Study on water resources allocation in the water-receiving area of the east route of the South-to-North Water Transfer Project

YOU JINJUN[1, 2], GAN HONG[2], WANG ZHONGJING[1], NIU CUNWEN[2], JIA YANGWEN[2] & JULIEN LECOLLINET[3]

1 *Key Laboratory for River Dynamics and Hydraulic Engineering, Tsinghua University, 100084 Beijing, China*
youjinjun@163.com

2 *China Institute of Water Resources and Hydropower Research (IWHR), Chegongzhuang West Rd, 100044, Beijing, China.*

3 *MED Ingegneria S.r.l., Via Pana, I- 56/A 35027 Noventa Padovana (PD), Italy*

Abstract The South-to-North Water Transfer Project (SNWTP) is a strategic measure to relieve water shortage in North China, with three routes to divert water from the Yangtze River basin; the East Route (ER) is one of them. To analyse reasonable water allocation and create a platform to assess comprehensively the impact of the ER on water-receiving areas, a rules-based water allocation simulation model (ROWAS) designed by object-oriented technology (OOT), is applied to simulate the possible effect of this water carrier project with consideration of interaction between local and diverted water. Through ROWAS, the scheme of water supply is defined and the diversion needs from a specific segment of the ER can be estimated. The hydraulic model, Res-Sim of HEC, is adopted to simulate the hydraulic process to check the feasibility of water allocation from the gates of the main channel. Based on this methodology, scenarios with and without ER are compared and analysed.

Key words object-oriented technology; SNWTP; water allocation

INTRODUCTION

Water shortage and related eco-environmental issues in North China have become the most insurmountable barrier for sustainable development. In order to solve water scarcity in this region, the Chinese government decided to divert water from the south to the north through three routes at the upstream, middle-stream and downstream sections of the Yangtze River, respectively; it is called the South-to-North Water Transfer Project (SNWTP). The East Route's mission is to draw water from Jiangdu downstream of the Yangtze River and pump water progressively northward through the historic Beijing-Hangzhou Grand Canal. According to plans, the ER project will be built based on some present hydraulic facilities, diverting water from the Yangtze River to the north part of Jiangsu Province, and pass through several lakes to enhance its capacity of regulation. Figure 1 illustrates the deployment of ER and its water-receiving area with its position in China.

The water diverted by ER is mainly supplied to agriculture in Jiangsu province, yet also to industry and domestic users in Shandong province due to the high cost of long distance water transfer. Therefore, it is a complicated but important issue to implement the optimal allocation of water at different districts and sectors. Accordingly, the operation of hydraulic facilities to carry out the scheme of allocation also needs to be elaborated.

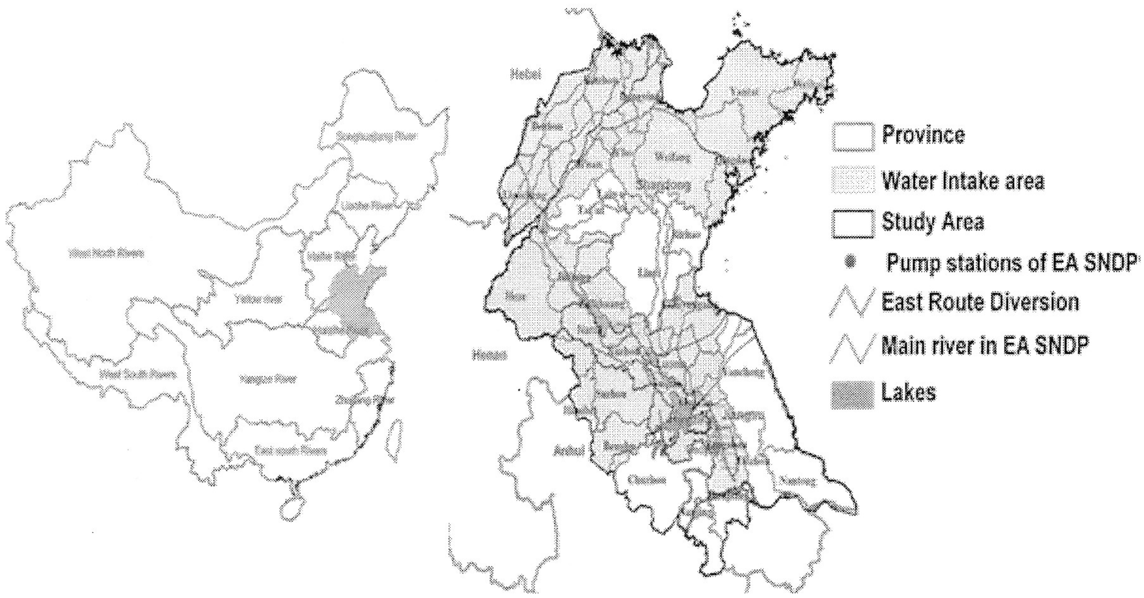

Fig. 1 Map of the study area.

Economically, local water will be used with higher priority by users than inter-basin diverted water, due to the higher cost of diverted water. In this way, diverted water can only be used in a season of dry or peak water demand. This is a challenge for implementation of the ER project, because only insufficient diverted water could be accepted by the water-receiving area compared with its capacity that could not support the sustainable maintenance of ER with limited benefit. It is not economical for the operation of this complex system. Aimed at this problem, the allocation model should balance utilization of diverted and local water rationally.

MODEL DEVELOPMENT

Conception and framework of ROWAS

Currently conceptual models with OOT design for simulation of river basins are common in the field of water resources. A Decision Support System (DSS) based on Object-Oriented Programming (OOP) was developed and applied to solve flood control problems in which reservoirs and related waterways are represented by predefined objects (Kazumasa *et al.*, 1996). A prototype spatial decision support system (SDSS), which combines GIS and DSS, was put forward to simulate the river basin, by extracting a collection of spatial objects which represent the river basins' physical entities, and thematic objects (Daene *et al.*, 1997). Under such conceptions of system design, more integrated software like MIKE BASIN, WATERWARE, AQUARIUS, EMS, IQQM and RIVERWARE give a solution for water system planning and management with the required data information.

Similarly, this kind of software is constructed based on the general conceptual description theoretically, and the object-oriented technology framework technically consists of interconnected components representing the major elements in the water cycle system.

To probe scientific and feasible techniques for the operation of ER, ROWAS was designed to realize reasonable allocation from different water sources to various water users. It was developed by a modelling technique for water system simulation according to the macroscopic realistic process. Conceptualizations are rational hypotheses to realize the reflection from reality to the framework as a whole. The framework is the backbone to develop the ROWAS model. In the framework, the movement and conversion of various water sources are defined. The first step to design a framework is selection and abstraction of real elements related to water resources (You *et al*., 2005). In conceptualization, various elements are represented by abstracted conceptual objects, which are described by different parameters.

There are two kinds of basic elements in the conceptual system, one is a node, and the other is a line. The node elements include water projects, water users, nodes of division, divarication or confluence, and other control sections in watercourses. Line elements are linkages through which water moves between different nodes. Different kinds of water sources exist and move through these node or line elements, and convert into each other. So there are several layers of network with links representing natural rivers, drainage of sewage, route of water supply, and discharge from the reservoirs. The simulation model is created with those conceptual objects and corresponding rules in mind. Based on the macroscopic process in the water system, a framework can be concluded, with the natural water cycle and artificial processes caused by human activities.

The networks composed of the main elements in water systems, including natural runoff, water supply, drainage and recycling of sewage, and inter-basin diversion, are designed to describe these water movements under the constraints of water balance. In the networks, a river basin or administrative region is conceptually modelled as an aggregate of normalized objects representing physical entities. Such generalized objects represent integrated water users and normalized hydraulic projects with major attributes and functions. Specific water sources move along with possible ways defined in the respective network and conversions between different water sources and are described inside corresponding objects based on the mechanism existing in water cycle and exploitation. In addition, all water balance relationships are checked in the simulation process. The water cycle process can be given with prepared data information and predefined controllable parameters through this system.

Joint allocation of diverted and local water in ROWAS

Aiming at joint allocation of diverted and local water, an algorithm called stepwise compensatory allocation of inter-basin diversion (DISAC) is designed in ROWAS to seek a reasonable balance in exploitation of the two kinds of water sources. In this algorithm, there are three steps to realize the joint allocation:

(1) Preallotment to units and lakes. A part of the diverted water is defined to specific units or lakes, according to the proportion and total diverted water available at the current time step:

$$V(i) = WC(i) \;\ldots.(i = 1, \ldots, n) \tag{1}$$

where $V(i)$ is the water allocated to unit or lake; W is the total available diverted water, including present diversion and surplus stored in ER from the last time step;

$C(i)$ is the proportion to withdraw the diversion, usually a number predefined by the related authority; n is the number of units and lakes receiving water from ER.

(2) First allocation to users. A part of preallotment is fixedly allocated to regular users with first priority, and the proportion of such a part out of the total preallotment is decided by adjustable parameters in calculation. After the first allocation, the local water will be supplied to users according to the dissatisfied demand and feasible physical routes.

(3) Reallocation of surplus water. In this step, the water shortage after the previous two steps will be supplied by the residual diverted water. The diverted water, which is not used from some units, will be collected and reallocated to other units where there is still a deficit with all preallotment and local water. Finally, the surplus of whole ER (if any) can be stored in the related lakes and network of ER in terms of their capacity, and then be used in the next step together with the coming diverted water.

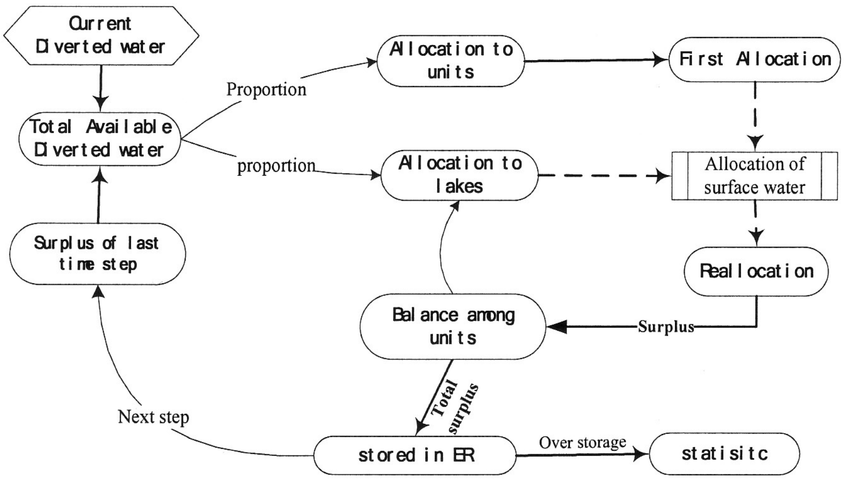

Fig.2 Schematic process of joint allocation of diverted and local water.

The general flowchart of DISAC with the detailed steps stated above, is illustrated in Fig. 2, where the simulation of "allocation of surface water" is performed in another part of the module in ROWAS to allocate the water in reservoirs. The process of diverted water allocation is designed under the framework of ROWAS, so it complies with various constraints and is operational with conceptualization of the diversion system. There are two major advantages in the 2-step DISAC algorithm: (a) the compensation regulation of local and diverted water can be realized by the "sandwich" pattern; and (b) it can carry out different scenario analysis with adjustable parameters, so it is flexible to simulate different scenarios.

Res-Sim model

Res-Sim is a simulation model for reservoirs operation developed by the Hydrologic Engineering Center of the US Army Corps of Engineers. Res-Sim offers three separate sets of functions called "modules" which provide access to specific types of data within a watershed. These modules are Watershed Setup, Reservoir Network, and Simulation. Each module has a unique purpose and an associated function accessible through a graphic user interface.

The Watershed Setup module is to provide a common framework for watershed creation and definition among different modelling applications. A watershed is associated with a geographic region for which multiple models and area coverage can be configured. In the Watershed Set-up module, the items that describe a watershed's physical arrangement are assembled together.

The purpose of the Reservoir Network module is to isolate the development of the reservoir model from the output analysis. In the Reservoir Network module, the canal network scheme is constructed; the physical and operational elements of the reservoir model are described.

The Simulation module is to simulate and isolate output analysis. Once the reservoir model is complete and the alternatives have been defined, the Simulation module is used to configure the simulation. Simulated results are viewed within this module through a database file containing all records that represent the input and output for selected alternatives.

Through the Res-Sim model, users can meet the needs of real-time reservoir regulators for a decision support tool, as well as the needs of modellers doing reservoir projects studies.

Interaction of two models

The two models are developed and integrated to identify the solutions to improve ER operation. ROWAS elaborates a water balance of all the resources available in the area (surface water, groundwater, diverted water, treated sewage, etc.) and estimates the needs of diversion from the ER to minimize the water shortage. Consequently Res-Sim analyses the possibility of the network to deliver the diversion schedule according to the hydraulic situation and the operation rules. Basically, the ROWAS model is to seek water balance and macroscopic alternatives of diverted water allocation, whilst the Res-Sim is to check the possibility and find out optimal measures to realize the macroscopic scenarios presented by ROWAS. Therefore the optimal and applicable schemes for diverted water allocation can be figured out through a combination of two such models, and provide suggestions for water management in the whole area.

According to the general design, the study area can be characterized by the two models (Fig. 3). ROWAS is concentrated on regional simulation and performs a detailed analysis of the water cycle within the area of interest discretized in homogeneous blocks. With application of the ROWAS model, the water quantities from different sources allocated to the five sectorial areas (industry, agriculture, services, rural and urban household) are obtained for each unit. However, Res-Sim focuses on simulation along the line of ER. It integrates all hydraulic facilities and reservoirs systems with their physical properties and management rules by its function modules, then it verifies the feasibility of the water allocation scenarios proposed by ROWAS in a more concrete time and spatial scale. It also optimizes the amount of water pumped from the Yangtze River according to the hydrological conditions. The flowchart of the combination of ROWAS and Res-Sim is illustrated in Fig. 4.

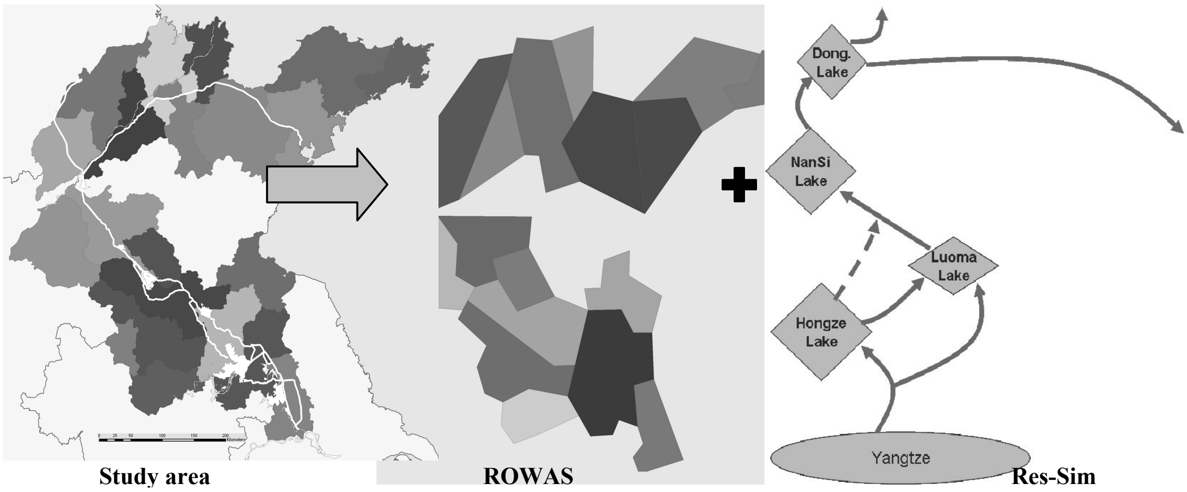

Fig. 3 Modelling of the study area from blocks and routes.

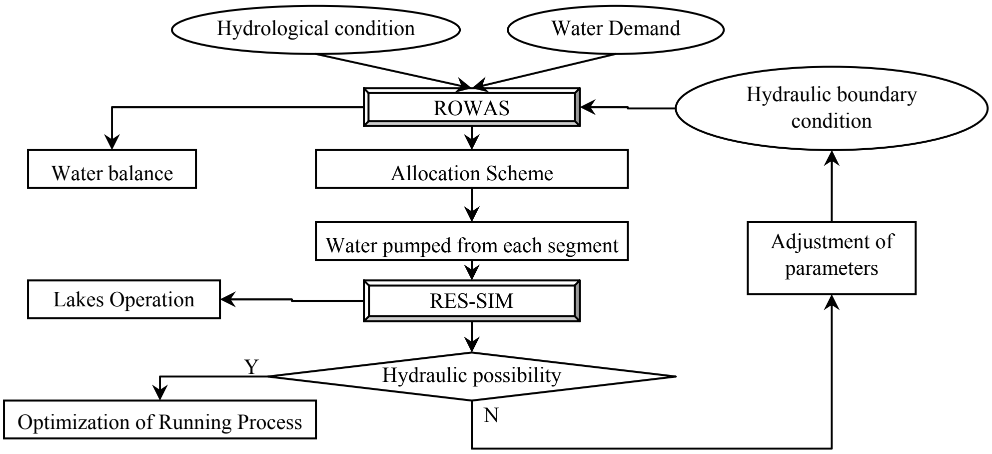

Fig. 4 Realization of integration of ROWAS and Res-Sim.

The connecting points of the two models are defined by the source points (intake) of every block of this conceptual model that will deliver water from the diversion. The ROWAS present water to be diverted in each segment as input of Res-Sim. ROWAS calculates in monthly time intervals and Res-Sim performs daily simulation, so the output of ROWAS will be transferred into daily data to satisfy Res-Sim requirements.

APPLICATION

Scenario setting

To get detailed and accurate results, multiple scenarios are analysed in the two models. ROWAS performs a long term simulation of two scenarios, one with ER and the other without. Basically, average annual results show the comprehensive impact on the balance of water demand–supply and a more significant role is undertaken by ER in a dry year, so only results of annual average and dry year are singled out and analysed to save pages. Res-Sim carries out operation simulation for ER in scenarios of average and dry years.

For ROWAS, a 45-year (1956–2000) long term monthly simulation was performed with water demand at the 2010 year level for scenarios with and without ER. For Res-Sim, the average year scenario was organized by the output of average value of the period 1956–2000 from ROWAS, and the scenario of dry year is the driest year in 1956–2000, i.e. 1966.

Basically, the average results present the yearly average statistics of the simulation and the dry year results describe the situation under a specific hydro-year. These two kinds of results can describe the general condition of simulation.

Water allocation

Table 1 shows concise results calculated by ROWAS. Water shortage decreases by about 3.1 billion and all sectors meet less water shortage. But there will be still some water shortage in agriculture, especially in Shandong Province. Further analysis discovers that water shortage will be largely relieved in urban area. In an average year, the water demand in the urban area will be fully satisfied, only meeting a shortage in a dry year. Besides, local surface water can be exploited more with ER because the construction will enhance the control capacity of local hydraulic facilities, whilst groundwater exploitation will reduce in all water-receiving areas, especially in Shandong Province. As a whole, ER will relieve water shortage and improve eco-environmental problems by resuming groundwater levels and increasing water release in dry seasons.

Table 1 Results of demand/supply and water supply from different sources.

Scenario	Province	Water demand (10^6 m^3)	Water supply (10^6 m^3)	Water shortage (10^6 m^3)	Diverted water (10^6 m^3)	Div. from Yangtze (10^6 m^3)	Div. from ER (10^6 m^3)
Average (without ER)	Jiangsu	17185	15612	1573	2700	2700	0
	Anhui	4301	3285	1016	0	0	0
	Shandong	25823	23352	2470	6604	0	0
	Total	47308	42249	5059	9304	2700	0
Dry (Without ER)	Jiangsu	24363	18843	5520	5235	5235	0
	Anhui	4894	2800	2094	0	0	0
	Shandong	26923	25046	1877	7373	0	0
	Total	56180	46689	9491	12608	5235	0
Average (with ER)	Jiangsu	17185	16941	244	4242	4242	1930
	Anhui	4301	4009	292	320	320	320
	Shandong	25823	24431	1392	7897	1351	1351
	Total	47308	45381	1927	12459	5913	3601
Dry (With ER)	Jiangsu	24363	22137	2226	7316	7316	3442
	Anhui	4894	3777	1117	638	638	638
	Shandong	26923	26245	678	8999	1782	1782
	Total	56180	52158	4022	16953	9735	5862

Validation of scenarios

According to models integration, monthly water needs of specific units for ER provided by ROWAS can be transferred into a daily water release schedule of the respective gates and pumping stations. Such schedules are taken as input of the Res-Sim model. If the schedule overpasses the capacity of the gates or pumping stations in Res-Sim simulation, the ROWAS will be carried out again, with corresponding adjustment for more strict limitation on related boundary conditions. Application shows that the scenario of average year can pass the check of Res-Sim easily, while more adjustment is needed for the scenario of dry year as more water should be diverted and distributed through the gates and pumping stations.

ROWAS provides water to be supplied by ER for calculating units to Res-Sim. Three parts of water can be supplied from ER routes physically, including supply from the current project, the newly increased part from ER, and water from Hongze Lake, i.e. the local Huai River. In ROWAS, the three parts are calculated independently according to the conceptualization. However, there is only one part of water released from gates in the Res-Sim system, which actually includes all three parts named in ROWAS. In addition, due to different division in the ER, one gate of ER in Res-Sim simulation probably can supply water to one or more calculating units, and one unit also possibly receives water from one or more gates. Therefore, the relationship between ROWAS and Res-Sim are needed for the validation.

Table 2 gives the relationship for data exchange between ROWAS and Res-Sim in the segment of ER near Hongze Lake, where the water supply ratio means the proportion from water to be supplied from the conceptual canal in ROWAS is transferred to water to be released from the corresponding gate. If the value of the ratio is lower than 1, it means water supply from one of the three parts can be supplied from other gates in Res-Sim simulation, and it represents the impossibility to release water to satisfy the water needs from the named part of water in the title row, by gate in the first column. The relationships are analysed by comparison of the network map used in the two models. The value of the ratio is ascertained through analysis of investigation and estimation. The flow capacity is the boundary condition for the gates in Res-Sim simulation, and there is a unit conversion since ROWAS simulates in monthly time step and Res-Sim simulates in daily or hourly time step. Similarly, there are more than 30 segments in the data change table. With the above definition of data change, the results from ROWAS can be transferred into input of Res-Sim.

Table 2 Definition of data change between ROWAS and Res-Sim

SN	Gate in Res-Sim	Calculating unit in ROWAS	Water supply ratio			Network's capabilities	
			From current project	From SNWTP	From Hongze	Flow Capacity ($m^3 s^{-1}$)	Flow capacity In monthly vol. ($10^6 m^3$)
13	Hongze–Sihong	Benghongbei_bengbu	no	0	1	120	316.2
		Benghongbei_huaian	no	0	1		
		Benghongbei_huaibei	1	1	no		
		Benghongbei_suqian	0	0	0.5		
		Wangbengnan_chuzhou	no	1	no		
14	Sihong–Suining	Benghongbei_suqian	0	0	0.5	120	316.2
		Benghongbei_suzhou	no	0	1		

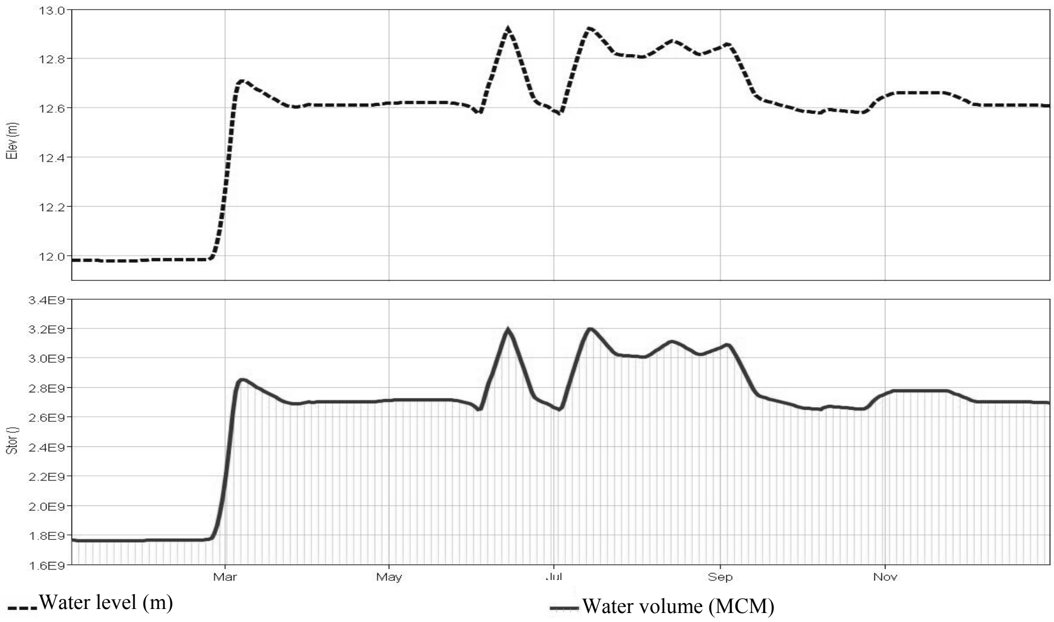

Fig. 5 Evolution of the water level and the Storage in the Hongze Lake in average year.

Figure 5 illustrates the time series of water level and volume in Hongze Lake based on daily simulation for the average year scenario. In a similar way, the situation of other lakes and hydraulic facilities can be characterized with the simulation.

CONCLUSIONS

(a) Management of ER can not just be concentrated on the operation and distribution of ER itself, since the local water influences the distribution. Therefore, the holistic analysis of water balance and allocation is necessary to calculate a reasonable quantity of water taken from ER.

(b) ROWAS fulfils comprehensive simulation on water allocation and the water balance is reliable. However, more specific study is needed on the operation of ER and local hydraulic facilities to satisfy the concrete requirements on detailed spatial and time scales, as well as to improve efficiency, because ROWAS only gives the general and macroscopic results.

(c) Since water from ER only supplies industry in Shandong due to the higher cost compared with local water, the results demonstrate water shortage of agriculture still exists in Shandong Province with ER. However, it is moderated with more local water resources transferred to agriculture.

The integration of planning and management models realized in this study is an innovative experiment. Application shows that the holistic allocation scheme and corresponding applicable operational measures can be elaborated in this way. It points out a prospective idea to realize a combination of long-term planning and short term operation for large hydraulic projects.

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