fluxes.

The objective of this paper is to develop a numerical model to simulate the subsurface temperature under time varying water fluxes. The study is aimed to reveal seasonal variations of flow rates and thermal properties of the medium by simulating time series data of soil temperatures measured in a region under monsoon climates. The model can eliminate limitations of analytical solutions and can expand the potentiality of subsurface temperature technique in real field situations. The developed model can be applied for any temperature variations and various kinds of initial and boundary conditions depending upon the field conditions of the study area. The objective of this paper is also to investigate the sensitivity of subsurface temperature to water fluxes and thermal properties.

2. MODEL DEVELOPMENT

Temperature at the land surface is controlled principally by an energy balance between incoming solar radiation and outgoing long wavelength thermal radiation. Temperature below the surface is affected by the flux of heat being conducted below from the land surface as well as the heat flux conducted out from the earth's interior and the heat transfers resulting from other external or internal physical, chemical and biological processes. However, in general, the heat conduction and the heat transfer resulting from the physical processes of water movement are of greater concerns and are major processes that control the subsurface temperature within the vadose zone mostly encountered in real situations.

Changes in the land surface temperature with time occur at several temporal scales. The largest of these changes are the daily and seasonal variations, both of which can have amplitudes of 10 degrees or more. The subsurface medium acts as a filter and attenuates these thermal waves with depth. The high frequency or short term variations die out more rapidly than long term variations.

When the precipitation occurs on the land surface, a part of the precipitation infiltrates down through the vaose zone as a source of groundwater recharge and the heat is also transported below the land surface as mass transfer. Thus, the movement of water results in the transfer of heat through convection process as well, which leads to the redistribution of heat within the subsurface and altering the subsurface temperature distribution. Relative importance of these mechanisms in controlling the subsurface thermal regime is site specific and may vary in space and time domain. The one-dimensional governing equation for the conductive and advective transport of heat through an isotropic and homogeneous porous medium can be expressed as:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\alpha \frac{\partial T}{\partial z}\right) - \frac{\partial}{\partial z}(\beta T) \tag{1}$$

where T is temperature, t is time, z is the depth from the ground surface taken as positive downward, α is the thermal diffusivity of the bulk medium and β is a variable dependent on vertical groundwater flux and thermal properties of water and aquifer. The variable β is given by:

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

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

In solving Eq. (1), there exist two inherent problems associated with the vadose zone. First, the solution requires specification of q_w, which leads to a coupled system of heat and water flow. However, this is quiet complicated, since a number of data are required to solve the unsaturated flow. Secondly, since the vadose zone has a considerable fraction of pore space filled with water and air, the thermal properties of a soil in the vadose zone vary with time according to variations of the volumetric water content. For these reasons, the heat transport in the vadose zone is a nonlinear process coupled with water flow. Since incorporating all the processes into the model is practically not feasible, it is assumed that the model variables α and β are time independent during a certain period of time. Thus, complex processes associated with heat transport in soils are simplified by freezing temporal variations of thermal and hydraulic parameters. Validation of this assumption can be achieved by selecting an appropriate period of time depending on temporal variability of precipitation which determines the water content and water flow in the shallow vadose zone.
The MacCormack scheme is used to solve Eq. (1) with appropriate initial and boundary conditions. This scheme is based on the second-order forward-time Taylor series:

$$T_i^{n+1} = T_i^n + T_t\,|_i^n\ \Delta t + \frac{1}{2} T_{tt}\,|_i^n\ \Delta t^2 + O(\Delta t^3) \tag{3}$$

where *i* is the space index, *n* is the time index, Δt is time interval, and O(.) indicates an order of error and subscript *t* with variable *T* indicates its time derivative. In the MacCormack scheme, $T_t\,|_i^n$ is determined directly from the Partial Differential Equation (PDE) and $T_{tt}\,|_i^n$ is determined from a second-order forward-time Taylor series expansion for $T_t\,|_i^{n+1}$:

$$T_t\,|_i^{n+1} = T_t\,|_i^n + T_{tt}\,|_i^n\ \Delta t + O(\Delta t^2) \tag{4}$$

Combining Eq. (3) and Eq. (4) yields:

$$T_i^{n+1} = T_i^n + \frac{1}{2}[T_t\,|_i^n + T_t\,|_i^{n+1}]\Delta t + O(\Delta t^3) \tag{5}$$

Eq. (5) can be solved by dropping the truncation error terms and replacing $T_t\,|_i^n$ and $T_t\,|_i^{n+1}$ in terms of spatial derivatives from the PDE:

$$T_i^{n+1} = T_i^n + \frac{1}{2}[\alpha T_{zz}\,|_i^n - \beta T_z\,|_i^n + \alpha T_{zz}\,|_i^{n+1} - \beta T_z\,|_i^{n+1}]\Delta t \tag{6}$$

The MacCormack scheme utilizes a two-step predictor-corrector approach to evaluate T_i^{n+1} explicitly for the considered Convection-Diffusion Heat Transport Equation (CDHTE). In the first step, $T_t\,|_i^n$ and $T_z\,|_i^n$ are approximated by the first-order forward difference approximation. The resulting Finite Difference Equation (FDE) of the first step for the PDE given by Eq. (1) can be expressed as:

$$\overline{T_i^{n+1}} = T_i^j - CN(T_{i+1}^n - T_i^n) + DN(T_{i+1}^n - 2T_i^n + T_{i-1}^n) \tag{7}$$

where *CN* and *DN* are cell convection number and cell diffusion number, respectively. These numbers are expressed as:

$$CN = \beta \frac{\Delta t}{\Delta z} \tag{8}$$

$$DN = \alpha \frac{\Delta t}{(\Delta z)^2} \tag{9}$$

Results obtained from the first step (predictor) are the provisional values and are modified in the second step known as corrector step to get the final results. In the second step, Eq. (6) is solved by evaluating $T_z\,|_i^n$ using the first-order forward difference approximation and $T_z\,|_i^{n+1}$ using the first-order back ward difference approximation based on the provisional values of $\overline{T^{n+1}}$. Thus, the resulting FDE for the second step can be written as:

$$T_i^{n+1} = \frac{1}{2}[T_i^n + \overline{T_i^{n+1}} - CN(\overline{T_i^{n+1}} - \overline{T_{i-1}^{n+1}}) + DN(\overline{T_{i+1}^{n+1}} - 2\overline{T_i^{n+1}} + \overline{T_{i-1}^{n+1}})] \tag{10}$$

Eq. (7) combined with Eq. (10) comprises the MacCormack scheme approximation of the CDHTE for the subsurface medium and can be solved with appropriate initial and boundary conditions of the system specific to the considered study area. The scheme is conditionally stable and convergent. The grid size and time scale for the considered application are chosen such that the cell convection and diffusion numbers are within the limits of CN ≤ 0.9 and DN ≤ 0.5 as reported by Hoffman (1992) for the MacCormack scheme to get the stable and convergent solutions.

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 described above. 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

Korea has unique meteorological characteristics influenced by the summer monsoon from June to August. Ho and Kang (1988) investigated spatial and temporal variation of precipitation in Korea using the rainfall data during the 23-year period of 1963-1985. In the Korean Peninsular, the mean annual precipitation is 1287 mm/yr. The rainfall in the summer monsoon period occupies more than 50% of the annual precipitation in most areas, and the intensity of the rainfall frequently exceeds 100 mm/day. These meteorological features suggest that the advective water movement and the subsequent nonconductive heat transport in the vadose zone are dominantly controlled by the amount and the pattern of rainfall occurring during the monsoon season. Thus, the monsoon may be a critical hydrologic component determining variations of subsurface temperature in the shallow vadose zone.

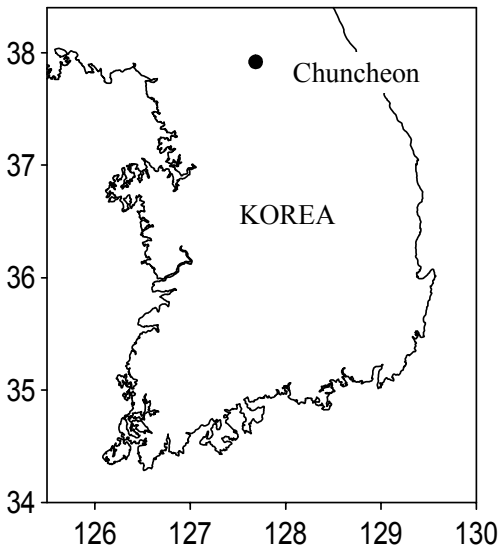

Figure 1. Location of the Chuncheon surface synoptic station of Korea.

The developed model is applied to 22-year (1981-2002) time series data of soil temperatures and precipitation measured at the Chuncheon synoptic station ($37^{\circ}54^{'}N$, $127^{\circ}44^{'}E$) of the Korea Meteorological Administration (Figure 1). The mean and the standard deviation of annual precipitation during the simulation period are 1378 mm/yr and 330mm, respectively. Comparing these to the statistical values during the period of 1963-1985 given by Ho and Kang (1988) indicates that temporal variability of precipitation has been enhanced by 100 mm/yr in the mean and 200 mm in the standard deviation for the last 20 years. Increase of the variability is mainly caused by the amount of rainfall in the summer monsoon months.

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.

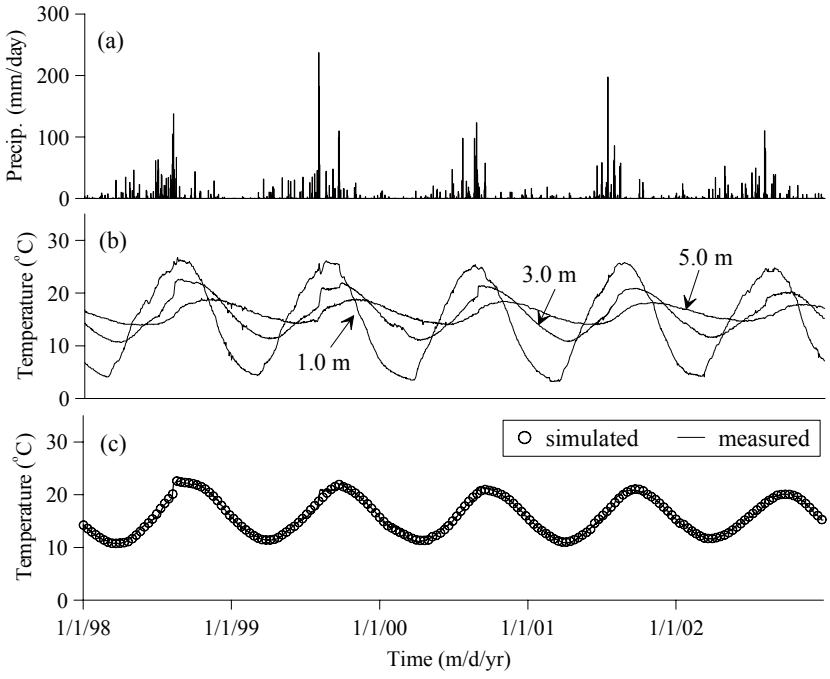

Figure 2. Time series data of (a) daily precipitation and (b) soil temperature at three depths measured at the Chuncheon synoptic station and (c) simulated and measured temperature.

Figure 2 shows the measured data of daily precipitation and temperature at the three depths during 5-year period and variations of simulated and measured temperature. The model used the temperature data at 1m and 5m as upper and lower boundary conditions, and used the temperature at 3m for optimization. The optimal values of α and β are searched by minimizing the RMSE between simulated and measured temperatures at 3m depth. Figure 3 shows the RMSE with respect to both α and β for a time segment. The figure illustrates that the RMSE is sensitive to both of the model parameters, and thus it is evident that the model is capable of quantifying those parameters.

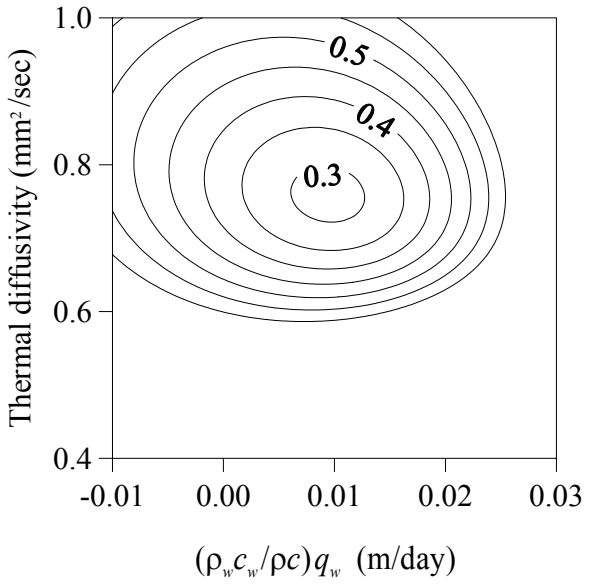

Figure 3. Sensitivity of the RMSE over a range of two known parameters.

Figure 4 shows variations of the estimated parameters in response to precipitation. During the monsoon period, a linear relationship between precipitation and the water flux 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.

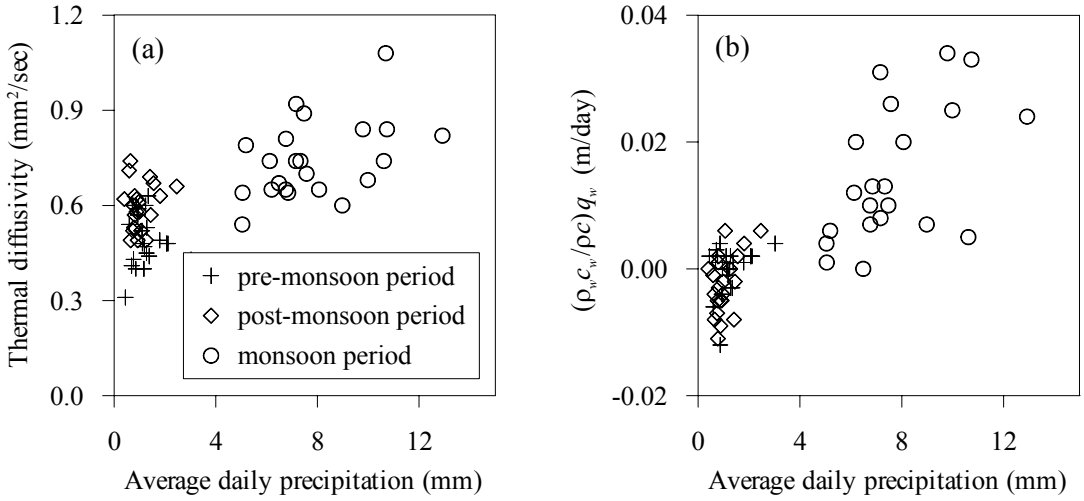

Figure 4. Variations of the estimated parameters in response to precipitation: (a) the thermal diffusivity and (b) the parameter related to the flux of water.

4. CONCLUSIONS

A numerical model based on the MacCormack scheme of the finite difference method is presented for estimating the vertical water fluxes and thermal properties of the vadose zone from the transient subsurface temperature profiles obtained from the field measurements. The developed model can be applied for any temperature variations and different kinds of initial and boundary conditions as appropriate to specific field conditions. The simulation results illustrate that the numerical model can estimate the transient behavior of water flow and thermal properties 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 and thermal properties, 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.

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