Study on water cycle simulation model of multi-sources and multi-functional irrigation area based on SWAT model (II): Application of Wanyao irrigation area

Jinhua Wen¹, Shiwu Wang¹, Helong Wang¹, Yuanlai Cui²

¹. Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China; ². Wuhan University, Wuhan 430072, China

E-mail: wenji80@sina.com.

Abstract. Aiming at the water cycle simulation in multi-sources and multi-functional irrigation area, the improved SWAT model was constructed and applied to Wanyao irrigation area, which is located in Jiangshan county, Zhejiang province. The measured data from 1990 to 2006 of the watershed outlet observation stations named Jiangshan and Daqiao were used to calibrate the model parameters, which measured data from 2007 to 2017 were used to validate the model. The correlation coefficient of verification period of monthly runoff simulation was 0.91, Nash coefficient was 0.90, relative errors of simulated results and measured data of 16 monitoring facilities in irrigation area were within 10%. The improved SWAT model simulation results were used to construct the statistical models of irrigation water consumption in Wanyao irrigation area on a monthly scale and an annual scale respectively. The mean relative error of the monthly scale model is 4.5% and the mean relative error of the annual scale model is 1.2%, which satisfy the needs of accurate water resources management.

1. Introduction

The irrigated areas in the south of China are characterized by various functions of water source projects, many water sources and large annual differences in irrigation water consumption, diversified management subjects of water source projects, and supplementary irrigation (except paddy field planting). The statistical methods of irrigation water consumption given by the current national and local policies and documents is limited and lack of practical examination to these irrigated areas [1]. The water cycle simulation model of the irrigation areas with multi functions and multi sources was intended to be constructed, and the statistical method of which irrigation water consumption were intended to be studied.

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]. However, the research about 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 is relatively scarce. In this paper, based on the first part of this paper, a water cycle simulation model of multi-functional irrigation area based on SWAT model is constructed. Taking Wanyao irrigation area of Jiangshan City as an example, the application research is carried out. Based on the results of water cycle simulation model of Wanyao irrigation area of Jiangshan City, the statistical model of irrigation water consumption is established.
2. Model construction of research area

2.1. Overview of research area

Wanyao irrigation area is located in the southwest of Zhejiang Province, the west end of Jinqu basin at the junction of Zhejiang, Fujian and Jiangxi provinces, covering most areas of Jiangshan City. The total area of the land is 1.343 million mu, and the irrigation scope mainly includes 12 towns of Wanyao, Qinghu, Shangyu, Sidu, Xiakou, Fenglin, xintangbian, Yutou, Hecun, Tanshi, Daqiao, Shimen and two streets of Hushan and Shuangta in Jiangshan City, as well as two towns of Huashu and Hangbu in Kecheng County, with a total population of 459000. The irrigation area consists of hills and plains, with high mountains in the East and West and low valleys in the middle. It spreads gently in steps from both sides of Jiangshan port to the downstream. The irrigation area is 265000 mu (including 172000 mu of paddy field and 93000 mu of dry land). The planting structure of the irrigation area is mainly grain production, supplemented by some economic crops. The grain is mainly single season rice, supplemented by a small amount of wheat, sweet potato, etc. the economic crops are mainly rape, vegetables, etc.

In the irrigation area, the plain area along both sides of Jiangshan port is sandy loam, accounting for 1/3 of the irrigation area; the hilly area is clayey loam, accounting for 2/3 of the irrigation area. The annual average precipitation is 1773 mm, the annual average evaporation is 990 mm, and the annual average runoff depth is 1200 mm. There are three large and medium-sized reservoirs in the irrigation area, namely Baishuikeng reservoir, Wanyao Reservoir and Xiakou reservoir. The three reservoirs have a total catchment area of 941.8 km², a total storage capacity of 533 million m³, and a total profit-making storage capacity of 365 million m³. Their functions are mainly irrigation, flood control, urban water supply, power generation and other comprehensive utilization functions. There are 16 small (1) sized reservoirs with a total storage capacity of 31.41 million m³, 54 small (2) sized reservoirs with a total storage capacity of 17.39 million m³, and 2498 ponds with a total storage capacity of 17.11 million m³. In addition, 22 barrages and 10 pumping stations are built on Jiangshan port and its tributaries for water diversion or pumping for supplementary irrigation. There are 6 main canals in Wanyao irrigation area, with a total length of 192.7 km. There are 113 branch canals along the 6 main canals, with a total length of 214 km. There are more than 800 canal system buildings on the main canal.

2.2. Construction of improved SWAT model

According to the characteristics of water resource system, water source projects and irrigation channel system of Jiangshangang basin where the Wanyao irrigation area is located, and the water consumption of various industries in the irrigation area, based on the principle and method of improved SWAT model, the Wanyao irrigation area is divided into 148 sub basins by SWAT Model (2012), which are shown in Figure 1. Then, the hydrological response unit (HRU) is divided by land use data shown in figure 2 and soil type. The Wanyao irrigation area is divided into 1010 hydrological response units (HRUs).
2.3. Model data input

2.3.1. Hydro meteorological data input. It includes rainfall, temperature, relative humidity, solar radiation, daily average wind speed and meteorological station parameters, etc. The data series is daily series data from 1986 to 2017.

2.3.2. Data files input. Including reservoir information, pond information, field management measures, reservoir operation rules, point source emission data, rice growth period division, evapotranspiration, field water layer control depth, crop coefficient, irrigation water source designation and other documents.

2.3.3. Other parameters input. The components include ridge coefficient, field loss coefficient, buried depth of phreatic floor, effective utilization coefficient of irrigation water, control coefficient of irrigation water for external river channel of sub basin, control coefficient of irrigation water for mountain pond, etc. See Table 1 for the initial value of SWAT model parameters in Wanyao irrigation area, and the final value of parameters to be calibrated shall be determined after model calibration and verification.
Table 1 Initial values of parameters of improved SWAT model in Wanyao irrigation area

| The serial number | The parameter name                              | Parameter meaning                                      | The initial value |
|-------------------|------------------------------------------------|--------------------------------------------------------|------------------|
| 1                 | Ridge coefficient                               | The ratio of field ridge to paddy field area            | 0.15             |
| 2                 | Field loss coefficient                          | Plot channel irrigation loss coefficient                | 0.83             |
| 3                 | Subsurface depth of phreatic layer (m)          | The depth from the diving floor to the ground           | 10               |
| 4                 | Effective utilization coefficient of irrigation water | The proportion of effective irrigation water to irrigation water | 0.5              |
| 5                 | River irrigation water control coefficient      | The proportion of water available for irrigation in the current period | 0.3              |
| 6                 | Control coefficient of irrigation water in pond | The proportion of water available for irrigation in the current period of time | 0.3              |

3. Calibration and validation

3.1. Parameter calibration and verification of SWAT model

3.1.1. Parameter calibration. Based on the monthly flow data of Jiangshan port and Daqiao town from 1990 to 2006, sufi_2 algorithm in swatcup software is used to analyze the parameter sensitivity of the SWAT Model in Wanyao irrigation area, and the top 10 parameters with relatively significant sensitivity are obtained. On this basis, using swatcup software and manual parameter adjustment method, the parameters with relatively significant sensitivity are calibrated. See Table 2 for the model sensitivity parameters.

Table 2. The value of sensitivity parameters of SWAT model in Wanyao irrigation area

| parameter   | woodland | rice | The dry land | The orchard | Cities and towns |
|-------------|----------|------|--------------|-------------|-----------------|
| LAT_TIME    | 0.65     | 0.92 | 0.65         | 0.8         | 0.52            |
| ALPHA_BF    | 0.66     | 0.66 | 0.66         | 0.8         | 0.52            |
| FLOWFR      | 0.84     | 0.36 | 0.79         | 0.71        | 0.61            |
| ESCO        | 13.42    |      | 13.42        |             |                 |
| SURLAG      | 0.11     |      | 0.11         |             |                 |
| CN2         | 0.43     |      | 0.43         |             |                 |
| MSK_CO2     | 0.98     | 0.98 | 0.98         | 0.71        | 0.84            |
| MSK_X       | 0.85     |      | 0.85         | 0.44        | 0.84            |
| SOL_AWC     | 1.15     |      | 1.15         |             |                 |

3.1.2. Model validation. Based on the monthly flow data of two exports of Jiangshan port and Daqiao town from 2007 to 2017, swatcup software was used to verify the model and verify the applicability and stability of the model after parameter calibration. See Table 3 for the evaluation of SWAT model validation results of Wanyao irrigation area.
### Table 3 Evaluation of SWAT model validation results

| Simulation period       | Station name | Exit sub-basin number | flow data of year | RE (%) | R²    | NS  |
|-------------------------|--------------|-----------------------|-------------------|--------|-------|-----|
| Validation period       | Jiangshan    | 6                     | 2007 ~ 2017       | 4.8    | 0.91  | 0.9 |
|                         | Daqiao       | 25                    |                   | 3.8    | 0.91  | 0.89|

It can be seen from table 3 that the evaluation grade of the relative error of the simulation results during the validation period of the water cycle simulation model of the Wanyao irrigation area calibrated by the parameters is excellent, the evaluation grade of the linear regression coefficient is good, and the evaluation grade of the Nash coefficient is excellent. It can be seen that the flow simulation accuracy is high and the stability is good during the validation period of the water cycle model of the bowl kiln irrigation area.

The comparison chart of the measured average flow and the simulated average flow of the two outlets of Jiangshan port and Daqiao town in Wanyao irrigation area from 2007 to 2017 is drawn in Figure 3 and Figure 4.

3.2. Parameter calibration of improved SWAT model
3.2.1. Parameters and calibration methods. The parameters needed to be calibrated including field loss coefficient, river irrigation water control coefficient and pond irrigation water control coefficient. The calibration steps are as follows. Firstly, the logical relationship between the monitoring facilities of irrigation area with the sub basins and the hydrological response unit (HRU) of the improved SWAT model is connected, and the water balance equation of the sub basins and the hydrological response unit (HRU) of the improved SWAT model with the monitoring facilities of irrigation area is established. Secondly, according to the simulation results of the improved SWAT model, the amount of water flow of each monitoring facility in the irrigation area is calculated (hereinafter referred to as the simulation results). Thirdly, comparing the simulation results of each monitoring facility in the irrigation area with the measured data, adjusting the field loss coefficient, river irrigation water control coefficient and mountain pond irrigation water control coefficient in the model by using the manual trial method, so that the simulation results of each monitoring facility are consistent with the measured data, then each parameter is the calibration value.

3.2.2. Calibrated parameters of improved SWAT model. The field loss coefficient, river irrigation water control coefficient and pond irrigation water control coefficient are determined by using the monitoring data of each monitoring facility in the Wanyao irrigation area in 2017 and the actual power generation capacity of Heshe power station, Muxiban power station, Xujiang power station and other channel power stations in 2017. The results are shown as $\xi = 0.93$, $\beta = 0.3$, $\zeta = 0.2$. The simulation error of each monitoring facility is shown in Table 4.

It can be seen from table 4 that through the calibration of the field loss coefficient, river irrigation water control coefficient and mountain pond irrigation water control coefficient in the improved SWAT model of the irrigation area, the absolute value of the relative difference between the simulation results and the measured results of the monitoring water volume of each monitoring facility in the irrigation period 2017 in the Wanyao irrigation area is within 10%. It shows that the new parameters in the improved SWAT model can further improve the simulation accuracy of water cycle simulation model in Wanyao irrigation area.

| Name of monitoring point                  | Simulated water volume (10,000 m³) | Monitored water volume (10,000 m³) | The relative error |
|------------------------------------------|------------------------------------|----------------------------------|--------------------|
|                                          | irrigation                        | Power generation (ecology)        |                    |
|                                          | Aug. | Sep. | Aug. | Sep. | Sum   | Aug. | Sep. | Sum   |                   |
| Jiantounong power station                | 2207 | 1133 | 1008 | 487  | 4835  | 3106 | 1590 | 4696  | 3.0%               |
| Heshe aqueduct intake                    | 836  | 647  | 0    | 0    | 1483  | 858  | 564  | 1422  | 4.3%               |
| Qingkou branch canal bleeder             | 70   | 44   | 0    | 0    | 114   | 67   | 43   | 110   | 3.6%               |
| Qingkou pump station intake              | 72   | 50   | 0    | 0    | 122   | 68   | 49   | 117   | 4.3%               |
| West trunk canal Qingkou branch canal intake | 42   | 50   | 0    | 0    | 92    | 39   | 49   | 88    | 4.5%               |
| West trunk canal Rugu pond inlet         | 31   | 23   | 0    | 0    | 54    | 29   | 23   | 52    | 3.8%               |
| West trunk canal Rugu pond branch canal bleeder | 20   | 15   | 0    | 0    | 35    | 19   | 15   | 34    | 2.9%               |
| West trunk canal Rugu pond branch canal bleeder | 11   | 8    | 0    | 0    | 19    | 10   | 8    | 18    | 5.6%               |
| Name of monitoring point                  | Simulated water volume (10,000 m³) | Power generation (ecology) | Monitored water volume (10,000 m³) | The relative error |
|------------------------------------------|-----------------------------------|----------------------------|-----------------------------------|-------------------|
|                                          | Aug. | Sep. | Aug. | Sep. | Sum  | Aug. | Sep. | Sum  |                  |
| East trunk canal intake                  | 386  | 306  | 721  | 532  | 1945 | 1090 | 827  | 1917 | 1.5%             |
| Fenglin town weir dam intake             | 148  | 33   | 0    | 0    | 181  | 150  | 24   | 174  | 4.0%             |
| Fenglin town bleeder of east trunk canal | 120  | 90   | 0    | 0    | 210  | 123  | 99   | 222  | -5.4%            |
| East branch canal bleeder                | 180  | 130  | 0    | 0    | 310  | 186  | 133  | 319  | -2.7%            |
| Lianjianong reservoir bleeder            | 9    | 10   | 0    | 0    | 19   | 11   | 7    | 19   | 1.5%             |
| Qiwulong pond intake                     | 5    | 5    | 0    | 0    | 10   | 6    | 5    | 11   | -8.9%            |
| Yangliufeng reservoir inlet              | 55   | 30   | 0    | 0    | 85   | 60   | 32   | 92   | -8.0%            |
| Water inlet of main canal of Wanyao      | 1869 | 1062 | 3827 | 2565 | 9323 | 5715 | 3638 | 9353 | -0.3%            |

4. Statistical model of irrigation water consumption in irrigation area

4.1. Construction method of statistical model of irrigation water consumption in irrigation area

On the basis of determining the independent variables of irrigation water consumption statistical model, the improved SWAT model of Wanya irrigation area is used to simulate the water cycle process of irrigation area under different scenarios. The relevant statistical model of irrigation water consumption and independent variables is constructed by using the simulation results of irrigation area, which provides the basis for the statistical work of irrigation water consumption in irrigation area.

4.2. Statistical model independent variable screening method

Step by step regression method [11] is adopted for independent variable selection of statistical model, and the specific operation is as follows. Firstly, the independent variables were adopted one by one. After each independent variable is adopted, the selected variables are tested one by one. When the original adopted variables are no longer significant due to the adoption of later variables, they are eliminated. Secondly, a variable from the regression equation is adopted or removed for step-by-step regression, each step should be tested as a whole to ensure that only significant variables are included in the regression equation before each new variable is adopted. Thirdly, the above process is repeated until no significant independent variable is selected into the regression equation and no insignificant independent variable is in the regression equation.

4.3. Construction of statistical model of irrigation water consumption

Based on the data of independent variable and dependent variable from 1990 to 2006 in Wanyao irrigation area, the basic data of monthly scale and annual scale were counted respectively, and the multivariate linear regression statistical model was constructed by SPSS software. The significance test of overall linear correlation and regression coefficient is 0.2, and stepwise regression method is used for independent variable screening, and the screening results are shown in Table 5. See formula 1 for the
construction results of monthly irrigation water consumption statistical model and formula 2 for the construction results of annual irrigation water consumption statistical model.

| Monthly scale model | Variable number | t significant | Annual scale model | Variable number | t significant |
|---------------------|----------------|---------------|---------------------|----------------|---------------|
| Q22                 | 2.83           | 0.01          | Q9                  | 1.64           | 0.12          |
| Q21                 | 2.31           | 0.02          | Q13                 | 2.05           | 0.05          |
| Q25                 | 2.27           | 0.03          | Q17                 | 2.12           | 0.05          |
| Q14                 | 3.34           | 0             | Q6                  | 1.89           | 0.07          |
| Q16                 | 2.91           | 0             | Q10                 | 1.43           | 0.17          |
| Q9                  | 1.94           | 0.06          |                     |                |               |

\[
W_{\text{month, gross}} = \begin{cases} 
9.94Q_{22} - 12.68Q_{21} + 67.58Q_{25} + 60.54Q_{14} + 35.63Q_{16} + 105.65Q_{9} + 234 & \text{From June to September} \\
0 & \text{Other months}
\end{cases}
\] (1)

Where: \( W_{\text{month, gross}} \) is the monthly irrigation water consumption of the irrigated area; \( Q_{22}, Q_{21}, Q_{25}, Q_{14}, Q_{16}, \) and \( Q_{9} \) respectively, are the upper bleeder of Hecun in east main canal, the lower bleeder of Hecun town in east main canal, the headstream inlet of suzhou pond reservoir, the headstream bleeder of Qiyigang ridge, the headstream bleeder of Fenglin town in east main canal, and the bleeder monitoring of Rugutang branch canal.

\[
W_{\text{year, gross}} = 2471.45Q_{9} + 63.09Q_{13} + 481.46Q_{17} + 50.14Q_{6} - 1180.25Q_{10} + 2409
\] (2)

Where, \( W_{\text{year, gross}} \) is the annual irrigation water consumption in the irrigated area; \( Q_{9}, Q_{13}, Q_{17}, Q_{6}, \) and \( Q_{10} \) respectively, are Rugutang branch canal bleeder, Yangliufeng reservoir canal head intake, Fenglin town vegetable field pump station intake, Qingkou branch canal bleeder, the west main canal rugutang intake water quantity monitoring.

4.4. Verification of statistical model of irrigation water consumption in irrigation area

The measured and monitored data from 2007 to 2017 in the Wanyao irrigation area are used for statistics on monthly and annual scales respectively. The irrigation water consumption in the Wanyao irrigation area is calculated by formula 1 and formula 2 respectively and compared with the measured data. The corresponding results are shown in Figure 5 and Figure 6.
It can be seen from figures 6 and 7 that the average relative error of monthly scale statistical model is 4.5%, and the relative error is within 10%. Meanwhile, the average relative error of annual scale statistical model is 1.2%, and the statistical accuracy is better than that of monthly scale statistical model, and the stability of monthly scale and annual scale statistical model is better.

5. Conclusions and recommendations
According to the characteristics of natural social dual water cycle system in Wanyao irrigation area, a multi sources and multi-functional water cycle simulation model based on the improved SWAT model is constructed. After the model parameters are calibrated, it can be used to quantitatively and accurately describe the water cycle process in Wanyao irrigation area, which provides a reference for the accurate management of water resources in similar irrigation areas.

On the basis of SWAT model, aiming at the disadvantages in simulating the water cycle process of multi sources and multi-functional irrigation area, the paper has successfully applied it in the Wanyao irrigation area through the improvement of the simulation structure of HRU water cycle, calculation of surface runoff, field water demand and consumption, multi-source irrigation mode, non-irrigation
function simulation, etc. The results show that the improved SWAT model can better simulate the water cycle process of multi sources and multi-functional irrigation area.

By using the improved SWAT model, aiming at the water cycle simulation results of Wanyao irrigation area, the statistical model of irrigation water consumption is constructed, and the analysis and prediction effect is good. It is suggested that the monthly irrigation water consumption statistical model should be used for analysis and prediction, and the annual irrigation water consumption statistical model should be used for review after the end of irrigation period in practical application.

Acknowledgment
This work was financially supported by National Key Science and Technology Plan Project (2019YFC0408800), and Water conservancy science and technology project of Zhejiang Province (RB1911), and Technology demonstration project of the ministry of water resources (sf-201801).

References
[1] Yuanlai C, Di W, Shiwu W, et al. Simulation and analysis of irrigation water consumption in southern multi-source irrigation area based on improved SWAT model. Transactions of the Chinese Society of Agricultural Engineering, 2018, 7 94-100.
[2] Xin S, Qiangkun L and Buhui C. Application of SWAT model in Qingtongxia irrigation area, Water Saving Irrigation, 2018, 6 0086-9.
[3] Chunhong M, Zhenguang L, Xixia M, et al. Application and research of distributed hydrological model in irrigation area based on binary water cycle, Journal of Water Resources and Water Engineering, 2013, 24 92-7.
[4] Yuzhi S, Chi Z, Huicheng Z, et al. Improvement and application of SWAT model in rice irrigation area, Water Resources and Power, 2010, 28 18-22.
[5] Xin S and Zhen C. Application of SWAT model in Qingtongxia irrigation water cycle research II: model application, Water Saving Irrigation, 2019, 1 18-21.
[6] Gosain A K, Rao S, Srinivasan R, et al. Return‐flow assessment for irrigation command in the Palleru river basin using SWAT model. Journal of Hydrological the Processes, 2005, 19 (3) 673-682.
[7] Ahmadzadeh H, Morid S, Delavar M, Et al. Using the SWAT model to enable the success of changing irrigation from surface to pressurized systems on water productivity and water saving in the Zarrineh Rud catchment. Agricultural Water Management, 2015, 175 15-28.
[8] Junfeng D and Yuanlai C. Based on distributed hydrological model irrigation area in SWAT II. Model application. Journal of Hydraulic Engineering, 2009, 40 311-8.
[9] Jie Z, Guangyong L and Zhenzhong H. Application of improved SWAT model in plain irrigation area. Journal of Hydraulic Engineering, 2011, 42 88-97.
[10] Jiangen Z, Jinhua W, Helong W, et al. Research on water cycle simulation and statistical model of irrigation water consumption in Jiangshan City Wanyao irrigation area. Zhejiang Institute of Hydraulics and Estuary, Oct. 2018.
[11] Qiong L, Jiahua W, Juan A, et al. Fusion correction of rainfall data of TRMM 3B43 based on topographic factors in the source region of the Yellow River, Journal of Basic Science and Engineering, 2016, 26 1147-1163.