A NUMERICAL STUDY ON THE OPEN CHANNEL NETWORK IN WUXI CITY

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ABSTRACT

Numerical simulations were conducted to estimate the performance of a drainage system of Wuxi City in China which is now under construction to realize the full plan of flood control system in 2009. The city has a complicated canal network which has served for water transportation from ancient times. Recently, however, the flood water coming through the canal system causes inundation in the city center. Accordingly, the system is separated from the ambient river system with water gates, which are equipped with pump stations of large capacity to discharge rain water from the city center to the outside.
In this study, a numerical simulation model to solve a networked open channel flow developed by Tokyo Institute of Technology was used to estimate the hydraulic characteristics of the channel network in Wuxi City. After constructing a model of channel network for calculation being based on a map of waterways and some related data, a numerical simulation is conducted under a condition of full pump operation without rainfall in order to estimate the total drainage capacity of the system. Then, the system capability under intense rainfalls was examined numerically for some realistic and possible conditions.
Major findings are as follows: (1) The present system can prevent inundation under the rainfall condition which caused a large flood disaster in Wuxi City in 1991. (2) The pumps at three eastside stations can be stopped even with the rainfall condition in 1991 in order to prevent inundation in the east suburbs where river channel capacity is not enough yet. (3) If the peak intensity of rainfall is two times larger than that in 1991, which might be caused by a change of atmospheric system depending on the global warming, local inundation might be generated. (4) When the conditions of (2) and (3) occur at a same time, it is necessary to discharge the water in networked channels at least one hour in advance being based on weather forecast.

INTRODUCTION

After a large flood in 1991, Wuxi City made a drastic plan of flood control, in which water gates can separate the canal network in the central area from ambient river system in rainy season and improved dikes raise the High Water Level the open channels in the city. These facilities will increase the safety level against flood waters coming into the city, but it will become difficult to discharge the rain water in the city to the outside. Therefore, pump stations of large capacity are also under construction at seven major water gates. The whole construction project will be finished in 2009.
Because any intense rainfall has not occurred after the construction started, the performance of the system has not been tested even partially. On the other hand, because the open channel network in Wuxi City, having more than 200 channel segments, is very complicated, it is difficult to examine the networked flow analytically, and only numerical simulation is considered to be a possible and effective method for this purpose. However, numerical simulation for the whole channel network has not been conducted yet because Wuxi City does not have any skills for it.
In this study, considering the situation mentioned above, the performance of the drainage system is examined by using a numerical simulation model recently developed by Tokyo Institute of Technology.

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STUDY AREA

Wuxi City is located on a flat low land at the south side of the lower Changjiang as shown in Fig. 1. The land has been cultivated for thousands of years because of the productive soil transported by the Changjiang. It is still one of the most important areas in China for its agricultural and economic development. Wuxi City has a complicated canal system by connecting the rivers and lakes since the ancient times as shown in Fig. 2. It has been utilized not only for water transportation but also as channels for flood water drainage to the outside of cities and as water amenity places for citizens.

In recent years, however, the potential of flood disaster is rising with the increase of rain run-off because of the modern development of the area. Flood water coming from the outside through the canal system causes larger flood damage in Wuxi City than before. Therefore, Wuxi City is now separating the canals from the outside river system by water gates. But, it decreases the drainage capacity to discharge the rain water to the outside of the city. In order to solve the problems, pump stations of large capacity are under construction at seven major water gates, the location of which are marked in Fig. 2. Construction of the facilities is scheduled to realize the full plan of flood prevention works in 2009. The important values of water surface level for the water management in the plan are listed in Table 1

Table 1 Important water level

Normal Water Level (NWL)	3.3 meter a.s.l.
Warning Water Level (WWL)	3.6 meter a.s.l.
Inundation Water Level (IWL)	5.0 meter a.s.l.

Fig. 1: Location of Wuxi City

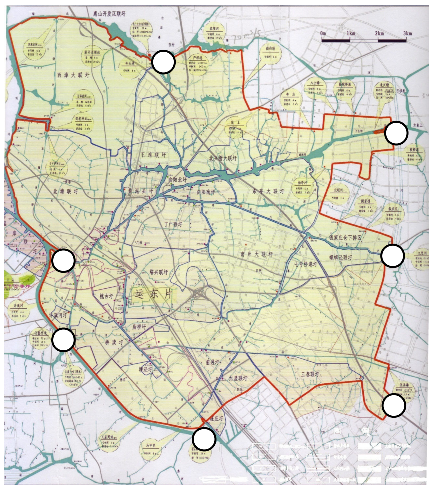

Fig. 2: Open channel network in Wuxi City

HYDRAULIC SIMULATION MODEL

The hydraulic simulation model adopted here (Tokyo Tech Model) is to solve 1-D equations of open channel flows for channel segments in a network by explicit finite difference scheme on staggered grids. Basic equations are the continuity equation and the momentum equation which are written as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (1), \qquad \frac{\partial Q}{\partial t}+\frac{\partial (UQ)}{\partial x}=-gA\frac{\partial H}{\partial x}-\frac{\tau}{\rho}P \qquad (2),$$

where t is time, x is distance along each channel, A is cross section, Q is flow rate, q is the side inflow per unit length of channel, U is mean velocity, g is gravity acceleration, H is water surface level, ρ is density of water and P is wetted perimeter, and τ is bottom shear stress which is expressed by Eq. (3), where n is so-called Manning's coefficient and h is water depth. At each channel junction, the volume conservation can be expressed by Eq. (4), where A_j is an area of junction which is assumed as a square of mean width of joining channels.

$$\frac{\tau}{\rho} = fU|U| = \frac{gn^2}{h^{1/3}}U|U| \qquad (3) \qquad\qquad A_j\frac{\partial h}{\partial t} = \sum_i Q_i \qquad (4)$$

Time integrals of eqs. (1) and (2) are calculated by finite difference formulation written as follows:

$$\frac{A_J^{K+1} - A_J^K}{\Delta t} + \frac{Q_I^{K+1} - Q_{I-1}^{K+1}}{\Delta x} = q_J^K \qquad (5)$$

$$\frac{Q_I^{K+1} - Q_I^K}{\Delta t} + \frac{U_{J+1}^K Q_{I+I_s}^K - U_J^K Q_{I-1+I_s}^K}{\Delta x} = -gA_I^K \frac{H_{J+1}^K - H_J^K}{\Delta x} - \frac{\tau_I^K}{\rho}P \qquad (6)$$

where superscripts and subscripts are time steps and grid numbers respectively as shown in Fig. 3.

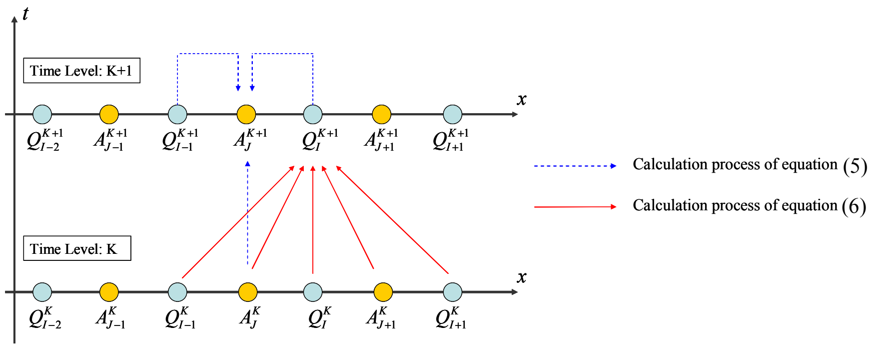

Fig. 3: Algorithm for time integral

CHANNEL NETWORK MODEL

The channel network in Wuxi City is very complicated as was shown in Fig. 2. In addition, dimensions of many small channels are not measured yet. Therefore, the model channel network for calculation was constructed by using the latest map, pictures and authors personal knowledge about the appearance of channels as well as some numerical data available for comparatively large channels. Channel cross sections for calculation are assumed to be rectangular with a flat bottom which elevation is 0.0 a.s.l.. It is a rough assumption and should be checked in the future. Fig. 4 shows the result which is simplified from the prototype shown in Fig.3.

In a usual river planning, Manning's coefficient, n, is estimated from field data obtained in a quasi steady-uniform condition. In the case of Wuxi channel network, however, those data do not exist because each channel segment is too short for such a condition to appear. Accordingly, the values of n were assumed being based on a literature (Ven Te Chow, 1959) and author's personal knowledge about the appearance of channels in the city. Values of n adopted in this study are listed in Table 2, where two kinds of values are assumed for the group of smallest channels. It is because the roughness coefficient especially of small channels can be changed by practical conditions such as block of flow by solid waste.

Table 2 Manning's coefficient

	$B \geq 40$	$40 > B \geq 20$	$B < 20$
C-1	0.02	0.04	0.06
C-2	0.02	0.04	0.1

B : channel width (m)

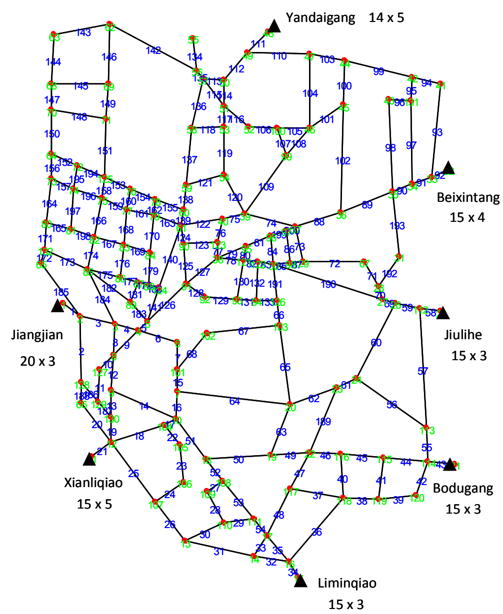

Fig.4: Channel network model

ESTIMATION OF DRAINAGE CAPACITY

The drainage capacity of the system was examined by checking the total flow resistance under the condition of full pump operation without rainfall. Water in the channel network was still at the level of 4.5 meters initially. Pump operation rule was assumed being based on the flood control plan: When the water level at each pump station is higher than WWL, all pumps are run. When the water level is between WWL and NWL, the total discharge is set to be 2/3 of the total capacity of the station. However, because each pump can take only two conditions, ON and OFF, the total discharge is set to close to the 2/3 at stations where the number of pumps is not in multiples of 3. When the water level becomes lower than NWL, all pumps at the station are stopped.

Fig. 5 shows the variations of water level at four points in the network, which are selected from some channel segments where the water levels are comparatively high or low. The location of each point is plotted in a reduced map in the figure. The water surface decreased with a rate of 0.5 meter/hour in average when pumps are full operated. The difference among the water levels is 0.2 meter at the maximum. This fact suggests that the flow resistance is not a very big problem. After stopping pump operation, oscillation of about 10 cm appeared but ceased in about two hours. This kind of motion is considered to be caused by propagation of waves (surging) in the channel network.

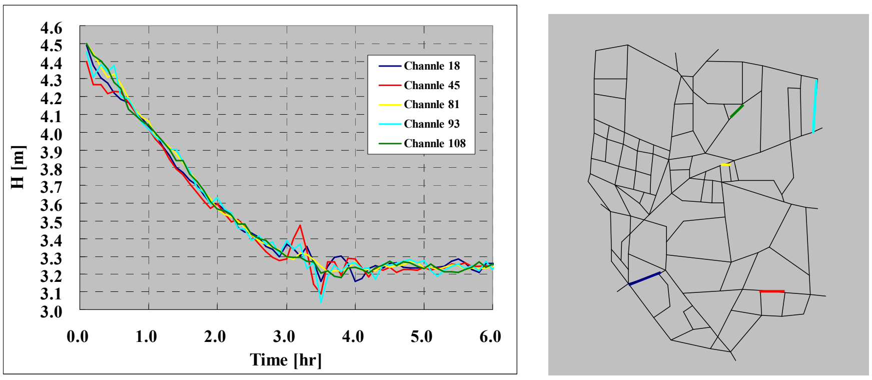

Fig. 5: Water surface decline under full pump operation

SYSTEM CAPABILITY UNDER THE INTENSE RAINFALL OBSERVED IN 1991

Fig. 6 shows the rainfall which caused a large flood disaster in Wuxi City in 1991. It is the largest rainfall of 24-hour in these 60 years, and the safety of the city center from the rainfall is required in the flood control project. Because there was no water gate and pump station in 1991, this calculation is the first attempt to estimate the capability of the present system under the recorded maximum rainfall.

Fig. 7 shows the water levels at four places as shown in a reduced map in the figure. They go up and down with the change of rainfall intensity with small difference from one another except in the time of surging. The water surface rises above WWL frequently, but the highest is 3.95 m. This fact means that the present

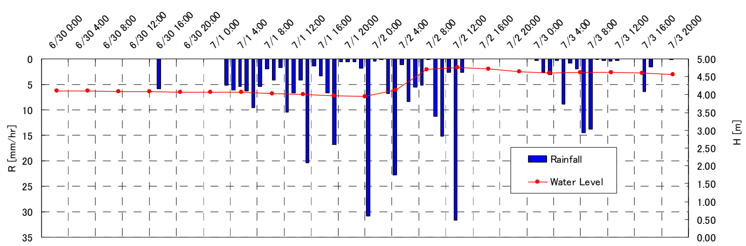

Fig. 6: Rainfall observed in 1991 (Nanmen meteorological station)

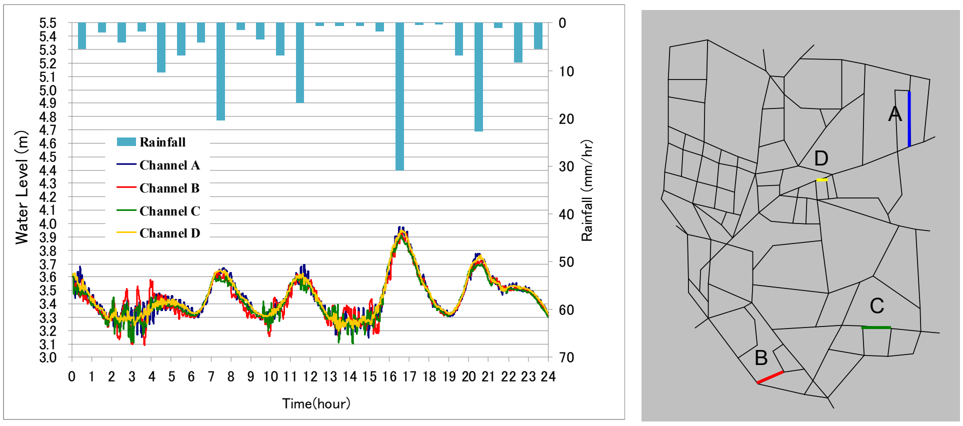

Fig. 7: Water level under the rainfall observed in 1991

total pump capacity is large enough to prevent the inundation disaster which occurred in 1991. By the way, even with larger roughness for small channels listed in Table 2, the result was almost the same as Fig. 7.

SYSTEM CAPABILITY UNDER SOME POSSIBLE CONDITIONS

Numerical simulations were conducted further, considering two kinds of uncertainty in practical situations. One is a local condition of eastside suburbs. River channels in the area are still under improvement and inundation frequently occurs. Because of the practical reason, there is a possibility that three pump stations at the east side of the city center cannot be operated when inundation occurs there earlier than in the city center. Therefore, the system capability without the operation of the three pump stations was examined. The calculation result showed that the city center is still safe from inundation under the condition, though the data are not shown here because of a limitation of space.

The other is a meteorological uncertainty. As mentioned before, the 24-hour rainfall observed in 1991 was the largest in these 60 years. But, more intense rainfall might occur because of a change of atmospheric system caused by the global warming. Therefore, a simulation was carried out for a rainfall in which the peak intensity in one hour was two times larger than that in 1991. The maximum rainfall intensity of the case was 60 mm/hour, which is not very unusual all over the world. Fig.8 shows the results. The water level exceeds IWL a little bit, which means that inundation might be generated locally.

Fig. 9 shows the calculation result for a combination of the two conditions mentioned above. The water surface keeps the level higher than IWL for a long time, and the maximum is 5.4 m. The rate of water surface rising before the first peak is about 2.0 meter/hour. On the other hand, the rate of water surface decreasing under the full pump operation is 0.5 meter/hour, as was shown in Figure 5. This fact means that

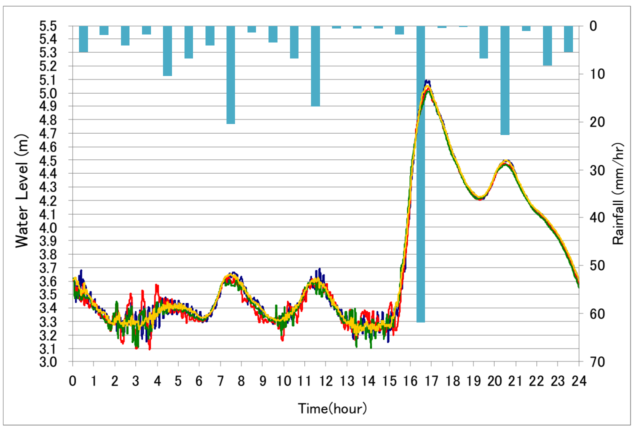

Fig. 8: Water level under the rainfall which peak intensity is two times larger than the rainfall observed in 1991

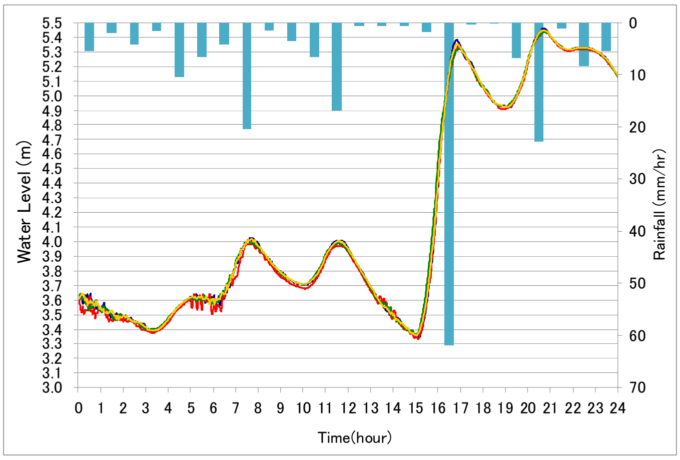

Fig. 9: Water level under the rainfall observed in 1991

pump operation at least one hour in advance is necessary when a rainfall of the order of 60 mm/hour is forecasted.

CONCLUSIONS

Major findings in this study are as follows:

1) Under the full pump operation without rainfall, the water surface falls almost uniformly in the channel network with a rate of 0.5 meter/hour. Spatial difference of the water level is less than 20 cm.
2) The drainage system of Wuxi City, which will be completed in 2009, can prevent inundation under the rainfall condition which caused a large flood disaster in 1991.
3) The pumps at three eastside water gates can be stopped even with the rainfall condition in 1991 in order to prevent inundation in the east suburbs where river channel capacity is not enough yet.
4) If the peak intensity of rainfall is two times larger than that in 1991, which might be caused by a change of atmospheric system depending on the global warming, local inundation might be generated.
5) When the conditions of 3) and 4) occur at a same time, it is necessary to discharge the water in networked channels at least one hour in advance being based on weather forecast.

ACKNOWLEDEMENT

The author would like to express his great appreciation to Prof. Tadaharu Ishikawa, Dr. Keisuke Yoshida and their students of Tokyo Institute of Technology who provided me the numerical simulation model and instructed me in a work on computer. Their help was essentially important for me to complete this thesis.

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