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# The Effects of Groundwater Depth on the Soil Evaporation in Horqin Sandy Land, China

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**Abstract:** The interactions between groundwater depth and soil hydrological processes, play an important role in both arid and semi-arid ecosystems. The effect of groundwater depth on soil water variations were neglected or not explicitly treated. In this paper, we combine a simulation experiment and a water flow module of HYDRUS-1D model to study the variation in soil evaporation under different groundwater depth conditions and the relationship between groundwater depth and evaporation efficiency in Horqin Sandy Land, China. The results showed that with an increase in groundwater depth, the evaporation of soil and the recharge of groundwater decrease. In this study, the groundwater recharge did not account for more than 21% of the soil evaporation for the depths of groundwater examined. The soil water content at 60 cm was less affected by the evaporation efficiency when the mean groundwater depth was 61 cm during the experimental period. In addition, the evaporation efficiency (the ratio of actual evaporation to potential evaporation) decreases with the increase in groundwater depth during the experiment. Furthermore, the soil evaporation was not affected by groundwater when the groundwater depth was deeper than 239 cm.

**Keywords:** groundwater depth; soil evaporation; evaporation efficiency; HYDRUS-1D

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## 1 Introduction

Water is one of the most important factors affecting the variation in the natural environment under drought conditions (Zhang and Liu, 2014; Nasr and Bachta, 2018; Wang and Wei, 2019), and it determines the survival and growth of plants (Wang et al., 2011; Pan et al., 2019; Zhao et al., 2020). Soil moisture is an essential element in processes that drive land surface water and energy fluxes, both of which affect ecosystem dynamics and biogeochemical cycles in the land-atmosphere system (Zheng et al. 2015; Jacobs et al., 2020). Moreover, soil moisture influences the water balance of precipitation, soil and vegetation, and it changes in the unsaturated zone because of precipitation recharge and water exchange with both the atmosphere and groundwater (GW) in arid and semi-arid regions (Han et al., 2008; Mosase et al., 2019). Many scholars have studied that the relationship between soil and water, plants and water, as well as between soil, plants and water (Alamusa et al., 2003; Guo and Shao 2003; Yang et al., 2012; Brendel, 2021). Additionally, some progress has been made that the soil, plants and the atmosphere (SPAC) as a whole (Tuo et al., 2008; Shou et al., 2013;

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Zhang and Huang, 2021). However, the role of groundwater in the whole system is not well considered.

In the arid and semi-arid regions that have sparse precipitation, the changes in groundwater and rainfall have a significant impact on soil water movement. Shallow groundwater may affect surface processes and states through capillary rise or direct root water uptake and interaction with soil, vegetation and climate (Soylu et al., 2011; Kroes et al., 2019). In areas with shallow groundwater, the soil evaporation of bare sandy land influence the efficiency that the precipitation turns into effective soil water. Therefore, it is very important to quantify the amount of bare soil evaporation influenced by groundwater. Some scholars have studied the effect of groundwater depth on bare soil evaporation. For example, Chen and Hu (2004) found that the groundwater treatments increased the evapotranspiration (ET) than that from a model without groundwater. Jin et al. (2014) suggested that the deeper the groundwater, the less the evapotranspiration in the rainy season. Wang and Hou (2008) indicated that the main influencing factor of bare soil evaporation was groundwater depth. The ETa/ETp ratio indicates what percentage of the available energy (ETp) is partitioned into latent heat flux (ETa) for a given simulation (de Camargo et al., 1999, Blain and de Matos Pires, 2011; Soylu et al., 2011). For example, Luo and Sophocleous (2010) use the ratio of actual evapotranspiration to potential evapotranspiration to study the relationship between evaporation and groundwater depth. These studies focused on the effect of the groundwater depth under different groundwater conditions and other conditions on soil evaporation and soil water. However, few studies focused on the quantitative relationship between groundwater depths on bare soil evaporation. We used the water flow module of HYDRUS-1D model to study the vertical transport process of soil water in bare land under different groundwater depths. The purpose of this study was to 1) to investigate the impacts of different groundwater depth on bare soil evaporation; 2) to quantify the groundwater recharge under different groundwater depth; 3) to examine diurnal variation in the relationship between groundwater depth and evaporation efficiency. This study could provide methods and foundations for making simulations and analyses of the relationship between soil evaporation and groundwater depth.

## 2 Materials and Methods

### 2.1 Field experimental data

#### *2.1.1 Study area*

The study site at Wulanaodu Station was located in the western Horqin Sand Land, northeastern Inner Mongolia, China (42°59′N–43°00′N, 119°37′E–119°39′E). Wulanaodu Station, built in 1975 and affiliated with the Institute of Applied Ecology of the Chinese Academy of Sciences, is one of the monitoring network stations of the Department of Desertification Control, State Forestry Administration of China. The climate of the study area is temperate, semiarid continental monsoonal. The mean annual precipitation is approximately 230 mm, with 70% of this falling during the experiment between June and September. Additionally, the annual open-pan evaporation is approximately 2000 mm. The annual average temperature is 6.2℃, with the minimum monthly mean temperature of −13.74℃ in January and the maximum 25.14℃ in July. The average aridity index is 1.99, and the relative humidity varies between 50%–60%. The annual mean wind velocity is in the range of 3.2–4.1 m/s, and the prevailing wind is northwest in winter and spring and southwest to south in summer and autumn.

#### *2.1.2 Experimental design*

The experiment was designed to observe interactions among the soil, soil water, and groundwater, and it was conducted in 2016 (from June 8th to June 20th and June 25th to August 18th, 2016). As shown in Fig. 1, we arranged two soil observation tanks at Wulanaodu Station, and established the underground observation room in the middle of the two soil tanks. We welded six iron boxes in the two soil tanks, and their length and width were 4.5 m and 1.5 m, respectively. The height was different as the different groundwater table (GWT); initial groundwater table were 70 cm, 80 cm, 130 cm, 140 cm, 190 cm and 200 cm. The six treatments were repeated 3 times each. The 10-cm stone layer was laid at the bottom of each iron box to simulate the underground aquifer. The bottom of the iron box was connected with the groundwater observation. Additionally, the two polyvinylchloride (PVC) pipes of 10 mm diameter on the side of the iron box which was higher than the 30 cm of the box body.

Holes with 5 cm in diameter were set at the depth of

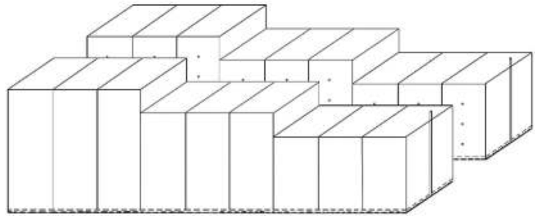

**Fig. 1** The schematic diagram of an experimental device. The two cylindrical positions are the groundwater observation pipe, and the circular hole in the device is the position of the time domain reflectometry

50 cm, 100 cm and 150 cm on the side of the iron box, which is convenient for inserting the time domain reflectometry (TDR). Finally, the iron box filled with the sand soil that were collected from soil samples.

#### 2.1.3 Measurements

The TDR devices (Jinzhou Sunshine Technology, Co. Liaoning of China) were used to measure the soil water content every day. The TDR devices were located at depths of 50 cm, 100 cm and 150 cm; they were below the surface with an attempt to minimize the destruction of topsoil vegetation and soil structure. The position of the groundwater table was measured every day. Evaporation data were observed using E601B pan (Weifang Jinshui Huayu Information Technology Co. LTD, Co. Shandong of China), which we considered to be the potential evaporation.

### 2.2 HYDRUS-1D model

#### 2.2.1 Model description

The HYDRUS-1D model was used as the benchmark model because it has been validated by analytical techniques and applied research (Šimůnek et al., 2008). In addition, the numerical model package HYDRUS-1D was used to simulate the processes of unsaturated water and evaporation from the soil surface in one-dimensional variably saturated media. The Hydrus-1D program solves the convection-diffusion equation for the saturated and unsaturated water flow and heat and solute transport of the Richards equation (Richards, 1931). The Richards equation is expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\partial)\left(\frac{\partial h}{\partial z}+1\right)\right]-S \tag{1}$$

where $\theta$ is volumetric water content (m$^3$/m$^3$), $t$ is time (d), $z$ is vertical coordinate (m) positive downward, $K$ is the unsaturated hydraulic conductivity function of soil (m/d), $h$ is the water pressure head (m), and $S$ is the source/sink term (m$^3$/(m$^3$/d)).

#### 2.2.2 The input parameters of water flow module

In water flow module, the soil water characteristic curve is the most basic hydraulic characteristic curve for solving the soil flow equation. Soil hydraulic properties were described using the van Genuchten-Mualem analytical functions (van Genuchten, 1980), expressed as:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{[1+|ah|^n]^m} & h\le 0\\ \theta_s & h>0\end{cases} \tag{2}$$

where $\theta$ is soil water content (cm$^3$/cm$^3$), $h$ is the water pressure head (m), $\theta_r$ is residual water content (cm$^3$/cm$^3$), $\theta_s$ is the saturated water content (cm$^3$/cm$^3$), $\alpha$ and $n$ are the shape parameters, $m$ is the parameter in the soil water retention function, $m$ =1−1/$n$. According to the particle analysis data of the experimental site, the model parameter values of reference are shown in Table 1.

#### 2.2.3 Initial and boundary conditions of water flow module

The atmospheric condition was the upper boundary condition; the deep drainage (with groundwater) condition was the lower boundary condition, which was imposed at the soil surface and bottom boundary of the flow domain, respectively (Neuman, 1974). The function of boundary condition is:

$$\begin{cases}\left|-K\dfrac{\partial\theta}{\partial x}-K\right|\le E & \\ h_a\le h\le h_s=0 \end{cases} \quad x=0 \tag{3}$$

where $E$ is maximum (potential) rate of infiltration or

**Table 1** The soil particle percentage and hydraulic parameters of HYDRUS-1D

| | Soil particle percentage | | | Hydraulic parameters | | | | |
|---|---|---|---|---|---|---|---|---|
| Soil type | Sand/ % | Silt/ % | Clay / % | Bulk density | $\theta_r$ | $\theta_s$ | $\alpha$ | $n$ |
| | > 0.05 mm | 0.05–0.002 mm | < 0.002 mm | (g/cm$^3$) | (cm$^3$ /cm$^3$) | (cm$^3$ /cm$^3$) | (1/cm) | |
| Sand | 86.00 | 13.64 | 0.36 | 1.28 | 0.045 | 0.41 | 0.045 | 2.68 |

Notes: $\theta_r$, the residual water content; $\theta_s$, the saturated water content; $\alpha$ and $n$, van Genuchten's shape parameters evaporation under the prevailing atmospheric conditions (L/T), $\theta$ is soil water content ($cm^3/cm^3$), $K$ is the unsaturated hydraulic conductivity function of soil (m/d), $h$ is the water pressure head (m), $h_a$ is the minimum pressure head allowed under the prevailing soil conditions (m), $h_s$ is the maximum pressure head allowed under the prevailing soil conditions (m).

The function of deep drainage condition is:

$$g = -A\exp(B|h - GWL0L|) \quad (4)$$

where $g$ is drainage rate (cm /T), $A$ and $B$ is experience parameters, $GWL0L$ is groundwater level (cm).

### *2.2.4 Criteria of model evaluation*

The consistency between simulation results and observation data for evaluation using the correlation coefficient $R^2$ is given by the following equation:

$$R^2 = \left[\frac{\sum_{i=1}^{r}\left(C_{\text{si}} - \overline{C}_{\text{si}}\right)\left(C_{\text{ob}} - \overline{C}_{\text{ob}}\right)}{\sum_{i=1}^{r}\left(C_{\text{si}} - \overline{C}_{\text{si}}\right)\sum_{i=1}^{r}\left(C_{\text{ob}} - \overline{C}_{\text{ob}}\right)}\right] \quad (5)$$

where $r$ is the total number of observed values used in the calibration and validation process, $C_{\text{ob}}$ is an observed value, $C_{\text{si}}$ and is a simulated value. $\overline{C}_{\text{ob}}$ and $\overline{C}_{\text{si}}$ are the mean values of the observed and simulated data points, respectively.

We use the root mean square error (RMSE) and mean absolute error (MAE) to measure the deviation between the observation data and simulated data.

$$RMSE = \sqrt{\frac{1}{b}\sum_{i=1}^{b}(f(x_i) - y_i)^2} \quad (6)$$

$$MAE = \frac{1}{b}\sum_{i=1}^{b}|f(x_i) - y_i| \quad (7)$$

where $b$ is the total number of observed or simulated values, $x_i$ is an observed value, $y_i$ and is a simulated value.

### 2.3 Meteorological data and groundwater data

All meteorological data were obtained from an automated meteorological station (43°02′N, 119°65′E) located near the study site (< 200 m) during the experimental period (June 8 to August 15, 2016), including daily precipitation and daily evaporation. Fig. 2 showed that rainfall events occurred during the experimental period and that the total precipitation was 17.9 cm. The seasonal distribution of precipitation was uneven, and was mainly concentrated in July and August. Three heavy rainfall events occurred during July and included relatively large precipitation on July 21 (5.5 cm), July 25 (4.3 cm) and July 28 (3.7 cm)). The total ET occurred during the experimental period was 53.6 cm.

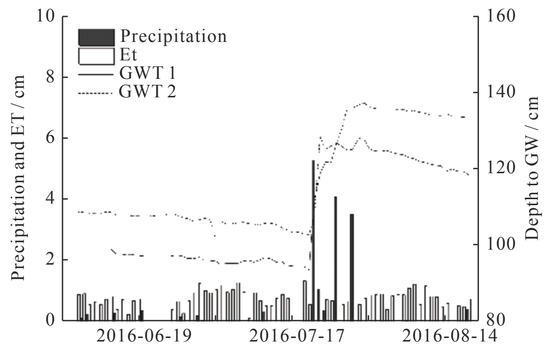


**Fig. 2** The precipitation, evapotranspiration (ET), groundwater Table 1 (GWT1) and groundwater Table 2 (GWT2) at Wulandodu Desertification Combating Ecological Station during the study experimental period (June 8 to August 15, 2016)

In this study, we use the static pressure probe of the input hydraulic meter with the digital display meter to measure the groundwater change. During the experimental period, the initial water levels of the devices was 100 cm (groundwater Table 1 (GWT1)) and 110 cm (groundwater table 2 (GWT2)), with the bottom of the device being the datum plane. Affected by precipitation and evaporation, the water table increased respectively 20.2 cm and 25.8 cm, respectively, during the experimental period.

## 3 Results

### 3.1 Model calibration and validation

We used the soil water content that at 50 cm soil depth of the six gradient iron boxes as the measured water content; the scatter plots of observed soil water content and simulated soil water content were shown in Fig. 3. There was a good agreement between the observed and simulated soil water content. The $R^2$ value is 0.96, the RMSE value is 0.02, and the MAE value is 4%. It can be seen that the simulated value is highly consistent with the observed values.

### 3.2 Relationship between soil evaporation and groundwater recharge

Based on the model simulation results, the cumulative bare soil evaporation and groundwater recharge at different groundwater table were shown in Fig. 4. In soil with the mean groundwater depth is 61 cm (GW61), 71 cm (GW71), 121 cm (GW121), 131 cm (GW131), 180 cm (GW180) and 191 cm (GW191), the accumulated bare soil evaporation were 23.5 cm, 21.8 cm, 12.6 cm, 10.1 cm, 9.8 cm and 9.8 cm, respectively. Furthermore, 21%, 21%, 14%, 12%, 4% and 1% of total evaporation from groundwater recharge, respectively. The results showed that the change trend of bare soil evaporation with different groundwater table are the same, but there are differences in value under different groundwater depth. According to the results, we found that with the increase of groundwater table, the evaporation of bare soil showed a decreasing trend.

### 3.3 Response of soil depth to soil evaporation

The model results provided the ratio of the actual evaporation (ETa) to potential evaporation (ETp). According to soil water contents that were provided by the model in 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and 60 cm soil depth to analyze the effect of soil evaporation on soil thickness in different GW (Fig. 5). The results showed that the ETa/ETp in soils have obvious variation at different groundwater table. Furthermore, the ETa/ETp tends to be stable with the increase of soil thickness; it indicated that the effect of evaporation on soil is smaller. Additionally, most of the soil layers are affected by evaporation at different GW soil during the experiment. In GW61 soil, the soil water at 60 cm was less affected by the evaporation efficiency. The results showed that the influence of evaporation on soil thickness is related to groundwater depth.

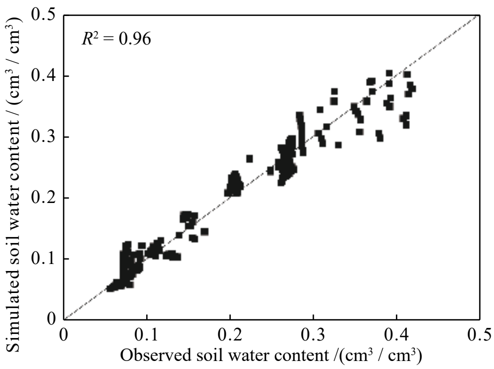


**Fig. 3** Comparison of observed soil water content and simulated soil water contents during the entire experiment period (June 8 to August 15, 2016) in Horqin Sandy land

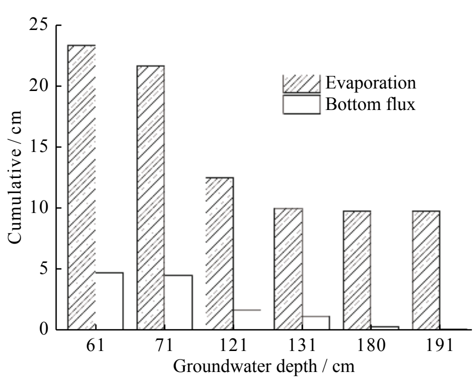


**Fig. 4** The cumulative bare soil evaporation and bottom flux at different groundwater depth during the entire experiment period (June 8 to August 15, 2016) in Horqin Sandy Land

### 3.4 Evaporation efficiency under different groundwater depths

The daily output data of Hydrus-1D model was used to calculate the mean evaporation efficiency. In order to eliminate the error of groundwater fluctuation, we took the average of the evaporation efficiency over 10 d to plot a function with mean GW. The regression analysis of GW and ETa/ETp was shown in Fig. 6. We explored the GW responses to ETa/ETp to study the contribution of the groundwater table to soil water. The ETa/ETp was negatively correlated with the groundwater table. The results showed that with an increase in groundwater table, the evaporation efficiency decreases. According to the linear relation formula, the evaporation efficiency was weak when the groundwater depth was deeper than 239 cm. The results showed that the groundwater table could affect the soil evaporation.

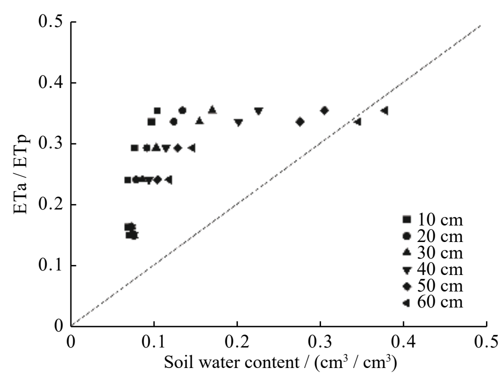


**Fig. 5** The relationship between ETa/ETp and soil water content, above the 1∶1 line is affected by evaporation during the entire experiment period (June 8 to August 15, 2016) in Horqin Sandy Land

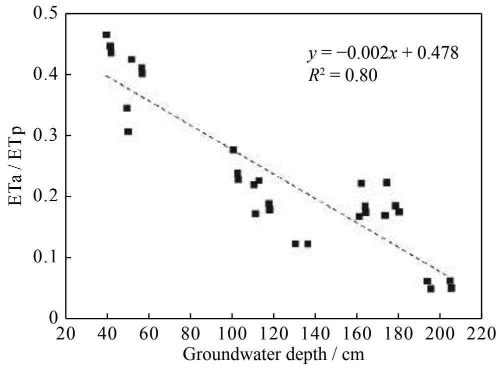


**Fig. 6** The variation of day in regression analysis of groundwater table and evaporation efficiency during the entire experiment period (June 8 to August 15, 2016) in Horqin Sandy Land

## 4 Discussion

### 4.1 Effect of groundwater depth on bare soil evaporation and groundwater recharge

Surface soil evaporation is dependent on the atmospheric evaporation capacity and the soil water supply capacity (Jia, 2008; Zhang et al., 2009; 2011; Abolafia-Rosenzweig et al., 2020). Previous studies have indicated that the soil evaporation mainly comes from groundwater recharge in the case of without precipitation recharge (Jia. 2008; Jin et al., 2014; Huo et al., 2020). Furthermore, the water rising along the capillary will be more because of the strong capillary action of soil water when the groundwater depth was shallow. Although, many scholars have studied the proportion of groundwater recharge and rainfall recharge, less quantitative research on the contribution of groundwater to evaporation. In this study, we established that the relationship between groundwater level depth and evaporation, and showed that with the increase of groundwater table, the proportion of groundwater recharge to evaporation has an increasing trend. Because the shallower the groundwater depth, the easier it is to be contaminated by soil and evaporation.

### 4.2 Response of soil depth to soil evaporation under different groundwater depth

In arid and semi-arid areas, bare sand evaporation is a complex process (Voortman et al., 2017). In the evaporation process, the water below the surface moves upward in the form of water vapor diffusion and capillary water. Therefore, it is necessary to study the effect of evaporation on soil depth. For example, Sun et al., (2002) found that the ratio of soil water to evapotranspiration in different depth layers is becoming weaker with the increase of depth. Zhai et al., (2007) suggested that the soil evaporation in saline alkali soil area was affected by deeper soil water. Liu et al., (2015) studied that the amount of evaporation and soil water content were significantly correlated at 0–60 cm soil depth. We also found that soil evaporation decreased as soil depth increased. However, these studies are concerned with the relationship between soil evaporation and soil depth under the influence of no groundwater; few scholars have studied the response of soil thickness to evaporation under different groundwater table conditions. We study the relationship between soil thickness and evaporation by water flow module of HYDRUS-1D model, and found that the ETa/ETp tends to be stable with the increase of soil thickness. The soil layers are affected by evaporation at different GW soil during the experiment, and we suspect that the influence of evaporation on soil thickness is related to groundwater depth.

### 4.3 The effect of groundwater depth on evaporation efficiency

In arid and semi-arid regions, the soil evaporation as an important component in annual water balance. Some studies have suggested that the groundwater depth could influence the soil evaporation efficiency (Hu et al., 2005, Zhang et al., 2009). For example, Soylu et al., (2011) examine the sensitivity of evapotranspiration at the land surface to the depth of groundwater through three model. Ibrahimi et al., (2014) suggested that the evaporation is influenced by the depth to groundwater through the HYDRUS-1D model. Luo and Sophocleous (2010) found that evapotranspiration decreases with increasing depth to watertable through the HYDRUS-1D model. Huang et al., (2015) used HYDRUS-1D model to indicate that with the increase of groundwater depth, evaporation decreases significantly and soil water storage decreases. These studies use the HYDRUS-1D model to illustrate the relationship between groundwater table and evaporation based on interannual patterns and variability of evaporation. However, we studied the relationship between groundwater table and evaporation efficiency every 10 d during experimental period. The results showed that the soil evaporation was mainly affected by rainfall and groundwater depth after rainfall, and was mainly influenced by groundwater depth before rainfall. Further, the contribution of groundwater to soil evaporation is weak when the groundwater depth is greater than 239 cm. The results provided that the critical value of the groundwater level of the replenished soil water according to the simulation of the model.

## 5 Conclusions

In this paper, we study the relationship between bare soil evaporation and groundwater depth by HYDRUS-1D model. The simulated soil water content matched the observed soil water content in this study. The HYDRUS-1D can be an effective tool for evaluating the relationship between bare soil evaporation and groundwater depth. We verified that the relationship between groundwater recharge and soil evaporation by the model. In this study, the proportion of groundwater recharge to soil evaporation increased with the increase of groundwater table. Additionally, the contribution of groundwater to soil evaporation is weak when the groundwater depth is greater than 239 cm according to the simulation results. Furthermore, we suspect that the influence of evaporation on soil thickness is related to groundwater depth according to the result which soil water at 60 cm soil depth was not affected by evaporation in GW61 soil.

However, the applicability of the models may be restricted to the relationship between soil bare evaporation and groundwater recharge as there is not involved root water absorption of plant.

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