Monitoring and statistical methods of irrigation water consumption of Wanyao Irrigation Area

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Abstract. Irrigation water consumption statistical work is very important to water resources management. As for Zhejiang province, the problems of irrigation water consumption statistics are that there are too many water sources to monitor which discharge and too many usages to separate from a certain amount of water. At the meantime, the irrigation water can return to the downstream fields and be reused in its irrigation, but the amount of reuse water is very difficult to monitor and count. Taking Wanyao irrigation area as the study object, the layout methods of monitoring facilities built to monitor the key sectors of water circulation were proposed, including the supplication sector, the utilization sector and the drainage sector. The water circulation model of irrigation area was constructed based on the monitoring facilities’ observed data, then the constructed model was applied to simulate the natural water circulation and the social water circulation. The supplication and utilization progress of irrigation water were extracted from the simulation results, and the reuse progress of irrigation water was analysed. Actual irrigation water consumption in irrigation area was counted in the last. The result shows that it’s feasible economically and technically to layout the monitoring facilities based on water circulation simulation of irrigation area, and the statistics method of irrigation water consumption by simulating the water circulation is reliable and high precise.

1. Introduction

Zhejiang Province is located in the southern region with abundant water, where the traditional irrigation mode is relatively extensive that has caused a series of problems such as water pollution and water shortage in some areas. It is an important work to carry out agricultural irrigation water monitoring and to statistic the water consumption of irrigation, which will strengthen the supervision of the process of water withdrawal in irrigations, realize the refined management of water resources and improve the agricultural water saving level. With numerous and scattered irrigation water sources, the massive investment makes it economically infeasible to monitoring water discharge directly [1]. In addition, the irrigation areas in Zhejiang Province are generally located in the valley plains where human activities are intensive. Most of the irrigation water sources assume a number of beneficial tasks such as water supply, irrigation, electricity generation and eco-environmental water, which means the discharge of water source generally includes multiple use water and it is difficult to isolate the consumption of irrigation [2]. At the same time, due to the continuous circulation of water resources in irrigation areas, there exists a common phenomenon that irrigation return water will reuse between the irrigation-connected irrigation patch [3]. It is hard to control the use of irrigation return water only by monitoring the water supply at the source [4]. Therefore, the way to statistic the amount of irrigation water by monitoring the water source discharge is technically unworkable. Aiming at these problems above,
based on the theory of water cycle, an irrigated water statistic method by simulating the natural-artificial water cycle in the irrigation areas to extract the process of irrigation is put forward in this paper. Under the guidance of this method, a way to arrange irrigation water consumption monitoring facilities based on the simulation of water cycle in the irrigation area was proposed, and the observed water quantity of monitoring facilities was applied to the calibration of parameters in the water cycle model of irrigation area. Taking Wanyao Irrigation Area of Quzhou City, Zhejiang Province as a research object, the layout of the monitoring facilities for irrigation water consumption in Wanyao Irrigation Area was developed, and a water cycle model of Wanyao Irrigation Area was constructed based on the observed water quantity of monitoring facilities. Then the model was used to simulate the process of water supply and consumption in all walks, such as agricultural irrigation, urban and rural water supply, and the utilization of irrigation return water was analyzed, the actual irrigation water consumption in the irrigation area was counted finally.

2. Overview of Wanyao Irrigation Area

2.1. Physical geography
Wanyao Irrigation Area is located in Jangshan, a city of southwest Zhejiang Province, at the western end of the Jinyu Basin at the junction of the three provinces of Zhejiang, Fujian, and Jiangxi, with Fujian in the south and Jiangxi in the west. The geographical location is between 118°22′29″S and 118°48′48″S, 28°14′29″N and 28°53′24″N. The total area of the irrigation area is 1,343,000 mu, the designed irrigation area is 424,500 mu, and the actual irrigated area is 265,000 mu, in which, 172,000 mu of paddy field and 93,000 mu of dry land. The current crops are based on double and single cropping rice, supplemented by a small amount of wheat and sweet potatoes, and cash crops mainly include rapeseed and vegetables.

2.2. Water source projects
There are various types and numbers of irrigation water sources in the Wanyao Irrigation Area. There are a total of 2571 existing water storage projects, including 2 large reservoirs, namely Baishuikeng Reservoir and Wanyao Reservoir, 1 medium reservoir, Xiakou Reservoir, and the total storage capacity of the three reservoirs is 533 million m$^3$, 16 small reservoir of type 1 with a total storage capacity of 31 million m$^3$, 54 small reservoirs of type 2 with a total storage capacity of 17 million m$^3$, 2498 mountain ponds with a total storage capacity of 17 million m$^3$. In addition, there are many barrage diversion works on the rivers in the irrigation area, and the number of irrigation areas whose designed irrigation area are above 1000 mu is 22.

2.3. Irrigation projects
The irrigation project in Wanyao Irrigation Area mainly includes three channel heads and five main canal projects. In the downstream of the Wanyao Reservoir, a canal diversion project with a designed diversion flow of 22.5m$^3$/s is constructed to collect the tail water of the hydropower station for irrigate. The project has three canals, including the main canal, the north canal, and the east canal, with a length of 71.49km. The Baishuikeng-Xiakou Cascade Reservoir has two canal head projects, east canal and west canal. The head of the east canal is located 1km below the reservoir dam, and the supporting east canal is 48.1km long with a designed diversion flow of 8.2m$^3$/s. The head of the west canal is located at the end of the tail water canal of the reservoir’s hydropower station. The supporting west canal is 58.5km long and the designed diversion flow is 12.9 m$^3$/s.

3. Layout of agricultural irrigation water monitoring facilities
There are many water source projects in Wanyao Irrigation Area, and the hydraulic connections are intricate. If the method of direct monitoring of irrigation water sources is adopted, thousands of monitoring facilities need to be built, and need a large investment. Even so, it is still impossible to know the reuse of returning irrigation water within the irrigation area\cite{5}. Therefore, based on the simulation of
water circulation in the irrigation area, this paper proposed a method to arrange irrigation water consumption monitoring facilities: on the basis of fully understanding the water circulation law of the irrigation area, monitoring facilities for agricultural irrigation water consumption shall be set up at the major nodes of water cycle such as supply, use and drainage, to satisfy the needs of the construction of the natural-artificial water cycle model in the irrigation area.

3.1. Channel head of typical water source projects

By monitoring the process of water discharge in a typical water source channel head, the water release rules of any water sources will be understood and the real-time water usage of agricultural irrigation can be mastered. The water source project monitored in Wanyao Irrigation Area should cover various types includes large, medium, small reservoirs, mountain ponds, machine ports, etc. And in all types of water source projects, water sources with complete information, relatively high management level, and good operating conditions should be selected, taking into account the need for operation and maintenance.

3.1.1. Channel heads of large and medium reservoirs. There are three large and medium-sized reservoirs built in the Wanyao Irrigation Area, of which the Baishui Reservoir and Xiakou Reservoir form a cascade reservoir to supply water to the irrigation area. Due to the large amount of water in large and medium-sized reservoirs, their water supply accounts for a large proportion of the total water supply of various industries in the irrigation area. Based on this, one monitoring facility is set up in each of the east and west trunk canals of the Baishui- Xiakou Cascade Reservoir, and one monitoring facility is set up in the main trunk canal of Wanyao Reservoir.

3.1.2. Channel heads of typical small reservoirs of type 1. Some small reservoirs of type 1 in the Wanyao Irrigation Area have only one main irrigation canal, while some reservoirs have two or more. In accordance with the principles of engineering characteristics and good representative planting structure of irrigation crops, better running status of water source and irrigation projects, and ease of operation and maintenance, considering the spending on construction as well, Lianjianong Reservoir, Tangbeilong Reservoir and Suzhoutang Reservoir with only one irrigation canal are selected. Each of the three small reservoirs has one monitoring facility at its head.

3.1.3. Channel heads of typical small reservoirs and mountain ponds. Although the small reservoirs and mountain ponds in the Wanyao Irrigation Area have a small storage capacity, they play an important role in the actual irrigation process because they are widely spread and mostly distribute around the farmland that provide convenient access to water. In order to reflect the irrigation water consumption of the small reservoirs in Wanyao Irrigation Area, two small reservoirs, including Yangliufeng Reservoir and Qiwloung Mountain Pond, are selected to set up the monitoring facilities at the head of the main canal in accordance with the principles of good representativeness, well running status and easier to maintain.

3.1.4. Channel heads of typical machine ports. Wanyao Irrigation Area also has the situation of pumping water from the machine port. In order to analyze the irrigation water of this type of water source project, Qingkou Pumping Station is selected to set up a monitoring facility.

3.2. Bleeders of Typical Irrigation Channels

By setting up monitoring facilities at the bleeders of typical irrigation channels, the water distribution process of the discharge of water source projects can be monitored, and the amount of water supplied by the water source projects to each irrigation patch can be grasped. It is proper that the main canal of reservoir which appear to play a regulatory role in Wanyao Irrigation Area and its first-order branch should be monitored. The monitored bleeders should be laid out according to the principles of uniform distribution, overall control, focusing on the main points, and taking into account the irrigation channels connected to a reservoir. According to this, 10 monitoring sites are set up at the intersection of the east
and west trunk canals of Baishuikeng-Xiakou Reservoir and their branch canals, of which there are 5 were set at the irrigation channels connected to a reservoir.

3.3. Typical irrigation patches
In order to master the actual irrigation water consumption per unit area of the irrigation area, Fenglin Stream Watershed in Fenglin town is selected as a typical irrigation patch, and monitoring facilities are arranged at three inlets and one outlet to monitor the actual irrigation water consumption.

3.4. Drainage outlet of watershed
According to the distribution of river system in Wanyao Irrigation Area, one monitoring facility is set up at the upstream of barrage in Fenglin town and Hecun town, which are respectively located in the midstream and upstream of Jiangshan port, to monitor the actual discharge process of the drainage outlets there. Then, with the help of the observed flow data of Shuangtadi Hydrological Station at the outlet of Jiangshan port, the correlation between the monitored flow of the drainage outlets and the observed flow of the hydrological station is established so that the monitoring data of the drainage outlets can be extended to calibrate the parameters of the water cycle model in the irrigation area. Figure 1 shows the arrangement of monitoring facilities for irrigation water in Wanyao irrigation area.

4. Statistics of agricultural irrigation water consumption in irrigation area
The general guidelines to statistic agricultural irrigation water consumption in Wanyao Irrigation Area are as follows: using the monitoring data of hydrological and agricultural irrigation water to construct the natural-artificial dualistic water cycle model of the irrigation area which will be used to simulate the natural and artificial water cycle processes of runoff, storage, diversion, supply, use, loss, drainage, etc. According to the results of simulation, the water supply and consumption processes of all industries include urban and rural water supply, agricultural irrigation, hydropower generation, ecological
environment can be extracted. Then, based on the irrigation water intake process and hydraulic relationship between each irrigation patch, the irrigation return water consumption is studied, and the actual irrigation return water consumption is analysed [7]. Finally, according to the simulation results of irrigation water supply and consumption and the analysis results of irrigation return water quantity, the actual irrigation water consumption in the irrigation area is calculated.

4.1. Construction of water cycle model in irrigation area

The water cycle model of Wanyao Irrigation Area is based on SWAT model [8-11]. Firstly, the structure, calculation method of water balance elements, irrigation mode, non-agricultural water simulation mode of SWAT model should be improved according to the law of water cycle in Wanyao Irrigation Area so that the improved SWAT model [13] suitable for simulating the water cycle process of Wanyao Irrigation Area is developed. Then, according to the data of digital elevation, soil distribution, land use type distribution, hydrometeorology, characteristic parameters of hydraulic works, the water cycle model of Wanyao Irrigation Area is established. The details of the water cycle model construction in irrigation area are referred to the articles [14, 15].

4.2. Parameter calibration and model verification

4.2.1. Parameter calibration and model verification of SWAT model. The basic data used for parameter calibration and model validation of SWAT model in Wanyao Irrigation Area include the observed flow data of Shuangtadi Hydrological Station at the outlet of Jiangshan port and the monitored flow data from monitoring facilities in the midstream and upstream of Jiangshan port. The data of new monitoring facilities are interpolated and extended by establishing relevant relationship with the observed data of Shuangtadi Hydrological Station. The period of parameter calibration is from 1990 to 2006, and the model verification period is from 2007 to 2017. The SWATCUP software was used to calibrate the parameters of the model, such as runoff simulation, terrain characteristics, land cover characteristics, conventional agricultural irrigation management and so on. Take the outlet of Shuangtadi Hydrometric Station as an example to illustrate the effect of parameter calibration and model verification. The results are displayed in Figure 2. At the same time, the simulation grades of the SWAT model in Wanyao Irrigation Area are excellent both in the calibration period and validation period. It can be seen that the SWAT model of Wanyao Irrigation Area has great simulation effect.

![Figure 2. Calibration and verification runoff results of Shuangtadi station](image)

4.2.2. Parameter calibration of improved SWAT model. According to the data of 2017 observed by 25 monitoring facilities in Wanyao Irrigation Area, the observed water volume of various types of water source monitoring facilities during the irrigation period (from June to September) is calculated, and the results are shown in Table 1. Then using the manual trial method to calibrate the parameters of improved SWAT model, such as field loss coefficient ($\xi$), river irrigation water control coefficient ($\beta$) and
mountain pond irrigation water control coefficient ($\zeta$). The calibration results are as follows: $\xi = 0.93$, $\beta = 0.3$, $\zeta = 0.2$.

| Location of monitoring facilities | Water volume during the irrigation period (million m$^3$) | observed value | simulated value | bias |
|----------------------------------|--------------------------------------------------------|----------------|----------------|------|
| Channel heads of large and medium reservoirs | 106.21 | 109.40 | 3.00% |
| Channel heads of typical small reservoirs of type 1 | 2.91 | 3.07 | 5.60% |
| Channel heads of typical small reservoirs and mountain ponds | 0.74 | 0.68 | -8.00% |
| Channel heads of typical machine ports | 0.09 | 0.09 | 4.30% |
| Bleeders of typical irrigation channels | 20.22 | 19.13 | -5.40% |
| Typical irrigation patches | 5.54 | 5.76 | 4.00% |
| Upstream drainage outlets | 241 | 225.34 | -5.40% |
| Middle drainage outlets | 640.54 | 602.75 | -5.90% |

4.3. Extract the simulation results of water cycle process

Based on the current digital elevation data, land use data, soil type data, water conservancy project parameters and hydrological and meteorological data from 1986 to 2017 in Wanyao Irrigation Area, the calibrated water cycle model is adopted to simulate the water cycle process of irrigation area from 1990 to 2017, and then the processes of water supply from the water source projects to users of different industries are extracted. The results are shown in Figure 3. It can be seen that, from an annual mean perspective, the water inflow of Wanyao Irrigation Area is 1.35 billion m$^3$ from the river, 1.51 billion m$^3$ from the reservoir. The water supplied for the agricultural irrigation from the irrigation area is 180 million m$^3$, 80 million m$^3$ for the urban and rural domestic, and 410 million m$^3$ for the ecological environment of the river.

![Figure 3. Statistical results of water supply in Wanyao irrigation](image)

4.4. Analysis of irrigation return water quantity in irrigation area

The mechanism of irrigation return water utilization is complex. If the irrigation water consumption of each irrigation patch is calculated according to the irrigation structure in turns, there will be technical problems such as the number of times of irrigation return water recycling is difficult to be determined, and the movement of irrigation return water cannot be accurately mastered. At present, there is no mature and effective solution in academia. In this paper, a generalized analysis method of irrigation return water is proposed. Aiming at the recycling of irrigation return water between different irrigation patches in the irrigation area, from the overall analysis of the irrigation area and in a long time scale, it is considered that the irrigation return water generated by each HRU (short for Hydrological Response Unit) of the model is only used for its own irrigation, thus forming a generalized analysis method that simulate the
time cycle instead of spatial cycle of irrigation return water. According to the above theoretical method, use the simulation results of water cycle model of Wanyao irrigation area from 1990 to 2017, and take into account the sub basin division results of SWAT model to statistic the return water volume of irrigation area. The statistical results are shown in Figure 4.

![Figure 4. Statistical results of irrigation return water supply in Wanyao irrigation](image)

### 4.5. Statistics of irrigation water consumption in irrigation area

According to the analysis results of irrigation return water in Wanyao Irrigation Area, combined with the simulation results of agricultural irrigation water supply in Section 3.3, the actual irrigation water consumption in the irrigation area is calculated, and the results are shown in Table 2. It can be seen that, from an annual mean perspective, the total amount of irrigation water in the irrigation area is 182 million m³ according to the supply of water sources without considering the use of return water, and the total amount of agricultural water in the irrigation area is 166 million m³ after deducting the return water amount of irrigation, a difference of about 8.9 percent. The proportion of actual irrigation water consumption of water sources, namely the rivers, mountain ponds, small reservoirs, Wanyao Reservoir, Xiakou Reservoir is 18.0:8.8:20.7:12.9:39.6.

| Frequency | Supply of Water sources (million m³) | Irrigation water consumption (million m³) | Irrigation quota (m³/mu) |
|-----------|-------------------------------------|------------------------------------------|-------------------------|
|           | Rivers | Mountain ponds | Small reservoirs | Xiakou Reservoir | Wanyao Reservoir | Rivers | Mountain ponds | Small reservoirs | Xiakou Reservoir | Wanyao Reservoir |
| 25%       | 19.83  | 14.85         | 25.97          | 51.08         | 6.34               | 118.07 | 351             |
| 50%       | 29.54  | 10.43         | 33.08          | 69.44         | 16.73              | 159.21 | 473             |
| 75%       | 37.39  | 10.01         | 40.93          | 89.10         | 24.23              | 201.66 | 599             |
| 90%       | 33.37  | 15.11         | 45.24          | 101.79        | 34.84              | 230.34 | 685             |
| Annual mean | 29.90 | 14.56         | 34.35          | 65.68         | 21.40              | 165.89 | 493             |

### 5. Conclusions and suggestions

Aiming at the problem that the monitoring investment of all water sources in Wanyao Irrigation Area is too large due to the wide range of irrigation water sources, the method that to arrange the monitoring facilities for irrigation water consumption on the basis of water cycle simulation of irrigation area and the method of analyzing irrigation water consumption by constructing water cycle model to simulate the process of water supply and consumption of users in each industry of irrigation area are put forward in this paper. Through the research, the following conclusions and suggestions are obtained.

It is economically feasible to arrange the monitoring facilities for irrigation water consumption based on the needs of master the process of irrigation water cycle and calibration of the water cycle model.
The method of arrangement of monitoring facilities for agricultural irrigation water consumption which is based on the simulation of irrigation water cycle, can accurately master the process of artificial water cycle, such as supply, consumption, loss, discharge, etc.

The calibration results of parameters in water cycle model using the observed data of monitoring facilities arranged to meet the needs of irrigation water cycle simulation are good. And the method of using the simulation results of water cycle model of irrigation area to calculate irrigation water consumption is feasible in technology and reliable in accuracy.

It is suggested that the irrigation water cycle model should be used to simulate the process of agricultural irrigation water consumption under more scenarios, so as to reveal the law of agricultural water consumption in the south of China.

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), and Science and Technology Plan Project of Research Institute of Zhejiang Province (A20003).

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