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Quantitative Simulation on Soil Moisture Contents of Two Typical Vegetation Communities in Sanjiang Plain, China

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Abstract: Different types of vegetation occupy different geomorphology and water gradient environments in the Sanjiang Plain, indicating that the soil moisture dynamics and water balance patterns of the different vegetation communities might differ from each other. In this paper, a lowland system, perpendicular to the Nongjiang River in the Honghe National Nature Reserve (HNNR), was selected as the study area. The area was occupied by the non-wetland plant forest and the typical wetland plant meadow. The Microsoft Windows-based finite element analysis software package for simulating water, heat, and solute transport in variably saturated porous media (HYDRUS), which can quantitatively simulate water, heat, and/or solute movement in variably-saturated porous media, was used to simulate soil moisture dynamics in the root zone (20–40 cm) of those two plant communities during the growing season in 2005. The simulation results for soil moisture were in a good agreement with measured data, with the coefficient of determination (R^2) of 0.44–0.69 and root mean square error (RMSE) ranging between 0.0291 cm^3/cm^3 and 0.0457 cm^3/cm^3, and index of agreement (d) being from 0.612 to 0.968. During the study period, the volumetric soil moisture content of meadow increased with the depth and its coefficient of variation decreased with the depth (from 20 cm to 40 cm), while under the forest the soil moisture content at different depths varied irregularly. The calculated result of water budget showed that the water budget deficit of the meadow was higher than that of the forest, suggesting that the meadow is more likely to suffer from water stress than the forest. The quantitative simulation by HYDRUS in this study did not take surface runoff and plant growth processes into account. Improved root water uptake and surface runoff models will be needed for higher accuracy in further researches.

Keywords: soil moisture; HYDRUS-3D; wetland; quantitative simulation; Sanjiang Plain

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1 Introduction

The diversity of wetland plant communities and species are influenced by chemical, physical and biological processes within a region, which involves climate, hydrology and geomorphology as important components of the plant and animal environment (Naumburg *et al*., 2005). Water is a key factor in wetland ecosystems, which are critical zones where water conditions are closely related to ecology (Gong *et al*., 2009; 2010). Humidity, determined by soil moisture, may have a direct impact on the spatial distribution patterns of wetland vegetation communities. Research on soil moisture is important because of its close exchange relationships with the atmosphere, surface water, groundwater, plants and other elements, and it is also highly related to the characteristic of plant environment gradients. Therefore, the dynamic patterns of soil moisture is a key factor to

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understand the plant ecosystems and the mechanisms, which also provides the critical information for the protection and recovery of wetland ecosystems.

Using quantitative simulation approaches to analyze wetland vegetation communities and their eco-hydrological processes has became an important aspect of researches, especially since the 1980s (Dane and Mathis, 1981; Wang, 1989; Chen and Qi, 1996; Xie *et al*., 1998; Li *et al*., 2002; Li *et al*., 2007; Zhou *et al*., 2008; 2009). Various soil moisture dynamic models have been developed (Belmans *et al.*, 1983; Baier and Robertson, 1996; Slavich *et al.*, 1998; Abrahamsen and Hansen, 2000; Schlegel *et al*., 2004; Shang, 2004; Ranatuga *et al*., 2008). These models can be divided into three types: system models (empirical models), conceptual models (water balance models) and mechanistic models (hydraulic models) (Shang *et al*., 2009). Compared with the empirical and water balance models, the Richards equation, which is based on Darcy′s law and the continuity equation, can describe soil moisture movement and transfer processes more accurately. The hydrological models can be divided into one-dimensional, two-dimensional and three-dimensional models, and the one-dimensional models are used most frequently (Huang *et al*., 2003).

HYDRUS-3D (the Microsoft Windows-based finite element analysis software package for simulating water, heat, and solute transport in variably saturated porous media) model (Šimůnek *et al*., 2008), based on Richards equation, is a hydraulic model developed by the US Salinity Laboratory and International Ground Water Modeling Center (IGWMC). It can simulate water, heat, and/or solute movement in variably saturated porous media. Using HYDRUS to simulate soil moisture dynamic under different vegetation types has mostly focused on farmland (Ndiaye *et al*., 2007; Hao *et al*., 2008; Mubarak *et al*., 2009; Zuo *et al*., 2009; Kandelous and Šimůnek, 2010). However, little attention has been paid to the research on the dynamic patterns of soil moisture in natural wetlands.

More researchers have discussed the mechanism and methodology of wetland models (Schot and Wassen, 1993; Thompson *et al*., 2004), but detailed data are still needed for the calibration and evaluation processes when analyzing soil moisture dynamics using these models. The complicated wetland environment with low accessibility and difficulty in monitoring and accessing data make it more difficult to describe the characteristics of wetland vegetation and eco-hydrological patterns as a transitional zone between terrestrial and aquatic ecosystems (Boswell and Olyphant, 2007). Therefore, few studies have been done on soil moisture dynamics under different wetland plants. In this paper, we used the HYDRUS-3D model to simulate soil moisture under wetland plants, and make a comparison between two plant communities in the Honghe National Nature Reserve of Heilongjiang Province. The purpose is to further understand the eco-hydrological processes and protect wetland vegetation communities in the study area.

2 Materials and Methods

2.1 Study area

Honghe National Nature Reserve (HNNR) (47°42′18″–47°52′00″N, 133°34′38″–133°46′29″E) covers an area of 251 km^2 in the center of the Sanjiang Plain in Heilongjiang Province (Fig. 1). The mean annual precipitation in HNNR is 579.3 mm, and the mean annual evaporation is 1166 mm. About 50%–70% of rain falls between July and September, which leads to the accumulation of surface water in lowland areas. The soils freeze for more than five months each year to the depths of 160–180 cm. The conditions in this area are suitable for marsh formation.

The Nongjiang River wetland ecological corridor, which crosses HNNR, is a primitive swamp area (Jiang *et al*., 2009) and is a typical and representative corridor in the Sanjiang Plain. The river section in HNNR is 30 km long with an average slope gradient from 1/8000 to 1/120000 (Zhu *et al*., 2009). The study area of this paper is located in the middle of the flood plain on the eastern bank of the Nongjiang River (Fig. 1). It covers about 78 m^2 and has a flat topography. Two soil moisture recording instruments and one auto weather station were installed as three monitoring sites. Widespread inundation by floods can submerge parts of the lowland, which indicates that nearby areas are in a saturated or over-saturated state all year around. Therefore, the water level in this area is always influenced by the water level of the Nongjiang River.

The plant in the study area and its fluctuating water level range (according to the mean annual water level of the Nongjiang River) are shown in Fig. 2. Albic and meadow marsh soils are present in the study area. The

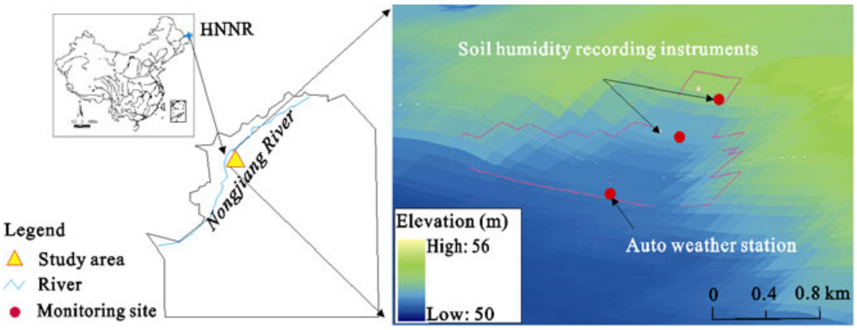


Fig. 1 Location of study area and monitoring sites

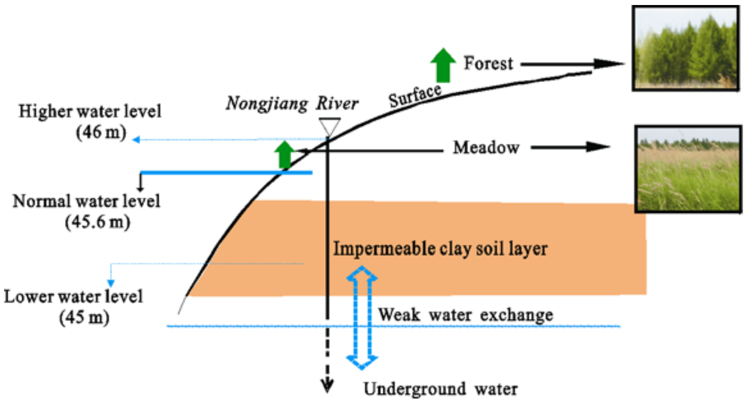


Fig. 2 Hydrological and plant gradients and their distribution in relation to hydro-geomorphic conditions

groundwater is 5–8 m below the surface in this area, and the presence of a thick clay layer hampers water exchange from the surface to groundwater, resulting in a strong connection between surface hydrological processes and soil moisture.

The vegetation communities investigated in this study are non-wetland plant forest and wetland plant meadow. The main species in the forest are *Populus davidiana*, *Betula platyphylla* and *Quercus mongolica*, and they occupy the higher discontinuous 'island' zone, which has unsaturated soil water conditions. Meadow is a widespread wetland plant in the Sanjiang Plain, and belongs to the perennial herb of the family Poaceae. Its optimum living environment is saturated or over-saturated soil water environment. The forest and meadow are the most typical and representative plant communities in the Sanjiang Plain.

2.2 Methods

In order to quantitatively analyze the dynamic patterns of soil moisture under forest and meadow plant communities, we integrated laboratory experiment results with the field data to calibrate and validate the modeling results. The flowchart of this study is shown in Fig. 3.

2.2.1 *Laboratory experiment*

Laboratory experiments were carried out in the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. The hydrometer method was used to measure particle-size distribution of the undisturbed soils sampled in the field (Lu, 1999). Two soil humidity recording instruments were installed at the forest and meadow vegetation sites (Fig. 1). The instrument measures humidity from 0 to 100% and the accuracy is ±3%, and the working temperature range is from –20℃ to 60℃. The instrument has six probes, and it can record the volumetric soil water content at six different depths.

2.2.2 *Numerical modeling*

The Richards equation governs water flow in the HYDRUS-3D model (Šimůnek *et al.*, 2006), which incorporates a sink term to account for water uptake by plant roots. The Richards equation can be expressed as:

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

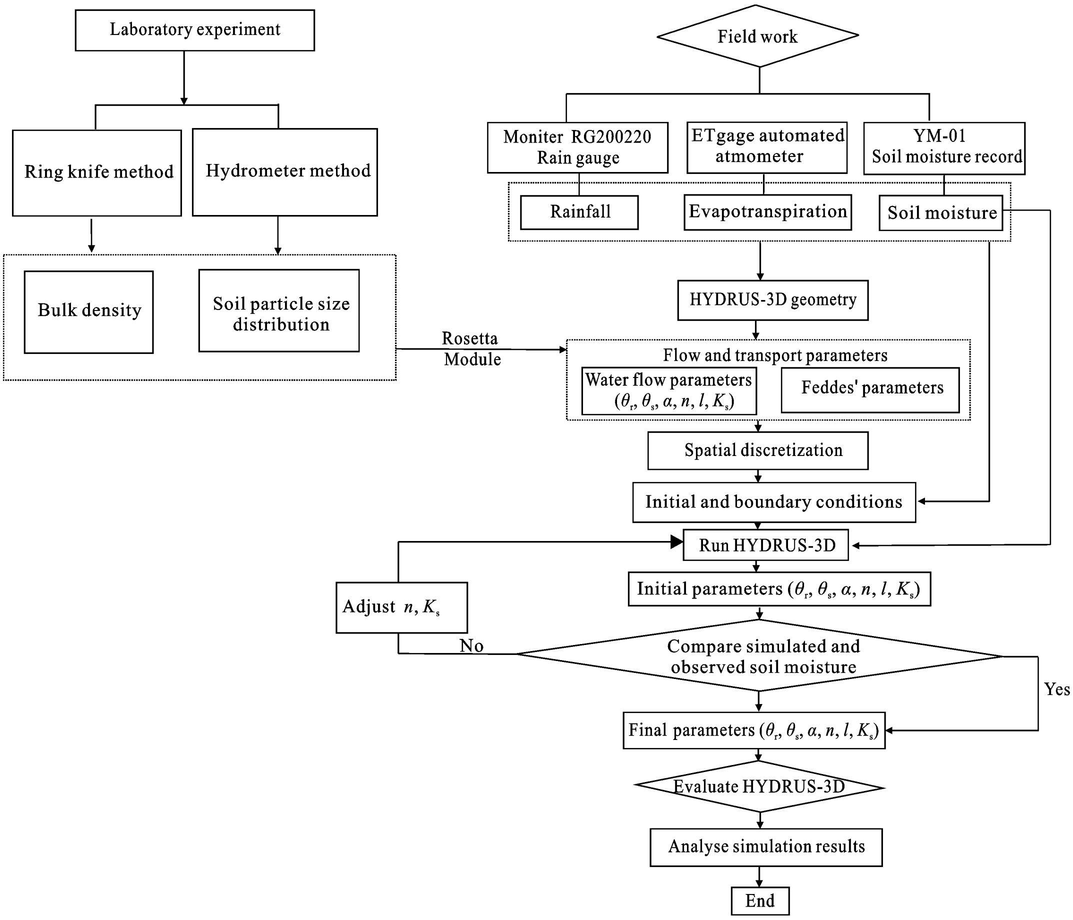


Fig. 3 Flow chart for analyzing dynamic patterns of soil moisture in this study

where θ is the volumetric water content (L^3/L^3), t is the time (T), h is the pressure head (L), S is a sink term (1/T), z is the vertical coordinate (L), x and y are the horizontal coordinates (L), and K is the unsaturated hydraulic conductivity function (L/T).

Two three-dimensional (100 cm × 100 cm × 100 cm) radial symmetrical regions were established and separated into six layers according to the location of the installed probes (10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 85 cm). The simulation time was the typical plant growing season (from 25 June to 19 August in 2005). The initial time step was 0.1 day (d), the minimal time step was 0.01 d, and the maximal time step was 5 d. A time-dependent boundary condition, which takes into account rainfall and evapotranspiration, was imposed on the soil surface as the atmosphere boundary, and a free drainage boundary was set as the bottom boundary. A zero flux boundary condition was imposed on the left and right vertical soil surfaces. The Feddes model (Feddes *et al.*, 1978) was used to calculate root water uptake. It is assumed that root water uptake is equal to plant transpiration, and thus evaporation can be ignored (at this wetland vegetation development stage).

The simulated soil water content and the observed soil water content were compared to rectify soil hydraulic parameters, and it was found that the saturated hydraulic conductivity (K_S) and an empirical parameter (n) were two important calibration parameters. Adjusted parameters are shown in Table 1.

It should be noted that this area has seasonally frozen soil, and most of them are not completely melted until August, usually the depth of frozen soil is less than 40 cm between June and August. Thus, there is some deviation between the measured and simulated soil moisture data. In addition, due to the low water permeability of the clay soils, water exchange from the surface to 40 cm underground was extremely low. Abnormally low soil moisture data are typically obtained near the soil surface because of the loss of electrons from the probe. Therefore, only the soil moisture data at the depths of 20 cm, 30 cm and 40 cm were used.

3 Results and Analyses

3.1 Simulation results

3.1.1 Differences in soil moisture between different vegetation communities

Soil moisture contents increase with the depth in the forest and meadow plant communities, however, the increase pattern are different (Fig. 4 and Fig. 5). As can be seen from Fig. 4, the soil moisture contents of the forest at 20 cm vary from 0.10 cm^3/cm^3 to 0.30 cm^3/cm^3 during the monitoring period . Soil moisture increased at 30 cm, and then decreased at 40 cm (0.07 cm^3/cm^3–0.20 cm^3/cm^3). However, the soil moisture contents under the meadow increased steadily with the increasing depth, varying from 0.12 cm^3/cm^3 to 0.35 cm^3/cm^3 at 30 cm and higher than 0.3 cm^3/cm^3 at 40 cm.

There was no significant difference in soil moisture contents between the forest and meadow at 20 cm (Fig. 5). Soil moisture contents were low before mid-July but increased dramatically after intense rainfall in mid-July. Soil moisture content of the forest was higher than that of the meadow at 30 cm, and this difference became

Table 1 Soil hydraulic parameters of forest and meadow after adjustment

Vegetation	Depth (cm)	Bulk density (g/cm^3)	θ_r	θ_s	α	n	l	K_s
Forest	10–20	0.73	0.1170	0.6940	0.0244	1.8960	0.5000	230.00
	20–30	1.04	0.1061	0.5800	0.0179	1.2000	0.5000	70.39
	30–50	1.41	0.0640	0.4629	0.0132	1.9990	0.5000	8.96
Meadow	10–20	1.20	0.1303	0.5036	0.0356	2.0030	0.5000	23.56
	20–30	1.37	0.1002	0.4885	0.0164	1.8900	0.5000	13.65
	30–50	1.46	0.0977	0.4638	0.0160	1.2212	0.5000	8.97

Notes: θ_r and θ_s are the residual and saturated water contents; k_s is the saturated hydraulic conductivity; α is an empirical constant that is related to the air-entry pressure value; n is a unitless empirical parameter related to the pore-size distribution; l is a unitless empirical shape parameter

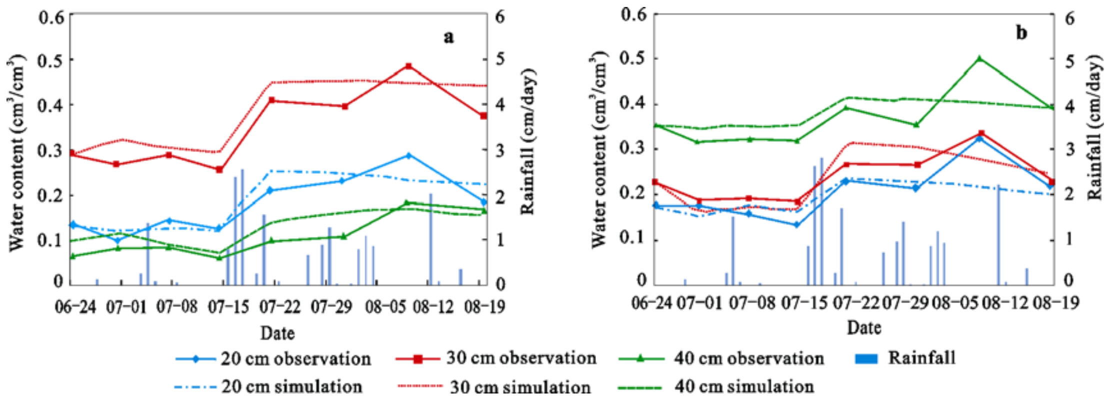


Fig. 4 Comparison of soil water contents between forest (a) and meadow (b)

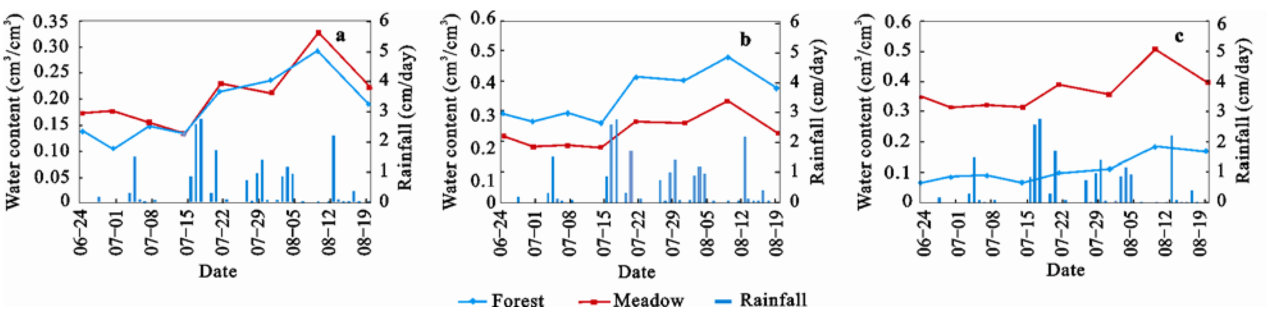


Fig. 5 Characteristic of soil moisture dynamics at depths of 20 cm (a), 30 cm (b) and 40 cm (c)

more significant after the mid-July rainfall. At the soil depth of 40 cm, the soil moisture content of meadow was almost three times that of the forest.

3.1.2 Variation in water budget of forest and meadow

The wetland water balance constitutes a set of hydrological processes under various conditions, and also has a great impact on the hydrological and ecological input and output processes in the wetland. For a typical wetland ecosystem, the wetland water balance equation can be expressed as follow equation：

$$P + G_{\mathrm{in}} + S_{\mathrm{in}} = ET + S_{\mathrm{out}} + G_{\mathrm{out}} + \Delta V \quad (2)$$

where P is the precipitation, G_{in} is the exchange from underground, S_{in} is precipitation-generated runoff from surrounding lands, ET is evapotranspiration, S_{out} is the runoff, G_{out} is discharge to groundwater, and ΔV is the wetland water variation.

Equation (2) is suitable for various kinds of wetland. In this study, Equation (2) can be reduced to Equation (3):

$$P = ET + D_{\mathrm{r}} + \Delta V \quad (3)$$

where D_{r} is deep drainage flux, and ΔV is the volume of wetland water variation. The calculated wetland water balance elements are presented in Table 2.

Because of the uneven distribution of rainfall, the water budget of the forest and meadow was in deficit most of the time, which resulted in continuous water consumption from the beginning of the simulation time (Table 2). The water variation was negative from late June to mid-July for both plant communities and positive from 15 July to 21 July except 1–7 July for forest, but then became negative again in late July and August. The total water output from meadow (–3.69 cm) was higher than that from the forest (–0.05 cm).

3.2 Evaluation of simulation results

The simulated and observed volumetric soil moisture contents of the forest and meadow are shown in Fig. 6. The simulation results of soil moisture for the forest and meadow plant are in good agreement with the observed data, and better results occurred in the forest.

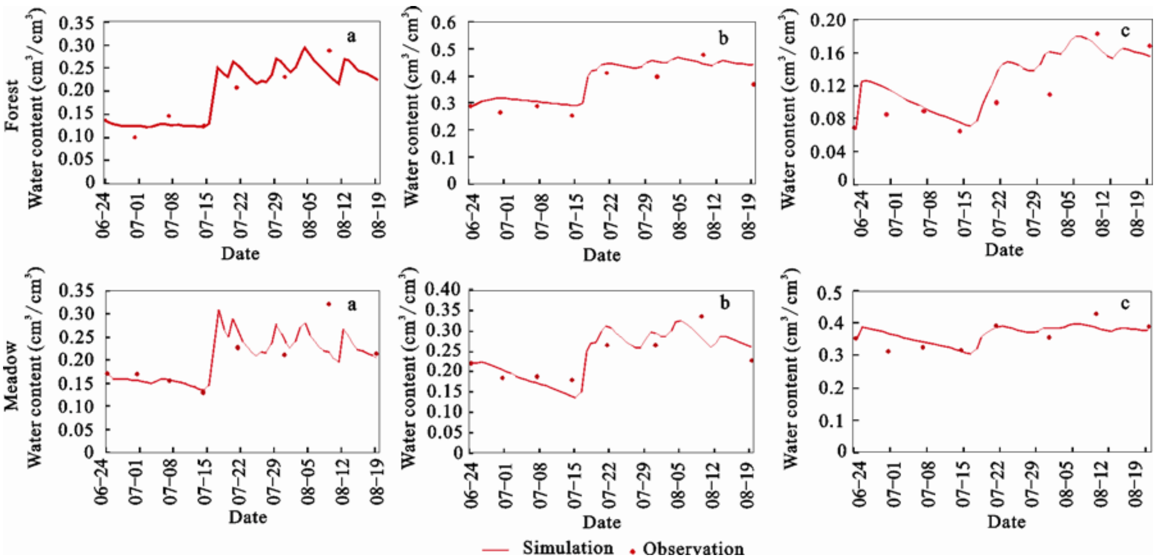
The agreement of HYDRUS-3D simulations with the measured data was quantified with the root mean square error (RMSE), the coefficient of determination (R^2) and index of agreement (d). RMSE has been used to compare predicted and measured parameters in previous researches (Skaggs *et al*., 2004; Arbat *et al*., 2008), and it expresses the error in the same units as a variable, thereby providing more information about the efficiency of the model (Legates and McCabe Jr, 1999). The lower the RMSE, the more accurate the simulation results are. The R^2 indicates the degree of linear correlation between the predicted and fitted values, with values from 0 to 1 and higher values indicating better agreement (Mubarak *et al*., 2009). The index of agreement d, accessing the simulation results, ranges between 0 and 1, and a value closer to 1 means a better simulation quality (Willmott, 1982). These statistical parameters are shown in Table 3.

The statistical values (RMSE, R^2 and d) of the forest and meadow vary with the soil depth (Table 3). The RMSE of the forest and meadow vary from 0.0291 to 0.0453 cm^3/cm^3, 0.0316 to 0.0457 cm^3/cm^3, respectively, with R^2 values ranging from 0.52 to 0.69, and 0.44 to 0.53, respectively, and the values of d are between 0.694 and 0.718, 0.612 and 0.968, respectively.

Table 2 Water balance elements of forest and meadow

Date	Cumulative rainfall (cm)	Cumulative transpiration (cm)		Cumulative deep drainage (cm)		Water variation (cm)	
		Forest	Meadow	Forest	Meadow	Forest	Meadow
06-25–06-30	0.14	1.45	1.99	0.44	1.35	–1.75	–3.20
07-01–07-07	1.86	1.98	2.69	0.13	0.21	0.25	–1.04
07-07–07-14	0.06	1.93	2.73	0.05	0.07	–1.92	–2.74
07-15–07-21	8.14	2.39	2.69	0.02	0.03	5.73	5.42
07-22–07-31	3.20	3.75	3.90	0.01	0.02	–0.56	–0.72
Total in July	13.26	10.05	12.01	0.20	0.33	3.01	0.92
08-01–08-09	3.00	3.30	3.40	0	0.01	–0.30	–0.41
08-09–08-19	2.70	3.70	3.70	0	0	–1.00	–1.00
Total	19.10	18.50	21.10	0.65	1.69	–0.05	–3.69

Note: '–' means water expense



a, b and c refer the soil depths of 20 cm, 30 cm and 40 cm, respectively

Fig. 6 Simulated and observed soil water contents in forest and meadow

Table 3 Statistical comparison of observed and simulated soil water content for forest and meadow

Forest	RMSE (cm³/cm³)	R^2	*d*	Meadow	RMSE (cm³/cm³)	R^2	*d*
20 cm	0.0330	0.6900	0.6943	20 cm	0.0457	0.4600	0.9680
30 cm	0.0453	0.6700	0.7059	30 cm	0.0354	0.5300	0.7600
40 cm	0.0291	0.5200	0.7180	40 cm	0.0316	0.4400	0.6126

The simulation results of soil water content of the forest is better than that of the meadow. It might be the reason that any overflow process was not considered for the simulation process in HYDRUS-3D. It assumes that rainfall infiltrates into the soil profile as soon as it reaches the soil surface, ignoring any surface runoff processes that might occur. Because interception of rainfall by the forest will be greater than that by the meadow, the runoff in the forest system will be lower than that in the meadow, therefore having less influence on simulation results of the forest.

3.3 Differences in soil moisture dynamics

Volumetric soil moisture contents in the forest and meadow increased between late-June and late-July (Fig. 4) because a large amount of rainfall fell during this period. Therefore, the water budget was positive and some soil water accumulated, moving to deeper soil depths by both gravity potential and matrix potential with some being stored at the depth. During early and mid- August, soil moisture contents under forest and meadow both decreased because, in spite of continual rainfall happening, the temperature was still suitable for plant growth and the water stored in the soil was insufficient for plant growth and transpiration. As a result, soil moisture contents declined.

The simulation results of soil moisture for the forest varied from 10% to 30% at 20 cm and reached a maximum value in early-August. Yang *et al*. (2004) also found that volumetric soil water contents in the forest at the soil depth from 10 cm to 20 cm ranged between 15% and 30%, with maximum soil mositure in August.

In this study, several statistical indices, which can clearly describe the fluctuating patterns of soil water contents at different soil depths, were used to analyze the dynamic characteristics of soil water content in forest and meadow plant in the soil depths of 20–40 cm. The values of these indices are presented in Table 4.

The maximum coefficient of variation (CV) of forest and meadow was at 20 cm (Table 4), as also found by Li *et al*. (2004), Chai *et al*. (2008) and Liu *et al*. (2009). In terms of soil texture and soil structure, forest soils above 20 cm have the same soil texture and thus the soil moisture below 20 cm show a similar response to rainfall, while the texture of the meadow soils above 30 cm depth is relatively the same, so soil moisture at these

Table 4 Statistical characteristics of soil moisture contents in forest and meadow

Vegetation	Soil depth (cm)	Amplitude of variation (%)	Mean value (%)	Standard deviation (%)	Coefficient of variation (%)
Forest	20	17.02	19.85	5.98	0.30
	30	17.78	38.94	6.89	0.18
	40	10.88	13.06	3.29	0.25
Meadow	20	17.17	20.58	4.68	0.23
	30	18.87	24.18	5.56	0.23
	40	9.51	36.81	2.54	0.07

depths showed a similar response to rainfall. For both plant communities, the amplitude of variation of soil moisture contents at the depths of 20 cm and 30 cm was higher than that at 40 cm. It might be the reason that the soil porosity and water permeability in the topsoil layer (0–30 cm) were more obvious than that at 40 cm depth, thus the soil moisture in the topsoil layer response to rainfall more significantly.

3.4 Differences in water budget

3.4.1 Differences in transpiration

The results of some researches have shown that the evapotranspiration from forest does not have seasonal differences, and that the discrepancy between high and low monthly evapotranspiration is not significant (Yan *et al.*, 2001; Wang and Pei, 2002; Elmaayar and Chen, 2006; Kuchment and Demidow, 2006). However, in this study, transpiration of the forest in July and August was obviously higher than that in June (Table 2). The different results might be that canopy interception and canopy evapotranspiration processes involved in previous studies. In this study, the HYDRUS model assumes rainfall infiltrates into the soil when it falls on the soil surface and that no canopy interception and canopy evapotranspiration happen. Also, the maximum transpiration value of meadow happened between late July and mid August (Table 2). It has been found by Chai *et al.* (1998) in the research on the meadow tranpiration rate.

Guo and Mo (2007) studied the evapotranspiration of forests in tropical and temperate zones and grasses in arid areas of Inner Mongolia and found that evapotanspiration from forests is greater than that from grass. However, in this study, we reached a different result that the transpiration of meadow was higher than that of the forest. It is because the forest and grass environments studied by Guo and Mo (2007) are quite different from the wetland conditions in this study. Also, transpiration of meadow was higher than that of the forest because meadow occupies the seasonally flooded area and forest occupies the non-flooded area, so the environment occupied by meadow is likely to be more humid than that of the forest. Most of the meadow roots are distributed in the top 30 cm, therefore, its transpiration mainly utilizes water at shallow soil depths. In contrast, the roots of the forest are mainly distributed in the relatively wetter and deeper soil depths so as to avoid water competition. Therefore, water uptake by the meadow is likely to be much easier than that by the forest, and, as a result, transpiration of the meadow is higher than that of the forest.

3.4.2 Differences in deep drainage

Some simulation results of HYDRUS show that deep drainage is closely related to rainfall and irrigation. Greater deep drainage around the root area usually results from intense rainfall and irrigation (Ndiaye *et al.*, 2007; Hao *et al.*, 2008; Bah *et al.*, 2009; Zuo *et al.*, 2009). However, in this study, the deep drainage rate decreased as rainfall increased. This difference might be that the previous studies were mainly conducted in irrigated fields with fine soil textures and good water permeability, while in this study, the clay soil with low water permeability might have minimized infiltration. In addition, the water permeability of the meadow marsh soil (meadow) is relatively greater than that of the albic soils (forest), and the higher water content of the meadow soil at 40cm depth might lead to water diffusion. Therefore, deep drainage was greater in the meadow than that in the forest in this study.

4 Conclusions

In this study, the HYDRUS-3D model was employed to simulate the volumetric soil water content of a non-wetland plant forest and typical wetland plant meadow during the growing season in 2005 in the Sanjiang Plain, and the characteristic of soil moisture dynamics and water budgets of the two different natural vegetation communities were analyzed. The following conclusions were obtained:

(1) Soil moisture contents in the forest and meadow simulated by HYDRUS-3D model show good agreement with measured data, and the values of RMSE range between 0.0291 and 0.0457 cm^3/cm^3, R^2 varies from 0.44 to 0.69 and d is between 0.612 and 0.968.

(2) The volumetric soil moisture contents of meadow increase while coefficients of variation of soil moisture decrease from the upper to lower soil layers in the depths of 0–40 cm. By contrast, the volumetric soil water contents of forest increase between 20 cm and 30 cm but then decrease in the depth of 30–40 cm. Influenced by the soil texture, the soil moisture contents in the forest below 20 cm depth respond to rainfall similarly, while the soil moisture contents of meadow above 30 cm depth show a similar response.

(3) Meadow, the typical and important wetland plant type in the study area, has a greater water deficit than forest during the growing season, therefore is more likely to suffer from water shortage. The most significant water supply time for meadow is therefore between late July and early August. And this is very important for maintaining meadow habitant water requirements.

In this study, the HYDRUS-3D model was used to simulate the soil moisture contents of the forest and meadow plant communities, however, the surface runoff and plant growth processes was not considered. In the future, the root plant growth module and water uptake routines module as well as the surface runoff module will be needed to incorporate into HYDRUS-3D software for higher accuracy.

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