Modeling and Control of Bi-Directional Water Flow with Application to the Taihu Lake Basin

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***Abstract*- Modeling river networks in plains such as deltas due to bi-directional water flows is a major challenge. An example of such a plain land is the delta region between Yangtze and Taihu Lake. Besides the Yangtze, the area is composed of several rivers, channels, tributaries and the Taihu Lake, which is one of five largest freshwater lakes in China with a total basin stretching over an area of 36.500 km2 of the plain land of the Yangtze Delta. This area is of great interest, because it is the most socially and economically developed region in China. There is natural water exchange between the Yangtze River and the local river network due to daily and seasonal tidal effects. The water from Yangtze is used for adjusting the water levels of local rivers for flood protection and navigation (i.e. securing the water transport way (Baiqugang River) between Taihu Lake and Yangtze River. Other uses of the water resources in the area include, irrigation and drainage for the agricultural areas, water for the industry and households and lastly water for maintaining the flow rate in the local river network and hence the water quality. Therefore, diverse types of artificial water conservancy projects (sluices, pumps, barriers) have been built for different purposes and specifications in the area. In order to be able to apply optimal control methods for water allocation to the multiple targets, a model based computer simulation model is required. Such a simulation model of the river system is described in this paper. It takes the hybrid behavior (i.e. water levels change continuously and some control devices such as barriers are either open or closed) of the system into consideration.**

Keywords*- *Bi-Directional; Water Flow; Hybrid System; River Network; Water Resources Management

I. INTRODUCTION AND MOTIVATION

Located in the Yangtze River Delta, Taihu Lake is the largest lake in the downstream of the Yangtze River. The Taihu Lake Basin has low-lying (Plain land) topography with a huge number of rivers, channels, and tributaries, which build the river network. Due to flat gradient, the water level of the rivers in the normal season only has small changes, water flows extreme slow, and flow direction of the rivers is very instable. In the flood season, the situation can change completely. These characteristics are typical of a river network of plain lands.

In the past this region was traditionally an area of agriculture, fishery and commerce. The lowland between the rivers was an important growing area for rice, to protect those agricultural lowland, dikes were built around the area. In dry season the water is pumped from the river network into lowland for irrigation, and in rainy season water is drained into the rivers. Now the whole model area has become the most vital region of the developed industrial China. Due to the high population density, the quantity and quality of Yangtze River and its tributaries have become more important for people living, the sustainable development of the industry, and also for the environment. Therefore, the regional water resources management is confronted with the following important tasks:

- adjust the water levels and ensure navigation according to the water exchange between the Yangtze River and the local river system due to daily and seasonal tidal effects,
- flood protection for the local river network area,
- drain water from regional agricultural areas in the wet season,
- provide water for the industrial and household use,
- maintain the flow of the water in local river network for securing water quality.

In order to achieve the above mentioned tasks, diverse artificial water conservancy projects (sluices, pumps, Barriers) for different purposes and specifications are built on the main river segments of the river network, the connection nodes between Yangtze River and the local rivers. Therefore, in order to be able to achieve a better river water allocation of the multiple targets, a model based computer simulation is seriously required. This paper describes a model, which can be applied to such a water resources management problem with multiple goals. The model is based on mathematic algorithms of a hybrid system and WaterLib module library. Through scenario analysis techniques the performance for the different objectives can be simulated and evaluated.

The motivation of this case study has several sources. Firstly, there are still no efficient simulation algorithm and well-known control models so far for a typical river network area of plain land. The existing traditional hydrological models are computationally intensive, and require a lot of data (e.g., time series of water velocity, channel gradient data, a number of parameters), which are not readily available in most river network areas. Furthermore, the rivers in plain lands flow extremely slow, the river gradient is negligible, and only the man-measured water level can be taken as the important reference data. In addition, the flow direction is unclear, and can change at any time. The already built artificial water conservancy projects can be directly used to control the water level, flow velocity, and flow direction in such river network areas.

The simulation model described in this paper for the special water management problems of a plain river network area is conceptual and based on mass balance principles. It is composed of a state space model consisting of continuous variables as well as binary variables. Therefore, it is computationally fast compared to the traditional hydrological models and very suitable for application in optimal control and support decision making.

In this case study, the developed model is applied in combination with the WaterLib Library developed by Fraunhofer Centre for Advanced System Technology (AST) [2]. The whole model system is implemented in Matlab/Simulink. The result is an effective tool for management of plain land river network areas with man-made hydraulic engineering projects. For demonstration purposes, the system has been applied to intelligent water resources management of Jiangyin City area, which is part of the Taihu Lake Basin. The remaining part of the paper is organized as follows. In Section 2 the study area is introduced. Section 3 describes the modeling concept and the models. The performance of the system is analyzed for different scenarios in Section 4 and finally conclusions and future work are given in Section 5.

II. STUDY AREA

Jiangyin City is located in north of Taihu Lake of Yangtze River Delta, Jiangyin City, from east to west, the length is 58.5 km; from north to south the length is 31 km, with a total area of 987.5 km2, land area of 811.7 km2, water area of 175.8 km2, wherein, the water surface of Yangtze River of 56.7 km2, deep water coastline along river of 35 km. (Figure 1). Jiangyin is a subtropical monsoon climate of the north, in the humid monsoon region, abundant rainfall, mild climate, abundant sunshine, and four distinct seasons. The annual average temperature is 15.2 ℃, annual average sunshine hours is 2113.3 h, average precipitations 1040.4 mm. Flood period (May ~ September) accounts for about 55% of annual rainfall and rainfall varies greatly.

Fig. 1 Location of model area Jiangyin

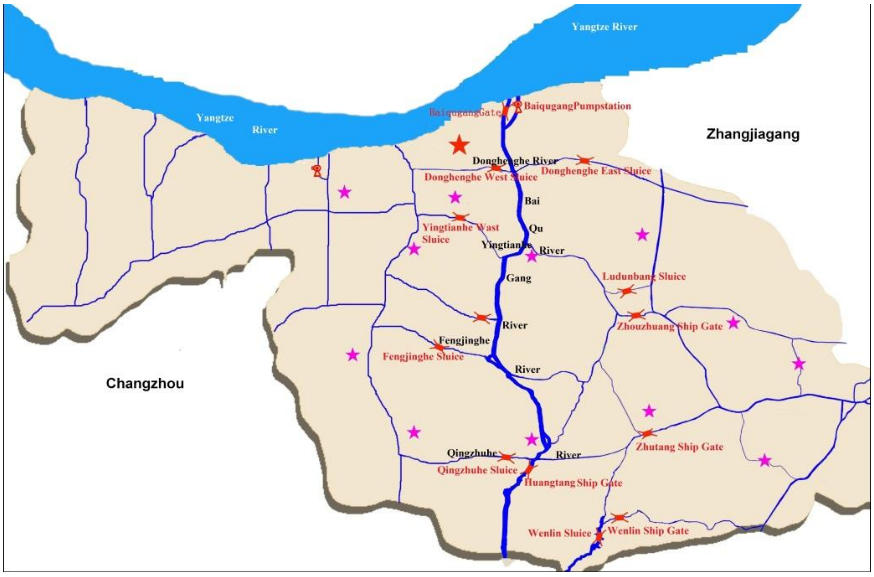

Fig. 2 River network of the model area

One of the most important rivers in this region is Baiqugang River, which joins the coastline of Yangtze River in the north and Taihu Lake in the south. In the model area Baiqugang river, several other rivers and channels form a typical river networks. The main rivers are Donghenghe, Yingtianhe, Fengjinghe, Qingzhuhe and the secondary rivers are Changshouhe and Zhutanghe. As shown in Figure 2, almost each river segment has either ship gate or water diversion sluice. Baiqugang River has two water ways to reach Yangtze River, one is in form of a ship gate, another is through a pumping station behind the dike. This pumping station contains 5 pumps, which are used to drain water from the inland river to the Yangtze River, but also pump water from the Yangtze River to the river water network. Each pump has a capacity of $20m^3/s$. This typical river network with the artificial water projects establishes a hybrid water system.

The follow table (Table 1) describes the current monitoring spots of model area:

TABLE 1 CURRENT MONITORING SITUATION OF MODEL AREA

Index	Monitoring spot	Water level of abstream	Water level of downstream	Rainfall	Flow	Quality
1	Baiqugang Pump Station	1	1	1		
2	Xiagang Pump Station	3				
3	Baiqugang Ship Gate	1				
4	Zhouzhuang Ship Gate	1	1			
5	Ludunbang Ship Gate	1	1			
6	Zhutang Ship Gate	1	1			
7	Wenlin Ship Gate	1	1	1		
8	Donghenghe East Sluice	1	1			
9	Donghenghe West Sluice	1	1			
10	Zingtianhe Sluice	2	2	1		
11	Fengjinghe Sluice	1				
12	Xiejinghe Sluice	1				
13	Huangtang Ship Gate					
14	Qingzhuhe Sluice	1	1			
15	Wenlin Sluice	1	1			

The artificial water projects form a closed river network system. Through the opening or closing of the gates and sluices, switching on or off the pumping station for drainage or diversion, the water states in this river network can be regulated. This regulation tasks can lead to the desired change in water level, flow rate and flow direction of the water system. The regulation targets are flood control, drainage, drought protection, maintenance of water quality, securing of navigation, and so on. Each target and target combinations impose different objective functions, which can be influenced by the status of each gate and sluice (opening or closing), capacities of pumping station and states of pumps (discharge, diversion). And in this closed river network there are a lot of constraints for each water situation. Therefore, reasonable water diversion, optimization control solutions must be supported by a computer simulation, and the simulation must be fast, robust and correct.

III. CONCEPT AND SIMULATION MODELS

The whole simulation model for decision support presented in this paper is composed of a human machine interface (HMI), preprocessing module, a model base and its model management system, and a post processing module. The simulation system is executed via a man-machine interactive platform. The pre-process includes designing a performance concept (scenario), considering all constraints, defining the initial conditions, then manipulating models and loading data into the system. By the running of the simulation system the scenario is executed in the virtual world. The scenario execution results can then be used by the operator to experiment with "what happens if". In this way different future scenarios can be examined to prepare some strategies for some anticipatory critical situations which may happen in the future.

A. The Model Base

The model base determines the usefulness of simulation model for decision support, and is an arsenal of methods, techniques, and models that can be used to perform the analysis and support the operators. These models or techniques are applied to the raw data in order to produce analysis or more meaningful output for the operators. A model base management is responsible for performing all tasks that are related to model management, such as model development, updates, storage, reporting and retrieval [4].

The model base of the study area is composed of the models of the individual components of the river network system described in the previous section. As the components include devices such as gates and sluices, river reaches and channels, crossing needed, etc. The models for channels and rivers are taken from our model library "WaterLib" [3]. The library (see part of it in Figure 3) implements control oriented simulation models needed for modeling channels, reservoirs or river sections with their special characteristics [3]. The water system enclosed by sluices with the states of sluices can be considered as a hybrid system. Each channel crossing node can be considered as virtual tank, which is modeled in accordance with the axiom of mass balance. All the models of the river network components are implemented in Matlab/Simulink and can be interconnected according to the river network in consideration.

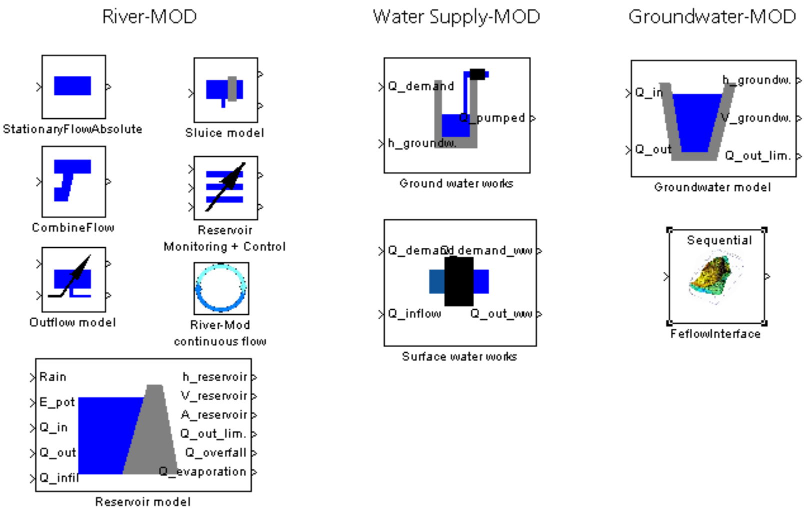

Fig. 3 WaterLib library

Figure 4 shows the structure of model for our study area.

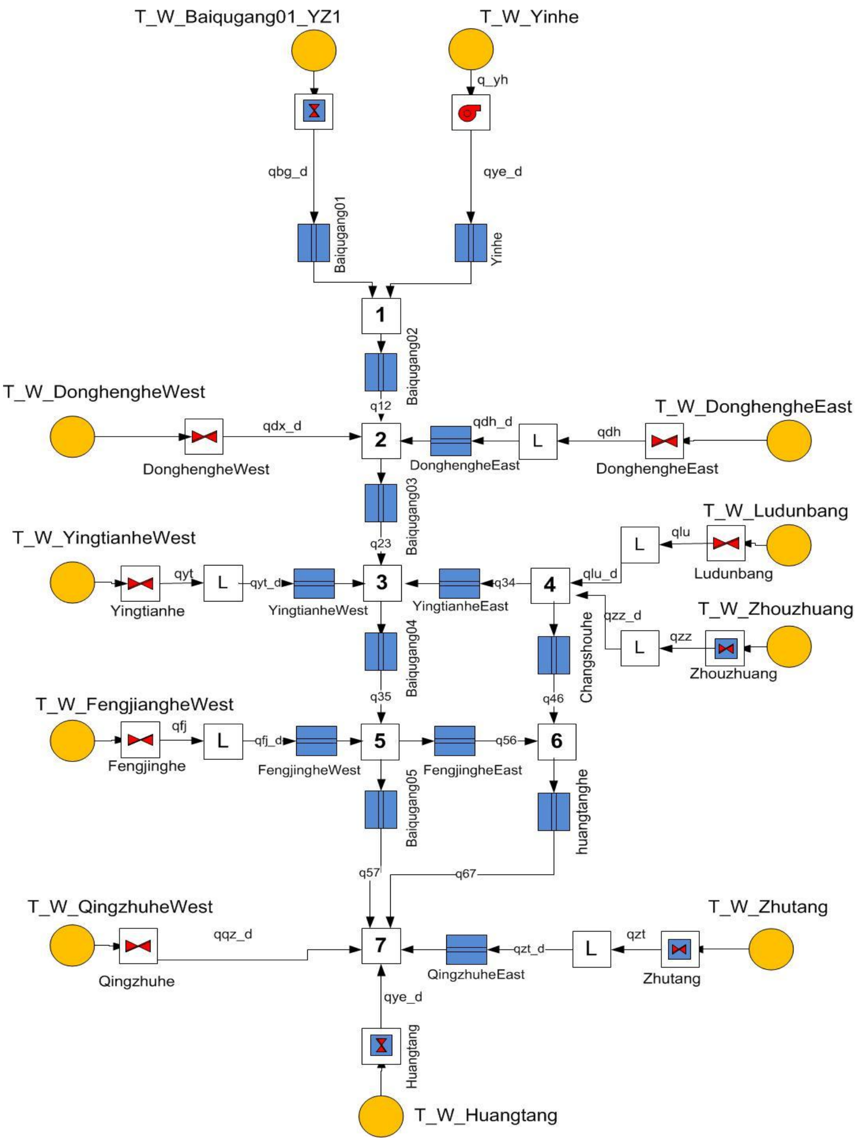

Fig. 4 The structure of model area

Some selected models of the "WaterLib" Library will be elaborated briefly in the next sub-section, starting with the hybrid system.

1) Hybrid System:

Hybrid aspects in water systems are the combination of the continuous dynamics of water with discrete dynamics [6]. For this case study the discrete dynamics means sluices with two states (open or closed), pumps in different capacities by discharge or diversion. Find a right way to simulate such hybrid aspects can lead to improved water management system, can also support the operator to make more reasonable management strategies.

Some useful algorithms of the Hybrid discrete-time model have been developed in [1]. For example, the Figure 5 shows the part of structure of the model of this hybrid water system, Xa and Xc are river segments, Xb, Xd and Xe are the crossing nodes of two or more rivers, they can be considered as virtual tanks, and the description of the model, including all equations and parameters can be expressed as follows.

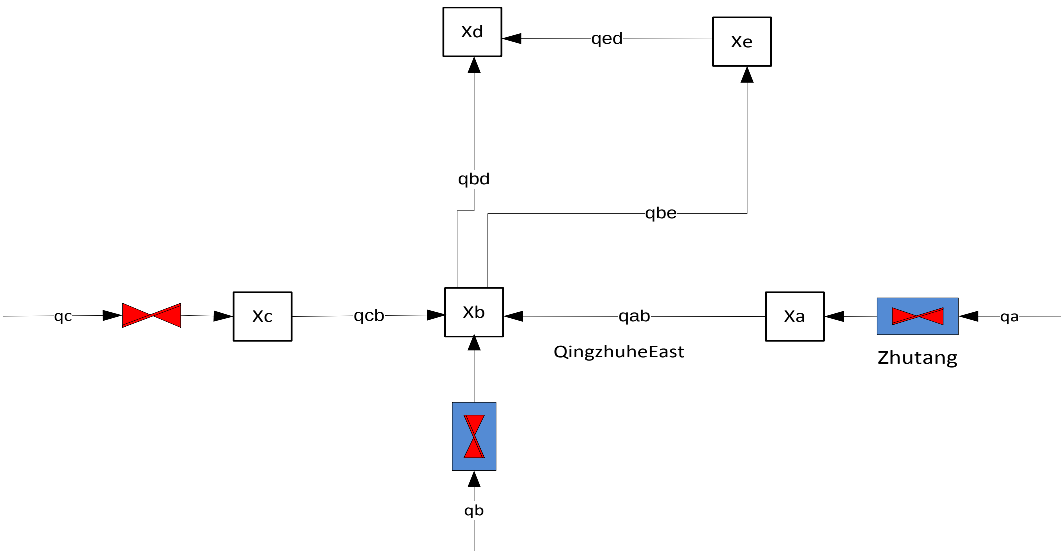

Fig. 5 State space based hybrid system

River segments and virtual tanks (Crossing nodes) are considered here as reservoirs, which are represented by the water level, the water of higher level reservoir at k time step should flow to the lower level reservoir till k+1 time step. The reservoirs comply with the principle of conservation of mass. Each reservoir is governed by the discretized mass balance to calculate the change in its water level. The increase of volume in a reservoir is equal to the sum of the inflows minus the sum of the outflows. For example for the reservoir Xb:

$$l_b(k+1) = l_b(k) + \frac{T}{A_b(k)}\left[q_{ab}(k) + q_b(k) - q_{cb}(k) - q_{bd}(k) - q_{be}(k)\right] \tag{1}$$

where k is the discrete time step, T is the simulation sample time, Ab(k) is the surface aera of reservoir, lb(k) is the water level in k time step, and qab(k), qcb(k), qbd(k), qbe(k) are flows between the reservoirs; qb(k) is the inflow of sluice b. The flows between reservoirs are computed using the formula of Chezy:

$$q_{bd}(k) = A_{c,bd}(k) \times C_{bd} \times \mathrm{sign}\big(l_b(k) - l_d(k)\big) \times \sqrt{R_{bd}(k) \times |l_b(k) - l_d(k)| \div L_{bd}} \tag{2}$$

where qbd(k) is the flow between reservoirs Xb and Xd, Ac,bd(k) is the water section of the river channel, Cbd is the Chezy roughness coefficient, and Rbd is the hydraulic radius, Lbd is the length of the river segment between reservoirs Xb and Xd. Sign(lb(k)-ld(k)) is a very important function, which represents the flow direction in the next time step.

$$q_{ab}(k) = \mu(k) \times A_{c,ab}(k) \times C_{ab} \times \mathrm{sign}(l_a(k) - l_b(k)) \times \sqrt{R_{ab}(k) \times |l_a(k) - l_b(k)| \div L_{ab}} \tag{3}$$

Calculation of qab is done similarly to Equation (2) only that the equation adds one more factor; because qab is dependent additionally on the status of the sluice "Zhutang".

$$\mu(k) = \begin{cases} 0 & \text{if the sluice closed} \\ 1 & \text{if the sluice open} \end{cases} \tag{4}$$

Other virtual reservoirs here have the similar calculation algorithms, the discrete time model and the related mathematic equations which are implemented in MatLab/Simulink as shown in Figure 6.

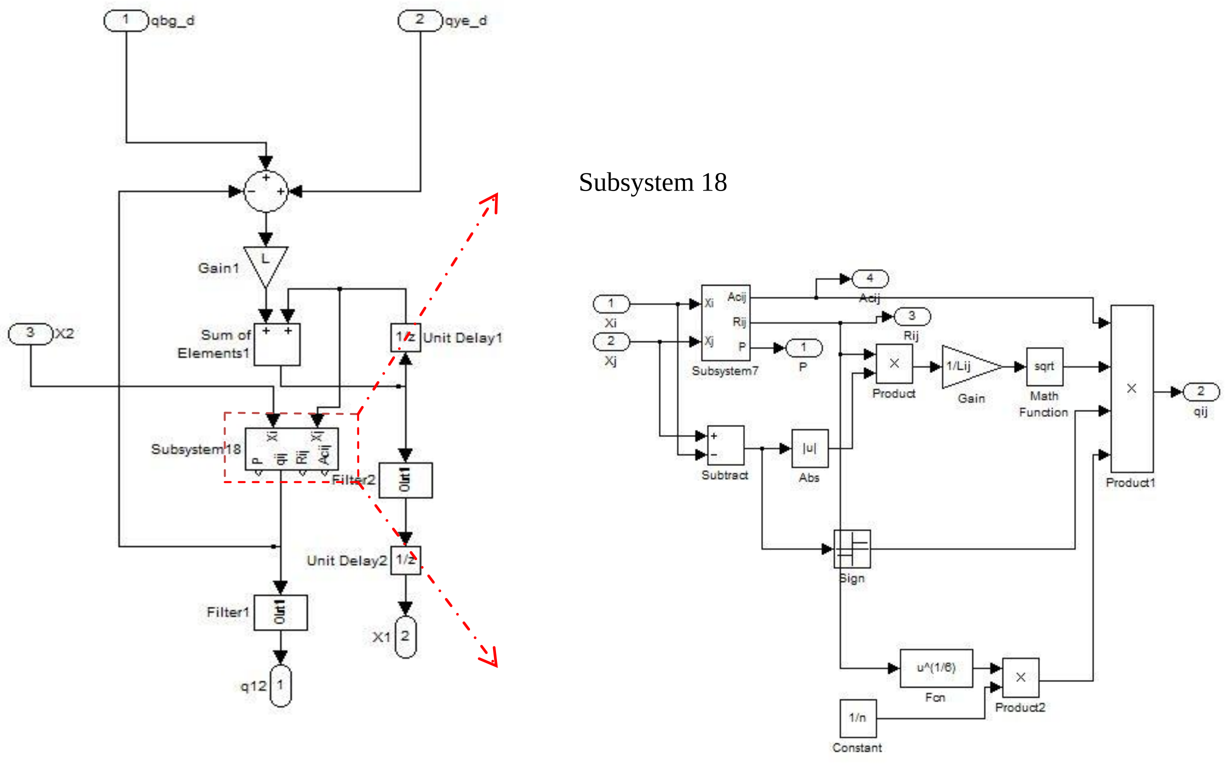

Fig. 6 Implementation of hybrid system in MatLab/Simulink

2) River and Channel Model:

The flow characteristics are represented in this rough simulation model by simple lag elements of the first order combined with dead-time elements. This is sufficient since the available data for model parameterization and simulation have at least a daily resolution (no flow dynamics). Using this solution, the flow-time of the water in the river or channel can be described [5].

If y denotes an output and u an input, the following mathematical relationship indicates a lag element of the first order.

$$T_1 \cdot \frac{dy}{dt} + y = u \tag{5}$$

T1 is the only parameter and denotes the time lag; t indicates the time. The following relationship represents the dead-time element:

$$y = u(t - T_t) \tag{6}$$

In this case the parameter is the dead-time Tt, which is thus the measure of the time taken for water to flow in a conduit over a known distance.

The two elements connected in series produce the simulation model for rivers and channels.

IV. SIMULATION RESULTS FOR DIFFERENT SCENARIOS

Scenario analysis was used for different purposes in this study, for example to calibrate the model parameters, to test different strategies using the historical data, in order to get more experience for the related situations in the future, and to use generated time series data and reasonable constraints to forecast the river situation and evaluate the proposals of the respective control strategies. Three scenarios were evaluated in this study:

Scenario I demonstrates the simulation model performance for the current water resources and controls strategic situation (16.03.2010 8:00 - 21.03.2010 8:00). It is an example of a scenario, which requires the discharge of the local river network water into the Yangtze River. Figures 7 and 8 illustrate part of the results of the Scenario I. From the simulation results, the model can represent the actual water resources situation. Therefore, the operator can apply this simulation model to analyze the current control strategies with existing data and test other decision concepts.

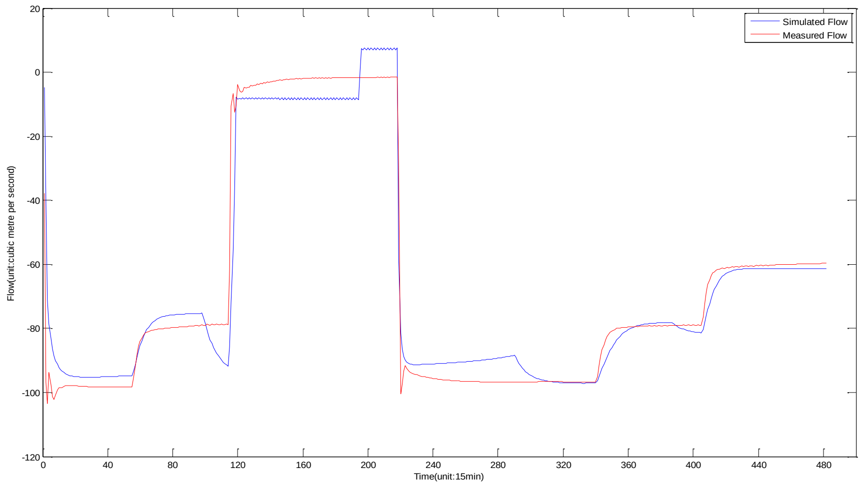

Fig. 7 Flow at river segment “Yinhe”

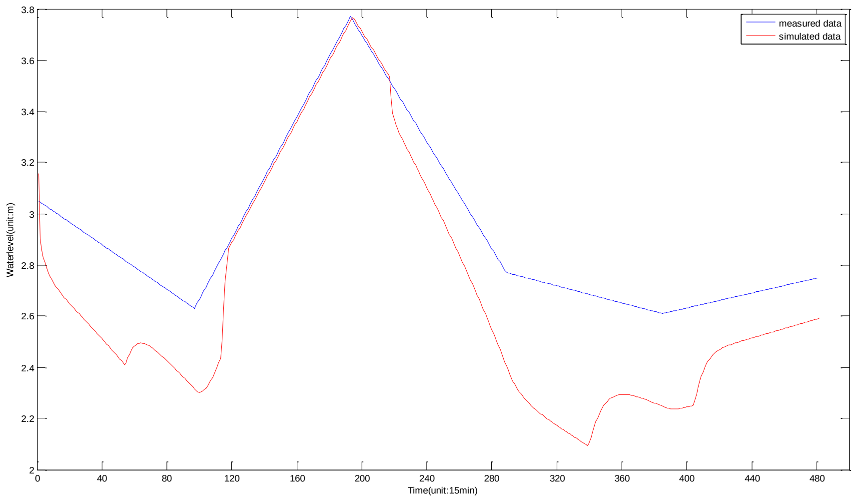

Fig. 8 Water level at river segment “Yinhe”

Scenario II demonstrates the simulation model performance for future water resources situation with different control rules. It simulates a situation which requires the diversion of Yangtze water into the local river network for environmental protection.

Figures 9 and 10 show the dangerous water level situation, which happens if the water is pumped continually from Yangtze into local river network without optimization of control strategies. In such high water level situation, one can decrease the pump capacity from Yingtze River, or find optimal sluices (Open or Closed) combination.

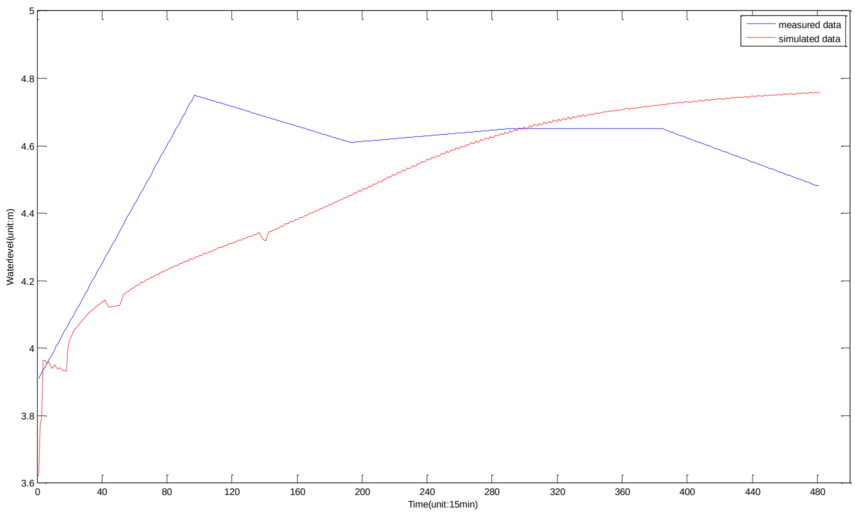

Fig. 9 Water level at river segment “Yinhe”

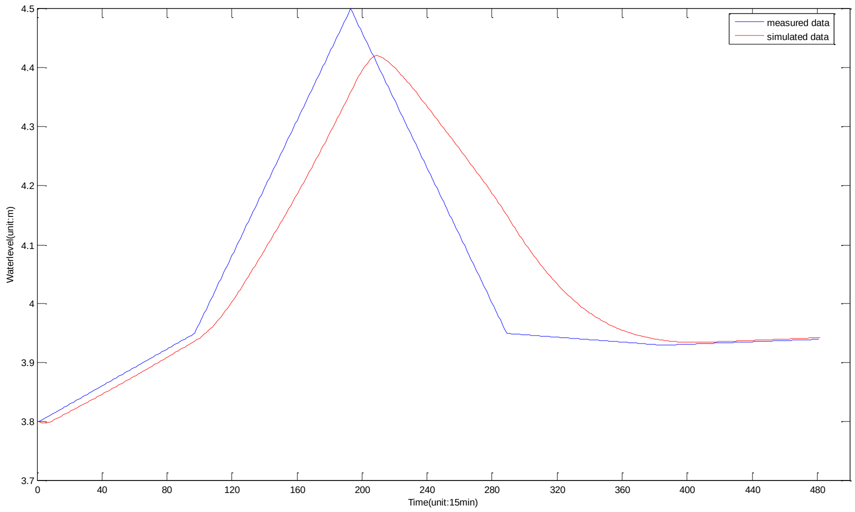

Fig. 10 Water level at Zhouzhuang Sluice

Scenario III demonstrates the simulation model performance for predictive water resources situation with different control rules. The scenario requires the discharge of the local river network water into Yangtze River to prevent flooding in Taihu area.

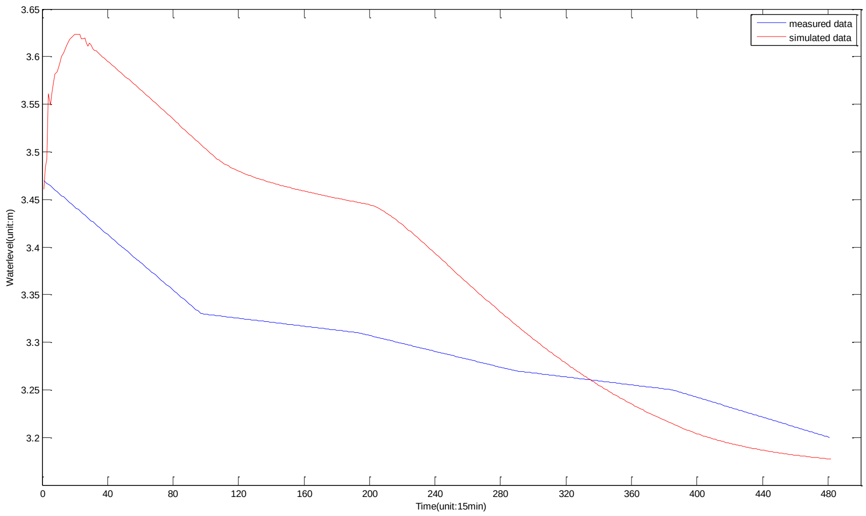

Fig. 11 Water level at river segment "Yinhe"

V. CONCLUSIONS AND FUTURE RESEARCH

The simulation system in this study is based on different methods, techniques, like conceptual model, discrete-time model, and virtual tank, hybrid model, scenario analysis. The hybrid model is the key technique to build such a simulation system for the typical river network of a plain land area. The methods in this paper integrated are adaptive for the simulation of current water situation. The developed simulation system described in this paper is used in the model area for evaluation of the decision and control strategies. The work of this study is a foundation for further work.

Now the local water administration in model area will be able to reconstruct the control system of sluices from individual manual control to full or semi-automated coordinated control, then based on the IOT (Internet of Things) techniques a centralized remote control system will be possible. In the future research, optimization algorithms for optimal control of multi sluices hybrid river network system based on scenarios and constraints will be developed. At the same time, a DSS system for the decision makers will be improved. In addition, the final system should adapt to the water resources management in the short and medium term requirements. Another challenging future work is how to improve the solutions for more efficient simulation speed and the communication protocol between the actual terminal control system and system simulation model.

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