The Waterlogging Process Model in the Paddy Fields of Flat Irrigation Districts

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Abstract: Flat, low-lying agricultural areas such as irrigation districts in southern China have been increasingly vulnerable to flood inundation disasters because of the increased runoff associated with urbanization and climate change. In this study, we developed a waterlogging process simulation model comprising two parts: runoff generation module and runoff confluence module. An improved tank model and hydrodynamic model based on Saint–Venant equations were adopted in the runoff generation and confluence module, respectively. The results show that the model’s relative error and root mean square error are 2.1% and 0.17 mm/h, and the Nash coefficient of the model is 0.91. The relative error of river level simulation was within 5%, and the Nash coefficient was higher than 0.9. The proposed waterlogging simulation model could be a valuable tool for describing the process of waterlogging generation, accumulation, and confluence in the studied irrigation district or other regions with similar climatic conditions.

Keywords: waterlogging; modeling; paddy field; tank model; rain runoff

1. Introduction

Irrigation districts rich in water and arable land are important grain-producing areas for many regions, mainly for Asian countries. According to the 2021 Global Report on Food Crisis published by Global Network Against Food Crises (GNAFC), COVID-19 could double the number of people experiencing a food crisis to 265 million. Therefore, protecting plain irrigation areas against disasters is vital in ensuring food security [1]. However, with the impact of global climate change in recent years, the frequency of extreme rainfall events has increased. Furthermore, with the influence of human activities and urbanization, flood disasters can quickly occur in irrigation areas, which can cause substantial damage to agricultural production [2,3]. Studies have shown that waterlogging can reduce rice yields by over 80% under certain conditions [4]. Generally, a flat irrigation district is characterized by complex drainage systems and variable river direction, complicating the waterlogging. This situation has become more complicated due to the impact of human activity. Therefore, it is vitally important to understand the occurrence and evolution of waterlogging in flat irrigation districts. The results of such an analysis are likely to help redesign and manage drainage structure systems to prevent flood inundation in these areas.

Accurate modeling of the waterlogging process in irrigated districts is essential for planning and scheduling drainage works in irrigated areas. The formation and development of waterlogging in farmland are complicated in space due to the variation of the underlying surface and human activities [5]. Therefore, it is necessary to study the formation and evolution of the waterlogging process in irrigation areas using numerical simulation. Most traditional hydrological and hydraulic models, such as SWAT, WEP, and the Stanford Model, were developed for a natural watershed and are suitable for large and medium-sized basins. However, the regional water migration path has changed due
to human activities, and the waterlogging process has become more complicated in the irrigation areas. Those models always provide the runoff process at the outlet section of the basin. Still, they cannot give futures on the waterlogging, such as the water depth of the hydrological response unit.

The Tank model was proposed by Sugawara in 1972 [6], and this model was applied to runoff analysis in a few studies. Shikasho used the Tank model to analyze the low-lying drainage basins of Japan in 1985 [7]. Chen improved a diffusive tank model and applied it to paddy fields [8] and upland fields [9] in Taiwan in 2003 and used a parameter optimization method to calibrate the Tank model in 2005. The Tank model has also been used successfully in the low-lying areas of Vietnam [10,11]. Other researchers showed that the Tank model had better adaptability for simulating runoff processes in flat, low-lying, agricultural areas [12–15], including paddy fields.

A flat irrigation district is characterized by complex drainage systems and variable river directions, complicating water flow [16,17]. The essence of the channel flow propulsion calculation is using the upper section's flow process to infer the lower section's future flow process. Both the hydraulic and hydrological methods are based on the Saint–Venant equation. The hydrological method involves replacing the dynamic equation with a simplified way within a reasonable range. This method is simple and easy to operate, and it has a sure accuracy [18,19]. The hydrological method is usually applied to conditions where the data are scarce, and faster calculation is required. With the rapid development of computer technology, it is possible to use numerical methods directly to solve the Saint–Venant equations [20]. Therefore, the hydraulic calculation of a plain river network can be carried out by using the hydraulic method. The one-dimensional (1D) Saint–Venant equations [21] are used as the basic confluence equations of a plain river network. The model could provide the spatiotemporal distribution of the flow and water level in each control section of each reach, thus reflecting the flood evolution process in the plain river network area.

This study aims to develop a waterlogging process simulation model that could describe various hydrological elements in a flat irrigation district and comprehensively describe the generation, accumulation, and confluence of waterlogging in irrigation areas. Therefore, we have improved the Tank model from the structure and calculation method according to the characteristics of the rice irrigation area. Firstly, to make the tank model reflect the water movement in paddy fields, we proposed a two-layer tank structure model. Two side holes and a bottom hole were set in the first layer of the tank. The lower side hole was used to simulate the lateral seepage of the paddy field ridge, and the upper side hole was used to simulate the paddy field overflow. Secondly, to make the outflow coefficient have a particular physical significance, we changed the formula for calculating the outflow from a linear formula to the weir formula. Thirdly, we coupled the field tank model with the river hydraulic model based on Saint–Venant equations by the interrelation and constraint between drainage of paddy fields and the adjacent river water level. This study will provide decision support for the formulation of flood control, waterlogging reduction, and mitigation strategies in flat irrigation districts.

2. Materials and Methods
2.1. Study Area

Gaoyou Irrigation District is to the east of Gaoyou City, Jiangsu Province, and on the lower reaches of the Huaihe River Basin, which is also a typical plain irrigation area in southern China. Gaoyou Irrigation District is in the northern subtropical monsoon climate area, prone to droughts and floods. The major flood and waterlogging disasters can be divided into the plum rain type and the typhoon type. The annual average sunshine amount is 1931 hours, the annual average relative humidity is 67%, and the yearly average rainfall is 1030 mm. Due to the influence of the monsoons, the rainfall has apparent seasonal variations. Rain is rare in winter and concentrated in summer, making up about 50% of the annual total precipitation. The surface soil layer in the irrigation area
is clay loam with 21.88 g/kg of organic carbon, a pH value of 7.4, and a bulk density of 1.32 g/cm³ in the 0–30-cm soil layer.

Longbenwei, a typical agricultural polder area in the middle of Gaoyou Irrigation District, was selected as the study area (as shown in Figure 1). The total area of the study area was about 2666 hectares, of which the cultivated area accounted for about 90%. According to the hydrological and geological characteristics of the low-lying irrigation district, the paddy field between irrigation ditches was regarded as a ‘paddy field unit’, and the water tank model was used to calculate the drainage of the paddy field on each cell. Therefore, the study area was divided into 23 field units in total.

Figure 1. Basic overview of the test area.

2.2. Description of the Waterlogging Process Model

2.2.1. Structure of the Model

Rice irrigation districts include irrigation canals, paddy fields, and drainage ditches. Water is irrigated from source to paddy fields through a complex irrigation canal system (main canal, branch canal, and lateral canal). The redundant water of the paddy fields is discharged through ditches and rivers. With the improvement of irrigation and drainage facilities, irrigation and drainage routes have become more directional. A ‘paddy field unit’ boundary is mainly surrounded by three irrigation canals and one river (Figure 2); thus, the ‘paddy field unit’ runoff flows into adjacent rivers unilaterally. Because of the isolation of the channel boundary in the irrigation area, there is a hydraulic connection between the paddy field and the specific river channel. Still, there is no hydraulic connection between fields. Therefore, the flowchart of the drainage system in the study area can be generalized as shown in Figure 3.

The waterlogging process model proposed in this article comprises two parts (Figure 4): a runoff generation module and a runoff confluence module. The runoff generation module is based on the original tank model, which took the meteorological data, the initial water depth of the paddy fields, and the river level as the input and simulated the runoff process of the paddy field through the side holes of tanks. Thus, the water storage depth of the paddy field in the irrigation district could be reflected directly by the water storage depth of the water tank in the first layer of the model. The confluence module adopted the hydrodynamic model based on Saint–Venant equations, which could simulate the water level and discharge of each channel section in the river network and achieve the simulation of the rainfall-runoff process.
Figure 2. Irrigation channel and drainage ditch system of the rice irrigation district.

Figure 3. Flowchart of the drainage system for waterlogging removal in the study area.
As shown in Figure 4, the runoff generation module and the confluence module of the river network were interrelated and constrained by the drainage of paddy fields and the adjacent river water level. The rainfall-runoff process simulated by the improved tank model was the lateral inflow boundary of the confluence model. In contrast, the river level simulated by the confluence model was the boundary of the paddy field runoff simulation. For the flat irrigation districts, the drainage of paddy fields was affected by rainfall and the adjacent river water level. With the drainage of the paddy fields, the adjoining river water level increased gradually, which changed the paddy field drainage boundary and might have had effects (such as jacking and pouring) on the drainage and water depth of the paddy fields. The change of water depth of the paddy fields changed the drainage of the paddy fields and acted on the river’s hydraulic calculation, changing the river water level. This cyclical effect determined that the paddy fields’ runoff generation and confluence processes were an organic whole. The simulation model of the waterlogging process in the irrigation district was based on this connection to closely couple the runoff generation module and the confluence module of the model.

2.2.2. Paddy Tank Model

The tank model could simulate rainfall-runoff processes at different time scales by changing the structure of the tank combination. A single rainfall event tank model was more suitable for waterlogging control and drainage project scheduling than the daily scale tank model. Therefore, a two-layer tank structure model was proposed in the rice irrigation district. For the model’s parameters to have specific physical significance, two side holes and a bottom hole were set in the first layer of the tank. The bottom hole outflow was used to simulate the lateral seepage of the paddy field ridge, and the upper hole outflow was used to simulate the paddy field overflow. Two side holes and a bottom hole were used to simulate the soil flow in the second layer. The bottom hole height of the second tank was equivalent to the paddy soil water-holding capacity, and the upper hole height was identical to the paddy soil saturated water content. In the model, the first layer of the tank was used to simulate the surface water movement in a paddy field. The upper hole of the first layer was used to simulate the overflow of the field ridge, the lower hole was used to simulate the lateral leakage of the field ridge, and the bottom hole was used to simulate the infiltration process (Figure 5). Since the drainage of the paddy fields was mainly affected by the adjacent river level, the calculation method of the water storage depth (S1) was 

![Figure 4. Structure of the waterlogging process simulation model.](image-url)
differed according to various outer river level \((h_{\text{River}})\) conditions. The calculation formula of \(S1\) was:

\[
\frac{dS1}{dt} = P - E - P1 - R11 - R12, \tag{1}
\]

where \(S1\) is the water storage depth of the paddy field, in m, \(P\) is rainfall, in m, \(E\) is evapotranspiration, in m, \(P1\) is the infiltration amount, in m, which could be ignored or treated as zero when the adjacent water level was higher than the bottom hole of the first layer tank, \(R11\) is the overflow flow of the paddy field, in m, and \(R12\) is the infiltration amount through the ridge of the paddy field, in m.

![Figure 5. Schematic diagram of the first layer tank.](image)

The outflow from the field tank to the river could be calculated based on the weir formula as

\[
\text{Submerged flow} \quad R = \frac{3\sqrt{3}}{2} \mu \sqrt{2gh} \frac{P1 - h_{\text{Field}} + \frac{1}{3} (1 - \frac{h_{\text{River}}}{h_{\text{Field}}})}{\frac{h1}{h2} \geq \frac{2}{3}}, \tag{2}
\]

\[
\text{Free flow} \quad R = \mu \sqrt{2gh} \left( \frac{h_{\text{Field}} + \frac{1}{3} (1 - \frac{h_{\text{River}}}{h_{\text{Field}}})}{h_{\text{Field}} + \frac{1}{3} (1 - \frac{h_{\text{River}}}{h_{\text{Field}}})} \right) \geq \frac{2}{3}; \tag{3}
\]

where \(B\) is the notch width of the weir, \(h_{\text{River}}\) is the water level of the adjacent river, \(\mu\) is the discharge coefficient, \(g\) is the gravitational acceleration, \(h1\) and \(h2\) are the water depths in the field tank and adjacent river above the weir (the side holes), respectively, \(hi\) is the weir height obtained with local field measurements, and \(h_{\text{Field}}\) is the height of the paddy field.

According to the condition of the water depth in the paddy fields and the adjacent river, \(R11\) and \(R12\) were calculated as follows [22]:

If \(h_{\text{River}} < h_{\text{Field}} + h12\):

\[
R11 = \begin{cases} 
0.0, & S1 \leq h11 \\
\frac{C_d\sqrt{2gh(S1 - h12)^{1.5}}}{A_{\text{tank}}}, & S1 > h11
\end{cases} \tag{4}
\]

\[
R12 = \begin{cases} 
0.0, & S1 \leq h12; \\
\frac{C_d\sqrt{2gh(S1 - h12)^{1.5}}}{A_{\text{tank}}}, & S1 > h12
\end{cases} \tag{5}
\]

where \(h11\) is the height of the upper hole, representing the water storage capacity of the rice field, \(h12\) is the height of the lower hole, reflecting the infiltration of the ridge of the paddy field, \(B\) is the weir width in the broad-crested weir overflow formula, \(C_d\) is the outflow coefficient, \(g\) is the gravitational acceleration, 9.8 m/s\(^2\), \(T\) is the time, in s, and \(A_{\text{tank}}\) is the area of the ‘paddy field unit’, in m\(^2\).
If \( h_{\text{Field}} + h_{12} < h_{\text{River}} < h_{\text{Field}} + h_{11} \):

\[
R_{11} = 0; \quad (6)
\]

\[
R_{12} = \begin{cases} 
C_d \sqrt{g H_{u1}^{1.5} T} (S_1 + h_{\text{Field}} - h_{\text{River}}), & H_{u2}^2 < 0.8; \\
C_d \sqrt{6 g H_{u2}^{1.5} (S_1 + h_{\text{Field}} - h_{\text{River}})}, & H_{u2}^2 > 0.8; 
\end{cases} \quad (7)
\]

where \( H_{u1} \) and \( H_{u2} \) are the upstream and downstream water heads of the lower hole in the first layer tank, respectively, in m.

### 2.2.3. River Network Confluence Model

The 1D Saint–Venant equations [21,23] were used as the basic confluence equations of the river network, describing the 1D unsteady flow of the river channel consisting of the continuity equation Equation (8) and the dynamic equation Equation (9). This study used Preissmann’s implicit scheme to solve the Saint–Venant equations, including the dynamics and continuity equations [24,25]:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L; \quad (8)
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \alpha \frac{Q^2}{A} \right) + g A \frac{\partial Z}{\partial x} + g A \frac{|Q| Q}{K^2} = q_L v_x; \quad (9)
\]

where \( x \) is the distance (m), \( t \) is the time (s), \( A \) is the area of the water-carrying section, in \( \text{m}^2 \), \( Z \) is the water level, in m, \( \alpha \) is the momentum modifying factor, \( g \) is the acceleration of gravity, in \( \text{m}^2/\text{s} \), \( K \) is the modulus of flow, in \( \text{m}^3/\text{s} \), and \( q_L \) is the lateral inflow per unit width, in \( \text{m}^2/\text{s} \). The influx was positive, and the outflow was negative. \( v_x \) is the velocity of inflow along the direction of the current in m/s. If the lateral influx direction was perpendicular to the mainstream path, then \( v_x = 0 \).

### 2.2.4. Parameters of the Model

The parameters of the waterlogging process model could be divided into the tank model parameters and the confluence model parameters. First, the tank model parameters comprised four categories [26]: the height of the outlet hole, the outflow coefficient, the width of the “overflow weir,” and the water storage height of the tank, with 12 parameters in total. Second, the parameters of the confluence model mainly included the length of the channel, the size of the cross-section, the roughness, and the discharge coefficient of the sluice, which had physical significance and were easy to calculate through measurement or the recommended formula of the specification. Therefore, the parameters needed to calibrate were mainly the tank model parameters of the runoff generation module (Table 1).

| Tank Layer | Meaning | Parameter | Unit | Value Range |
|------------|---------|-----------|------|-------------|
| 1st        | Height of upper hole | \( h_{11} \) | m | 0.02–0.1 |
|            | \( h_1 \) | m\(^{-1} \) | 0.0–0.05 |
|            | Weir width per unit area | \( b_1 \) | m\(^{-1} \) | 0.00–0.0001 |
|            | Infiltration coefficient | \( \beta_1 \) | 1 | 0.0–0.001 |
| 2nd        | Outflow coefficient | \( \alpha_{21} \) | 1 | 0.0–0.3 |
|            | \( \alpha_{22} \) | 1 | 0.0–1.0 |
|            | \( h_{21} \) | m | 0.0–1.0 |
|            | Height of upper hole | \( h_{22} \) | m | 0.3–0.5 |
|            | Infiltration coefficient | \( \beta_2 \) | 1 | 0.0–0.2 |
2.2.5. Implementation of the Model

The software of waterlogging process model was developed by ourselves. The paddy tank and river network confluence model were built and coupled based on Microsoft Visual Studio 2010 and C# language code. It has a friendly interface with the Client/Server framework. Each module adopts component development, making it expandable and portable.

2.3. Experiment and Data
2.3.1. Monitoring Data

(1) Rainfall Data: The rainfalls were recorded by an automatic weather station (SPEC-TRUM WatchDog2000 series, Aurora, Illinois, USA.) installed in the study area from 2012 to 2015. We selected ten typical rainfall processes according to the monitoring data of runoff and water level in the study area. Two rainfall events (Rainfall Event 1 and 2) were selected to verify field water depth and river water level for the waterlogging model. Remaining eight rainfall events were used for calibration and verification of the tank model.

Rainfall Event 1 occurred from 13 August to 14 August, 2014 (Figure 6a). The cumulative rainfall was 133.8 mm, the maximum 24-h rainfall was 108.8 mm, and the peak intensity was 18.4 mm/h. As a result, the lowest water level of the Nanchengzi River was 1.77 m, and the highest water level was 2.54 m. All of the pumping stations were closed during the rainfall.

Rainfall Event 2 occurred from 9 August to 11 August 2015 (Figure 6b). This rainstorm was a typhoon-type rainfall with a cumulative rainfall of 271.6 mm, a maximum cumulative rainfall of 269.2 mm in 24 hours, and a peak intensity of 47.4 mm/h. The total amount of rain was equivalent to the standard of 100-year rainfall in Gaoyou City. The average water level of the Nanchengzi River was 1.53 m at the beginning of the precipitation, and the peak water level was 2.95 m. The change processes of the average water level at the four observation points (Node 28, 29, 30, 32) of the Nanchengzi River are plotted in Figure 6. During Rainfall Event 2, some pumping stations in the study area were operated for discharging the waterlogging, as shown in Table 2.
Table 2. Actual scheduling strategy of waterlogging drainage engineering (Rainfall Event 2).

| Pumping Station | Category | Rated Flow (m$^3$/s) | Opening Time          | Closing Time          |
|-----------------|----------|-----------------------|-----------------------|-----------------------|
| P1              | Gate     | -                     | 11 August 2015 05:00  | 14 August 2015 18:00 |
|                 | Pump     | 4.00                  | 11 August 2015 05:00  | 11 August 2015 05:00  |
| P2              | Gate     | -                     | 11 August 2015 09:00  | 13 August 2015 16:00 |
|                 | Pump     | 1.45                  | 11 August 2015 09:00  | 13 August 2015 16:00 |
| P3              | Gate     | -                     | 11 August 2015 08:00  | 13 August 2015 20:00 |
|                 | Pump     | 1.00                  | 12 August 2015 08:00  | 12 August 2015 20:00 |
|                 |          |                       | 13 August 2015 08:00  | 13 August 2015 20:00 |
| P4              | Gate     | -                     | 11 August 2015 05:00  | 11 August 2015 05:00  |

Note: P1 is the Jiangmahe pump station, P2 is the Zhongshihe pump station, P3 is the Hongqi pump station, and P4 is the Lvyanghe gate.

(2) Waterlogging Features: The waterlogging features were measured in the specific paddy fields and rivers in the Longbenwei, Gaoyou irrigation district to verify the mathematical model results. These measurements included the paddy field runoff, river water level, and water storage depth in the paddy field (Table 3).

Table 3. Basic information for primary monitoring data.

| Data Type                | Monitoring Period | Monitoring Location                  | Monitoring Frequency | Measuring Method                          |
|--------------------------|-------------------|--------------------------------------|----------------------|-------------------------------------------|
| Paddy field runoff       | 2012–2014         | Two ditches in paddy 4 and 5         | One h                | Odyssey water level gauge and triangular weir |
| River water level         | 2014–2015         | Node 3, 7, 17, and 18                | One h                | Odyssey water level gauge                 |
| Paddy water storage depth | 2014–2015         | Paddy 4, Paddy 5                     | Two h                | Odyssey water level gauge                 |

Paddy field runoff: In the paddy field scale, eight rainfall-runoff processes of ditches in paddies 4 and 5 were monitored from 2012 to 2014 with Odyssey (New Zealand) water level gauge and triangular weir per hour. Four rainfall-runoff processes in which the rainfall is more than 50 mm were selected for Tank model calibration. The rest four rainfall-runoff processes were used for Tank model validation.

Water storage depth of paddy fields: the water storage depths of the paddy fields were observed in Fields 4 and 5 (Figure 3) from 2014 to 2015 by an Odyssey water level gauge per two hours. Those data were used for Tank model validation of the performance in water storage depth simulation.

River water level: Nodes 3, 7, 17, 18, 28, 29, 30, and 31(Figure 3) in the river network were selected as typical sections for water level observation, and the process of river water level from 2014 to 2015 was monitored cumulatively by Odyssey water level gauge per hour. These data were used for model validation of the performance in river water level simulation.

2.3.2. Collected Data and Sources

In addition to field observation, some other basic information was necessary for the model. Table 4 summarizes the data types and sources collected for model calibration and validation.
Table 4. Main data for the model and its sources.

| Data Type          | Name                                      | Source                                                                 |
|--------------------|-------------------------------------------|------------------------------------------------------------------------|
| Terrain data       | Ground elevation                          | Topographic Map of Gaoyou City                                         |
| River network data | River network distribution map            | Water system distribution map of Gaoyou City (provided by Gaoyou Water Resource Bureau, Gaoyou, China) |
|                    | Channel size, historical water level      | Measured data (provided by Water Resource Bureau, Gaoyou, China)        |
| Roughness coefficient |                                        | The empirical calculation, set to 0.025                                |
| Engineering data   | Essential information for drainage works  | Survey data (provided by Xiejia Water Resource Station, Gaoyou, China) |

2.4. Evaluation Method of the Model

With the rapid development of computer technology, automatic parameter calibration methods have been widely used in the parameter calibration of hydrological models [27], such as genetic algorithms [28–31], particle swarm optimization [32–34], and ant colony optimization algorithms [35]. Those methods speed up parameter calibration, make up for the staff’s lack of experience, and increase the objectivity and credibility of the simulation results. In this study, an adaptive genetic algorithm was proposed to calibrate the parameters of the tank model.

The model parameter calibration process is a parameter optimization process used to minimize the errors between simulated and measured values. Therefore, the Nash–Sutcliffe Efficiency Coefficient [36] was taken as an evaluation index of the hydrological model effectiveness, and an adaptive genetic algorithm was adapted for optimization [37]. The objective function was:

$$\text{Max}\{\text{NSE}\} = \max\left\{1 - \frac{\sum_{i=1}^{n} (Q_0(i) - Q_c(i))^2}{\sum_{i=1}^{n} (Q_0(i) - \overline{Q_0})^2}\right\},$$  \hspace{1cm} (10)

where $Q_0(i)$ is the measured runoff, in mm/h, $Q_c(i)$ is the runoff simulated by the model, in mm/h, and $\overline{Q_0}$ is the average measured runoff, in mm/h.

The leading statistical indicators used in the effect evaluation of the model included the Nash coefficient $\text{NSE}$, mean absolute error $\text{MAF}$, root mean square error $\text{RMSE}$, mean relative error $\text{MRE}$, and correlation coefficient $R$.

3. Result and Discussion

3.1. Calibration of the Model Parameters

Four typical rainfall processes were used to calibrate the tank model parameters in the Gaoyou Irrigation District. The obtained parameters are presented in Table 5. As can be seen from Figure 7 and Table 6, the linear regression coefficient of the model simulation value and the measured value were ranged from 0.91 to 0.99, and the linear fitting determination coefficient $R^2$ were ranged from 0.81 to 0.94.
### 3.2. Verification of the Model

The output variables of the waterlogging process simulation model mainly included the runoff from the paddy field, the river water level, and the change of water storage depth in the paddy field. Therefore, this study verified the model with three waterlogging features: the paddy field runoff, river water level, and water storage depth in the paddy field.

#### 3.2.1. Verification of the Paddy Field Runoff Process

During the validation period, the absolute errors between the simulated and measured runoff values of the four specific rainfall events were 0.54–4.59 mm/h. The relative error ranged from 6.4% to 20.8%, the root mean square error ranged from 0.06 to 0.29 mm/h,

#### Table 5. The optimizing results of Tank model parameters.

| Layer | Meaning                        | Parameter | Unit | Optima |
|-------|--------------------------------|-----------|------|--------|
| 1st   | Height of upper hole           | \( h_{11} \) | m    | 0.047  |
|       | Weir width per unit area       | \( b_1 \) | \( m^{-1} \) | 0.000014 |
|       | Infiltration coefficient       | \( b_2 \) | \( m^{-1} \) | 0.000076 |
| 2nd   | Outflow coefficient            | \( \alpha_{21} \) | 1    | 0.41   |
|       | Height of upper hole           | \( h_{21} \) | m    | 0.50   |
|       | Infiltration coefficient       | \( \beta_2 \) | 1    | 0.032  |

#### Figure 7. Scatter plot of simulated and measured runoff values in the calibration period.

#### Table 6. Statistical indexes for the performance of the paddy field runoff model. (calibration period, \( \Delta \text{T} = 1 \) h).

| Time              | Rainfall (mm) | Measured Runoff (mm) | Simulated Runoff (mm) | RMSE (mm) | \( R \) | NSE  |
|-------------------|---------------|----------------------|-----------------------|-----------|-------|------|
| 8 August 2012     | 130.20        | 53.00                | 46.94                 | 0.17      | 0.96  | 0.79 |
| 3 September 2012  | 58.20         | 26.35                | 21.96                 | 0.17      | 0.99  | 0.96 |
| 25 June 2013      | 90.70         | 56.46                | 58.02                 | 0.25      | 0.97  | 0.94 |
| 4 July 2014       | 92.00         | 53.57                | 51.67                 | 0.28      | 0.95  | 0.81 |
and the correlation coefficient $R$ ranged from 0.88 to 0.97. The simulated $NSE$ ranged from 0.73 to 0.93 (Table 7). The linear regression coefficients of the simulated runoff and the measured runoff in the verified irrigation area ranged from 0.85 to 0.99, and the determination coefficients ranged from 0.71 to 0.85 (Figure 8). In general, the accuracy of the model in the validation period was consistent with the calibration period. It proved the effectiveness of the waterlogging process simulation model in runoff process simulation in the paddy field, which is efficacious in simulating the individual rainfall-runoff process in the study area.

Table 7. Statistical indexes for the paddy field runoff model (validation period, $\Delta T = 1\; h$).

| Time             | Rainfall (mm) | Measured Runoff (mm) | Simulated Runoff (mm) | RMSE (mm) | $R$  | NSE  |
|------------------|---------------|----------------------|-----------------------|-----------|------|------|
| 18 June 2013     | 48.30         | 22.01                | 26.60                 | 0.29      | 0.96 | 0.88 |
| 24 September 2013| 25.90         | 4.92                 | 4.16                  | 0.06      | 0.88 | 0.73 |
| 7 August 2014    | 66.40         | 39.51                | 33.54                 | 0.19      | 0.97 | 0.93 |
| 24 August 2014   | 43.20         | 8.41                 | 8.95                  | 0.12      | 0.92 | 0.85 |

Figure 8. Scatter plot of simulated and measured runoff values in the verification period.

3.2.2. Verification of the River Water Level

Figures 9 and 10 show the analyses of the simulation effect of the plain river network hydrodynamic model on the river level process under conditions of no engineering operations (Rainfall Event 1) and engineering operations (Rainfall Event 2), respectively. The water level rose faster and receded for a longer time for the conditions shown in Figure 9. The rapid rise of river water was that the rainfall intensity was high, and the rainfall was relatively concentrated. The long subsidence time was that the flat irrigation districts had a flat terrain and a slight river gradient. The river water had a jacking influence on the field drainage. The above results revealed that the simulated water level was consistent with that measured without drainage engineering operation. The model could accurately capture the rising and falling process of the water level and the peak water level.
Table 7. Statistical indexes for the paddy field runoff model (validation period, \(\Delta T = 1\) h).

| Time          | Rainfall \(\text{mm}\) | Measured Runoff \(\text{mm}\) | Simulated Runoff \(\text{mm}\) |
|---------------|------------------------|-------------------------------|-------------------------------|
| 18 June 2013  | 48.30                  | 22.01                         | 26.60                         | 0.29 | 0.96 | 0.88 |
| 24 September 2013 | 25.90              | 4.92                          | 4.16                          | 0.06 | 0.88 | 0.73 |
| 7 August 2014 | 66.40                  | 39.51                         | 33.54                         | 0.19 | 0.97 | 0.93 |
| 24 August 2014 | 43.20                 | 8.41                          | 8.95                          | 0.12 | 0.92 | 0.85 |

Figure 8. Scatter plot of simulated and measured runoff values in the verification period.

3.2.2. Verification of the River Water Level

Figures 9 and 10 show the analyses of the simulation effect of the plain river network hydrodynamic model on the river level process under conditions of no engineering operations (Rainfall Event 1) and engineering operations (Rainfall Event 2), respectively. The water level rose faster and receded for a longer time for the conditions shown in Figure 9. The rapid rise of river water was that the rainfall intensity was high, and the rainfall was relatively concentrated. The long subsidence time was that the flat irrigation districts had a flat terrain and a slight river gradient. The river water had a jacking influence on the field drainage. The above results revealed that the simulated water level was consistent with that measured without drainage engineering operation. The model could accurately capture the rising and falling process of the water level and the peak water level.

Figure 9. Curves of the measured and simulated processes of the river level at (a) Node 3, (b) Node 18, (c) Node 7, (d) Node 17 (Example 1).

Figure 10 shows that, with the pumping station operation (during 48–170 h), the simulated water level and the measured water level varied with the same trend. Still, the simulation accuracy was worse than that without an engineering schedule. The main reasons for this included two aspects. First, the model assumed that the pump station worked at a rated flow rate, not following the actual operation process. Second, the project operation situation adopted by the model was obtained from the field investigation after the occurrence of waterlogging, which differed from the actual situation.
The consistency between the simulated water level and the measured water level can be seen from Figure 11, in which the scattered points fell on the line $y = x$ for the condition of a low water level, while the scattered points were very scattered under the condition of a higher water level. Through linear fitting, it was found that the zero-intercept linear regression coefficient between the simulated water level and the measured water level was between 0.98 and 1.05, close to 1, and the determined coefficient $R^2$ of the linear fitting correlation was more significant than 0.95. According to Table 8, without pumping operations, $PRE$ was 0.2–3.1%, and the $MAE$ and the $RMSE$ were in the ranges of 0.033–0.068 and 0.035–0.076 m, respectively. The average relative error $MRE$ was lower than 3%, and the correlation coefficient $r$ and the Nash coefficient $NSE$ were greater than 0.95 and 0.9, respectively. For the condition of pumping operations, the $PRE$ and the $MRE$ were less than 5%, the $MAE$ and the $RMSE$ were in the ranges of 0.062–0.077 and 0.086–0.098 m, respectively, and the $r$ and the $NSE$ were greater than 0.95 and 0.9, respectively. In summary, the peak value and the average relative error of the model
simulation could be lower than 5%, and the root mean square error was less than 0.1 m, which could meet the requirements of the waterlogging process simulation.

The consistency between the simulated water level and the measured water level can be seen from Figure 11, in which the scattered points fell on the line \( y = x \) for the condition of a low water level, while the scattered points were very scattered under the condition of a higher water level. Through linear fitting, it was found that the zero-intercept linear regression coefficient between the simulated water level and the measured water level was between 0.98 and 1.05, close to 1, and the determined coefficient \( R^2 \) of the linear fitting correlation was more significant than 0.95. According to Table 8, without pumping operations, \( \text{PRE} \) was 0.2–3.1%, and the \( \text{MAE} \) and \( \text{MRE} \) were in the ranges of 0.033–0.068 and 0.035–0.076 m, respectively. The average relative error was lower than 3%, and the correlation coefficient \( R \) and the Nash coefficient \( NSE \) were greater than 0.95 and 0.9, respectively. For the condition of pumping operations, the \( \text{PRE} \) and the \( \text{MAE} \) were less than 5%, the \( \text{MRE} \) and the \( \text{RMSE} \) were in the ranges of 0.062–0.077 and 0.086–0.098 m, respectively, and the \( R \) and the \( NSE \) were greater than 0.95 and 0.9, respectively.

In summary, the peak value and the average relative error of the model simulation could be lower than 5%, and the root mean square error was less than 0.1 m, which could meet the requirements of the waterlogging process simulation.

3.2.3. Verification of Water Storage Depth in Paddy Fields

The simulation of water storage depth in paddy fields is the basis of waterlogging loss assessment. Therefore, the monitoring results of the typical field water storage depth were used to verify the model’s simulation results. As shown in Figure 12, the simulated water storage depth variation in paddy fields was consistent with the variation measured in practice. In particular, when the water storage depth in paddy fields was relatively low,
the simulated value essentially coincided with the measured value. However, there was a difference between the simulated peak value of the water storage in paddy fields and the measured value. The main reason for this was that the field surface elevation used in the model simulation was the regional average height, which differed from the field elevation monitored in practice. According to the statistical parameters (Table 9), the MAE and the RMSE of the simulated water depth in the rice field were 0.007–0.015 and 0.015–0.02 m, respectively. The correlation coefficients for the simulated values and the measured values were all greater than 0.95, while the NSE ranged from 0.84 to 0.90, approaching 1. In summary, the simulation model of the waterlogging process in the irrigation area had high accuracy for the simulation of the water storage depth of the paddy field, and the model could be used to simulate the waterlogging process in the paddy field.

![Graph of the measured and simulated flooded depth of specific fields.](image)

**Figure 12.** Graph of the measured and simulated flooded depth of specific fields.

| Event          | Field Number | MAE (m) | RMSE (m) | R   | NSE |
|----------------|--------------|---------|----------|-----|-----|
| Example 1 (2014) | Paddy field 5 | 0.008   | 0.015    | 0.972 | 0.85 |
|                | Paddy field 6 | 0.007   | 0.015    | 0.952 | 0.84 |
| Example 2 (2015) | Paddy field 5 | 0.015   | 0.020    | 0.987 | 0.89 |
|                | Paddy field 6 | 0.015   | 0.020    | 0.977 | 0.90 |

### 4. Conclusions

The waterlogging process model proposed in this study is a handy tool in the drainage analysis of the rice irrigation district. Through a reasonable correction on the structure of the Tank model, the accuracy of drainage simulations on the paddy fields can be improved to enhance its local applicability. Several conclusions are summarized as follows:

1. The evaluation of the simulation results of the waterlogging process model in the rice irrigation district with six commonly used indicators in statistics and hydrology confirms that the overall performance of the waterlogging process model is excellent. Therefore, the model is applicable for simulating the waterlogging and rainfall-runoff of flat irrigation districts.

2. The structure and calculation principle of the tank model can be modified to enhance the physical significance of model parameters. Traditional tank models use drainage simulations, while this study successfully conducted water-depth simulations in paddy fields. The results of water depth in paddy-field simulations demonstrate that the model is applicable to waterlogging simulations.

3. The reason for the high accuracy in this waterlogging process model is that it is modified by considering the interrelated and constrained relationship between the drainage of paddy fields and river water level. Overall, the waterlogging process model gives an impressive performance, precisely predicting drainage and water-depth changes.
Furthermore, the evaluation values of both the RMSE and the NSE show that this model can achieve good waterlogging simulation results in plain irrigation areas.

Due to the limitation of the research depth, the waterlogging process model in this study is still in an exploratory stage and has some drawbacks, which are embodied in the following three aspects. First, the tank model’s parameters lack physical meaning, and many measured rainfall-runoff data were needed to calibrate the parameters. Therefore, the problem of 'equifinality for different parameters' has not been effectively solved. Second, the 'paddy field units' used for runoff calculation were manually divided based on the irrigation and drainage engineering characteristics. When the scale of the study area expended, the workload of the unit division will increase sharply. Third, we assumed that the 'paddy field unit' was a single rice field while ignoring other land use types, inconsistent with the actual underlying surface. Therefore, we need to improve the model structure and outflow calculation formula continually to make the model parameters have more physical significance. Meanwhile, we should propose a gis-based 'paddy field unit' division method and develop distributed waterlogging process models considering different land-use in a 'paddy field unit.'

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