A Modeling of Hydrological Processes in a Large Low Plain Area Including Lakes and Ponds

湖沼群を含む広域低平地における雨水流出過程のモデリング

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A numerical hydrological model that is universally applicable in large low plain area is developed. In this paper, common characteristics of large basin area such as channel network connecting with lakes and ponds are described in detail and the hydrological processes can be simulated by the numerically combined method between two-dimensional model for large lake and one-dimensional model for channel network. This model has been calibrated against the observed data in 1984 and 1985 from May to September in Taihu Lake Basin, China. From the result, good agreement between simulated water level and discharge to those from the observation data was indicated and therefore, this model satisfies the hydrological processes for practical use.

Key words: Low plain area, Lakes and channel network, Taihu Lake Basin, Numerical hydrological model

広大な低平地で適用可能な流出水文モデルを開発した。このモデルでは、広域の低平地で発達している河道網と湖沼群を詳細に考慮し、数値方法で二次元の大湖沼モデルと一次元の河道モデルをリンクして、雨水流出過程のシミュレーションを行っている。1984年と1985年の二年間の中国の太湖流域の水文データを用いて、このモデルの検証を行った。その結果、流域内各地点の水位と流出量が良好に再現されることが明らかとなった。

キーワード：低平地、河道網と湖沼群、太湖流域、水文モデル

I. INTRODUCTION

For many cases of flood routing, the momentum of St Venant equations may be simplified. For example, the resulting kinematic wave approximations have widely been used in flood routing studies, which does not require much computational effort compared with dynamic waves (Beven, K. *et al.*, 1993). However, these approximate calculations are handicapped by the

river characteristic. It is a common geomorphological phenomena that channel network connects with lakes in large low plain basin (Fig. 1). Since the gradient of channel is very small, the direction of flow is quite complicated. Therefore, the kinematic wave method used to solve transport of flood is unsuitable in this area. The local water level or discharge is affected by conditions around branches including artificial constructions such as sluice gate and tidal fluctuation. Thus, it

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Fig. 1 Schematic diagram of low-lying area

cannot neglect any terms of the momentum equation here. In other words, the full dynamic wave equation must be used for solving transport of flood (Cheng, W., 1985). The St Venant equations are coupled hyperbolic partial differential equations that cannot be solved analytically. With the development of the technology of computer, this problem has been overcome, thus a great number of different numerical methods have been proposed for developing numerical model (Abbott, M.B., 1979).

In addition, there are many lakes that regulate the flow of water in low plain area. From environment review, this is an important topic in water quality study because, it is axiomatic that polluting solutes flowing into lake will be transported and dispersed, affect the environment of lake and downstream in various ways. Thus, it will be required that mathematical model in which the characteristics of lake like bathymetric and boundary are considered, including inflow and outflow along the lake.

The present paper, therefore, will try to set up a basin model that can be applied on low plain area with economical in computation. For this study, Taihu Lake Basin located in Yangtze River Delta of China was selected as the study area.

II. STUDY AREA

Taihu Lake Basin is located in the Yangtze River Delta of China, covered with a part of

Fig. 2 Taihu Lake Basin

Table 1 Distribution of relief and altitude in Taihu Lake basin

Altitude(m)	Area(km ²)	The ratio of area(%)
<2.5	130.3	0.36
2.5~3.5	5952	16.31
3.5~4.5	10335	28.32
4.5~5.5	3407.3	9.33
5.5~6.5	1965.7	5.39
6.5~10	5467.7	14.98
>10	6083	16.67
Lakes	3159	8.65
Total	36500	100

Jiangsu, Zhejiang Province and Shanghai City entirely (Fig. 2). The basin area is 36,500km² (29°48'N-32°12', 119°E-121°50') and, the northern border is Yangtze River, and for southern one is Hangzhou Bay, and the boundary of eastern is Donghai Sea, the west is hilly land and mountains contributing one-sixth of the basin area. The distribution of relief and altitude of this basin is shown in Table 1 (Sun, S. *et al.*, 1993). Lakes spread all over the basin, and its total area is 3,159km². Taihu Lake is the largest lake situated in the center of the basin. Its area is 2,338km² and annual average depth is 1.99m (annual average water level is 2.99m). Therefore, this lake is characterized by its shallow but large area. It is one of the important water sources of this basin.

Taihu Lake Basin is a typical area of channel network which interfered by tide. This basin is a humid area, annual average precipitation is 1200 mm and evaporation is 800mm. In general, water flow empties into Taihu Lake from west and north hilly land area, then outflow from Taihu Lake into the east and south plain, finally empties into Yangtze River, Donghai Sea and Hangzhou Bay during the flood (The Management Bureau of Taihu Lake Basin (MTLB), Ministry of

Water Resource, China, 1986).

Taihu Lake Basin is one major economic area in China. Flood and drought, however, often take place due to the flat and low terrain characteristics, and to the unfluent draw and drainage features. On the other hand, the water quality protection is a serious problem with the economic development and population growth. The researches of Taihu Lake Basin have been started since 1970s. Some local area models have been set up (Liang, R. *et al.*, 1993) at the present, but the representatives and completeness of model are not enough because, 1) complicated area of channel network, it is important that the flow condition is considered in all over the basin, especially when quantity model incorporate water quality model and 2) the natural sense of large lake, like Taihu Lake, must be considered for research hydrological process and water quality process. Therefore, a combined model of two-dimensional model for large lake and one-dimensional model for channel viewing all basin area will be required.

III. MODELING PRINCIPLES

The dynamic wave approximation requires specification of both upstream and downstream boundary conditions, and patterns of lateral inflows. For low plain area, the upstream condition may be hilly plain or mountain, and the downstream condition may be sea. Thus the plain area model included channel network and lakes will be main point at developing basin model. In this paper, the basin model consists of outflow modeling for hilly land, plain model and the tidal process modeling at outlets.

1. Outflow Modeling for Hilly land

In Taihu Lake Basin, the region whose altitude over 10 meters is called hilly land, and the area is one-sixth of the whole basin area. There are lots of reservoirs and pools, and the runoff can be regulated. Net rainfall was changed into discharge that will become to inflow of plain channels using an instantaneous unit hydrograph (Jiangsu General Hydrological Station, Jiangsu

Hydrological Handbook, 1988).

2. The tidal process modeling at outlets

There are forty-seven channels joined with Yangtze River, Hangzhou Bay and Donghai Sea. The boundaries of these channel outlets are tides. Along Yangtze River and Hangzhou Bay, there are six and three tidal stations respectively. First, the tidal continuous process can be produced using the data of tidal characteristic value each tidal station. Using above produced tidal process, the tidal boundaries of channels at outlet every time step can be reckoned according to the place of channel outlet.

3. Plain Model

For modeling hydrological process in plain, the rainfall and evaporation process are simulated. Channels and lakes are simplified. In this section, four main parts are included: 1) the simplification of channels and lakes; 2) runoff modeling in plain; 3) modeling for unsteady flow in channel network and 4) Taihu Lake model.

1) Simplification of channels and lakes

The channels are simplified according to equivalent of over water between natural channel and simplified channel. The channel course section can be described by simplification (Fig. 3(a)). Some small channels paralleled with main channel are combined into main channel, while water level are nearly each others. Thus, the hydrological process of simulation can be cali-

Fig. 3 Schematic diagram of simplified channel

Fig. 4 The map of simplified channel network for Taihu Lake Basin

Fig. 5 Schematic diagram of land width

brated by the observed data. For example, in Fig. 3(b), observed process in point A (natural channel section) can be represented by simulated process in point B (simplified channel section) which is the nearest point A in place. The lakes are combined based on the same of volume and area (Taihu Lake is simplified as plane two dimensions). The junction of two and over channels is called node in simplified network channels. The calculation sections every channel are defined by suitable interval (less than 5km) Fig. 4 is a map of simplified channel network of Taihu Lake Basin. There are 39 lakes beside Taihu Lake, 1,286 channels, 674 nodes, and over 3,000 channel sections.

The conception of unit land width is used to consider the catchment area of channel. In Fig. 5, A_1 and A_2 are area; $L_1, L_2, \dots, L_7$ are the length of channel 1, channel 2, ..., channel 7, respec-

tively. Assuming that rainfall is collected well distributed along the channel, there are:

$$B_1 = \frac{A_1}{L_1 + L_2 + L_3 + L_4} \quad (1)$$

$$B_2 = \frac{A_2}{L_1 + L_5 + L_6 + L_7} \quad (2)$$

$$\text{so, } L_{W_i} = B_1 + B_2 \quad (3)$$

where L_{W_i} is the width of catchment area for unit length of channel 1, called unit land width. Thus the catchment area of channel 1 (A_{L_1}) can be described, as follows:

$$A_{L_1} = L_{W_1} L_1 \quad (4)$$

2) Runoff Modeling in Plain

The plain of Taihu Lake Basin is a low plain area, and that altitude is lower than 10m. Because agricultural activity is flourishing in this area, there are lots of kinds of landscapes. For modeling precipitation and evaporation process in great detail, the plain is divided into fifteen regions according to administrative division and hydrographic net. The daily data of rainfall and evaporation are simulated into the continuous processes with the same time step unit as of model.

In each region, the landscape is classified simply into three fields namely, water field, paddy field and cultivated land. That runoff are called R_1, R_2 , and R_3 respectively. The simulated runoff is described as follows:

In water field

The basic formulation is

$$R_1 = P - \beta E_{pan} \quad (5)$$

where P is rainfall (mm), E_{pan} is pan evaporation (mm), β is a conversion coefficient of evaporation of evaporimeter, it is a seasonal variable. For example, Fig. 6 shows the relation of β with time in Jiangsu Province.

In paddy field

The runoff from paddy depends on irrigation and drainage in growing season and suitable water depth for rice. It can be calculated through daily water balance for paddy.

$$H_2 = H_1 + P - \alpha E_{pan} \quad (6)$$

where H_1 is initial daily water depth (mm), H_2 is end daily water depth (mm),

Fig. 6 Evaporation simulated in water field

Fig. 7 Evaporation simulated in paddy field

α is a coefficient of need water for rice. H_P , H_U , H_D are a limit water depth, maximum suitable water depth and minimum suitable water depth respectively (shown in Fig. 7(a)), so

if $H_2 > H_P$, then $R_2 = H_2 - H_P$, $H_2 = H_P$;

if $H_U < H_2 \leq H_P$, then $R_2 = H_2 - H_U$, $H_2 = H_U$;

if $H_D \leq H_2 \leq H_U$, then $R_2 = 0$;

if $H_2 < H_D$, then $R_2 = H_2 - H_D$.

αE_{pan} means transpiration of rice. α is a seasonal variable of rice. Fig. 7(b) is an example in Jiangsu Province. The former parameters (α , β , H_P , H_U and H_D) were provided by MBTLB in 1993.

In cultivated land

Taihu Lake Basin plain is a humid area during May to September. Soil water can be supplemented easy. Thus the runoff of cultivated land can be calculated by one layer Xinganjiang model (Zhao, R. *et al.* 1980) as follows:

$$E = \alpha E_{pan} \frac{W}{W_M} \quad (7)$$

$$W_{MM} = W_M(1 + b) \quad (8)$$

$$A = W_{MM} \left\{ 1 - \left(1 - \frac{W}{W_M} \right)^{\frac{1}{1+b}} \right\} \quad (9)$$

where E is evapotranspiration,

W is initial soil moisture,

W_M is mean moisture capacity, and

W_{MM} is maximum possible lack of mois-

ture.

b and α are an index of soil moisture capacity curve distribution and a conversion coefficient of cultivated land evaporation respectively.

if $P - E \leq 0$, then $R_3 = 0$;

if $P - E + A \leq W_{MM}$, then

$$R_3 = P - E - (W_M - W)$$

$$+ W_M \left(1 - \frac{P - E + A}{W_{MM}} \right)^{1+b} \quad (10)$$

$$\text{else } R_3 = P - E - (W_M - W) \quad (11)$$

In this paper, α is 0.9 and b is 0.

The total runoff process of each district ($R(t)$) is:

$$R(t) = C_1 R_1(t) + C_2 R_2(t) + C_3 R_3(t) \quad (12)$$

where C_1 , C_2 and C_3 are fractional area.

This runoff becomes lateral inflow for channels while difference of runoff characteristic of enclosed and nonenclosed regions are considered.

3) Model for Unsteady Flow in Channel Network

The water transportation in channel network can be described by some forms of the St Venant equations. These equations can be written in one dimensional form on a unit width as follows:

$$\frac{\partial Q}{\partial x} + B_r \frac{\partial Z}{\partial t} = q_L \quad (13)$$

$$\frac{\partial Q}{\partial t} + 2u \frac{\partial Q}{\partial x} + (gA - Bu^2) \frac{\partial Z}{\partial x} - u^2 \frac{\partial A}{\partial x} \Big|_{x=z} + g \frac{n^2 |u| Q}{R^{3/2}} = 0 \quad (14)$$

where Q is discharge,

Z is water level,

A is the cross-sectional area of the flow,

u is flow velocity,

R is hydraulic radius,

B_r and B are the width of the flow, explained in later,

q_L is lateral inflow unit channel length,

n is roughness coefficient,

x is distance, and

t is time.

In Taihu Lake Basin, natural channel consists of main bed and flood land. Flood can be drained and stored in main bed. In flood land (including

 Fig. 8 Schematic diagram of the B and B_T

Fig. 9 The scheme of Pressman

some small pools and channel branches), since the flow velocity is very small, its drainability may be neglected. Though the effects of water transport may be neglected, those of water storage must be considered. Consequently, the width of flow is considered separately in this paper. B is simplified width of the flow for the calculation of momentum, and B_T is width of the flow include flood land (shown in Fig. 8). B_T can be calculated using simple relationship, as follows:

$$B_T = B + (\lambda_1 + \lambda_2 Z) L_w$$

where λ_1 , λ_2 are parameters of storage capacity curve, L_w is land width of channel. According to data and investigation, there are thirty-three storage capacity curve regions in plain.

The St Venant equations are hyperbolic partial differential equations, which cannot be solved analytically. Since 1960, a variety of finite difference methods and finite element schemes have been developed. In this paper, the method of finite difference is used. The St Venant equations are separated by implicit Priessman's scheme (Mahmood, K. *et al.*, 1975; Cunge, J.A., *et al.*, 1980) (shown in Fig. 9). Thus, the differences of variable in temporal and spatial can be described as follows:

$$\frac{\partial \xi}{\partial t} = \frac{\xi_{i+1}^{j+1} + \xi_{i+1}^{j+1} - \xi_i^j - \xi_{i+1}^j}{2 \Delta t}$$

$$\frac{\partial \xi}{\partial x} = \frac{\theta (\xi_{i+1}^{j+1} - \xi_{i+1}^{j+1}) + (1 - \theta) (\xi_{i+1}^j - \xi_i^j)}{\Delta x} \quad (15)$$

$$\xi = \frac{1}{2} (\xi_i^j + \xi_{i+1}^j) = \xi_{i+1/2}^j$$

where ξ represent Q , Z and A respectively, θ is a coefficient of weight (in this paper $\theta = 1$). Therefore, the different equations of eq. (13) and eq. (14) can be set up, then the double sweep equations can be found out.

In addition, from quantity balance, the nodal equations for every node can be developed, in which the relation about water level of each node can be decided. Thus discharge and flow velocity of each channel section can be solved when water levels are calculated by nodal equations.

4) Model for Taihu Lake

The following two equations are used to describe an incompressible fluid in two dimensions:

conservation of mass:

$$\frac{\partial \xi}{\partial t} + \frac{\partial u(h + \xi)}{\partial x} + \frac{\partial v(h + \xi)}{\partial y} = q \quad (16)$$

conservation of momentum:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial \xi}{\partial x} + \frac{1}{\rho_w(h + \xi)} (\tau_{sx} - \tau_{bx}) + f_v$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial \xi}{\partial y} + \frac{1}{\rho_w(h + \xi)} (\tau_{sy} - \tau_{by}) - f_u \quad (17)$$

$$f = 2\omega \sin \theta$$

$$\tau_{sx} = c^* \rho_a w_a^2 \sin \varphi$$

$$\tau_{sy} = c^* \rho_a w_a^2 \cos \varphi$$

$$\tau_{bx} = -\frac{n^2 u \sqrt{u^2 + v^2}}{(h + \xi)^{1/3}} \rho_w$$

$$\tau_{by} = -\frac{n^2 v \sqrt{u^2 + v^2}}{(h + \xi)^{1/3}} \rho_w$$

where u is depth-averaged flow velocity in x -direction,

v is depth-averaged flow velocity in y -direction,

ξ is vertical flow depth,

Fig. 10 The scheme of Leendertes

- h is averaged water depth,
 q is net rainfall depth,
 ρ_w is density of water,
 τ_{sx} and τ_{sy} are the stresses of wind in the x - and y -direction respectively,
 τ_{bx} and τ_{by} are the stresses of bottom in the x - and y -direction respectively,
 c^* is resistance coefficient of wind,
 ρ_a is density of air,
 w_a is wind velocity above 10m,
 ϕ is an angle between wind direction and y -direction,
 ω is the speed of rotation of the earth,
 θ is local latitude.

The differential equations can be set up by Leendertes's method (Leendertes, J., 1970) (shown in Fig. 10). When boundary conditions gotten, variables of each node in lake can be calculated.

The plain model would be set up when two dimensional model for Taihu Lake is coupled to one dimensional model for channel network.

III. VALIDATION

This model has been tested with observation data obtained in 1984 and 1985, from May to September, 153 days every year. The data of channels, lakes, reservoirs, area and land used *etc.* are supplied by MBTLB and The Communication Department of Jiangsu Province. Evaporation, rainfall, water level and tide are got from Hydrological Annual Book of China.

Initial condition:

in channel $u(t=0)=0$; $z(t=0)=z_{\text{observed}}$

in Taihu Lake $u(t=0)=v(t=0)=0$,

$$\begin{aligned}\xi(t=0) &= 0, \\ h(t=0) &= z_{\text{observed}}.\end{aligned}$$

The calculation of soil water content was started from April to assume initial condition of soil water closed to actual value.

The time step is fifteen minutes and space step is less than 5km in channel network. In Taihu Lake, the time step is five minutes and space step is 1.49km. The wind was not considered in Taihu Lake. The water level of Taihu Lake is an average water level of six hydrological stations around the Taihu Lake.

Twenty-seven hydrological stations well-distributed in this basin are selected and results of calculation are compared with observed data. The maximum difference of mean daily high flood level is -0.28m in 1985 during typhoon. The error of water level in Taihu Lake is 0.01m in 1984 and 0.08m in 1985. There are 64.8%, 27.8% and 7.4% hydrological stations their absolute errors of water level are less than 0.10m , between 0.10m and 0.20m , and great than 0.20m respectively. Fig. 11(a) shows water level processes of main hydrological stations, in 1984, 1985, from May to Sept. In addition, the diversion and drain water along the Yangtze River are interested for flood regulation and drought defying. Fig. 11(b) shows the comparison result of fourteen hydrological stations along Yangtze River between observed and simulated data. From Fig. 11(a) and Fig. 11(b), good agreement between water level and drainage simulated by present model, and those from observed data is shown. Thus, the structure and parameters of this model are reasonable and satisfactory.

IV. THE NUMERICAL TEXT OF CURRENT FIELD FOR TAIHU LAKE

The research of current field for Taihu Lake is a foundation of water environment research. Taihu Lake is too larger, there is no observed data about current velocity in all over the lake now. Taihu Lake is the largest water source in this basin. Water supply to Shanghai City from Taihu is planning. The bathymetric map of

Fig. 11(a) Comparison between observed and simulated water level for main hydrologic station in 1984, 1985 (m)

Fig. 11(b) Comparison between observed and simulated diversion and drain water for sluice gates along the Yangtze River from May to September in 1984, 1985 (10^8 m^3)

Taihu Lake is shown in Fig. 12. This paper is attempting to understand the current field by numerical text using Taihu Lake model. Eight direction winds are designed and wind velocity is constant (10m/s). Main results are as follows:

1) Suppose the water quantity along the Taihu Lake does not change and mean water level of Taihu Lake is 2.99m . Fig. 13(A) shows a steady current field under the south wind. The current field is composed of a large against clockwise circulation around Xishan island and other local small circulation. The greatest flow velocity is 0.23m/s , located in narrow place between Xishan island and Dongshan. Nearby the bank of lake, the flow velocity is larger than deep water area.

Fig. 12 Bathymetric map of Taihu Lake

Fig. 13 The current field in Taihu Lake

In this condition, if diversion at Taipu outlet is happened, it can be found that the water comes from north, transported with a long distance and mixed fully. The results show that is advantageous for water quality when wind direction is between east and south. When wind comes from between north and west, it will be unadvantageous.

2) The analysis of producing current field has been done. The outflow is only in Taipu outlet, others are inflow and the total of inflow is equal to outflow to keep the same mean water level condition as 1). A steady current field is shown in Fig. 13(B), in which the wind is come from southeast. It can be found that Fig. 13(B) is similar to Fig. 13(C) produced only by the same wind. It shows, thus, water exchange of Taihu Lake cannot form main flow current field in this grid. Actually, since the area of lake is very large, local inflow of outlet will be diffused easily. For this reason, the condition of wind could be considered precedently to get quality water from Taihu Lake.

It is a preliminary study for Taihu Lake using this model. With the deepening of the observation, the research of Taihu Lake model will go further.

V. CONCLUSION

Hydrological model of low plain basin has been set up, in which the geomorphological phenome-

non that channel network connects with lakes is described. Numerical different method is used to solve St Venant equations, the momentum equation is dynamic wave equation in one dimensional channel network. The channels are simplified, as the same time the characteristics of nature channel are considered such as catchment area and storage capacity of channel. Two dimensional model for large lake is also built. The Xinganjiang Model is used in runoff model of cultivated land.

This model has been calibrated with observed data in Taihu Lake Basin. The agreement of simulation with observed data shows the structure and main parameters of this model are reasonable. Because the mathematical method was optimized, the driving of this model in personal computer can be realized. Especially, the calculation is not limited by order and numbers of channels and nodes, thus, this model has a good practicality for many research teams.

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