Study on water cycle simulation model of multi-source and multi-functional irrigation area based on SWAT model (I): Principles and construction methods

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Abstract. Aiming at the water cycle simulation of multi-sources and multi-functional irrigation area, the coupling relationship between natural water cycle and social water cycle was established based on SWAT model. The methods of sub basins divisions in SWAT model were improved, which were incorporated into the improved SWAT model. The water cycle process of complex water resource system and the response to various human activities in irrigation area were simulated accurately and quantitatively to meet the needs of accurate water resource management.

1. Introduction
Zhejiang Province is located in the southeast coast of China, with abundant rainfall. The annual average rainfall is 1604mm. The total land area of Zhejiang Province is 103800 km², including 70.4% of mountains and hills, 23.8% of plains and basins, and 5.8% of rivers and lakes. The specific topography, hydrological and meteorological conditions determine the characteristics of irrigation areas and agricultural irrigation water [1]. Firstly, the functions of water source project in irrigation areas are diversified. Irrigation areas are generally the regions with relatively good soil and water resources. They are not only the key areas of society economic constructions, but also the main places of beautiful China and Rural Revitalization. The large and medium-sized water source projects in the irrigation area undertake various functions such as irrigation, water supply, breeding, power generation, improvement of ecological environment, and their functions are becoming more and more diversified. Secondly, there are many water source projects in the irrigation areas, and the irrigation water consumption of various water sources varies greatly from year to year. Most irrigation areas have multiple water sources, some of which are independent of each other, some of which are interconnected. They belong to the long vine and melon type irrigation system with the combination of large, medium and small, storage, diversion and lifting. There are direct or indirect hydraulic connections between irrigation water sources. Different types of water sources in the irrigation area have significant differences in irrigation water consumption in different hydrological years. The irrigation water consumption of a water source varies obviously in different hydrological years. Thirdly, the main body of water source project management and the nature of irrigation have regional characteristics. Large and medium-sized water source projects and main channels are generally managed by special management organizations, while other projects are generally managed by township or village collective. The crops in the south area of rich water are generally irrigated with supplementary water except for rice planting. When irrigation is needed, it is generally
carried out according to the order of river water, pond water, and reservoir water intake. Weir dams, ponds and small reservoirs in the irrigation area play an important role in irrigation. The measurement and statistical methods given by the current national and local policies and documents have limitations and it’s difficult to implement for such irrigation areas. The water cycle simulation model of the irrigation areas with multi functions and multi sources was intended to be constructed, and the measurement and statistical method of which irrigation water consumption were intended to be studied.

In order to solve the above problems effectively, we need to focus on two key problems from the coupling relationship between natural water cycle and social water cycle. One is that how to carry out the comprehensive simulation of the water cycle process in the irrigation area effectively, including the natural water cycle process and the multi-functional social water cycle process, and how to describe the water cycle changes accurately in the irrigation area under the multiple impacts of human beings. The other one is that how to couple the natural water cycle and social water cycle process orderly and realize the orderly utilization and reasonable description of all kinds of water resources under the dynamic change.

2. Principles of SWAT model and the improvements
The researchers domestic and overseas have carried out a lot of studies and achieved remarkable progress at the simulation of water cycle in irrigation area [2-9]. Most of the researches are based on SWAT model [10-14]. The SWAT model was improved based on the characteristics of multi-source and multi-functional irrigation area, which provides a new method and tool to solve the above two key problems.

2.1. The principles of SWAT model

2.1.1. The basic principles. SWAT (Soil and Water Assessment Tool) model is a distributed hydrological model with physical basis, which has been modified for many times and has a variety of functions. It can not only simulate the daily, monthly and annual Water cycle process in the basin, but also be used to analyze and study the impact of human activities on the Water cycle. The SWAT model takes the hydrologic response unit (HRU) as the basic computing unit and divides the watershed into several sub-basins according to the topographic features, soil, vegetation and other factors. Each sub-basin contains several HRU. The rainfall, vegetation intercept, evapotranspiration, surface runoff, soil and underground runoff of HRU are calculated first, then the sub-basins’ runoff is calculated through the calculation of slope confluence, finally the watershed’s water resource is calculated through the calculation of riverbank confluence. The calculation of water balance in HRU in each sub-basin adopts lumped method, and distributed method is adopted among different sub-basins, that is, there is hydraulic connection existing between sub-basins. The water cycle process in HRU calculation includes four parts. surface, soil layer, shallow aquifer and deep aquifer. The movement calculation of soil water includes five processes. infiltration, evaporation, vegetation interception, lateral flow, and subsurface boundary seepage. The groundwater recharge calculated in SWAT model is the sum of the seepage amount at the bottom boundary of the soil layer, the channel transport loss and the infiltration amount of the reservoir and pond. The schematic diagram of SWAT model is shown in Figure 1.
2.1.2. The disadvantages of SWAT model. The irrigation module defines the HRU where the irrigation field is located as a pond, and carries out irrigation water simulation according to its pre-set rules of irrigation, water storage or drainage. The threshold method of water stress or the threshold method of soil water shortage is used to start irrigation operation in irrigation simulation, and the method of irrigation water consumption simulation is from top to bottom of the HRU, and the water balance calculation of surface runoff, water inflow, leakage, evapotranspiration and phreatic water evaporation is carried out successively. Meanwhile, there are three ways to simulate the operation of the reservoir. one is to release water according to the daily and monthly discharge specified by the user, the other is to release water when the water level of the reservoir exceeds the normal storage level by using the discharge method without control measures, the third is to release water according to the target storage capacity set by the water user.

Based on the analysis of the functions of SWAT model, there are six aspects of improvement about SWAT model in order to simulate the water cycle of irrigation area accurately. First, when the water cycle process in irrigation area is simulated, paddy field planting is regarded as a part of independent HRU, which is not simulated as an independent HRU, and paddy field planting and dry field planting are treated equally, resulting in the simulation process of paddy field water inconsistent with the actual situation. Second, the calculation method of water balance factors in irrigation area needs to be improved. The calculation method of SWAT model for water balance factors such as paddy field storage volume, paddy field surface runoff, paddy field evapotranspiration and phreatic water evaporation is inconsistent
with the actual situation of irrigation area. Thirdly, the irrigation mode is not in accordance with the actual situation. The model can’t accurately reflect the actual irrigation operation of paddy field by using the threshold judgment method of plant water stress or soil water shortage. Fourthly, when a single HRU implements the irrigation module, only a single water source can be selected for irrigation, and other water sources in the sub basin can’t be used. Fifthly, the irrigation water is directly input to the field, without considering the water loss of the canal system in the original model, which is inconsistent with the actual situation. Sixthly, the model can’t simulate other functions of irrigation area. The model does not have water use simulation modules, such as urban water supply, hydropower generation and ecological water supply. Therefore, SWAT model needs to be improved.

2.2. Improvements of SWAT model
In view of the disadvantages of SWAT model, the improvements were as following five aspects.

2.2.1. Improvement of the simulation structure of water cycle of HRU. The simulation sequence of water balance in SWAT model is improved, and the paddy field is simulated as an independent HRU. So that its water cycle simulation level is the same as that of other land use types. At the same time, the runoff and seepage calculation of paddy field in impoundment period and non-impoundment period are distinguished. The structure of water cycle simulation of improved SWAT model is shown in Figure 2.

![Diagram of water cycle simulation of improved SWAT model]

2.2.2. Improvement of surface runoff calculation of HRU. Firstly, the surface area of paddy field is set as its HRU area, and the ridge coefficient is adopted to deduct the area occupied by the ridge, so that the irrigation area of paddy field is more practical. Secondly, three control water depths (i.e. the upper limit $H_{max}$, the lower limit $H_{min}$, and the maximum storage depth $H_p$ after rain) are adopted to calculate the surface runoff during the irrigation period of paddy field.
2.2.3. **Improvement of water demand and consumption calculation of field.** First of all, the calculation of free drainage flux and leakage when there is no water layer in paddy field growth period is improved. Secondly, the limitation condition that the evapotranspiration of paddy field is less than that of reference crop is modified, and the evapotranspiration of paddy field is calculated according to the two situations of water layer and no water layer in the field. Thirdly, the evaporation of phreatic water is calculated by using the empirical formula of Mao Zhi. Fourthly, According to the actual operation of paddy field in irrigation area, the triggering condition of paddy field irrigation and the calculation model of water demand are improved.

2.2.4. **Improvement of multi-source irrigation operation.** Firstly, the regulation that it is impossible to take the pond as an irrigation water source in the sub basins simulation is improved by adopting multi-source irrigation operation. Secondly, considering the loss of water transmission and distribution during irrigation of various water sources, the effective utilization coefficient of irrigation water is adopted to modify the irrigation water consumption. Thirdly, the sequence of water sources is specified by compiling water source code.

2.2.5. **Improvement of non-irrigation function simulation of multifunctional reservoirs.** The non-irrigation function of multi-functional reservoir is simulated according to the regulation and operation rules of reservoirs. Among them, the water supply function is improved by loading the actual water supply in the water consumption module of the model.

3. **Sub basins division and HRU dispersion of improved SWAT model**

Sub-basins division is an important part of water resources system simulation in irrigation area. The division method has a direct impact on the accuracy of water cycle simulation in irrigation area, and is the key to improve the function of SWAT model [14]. SWAT model divides sub basins on the basis of digital elevation map (DEM), which is suitable for runoff simulation of large basins or river channels. However, for the irrigation water resources system composed of natural and social binary water circulation system, managed by multi-level main body and with multi-source and multi-functional multi-level canal system, this method is difficult to realize the hydraulic relation simulation of all kinds of water source projects and irrigation canals in the irrigation area. It is difficult to accurately describe the relationship between the natural water cycle process and the social water cycle (formed by the irrigation channels and drainage system of the irrigation area). At the same time, when the original SWAT model is used to generate sub basins, there may be a phenomenon that a sub basin spans several channel control areas, and there may also be cases where the water cycle process of the sub basin does not coordinate with the irrigation and drainage processes of the irrigation area. Therefore, the sub basin division method of SWAT model needs to be improved in solving the simulation of water resources system in the irrigation area.

According to the characteristics of multi-functional and multi-water sources irrigation area system, based on the sub basins automatically generated by SWAT model, and closely combined with the layout and structure of irrigation channel and drainage system, this paper proposes an improved method for sub basin division of irrigation district water resources system, as shown in Figure 3 below. The specific operation steps are as follows, firstly, through continuous debugging of SWAT model, appropriate unit area is set to divide sub basins with appropriate distribution density, secondly according to the layout of irrigation channel system, drainage system and spatial distribution of field block in the irrigation area, the sub basin distribution in line with the social water cycle structure of the irrigation area is formed by deleting the catchment nodes and sub basins. This method not only reflects the characteristics of natural water cycle process, but also conforms to the objective reality of social water cycle process in irrigation area.
4. The main calculation principles of the improved SWAT

4.1. Surface runoff Calculation of paddy fields

The calculation principle of surface runoff in paddy field is divided into irrigation period and non-irrigation period [15].

4.1.1. Irrigation periods. When the water storage depth exceeds the maximum water storage depth \( H_p \) after rain of the field, all the precipitation forms surface runoff. At the same time, the relationship between rainfall and runoff is used to calculate the surface runoff formed by rainfall on the ridge. The calculation formula of surface runoff of rice field in the impoundment stage is as follows.

\[
h_{t1} = h_0 + (1 - \text{ridge}) \cdot P + \text{ridge} \cdot (1 - \alpha) \cdot P \quad (1)
\]

\[
q_{\text{day}} = \text{ridge} \cdot \alpha \cdot P \quad \text{when } h_{t1} \leq H_p \quad (2)
\]

\[
q_{\text{day}} = (h_{t1} - H_p) \cdot (1 - \text{ridge}) + \text{ridge} \cdot \alpha \cdot P \quad \text{when } h_{t1} > H_p \quad (3)
\]

\[
h_{t2} = H_p \quad (4)
\]

Where, \( h_{t1} \) is the depth of water layer after rainfall of the field, mm, \( h_0 \) is the depth of water layer before rainfall of the field, mm, \( \text{ridge} \) is the ridge coefficient referring to the ratio of the ridge to the whole field, \( \alpha \) is the rainfall-runoff coefficient, \( P \) is the rainfall in time period t, mm, \( q_{\text{day}} \) is the surface runoff in time period t, mm, \( h_{t2} \) is the depth of water layer after surface runoff is generated of the field in time period t (mm).

4.1.2. Non-irrigation period. The runoff formation is discharged completely from the field. At this time, the principle of full storage and runoff yield is adopted in the calculation of surface runoff.
4.2. Calculation of leakage
According to the growth period of paddy field, it can be divided into two types: the one with water layer and the one without water layer.

4.2.1. Water layer. When there is an aquifer in the rice growth period, its leakage is affected by factors such as field soil quality, groundwater level, field water depth and management measures, etc., which can be determined by the observation value in this area or by referring to relevant data.

4.2.2. No water layer. When there is no water layer in the rice growth period, the free drainage flux is calculated according to the soil moisture content, water conductivity, etc., using the mechanism of full storage and flow production. That is to say, when the upper soil moisture content is greater than the field moisture content, the excess soil moisture moves downward to supply the lower soil, and so on. The soil water leaving the water absorbing layer of crop roots forms the deep leakage.

4.3. Calculation of evapotranspiration
The evapotranspiration of paddy field can be divided into two types: the one with water layer and the one without water layer. When there is a water layer in the field, evapotranspiration of paddy field is calculated according to water surface evaporation, ignoring soil evaporation, when there is no water layer on the field surface, evapotranspiration of paddy field is calculated according to soil evaporation, ignoring water surface evaporation. In the calculation process, the rice crop coefficient (kc) is considered to calculate the maximum transpiration.

4.4. Calculation of phreatic water evaporation
Mao Zhi et al.’s empirical formula was adopted.

\[ CR = ET_a \cdot \exp(-\sigma \cdot d) \]  

(5)

Where, \( CR \) is the capillary rising water volume, mm/d, \( ET_a \) is the actual evapotranspiration, mm/d; \( \sigma \) is a represent the empirical coefficient of soil water conveyance capacity, 2.1, 2.0 and 1.9 can be taken respectively for sandy soil, loam and clay; \( d \) is depth in the ground water, m.

4.5. Irrigation conditions and calculation of water demand

4.5.1. Irrigation conditions. The concepts of upper and lower limit of suitable water layer depth in paddy field development period is adopted, namely, \( H_{\text{max}} \) and \( H_{\text{min}} \) as mentioned above. When the water layer depth (\( h \)) of paddy field is close to or equal to the lower limit of suitable water layer (\( H_{\text{min}} \)) and the daily rainfall is less than 5mm, irrigation conditions is triggered and irrigation is required.

4.5.2. Calculation of irrigation water demand. Through the upper limit of the suitable water layer and the current depth of the water layer in the field, the net water amount needed to be irrigated to the field is analysed, and then the field loss coefficient is adopted to calculate the amount of water needed to be irrigated. The calculation formula is as follows.

\[ m = \xi \cdot (H_{\text{max}} - h) \]  

(6)

Where, \( m \) is the quantity of irrigation water, mm, \( \xi \) is the loss coefficient of the field, whose value range is 1.1~1.3, \( H_{\text{max}} \) is the upper limit of suitable water depth of rice field, mm, \( h \) is the depth of field water layer during irrigation, mm.

4.6. Multi-source irrigation operation
It was modified that the original SWAT model can’t use the pond in the sub basin as the irrigation water source, and the multi-source irrigation operation was adopted. That is to say, for a certain irrigation user,
the water source is selected for irrigation according to the given water supply sequence until the water demand is met. The order of multi-source water supply is generally set as the internal river channel of the sub basin, the sub basin’s internal pond, and the small (I) and bigger reservoirs outside the sub basin, the leading control reservoir of the irrigation area, etc.

4.7. Calculation of available water supply for irrigation sources
Considering the loss of water transmission and distribution during irrigation, the effective utilization coefficient of irrigation water is introduced to modify the available water supply calculation of the original SWAT model. The calculation formula of available water supply for each type of water source is as follows.

River, \[ A = \text{wtr} \cdot \beta \cdot \eta / (10 \cdot \text{area}) \]  
(7)

Pond, \[ A = (V_t - \zeta \cdot V_{\text{total}}) \cdot \eta / (10 \cdot \text{area}) \]  
(8)

Reservoir, \[ A = V_r \cdot \eta / (10 \cdot \text{area}) \]  
(9)

Where, \( A \) is the water available of irrigation water source, mm. \( \text{wtr} \) is the current water volume of the river, \( 10^4 \text{m}^3 \). \( \eta \) is the effective utilization coefficient of irrigation water. \( V_r \) is the current water storage capacity of the reservoir or pond, \( 10^4 \text{m}^3 \). \( V_{\text{total}} \) is the total reservoir capacity of the ponds within the sub-basin, \( 10^4 \text{m}^3 \). \( \text{area} \) is the area to be irrigated for the current simulated HRU, \( \text{hm}^2 \), refers to the area of HRU for dry land, and the area except the ridge for paddy field. \( \beta \) is the control coefficient of river irrigation water, that is, the proportion of the actual irrigation water in the available water, which mainly considers the water intake capacity of the project and the ecological base flow. The specific value is determined at parameter calibration. \( \zeta \) is the control coefficient of irrigation water in the pond, that is, the proportion of dead storage capacity in the total storage capacity. This parameter mainly considers that the pond needs to retain a certain amount of water to ensure its cultivation, ecology and other functions.

4.8. Calculation of channel leakage
The water loss of irrigation canal system is an important supply of groundwater. Generally, the area that irrigation canal passes through is the area that needs irrigation, and its water loss is also the supply of groundwater in these areas. Therefore, it is considered that the water loss of the channel during irrigation of the HRU is directly supplied to the groundwater of the HRU in this improvement. The calculation formula is as follows.

\[ \text{Loss} = \text{Irr} \cdot (1 - \eta) \]  
(10)

Where, \( \text{Loss} \) is the amount of canal system leakage, mm, which directly replenishes the groundwater. \( \text{Irr} \) is the amount of water taken from the multi-source, mm, \( \eta \) is the effective utilization coefficient of irrigation water.

5. Parameter calibration of improved SWAT model
The parameters of the improved SWAT model can be generally divided into two categories. One is the parameters of the original SWAT model, and the other is the parameters of the improved SWAT model.

5.1. Parameters calibration of original SWAT model
There are many parameters in SWAT model. Firstly, the sensitivity analysis of parameters is carried out to find out the parameters which have significant influence on the simulation results. In this paper, the sufi_2 algorithm in SWATCUP software is used to analyze the parameter sensitivity of SWAT model and select the sensitive parameters. For the selected sensitive parameters, SWATCUP software and manual adjustment method are used to adjust the parameter value continuously until the model simulation effect evaluation parameters reach the reasonable value range.
5.2. **Parameter calibration of improved SWAT model**

In order to further improve the simulation effect of the improved SWAT model on the water cycle process in the irrigation area, the actual monitoring data in the irrigation area were used for calibration of the parameters added to the improved SWAT model, including three parameters, field loss coefficient $\xi$, river irrigation water control coefficient $\beta$ and pond irrigation water control coefficient $\zeta$. The calibration steps are as following. Firstly, according to the hydrological response unit division method of the improved SWAT model, the sub basins and HRU are divided and connected with the layout of the actual monitoring points in the irrigation area. Secondly, according to the monitoring points in the irrigation area, the sub basins and HRU division results in the irrigation area, the water balance model of the water quantity at each monitoring point and the water intake of the water source is established. Thirdly, according to the water balance model of the water quantity at each monitoring point and the water intake of the water source, the manual method is adopted to adjusts the field loss coefficient $\xi$, river irrigation water control coefficient $\beta$ and mountain pond irrigation water control coefficient $\zeta$ in the model until the simulated water amount results of each monitoring point are basically consistent with the measured monitoring results.

6. Conclusion

In the water resources system of multi-functional Irrigation District, there are relations, dynamics and mutual feedbacks between each sub basin and HRU, between the same sub basin and HRU, between the upper sub basin (or HRU) and the lower sub basin (or HRU), between the previous period and the later period of the whole system, and between the elements of the water resources system.

The improved SWAT model can carry out the system simulation of natural water circulation process and social water circulation process in irrigation area, realize the orderly coupling and response analysis of natural water circulation and social water circulation process in complex water resource system, and accurately and quantitatively describe the water circulation law in multi-functional irrigation area.

The HRU partition method of improved SWAT model is practical. It can not only describe the relationship between the natural water circulation process and social water circulation, but also combine the HRU division with the hydraulic connection between the water source project, the irrigation channel and the drainage system in the irrigation area, which conforms to the water circulation process and the reality of the irrigation area.

The improved SWAT model parameter calibration method not only makes full use of the function of SWAT model, but also uses the actual monitoring results to increase the parameters of the model. It realizes the orderly combination of water cycle simulation and water resource allocation process in irrigation area.

The application case of improved SWAT model is given in the next part.

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