A METHODOLOGICAL STUDY TO IMPROVE FLOOD MANAGEMENT OF THE TAIHU LAKE BASIN

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ABSTRACT

The Taihu Lake Basin is facing a rapid socio-economic development, and already become one of the most developed areas in China. However, its flat terrain and rapid development lead to great challenges in water resource management. This study aims to improve the flood management of this lake basin. Subsequently, two sub-objectives are set up: assess and improve the non-structural measures for flood management and study on best practices of Japanese experiences on Integrated Lake Basin Management (ILBM). In order to achieve the objects of this study, at first the challenges of flood management in the Taihu Lake Basin are clearly identified. Subsequently, “flood dispatching method” is introduced as an effective non-structural measures for flood management. In this method the relationship among the water level of the Taihu Lake, the water level of the downstream area, and the discharge of structures, become the focusing point. A 1-D flood routing model (SDRHM) is developed by discretizing St. Venant unsteady flow equations using an implicit four points numerical scheme. An innovational model inter-comparison of the SDRHM, the U.S. Army Corps of Engineers’ River Analysis System (HEC-RAS), and the Taihu Lake Basin Hydrodynamic Model (TLBHM) has been done for different river systems. The model inter-comparison result illustrates that the TLBHM has advantages to other models and it is appropriate to simulate the hydrodynamic phenomena in the Taihu Lake Basin. By using TLBHM, nine different scenarios for flood dispatching method were set up and simulated. The simulation results clearly show that the dispatching method is actually balancing flood risk along the river-lake system by distribution of the risk. However it has been learned that flood risk cannot be smoothly eliminated by this kind of non-structural methods only. Moreover, a case study of the application of ILBM has been done in two Japanese lakes, the Biwa Lake and the Kasumigaura Lake. Inter-comparisons of characteristics of the lakes and their basins are also implemented, which will help to develop proposals toward application of ILBM in the Taihu Lake Basin.

Keywords: Flood Management, Unsteady flow, River Network Hydrodynamic Modeling, Integrated Lake Basin Management, Taihu Lake Basin

INTRODUCTION

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Floods have a history as long as human being. There are many factors which can trigger a flood disaster. To a hydrologist, a flood is simply a discharge rate in a stream or a river that exceeds an ‘acceptable’ threshold value, and is often an expression of the variability of rainfall in the river catchment (P. P. Mujumdar, 2001). Lakes are usually considered as huge natural flood retarding areas, in order to secure the surrounding areas, especially the downstream areas, during floods. However, for flood in a lake basin , water level becomes an important indicator. It is normally considered that once the water level of the lake exceeds an ‘acceptable’ threshold value, flood occurs and all the stakeholders should be ready to implement counter-measures.

The capacity of a lake in a flood situation is determined by its natural characteristics and also influenced by strong winds over the water surface. Unregulated human activities could also result in lake degradation and trigger related negative influences on retarding capacity of a lake during flood.

On the other hand, it has been proved that it is not suitable to consider only the lake itself while implementing management activities. As the concept of Integrated Lake Basin Management (ILBM) says, the lake basin should be considered as a whole while takes into account the biophysical features of lake basins as well as managerial requirements for lake basin systems. It is quite necessary to improve flood management by the advances of ILBM.

STUDY AREA

Yangtze Delta Urban Agglomeration is the world’s No. 6 urban agglomeration, which is also the No. 1 urban agglomeration in China. Comparing with other five urban agglomerations in the world, it is comparatively weak in economic contribution, but it plays a very important role in the development of China. Taihu Lake Basin, which locates at the core position of Yangtze Delta, covers more than half of the area of the Yangtze Delta Urban Agglomeration, and includes the four most important cities. In order to obtain a sustainable development, water resources are of vital importance.

Taihu Lake situates at the center of the lake basin. It occupies a large share of the water within the basin, and its optimum water level is from 3.0 m to 3.5 m. The water level lower than 3.0 m is considered a dry year and if it goes to more than 3.5 m there is risk of flooding. As a large amount of population settles in the basin and a large amount of national GDP is contributed from the basin, only 0.5 m of suitable fluctuation range makes it very vulnerable to both flood and drought disasters. Moreover,

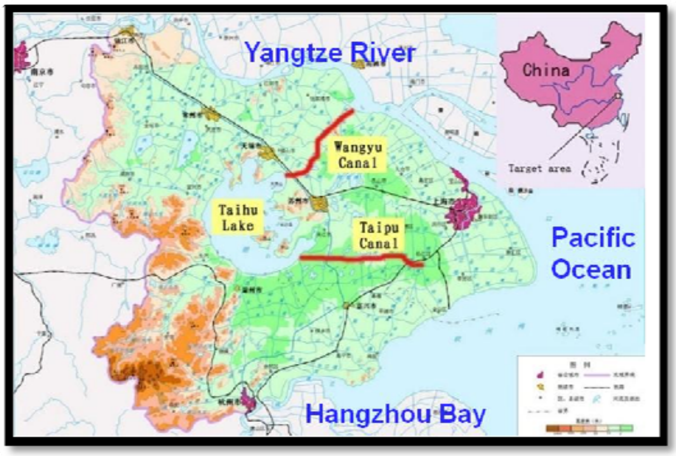

Fig. 1 Taihu Lake Basin

More than 80% of the basin area is plain area with complicated river networks. Its river length reaches 120,000 km, making a river density of 3.25 km/ km^2, which is the highest in China. Due to its flat terrain, complicated river networks, and the affect of surrounding tidal, the downstream rivers flow slowly and sometimes flow adversely. After concentrated rainfall, inflow discharge of the Taihu Lake would easily exceeds outflow discharge, making the water level of the lake rise quickly, and result in inundation of surrounding areas sooner or later.

In 2007, the basin's total amount of water resources was 17.27 billion m^3, but the amount of water usage reached 37.27 billion m^3. Besides retrench and re-use of water resources, the basin authority transfers water from the Yangtze River into the Taihu Lake Basin every year. Normally, the total transferring quantity could reach 2 billion m^3, among which around 1 billion m^3 could be transferred into the Taihu Lake. Sometimes the transferring is implemented during summer, which is the flood season of the basin, to ensure the water quantity and sanitation. However, it increases the risk of floods at the same time.

Construction of hydraulic structures in the Taihu lake Basin may be backward to nearly a thousand years ago. After the catastrophic flood in 1991, the State Council decided to implement comprehensive rehabilitation to this lake basin. Eleven key projects had been constructed since then. Nowadays, the lake basin has formed a flood drainage system which could drain floods northward to the Yangtze River, eastward to the Huangpu River, and southward to the Hangzhou Bay. However, compared to its fast development, the flood management capability is still comparatively low.

FLOOD ROUTING MODELING AND MODELS INTER-COMPARISON

Based on the current flood control system, this study assesses and improves an important non-structural measure, "flood dispatching method", by hydrodynamic modeling. The flows in natural rivers are normally unsteady flow, whose flow conditions vary with time at a discrete location. Both continuity equation (conservation of mass) and momentum equation (essentially, Newton's second law of motion), which are put together to form the St. Venant Equations, are used as governing equations for one dimensional unsteady open channel flow. In differential form, the equations could be written as: (The following part of this section takes (Wang, 1989) as reference)

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q}{\partial x} = q & (1) \\ \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{Q^2}{A}\right) + gA\dfrac{\partial H}{\partial x} + gA\dfrac{Q|Q|}{K^2} = qV_x & (2) \end{cases}$$

where, A: area of cross-section; t: time interval; Q: flow rate; x: distance between crosess-sections; q: the lateral inflow per unit length of channel; g: gravity acceleration; H: water surface level; K: conveyance, $K = \frac{1}{n}AR^{2/3}$; n: Manning's coefficient; R: hydraulic radius; V_x: velocity of the lateral inflow in the x direction.

Usually, V_x is considered as 0, and the lateral inflow could be avoided by dividing the rivers at the junction points. Here, Preissmann four points implicit scheme is used for discretizing the equations.

As shown in Fig. 2.2, the values of point a and point b are

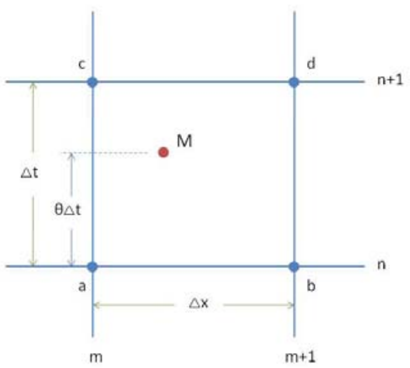

Fig. 2 Preissmann Four Points Implicit Scheme

known and the values of point c and point d are unknown for each calculation step. The value of arbitrary point M could be expressed as:

$$f(M)=f(x,t)=\frac{\theta}{2}(f_{m+1}^{n+1}+f_m^{n+1})+\frac{1-\theta}{2}(f_{m+1}^{n}+f_m^{n}) \tag{3}$$

where, θ: time weighting coefficient, $0\le\theta\le 1$, introduced in the spatial derivatives to aid in the numerical solutions.

If consider $f^{n+1}=f^n+\Delta f$, the following expressions could be derived:

$$f(x,t)=\frac{\theta}{2}(\Delta f_{m+1}+\Delta f_m)+\frac{1}{2}(f_{m+1}^{n}+f_m^{n}) \tag{4}$$

$$\frac{\partial f}{\partial x}=\theta\frac{\Delta f_{m+1}-\Delta f_m}{\Delta x}+\frac{f_{m+1}^{n}-f_m^{n}}{\Delta x} \tag{5}$$

$$\frac{\partial f}{\partial t}=\frac{\Delta f_{m+1}+\Delta f_m}{2\Delta t} \tag{6}$$

Applying equations (4) ~ (6) into equations (1) ~ (2), they yield a nonlinear system as (7) ~ (8):

$$\frac{\Delta H_{m+1}+\Delta H_m}{2\Delta t}+\frac{2}{\theta(\Delta B_m+\Delta B_{m+1})+(B_m^n+B_{m+1}^n)}\left[\theta\frac{\Delta Q_{m+1}-\Delta Q_m}{\Delta x}+\frac{Q_{m+1}^n-Q_m^n}{\Delta x}\right]=0 \tag{7}$$

$$\begin{aligned}
&\frac{\Delta Q_{m+1}+\Delta Q_m}{2\Delta t}+\frac{\theta}{\Delta x}\left[\frac{(Q_{m+1}^n+\Delta Q_{m+1})^2}{A_{m+1}^n+\Delta A_{m+1}}-\frac{(Q_m^n+\Delta Q_m)^2}{A_m^n+\Delta A_m}\right]+\frac{1-\theta}{\Delta x}\left[\frac{(Q_{m+1}^n)^2}{A_{m+1}^n}-\frac{(Q_m^n)^2}{A_m^n}\right]\\
&\quad+\left[\frac{g\theta}{2}(\Delta A_{m+1}+\Delta A_m)+\frac{g}{2}(A_{m+1}^n+A_m^n)\right]\left[\frac{\theta}{\Delta x}(\Delta H_{m+1}-\Delta H_m)+\frac{1}{\Delta x}(H_{m+1}^n-H_m^n)\right]\\
&\quad+\frac{g\theta}{2}\left[\frac{(A_{m+1}^n+\Delta A_{m+1})(Q_{m+1}^n+\Delta Q_{m+1})|(Q_{m+1}^n+\Delta Q_{m+1})|}{(K_{m+1}^n+\Delta K_{m+1})^2}\right.\\
&\quad\left.+\frac{(A_m^n+\Delta A_m)(Q_m^n+\Delta Q_m)|(Q_m^n+\Delta Q_m)|}{(K_m^n+\Delta K_m)^2}\right]\\
&\quad+\frac{g(1-\theta)}{2}\left[\frac{A_{m+1}^nQ_{m+1}^n|Q_{m+1}^n|}{(K_{m+1}^n)^2}+\frac{A_m^nQ_m^n|Q_m^n|}{(K_m^n)^2}\right]=0
\end{aligned} \tag{8}$$

By introducing Taylor's Series and neglecting some small elements, two linear equations could be derived as (9) and (10).

$$A_{1m}\Delta Q_m+B_{1m}\Delta H_m+C_{1m}\Delta Q_{m+1}+D_{1m}\Delta H_{m+1}=E_{1m} \tag{9}$$

$$A_{2m}\Delta Q_m+B_{2m}\Delta H_m+C_{2m}\Delta Q_{m+1}+D_{2m}\Delta H_{m+1}=E_{2m} \tag{10}$$

where, $A_{1m}=-\frac{4\theta\Delta t}{\Delta x(B_m^n+B_{m+1}^n)}$, $B_{1m}=1-\frac{4\theta\Delta t(Q_{m+1}^n-Q_m^n)}{\Delta x(B_m^n+B_{m+1}^n)^2}\frac{dB_m^n}{dH_m^n}$, $C_{1m}=\frac{4\theta\Delta t}{\Delta x(B_m^n+B_{m+1}^n)}$, $D_{1m}=1-\frac{4\theta\Delta t(Q_{m+1}^n-Q_m^n)}{\Delta x(B_m^n+B_{m+1}^n)^2}\frac{dB_{m+1}^n}{dH_{m+1}^n}$, $E_{1m}=-\frac{4\Delta t}{\Delta x(B_m^n+B_{m+1}^n)}(Q_{m+1}^n-Q_m^n)$, $A_{2m}=1-\frac{4\theta\Delta t}{\Delta x}\left(\frac{Q_m^n}{A_m^n}\right)+2g\theta\Delta t\frac{A_m^n|Q_m^n|}{(K_m^n)^2}$,

$B_{2m}=\frac{\theta\Delta t}{\Delta x}\left[\frac{2(Q_m^n)^2B_m^n}{(A_m^n)^2}-g(A_{m+1}^n+A_m^n)+g(H_{m+1}^n-H_m^n)B_m^n\right]+g\theta\Delta t\frac{Q_m^n|Q_m^n|}{(K_m^n)^2}\left[B_m^n-\frac{2A_m^n}{K_m^n}\frac{dK_m^n}{dH_m^n}\right]$,

$C_{2m}=1+\frac{4\theta\Delta t}{\Delta x}\left(\frac{Q_{m+1}^n}{A_{m+1}^n}\right)+2g\theta\Delta t\frac{A_{m+1}^n|Q_{m+1}^n|}{(K_{m+1}^n)^2}$, $D_{2m}=\frac{\theta\Delta t}{\Delta x}\left[-\frac{2(Q_{m+1}^n)^2B_{m+1}^n}{(A_{m+1}^n)^2}+g(A_{m+1}^n+A_m^n)+g(H_{m+1}^n-H_m^n)B_{m+1}^n\right]+g\theta\Delta t\frac{Q_{m+1}^n|Q_{m+1}^n|}{(K_{m+1}^n)^2}\left[B_{m+1}^n-\frac{2A_{m+1}^n}{K_{m+1}^n}\frac{dK_{m+1}^n}{dH_{m+1}^n}\right]$, $E_{2m}=\frac{\Delta t}{\Delta x}\left[-\frac{2(Q_{m+1}^n)^2}{A_{m+1}^n}+\frac{2(Q_m^n)^2}{A_m^n}-\right.$

$$g(A_{m+1}^{n}+A_{m}^{n})(H_{m+1}^{n}-H_{m}^{n})\Big]-g\Delta t\left[\frac{A_{m+1}^{n}Q_{m+1}^{n}|Q_{m+1}^{n}|}{(K_{m+1}^{n})^{2}}+\frac{A_{m}^{n}Q_{m}^{n}|Q_{m}^{n}|}{(K_{m}^{n})^{2}}\right]$$

For a river system, the number of unknowns would always be more than the number of equations by two. Thus, once the boundary conditions of the upstream and downstream are satisfied, the hydrodynamic of the whole river system could be simulated. The SDRHM is developed based on the understanding of the mechanism of unsteady flow. Subsequently, the SDRHM, the HEC-RAS, and the TLBHM are inter-compared by different river conditions.

In the first step, the hydrodynamics of a single river with different cross-section shapes are simulated by the three models. The results show that the three models have similar final outputs. However, due to the iteration method of SDRHM, it takes longer time before the water level become stable. Thus, HEC-RAS and TLBHM are selected to implement the simulations of river networks afterwards.

The second step of the inter-comparison is done by a simple river network, as shown in Fig. 4. The simulation results are still can be considered as completely same. However, the TLBHM is faster and more appropriate to be applied to the Taihu Lake Basin.

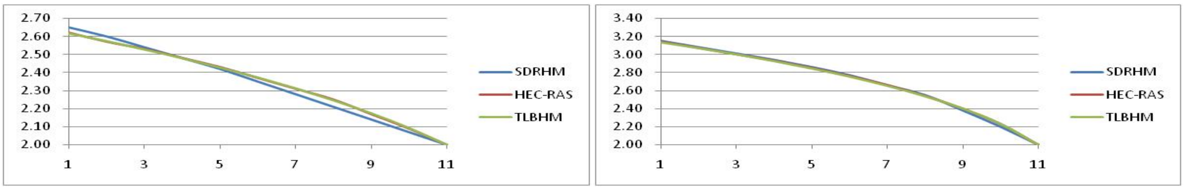

Fig. 3 Simulation Results of the Single River (Rectangle Cross-Section and Trapezoid Cross-Section)

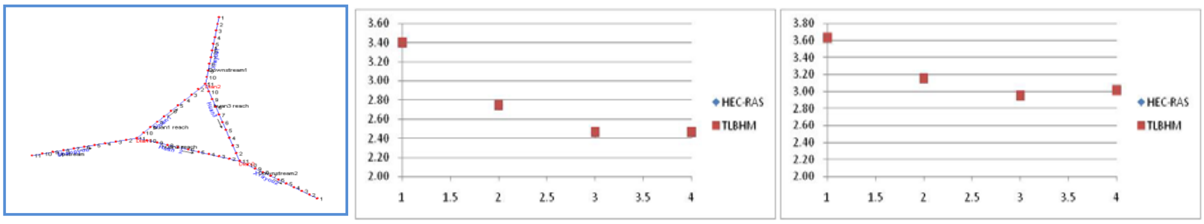

Fig. 4 Interface and Simulation Results of the Simple River Network (Same downstream condition and differed downstream conditions)

TAIHU LAKE BASIN HYDRODYNAMIC MODEL AND SIMULATION RESULTS

Floods are always historical scenarios which are not possible and not practical to replay. Accordingly, it is not possible to pick up a better flood dispatching solution by comparing different dispatching scenarios in reality. Model simulation can solve this problem to some extent. A basin-wide hydrodynamic model can simulate historical floods, and apply different dispatching methods as different scenarios. The hydrological changes could be used to identify the influences of the different dispatching methods. TLBHM generalizes the complicated river networks with the principle that the generalized items should have the same discharge and storage capability under the same water level, once compared to the original ones.

Table 1 Generalization and Simulation for Different Areas (Jin et al., 2008)

Units	Mountainous Areas	Plain areas	Rivers	Lakes, Reservoirs, Flood retarding areas	Flood control structures

Remarks	Applied for southwest mountains, in total 10 sub-basins	Applied for northwest hilly area, in total 10 sub-basins; other plain areas, in total 16 sub-basins	Applied for 1482 rivers, with total length of 7879.4 km and 4270 cross-sections	Applied for 104 lakes, with total area of 871 km2	Applied for 168 structures

The simulation process starts from the precipitation, which would generate certain amount of runoff according to the land use data. Then, the runoff would be routed to the generalized rivers as lateral inflow and trigger hydrodynamic process in the river network subsequently.

By studying the hydrology and hydraulic of the lake basin, and taking into consideration of the mechanism of the TLBHM, it is not difficult to find out that the dispatching method is actually affecting the operation of the water conservancy structures according to different background situation. Among all of the inflows and outflows of the Taihu Lake, only Wangyu Canal and Taipu Canal are directly controlled by the Taihu Basin Authority (TBA). This study tried to keep constant discharge rate of these two canals and increase them separately to identify their influences to the water level of the Taihu Lake.

By calculating with the data of 1999-flood, the yearly hydro- dynamic process of the lake basin under different scenarios are simulated, and water level variations of the Taihu Lake and the downstream can be figured out.

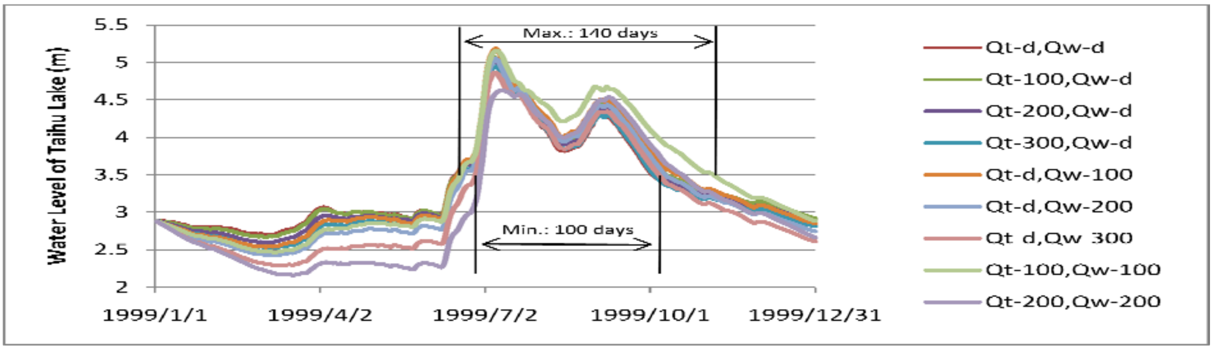

Fig. 4 Water Levels of the Taihu Lake Based on Different Simulation Scenarios (Qt: discharge rate of Taipu Canal; Qw: discharge rate of Wangyu Canal; d: the discharge is controlled according to the current dispatching method.)

CASE STUDY ON INTEGRATED LAKE BASIN MANAGEMENT

Japan is one of the countries who are suffering from different kinds of disasters, among which, flood is always considered as long threatening one, and it appears almost every year. However, benefit from the advanced management activities, Japan never had more than 700 flood victims per year since 1960s. Similarly, an Integrated Lake Basin Management has been formed to deal with the lake problems, which full-fills the demands of comprehensively managing and considering flood prevention, water resource protection, and ecological system protection at the same time. The management activities of the Biwa Lake and the Kasumigaura Lake are studied and their characteristics are compared with the Taihu Lake.

The Biwa Lake is the largest lake in Japan. It has hundreds of inflows but only one outflow. In order to protect, make full use, and keep sustainable development of the Biwa Lake, Japanese government implemented a Comprehensive Development Project for 25 years, consisting three major objectives which are the preservation measures to conserve the water quality of the Biwa Lake and the affluent natural environment, the flood control measures to solve the flood damages around the Biwa Lake, and the water use measures to utilize the water of the Biwa Lake effectively (Biwa Lake Construction Work Office et al, 2005). Since then, levees, weirs, by-pass tunnels are constructed for different purposes, and the downstream river was enlarged and dredged. Nowadays, a unified management system, which considers the operation of both the Biwa Lake and all of the structures within the Biwa Lake and Yodo River Basin together, has been formed. During floods, the storage distribution and discharge amount of the whole system would be determined by the Yodo River Dam Integrated Control Office.

Kasumigaura Lake is the second largest lake in Japan, which is located at the downstream area of the Tone River. It has only one downstream river as outflow to the Tone River and its flood problems are related to the Tone River. For one thing, the drainage capability of the downstream of Tone River is not sufficient. After rainfall, some water would remain in the lake and difficult to drainage out. For the other thing, there is an apparent problem: the design water level of the lake is two meters lower than that of Tone River. Once flood happens in Tone River, the flood flow would enter the lake adversely due to the differences of the water levels. On the other hand, it is a shallow lake, which is easily influenced by strong winds and would result in high waves. In order to deal with these problems, its downstream river was dredged and weirs were constructed to control the discharge and prevent the backwater from the Tone River. Furthermore, wave dissipation facilities were constructed to control the high waves and protect the levees (Kanto Regional Bureau of MLIT et al, 2009).

The Taihu Lake shows some similarity with these two Japanese lakes for plenty of inflows and limited outflows. It is also influenced by high waves due to its shallow characteristic. Some advanced lake management concepts could be introduced to help the flood management of the Taihu Lake.

CONCLUSION

a) Unsteady flood analysis and the results of model inter-comparison showed that TLBHM has advantages in flood flow routing with the Taihu Lake Basin’s river networks. Its less calculation time with complicated river networks and more accurate result up to round-off of three decimals make it more suitable for the daily work of flood management. Therefore TLBHM was selected and applied for the simulation of different flood dispatching methods.

b) “Flood dispatching method” has direct effect on the water level of the Taihu Lake. However, due to the limitation of drainage capability at downstream of the basin, it is actually balancing the flood risks over the Taihu Lake Basin by transferring flood risk of upstream (Lake) to the downstream area. Considering available and in operation structural measures, it is better to use the existing dispatching method as the reference and apply real-time modification by considering flood risk according to the weather forecast for precipitation.

c) Regarding ILBM concept, the lake basin should be considered as comprehensive as possible. More attentions should be paid to reduce the negative influences of human activities and try to maintain the environmental impacts during the construction of new projects. As Taihu Lake Basin is a comparatively developed region of China, the benefits of flood mitigation and water resources protection are obvious. More investments should be concentrated into the Taihu Lake Basin toward implementation of ILBM.

d) By comparative study with Japanese ILBM cases, a centralized and basin-wide consideration of hydro-structures is suggested for Taihu Lake Basin. Moreover, in order to reduce the damage of lake waves to coastal areas and relieve the influences from high waves, constructing and operating wave dissipation structures are suggested.

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