An integrated hydrological model based on improved Green-Ampt model and HYDRUS model for semi-humid and semi-arid plain areas

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Abstract: Hydrology models of humid areas have always been studied deeply with higher model accuracy, but relatively less so for semi-humid and semi-arid areas, especially in plain. Here an integrated hydrology model (GA-HYDRUS model) was developed based on improved Green-Ampt model and HYDRUS model using the dataset of 7 rainfall events in Tianjin, China. The SCE-UA optimization algorithm was applied based on the data of soil moisture content to calibrate GA-HYDRUS model. The calibration and verification results demonstrated that the NSE values of the average soil moisture content were above 0.7. Meanwhile, the NSE values of the soil moisture content at the depths of 10, 20, and 40 cm were generally high and the R^2 were all greater than 0.75. The average runoff coefficient of permeable surface was 0.54. Furthermore, the relationships between different hydrological fluxes (rainfall, surface runoff, soil infiltration and vertical groundwater recharge) calculated by GA-HYDRUS model were analyzed. The results showed that rainfall characteristics such as rainfall, rainfall intensity and duration greatly affected the runoff, indicating that high rainfall intensity and short rainfall duration would produce more surface runoff. On the contrary, bimodal rainfall with small rainfall intensity and long duration made the effect of vertical groundwater recharge to supplement groundwater more significant. Therefore, the GA-HYDRUS model is a highly effective approach to simulate the transformation processes between surface runoff, soil water and groundwater in semi-humid and semi-arid plains. This study may have important applications in aiding water resources management.

Keywords: Green-Ampt model, HYDRUS model, integrated hydrology model, rainfall characteristics, soil moisture, semi-humid and semi-arid plains

1. Introduction

Hydrology model is the inevitable product of people's research understanding of the laws of the water cycle, simulation of hydrological processes in nature can be carried out by a series of generalized methods. Hydrology models of humid areas have always been studied by people more deeply with higher model accuracy, but relatively less so for semi-humid and semi-arid areas (Sunwoo & Choi, 2017). In the recent years, with the usage of technology such as computer, remote sensing, geographic information and other technologies during the research of hydrology process, studies of hydrology model in semi-humid and semi-arid areas are further developed (W. Huo, Li, Zhang, Wang, & Yao, 2020; Miao, Yang, Yang, & Li, 2016; Perrin et al., 2012). For semi-arid regions, the dominant runoff generation mechanism is infiltration-excess process and the central part of the hydrological model is soil infiltration.

Soil infiltration is the component of hydrologic circulation that connects overland flow with underground water, and has been widely applied to irrigation system design, hydrological runoff estimation, and groundwater replenishment (Milla & Kish, 2006). Green-Ampt infiltration equation is one of the most widely used equations in hydrology and soil erosion models. At present, it has been included in WEEP (Flanagan, Ascough, Nearing, & Laflen, 2001), SWAT (Neitsch, Arnold, Kiniry, Williams, & King, 2002) and ANNSWERS (Cunge, 1998). The Green-Ampt model is a simplified representation of the infiltration process, which assumes that a sharp wetting front separates the soil profile into an upper saturated zone and a lower unsaturated zone (Green & Ampt, 1911). Russell G Mein and Larson (1973) modified the original model to simulate infiltration during a steady rainfall event. This form of the model is commonly called the Green-Ampt Mein–Larson (GAML) model. However, unsteady rainfall makes the infiltration process more complicated due to the recurrence of ponding and non-ponding conditions. Therefore, in most model implementations the GAML model as modified by Chu to account for temporally varying rainfall is used (S. T. Chu, 1978). So far, the traditional infiltration model has applied to soil infiltration simulation under various conditions, such as unsteady rainfall soil infiltration (X. F. Chu & Marino, 2005; Esteves, Faucher, Galle, & Vauclin, 2000), side slope stability analysis (Yao, Li, Zhan, & Zeng, 2019) and layered soils (Mao et al., 2016; Mohammadzadeh-Habili & Heidarpour, 2015). However, condition of underlying surface is relatively complicated in semi-humid and semi-arid areas. Infiltration ability of soil in different sites exists space differences. Thus, more complicated infiltration equation should be adopted for explaining space variability of hydrodynamic soil specialty, otherwise, predicated runoff may have huge differences from observed results (Cerdan, Le Bissonnais, Couturier, & Saby, 2002). Therefore, some scholars introduced an empirical infiltration distribution curve into the Green-Ampt rainfall-runoff model in order to deal with the heterogeneity of rainfall, topography and soil type.(Bao, 1993; W. Huo et al., 2020)。

The scarcity of data in semi-humid and semi-arid regions, especially in plain, has necessitated the use of combined the available measured data and integrated model that can effectively simulate groundwater hydrological processes to estimate hydrological elements (surface runoff, soil water content and vertical groundwater recharge). In semi-humid and semi-arid areas, data of soil moisture content is easy to be obtained. A variety of ways were used to measure soil water content (Brocca, Melone, & Moramarco, 2008; Z. Huo, Shao, & Horton, 2008; Sunwoo & Choi, 2017; Tramblay et al., 2010).

Soil moisture is the core of water balance in catchment scale, which affects process of evaporation, infiltration, runoff and groundwater recharge, and connects agriculture, hydrology and environment closely in the meanwhile. The Richards' equation was derived using the mass conservation law and Darcy's law to describe one-dimensional vertical flow motion in unsaturated soil. However, the Richards' equation is strongly non-linear. Consequently, numerical methods such as finite difference and finite element methods have been used to solve Richards' equation (Arampatzis, Tzimopoulos, Sakellariou-Makrantonaki, & Yannopoulos, 2001). Based on finite element method, the HYDRUS-1D code was developed to solve the Richards' equation and widely used to simulate one-dimensional water movement in variably saturated media (Šimunek, Th. van Genuchten, & Šejna, 2012). This model has served an important role in studies of the vadose zone and has been used in a variety of applications (Simunek & van Genuchten, 2008). M. Chen, Willgoose, and

Saco (2014) conducted a 3-year study of soil moisture dynamics in two watersheds in New South Wales, using continuous time and point-scale soil water content data to validate the applicability of the HYDRUS-1D model to simulate soil moisture dynamics. Yi and Fan (2016) used HYDRUS-1D to simulate continuous soil water content, which provided a predictive method to study the effects of soil water content on runoff and soil erosion in the Loess Plateau where only sand production data were available. The results have shown that the model is highly accurate and widely applicable in predicting soil moisture content. In the recent years, HYDRUS-1D has also been used for estimating vertical groundwater recharge. Tonkul et al. (2019) calibrated the HYDRUS-1D using measured water level data from 25 research wells at depths of 20-50 meters, calculating the supply that rainfall gave to the alluvial aquifer of Gediz basin. Based on inverse model, T. J. Wang et al. (2016) used data of soil water content at 34 sites of AWDN, to estimate groundwater recharge using the HYDRUS-1D model and compared it with recharge obtained by other techniques to further verify the feasibility of the model.

At present, Green-Ampt model and HYDRUS-1D model have already been compared in many studies (Ma, Feng, Su, Gao, & Huo, 2010; Zhang, Han, Dou, & Li, 2014), verified the feasibility and simulation precision of the models. The estimated soil infiltration capacity of two models could be made extremely close through parameter transform (L. Chen et al., 2015; Lv, Zhang, Xue, Huang, & Yu, 2015). Compared to Richards' equation, the Green-Ampt model is simpler and could be directly used to describe infiltration. Meanwhile, it would calculate precisely soil water infiltration content and surface runoff by combining with infiltration distribution curve. However, the simulation of soil moisture movement processes is relatively simpler. Traditional Green-Ampt model assumes that a sharp wetting front exists if continuous ponding is maintained at the surface, dividing the upper saturated zone and the lower unsaturated zone as infiltrated water moves down into the lower zone with uniform antecedent moisture content (Green & Ampt, 1911). In fact, the distribution of soil water content over time and soil depth is more complicated in the process of soil water movement. However, the HYDRUS-1D model based on Richards' equation could accurately simulate the redistribution process of soil water infiltration and calculate the vertical groundwater recharge. In summary, the Green-Ampt model is complementary to the HYDRUS-1D model and their coupling is feasible.

The objectives of this study were to: (1) develop an integrated hydrology model (GA-HYDRUS model) based on improved Green-Ampt model and HYDRUS model to simulate comprehensive hydrology processes of earth surface and underground in semi-humid and semi-arid plain areas, so as to calibrate the model based on measured soil moisture content data; and (2) compare the relationships between different hydrological fluxes (precipitation, surface runoff, soil infiltration and vertical groundwater recharge) calculated and analyzed by the GA-HYDRUS model in the study area, which provided a theoretical basis for an in-depth understanding of the hydrological processes in the semi-humid and semi-arid plains.

2. Material and methodology

2.1. Study area and data

The study area is a closed facility agricultural community (Fig. 1) which is located in a semi-humid and semi-arid area of Tianjin, China (39°02′32″~39°02′38″N, 117°00′16″~117°01′17″E) with an area of about 0.507km^2. The region is classified as a typical monsoon-influenced semi-humid continental climate with obvious dry and wet seasons. The annual average temperature is 11.6°C and the multi-annual average rainfall is about 586.1mm, of which 443.2 mm in summer. The dominant wind direction throughout the year is southwest wind, with an average annual wind speed of 3.1m/s.

[Please insert Figure 1 here]

The soil type in the study area is mainly loam. The thickness of the soil layer monitored by the soil moisture meter is 40cm, and the groundwater depth is relatively shallow about 1.2m. According to the Harmonized World Soil Database version 1.1 (HWSD) constructed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA), the soil properties of the study area are determined. Soil physical properties were given in Table 1.

[Please insert Table 1 here]

The data required to establish the GA-HYDRUS coupling model are all field test data. Observation equipment such as rain gauge, soil moisture measuring instrument and groundwater level observation instruments, which provided a reliable data source for model, were installed to obtain the data of rainfall, soil moisture content and groundwater level. The specific models of the equipment were: automatic rain gauge (LC-YL1), soil moisture sensor (FDS120), piezoresistive water level gauge (Unisens-WL20). From 2016 to 2017, 7 rainfall events' data were collected. The impermeable area percentage of the study area accounts for 41%.

2.2. Model coupling

GA-HYDRUS coupling model includes three modules: surface runoff, soil water movement and vertical groundwater recharge. The relationship between the various modules and the input and output items were shown in Fig. 2. For the permeable surfaces, the runoff generation mechanism is infiltration-excess process coupled with the infiltration distribution curve. When the net rainfall (the value of evaporation during rainfall is small and negligible) reached the ground, the infiltration and surface runoff was calculated by the improved Green-Ampt rainfall-runoff model with an infiltration distribution curve. The infiltration calculated by the improved Green-Ampt model was used as the input of the groundwater model. This paper used the HYDRUS-1D model based on the Richards' equation to simulate the process of soil water movement and calculate the vertical groundwater recharge (VGR). And the soil moisture content was used to drive the operation of the improved Green-Ampt rainfall-runoff model at the next time.

[Please insert Figure 2 here]

2.3. Surface runoff model

2.3.1. Improved Green-Ampt model for computing infiltration under unsteady Rain

The Green-Ampt infiltration model describes the infiltration that the soil profile and initial soil water content are homogeneous. The Green-Ampt infiltration equation is written as:

$$f = \frac{dF}{dt} = K_c\left(1 + \frac{S_f M}{F}\right), \qquad 11\backslash{*}\ \text{MERGEFORMAT ()}$$

where f is the infiltration capacity (mm/h), F is the cumulative infiltration (mm), K_c is the saturated soil hydraulic conductivity (mm/s), S_f is the wetting front suction head (mm), M is the change of soil water content across the wetting front.

The precondition of the traditional Green-Ampt model is that there is water on the soil surface at the beginning of the infiltration which does not change with time. Russell G Mein and Larson (1973) modified the original model to simulate infiltration during a steady rainfall event. The rainfall infiltration process was divided into two stages: water supply control and infiltration capacity control, which obviously did not match the actual rainfall situation. Therefore, S. T. Chu (1978) analyzed the infiltration process during an unsteady rain on this basis and divided the surface water state into four conditions.

The main distribution processes of rainfall involve filling depressions, evaporation, infiltration, and runoff. During this period the effect of evaporation would be considered as not significant. The water budget equation which describes the balance of water quantity for the variables involved in an infiltration process is:

$$P = P(t) = F(t) + G(t) + R(t) = F + G + R,$$ 22* MERGEFORMAT ()

where P is the cumulative rainfall (mm), t is the time (h) , F is the cumulative infiltration (mm), G is the amount of surface ponding (mm) , R is the cumulative surface runoff (mm).

To solve the integrated form of Eq. 1, the limit condition of integration should be determined. The time when the surface reaches the critical state of surface ponding is set as t_p , and there is no surface ponding before this time point that is, G = 0. Thus, the cumulative infiltration at the ponding time is:

$$F(t_p) = P(t_p) - R(t_p) = F_0,$$ 33* MERGEFORMAT ()

where F_0 is the cumulative infiltration at the ponding time t_p (mm).

Regarding the ponding time t_p as the time node, the infiltration process can be divided into two stages:

$$f = \begin{cases} i & t \le t_p \\ K_c\left(1 + \dfrac{S_f M}{F}\right) & t > t_p \end{cases}$$. 44* MERGEFORMAT ()

At the ponding time the rainfall intensity i equals the infiltration capacity, so that

$$i = K_c\left(1 + \frac{S_f M}{F_P}\right) \qquad t = t_p$$. 55* MERGEFORMAT ()

When t is $t_p \sim t$ and F is $F_0 \sim F_P$, the integral formula of Eq. 1 is:

$$\frac{K_c\left(t - t_p\right)}{S_f M} = \frac{F_P}{S_f M} - \ln\left(1 + \frac{F_P}{S_f M}\right) - \frac{F_0}{S_f M} + \ln\left(1 + \frac{F_0}{S_f M}\right)$$. 66* MERGEFORMAT ()

Let the limit constant $\dfrac{F_0}{S_f M} - \ln\left(1 + \dfrac{F_0}{S_f M}\right)$ be represented by a symbol t_s such that

$$\frac{F_0}{S_f M} - \ln\left(1 + \frac{F_0}{S_f M}\right) = \frac{K_c t_s}{S_f M}$$. 77* MERGEFORMAT ()

Here t_s can be interpreted as a shift of time scale due to the effect of cumulative infiltration at the ponding time. Substitute Eq. 7 into Eq. 6 to obtain

$$\frac{K_c\left(t-t_p+t_s\right)}{S_f M}=\frac{F_P}{S_f M}-\ln\left(1+\frac{F_P}{S_f M}\right)$$. 88* MERGEFORMAT ()

Generally, the continuous rainfall events are divided into multi-period short-term rainfall events in the study, and the rainfall intensity in each period is continuous. For such a case:

$$i\left(t\right)=\frac{P\left(t_n\right)-P\left(t_{n-1}\right)}{t_n-t_{n-1}}=I$$, 99* MERGEFORMAT ()

where n is the an index to identify a short period, t_{n-1} and t_n are the initial and terminal time of a short period (h) respectively, I is the constant rainfall intensity within a short period (mm/h).

Thus, the variation of the cumulative rainfall within a short period is:

$$P\left(t\right)=\int_{t_{n-1}}^{t_n} i\left(t\right)dt=P\left(t_{n-1}\right)+\left(t_n-t_{n-1}\right)I$$. 1010* MERGEFORMAT ()

Combined Eq. 3, 5, 9 and 10, the ponding time can be obtained:

$$t_p=\frac{K_c S_f M/\left(I-K_c\right)-P\left(t_{n-1}\right)+R\left(t_{n-1}\right)}{I}+t_{n-1} \qquad I>K_c$$. 1111* MERGEFORMAT ()

In summary, when there is no surface ponding from t_{n-1} to t_n:

$$\begin{aligned} G(t_n) &= G(t_{n-1}) = 0 \\ R(t_n) &= R(t_{n-1}) \end{aligned}$$ 1212* MERGEFORMAT ()

and

$$I < f_p = K_c\left[1 + \frac{S_f M}{F(t_n)}\right]$$ 1313* MERGEFORMAT ()

or

$$F(t_n) < K_c S_f M / (I - K_c) \quad I > K_c.$$ 1414*

MERGEFORMAT ()

When there is surface ponding from t_{n-1} to t_n:

$$\begin{aligned} G(t_n) &> 0 \\ R(t_n) &\quad R(t_{n-1}) \\ F(t_n) &= F_p \end{aligned}$$ 1515* MERGEFORMAT ()

and

$$I > f_p = K_c\left[1 + \frac{S_f M}{F_p}\right]$$ 1616* MERGEFORMAT ()

or

$$F(t_n) > K_c S_f M / (I - K_c).$$ 1717* MERGEFORMAT ()

According to the above classification of the surface ponding status, the infiltration rate during the rainfall can be summarized into 4 situations:

1. Without surface ponding at the initial time t_{n-1} and terminal time t_n:

$$P(t_n) - R(t_{n-1}) - \frac{K_c S_f M}{I-K} < 0 \qquad I > K_c$$, 1818* MERGEFORMAT ()

$$F(t_n) = P(t_n)$$. 1919* MERGEFORMAT ()

2. Without surface ponding at the initial time t_{n-1} and with surface ponding at the terminal time t_n:

$$P(t_n) - R(t_{n-1}) - \frac{K_c S_f M}{I-K} > 0 \qquad I > K_c$$. 2020* MERGEFORMAT ()

Calculate t_p, t_s then substitute them into Eq. 8 to get the cumulative infiltration.

3. With surface ponding at the initial time t_{n-1} and terminal time t_n:

$$P(t_n) - F_p(t_n) - R(t_{n-1}) < 0$$. 2121* MERGEFORMAT ()

Surface ponding always occurs at this situation. Substitute t_p, t_s of the previous stage into Eq. 8 to get the cumulative infiltration.

4. With surface ponding at the initial time t_{n-1} and without surface ponding at the

terminal time t_n :

$$P(t_n) - F_P(t_n) - R(t_{n-1}) > 0$$, 2222* MERGEFORMAT ()

$$F(t_n) = P(t_n) - R(t_{n-1})$$. 2323* MERGEFORMAT ()

After determining the cumulative infiltration at each stage, substitute it into Eq. 1 to obtain the soil infiltration rate at the corresponding time.

In semi-humid and semi-arid area, rainfall and underlying surface characteristics are highly heterogeneous. To represent the effect of spatial heterogeneity on runoff process, Bao (1993) introduced an infiltration distribution curve (Fig. 3) into the Green-Ampt rainfall-runoff model. Therefore, this paper introduced the parameter B to indicate uneven distribution of infiltration capacity in the improved Green-Ampt model described above, and the actual infiltration situation is:

$$FMM = f(1 + B)$$, 2424* MERGEFORMAT ()

$$FA = \begin{cases} f & i \quad FMM \\ f - f\left(1 - \dfrac{i}{FMM}\right)^{1+B} & i \le FMM \end{cases}$$, 2525* MERGEFORMAT ()

$$R_1 = P - FA(t_n - t_{n-1})$$, 2626* MERGEFORMAT ()

where FMM is the maximum infiltration capacity (mm/h) in the study area, B is the exponent of the infiltration distribution curve, FA is the actual infiltration capacity (mm/h), R_1 is the surface runoff on the permeable surface (mm).

[Please insert Figure 3 here]

2.3.2. Runoff on impervious surface

The surface runoff on the impermeable surface is direct runoff:

$$R_2 = P \times \beta ,$$ 2727* MERGEFORMAT ()

where R_2 is the surface runoff on the impermeable surface (mm), β is the runoff coefficient of impermeable surface.

2.3.3. Total surface runoff

The total surface runoff in the study area merged into the nearby river and discharged through the pumping station:

$$R_z = R_1 \times (1 - IMP) + R_2 \times IMP ,$$ 2828* MERGEFORMAT ()

where R_z is the total surface runoff in the study area(mm), R_1 is the surface runoff on the permeable surface (mm), R_2 is the surface runoff on the impermeable surface (mm), IMP is the proportion of impermeable surface to study area.

2.4. HYDRUS-1D model

HYDRUS-1D model is developed based on the Richards' equation for simulating the water movement, solution and heat transport in a one-dimensional variable saturation medium. This model assumed that the water movement in the soil profile was vertical.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K\frac{\partial h}{\partial z}\right]-\frac{\partial K}{\partial z}-S$$

, 2929* MERGEFORMAT ()

where θ is the volumetric moisture content, h is the water pressure head (mm), t is the time (h), K is the unsaturated hydraulic conductivity (mm/h), z is the spatial coordinate, positive upward (mm), S is the sink term (1/h).

HYDRUS 1D allows the use of 5 different analytical models for hydraulic features. One of the most widely used water retention function was developed by van Genuchten (1980) who used the statistical pore-size distribution model of Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The expressions of van Genuchten (1980) are given by:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h > 0 \end{cases},$$ 3030* MERGEFORMAT ()

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2,$$ 3131* MERGEFORMAT ()

where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r},$$ 3232* MERGEFORMAT ()

$$m = 1 - \frac{1}{n} \quad n > 1,$$ 3333* MERGEFORMAT ()

where θ is the volumetric moisture content, θ_r is the residual moisture contents, θ_s is the saturated moisture contents, α, n, m are the empirical coefficients affecting the shape of the hydraulic functions, α is the inverse of the air-entry value, n is a pore-size distribution index, h is the water pressure head (mm), K_s is the saturated hydraulic conductivity (mm/h), S_e is the saturation degree, l is a pore-connectivity parameter, assumed to be about 0.5 as an average for many soils.

For the HYDRUS-1D model, the soil surface boundary condition was the flux boundary condition. A free drainage condition was set at the lower boundary. In this study, the vertical groundwater recharge was defined as the amount of water that passed the lower boundary. While determining the upper and lower boundaries, it was assumed that infiltration took place only in the vertical direction for vadose zone and no flux occurred from lateral boundary.

2.5. Parameters determination

The key to coupling the improved Green-Ampt model and HYDRUS model is the consistency of the parameters. In order to make the infiltration calculated by the Green-Ampt model fit the Richards' equation as much as possible, it is necessary to unify the parameters in the improved Green-Ampt model and the HYDRUS-1D model. Therefore, the equivalent conversion between different parameters of the two models is needed to ensure that the calculation error is independent of the difference of input parameters.

2.5.1. Green-Ampt model and Hydrus-1D model parameters conversion

There are two key parameters in GA-HYDRUS model. One is the suction head at the wetting front which reflects the infiltration characteristics of unsaturated soil. van Genuchten (1980) used the following equation to establish the relationship between the suction head and soil moisture content:

$$S_f\left(S_e\right) = \frac{1}{\alpha}\left(\frac{1-S_e^{1/m}}{S_e^{1/m}}\right)^{1/m}$$

. 3434* MERGEFORMAT ()

It can be seen that Eq. 31 and 34 have the same variable S_c , so the suction head at the wetting front in the Green-Ampt model could be related to the hydraulic conductivity in the HYDRUS-1D model. This paper used the method proposed by R. G. Mein and Farrell (1974) to calculate S_f :

$$S_f = \frac{1}{K_s}\int_{S_i}^{0} K(S)\,dS$$, 3535* MERGEFORMAT ()

where S_i is the initial suction in the soil.

According to the traditional Green-Ampt model, the hydraulic conductivity for wetted zone above the wetting front is considered as the saturated hydraulic conductivity. However, Bouwer (1969) pointed out that because of entrapped air, the soil pores in saturated zone cannot be fully filled with water. K_c should be somewhat less than K_s. Bouwer’s suggestion was that $K_c = 0.5K_s$. Therefore, we added a correction coefficient a to the hydraulic conductivity in the improved Green-Ampt model:

$$a = \frac{K_c}{K_s}$$. 3636* MERGEFORMAT ()

2.5.2. Model calibration and validation

There are 10 parameters of the GA-HYDRUS coupling model. Among them, the 6 parameters of van Genuchten were calculated using the soil transfer function in the HYDRUS-1D software. According to the HWSD constructed by the FAO and the IIASA, the soil properties of the study area were determined, and the results of the soil transfer function calculation were referred to as the initial values of GA-HYDRUS model parameters for calibration. The parameters' meaning and range were listed in Table 2.

[Please insert Table 2 here]

The SCE-UA algorithm were used to optimize the parameters listed in Table 2. The calibration and validation rainfall events were 160720, 160724, 160801, 160807 and 160818, 170706, 170709, respectively. For comparing the measured soil moisture content at soil depths of 10, 20, 40mm and average soil moisture content with the simulated soil moisture content, the sum of the Mean Relative Error (MRE), Maximum Relative Error (MMRE) and Mean Relative Logarithm Error (MRLE) were used as the objective function to find the best parameters. The model performance was evaluated by the Average Error (AE) and Nash–Sutcliffe Efficiency (NSE).

(1) Objective function：

Evaluation objective	Objective function
Mean Relative Error	$MRE = \frac{1}{N}\sum_{i=1}^{N}\frac{\left\|\theta_{i,obs} - \theta_{i,sim}\right\|}{\theta_{i,obs}}$

Maximum Relative Error	$MMRE = \max\left(\frac{\lvert\theta_{t,obs} - \theta_{t,sim}\rvert}{\theta_{t,obs}}\right)$
Mean Relative Logarithm Error	$MRLE = \frac{1}{N}\sum_{t=1}^{N}\log\left(\frac{\lvert\theta_{t,obs} - \theta_{t,sim}\rvert}{\theta_{t,obs}} + 1\right)$
Total objective function	$Y = \min\sum\left(MRE + MMRE + MRLE\right)$

where $\theta_{t,obs}$ is the actual soil moisture content, $\theta_{t,sim}$ is the simulated soil moisture content, t is the time (h), $t = 1, 2, \cdots, N$, N is the rainfall events series length.

(2) Evaluation index:

$$AE = \frac{1}{N}\sum_{t=1}^{N}\left|\theta_{t,obs} - \theta_{t,sim}\right|$$, 3737* MERGEFORMAT ()

$$NSE = 1 - \frac{\sum_{t=1}^{N}\left(\theta_{t,obs} - \theta_{t,sim}\right)^2}{\sum_{t=1}^{N}\left(\theta_{t,obs} - \overline{\theta_{t,obs}}\right)^2}$$, 3838* MERGEFORMAT ()

where $\overline{\theta_{t,obs}}$ is the measured average soil moisture content.

3. Results and discussion

3.1. Model parameters and simulation results

When ran the SCE-UA algorithm, the number of cycles was set to 500, 1000, 2000, until the number of calibration cycles reached 2000, the objective function result became stable. Since there were few measured rainfall events without the measured flow process, so in the process of calibration, the average error of soil moisture content was used as the evaluation index. Using automatic calibration combined with manual calibration method, the final parameters values were shown in Table 3.

[Please insert Table 3 here]

The results of each evaluation index in the calibration and validation periods were shown in Table 4.

[Please insert Table 4 here]

The NSE values of the average soil moisture during the calibration and validation periods were above 0.7, and the NSE values of the soil moisture content at the depths of 10, 20, and 40 cm were generally high. By comparison, it was found that the NSE values of soil moisture content at the depth of 20cm were fluctuated, and the simulation effect was unstable. On the contrary, for the soil moisture content at the depth of 40cm, the NSE values of each rainfall event were above 0.5. The values of

AE during the calibration and validation periods were very low (all below 5%), demonstrating the high accuracy of the GA-HYDRUS model. These results demonstrated the applicability of the procedure used for model parameterizations in the study area.

The runoff coefficient range of permeable surface was 0.33~0.77 with an average value of 0.54. Xiong and Guo (2004) investigated how the catchment runoff coefficient affects the performance of TOPMODEL in the semi-arid Yihe catchment. Their values of runoff coefficient were from 0.33 to 0.70 which were consistent with the range of our results. The soil surface had the high clay plus fine silt content (66%) and low bulk density (1.41 kg/dm^3) in the study area. Literature has shown that soil types with high clay and silt sediments produce high runoff and low infiltration (Mavimbela, Dlamini, & van Rensburg, 2019). Liu, Feng, Deo, Yao, and Wei (2020) estimated that the mean runoff coefficient of grassland surface under high intensity rainfalls was about 0.68, which was 1.3 times higher than that under low intensity rainfalls in Beijing. Therefore, the high values of runoff coefficient calculated by GA-HYDRUS model was due to the soil properties and high intensity rainfalls in the rainy season from June to July. Detailed analysis was carried out in section 3.2. In summary, the surface runoff simulation of this model conformed to the characteristics of the semi-humid and semi-arid area. The values of each evaluation index were within a reasonable range, indicating that the model parameters were reasonable and applicable to the study area.

3.2. Surface runoff simulation results

According to the amount of rainfall, the 7 rainfall events were classified for the convenience of subsequent analysis (Table 5). The rainfall events can be divided into three categories: very heavy rainstorm, hard rain and heavy rain (Table 6).

[Please insert Table 5 here]

[Please insert Table 6 here]

Generally, the relationship between rainfall and runoff is that the greater the rainfall, the more the surface runoff and the higher the runoff coefficient (Table 7). However, surface runoff and runoff coefficient are not only related to rainfall, but also significantly affected by rainfall intensity and duration. Although the rainfall in case 2 was only half of that in case 1, the permeable surface runoff coefficient of the latter was 0.09 higher than the former. Heavy rain of case 3~7 showed the same phenomenon. Case 7 had the least rainfall, but more surface runoff, and the runoff coefficient is higher than other rainfall events of the same rainfall grade. Fig. 4 showed the relationship between rainfall and surface runoff on permeable surface, impermeable surface and average surface runoff in the study area. The rainfall peak of case 2 was significantly higher than case 1, and the rainfall duration was shorter, which was more conducive to the generation of surface runoff. Case 7 and case 6 were the same. This phenomenon indicated that high rainfall intensity and short rainfall duration would produce more surface runoff.

[Please insert Table 7 here]

[Please insert Figure 4 here]

In addition, it can be seen from the runoff curve that the higher the rainfall intensity, the smaller the gap between R1, R2 and Rz, which was due to the rainfall intensity play an important role in the infiltration-excess process. From the increase ratio of the average runoff coefficient and the permeable surface runoff coefficient in the study area, it can be seen that the surface runoff increased with the construction of agricultural facilities increase. Especially during the rainfall event with less rainfall, the runoff coefficient increased significantly.

3.3. Soil water movement and groundwater recharge

The comparison of the measured and simulated values of soil moisture content at different depths of the soil were given in Fig. 5. The distribution of the measured values and the simulated values were relatively concentrated, and the R^2 at different soil depths were all greater than 0.75. The measured and simulated values at the depth of 10 cm were generally distributed on the left side of the 1:1 line, indicating that the soil moisture content in the upper layer of the soil was overall overestimated; the measured and simulated values of soil moisture in multiple rainfall fields at the depth of 20 cm were distributed on the lower side or both sides of the 1:1 line which indicates that the soil moisture content was generally underestimated; the soil moisture content and average moisture content at the depth of 40 cm were mostly distributed near the 1:1 line, showing that the model was effective in fitting deep soil moisture content and average moisture content. In general, the simulated and measured values had high fitting accuracy and strong correlation, which further proves the rationality of the model to simulate soil water movement process.

[Please insert Figure 5 here]

[Please insert Figure 6 here]

Fig. 6 showed the measured and simulated soil moisture content and average soil moisture content at the depths of 10, 20, and 40 cm of soil with the infiltration changes. When the infiltration started, shallow soil moisture content was preferentially replenished. Therefore, the general situation was that the soil moisture content increases sharply at a depth of 10 cm, then 20 cm, and finally infiltrated to 40 cm which was similar to the piston-type infiltration of the original Green-Ampt. Original Green-Ampt assumed that there were only saturated zone and un saturated zone in the soil. Nevertheless, there were transition zones in the soil water movement process simulated by HYDRUS-1D. This was caused by the decrease of capillary water due to the downward movement of the water potential gradient in the soil or the difference in soil pores, which also explained why the shallow soil moisture content tended to decrease in the later stage of infiltration.

Studying the relationship between precipitation characteristics and groundwater recharge (Jasechko & Taylor, 2015; Tashie, Mirus, & Pavelsky, 2016) is essential for the comprehensive understanding of the groundwater recharge process and groundwater restoration. In order to compare the groundwater level changes with the calculated VGR, it is necessary to convert the groundwater table into groundwater recharge amount (water depth). First, the amplitude of groundwater level is multiplied by soil aeration porosity, then according to the proportion of permeable area to the study area, the groundwater depth is averaged over the whole area.

Table 8 listed the initial and terminal measured groundwater level, groundwater depth changes and VGR simulated by the HYDRUS-1D. The ratio of the vertical groundwater recharge to the total actual groundwater recharge was given. Except for case 3 and case 6, the VGR accounted for a high proportion of the measured groundwater depth changes, with an average of about 78%, explaining that VGR was the main source of groundwater recharge in the study area. This was because the study area is located in the North China Plain with low terrain and small groundwater potential gradient.

H. Wang et al. (2015) assessed the impact of rainfall intensity on groundwater regime under the bare slope condition based on simulated rainfall experiments and MODFLOW. The recharge rate increased with rainfall intensity increased from 45mm/h to 75mm/h, whereas that decreased gradually with increasing rainfall intensity from 75 mm/h to 120 mm/h. Jan, Chen, and Lo (2007) revealed that a small rainfall intensity with a long duration can induce a greater groundwater level variation than a large rainfall intensity with a short duration. The results of this paper were consistent with previous studies. The VGR of case 4 and case 5 accounted for a relatively high percentage due to the two rainfall events had small rainfall intensity with a long duration (see Figs. 4 and 6). In addition, it was found that the two rainfall events patterns had double peaks. The results showed that bimodal rainfall with small rainfall intensity and long duration made the effect of VGR to supplement groundwater more significant. However, case 3 was also a bimodal rainfall, but VGR did not occur which indicating that soil moisture content also has an impact on VGR (Fig. 6). Low soil moisture content in the initial stage enhanced the water storage capacity of the aquifer instead of replenishing groundwater. The correlation of various hydrological elements was analyzed in detail in 3.4.

[Please insert Table 8 here]

3.4. Response relationship between precipitation, surface water, soil water and vertical groundwater recharge

Precipitation is the main source of surface runoff; soil water replenishment and groundwater recharge and various hydrological elements are closely related and affect each other. The percentage bar graph (Fig. 7) showed the percentage of each hydrological element in the seven rainfall events. The amount of rainfall, rainfall duration and rainfall intensity all have a significant impact on the generation of surface runoff. Generally, the surface runoff increases with the rainfall increase. When the rainfall intensity is high at a certain moment, it is conducive to the generation of surface runoff. Fig. 7 illustrated that a large rainfall intensity with a short duration and more rain can induce more surface runoff than a small rainfall intensity with a long duration and less rain.

In comparison, although soil water infiltration is also affected by rainfall intensity, when the rainfall intensity exceeds the saturated soil permeability, the soil infiltration rate tends to stabilize and decreases with the increase of soil water content. Dourte, Shukla, Singh, and Haman (2013) found that greater intensity storms might reduce groundwater recharge and increase runoff. Part of the soil infiltration is stored in the aquifer to replenish the soil moisture content, while the rest replenishes the groundwater through the lower boundary of the soil. Soil water infiltration is closely related to the soil texture and rainfall intensity. The soil texture in this study area is single which would not be discussed. It can be seen from Fig. 7 that the soil water infiltration increased with the rainfall intensity and duration increase. The ability of the soil to store water is related to the initial water content of the soil. The average soil moisture content curve in Fig. 7 showed that when the initial soil moisture content was low, the soil could store more water, but it would also reduce the VGR. VGR for different rainfall intensity indicated that a larger rainfall intensity with longer duration would be helpful to VGR generation. Moreover, it was found that the double-peak rain pattern was more conducive to the VGR to supplement groundwater. The influence of rain pattern on groundwater recharge deserves further study.

[Please insert Figure 7 here]

4. Conclusions

In this study, an integrated hydrological model based improved Green-Ampt model and HYDRUS model for Semi-humid and semi-arid plain was proposed. The seven measured rainfall events data from a closed community in Tianjin, China were used to calibrate and validate this model. With the help of the data in public domain and literature values for parameterization of the GA-HYDRUS model, surface runoff, soil water movement and vertical groundwater recharge were simulated. The major findings were as follows:

(1) The calibration and verification results demonstrated that the NSE values of the average soil moisture content in the calibration and validation periods were above 0.7, and the NSE values of the soil moisture content at the depths of 10, 20, and 40 cm were generally high. The distribution of the measured values and the simulated values were relatively concentrated, and the R^2 at different soil depths were all greater than 0.75. This proved that the soil moisture content simulated by GA-HYDRUS model were in good agreement with the observed data. Furthermore, the range of runoff coefficient on permeable surface was 0.33~0.77, which was consistent with the reference values of semi-humid and semi-arid areas. The values of each evaluation index were within a reasonable range, indicating that the model parameters were reasonable and applicable to the study area.

(2) The surface runoff results estimated by the model showed that there was a

positive correlation between surface runoff on the permeable surface and rainfall intensity and amount. In particular, rainfall intensity, which is one of the most important characteristics of rainfall, influences the surface runoff and recharge of both soil and ground water. The results indicated that high rainfall intensity and short rainfall duration would produce more surface runoff. Compared with the permeable surface, the runoff coefficient of the impermeable surface was higher, so the average runoff coefficient of the study area was raised. The higher the rainfall intensity, the smaller the gap between R1, R2 and Rz which was due to the rainfall intensity played an important role in the infiltration-excess process.

(3) The simulation results of soil moisture content indicated that the soil moisture content in the upper layer of the soil was overall overestimated and the middle soil moisture content was generally underestimated, but the model was effective in fitting deep soil moisture content and average moisture content. The curve of soil moisture content over time showed that the movement of soil moisture has hysteresis. Firstly, infiltration replenished the upper soil and slowly moves downward over time. Therefore, the shallow soil moisture content generally had a downward trend in the later period. Except for case 3 and case 6, the VGR accounted for a high proportion of the measured groundwater depth changes, with an average of 78%, explaining that VGR was the main source of groundwater recharge in the study area. In addition, the results showed that bimodal rainfall with small rainfall intensity and long duration made the effect of VGR to supplement groundwater more significant.

In short, the GA-HYDRUS model has a good simulation effect in the semi-humid and semi-arid plain. This method provides a new way to determine surface runoff, soil water infiltration, soil moisture storage, and groundwater vertical recharge, which will be useful in the fields of hydrology, soil erosion, and water resources.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Data Availability Statement

The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

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