Responseof land surface water and heat fluxes to groundwater level change

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ABSTRACT

Based on observations in lysimeters with different water table depths, numerical simulations are conduced to obtain impacts of groundwater table on surface soil water content, temperature, and fluxes of vapor, radiation and heat. The observed soil water content and temperature data in the lysimeter for one year were used to compare with the simulated values. Results indicated simulated water contents and soil temperatures matched well the measured data in the lysimeter in Huaihe River basin of China. Under the same atmospheric forcing condition, the change of groundwater depth has an impact on the soil surface water content, temperature and the exchange of water and heat flux between land and air. There is a critical depth of 250 cm in our study site, in which groundwater can have strong effect on soil moisture content, temperature and heat flux. When the groundwater depth is deeper than the critical depth, the change of groundwater level will no longer affect these variables.

STUDY AREA

The observation data used in this study was taken from lysimeter at the Hanwang Hydrology and Water Resources Experimental Station (HHWES) in the Huaihe River plain region in China. The climate at HHWES (34o 11’N, 117o 18’E) is semi-humid temperate continental monsoon with a mean annual temperature and precipitation of 15.5 ^{o}C and 750 mm, respectively. Most precipitation (60% to 80 %) occurs during summer from June to September. The lysimeters used in this study were bare during the simulation period, with no need to consider the effect of vegetation. The volumetric water content and matric potential were monitored by the neutron probe tube and the tensiometer, respectively. There was a subsurface observation room around the lysimeter to collect data of surface runoff, groundwater evaporation and recharge to groundwater for the lysimeter. The water table of the lysimeter was controlled by the Marriott bottle system inside the observation room. In this study, we considered two lysimeters with water tables of 50 cm and 350 cm, respectively, which kept constant groudwater table below the soil surface during the simulation period. Regularly observed meteorological variables in this experimental station included air temperature, soil temperature, precipitation, solar radiation, wind speed, sunshine hours and pan evaporation. The soil temperatures were observed at the depths of 0, 5, 10, 15 and 20 cm below the soil surface at the site near the lysimeter, where had the same soil type and surface elevation with the lysimeter.

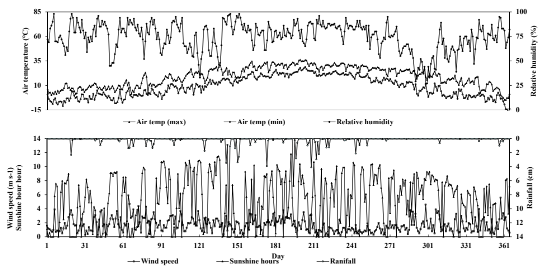

Fig. 1 The observed daily atmospheric data used in the simulation, including maximum and minimum air temperatures, relative humidity, wind speed, sunshine hours and rainfall.

METHODOLOGY

➢ Governing equations

Based on the PDV (Philip and De Vries) models, governing equations of the one-dimensional water and heat flow in the soil under variably saturated, non-isothermal conditions can be expressed as:

$$\frac{\partial(\theta_L+\theta_v)}{\partial t} = -\frac{\partial q_w}{\partial z} = -\frac{\partial q_L}{\partial z} - \frac{\partial q_v}{\partial z}$$

$$\frac{\partial S_h}{\partial t} = -\frac{\partial q_h}{\partial z}$$

where θ_L is the volumetric liquid water content; θ_v is the volumetric water vapor content,; q_w is the total water flux; q_L and q_v are the flux densities of liquid water and water vapor, respectively; t is time (s) and z is the spatial coordinate positive upward (m); S_h is the heat storage in the soil (J m^{-3}), q_h is the total heat flux density of the soil (J m^{-2} s^{-1}).

➢ Initial and boundary conditions and numerical procedure

The simulated values at the end of the spin-up period were treated as the initial conditions of the simulation period for the model. Surface precipitation, evaporation, runoff and heat fluxes are used as boundary conditions for water flow and heat transfer in the soil. The atmospheric forcing data used for the simulation included wind speed, air temperature, sunshine hours, precipitation and air humidity during the year of 1991 (Fig.1). Surface boundary conditions for the water and energy equations are respectively given by:

$$q_w(0,t) = P - R - E$$

$$R_n = H + LE + G$$

where $q_w(0,t)$ is the total water flux across the soil surface, P represents the rate of precipitation, R represents the rate of surface runoff, E is the evaporation rate from the soil, R_n is net radiation, H is the sensible heat flux density, LE is the latent heat flux density, and G is the surface heat flux density. The governing equations of water and heat flows subject to initial and boundary conditions were numerically by using the finite difference method.

RESULTS AND DISCUSSION

➢ Soil moisture and evaporation

Fig.2 shows monthly average of soil moisture and evaporation at 50 cm and 350 cm groundwater depth, respectively. Soil surface moisture increases with rainfall, and decreased with soil evaporation. The soil moisture at shallow groundwater depth (50 cm) is obviously higher than that of deep groundwater depth (350 cm), indicating that lost water by evaporation can be timely supplied by shallow groundwater. Even in autumn and winter with less rainfall, soil moisture can be kept at a higher level than that in the rainy seasons, since soil evaporation is higher in warm seasons. The annual variation of evaporation presents typical seasonal characteristics: from May to September, the radiation is stronger, the evaporation potential is higher, and the soil is wetter, resulting in higher evaporation; in other months, the radiation is lower, the evaporation potential is lower, and the soil is relatively dry, resulting in relatively low evaporation. For the same month and the same atmospheric environment, the soil moisture content under shallow groundwater depth is always higher than that under the deep condition, resulting in significantly higher evaporation for the shallow groundwater depth. Especially in the dry autumn and winter seasons (such as October to December), the impact of different groundwater levels on evaporation is particularly significant. Although there is less rainfall at this time, the water content at shallow groundwater is still very high, making evaporation mainly limited by the amount of atmospheric energy supply and less limited by soil moisture supply, and can still be maintained at a high level.

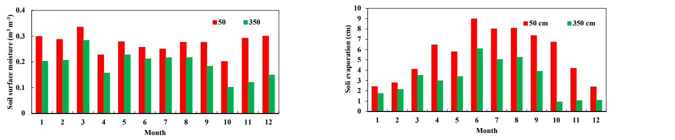

Fig. 2 Monthly average soil surface moisture and evaporation at 50 cm and 350 cm groundwater depth

➢ Soil temperature and energy terms

Fig.3 shows monthly average of soil surface temperature, net radiation flux R_n, sensible heat flux H and latent heat flux LE at 50 cm and 350 cm groundwater depth, respectively. It can be seen that soil surface temperature under shallow groundwater depth is lower than that under deep condition. During the humid and cold months of January to March, the difference in soil surface temperature between the two depths is relatively small than that in other months. Due to the significant correlation between air temperature and soil surface temperature, the impact of groundwater depth on soil surface temperature essentially represents the impact of groundwater level on air temperature. Therefore, this conclusion is very important and help us understand local and even global climate change issues. Soil temperature is controlled by the combined action of radiation flux and ground heat flux, and on the other hand, the magnitude of these variables will be affected by the level of soil temperature. The mechanism of the influence of groundwater depth on soil surface temperature is closely related to the radiation budget and energy distribution of soil surface.

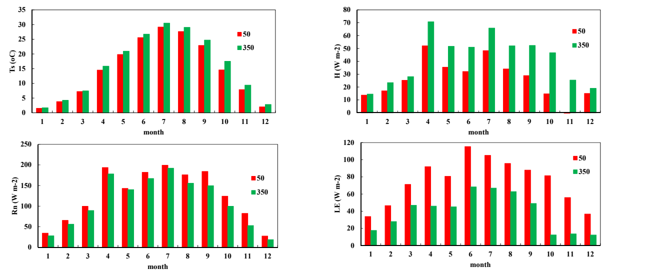

Fig. 3 Monthly average of soil surface temperature, net radiation flux R_n, sensible heat flux H and latent heat flux LE at 50 cm and 350 cm groundwater depth.

As shown in Fig.3, net radiation flux R_n is higher in summer and lower in winter, and it’s higher at the shallow groundwater depth than the deep condition. This means that for the shallow groundwater depth condition, the energy absorbed by the soil surface is greater than that for the deep condition, indicating that the soil temperature should have the potential for higher values for the former condition. In fact, that is not true by Fig. 3. This is because the net radiation energy obtained by the soil surface is not only used to heat the soil layer, but also used to heat the air above the ground, and also used to complete the evaporation process of water.

Heat flux H is related to the difference between soil surface temperature and atmospheric temperature, as well as wind speed, surface roughness, etc. In general, when the soil surface temperature is higher in the warm season and at the deep groundwater table, the sensible heat flux is correspondingly higher, and the soil surface supplies more energy to the atmosphere, and vice versa. The annual distribution of latent heat flux LE is consistent with soil evaporation E. For shallow groundwater depth, although the net radiation is greater than that of the deep situation, it will consume more heat to complete the water vaporization process, leaving less heat to increase its own temperature. However, for deep groundwater depth, the opposite is true, which leads to higher soil surface temperature as shown in Fig. 2.

➢ The critical depth of groundwater

As shown in Fig. 4, when the groundwater depth increases from 30 cm to 100 cm, the water content decreases significantly from 0.35 m^3 m^{-3} to 0.2 m^3 m^{-3}. When the depth increases to 250 cm, the water content decreases to 0.19 m^3 m^{-3}, with a small decrease; and the water content no longer decreases when the depth is greater than 250 cm. This indicates that the critical depth of the influence of groundwater on soil surface is about 250 cm. Within the critical depth , the soil surface temperature increases by 1.5 ^{o}C when the groundwater depth increases from 30 cm to 250cm. There is a good correlation between soil surface temperature and air temperature, which means that changes in groundwater depth may also have a significant impact on air temperature.

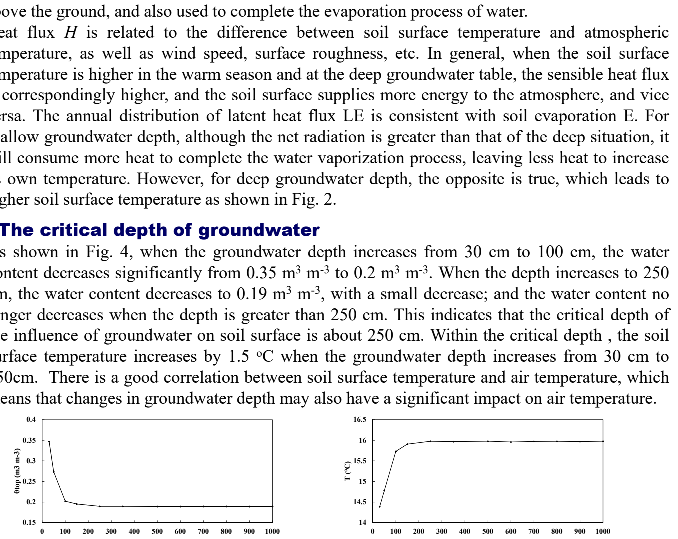

Fig. 4 Annual average values of soil surface water content and temperature with groundwater depth