Study on Rainfall-runoff Process of the Lower Plain Areas with Multi-level Drainage System

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Abstract: Accurately simulate rainfall-runoff process of the lower plain areas is highly complex because of the multi-level drainage system, which is operated by the different authorities in different decision level. The multi-level drainage system is characterized with the high density drainage canals and the large number of sluices and pump stations. A combination of the hydrodynamic model, the hydrologic model, the sluice and pump model was adopted to simulate the rainfall-runoff process in the lower plain area. The outflow of second-level sluice or pump station in sub-district was simulated by the sluice and pump model, and it was coupled to hydrodynamic model in the form of point inflow or distributed inflow. This model combination was verified with the rainfall-runoff process of the Diaocha lake area, which is located in the middle reach of the Yangtze River. Simulation results show that the proposed model combination is effective in modeling historical floods which occurred in the Diaocha lake area.

1. Introduction
It is essential to develop proper rainfall-runoff model for the prediction of discharge rate of the lower plain areas with multi-level drainage system, characterized with the high density drainage canals and pump stations. Due to extremely high percent of farming area, high density of crisscrossed drainage canals and ditches with large number of sluices and pump stations, the hydrological process of the lower plain area is strongly affected by the human activities, such as the different operating rules of sluice and pump station, and the layout and cropping structure of agriculture. Therefore, the rainfall-runoff process of the low plain areas is a non-natural process under multi-level artificial control, resulting in that the direction of flow, the velocity of flow, the rate of flow and water level is most controlled by the operating rules of sluice and pump station.

The past two decades have witnessed the development of a number of rainfall-runoff models for the lower plain areas of different complexity, ranging from conceptual model to physically based mode (Wu, et. al, 2001; Kim, et. al, 2005; Jia, et. al, 2005). However, the current rainfall-runoff simulation model focusing on the description of the natural water cycle process (Chahinian, et. al, 2005) is on the basin scale, and the agricultural hydrological model, focusing on the description of the natural-agricultural compound water cycle process is on the soil column scale and field scale. The agricultural hydrological model on the basin scale is lacking in the description of the mechanism of natural - agricultural compound hydrological circulation system (Moussa, et. al, 2002). In a word, research on rainfall-runoff model to the scale of drainage area is still in the stage of initiation and exploration (Chen, et. al, 2003). It is an effective method to simulate the rainfall-runoff process of the lower plain areas by coupling the distributed hydrological model of the drainage area, the hydrodynamic model of hydraulic structure including sluice or pump at each level, and the
optimization model for the operation of the pump station. However, on the scale of the drainage area, this method requires a lot of high-precision data with performance computing equipment, so in fact this method does not get good results for engineering applications in lower plain areas. How to build a simple and reliable rainfall-runoff simulation method is critical in the face of increasingly urgent flood disaster control in lower plain area. The Diaocha lake area, located in the middle reach of the Yangtze River, is selected as the study area, a combination of the hydrodynamic model, the hydrologic model, the sluices and pump model is adopted to simulate the rainfall-runoff process in the Diaocha lake area.

2. Study Area

As shown in Figure 1, the Diaocha Lake area is located in the northeast of the Jianghan Plain with the Hanbei River in the northeast, and the Han River in the south and the Tianmen flood control sluice in the west. The total drainage area is 1936km², among which Tianmen is 919km², Hanchuan is 984km² and Yingcheng is 33km². The terrain of this region is relatively flat, little tilted from northwest to southeast. Most of the ground elevation is of 24.0m-28.0m in Tianmen and most of the ground elevation is of 23.0 ~ 26.0m in Hanchuan.

The drainage system of Diaocha Lake area is mainly composed of intersecting artificial ditches around the storage area and the spare storage area. The storage area and the spare storage area, known as the Diaocha Lake, is divided by separation levee and the spare storage area is located in the east. The area of storage area and spare storage area is 48.7km² and 38km² respectively.

The study area is crisscrossed by rivers and artificial canals, ditches. The main drainage canals are mainly composed of the east-west canals and the north-south canals with double dikes. The former includes the Xiatianmen river, the Nanzhi river, the Beizhi river, the south canal, the north canal, the Minle canal, the pump station river, and the latter includes the Fenshui canal, the east canal, the west canal. In addition to the above-mentioned river or canal, there are four branch with total area more than 150km², respectively, Yangjiaxin ditch, Longzui ditch, Huayan Lake drainage canal, Nan Yu canal.

The study area is dotted with sluices and pump stations. There are more than 30 first-level sluices in the Diaocha Lake area, among which the Minle sluice, the Hanchuan sluice and that the Hanchuan pumping station sluice is the three main first-level sluice with a total design flow of 900m³/s. The total installed capacity of the 29 first-level pump stations is 46400kW, with a total design flow of 516.59m³/s, in which 12 first-level pump stations discharge into the Han River with a total flow of 420.89m³/s, and the others discharge into the Hanbei River with a total flow of 95.7m³/s. The 1st and the 2nd Hanchuan station and the Fenshui pump station is the three main drainage station under jurisdiction of Hanchuan Water Resources Bureau and the others belong to the village with limited drainage area.

There are 129 second-level sluices in the Diaocha Lake area, most of the control area is limited. The north floodgate on the north canal and the south floodgate on the south canal is the main sluice, which discharge water into the storage area when the water level of the canal is higher than 25.3m. The east floodgate on the east canal is the main sluice, which discharge water into the spare storage area when the water level of the canal is higher than 26.0m. The Hukou sluice at the intersection of the south canal and the Fenshui canal can adjust water between the Fenshui pump station and the Hanchuan one-station or the Hanchuan two-station. There are 102 second-level pump stations dotted along the main canal with the total design flow of 236.16m³/s , and the total installed capacity is 21857kW.
3. Model Descriptions

The drainage rainfall-runoff model is established by combining the hydrologic model, the pump and sluice model, the hydrodynamic model. In this study, a simple hydrologic model is used based on the dividing of sub-district. The pump and sluice model is employed to simulate the outflow of each sluice or pump, and the outflow is coupled as inflow to the hydrodynamic model.

3.1 District division and hydrologic model

It is effective to improve the accuracy of hydrologic simulation by dividing the study area into sub-districts. The four main factors for this dividing are the similar surface condition, bounded by rivers or canals, control area of second-level sluices or pump stations, and the accomplished district by limited drainage area stations. However, the joint control area of some second-level sluices and corresponding pump stations is varied according to the water level around, so it is not easy to accurately divide the joint control drainage area of each couple. After investigation, due to the electricity bills of drainage, the control area of the second-level pump station is relatively clear, it can be accurate to the administrative village, and considering the model is most applied for flood years when second-level sluice hardly has the chance to drainage, so the joint control area of the couple second-level sluice and pump station is the same as that of the second-level pump station. According to the above principles, the entire Diaocha lake area can be divided into 73 sub-districts.

According to the characteristic of rainfall-runoff of lower plain area: the total rainfall is the deciding factor to runoff depth and the process of runoff is flat, a simple hydrologic model is used:

\[ R = P - b_0 \cdot I_a - L_a \]  

Where, \( R \) is the runoff in sub-districts, \( P \) is daily precipitation, \( I_a \) is initial abstraction, \( L_a \) is later abstraction, and \( b_0 \) is the reduction coefficient of initial abstraction. The value of \( I_a \) and \( b_0 \) is analyzed through the test data collected from the Hanchuan runoff test field and \( L_a \) is equal to the evaporation by E601.

3.2 Pump model and Sluice model

Pump model
Second-level pump stations usually belong to township or village. There is no fixed operation and
scheduling rules, in the principle of maximizing their own interests, township or village usually fully load the pump station no sooner than the rain starting, so there is nearly no surface water soon after the rain stops. Therefore, the outflow of the second-level pump station is a function of the drainage capacity and the remaining waterlogging. Drainage capacity can be approximated by the design flow of the pump station. Owing to the small control drainage area of each station and the rapid confluence velocity in crisscrossed ditch, the remaining waterlogging depends mainly on the runoff depth yielded. The outflow of the second-level pump station in the Spump model can be expressed by a bilinear function:

\[ Q_{\text{pump}} = \begin{cases} \frac{b_2 V}{Q_{\text{max}pump}} & \text{if } V \leq V_0 \\ Q_{\text{max}pump} & \text{if } V > V_0 \end{cases} \]  

(2)

Where, \( Q_{\text{pump}} \) is the outflow of second-level pump station(m³/s), \( V \) is the remaining waterlogging of sub-distric drainage area(m³), \( Q_{\text{max}pump} \) is Maximum drainage capacity(m³/s), \( V_0 \) is the minimum remaining waterlogging required for the pump station to enter full load operation(m³), \( b_2 \) is a parameter(The value is equal to the slope which can be analyzed from measured data)(1/s). The remaining waterlogging in the drainage area is simulated by a linear reservoir.

**Sluice model**

Most of the upstream part in the Diaocha Lake area is self-draining area, and the outflow of the self-draining area is controlled by the water level of the downstream main canal. It is mainly a function of the scale of the second-level sluice and the water level under sluice. Part of the sluice measured data show that its process line approximation shown in Figure 2 right, the Ssluice simulation model can be expressed as:

\[ Q_{\text{sluice}} = \begin{cases} Q_{\text{max}sluice} & \text{if } Z \leq Z_0 \\ kQ_{\text{max}sluice} & \text{if } Z > Z_0 \end{cases} \]  

(3)

Where, \( Q_{\text{sluice}} \) is the outflow of second-level sluice( m³/s), \( Q_{\text{max}sluice} \) is the maximum drainage capacity( m³/s), \( Z \) is the water level under sluice(m), and \( Z_0 \) is a parameter (critical water level above which the outflow will be limited), \( b_2 \) is a parameter (Can be obtained from the measured data analysis).

### 3.3 Hydrodynamic model of Drainage Network

The Saint-Vernan equations [3] is used to simulate the water level and flow in the main canal, including the Xiatianmen River, the Nanzhi river, the Beizhi river, the south canal, the north canal, the east canal, the west canal, the Minle canal, the pump station river, the Fenshui canal and the sluice canal.

Treat the storage area and the spare storage area as the intersection with storage and the intersection
of canals as the intersection without storage, continuity equation and momentum conservation equation is used to simulate the water level and flow of the intersection.

Treat the main control sluice, such as the Hukou sluice, the north floodgate, the south floodgate and the east floodgate, as inner-boundary node, the hydraulic formula of sluice is used to simulate the flow of those sluice.

The upper boundary condition is flow, the value is the outflow of the Tianmen flood control sluice. The lower boundary condition is the relationship between water level and flow of the first-level pump station or sluice.

![Figure 3 Hydrodynamic Model Structure of Drainage Network of the Study Area](image)

### 3.4 Model Coupling

Using the hydrologic model to simulate the runoff that will be taken as the inflow of pump model or sluice model in the sub-district, and the outflow of pump model or sluice model is coupled to the hydrodynamic model by the form of external inflow. According to the drainage network and the status of second-level sluice or pump stations in sub-district area, the outflow is generalized into a point inflow or distributed inflow. Specific diagram of canal inflow is shown in the Figure 4.

![Figure 4 Some Coupling Details at the Main Canal](image)

## 4. Model Validation and Application

### 4.1 Model validation

The model was validated by using the flood events with the number of 19990622, 20030702,
20040710. Due to the storage area and the spare storage area was not be used in the three flood, so only the water level at Nanyu station in south canal near No.5 intersection is taken as verification station. As can be seen from Table 1, the absolute error of the water level of the three typical floods are less than 0.2m. Figure 5 shows a comparison between the simulated and observed daily forebay water level of the 1st Hanchuan station and Fenshui pump station of 20030702 flood. A good agreement is achieved at the high water level stage. However, they are not consistent at the low water level stage. For the real operation rules of the first-level pump station is relatively free by hand, but the simulation operation rules is strictly carried out by computer. Such as the Fenshui pump station was stopped before the water level falling to 24.5m in the real, but in the model it will still run until the water level falling under 23.5m according to the scheduling rules.

| Years | Precipitation (mm) | Highest Water Level at Nanyu Station (m) | Absolute Error |
|-------|-------------------|----------------------------------------|----------------|
|       |                   | Observed                  | Simulated     |
| 1999  | 336.4             | 26.23                     | 26.41         | 0.18           |
| 2003  | 294.7             | 26.54                     | 26.59         | 0.05           |
| 2004  | 367.0             | 26.51                     | 26.50         | -0.01          |

Figure 5 Comparison of Simulated and Observed Daily Forebay Water Level of the 1st Hanchuan Station(left) and the Fenshui Pump Station(right)

4.2 Model application
Influenced by El Nino, In Meiyu rainy period of 2016 in Hubei Province, six rounds of heavy rainfall showed unprecedented extreme value. The five famous lake areas of the Plain lake area were all lost into emergency floods, the water level of the five famous lake either hit an all-time high or exceed the guarantee. The fourth round of heavy rainfall brought the study area to the highest water level of 26.87m on July 9th. And after that the rainfall intensity at the study area was not big, but the neighbouring Hanbei river basin was strongly influenced by the sixth round of heavy rainfall. Within 43 hours, the water level of downstream river at Minle sluice jumped more than 3m from 27.2m on July 18. On July 20, the government department concerned issued a series of flood diversion orders, including diverting flood into the Diaocha lake area by the Tianmen flood control sluice. In order to maximize flood diversion volume of the Hanbei River, and at the same time not obviously increase the waterlogging of the Diaocha lake area, the model was used to simulate the water level of drainage network after flood diversion under different discharge condition of the Tianmen flood control sluice. Figure 6 shows the water and rainfall condition during the Meiyu rainy period at main hydrological station and the comparison of simulated and observed hourly water level at Nanyu station under observed flood discharge of the Tianmen flood control sluice. The Tianmen flood control sluice open at 6 o’clock on July 20 and closed at 15:30 on July 21, the total diverted flood was more than 1300 million m$^3$, and at the same time the waterlogging in the Diaocha lake area was almost not increased.
5. Conclusion
In this paper, the combination of hydrologic model, sluice model and pump model, hydrodynamic methods is developed for simulating the rainfall-runoff process of the multi-level artificial controlled drainage systems in the Diaocha lake area, which is located in the middle reach of the Yangtze River. Through dividing the drainage area into a number of small sub-districts, the difficulty of hydrologic simulation will be simplified without sacrificing the simulation accuracy because that simpler model can be used to simulate the runoff of sub-district. In order to simulate the outflow of sub-district, the pump model of second-level pump station and sluice model of second-level sluice is developed. Similarly, in order to simulate the water level and flow in the main canal, the hydrodynamic model of drainage network is developed by using Saint-Vernan equations, using continuity equation and momentum conservation equation to simulate the water level and each way flow of the intersection, using hydraulic formula to simulate the first-level pump station or sluice. The outflow of sub-district which is simulated using the pump model or the sluice model is coupled to the hydrodynamic model by the form of point inflow or distributed inflow. The case study show that the method developed for the flood simulation was successfully in the Hanbei river on the "98+" flood event in 2016.

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