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A numerical analysis of precipitation recharge in the region of monsoon climates using an infiltration model

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Abstract

Based on the transient finite difference solution of Richards' equation, an infiltration model is developed to analyze temporal variation of precipitation recharge in the region of monsoon climates. Simulation results obtained by using time series data of 20-year daily precipitation and pan evaporation indicate that a linear relationship between the annual precipitation and the annual recharge holds for the soils under the monsoon climates with varying degrees of the correlation coefficient depending on the soil types. A sensitivity analysis reveals that the water table depth has little effects on the recharge for the sandy soil, whereas, for the loamy and silty soils, rise of the water table at shallow depths causes increase of evaporation by approximately 100mm/yr and a corresponding decrease in recharge. A series of simulations for two-layered soils illustrate that the amount of recharge is dominantly determined by the soil properties of the upper layer, although the temporal variation of recharge is affected by both layers.

Key words: groundwater recharge, Richards' equation, infiltration model

1. Introduction

From the early 1990's, a number of infiltration models have been introduced in literature to describe infiltration and the subsequent recharge process from the vadose zone to the groundwater system (Hendrickx et al., 1991; Wu et al., 1996; Wu et al., 1997; Pohll et al., 1996). Recently, attempts to deal with both hydrological and ecological parameters (Zhang et al., 1999; Guswa et al., 2002) and to analyze multi-dimensional rainfall infiltration (Disse, 1999; Zhou et al., 2002) were made to provide a more realistic description of the infiltration process in the vadose zone.

In this paper, an infiltration model is developed to simulate the recharge process using time series data of precipitation and pan evaporation. Based on the transient finite difference solution of Richards' equation, the model simulates flow features in the vadose zone including infiltration, surface ponding, evaporation and groundwater recharge. The model is used to analyze relationships between precipitation and recharge for various soil types, groundwater depths and precipitation patterns in the region of monsoon climates.

2. Model development

Fig. 1 shows the conceptual model for the flow process of precipitated water occurring in the surface and the subsurface of a bare soil. A finite difference model is developed to deal with the flow process by taking into account infiltration and surface ponding of precipitation at the top of the soil profile, evaporation and the unsaturated flow in the vadose zone governed by Richards' equation.

2.1. Constitutive equations

The closed-form analytical expressions of van Genuchten (1980) are employed in the model to describe constitutive equations.

2.2. Precipitation and surface ponding

It is assumed in the model that precipitation is not intercepted by the vegetation canopy, and gross precipitation reaches the soil surface. the ponded water on the surface is assumed to be immediately removed by runoff. When the surface ponding occurs, the model automatically converts the pressure head of the top layer to zero.

2.3. Evaporation

A linear relationship between the evaporation rate and the volumetric water content is used to describe the evaporation process in the vadose zone. Evaporation is assumed to takes place over a certain depth, and an exponential function is used to describe vertical variation of the evaporation rate. The maxium evaporation rate, that would occur when the water content exceeds the threshold water content, is assumed to be the same as the pan evaporation rate measured at the surface synoptic station.

2.4. Source/sink term

Precipitation and evaporation are incorporated into the source/sink term of Richards' equation. Time series data of daily precipitation are given into the source term of the top layer, and evaporation as a sink term is calculated over the evaporation depth by using the linear relationship between the evaporation rate and the water content.

2.5. Boundary and initial conditions

The upper boundary condition is specified as no flow at the soil surface, and the lower boundary is considered as the water table, which is assumed not to fluctuate with time. The initial conditions of the model are generated by running a certain period of preliminary cyclic simulation prior to the time of interest until the resulting solutions produce the same cyclic pattern. Preliminary simulations are performed by a multiple-year precipitation sequence having a cyclic pattern of the first-year precipitation sequence.

3. Simulation results and discussion

3.1. Input

Simulations are made for 3 soil textural groups: sand, loam and silt. Table 1 shows the van Genuchten parameters of the soils as estimated by Carsel and Parrish (1988) from analyses of a large number of soils. 20-year records of daily precipitation (1981-2000) monitored at the Daejeon surface synoptic station are used as input data of the simulations (Fig. 2). Fig. 3 shows pan evaporation rates measured at the Daejeon surface synoptic station during the period of 1999-2002. The solid line in the figure represents a least squares sinusoidal curve for the set of the measured data. The best-fitting sinusoidal curve is used for temporal variation of the maximum evaporation rate. It is assumed that evaporation ceases at the effective saturation of 0.01 and evaporation reaches its maximum at the effective saturation of 0.2. It is also assumed that evaporation takes place over a depth of 30cm and the water table is at a depth of 500cm.

3.2. Precipitation-recharge relationships

Fig. 4 shows relationships between annual precipitation and annual recharge obtained from the 20-year transient simulations conducted with input data discussed above. The results indicate that a linear relationship between the annual precipitation and the annual recharge holds for the soils under the monsoon climates with varying degrees of the correlation coefficient depending on the soil types. Deviation from the linearity is mainly caused by variation of water storage in the vadose zone at the end of the antecedent year.

3.3. Effects of water table depth

A sensitivity analysis of the model is performed to elucidate effects of the water table depth on the simulated recharge estimates. A series of simulation results demonstrate that the water table depth has little effects on the recharge for the sandy soil, whereas, for the loamy and silty soils, rise of the water table at shallow depths causes increase of evaporation by approximately 100mm/yr and a corresponding decrease in recharge. The results also show that, in case of the silty soil, evaporation can induce the upward flow through the vadose zone to cause groundwater discharge from the water table at a shallow depth. Thus, if the amount of groundwater discharge into the vadose zone in the dry season exceeds the precipitation recharge in the rainy season, the overall annual recharge can be negative.

3.4. Effects of soil heterogeneity

The effects of soil heterogeneities on recharge are also examined by performing a series of model simulations for two-layered soils having contrast in the properties. The results illustrate that recharge is dominantly determined by the soil properties of the upper layer regardless of its thickness if it is greater than 1m. As a consequence, it can be inferred that as far as the amount of recharge is concerned, the properties of the soil at shallow depths need to be determined as the most critical input parameters of the model. Uncertainties of the model parameters for the soils at deep depths, which are difficult to obtain in the field, do not considerably affect the recharge estimates.

3.5. limitations of the model

There are two limitations on the use of the model. First, the model does not incorporate the preferential flows driven by drying cracks, macropores and root channels which are frequently observed in the actual field conditions. The preferential flows are known to dominate recharge processes in many soils. Thus, the model may underestimate recharge. Secondly, the assumption employed in the model that the ponded water is immediately removed by runoff is generally not representative of the actual flow process on the surface. It can be a continuing source for infiltration and the subsequent recharge depending on the surface topography.

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Table 1. Selected van Genuchten parameters used for the analysis (Carsel and Parrish, 1988)

Soil type	θ_r	θ_s	$\alpha (cm^{-1})$	n	K_s (cm/day)
Sand	0.045	0.43	0.145	2.68	712.8
Loam	0.078	0.43	0.036	1.56	24.96
Silt	0.034	0.46	0.016	1.37	6.00

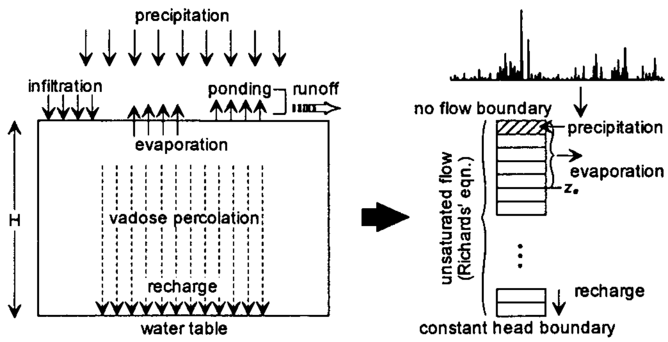

Fig. 1. Schematic diagram of the developed precipitation recharge model.

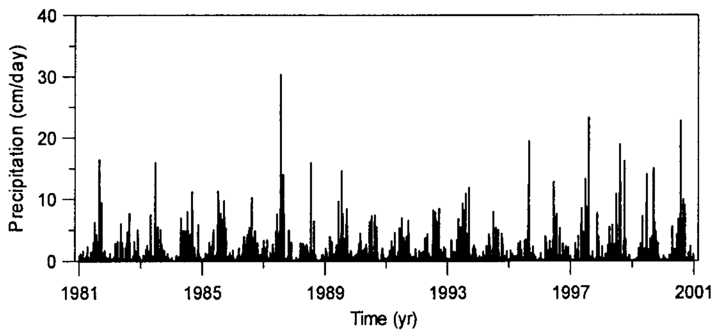

Fig. 2. Daily precipitation data measured at the surface synoptic station of Daejeon.

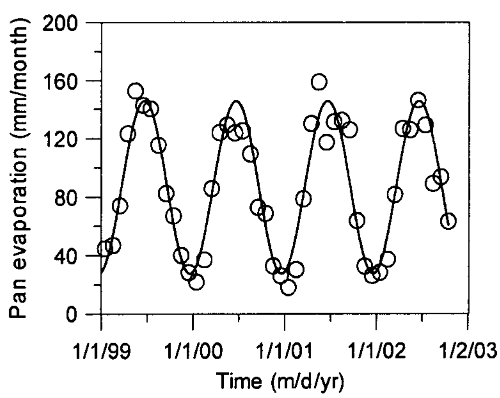

Fig. 3. Pan evaporation data measured at the surface synoptic station of Daejeon.

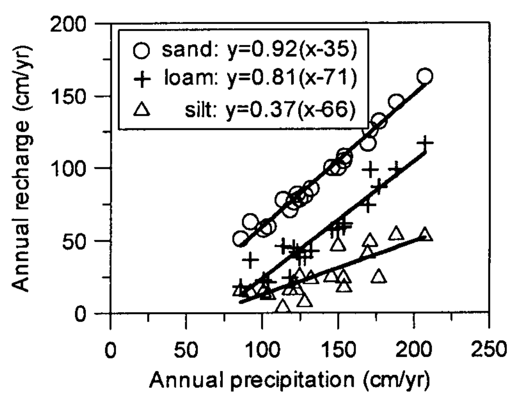

Fig. 4. Simulated relationship between annual precipitation and recharge.