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Integration application of finite difference flow modeling and SWAT model in the distribution and transformation of water resources in irrigation areas

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A B S T R A C T

The current strange way in irrigation areas has led to the problem of shallow groundwater overexploitation and continuous decline in groundwater level during the hydrological cycle. Therefore, a coupling model is constructed by integrating the modular three-dimensional finite difference groundwater flow model in finite difference flow modeling with soil and water assessment tools, and its effectiveness and practicality are verified. The experimental results showed that the model maintained the infiltration rate of precipitation in the irrigation area between 0.11 and 0.27, the infiltration rate of irrigation between 0.3 and 0.4, and the infiltration rate of the soil and water assessment tool model between 0.21 and 0.26. The coefficients of determination of the five verification wells in the coupling model comparison were 0.72, 0.13, 0.72, 0.54, and 0.32, respectively, with good fitting effect; the spatial interpolation results of the measured groundwater level related data and the 60 m flow field line in the coupled model simulation results were both located in the middle of the irrigation area, which was superior to the comparative model. In addition, when the coupled model was applied to the actual distribution and transformation of water resources, the correlation coefficient between soil moisture content and irrigation amount under mining irrigation conditions was 0.21, showing a positive correlation between the two; the correlation coefficient between soil water infiltration and precipitation under non mining irrigation conditions was 0.46, showing a positive correlation. Overall, the coupling model has good coupling effect and effectiveness, while in practical applications, the simulation results are basically in line with reality and have practicality. It can provide data support for promoting water-saving irrigation and optimizing irrigation systems in irrigation areas.

Keywords: MODFLOW; SWAT; Coupling model; Irrigation area; Groundwater

1. Introduction

In recent years, the actual water resource situation in some major river basins has become increasingly pessimistic, and a contradiction has gradually formed between the actual increasing water resource demand of various provinces within the basin and the limited water resources [1]. Due to the scarcity of available water resources in the northern irrigation areas, the relevant river channels in the northern irrigation areas are mostly in a dry and dry state. At the same time, the increasing irrigation costs of surface water have gradually made groundwater an important water source supporting agricultural development [2]. In this context, many northern irrigation areas have shown a distribution transformation of water resources, and the actual irrigation method is gradually transitioning from canal irrigation to well irrigation, resulting in fundamental changes in the hydrological cycle system composed of surface and underground water

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in the irrigation areas, resulting in a continuous decrease in groundwater levels [3]. However, current research on the distribution and transformation of water resources in irrigation areas has applied the Soil and Water Assessment Tool (SWAT) model and the Modular Three-Dimensional Finite Difference Ground Water Flow (MODFLOW) model in finite difference flow modeling. However, the former only considered the water balance of the soil and shallow aquifers within the hydrological response unit (HRU), and did not calculate groundwater level information and discharge flow. The research on the latter ignores the accuracy of groundwater recharge rate. Therefore, the study organically combines the two to construct a coupling model for the distribution and transformation of water resources in irrigation areas, aiming to optimize the shortcomings of the two while solving the problem of continuous decline in groundwater level and shallow groundwater overexploitation.

The study is divided into four parts in total. The first part is a summary and discussion of relevant research on the distribution and transformation of water resources in irrigation areas. The second part constructs a SWAT MODFLOW model for the distribution and transformation of water resources in irrigation areas, including the construction of SWAT and MODFLOW models, which are organically combined to construct a coupled model. The third part is to verify the effectiveness and practicality of the coupling model. The fourth part is a summary of the entire article.

2. Related works

The distribution and transformation of water resources in the irrigation area is essentially to analyze the hydrological cycle process of the irrigation area, which includes the natural hydrology such as precipitation and infiltration, and the impact process of human activities such as irrigation and drainage. Therefore, the water cycle process in the state of nature is replaced by the water cycle process in the natural and artificial combination state [4,5]. The agricultural and ecological hydrological processes in irrigation areas typically involve the distribution and transformation of water resources such as atmospheric water, shallow surface water, soil water, and groundwater within farmland and regions, as well as water migration, heat transfer, and crop growth processes in the soil. The hydrological process in irrigation areas is crucial for their internal water cycle and crop growth, as well as for their impact on groundwater. Many scholars have studied it. Li et al. [6] put forward the idea of building an optimal allocation model of water resources in irrigation areas through a detailed analysis of Dujiangyan Irrigation Project irrigation area in China, aiming at the rational allocation problem in the distribution and transformation of water resources in irrigation areas, so as to reduce the problem of high regional missing rate on the basis of minimizing the exploitation of groundwater. Wang et al. [7] conducted a detailed analysis of water resource management in cross-border watersheds with lower pressure, addressing the issue of hydrological and ecological processes at the scale of cross river basins. At the same time, they introduced dynamic changes in hydrology and politics, effectively alleviating water resource crises while improving water resource allocation. Das et al. [8] conducted a detailed study on the spatial and temporal characteristics of seasonal rainfall in Bangladesh by introducing innovative trend analysis to address issues related to the distributed spatiotemporal characteristics of water resources. This provided planning guidance for agricultural irrigation. Yao et al. [9] conducted a comprehensive analysis of the observed evidence and model predictions of the imbalance of water towers in Asia, aiming to address the issue of watershed scale water resources related to the imbalance of water towers in Asia. This provided feasible strategies for alleviating water resource shortages and sustainable water resource management in major river basins.

In addition, Saadatpour and Kamali [10] conducted a detailed analysis of the spatial distribution optimization problem of multiple crops at the watershed scale by transforming the distribution of water resources at the watershed scale. This organically combined the SWAT model with the multi-objective particle swarm optimization algorithm, and constructed a corresponding optimization framework to achieve the optimal mode of crop planting while reducing water resource consumption. Tesfaw et al. [11] conducted a comprehensive analysis of the impact of land use on water resources in the distribution and transformation of water resources, using the SWAT model to analyze the land use of some watersheds in Central Asia, effectively alleviating the related problems of water resource shortage. Panda et al. [12] improved the SWAT model to optimize the surface runoff related issues in the distribution and transformation of water resources at the watershed scale, providing data support for the structural intervention of surface runoff in the research area. Lyra and Loukas [13] built a comprehensive simulation system by combining MODFLOW model, surface hydrology, etc. to solve the problems related to the impact of climate change on water resources and groundwater quality in the basin, so as to effectively overcome the degradation of groundwater quality and quantity in the basin [13].

From the research of domestic and foreign scholars, it can be seen that although the current research has applied SWAT model and MODFLOW model to the distribution and transformation of water resources in irrigation areas, the former only considers the water balance of the soil and shallow aquifer inside the HRU, and does not calculate groundwater level information and discharge flow. The research on the latter ignores the accuracy of groundwater recharge rate. At the same time, current research on water cycle mainly focuses on basin scale analysis, and there is relatively little research on water cycle at the irrigation area scale, especially for plain irrigation areas. Therefore, the study of constructing a SWAT-MODFLOW coupling model for the distribution and transformation of water resources in plain irrigation areas is innovative. It not only effectively compensates for the shortcomings of the two model studies, but also provides data support for the practical application of the distributed surface water groundwater coupling model.

3. SWAT-MODFLOW model construction for the distribution and transformation of water resources in irrigation areas

3.1. SWAT model and MODFLOW model construction

In response to the fundamental changes in the hydrological cycle caused by the current actual irrigation methods in irrigation areas, which have led to shallow groundwater overexploitation and continuous decline in groundwater levels, this study focuses on a canal irrigation area in the plains of China. The MODFLOW model and SWAT model are integrated to construct a SWAT-MODFLOW model for the distribution and transformation of water resources in irrigation areas. The actual irrigation methods studied in the irrigation areas are mostly combined with well irrigation and canal irrigation. With the continuous consumption of groundwater by agricultural irrigation, the groundwater level in the irrigation areas continues to decrease, and in some places it has exceeded the normal level, forming an underground funnel. Therefore, 14 observation points are set up for real-time monitoring of their groundwater levels, with each set at 1–14. Among them, 7 observation points are located in the head area of the canal in the west and 7 observation points are located in the tail area of the canal in the east. The groundwater level in the west is generally higher than that in the east, while observation point A in the west has the highest groundwater level all year round, fluctuating around 81 m. The groundwater level in the entire west remains between 57 and 85 m, while in the east it remains between 52 and 67 m. The specific content is shown in Fig. 1.

From Fig. 1 it can be seen that overall, except for the downward trend of groundwater level at observation point 7, the groundwater level at most observation points fluctuates significantly during the study period, and the overall variation is not significant. Most observation points had a variation of less than 2 m in monthly variation. At the same time, by collecting the soil in the irrigation area in real-time, it can be found that the overall soil moisture content has fluctuated significantly during the research period, with significant changes in magnitude. In addition, under the influence of long-term irrigation activities in irrigation areas, the variation pattern between groundwater and soil water is completely opposite, but this obvious pattern is affected by precipitation and evaporation in the irrigation area. When the hydrological process of the irrigation area is highly complex under the intense influence of human activities, the SWAT-MODFLOW coupling model is applied to the irrigation area to achieve scientific and reasonable irrigation. SWAT model is developed from the Simulator for Water Resources in Rural Basins (SWRRB), which has powerful functions. It is originally designed to realize the relevant prediction of complex soil type and land use patterns in large basins [14–16]. In the relevant calculations of the SWAT model, water balance is a necessary guarantee for all calculation processes, and its related formula expression is shown in Eq. (1).

$$\mathrm{ZM}_\tau = \mathrm{ZM}_0 + \sum_{j=1}^{\tau}\left(D_{\mathrm{day}} - R_{\mathrm{surf}} - F_b - M_{\mathrm{seep}} - R_{\mathrm{gw}}\right) \tag{1}$$

where ZMτ represents the actual soil moisture content at time τ, in mm; ZM_0 represents the actual initial soil moisture content, in mm; D_{day} represents the actual precipitation on day *j*, in mm; R_{surf} represents the actual surface runoff on day *j*, in mm; F_b represents the actual evapotranspiration amount on day *j*, in mm; M_{seep} represents the actual surface water leakage on day *j*, in mm; R_{gw} represents the actual regression flow on day *j*, in mm. The SWAT model divides the relevant hydrological cycle processes in natural watersheds into land hydrological processes and river hydrological processes in practice, as shown in Fig. 2.

It can be seen from Fig. 2 that the hydrological cycle is similar to the natural cycle, which is summarized into four layers, namely, the surface, vadose zone, phreatic aquifer and confined aquifer. Meanwhile, the constructed SWAT model utilizes the soil conservation service curve number method (SCS) to calculate surface runoff and infiltration; the Priestley Taylor method is used to calculate the evapotranspiration; the Muskingen method is used to calculate the river confluence. Among them, the Priestley Taylor method is a method for calculating potential evapotranspiration, which comprehensively considers the energy required to support evaporation and the ability to remove water vapor mechanisms [17,18]. The expression of the relevant formula is shown in Eq. (2).

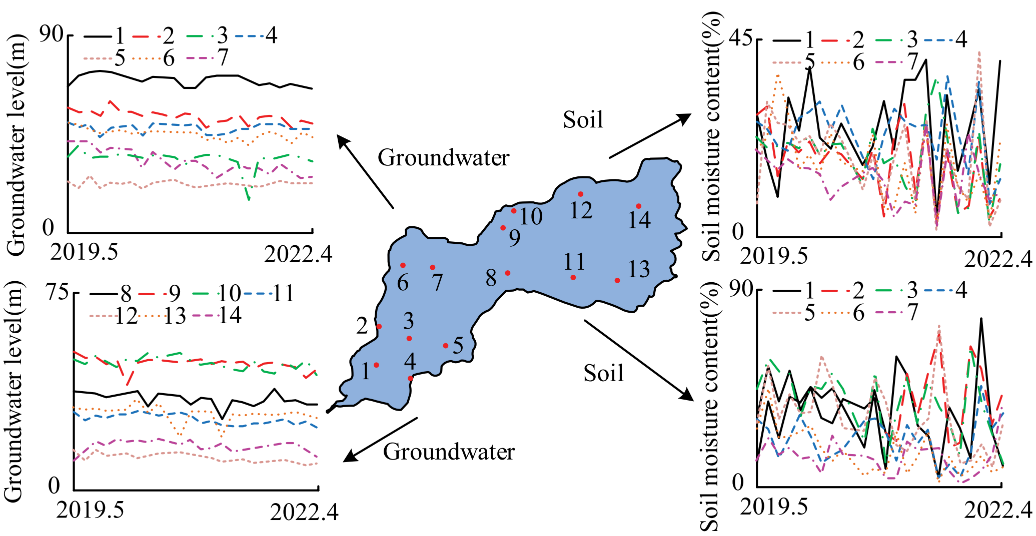

Fig. 1. Schematic diagram of temporary variation of groundwater level in research irrigation areas.

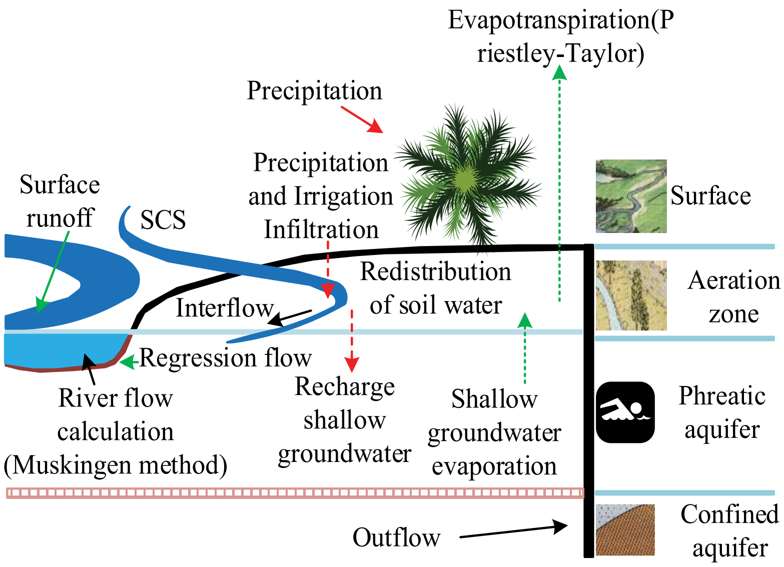

Fig. 2. Schematic diagram of SWAT model hydraulic cycle.

$$\gamma F_0 = \phi_{\text{pet}} \frac{\Delta}{\Delta + \lambda} \left(G_{\text{net}} - H \right) \tag{2}$$

where γ represents the potential heat after water vaporization, MJ/kg; F_0 indicates potential evapotranspiration, mm/d; Δ is the actual slope of the saturation pressure temperature curve, kPa/°C; ϕ_{pet} represents a coefficient, with a default value of 1.28 in this model; λ represents the constant of the humidity meter, kPa/°C; G_{net} represents net radiation, MJ/m²·d; H is the heat flux in the earth, MJ/m²·d. Therefore, according to Fig. 2, the actual construction process of SWAT model is to discretize the actual space of the irrigation area. Secondly, the database of land use and soil type is constructed, that is, the corresponding hydrological response unit is generated. Next, the corresponding meteorological database is constructed. Finally, the relevant management methods are set for crop actual growth and irrigation. In addition, the relevant data sources required for SWAT distributed hydrological model to study relevant modeling data in canals are mainly the Chinese Academy of Sciences, field surveys and meteorological stations. In the construction of the MODFLOW model, the study utilizes the Groundwater Model System (GMS) 10.4 to construct its conceptual model, and uses MODFLOW-NWT to simulate groundwater.

Among them, due to the fact that the irrigation areas studied mainly utilize shallow groundwater during groundwater extraction, the aquifer studied for numerical simulation of groundwater in irrigation areas is a shallow aquifer. The shallow aquifer is dominated by pore water, and its seepage mode obeys Darcy's law. The groundwater in the study area can be attributed to an uneven and unstable three-dimensional groundwater flow system. The boundary conditions along the lateral direction of the research area can be summarized as variable flux output boundaries in the north and northeast directions, and variable flux input boundaries in the west and southwest directions; the boundary between the northwest, south, and southeast regions is defined by water. The vertical boundary conditions of the research area can be summarized as follows: vertical replenishment mainly relies on precipitation and farmland irrigation; the vertical discharge is mainly caused by phreatic evaporation and industrial and agricultural pumping; the bottom of the quaternary loose rock layer is the bottom, which is a type of impermeable layer. The hydrogeological conceptual model of the irrigation area constructed based on the generalization of the research area can be represented by a mathematical model, and the relevant expressions are shown in Eqs. (3)–(6).

$$\frac{\partial}{\partial p}\left[L_p(s-g)\frac{\partial s}{\partial p}\right] + \frac{\partial}{\partial q}\left[L_q(s-g)\frac{\partial s}{\partial q}\right] + \frac{\partial}{\partial z}\left[L_z(s-g)\frac{\partial s}{\partial z}\right] + \eta = \varphi\frac{\partial s}{\partial \tau} \tag{3}$$

where p, q, and z represent the three directions within the seepage study area; L represents the permeability coefficient of the aquifer, m/d; s represents the actual water head of the aquifer, m; g represents the relevant bottom plate elevation of the aquifer, m; φ is the gravity water yield representing the aquifer; τ represents time, in which it is greater than 0; η represents the actual vertical replenishment and drainage intensity of the aquifer, m/d. When it is less than 0, it is outflow, and when it is greater than 0, it is inflow. It includes the source and sink terms of SWAT's actual East Lake Chu leakage, the actual evaporation of groundwater, and the actual total amount of industrial and agricultural exploitation.

$$s(p,q,z,\tau)\big|_{\tau=0} = s_0 \tag{4}$$

where s_0 represents the initial relevant water level of the aquifer, m.

$$L_{\vec{m}}(s-g)\frac{\partial s}{\partial \vec{m}}\Big|\Gamma_1 = y(p,q,\tau) \tag{5}$$

where $\vec{m}$ represents the relevant direction of the actual outer normal on the boundary; Γ_1 represents the actual boundary of flow; y represents the actual unit width flow rate of the second type boundary, m²/d.

$$\frac{\partial s}{\partial \vec{m}}\Big|\Gamma_2 = 0 \tag{6}$$

where Γ_2 represents the relevant bottom plate of the shallow aquifer, which is the boundary of the water barrier. In the model discretization and parameter zoning, the studied irrigation area is divided into 9 hydrogeological parameter zones (set as A-I) according to the relevant aquifer data collected from the field survey and the experimental results of relevant hydrogeology. Meanwhile, based on the actual control range of the irrigation area as a boundary, the actual plane of the irrigation area is divided into 114 rows in GMS × A rectangular structure with 167 columns and vertically divided into 1 layer, totalling 19,038 cells, each with an actual size of 500 m × 500 m. The number of valid cells is 8,077, and the actual number of invalid cells is 10,961. The calculation and processing of source and sink items include the upper boundary recharge, lateral inflow recharge, phreatic water evaporation and groundwater mining output. The expression for calculating the inflow supply volume in the lateral direction is shown in Eq. (7).

$$V_k = \chi \cdot \vartheta \cdot C \cdot \rho \tag{7}$$

where V_k represents the actual replenishment amount of lateral runoff; χ represents the actual permeability coefficient of the aquifer; ϑ represents the actual thickness of the boundary where the aquifer is located; C represents the actual length of the boundary section; ϱ represents the hydraulic gradient of groundwater. The calculation expression of potential evaporation is shown in Eq. (8).

$$I = \kappa \cdot A \cdot t \tag{8}$$

where I represents the actual evaporation of diving; κ indicates the actual evaporation intensity of diving; A represents the actual total area of the diving water level at a depth of 0–5 min the buried area; t indicates the actual number of days of evaporation during diving.

3.2. SWAT-MODFLOW model coupling study

Based on the construction of SWAT and MODFLOW models, a distributed Hydrological model for soil water groundwater coupling simulation, namely SWAT-MODFLOW, is built according to the field measured data. In the practical coupling principle of the SWAT MODFLOW model, SWAT is used to simulate surface processes, crop growth, river and soil zone processes; Simulate the three-dimensional flow of groundwater and all related source and sink terms using the MODFLOW model. The specific content is shown in Fig. 3.

From Fig. 3 it can be seen that the SWAT model calculates surface related content, including evapotranspiration, surface runoff, actual water level of rivers, irrigation outflow, soil flow, precipitation, infiltration recharge, irrigation, and channel infiltration. Surface plants evaporate upwards through evaporation operations and form surface runoff that flows towards rivers to increase river water levels. The amount of evaporated water forms various surface water quantities through precipitation in the clouds. Irrigation is achieved by extracting groundwater to irrigate surface plants, and excessive water flow can cause irrigation backwater and flow into rivers in the soil, forming leakage supply and channel leakage returning to the underground. The MODFLOW model calculates underground related content, including groundwater level, groundwater discharge, groundwater movement, aquifers, and groundwater extraction. The main flow direction and rivers for groundwater utilization. The coupled SWAT-MODFLOW model mainly calculates the evaporation of groundwater. Overall, the basic process of connecting the SWAT model and the MODFLOW model is to transfer the relevant deep seepage calculated by HRU as actual recharge to the grid units of the MODFLOW model, and then transfer the relevant groundwater surface

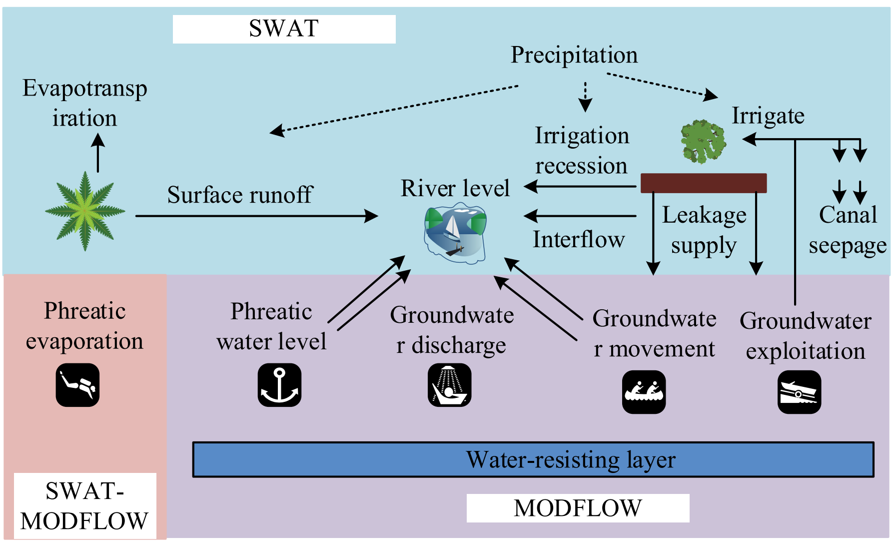

Fig. 3. Schematic diagram of the SWAT MODFLOW model.

water interaction flux calculated by MODFLOW to the SWAT model's river channel. Among them, deep seepage is mainly the water flowing out from the bottom of the soil profile.

In general, the SWAT model in SWAT-MODFLOW model is used to realize the relevant routing of river confluence; MODFLOW Mexico is used to realize the simulation of river packet of groundwater surface water interaction, and finally Darcy's law is used to calculate the water flow discharge through the cross-section area between the aquifer and the river channel. This coupling model utilizes the relevant subroutines of the overall program in the SWAT MODFLOW model for data transmission, which in turn connects the actual HRU and the grid units in the MODFLOW model with the river channels in the SWAT model to enhance correlation. The relevant elements include HRU, DHR (which divides the original HRU into separate and adjacent areas within sub watersheds to facilitate the calculation of relevant geographic positioning of HRU) relevant grid units of the MODFLOW model, relevant river units of the MODFLOW model, and SWAT river channels. Among them, the actual simulation process of surface water groundwater mainly involves reading the input data of the SWAT and MODFLOW models based on the relevant operational level of the SWAT MODFLOW model. The specific process is shown in Fig. 4.

From Fig. 4 it can be seen that the SWAT model mainly analyzes soil leakage, potential evapotranspiration, and river water level, while converting relevant variables in HRU into variables in the actual grid; the MODFLOW model mainly analyzes groundwater head and leakage/discharge. It converts the actual variables of the internal grid of the model into relevant variables in the decomposed hydrological response units (DHRU); convert the relevant variables in DHRU to those in HRU; the relevant units in the MODFLOW model are transformed into relevant variables in SWAT. The SWAT model returns to the original SWSY model after simulating watershed calculations in the next time step. In terms of detailed description, the HRU deep leakage calculated by SWAT is first projected onto each DHRU. Secondly, the HRU deep leakage data will be corresponding to each MODFLOW grid unit according to the proportion of DHRU it contains, and used for MODFLOW supplementary software. The water depth of each sub basin calculated by SWAT is mapped to a set of MODFLOW river sections in that sub basin, which are used by the MODFLOW river software package. Then, MODFLOW software is used to calculate the interaction between groundwater head, groundwater, and surface water, and the results are transmitted to the SWAT system.

Then, the MODFLOW software is used to summarize the groundwater discharge of each watershed and add it to the inland river runoff of each SWAT watershed. Finally, SWAT completes a time step flow calculation, and calculates the river basin confluence through the river network until the SWAT simulation is completed. In addition, the study summarized the overview and sample collection of irrigation areas. The irrigation section has a total length of over 100 km, an average width of 5–25 km, and a total land area of about 1,486 km², of which agricultural land accounts for 67%. There are currently 47 main and branch canals in the irrigation area. The southwest of the irrigation area is the head of the canal, and most of the river flows from southwest to northeast. At the north end of the Wei River and the northeast corner of the north end are drainage ditches. The rivers in the irrigation area have a small amount of flow throughout the year, and the water level is very low. Their purpose is to provide irrigation, drainage, and flood control and drainage during the flood season. The irrigation area belongs to a warm temperate continental monsoon climate, with an average annual temperature of 14.5°C, an average annual evaporation of about 1,100 mm, and an average annual precipitation of about 550 mm. The distribution of rainfall within the year is extremely uneven, mainly from June to September, accounting for about 70% of the annual precipitation. It is dry in spring and stagnant in summer. The research project surveys 14 observation stations in the region from May 2019 to April 2022, and the distribution of

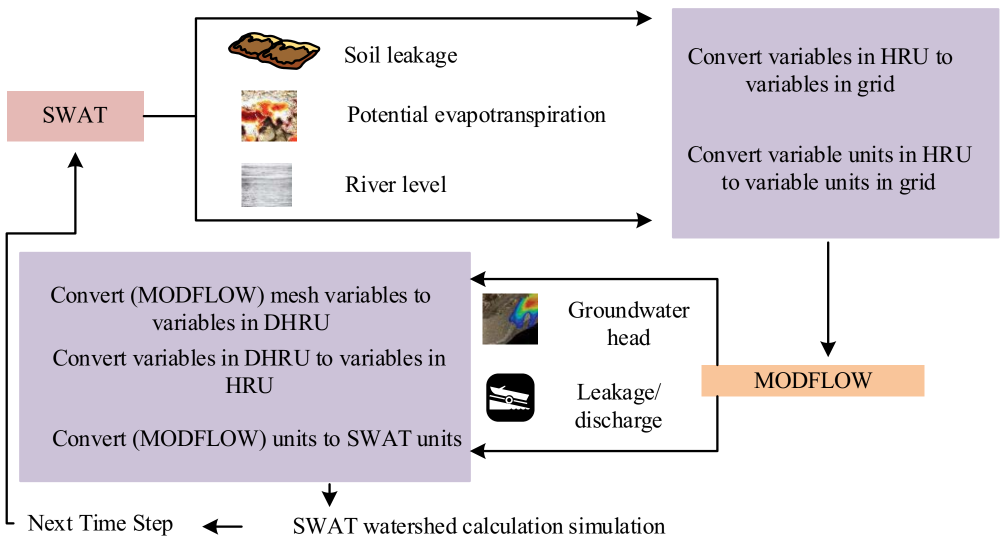

Fig. 4. Schematic diagram of the actual calculation process of the SWAT MODFLOW coupling model.

these 14 observation points is shown in Fig. 1. At the same time, the monthly temperature, precipitation, and other changes in the irrigation area are shown in Fig. 5.

From Fig. 5 it can be seen that the annual precipitation in the irrigation area does not exceed 100 mm, showing a significant downward trend from July to February of the following year, while the precipitation continues to increase from February to September each year. The evaporation volume is maintained between 50 and 250 mm all year round, and the monthly evaporation volume is significantly higher than the precipitation, so the dependence on channel drainage is significantly higher. At the same time, the monthly average maximum temperature is at a relatively high level from May to October, maintaining between 30°C and 35°C, reaching its lowest level in January, below 10°C, and below 0°C. The trend of the 3-y average temperature is consistent with the monthly average minimum and maximum temperatures. Overall, the overall situation in the irrigation area is characterized by severe insufficient precipitation and generally high temperatures, resulting in a strong demand for groundwater. In addition, the irrigation area is mainly composed of corn, rice, etc. Observation point 1 in the southwest of the irrigation area is mainly composed of winter wheat and summer rice, while the northeast is mainly composed of winter wheat and summer peanuts. Among them, observation points 14, 11, and 13 are mainly winter wheat and summer peanuts. The wheat growing season in irrigated areas is from early October to late May of the following year, while the rice, jade, and peanut growing season is from June to late September. The management methods of crops vary in different regions, climates, and farmers.

In the case of sufficient summer rainfall, the irrigation amount in the area will significantly decrease; in the case of insufficient seasonal precipitation, the irrigation amount in this area significantly increases. Through on-site investigation, it was found that observation point 1 and observation point 3, due to their proximity to the main canal, often use a combination of well and canal irrigation. In summer, large river water irrigation is often used, and in winter, well irrigation is often used to extract groundwater sources. In recent years, due to the high cost of irrigation by diverting large rivers, the downstream riverbed of the river being cut down, and the reduced water diversion capacity of the culvert gates of diverting large rivers, the crop irrigation mode in irrigation areas has also undergone changes. The irrigation area of well irrigation and the combination of well irrigation and canal irrigation has increased, while the area of canal irrigation has decreased. During the research period, from the 25th to the 30th of each month, soil depths of 0–30 m are measured and sampled at 14 observation stations. Soil samples are collected in the laboratory using a dry method and perform moisture analysis on them. Malvern particle size analyzer is used to measure soil particle size.

4. SWAT-MODFLOW model calibration and simulation analysis of water resource distribution and transformation in irrigation areas

In order to verify the scientific and effective nature of the SWAT MODFLOW model, the study first calibrated it, including the SWAT model's infiltration rate and evapotranspiration rate; SWAT-MODFLOW model for groundwater

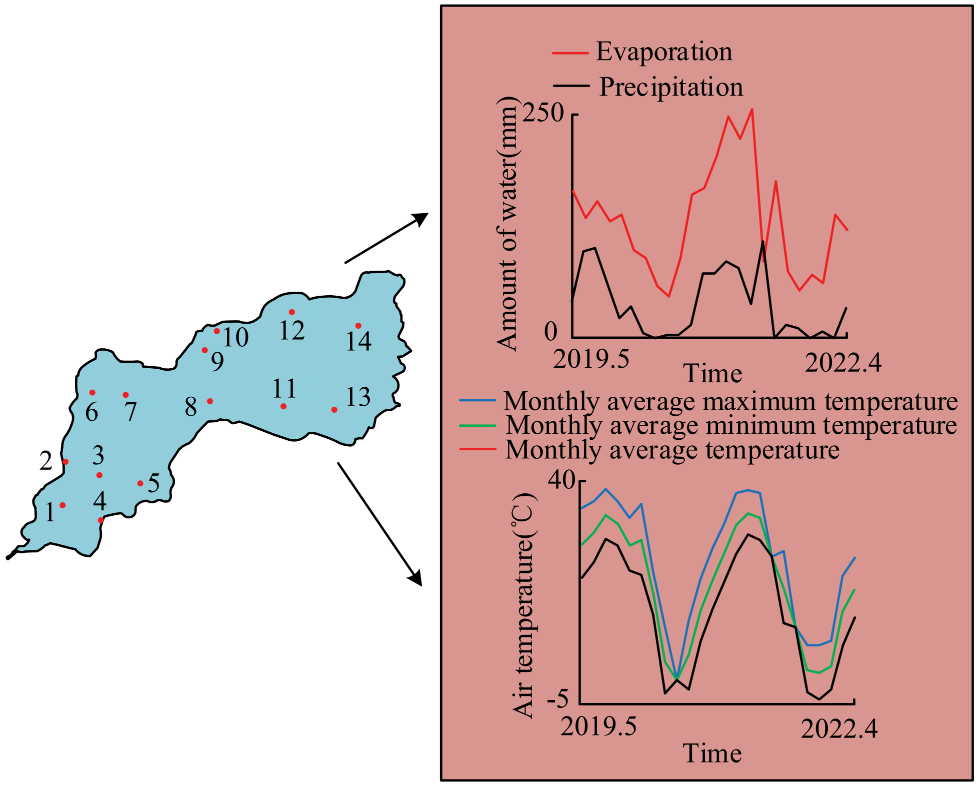

Fig. 5. Monthly changes in temperature, precision, and other factors in the inflation area.

level calibration. The results of determining the infiltration rate and evapotranspiration rate of the SWAT model are shown in Fig. 6.

The vertical axis in Fig. 1a and the horizontal axis in Fig. 1b represent the study period from 1 to 23, with monthly intervals. From Fig. 6 it can be seen that the annual average irrigation water volume in the irrigation area is 405 mm, so its average annual infiltration rate is approximately 0.21. The actual infiltration amount of the model constructed in the study is maintained below 30 mm per month, and the infiltration rate is maintained between 0.21 and 0.26, while the infiltration rate of precipitation in the irrigation area is maintained between 0.11 and 0.27, and the infiltration rate of irrigation is maintained between 0.3 and 0.4. Therefore, the SWAT model constructed in the study is in line with reality. In addition, the monthly variation trend of possible evapotranspiration simulated by the SWAT model is consistent with the observed data, and its fitting effect with the observed data is good, with a correlation coefficient R^2 exceeding 0.6. This also indicates that the results obtained from the SWAT model constructed in the study for predicting evapotranspiration are also in line with the actual situation. Overall, the SWAT model constructed in the study is effective. Therefore, the groundwater level of the SWAT-MODFLOW model is calibrated. The calibration of the coupled model includes two aspects: surface water and groundwater. The calibration of surface water has been completed in the calibration calculation section of the SWAT model, while the calibration calculation of groundwater is achieved by multiple adjustments to the permeability coefficient and water supply in the MODFLOW model. The groundwater dynamic process simulated by the coupled model is basically consistent with the observed dynamic process, thereby improving the accuracy of model simulation.

It mainly includes the fitting of groundwater level in representative observation well sections and the fitting of representative groundwater flow field. In addition, in order to effectively improve the dynamic simulation accuracy of the coupled model for groundwater in the irrigation area, based on the actual measurement of 14 observation points, five observation wells were extracted by using the spatial control principle, which are observation points 1, 6, 8, 12, 13 from left to right. Therefore, the hydrogeological zoning parameter calibration and coupling model simulation

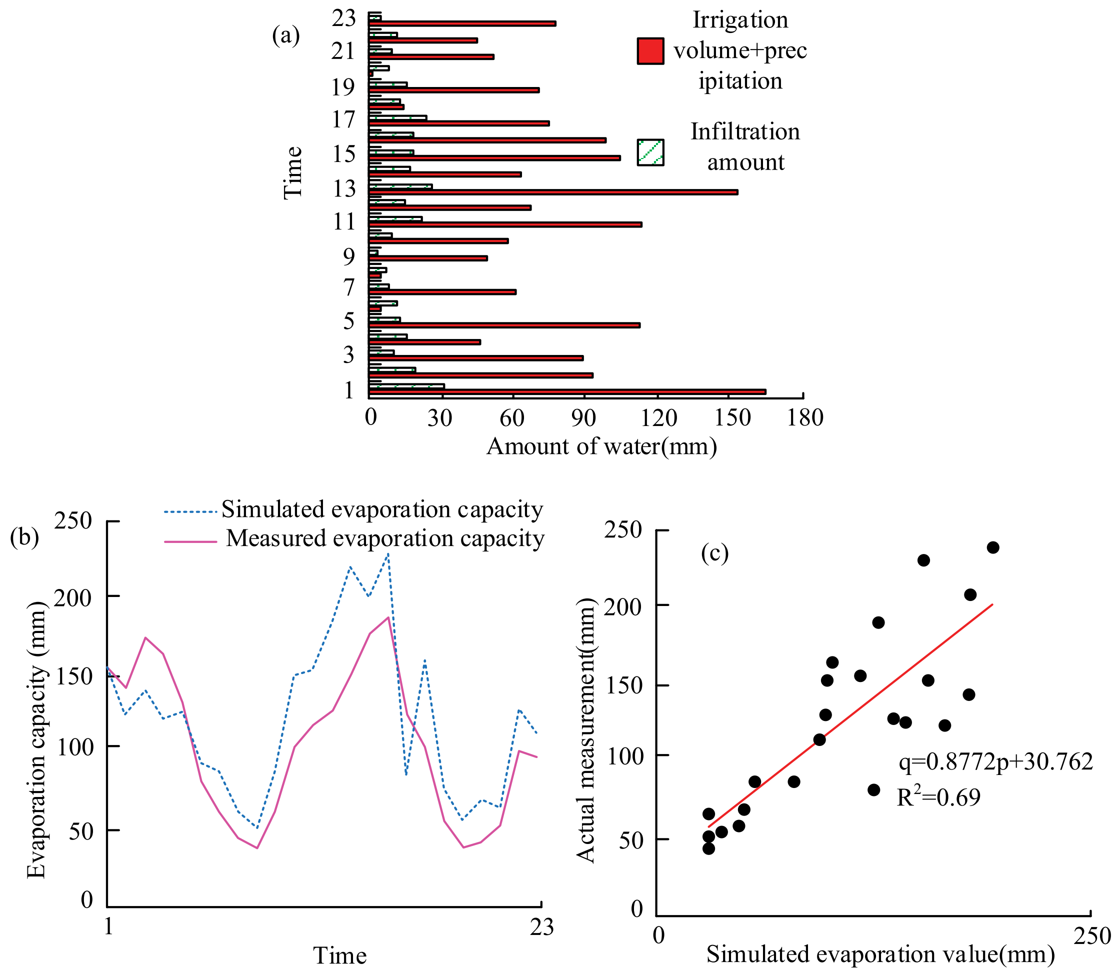

Fig. 6. Determination of infiltration rate and evapotranspiration rate using SWAT model. (a) Monthly precipitation, irrigation water volume, and infiltration water volume, (b) simulated and measured monthly average evaporation during the research period, and (c) fitting of calculated and measured monthly average evaporation during the research period.

results using the MODFLOW model in the irrigation area are shown in Table 1.

From Table 1 it can be seen that the water yield calibration results are maintained between 0.03 and 0.29, and the fitting results show that the coupling model's numerical simulation results of the monthly groundwater level of each observation well are in good agreement with the actual situation. For each rated well, the regression coefficient between the calculated groundwater level using this model and the actual measured groundwater level is between 0.5 and 0.7, indicating that the fitting effect of this model is very good. The range of root-mean-square deviation is 0.40–0.75 m, and the error is small. Overall, the coupled model has a good practical simulation effect and effectiveness, so it is applied to the actual simulation of soil water and groundwater transformation. Among them, in the coupled model groundwater level simulation, in addition to the 5 observation wells used for calibration, 5 observation wells were re-selected as the validation wells for the experiment, with observation points 2, 7, 5, 9, and 11 from west to east. The main purpose is to dynamically fit the simulated and measured values of the groundwater level coupling models of five observation wells, as shown in Fig. 7.

From Fig. 7 it can be seen that the simulated values of the monthly actual groundwater level of each validation well under the coupled model are basically similar to the measured values, and the actual fitting effect is good. At the same time, the coefficient of determination R^2 of the five verification wells is 0.72, 0.13, 0.72, 0.54, and 0.32, respectively, maintaining between 0.1 and 0.72, while the root-mean-square deviation values are 0.66, 0.58, 2.36, 0.66, and 0.54 m, respectively, maintaining between 0.50 and 2.40 m, further proving that the actual matching effect is good. In general, the coefficient of determination between the simulated and measured groundwater levels of verification well 7 and verification well 11 in the coupled model is lower than 0.32, which means that the fitting effect is poor, but the root mean square error is also low; however, the actual fitting effect between the simulated groundwater level and the measured groundwater level in verification well 5 is good, but the root-mean-square deviation value is large, indicating that the actual simulation results of the coupled model are good in most months, and the error is large only in individual months. In order to further verify the actual simulation effect of the coupled model, the study compared it with the simulation results of the MODFLOW model. Therefore, the leakage of relevant soil water actually output by SWAT model into the groundwater is taken as the supplement of the upper boundary of the actual groundwater, and the hydrogeological parameters of the aquifer determined in the calibration process of the coupled model are used to obtain the groundwater level simulation results of the five verification wells, as well as the determination coefficient values and root-mean-square deviation results between the measured water level and the measured water level, as shown in Fig. 8.

From Fig. 8 it can be seen that compared with the simulation results of the coupled model in Fig. 7, the MODFLOW of the actual groundwater levels of the five validation wells is relatively close to the simulation results of the coupled model. However, there are certain differences in the simulation results of individual validation wells and some months, and the overall simulation effect of the coupled model is better than the MODFLOW model. In addition, the R^2 values of the five verification wells were maintained between 0.10 and 0.57, while the root-mean-square deviation was maintained between 0.65 and 3.29. Overall, the actual simulation performance of the MODFLOW model is similar to that of

Table 1
Calibration of hydrogeological zoning parameters in irrigation areas using the MODFLOW model and simulation results of coupled models

Permeability coefficient and water yield calibration results									
–	A	B	C	D	E	F	G	H	I
L_p	Two point nine one	Eight point five one	Twelve point six zero	Twelve point one zero	Fifteen point six zero	Ten point six zero	Ten point one zero	Six point five one	Twelve point nine zero
L_q	Two point nine one	Eight point five one	Twelve point six zero	Twelve point one zero	Fifteen point six zero	Ten point six zero	Ten point one zero	Six point five one	Twelve point nine zero
L_z	Zero point three zero	Zero point eight six	Twelve point six zero	One point two one	One point five six	One point zero six	One point zero one	Zero point six five	One point two one
φ	Zero point two one	Zero point two nine	Zero point one one	Zero point zero three	Zero point one five	Zero point zero eight	Zero point one three	Zero point one one	Zero point zero nine

Coupling model simulation results					
–	Observation point 1	Observation point 6	Observation point 8	Observation point 12	Observation point 13
Root mean square error	0.62 m	0.70 m	0.56 m	0.40 m	0.72 m
R^2	Zero point five two	Zero point six six	Zero point six four	Zero point six nine	Zero point five two

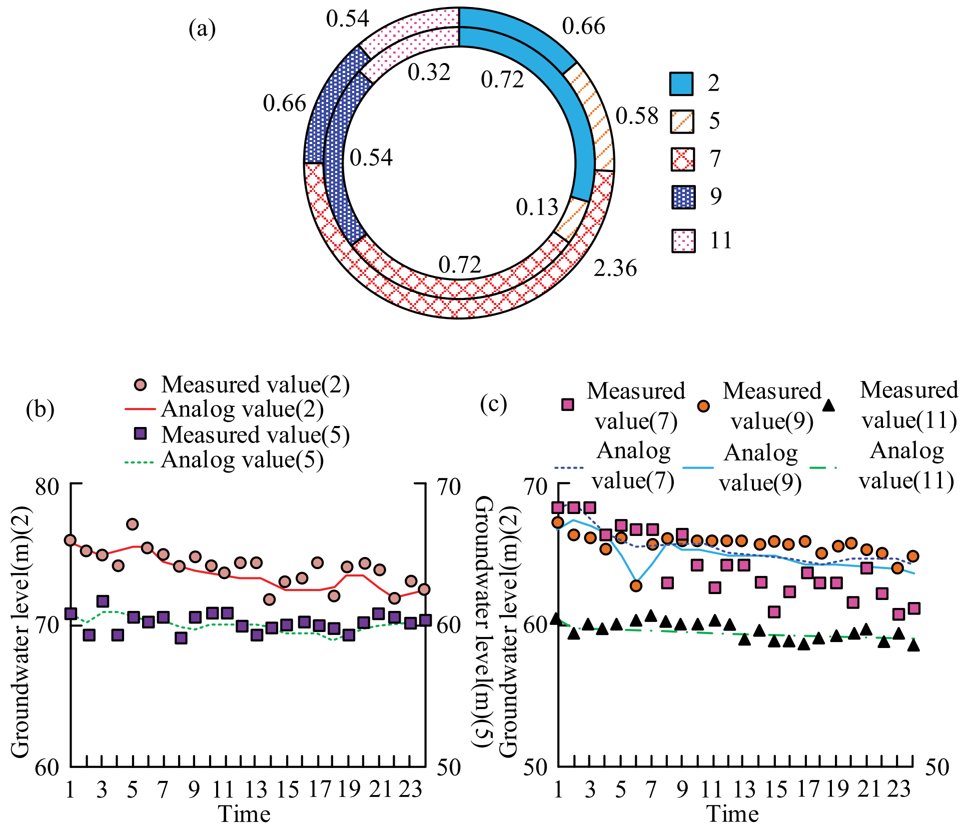

Fig. 7. Dynamic fitting results of simulated and measured groundwater level coupling models for 5 observation wells. (a) Linear regression coefficient and root-mean-square deviation of coupled model simulation, (b) verify the results of wells 2 and 5, and (c) verify the results of wells 7, 5, 9, and 11.

the SWAT-MODFLOW model, showing high simulation performance in most months. However, overall, the SWAT-MODFLOW model outperforms the MODFLOW model. To verify this result, the groundwater related data and flow field simulated by the two models were compared, and the results are shown in Fig. 9.

Based on Fig. 9 it can be seen that under the simulation results of the SWAT-MODFLOW model, the simulated values of the monthly groundwater contour line are well fitted with the measured values of the monthly groundwater contour line. The spatial interpolation results of the measured groundwater level related data and the 60 m flow field line in the coupled model simulation results are located in the middle of the irrigation area, indicating that the actual groundwater level in most areas of the eastern part of the irrigation area should be lower than 60 m. The simulated water level of the MODFLOW model is higher than the measured water level, and the simulated groundwater level in some areas outside the 60 m flow field line in the eastern part of the irrigation area is higher than 60 m. The overall results clearly show that the coupled model simulation results are superior to the MODFLOW model. On this basis, the simulation effects of the two models on 14 observation points were compared, and the results are shown in Fig. 10.

From Fig. 10 it can be seen that during the study period, the actual errors simulated by the MODFLOW model were relatively large, while the actual errors of the coupled model were relatively small. By comprehensively comparing the 14 observation points, it can be seen that in the MODFLOW model simulation results, most of the observation points have simulated values higher than the measured values, while most of the observation points in the coupled model coincide with the measured points. In general, the actual simulation effect of the coupled model is significantly better than that of the MODFLOW model, which significantly improves the simulation accuracy of the model for groundwater recharge and groundwater level. On the basis of verifying the superiority of the coupling model, it is applied to the analysis of the transformation characteristics between soil water and groundwater in irrigation areas, namely the analysis of water resource distribution transformation. Among them, according to the water balance results actually output by the coupled model, the monthly average soil water content and water infiltration, groundwater reserves and evaporation in the irrigation area can be analyzed under the conditions of precipitation evaporation and irrigation (the data in May 2019 is not included because of the actual data export of the coupled model), and the results are shown in Fig. 11.

From Fig. 11 it can be seen that the monthly precipitation during the study period was maintained between 0.3 and 92.8 mm using the coupled model analysis. Overall, there was more precipitation in summer and less precipitation in winter. The irrigation amount remained between 0 and 75, without significant changes. The trend of evaporation

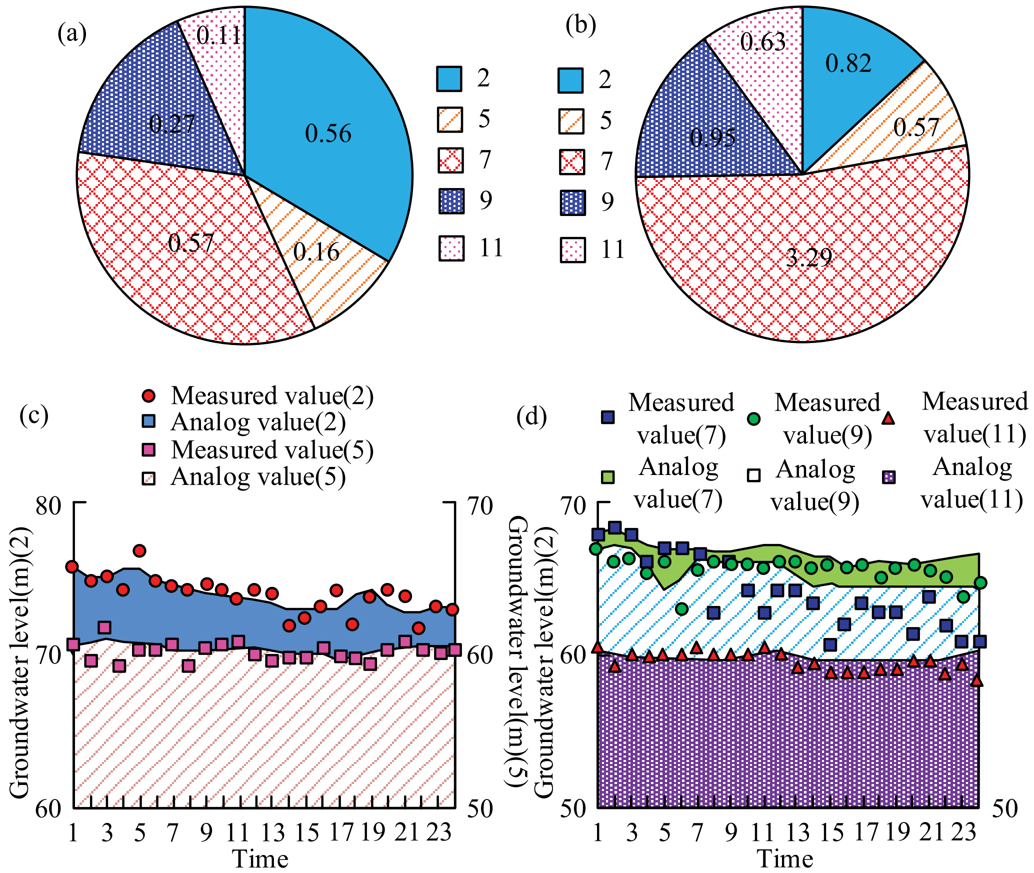

Fig. 8. MODFLOW model groundwater level simulation results. (a) Correlation coefficient results, (b) root-mean-square deviation result, (c) verify the results of wells 2 and 5, and (d) verify the results of wells 7, 5, 9, and 11.

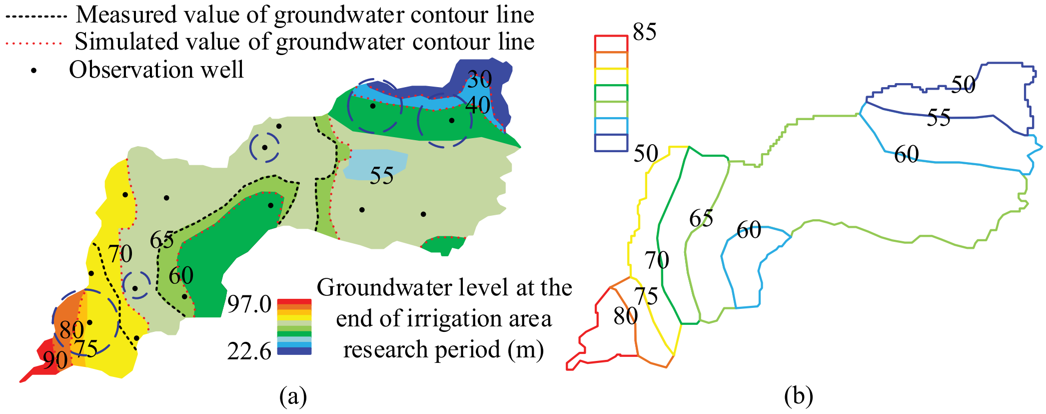

Fig. 9. Comparison of groundwater related data and flow field results from two simulation simulations at the end of the research period. (a) Comparison between measured and simulated data of the coupled model at the end of the research period and (b) groundwater flow field simulated by MODFLOW at the end of the research period.

is similar to precipitation, with an average annual evaporation higher than precipitation. The time variation and correlation analysis results of the output water balance term of the irrigation coupling model based on the simulation data results in Fig. 11 are shown in Fig. 12.

From Fig. 12 it can be seen that there is a fluctuation in soil water changes and groundwater storage changes. The former maintains a range of –20 to 20 mm, while the latter maintains a range of –80 to 30 mm. Overall, the changes in soil water are basically consistent with the changes in groundwater, meaning that as the soil water content increases, the groundwater volume will show a downward trend. This result is consistent with the measured data in Fig. 1, indicating the effectiveness of the coupling model in the analysis of actual water resource distribution transformation. At the same time, it also indicates that groundwater will transform into soil water under the action of this irrigation activity. In addition, the correlation analysis results show that the correlation coefficient between soil water infiltration and precipitation irrigation is 0.51, showing a positive correlation, indicating that the recharge of groundwater mainly comes from the infiltration of rainfall and irrigation water. The simulation results are in line with the actual situation. The correlation coefficient between soil moisture content and irrigation amount is 0.21, showing a positive correlation, indicating that the soil age content will be affected by the irrigation part, but the correlation is not significant. Overall, the cross-sectional model has practicality in the analysis and application of actual water resource distribution transformation. Under its simulation results, the groundwater in irrigation areas is mainly affected by the comprehensive effects of precipitation and mining irrigation.

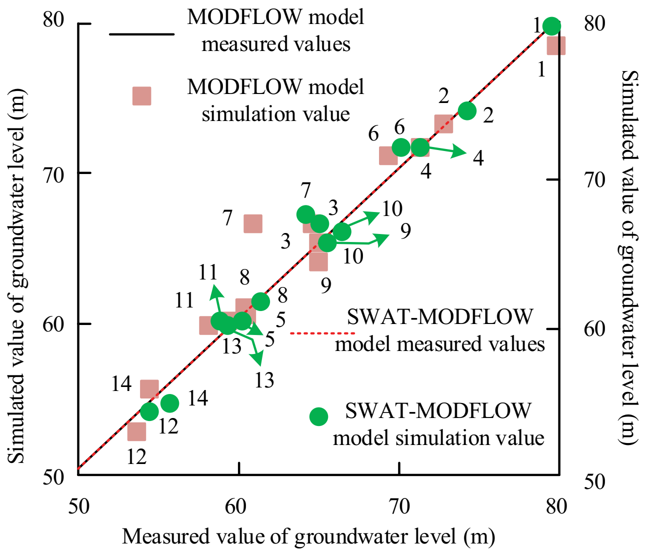

Fig. 10. Comparison of simulation results between two models for 14 observation points.

In order to analyze the impact of irrigation and mining on the water cycle process in irrigation areas, a simulation without mining irrigation was set up in a coupled model. The water balance output results under this condition are shown in Fig. 13.

Based on Fig. 13 it can be seen that under the condition of no mining irrigation, the irrigation volume index has been removed. Except for the unchanged precipitation, all other indicators have undergone significant changes. For example, in June 2019, the underground water volume increased from –27.06 to 23.46 mm, while the overall evaporation showed a downward trend. Under the output results of this data, the coupling model of the irrigation area outputs the time variation and correlation analysis results of the water balance term, as shown in Fig. 14.

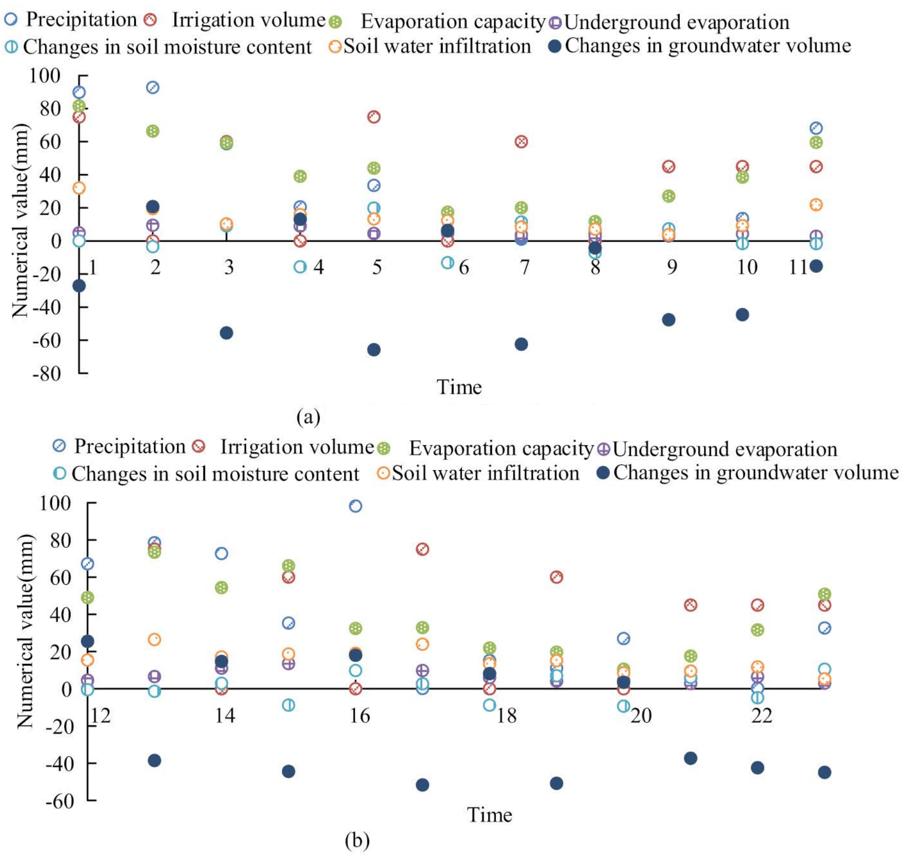

Fig. 11. Coupling model water balance output results. Results from the first (a) 11 months and (b) 12 months.

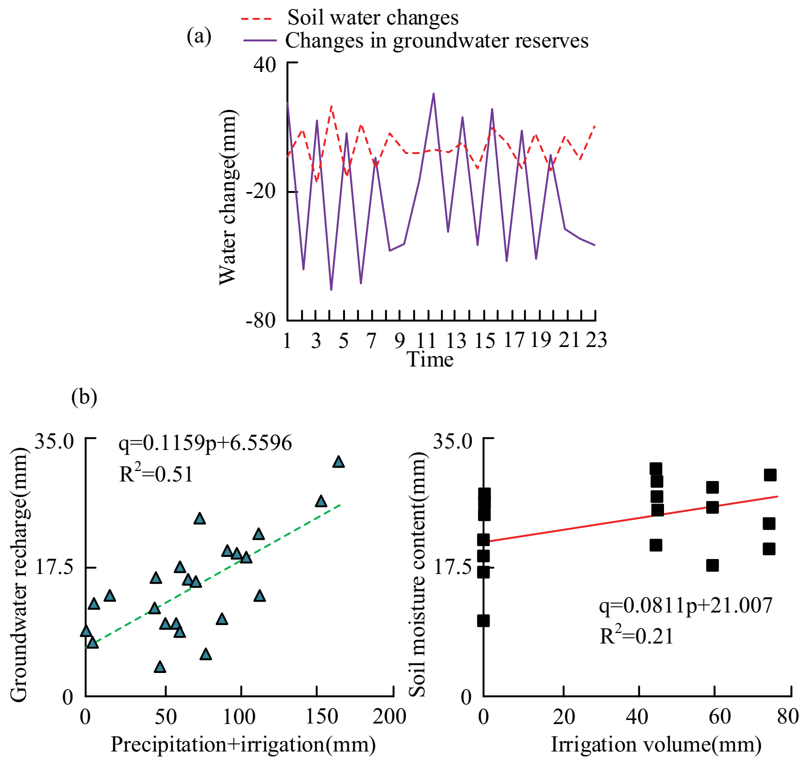

Fig. 12. Time variation and correlation analysis results of the output water balance term of the coupled model in inflation areas. (a) Time variation of water balance term output from SWAT-MODFLOW model in irrigation areas and (b) correlation analysis of the output water balance term of SWAT-MODFLOW model in irrigation areas.

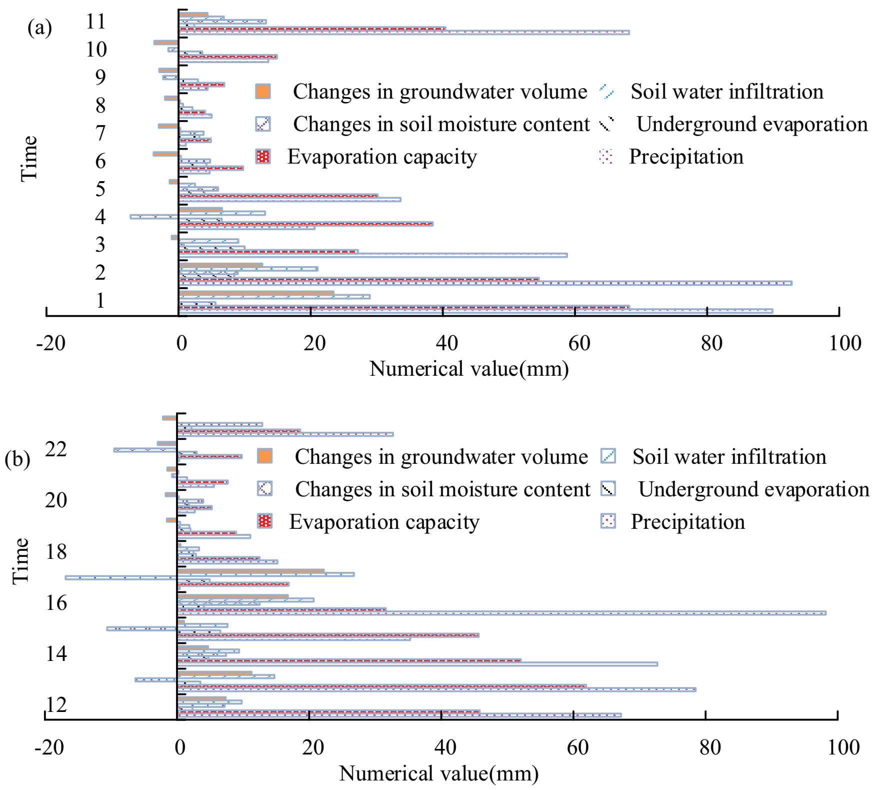

Fig. 13. Water balance output results of coupled model under non mining irrigation. Results from the first (a) 11 months and (b) 12 months.

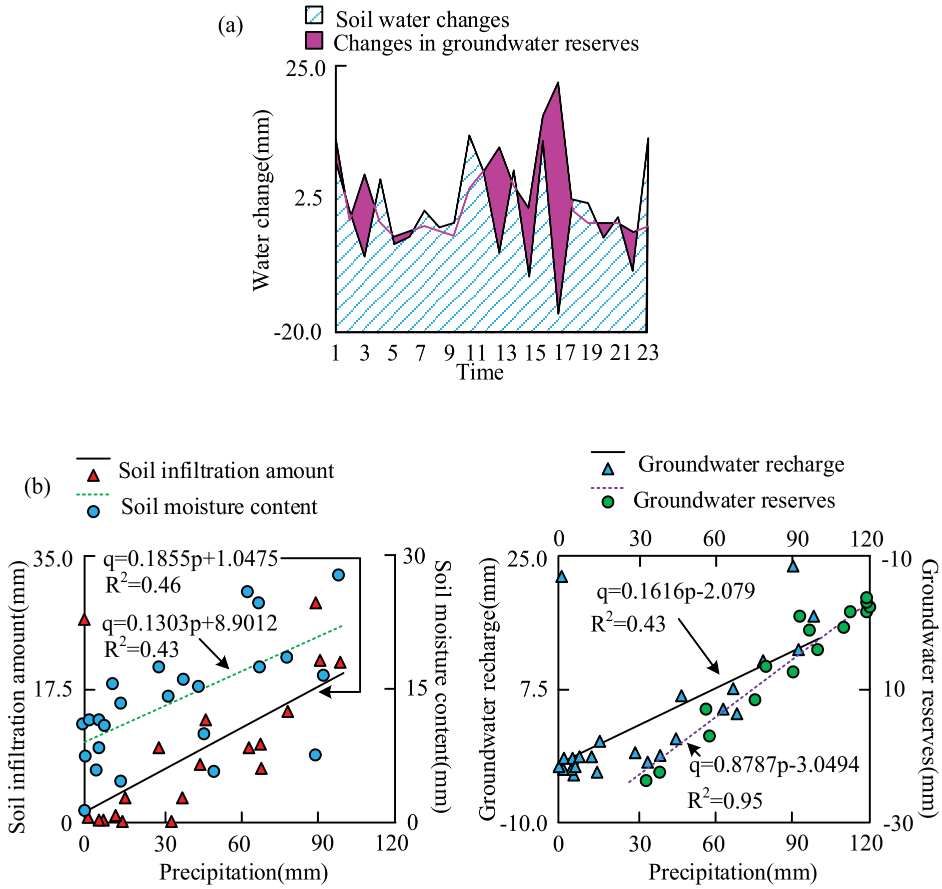

Fig. 14. Time variation and correlation analysis results of the output water balance term of the coupled model in inflation areas under non mining inflation conditions. (a) Time variation of output water balance term of SWAT-MODFLOW model in irrigation areas under non-mining irrigation and (b) correlation analysis of the output water balance term of the SWAT-MODFLOW model in irrigation areas under non-irrigation mining.

From Fig. 14 it can be seen that the overall soil water content under non mining irrigation conditions is lower than that under mining irrigation price adjustment, with a maximum of only 14 mm. There is a significant difference between the two, and the pattern of groundwater decrease is not obvious when the soil water content increases. This result indicates that groundwater extraction irrigation has a significant impact on the actual water circulation process in the irrigation area. In addition, the correlation coefficient between soil water infiltration and precipitation is 0.46, showing a positive correlation, but the value is smaller than the value under mining irrigation conditions. The correlation coefficient between soil moisture and precipitation is 0.41, showing a positive correlation, indicating that in the absence of mining irrigation, soil moisture is mainly affected by rainfall, and its impact is greater than that of mining irrigation. Meanwhile, the correlation coefficient between groundwater reserves and precipitation is 0.43, showing a positive correlation. The correlation coefficient between groundwater reserves and soil infiltration is 0.95, showing a positive correlation, indicating that soil water infiltration recharge has a significant impact on groundwater.

From Figs. 11–14 it can be seen that the coupled model is effective and practical in the practical application of water resource distribution transformation, and the simulated results are basically consistent with the actual results. From the simulation results, it can be seen that rainfall has the greatest impact on groundwater in irrigation areas without irrigation, but the relationship between groundwater and soil water is the same as in the case of irrigation. Under non mining irrigation conditions, the anomalous changes in soil moisture content and groundwater moisture content are not significant.

5. Conclusion

In response to the fundamental changes in the hydrological cycle caused by the current irrigation methods in irrigation areas, which lead to shallow groundwater overexploitation and continuous decline in groundwater level, a SWAT-MODFLOW model for the distribution and transformation of water resources in irrigation areas is studied and constructed, and its effectiveness is verified in a certain irrigation area. The experimental results showed that the actual infiltration rate of the SWAT model constructed in the model calibration was maintained below 30 mm per month, and the infiltration rate was maintained between 0.21 and 0.26, which was in line with reality. The regression coefficient of the coupling model for calibration wells was 0.5–0.7, and the root-mean-square deviation range was 0.40–0.75 m, which was small. The coefficient of determination R^2 of the five verification wells was maintained between 0.1 and 0.72, while the root-mean-square deviation was maintained between 0.50 and 2.40 m. In addition, the spatial interpolation of the measured groundwater level in the model comparison and the 60 m flow field line in the coupled model simulation results were all located in the central position of the irrigation area, while the MODFLOW model's simulated water level was higher than the measured water level. Meanwhile, applying the coupling model to the actual transformation of water resource distribution, it was found that the correlation coefficient between soil water infiltration and precipitation irrigation under mining irrigation conditions was 0.51, showing a positive correlation between the two; the correlation coefficient between soil moisture content and precipitation under non mining irrigation conditions was 0.41, showing a positive correlation. Overall, the coupled model has effectiveness and practicality in the analysis of water resource distribution and transformation, and its performance is superior to the comparative model. The simulation calculation of crops in growing region in the construction of SWAT model is not deep enough, so it needs to be improved in the future.

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