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Determination and Simulation of Soil Moisture Dynamics in Upland Fields in the Cerrados Area (Brazil)

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Abstract

The objective of the studies was to analyze the soil moisture dynamics of upland fields in the Cerrados area of Brazil. Soil moisture level obtained by using tensiometers set in the soil layers was compared with the soil moisture dynamics simulated by the TANK-model. It was found that the actual soil moisture dynamics agreed well with the simulated results, suggesting that the TANK-model could be used to predict the soil moisture dynamics of upland fields based on meteorological and soil property data.

Discriplines: Agro-meteorology / Irrigation, drainage and reclamation
Additional key words: water balance, TANK-model, groundwater

Introduction

The Cerrados of Brazil account for about 21% of the total land area (850×10^4 km^2). The annual mean temperature ranges between 22°C in the southern part and 27°C in the northern part. The monthly mean temperature at CPAC (Centro de Pesquisa Agropecuaria dos Cerrados) located in the center of this area ranges from 26.7°C in October to 17.7°C in July. Although the annual precipitation in this area is known to be in the range of 1,200~1,800 mm, 90% is concentrated in the warm rainy season from October to April. However, this warm rainy season is often interrupted by a relatively longer dry spell called "Veranico". During the remaining period of the year, the weather is dry with little precipitation.

Therefore, crop cultivation in this area is strongly affected by hydrological conditions as mentioned above. Major techniques for improving and stabilizing crop production in the area aim at the development of irrigation practices appropriate to the natural and farming conditions of this area, selection and cultivation of crop species and/or cultivars with higher drought resistance, and development of cropping systems suitable for the annual hydrological conditions.

The data on soil moisture dynamics play an important role in developing more appropriate farming systems in this region with a relatively longer dry spell. For this reason, several researchers[3,7,9,10] have studied the seasonal and geographical changes of potential and actual evapotranspiration in the Cerrados area. However, research on the soil moisture dynamics of crop fields in this area is too limited to enable the development of farming systems appropriate to the climatic conditions.

Modeling of water balance of upland fields

Data on soil moisture dynamics in surface soil layers (root zone) are very important to determine the initial and final time of application of irrigation water into crop fields. These data play also an important role in preventing the occurrence of nitrogen pollution of the soil in the root zone and shallow groundwater caused by long applications of nitrogen fertilizer.

Several methods have been applied to study the soil moisture dynamics in upland crop fields[8,11,12]. In this paper, the TANK-model developed by Ohta et al. (1990)[8], which was originally designed to predict evapotranspiration and the soil moisture level in upland fields consisting of Kanto loam, was applied to simulate the soil moisture dynamics in upland fields in the Cerrados area.

As shown in Fig. 1, the TANK-model consists of 5 tanks and a groundwater tank. The first tank corresponding to the first surface soil layer has 2 holes (e_0 and e_1) for water evaporation, one hole (P_1) for deeper percolation of water, and one hole (r_1) for surface runoff of precipitation. Each

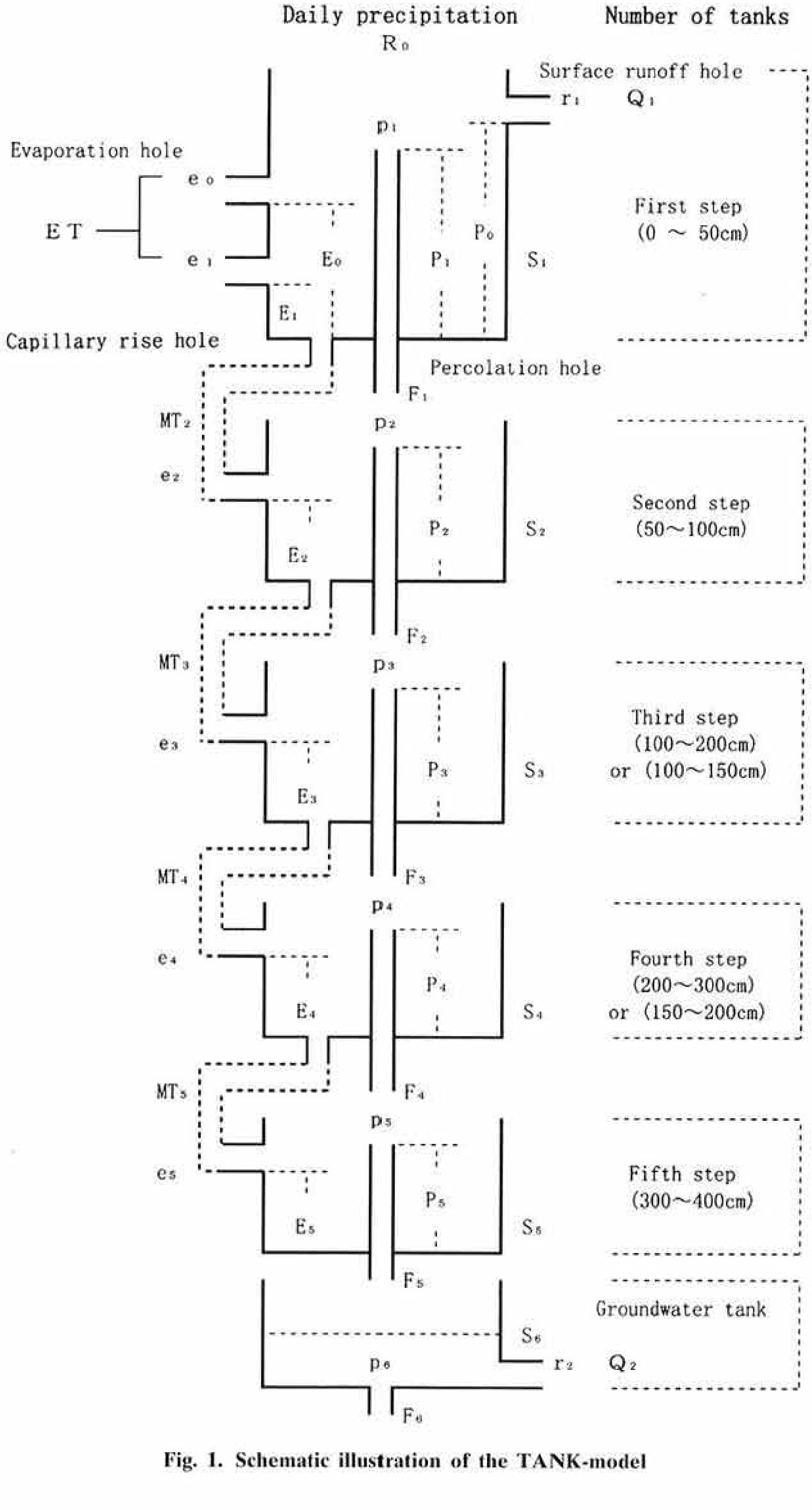


Fig. 1. Schematic illustration of the TANK-model

tank from the second tank to the fifth one has, respectively, holes (E_1, E_2, E_3, E_4, E_5) for rupture of capillary water rise and holes (P_2, P_3, P_4, P_5) for deep percolation of water. The 2 holes for evaporation of the first tank mentioned above were utilized to simulate the following 2 stages of evaporation of water[1]: first evaporation hole (e_0) simulates the constant-rate stage of evaporation, and second evaporation hole (e_1) simulates the falling-rate stage of evaporation.

The water balance in the first tank is mathematically represented in Fig. 1, by the following equations:

$$H_1 = S_{10} + R_0 \quad \cdots\cdots (1)$$
$$Q_1 = (H_1 - P_0) \times r_1 \quad \cdots\cdots (2)$$
$$ET = (H_1 - E_0) \times e_0 + (H_1 - E_1) \times e_1 \cdots\cdots (3)$$
$$F_1 = (H_1 - P_1) \times p_1 \quad \cdots\cdots (4)$$
$$S_1 = H_1 - (Q + ET + F_1) \quad \cdots\cdots (5)$$

In equations (1)~(5), Q_1, ET, and F_1 are the surface runoff (mm/day), evapotranspiration (mm/day), and percolation (mm/day), respectively; H_1 and S_{10} are the daily retention (mm/day) and storage change in the previous day in the first tank. R_0 is the precipitation on that day (mm/day). r_1, e_0, e_1, and p_1 are the coefficients of ground surface runoff, evapotranspiration, and percolation, respectively.

The water balance in the second tank can then be written as:

$$H_2 = S_{20} + F_1 \quad \cdots\cdots (6)$$
$$MT_2 = (H_2 - E_2) \times e_2 \quad \cdots\cdots (7)$$
$$F_2 = (H_2 - P_2) \times p_2 \quad \cdots\cdots (8)$$
$$S_2 = H_2 - (MT_2 + F_2) \quad \cdots\cdots (9)$$

Where MT_2 is the capillary rising water (mm/day).

As indicated previously, the water budget from the third to the fifth tank can be expressed by equations (6)~(9) in a similar way. The groundwater level is calculated from:

$$H_6 = S_{60} + F_5 \quad \cdots\cdots (10)$$
$$F_6 = H_6 \times p_6 \quad \cdots\cdots (11)$$
$$Q_2 = H \times r_2 \quad \cdots\cdots (12)$$
$$S_6 = H_6 - (F_6 + Q_2) \quad \cdots\cdots (13)$$
$$S_T = S_1 + S_2 + S_3 + S_4 + S_5 \quad \cdots\cdots (14)$$

Where S_6, F_6, Q_2 and S_T are the groundwater level (mm), groundwater percolation (mm/day), discharge of groundwater (mm/day) and sum of storage soil–water amounts, respectively. r_2 is the coefficient of discharge across groundwater movement. The subscripts 1~6 refer to the number of tanks, respectively.

The hydrological behavior of these tanks was characterized by hydrological constants as shown in each tank. These constants were estimated using experimental data on the soil–water relations in this area. The unit of calculation in the water balance was represented in terms of the water depth, and the volumetric water content corresponds to the thickness of the soil layer.

Experimental method

1) Geographical characteristics of experimental fields

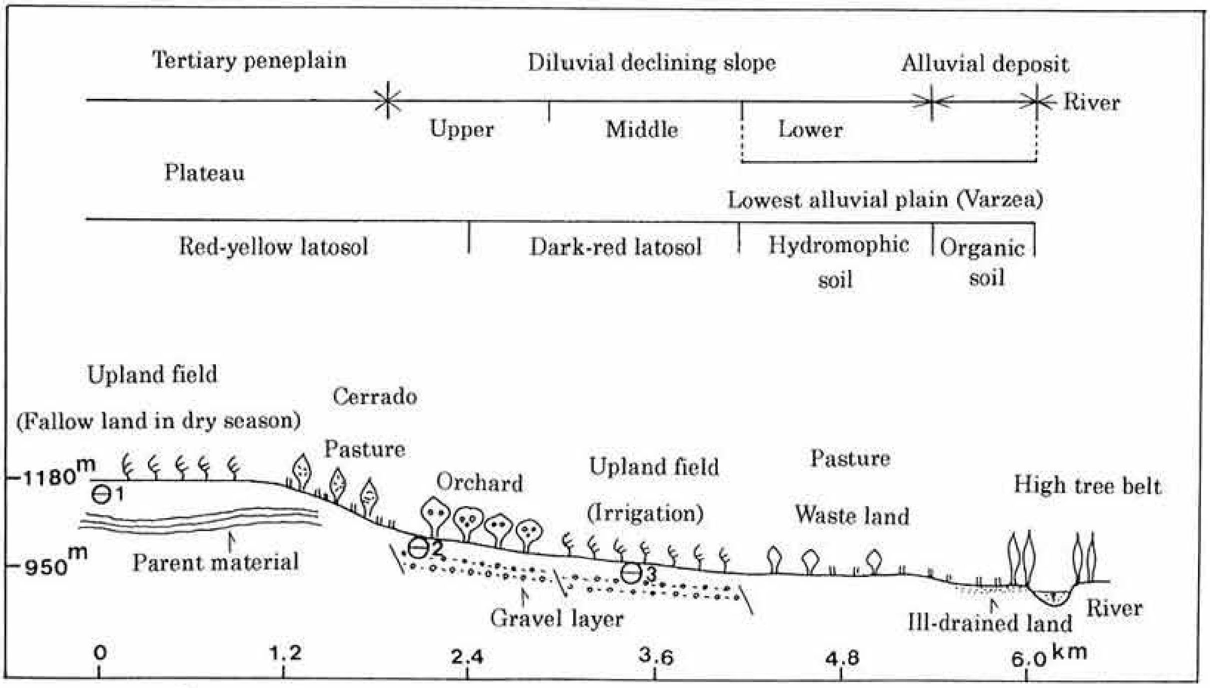
Fig. 2 illustrates the aerial distribution of soils and vegetation, and topographical characteristics of the experimental fields at the CPAC in Brazil. This figure was quoted from Hayasaka[2]. As shown in Fig. 2, the experimental fields can be divided into 3 parts such as tertiary peneplain, diluvial declining slope, and alluvial deposit area. The diluvial declining slope can be furthermore classified into 3 subparts such as upper, middle, and lower parts. The most representative soil in the Brazilian Highlands is a latosol.

However, soil types in the experimental fields ranged from red-yellow latosol on the Tertiary peneplain, through dark-red latosol in the middle subpart of the diluvial declining slope and hydromorphic soil in the lower subpart of the diluvial declining slope, to organic soil on the Alluvial deposit part.

2) Physical characteristics of vertical profiles in each pit

In Fig. 2, Pit 1, Pit 2, and Pit 3 are located, respectively, in a non-irrigated upland field with red-yellow soil on the plateau, in an orchard field with dark-red soil on the upper diluvial declining slope, and in an irrigated upland field with dark red soil on the middle diluvial declining slope.

When the soil moisture corresponded to the field capacity, solid phase of soils collected at Pit 1, Pit 2, and Pit 3 was found to range from 35 to 45% of the volume. The saturated hydraulic conductivity of these sample soils changed from 10^{-2} to 10^{-3} cm/s. The vertical profile of the soil moisture level in the sample soil columns was found to be rather even, indicating that soil water can move very freely upward and/or downward. The groundwater levels at Pit 1 and Pit 2 were about 5 m and 2 m, respectively.



⊖1 : Pit 1, ⊖2 : Pit 2, ⊖3 : Pit 3.

Fig. 2. Distribution of soils and their relation to the topography and vegetation[2)]

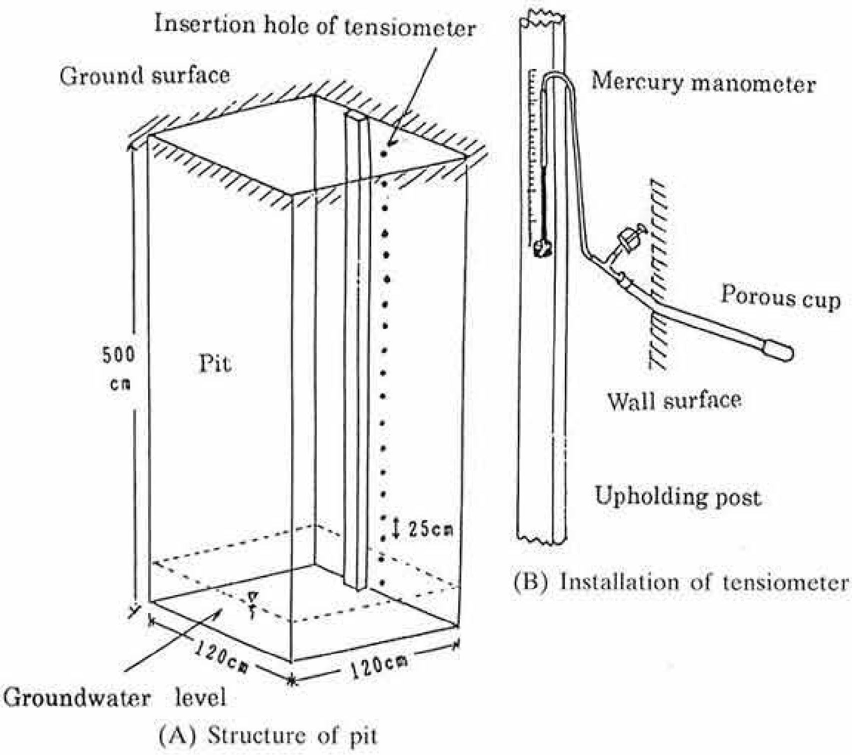


Fig. 3. Method of measurement of soil moisture content[2)]

Soil moisture and meteorological data and calculation method

1) Method of measurement of soil moisture

As described already, in this report, the soil moisture dynamics simulated by the TANK-model using soil hydraulic constants estimated from experimental data was compared with the soil moisture data obtained by Hayasaka in upland fields in this area (personal communication).

As shown in Fig. 3, each Pit was a rectangular solid structure with 4 sides (square) measuring each 1.2 and 5.0 m in depth. The tensiometer was set up with the pit walled in on one side. The soil moisture data at these pits were obtained using tensiometers set in the soil at an interval of 25 cm from the surface up to a 400 cm depth. Observation data of groundwater level and soil moisture tension in upland fields of the Cerrados were continuously obtained at intervals of 3~7 days during the period between 1983 and 1985. The soil moisture could not be measured in the soil layer of the ground surface in the dry season in and after April.

2) Water characteristics of soils in the Cerrados

Fig. 4 shows the water content–pF curve for representative soils obtained using undisturbed soil samples (red-yellow and dark-red latosols)[2,4,6,7]. Using a non-linear regression analysis, it was found that the following polynomial expression could approximate the dependence of the volumetric soil moisture content (Y: %) on the pF-value (X):

$$Y = 1.07X^3 - 5.38X^2 - 5.31X + 64.76 \quad \text{...........(15)}$$

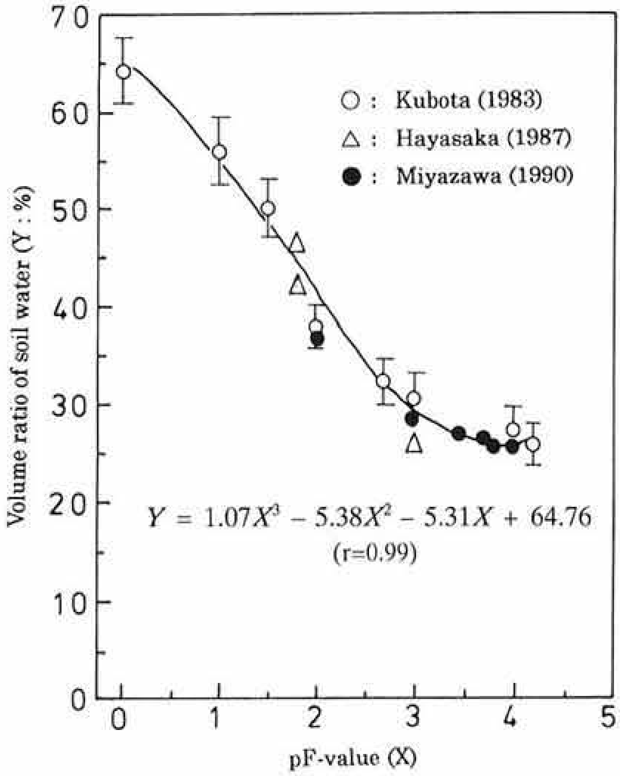


Fig. 4. Curve of moisture characteristics of Cerrados soils

The above equation can be used to estimate indirectly and easily the volumetric soil moisture from data of pF-value or soil–water suction (head cm H_2O) obtained by tensiometers.

3) Simulation method of soil moisture dynamics

The quantitative water movement in the soil profile can be predicted by the optimized simulation TANK model. In the model, each soil layer was considered as a tank having holes at different heights representing the water balance parameters including surface runoff, deep percolation, capillary water rise and evapotranspiration. Hole heights representing the limited magnitude of the parameters were determined based on the soil physical properties, namely water constants. Hole diameters representing the coefficient of the respective parameters in the model were determined by simulating the measured values.

The individual tanks (Pits 1 & 3) of the TANK-model corresponded to the 0~50, 50~100, 100~200, 200~300, and 300~400 cm soil layers, and Pit 2 corresponded to the 0~50, 50~100, 100~150 and 150~200 cm soil layers, respectively. In the soil layer of Pit 2, the groundwater level appeared at about 200 cm. The measurements of the soil–water suction were performed in the upland field of the campus of CPAC. The measurements of the groundwater level were performed at staff gauges in the individual experimental sites. The soil moisture dynamics was simulated by the TANK-model using meteorological data, namely air temperature, solar radiation, wind speed, humidity, data (precipitation and evaporation of class A pan) obtained at the weather station of CPAC (15°35' S, 47°42' W, SL : 1,000 m) during the period between 1978 and 1990.

Results and discussion

1) Frequency of occurrence of "Veranico" phenomenon

As is well known, the term "Veranico" refers to a continuous period without rainfall exceeding 6 days during the rainy season. The frequency of occurrence of the Veranico phenomenon was investigated using daily precipitation data obtained at CPAC during the period from 1978 to 1990. It was found that the Veranico phenomenon is most frequent during the period from December to February.

During this study, the longest duration of the Veranico phenomenon was 32 days for the period between February and March. The frequency of occurrence of the Veranico phenomenon over a 20-day period was found to be about 4 times per year. Due to the Veranico phenomenon, upland crops in this area were damaged by drought, at a frequency of once every 3 years.

2) *Application of TANK-model to the prediction of the soil moisture dynamics in upland fields*

In semiarid and arid regions with a distinct dry spell in a year, crop production is markedly affected by the amounts of soil moisture available in the root zone. Therefore, the TANK-model as described in Fig. 1 was used to simulate the soil moisture dynamics in upland fields, using each coefficient empirically estimated. The coefficients are listed in Table 1. The simulation results so obtained were compared with the data on the soil moisture dynamics obtained at the individual experimental sites (Pits 1 & 2).

Figs. 5 and 6 show the seasonal changes in related meteorological data and the amounts of soil-water stored in each soil layer at different

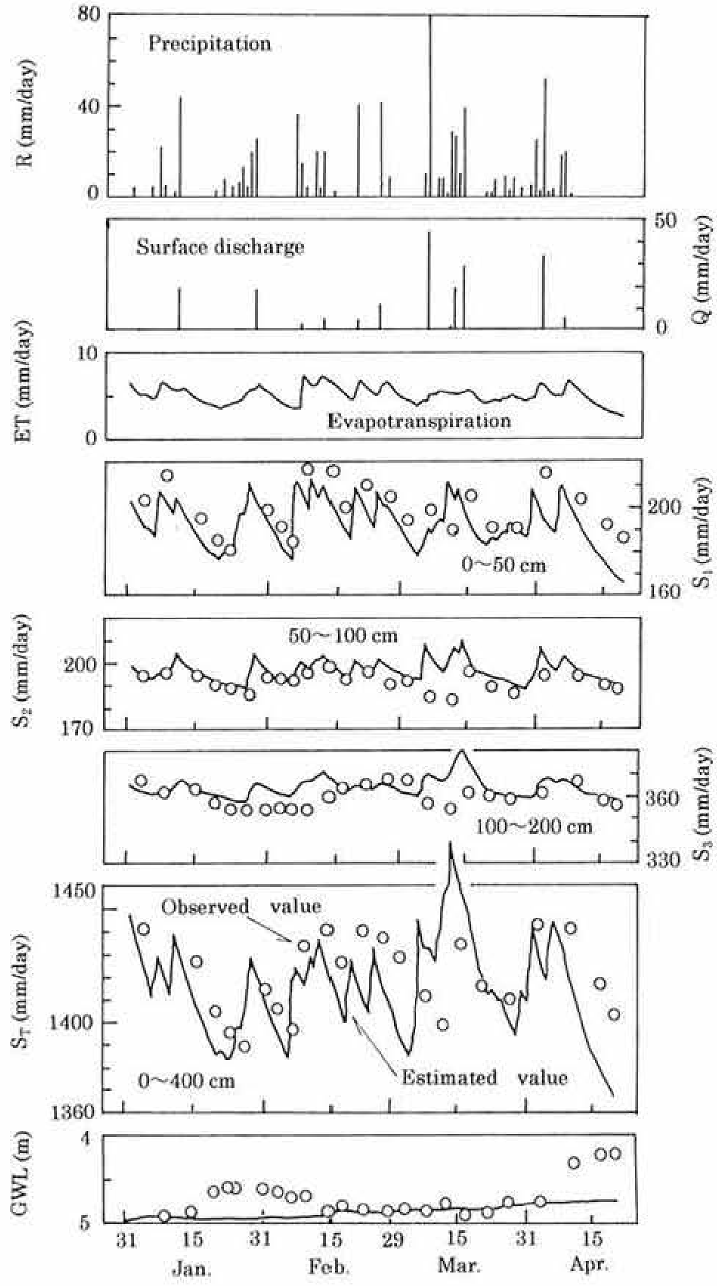


Fig. 5. Comparison of estimated values of soil moisture, groundwater level and evapotranspiration at Pit 1 with observed values

Table 1. TANK coefficient used to estimate the soil moisture

	Percolation level (mm)					Percolation coefficient						Discharge		
	P_1	P_2	P_3	P_4	P_5	p_1	p_2	p_3	p_4	p_5	p_6	R_1	r_1	r_2
Pit 1	205	197	361	343	332	0.5	0.5	0.3	0.2	0.1	0.0001	220	1.0	0.001
Pit 2	205	190	180	180	—	0.5	0.5	0.3	0.2	—	0.005	220	1.0	0.02

	Evapotranspiration level (mm) and capillary rising level (mm)					Evapotranspiration coefficient and capillary rising coefficient					
	E_1	E_2	E_3	E_4	E_5	e_0	e_1	e_2	e_3	e_4	e_5
Pit 1	160	135	160	320	320	0.06	0.03	0.02	0.01	0.0	0.0
Pit 2	160	135	160	160	—	0.06	0.03	0.02	0.01	0.0	—

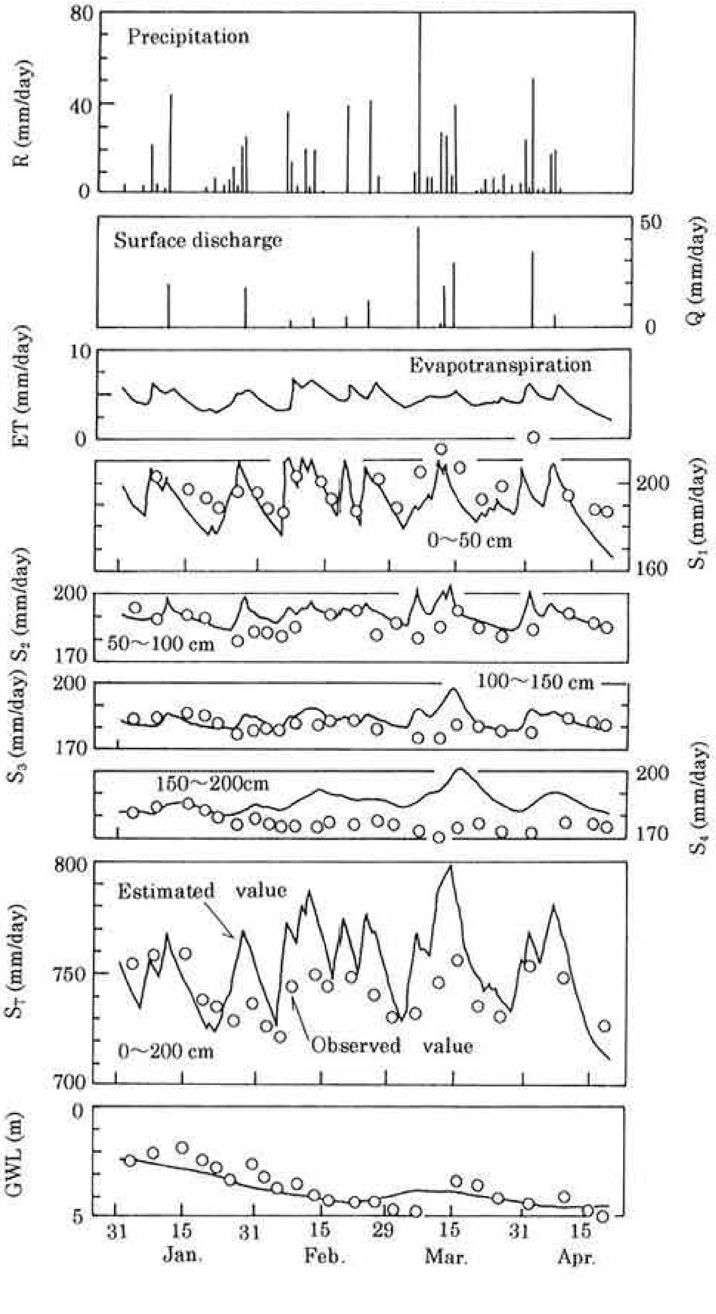


Fig. 6. Comparison of estimated values of soil moisture, groundwater level and evapotranspiration at Pit 2 with observed values

depths. The observation data of the amounts of soil–water can be calculated by equation (15) with the mean soil–water suction obtained with a tensiometer in each soil layer. The soil moisture dynamics simulated by the TANK-model was also presented to evaluate its applicability to upland fields. Comparison between the observed and simulated results was made using the meteorological data in 1984 with little precipitation.

As shown in Figs. 5 and 6, although there was some discrepancy between the observed soil moisture (circles) and simulated soil moisture (solid lines) data, it appears that the seasonal changes in the soil moisture of the upland fields simulated by the TANK-model agreed well in general with those determined with the tensiometers.

Soil moisture dynamics (S_1, S_2, S_3, S_4) in each soil layer simulated by the TANK-model using weather data agreed well with the measured soil moisture dynamics (○) with an error of ±10%. Furthermore, the estimation error for the soil moisture dynamics (S_T) in the total root zone decreased

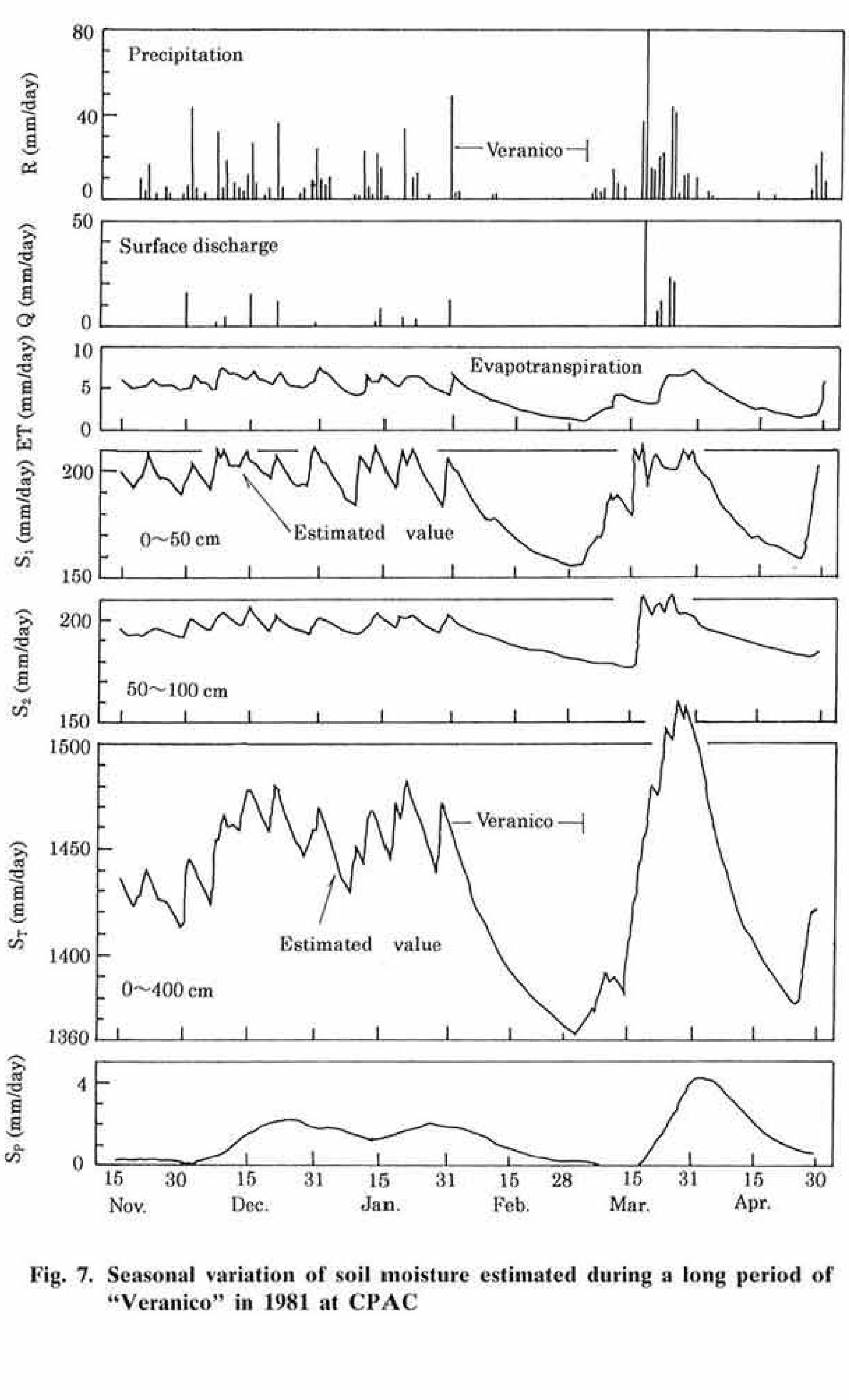


Fig. 7. Seasonal variation of soil moisture estimated during a long period of "Veranico" in 1981 at CPAC

by about ±5%. Seasonal changes in the observed groundwater level (GWL) were found to follow those (S_6) simulated by the TANK-model.

This general agreement indicates that the TANK-model can be applied to simulate seasonal changes in the soil moisture of upland fields using data on meteorological conditions and hydraulic characteristics of soils.

The calculation of the water balance for the root zone of upland fields revealed that the maximum deep percolation of water and the maximum capillary rise of water in this experimental field were 4.0 mm/day and 1.8 mm/day, respectively. Expected maximum capillary water rise in this field agreed well with the recovery rate of the soil moisture in volcanic ash soils (Japan) during the night[12]. The runoff ratio calculated for the upland fields during the experimental period was found to be 26.3%, with a good agreement with that obtained in flat upland fields of Japan[5].

3) Soil moisture dynamics during the "Veranico" period

The weather data during the Veranico period in 1981 were used to analyze the soil moisture dynamics for a longer and stronger Veranico period. The soil moisture dynamics simulated by the TANK-model using Pit 1 for this period are shown in Fig. 7, which indicates that soil moisture in the surface soil layer (0~50 cm) decreased very drastically with the start of the Veranico phenomenon.

That is, the soil moisture in this layer decreased from 200 mm at the beginning (Jan. 31) to 156 mm at the end (March 15), because of the very high evaporation loss of water from heated soil surface and the absence of rainfall during this period. The soil moisture at the end (March 15) was about 70% of the field capacity of soils. For this reason, the growth and yield of the soybean crop in this year were severely reduced due to the considerable shortage of available soil moisture in the root zone.

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