Sponge Basin Characteristics of the Original Ecosystem in Ziquejie Terraces and its Adaptive Water Supply and Demand Balance Mechanism

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Abstract. Based on the analysis of the observation results of rainfall and runoff and hydrogeological exploration in the Ziquejie terraces, the concept of "equal slope underground sponge reservoir" in the terraces is proposed. Compared with the ordinary linear storage and drainage process of groundwater in the basin, the "equal slope underground sponge reservoir" has a very significant characteristic of "sponge basin" which can adjust peak and relieve dry and prolong the outflow time. The calculation formula of non-linear outflow of underground water in the "sponge basin" is given. The characteristics of this "sponge basin" and its non-linear outflow principle and the coupling relationship among irrigation, water supply and drainage of ancient terraces are demonstrated. An adaptive balance model of water supply and demand in the original ecosystem of ancient terraces is established. The model is applied to simulate a long series of water supply and demand balance in the original ecosystem of the ancient terraced field, and the check results are highly consistent with the Historical Drought Resistance records of the ancient terraced field. It is proved that the principle of non-linear groundwater outflow in sponge basin and its calculation formula are correct and practical. The research results have important guiding significance for the development, utilization and protection of other ancient terraces, and also have important reference value for the development of sloping farmland.

1. Introduction

The Ziquejie ancient terraces originated from the Qin Dynasty and flourished in the Song and Ming dynasties. It has been developed for more than two thousand years. It is one of the three famous ancient terraces in China. It has many titles such as the World Irrigation Project Heritage, the Global Important Agricultural Cultural Heritage, and the Double Nature of China's Nature and Culture[1,2].

Water is the foundation of ecology and the key to life. The Ziquejie ancient terraces are steep, but rice is grown on a large scale. There is no reservoir on the mountain, and there are no water storage facilities such as water storage. However, no matter whether it is suffering from drought or heavy rain, the mountains can be protected from drought and flood, the drinking water of humans and animals is worry-free, and the ecological water demand is guaranteed[3]. Known as the "the world has a drought, this place has a collection" reputation, after thousands of years. To study the autonomous guarantee of water resources in the original ecosystem of Ziquejie Ancient Terraces, to find out the source, storage and migration mechanism of water sources, and to reveal the internal mechanism of this magical phenomenon, which can not only enrich the natural heritage of ancient terraces, but also have important reference value for the development and protection of other ancient terraces[4,5].

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2. Research area

The Ziquejie terraces is located in Shuiche Town, southwest of Xinhua County, between East Longitude 110°0′52″~111°0′01″ and North latitude 27°0′40″~27°0′45″. It belongs to the mid-subtropical monsoon climate zone. There are many southeast winds in summer and northwest winds in winter. The annual average temperature is 13.7 °C, the highest temperature is 39 °C, the lowest temperature is -5 °C, and the annual precipitation is 1650~1700mm. The area is a low hilly area, which is a shallow-cut middle and low mountainous landform and a shallow-cut and taro-shaped hilly landform. In the earth structure, the inner side of the arc of the middle part of the snow-peak curved structural belt is inclined to the southeast direction due to the influence of the regional structure. The highest elevation in the area is 1464m, the lowest is 400m, and the height difference is more than 1000m. The terraces are excavated, ranging from 450m to 950m above sea level, there are more than 500 levels and more than 100,000 hills. The Fengjiashan system in which the terraces are located covers an area of 93km², with 56,000 mu of terraces and a population of about 50,000[6-8].

3. Methods

In order to study the water resources adaptive guarantee mechanism of the original ecosystem in Ziquejie terraces, and to find out the source, storage and migration mechanism of terraced irrigation water sources [9-11]. 2 rainfall-runoff-sand observation stations, 2 meteorological observatories, 3 groundwater level observation stations, and 9 hydro-geological drilling stations were deployed in the study area [12] (Fig.1). The experimental observation data for two consecutive years from 2012 to 2013 were obtained. The main experimental observation results are summarized as follows:

3.1 Rainfall runoff observation

In order to explore the characteristics of rainfall runoff in Ziquejie terraces, a small watershed with closed boundary was selected in the ancient terrace area, and a control section was selected in the middle stream and the downstream outlet respectively. Rainfall runoff observation station is established to carry out rainfall runoff observation. The control area of station A is basically the original ecological natural vegetation coverage area, with a controlled rainwater collection area of 5.48hm². The interval between station A and station B is basically terrace area, with a rainwater collection area of 6.17hm². (Fig.2).
Fig. 2. Schematic diagram of rainfall runoff observation Basin

The geomorphic characteristics of the control area of station A and station B were totally different. Quantitative analysis of the structural proportion and difference between surface runoff and underground runoff of station A and station B would help to reveal the characteristics of "sponge basin" in the ancient terrace area. The daily runoff hydrograph observed at station A and station B in 2012 was divided into two parts of surface and underground by digital filtering method [13]. According to statistics, the relationship between rainfall and runoff and the structural proportion of underground runoff (base flow) to total runoff in area A and area B were shown in table 1.

| Geomorphologic condition | Basin area (hm²) | Total annual rainfall (mm) | Total runoff (10⁴ m³) | Total runoff coefficient | Runoff modulus (10⁴m³/hm²) | Total base flow (10⁴m³) | Base flow modulus (10⁴m³/hm²) | Base flow coefficient |
|--------------------------|-----------------|---------------------------|-----------------------|-------------------------|-----------------------------|------------------------|---------------------------|------------------------|
| Ecological vegetation area | 5.48            | 1814.5                    | 6.75                  | 0.68                    | 1.23                        | 3.18                   | 0.42                      | 0.32                   |
| Terrace area             | 6.17            | 1814.5                    | 6.52                  | 0.58                    | 1.06                        | 2.91                   | 0.23                      | 0.26                   |

It can be known from table 1: (1) In Ziquejie terraces, the proportion of base flow to total runoff is as high as 44% (terrace area) to 47% (ecological vegetation area), which is far higher than the experience value (20% ~ 30%) of general areas in Hunan Province, indicating that the area has strong rainfall infiltration supply capacity and strong water conservation capacity; (2) The runoff modulus, base flow modulus and base flow coefficient of ecological vegetation area are very large in the terrace area, it shows that the original forest coverage area has more powerful functions of water storage and water conservation.

3.2 Hydrogeological exploration
In order to deeply reveal the hydrogeological structure of the ancient terrace area, 9 hydrogeological exploration boreholes were arranged along the slope, with a total depth of 158 meters, and geological sampling and laboratory testing, field water pressure, water injection and other experiments were carried out. The characteristics of regional hydrogeological structure and the main parameters of hydrogeology are shown in Fig.3, Fig.4 and table 2, table 3. The experimental results show that the hydrogeological structure of this area is simple and can be divided into three layers. The overburden is strongly weathered
granite sandy clay, followed by granite strongly weathered layer (which is groundwater aquifer), weakly weathered granite and fresh granite impermeable layer.

Table 2. Results of hydrogeological drilling

| Drilling number | Location         | Elevation(m) | Drilling depth(m) | Cover layer (m) | Strong weathered layer(m) | Weakly weathered layer(m) |
|-----------------|------------------|--------------|-------------------|-----------------|--------------------------|--------------------------|
| ZK1             | Mounta-in foot   | 564          | 20.7              | 0~0.9           | 0.9~7.6                  | 7.6~20.7                 |
| ZK2             | Mounta-inside    | 761          | 38.3              | 0~3.7           | 3.7~6.3                  | 6.3~38.3                 |
| ZK3             | Mounta-in peak   | 973          | 39.2              | 0~6.9           | 6.9~18.0                 | 18.0~39.2                |
| ZK4             | Mounta-inside    | 617          | 7.0               | 0~1.4           | 1.4~4.0                  | 4.0~7.0                  |
| ZK5             | Mounta-in foot   | 790          | 7.0               | /               | 0~4.0                    | 4.0~7.0                  |
| ZK6             | Mounta-inside    | 892          | 4.0               | /               | 0~0.3                    | 0.3~4.0                  |
| ZK7             | Mounta-in peak   | 990          | 14.5              | 0~5.9           | 5.9~13.1                 | 13.4~14.5                |
| ZK8             | Mounta-in peak   | 1013         | 16.9              | 0~4.9           | 4.9~14.6                 | 14.6~16.9                |
| ZK9             | Mountainside     | 495          | 4.0               | /               | 0~0.9                    | 0.9~4.0                  |

Fig. 3. The profile of geological drilling

Fig. 4. Geological structure
Table 3. Drilling and water injection test results

| Drilling number | Test section (m) | Lithology                        | Test layer Thickness (m) | Permeability coefficient (cm/s) | Specific yield (u) |
|-----------------|------------------|----------------------------------|--------------------------|---------------------------------|-------------------|
| ZK1             | 2~5              | Strongly weathered granite       | 3                        | $8.9 \times 10^{-5}$            | 0.10              |
| ZK2             | 2.0~3.7          | Sandy cohesive soil              | 1.7                      | $4.5 \times 10^{-4}$            | 0.137             |
| ZK3             | 1.5~6.9          | Sandy cohesive soil              | 4.4                      | $5.7 \times 10^{-4}$            | 0.163             |

3.3 Groundwater level observation

Combined with geological drilling, 3 groundwater level observation stations were set up at the mountain peak (elevation 973m), mountainside (elevation 761m) and mountain foot (elevation 564m) to carry out groundwater level observation. The groundwater level was observed once a day by using the groundwater monitoring system\cite{14}. The highest and lowest water levels and their changes (falling depth) measured by the groundwater level observation stations from July 2012 to July 2013 are shown in table 4:

Table 4. Characteristics of groundwater depth (m)

|       | 2012 .07 | 2012 .08 | 2012 .09 | 2012 .10 | 2012 .11 | 2012 .12 | 2013 .01 | 2013 .02 | 2013 .03 | 2013 .04 | 2013 .05 | 2013 .06 | 2013 .07 |
|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| ZK1   |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Lowest| 8.9      | 8.1      | 8.4      | 8.6      | 8.8      | 8.6      | 8.6      | 8.7      | 8.7      | 8.7      | 8.7      | 8.6      | 8.7      |
| Highest| 7.8     | 7.2      | 8.3      | 8.5      | 8.6      | 8.5      | 8.1      | 8.6      | 8.4      | 8.2      | 8.4      | 8.4      | 8.4      |
| Falling depth | 1.1 | 0.9 | 0.1 | 0.2 | 0.1 | 0.5 | 0 | 0.3 | 0.5 | 0.3 | 0.2 | 0.3 |
| ZK2   |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Lowest| 19.3     | 18.4     | 18.2     | 18.6     | 18.8     | 18.8     | 20.1     | 19       | 19.4     | 19.1     | 18.9     | 17.7     | 17.7     |
| Highest| 15.6    | 15.3     | 17.8     | 18.1     | 18.4     | 18.4     | 18.3     | 18.8     | 18.8     | 18.9     | 17.5     | 17.4     | 16.5     |
| Falling depth | 3.7 | 3.1 | 0.4 | 0.5 | 0.4 | 0.4 | 1.8 | 0.2 | 0.4 | 0.2 | 1.4 | 0.3 | 1.2 |
| ZK3   |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Lowest| 19       | 17.4     | 18.1     | 18.3     | 18.5     | 17.9     | 18.7     | 18.9     | 19.9     | 18.1     | 17.4     | 16.9     | 17.7     |
| Highest| 15.2    | 15.2     | 17.6     | 17.9     | 17.8     | 17.6     | 17.5     | 18.5     | 18.9     | 17.3     | 16.5     | 16.4     | 16.4     |
| Falling depth | 3.8 | 2.2 | 0.5 | 0.4 | 0.7 | 0.3 | 1.2 | 0.4 | 1     | 0.8 | 0.9 | 0.5 | 1.3 |

4. Results and discussion

4.1 The concept of "equal slope underground sponge reservoir"

Fig. 5. Groundwater depth process line
From July 2012 to July 2013, the groundwater depth hydrograph and its rainfall hydrograph in the same period were measured from three groundwater level observation wells (upper (ZK3), middle (ZK2) and lower (ZK1)) in Fig. 5 and Fig. 6.

The analysis of Fig. 5, Fig. 6 and Table 4 reveals that: (1) The process lines of groundwater depth change in mountain peak (ZK3) and mountainside (ZK2) are basically coincident, and are almost parallel to the process of groundwater depth change in mountain foot (ZK1), which shows that the groundwater depth of ancient terraces from mountain peak (ZK3) to mountain foot (ZK1) is almost the same rise and fall. Combined with the analysis of hydrogeological exploration results, it can be determined that there is a sponge like water storage body in ancient terraces all the year round, which can be called the underground sponge reservoir, and the water surface line of the reservoir is basically parallel to the contour line of the hillside landform (inclining downward). We call it the "equal slope underground sponge reservoir", as shown in Fig. 7.

(2) The peak period of irrigation water demand in this area is generally in July, while the maximum monthly drawdown depth of the underground reservoir appears in July, reaching 3.8m, indicating that the maximum regulating capacity of the underground reservoir is used in this month, indicating that
there is an adaptive balance process between the water supply of the underground sponge reservoir and the water demand of the terrace.

(3) The lowest water level of the underground reservoir appears in March (ZK3 buried depth is 19.9m), the highest water level appears in August (ZK3 buried depth is 15.2m), and the maximum water dissipation depth in the year reaches 4.7m, indicating that the underground reservoir has at least 4.7m regulation space between seasons.

(4) There is a significant corresponding relationship between the rainfall duration greater than 50 mm and the fluctuation trend of groundwater level, and the rise and fall of water level generally lags behind the rainfall for 5-8 days, which shows that the underground reservoir has a better function of storing abundant water and relieving dry water than the surface reservoir.

4.2 Estimation of water storage capacity of underground water reservoir and its annual recharge

The average thickness method is used to estimate the groundwater static reserves in the region:

\[ Q = \sum 100\mu HF \] (1)

In the formula: \( Q \)—Groundwater reserves\((10^4 \text{m}^3)\); 
\( \mu \)—Specific yield of aquifer; 
\( H \)—Aquifer thickness(m); 
\( F \)—Aquifer area\((\text{km}^2)\).

The area of the aquifer is 93 km², the average thickness of the aquifer in the sandy cohesive soil is 5m, the water supply is 0.15, the average aquifer thickness of the strongly weathered rock is 8m, and the water supply is 0.1. The groundwater reserve calculated by Eq. (1) is 14415 \((10^4 \text{m}^3)\).

The average annual recharge of groundwater is estimated by the following formula:

\[ Q = \frac{\sum F \alpha X}{10} \] (2)

In the formula: \( Q \)—annual average precipitation infiltration recharge \((10^4 \text{m}^3)\); 
\( F \)—infiltration area \((\text{km}^2)\); 
\( \alpha \)—annual average precipitation infiltration coefficient; 
\( X \)—annual average rainfall \((\text{mm})\).

The ecological vegetation area and the paddy field are estimated separately. The ecological vegetation area is 55 km² and the terraced area is 38 km². According to the rainfall-runoff observation experimental station data \([15]\), the ecological vegetation area \( \alpha \) is 0.32, the paddy field \( \alpha \) is 0.26, and the annual average rainfall is 1452mm. Based on this, the groundwater resources (year-old average) of the ancient terraced area are estimated as : 3991\((10^4 \text{m}^3)\).

4.3 Adaptive balance principle of water supply and demand in original ecosystem

The water demand of the original ecosystem in the ancient terraced field includes: the regional ecological environment water demand \( C \) (T), the human and animal drinking water consumption \( M \) (T), the terrace crop water consumption \( E \) (T). The water demand for maintaining the original ecosystem of the ancient terraced field mainly comes from the discharge \( W_G \) (T) of the underground sponge reservoir at the same slope position and the natural rainfall \( P \) (T) retained and utilized by the terraced field. If the water demand of ancient terrace system in any period is \( W_x \) (T), the water supply-demand relationship of ecosystem can be described by the following formula:

\[ \text{let } W_x(t) = C(t) + M(t) + E(t) \] (3)

When \( W_G(t) + P(t) \geq W_x(t) \), the original ecosystem water supply can be met.

When \( W_G(t) + P(t) < W_x(t) \), the original ecosystem water supply could not be satisfied.

Due to the ecological environment water demand (C) and the amount of drinking water for humans and animals(M) are given priority and easy to obtain (Drilling water from residents), the water consumption is small, and the main water demand of the system comes from the terraced rice water consumption(E). Therefore, whether the terraced irrigation water supply can be met (whether the terraces are dry or not) is a sign to judge the balance of water supply and demand in the original ecosystem.
4.3.1 Adaptive balance principle of irrigation water supply and demand for terraced crops

The water demand of terrace crops is determined by local climate factors, which can be calculated by the Penman method according to meteorological observation data and irrigation test data. The water supply is composed of two parts: the rainfall of rice field and groundwater outflow. In the dry period, the water potential of the underground sponge reservoir with equal slope position is always higher than that of the terrace, and it can flow slowly and continuously to the downstream terrace under the action of gravity along the geological structure channel [8], providing the terrace irrigation water source with continuous and long flow of fine water, forming the adaptive balance between the supply and demand of the terrace crop irrigation water. The principle can be described as follows:

\[ H(t) = H(t-1) + P(t) + R_g(t) - E(t) - C_N \] (4)

- \( H(t) \) —— At the end of the period t, the depth of the terraced field (mm)
- \( H(t-1) \) —— At the beginning of the time t, the depth of the terraced fields (mm)
- \( P(t) \) —— Effective use of rainfall during the period t (mm)
- \( R_g(t) \) —— Effective use of groundwater in terraced fields during the period t (mm)
- \( E(t) \) —— Field crop water consumption during the period t (mm)

\[ E(t) = K_c \cdot ET_0(t) \] (5)

- \( E(t) \) —— Meteorological observation data and irrigation experiment data can be used to calculate the Penman formula.
- \( C_N \) —— Terrace field leakage (mm). According to the soil structure of terraces, take \( C_N = 2.5 \text{mm/d} \).

4.3.2 Coupling relationship between drainage (outflow) and irrigation, water supply and drainage of underground sponge reservoir

The outflow process of groundwater reservoir \( W_G(t) \) is based on its own drainage rules. The part of water \( R_g(t) \) that can be used by terraces is not only related to \( W_G(t) \), but also the depth of water in the terrace field at the beginning of the time period. Only when the field depth \( H(t) \) of the terrace is less than the upper limit \( H_m(t) \), the groundwater \( W_G(t) \) entering the field is intercepted until the upper limit \( H_m(t) \) of water storage, and the groundwater intercepted in this part is \( R_g(t) \). When the water depth in the field
exceeds Hm(t), the excess WG(t) naturally overflows and is channeled into the downstream channel. The relationship can be described by the following conditions:

When H(t-1)+P(t)-Kc*ET0(t)-CN > Hm(t), Terraces do not require groundwater during this time, Rg(t)=0.

When H(t-1)+P(t)+WG(t)-Kc*ET0(t)-CN > Hm(t), Terraced land use of part of groundwater WG(t), to keep terrace water level at Hm(t). At this time:

\[ Rg(t) = Hm(t) - H(t-1) - P(t) + Kc*ET0(t) + CN \] (6)

When H(t-1)+P(t)+WG(t)-Kc*ET0(t)-CN < Hm(t), Groundwater exposed during this period was fully used. At this time, Rg(t)=WG(t).

When H(t-1)+P(t)+WG(t)-Kc*ET0(t)-CN < Hn(t), The amount of exposed groundwater WG(t) during this period was insufficient to meet the water requirements of the terraced crops, and the terraced fields encountered drought during this period.

Hm(t) —— The growth period of crops taken at t period is resistant to the depth of flooding(mm)
Hn(t) —— The drought-resistant depth of the crop during the period of t(mm).

\[ E(t) = Kc*ET0(t) + CN \] (7)

CN—— Terrace field leakage(mm). According to the soil structure of terraces, take CN=2.5mm/d
Kc* ET0(t)—— Evaporation in the field.

The above conditions describe the coupling relationship between the outflow of underground sponge reservoir and the supply and drainage of terrace irrigation. Among them, WG(t) is the key factor to balance the supply and demand of terrace irrigation water. However, WG(t) depends on the supply of rainfall to the underground reservoir and the regulation, storage and discharge mechanism of the underground reservoir itself.

4.4 Characteristics of "sponge basin" of underground reservoir and its nonlinear outflow mechanism

WG(t) comes from rainfall P(t) to groundwater sponge reservoir infiltration supplement quantity Q0. According to the theory of "full storage and flow generation" [16], the storage and discharge process of the underground reservoir is treated as a linear reservoir. The total amount of underground runoff Q0 and its outflow process Qt formed by a rainfall process are described by the following formula:

\[ Q_0 = a * P \] (8)
\[ Q_t = Q_0 * e^{-at} \] (9)

In the formula:

a——runoff coefficient of groundwater formed by one rainfall. According to the analysis of the observation data of the runoff observation station [8], it is found that a = 0.295.
P——Rainfall(mm)

By introducing the storage and discharge coefficient K, the groundwater recession coefficient Kr and the groundwater outflow coefficient Kp, and combining with the water balance equation - Q * dt = dw in the backwater section. Based on the principle of linear reservoir storage and discharge, the discharge Δ W from t-period to t+Δt-period of underground reservoir can be obtained:

\[ \Delta W = \int_{t}^{t+\Delta t} Q_e e^{-kt} / k \, dt = K Q_t (1 - K_r) = K \cdot Q_t \cdot K_p \] (10)

\[ K_r = Q_{t+1} / Q_t, K_p = 1 - K_r \] (11)
\[ K = -1 / \ln K_r \] (12)

Δ W is the outflow W(t) of the underground sponge reservoir in t period.

Equation 10 is to simulate the underground reservoir as a linear reservoir and treat the underground water storage space as a one-dimensional plane medium with even gap distribution, which simplifies the calculation of runoff generation and the division of surface and underground runoff, and is basically available for general basins. But the purple magpie area has the characteristics of "sponge basin" which can store the peak and relieve the dry, and extend the outflow time. The underground reservoir has a regulation and storage space of up to 4.7 meters in the year. For such an underground sponge reservoir...
with equal slope position, it is not suitable to simply describe the outflow process of the underground runoff with equation 10. The influence of the regulation and storage of the underground reservoir on the discharge process should be considered.

Based on this, the regulating capacity \( q_m \) of the underground reservoir is introduced, and the structural principle of the underground reservoir is shown in Fig. 9. After the rainfall infiltration supplement quantity \( q_0 \) enters the sponge reservoir, a part \( (q_0) \) is absorbed and filled by the cavernous body. In fact, this part of water body is temporarily accumulated by the cavernous body of the underground reservoir to form the regulating storage capacity \( q_m \), which is characterized by the rise of the water level of the underground reservoir. The other part \( (Q_0-q_0) \) is like the groundwater runoff of the general River Basin, which flows outward according to the similar linear reservoir recession \( (q_s) \), and becomes a part of \( W_G (t) \). As the water level of the underground reservoir at the equal slope position is always higher than the terrace surface, under the action of gravity, as long as \( q_m \) is not dry, the water will be released to the downstream automatically at any time. When the rainfall stops and the infiltration supply stops, the runoff \( (q_m) \) accumulated through the cavernous body will continue to flow outward \( (q_n) \) with the joint of the linear reservoir and become another part of \( W_G (t) \). Therefore, the outflow process \( W_G \) of the underground reservoir is actually composed of two parts: the natural outflow \( q_s \) of the underground reservoir and the outflow \( q_n \) after the regulation and storage of the cavernous body.

In order to simplify the calculation, two kinds of outflow processes are simulated according to the principle of linear reservoir. In which \( q_s \) comes from \( (Q_0-q_0) \), which can be calculated directly with reference to equation 8. \( q_n \) comes from the regulated storage capacity \( q_m \) of the underground cavernous body, and \( q_m \) is always in a state of change. With the outflow of \( q_n \), \( q_m \) will be smaller and smaller, and the outflow of any period is the source of the regulated storage capacity \( q_m \) at the end of the previous period. This dual regulation process is called "nonlinear adaptive regulation".

The calculation formula of groundwater outflow process based on the characteristics of sponge basin is as follows:

\[
W_G(t) = \int_t^{t+\Delta t} (Q_0 - q_0) e^{-t/k} dt + \int_t^{t+\Delta t} q_m(t) e^{-t/k} dt \tag{13}
\]

\[
q_m(t) = q_m(t-1) + q_0 \tag{14}
\]

In the formula:

\( q_m(t) \)—Groundwater reservoir storage volume during the period \( t \).

\( q_m \) is the maximum adjustment storage capacity, that is, the maximum falling space of the underground reservoir.

![Fig. 9. Schematic diagram of the structure principle of underground reservoir](image-url)
4.5 Empirical analysis

4.5.1 Calculation of groundwater outflow based on characteristics of sponge Basin

In order to verify the rationality of the underground runoff calculation formula (13) based on the characteristics of the sponge basin, the three water source Xin'anjiang model is used to simulate the runoff process of the same section of the experimental observation basin from June 1 to September 30, 2012, and the model parameters are calibrated with the measured data of the experimental observation station. Among them, the part of underground runoff is calculated in two ways: without considering the characteristics of sponge basin, the underground runoff is calculated according to formula (10), and the underground runoff is calculated according to formula (13), and the other parameters of the model are the same. The runoff process simulated by the two models is compared with the measured process to demonstrate the rationality of the method. The measured and simulated runoff processes are shown in Fig.10.

![Measured runoff and simulated runoff hydrograph](image)

Fig. 10. Measured runoff and simulated runoff hydrograph

Fig.10 shows that when the characteristics of sponge basin are not considered, the simulated runoff peak is thinner and the recession is faster. When the characteristics of sponge basin are considered, the simulated runoff peak is fat and the recession is more gentle and the recession lasts longer, which is more consistent with the measured runoff process.

4.5.2 simulation and verification of adaptive balance of irrigation water supply and demand in ancient terrace area

Based on the principle of “equal slope underground sponge reservoir”, the balance of supply and demand of daily irrigation water in the terraced rice field of Ziquejie from 1971 to 2013 was calculated. The results show that in the 43 consecutive years from 1971 to 2013, there was a brief shortage of water only occurred in 2003, 2013 from late August to early September. According to the calculation of 43 years, the original terraced ecological self-flow irrigation guarantee rate is 95%.

| parameter name                                  | unit     | Value | parameter name                                  | unit     | Value    |
|-------------------------------------------------|----------|-------|-------------------------------------------------|----------|----------|
| Runoff area (ecological vegetation area)        | km²      | 55    | Groundwater flow coefficient                     |          | 0.32     |
| Production area (ancient terrace area)          | km²      | 38    | Groundwater flow coefficient                     |          | 0.26     |
| Flat terrace area ratio                         |          | 2.47  | Groundwater flow coefficient (Kₚ)                |          | 0.075    |

Table 5. Parameter Table (Hydrogeological Parameters) for Simulation of Supply and Demand Balance of Gravity Irrigation Water in Ancient Terraces
Table 6. Parameters used in the simulation of water supply and demand balance of artesian irrigation in ancient terraces (irrigation schedule control parameters)

| Crop name   | Turn green (8 days) | Before childbirth (10 days) | After childbirth (16 days) | Field drying (7 days) |
|-------------|---------------------|----------------------------|----------------------------|----------------------|
| Medium rice | H<sub>n</sub> 30   | H<sub>m</sub> 100          | H<sub>n</sub> 0            | H<sub>n</sub> -10    |
|             | Jointing booting (10 days) | H<sub>m</sub> 150   | H<sub>m</sub> -10         | H<sub>m</sub> -20    |
|             | Heading (13 days)    | H<sub>m</sub> 150   | H<sub>m</sub> -20         | H<sub>m</sub> 0      |
|             | Milk ripeness (18 days) | H<sub>m</sub> 150 | H<sub>m</sub> 0          | H<sub>m</sub> 0      |
|             | Yellow ripe (12 days) | H<sub>m</sub> 150 | H<sub>m</sub> 0          | H<sub>m</sub> 0      |
|             | Field drying (7 days) | H<sub>m</sub> -20 | H<sub>m</sub> 0          | H<sub>m</sub> 0      |

Table 7. Summary of Simulation Calculation Results of Irrigation Water Supply and Demand Balance Based on Underground Irrigation Water in Ancient Terraces

| Year/month | Water supply for irrigation(m³/Mu) | Water shortage month | Water shortage days |
|------------|-----------------------------------|----------------------|---------------------|
| 1971       | 56.6 53.9 50.2 33.9 194.7         | 0                    | 0                   |
| 1972       | 50.2 33.7 76.9 22.2 183           | 0                    | 0                   |
| ...        | ...                                | ...                  | ...                 |
| 2003       | 65.2 53.5 69 20.8 208.4           | 8, 9                 | 13                  |
| ...        | ...                                | ...                  | ...                 |
| 2013       | 32.5 73.4 83 0 188.9              | 8                    | 8                   |

According to the statistical yearbook of Xinhua County, 2003 and 2013 have been two years of particularly serious drought since the liberation of Xinhua County. In 2003, 70% of the farmland in the county suffered from drought, with an area of 420000 mu. In 2013, it was also a systematic drought year in Xinhua County, with some areas experiencing difficulties in drinking water for people and animals. Compared with the disaster situation in Xinhua County, in the past two years, there was no difficulty in drinking water for people and animals in the echelon area of zique boundary, only a few days of water shortage in the echelon area, but no significant reduction in production. The above simulation results are in good agreement with the actual situation of echelon field in magpie boundary. It shows that "the equal slope underground sponge reservoir has played an important role in the drought and flood protection of echelon fields in the zique boundary."

5. Conclusions

Based on a variety of experimental observation data such as hydrological and geological exploration, this study puts forward the storage and drainage mechanism of underground sponge reservoir with equal slope position, clarifies the source, storage and transfer mode of irrigation water source in echelon field of magpie boundary, and establishes the coupling relationship between the supply, regulation, storage and drainage of underground reservoir and the irrigation, water supply and drainage of echelon field, which profoundly reveals the adaptive balance between the supply and demand of original ecological water in mountain echelon field Mechanism.

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