A decision support system for water supply emergency management with multiple sources

Yu Gao, Yu Li, Tianyu Song and Chuanhai Wang

ABSTRACT

The construction of water transfer projects brings new challenges to water resources management, especially in water supply security with the use of multiple water sources. However, the operations of water diversion and water supply have been considered in separation in practice. In particular, there are few decision support systems (DSS) designed to tackle the challenges in emergency planning of water transfer operation. This paper describes a generic DSS which is designed for the operation of multiple water sources supply and complex water supply targets. Emergency management is incorporated in the DSS to provide more effective water supply under extreme conditions. Specifically, the emergency scheduling plans regenerate the water supply strategy of Biliuhe Reservoir and Yingnahe Reservoir, and then reduce the impact of severe drought year on Dalian. The scheduling results of the case study reveal that this DSS makes good use of mutual compensation functions among multiple water sources when it is applied to the water supply emergency management of Dalian in a severe drought year. The results indicate that this developed DSS can be easily generalized and further applied to similar cities in China and other countries in the world.

Key words | decision support system, emergency management, multiple water sources, water division, water supply allocation

Yu Gao
Chuanhai Wang
College of Hydrology and Water Resources,
Hohai University,
Nanjing,
Jiangsu 210098,
China

Yu Gao
Construction and Administration Bureau of South-to-North Water Diversion Middle Route Project,
China

Yu Li (corresponding author)
Tianyu Song
School of Hydraulic Engineering,
Dalian University of Technology,
Dalian,
Liaoning 116024,
China
E-mail: dagongliyu@qq.com

INTRODUCTION

The geographical mismatch between water demand and water resources is a major threat to sustainable water supply in China (Yu 2011), and the rapid economic development and urbanization add further strain to the already challenging water supply situations in the country (Chang et al. 2013). To tackle the water supply problems, China, like many countries in the world, has developed over 20 major physical water transfer projects with a total length of over 7,200 km (Aeschbach-Hertig & Gleeson 2012), including the world's largest, the South-North Water Transfer Project (SNWTP) (Liu et al. 2013). Water supply from the use of multiple water sources, especially through water diversion, has significant implications on water supply security and reliability, raising new challenges in water resources management.

In a water transfer operation, a key issue is to determine when and how much water should be diverted, in conjunction with the operation of existing reservoirs in the water supply system. This is a complex problem and needs to consider a number of factors, including the variability of water sources in water importing and exporting regions, operational costs, and water supply reliability. Further, the frequency and intensity of extreme weather events also have a significant impact on water transfer operation. More specifically, during severe droughts, emergency scheduling of water transfer is required to meet water demands to a maximum extent and reduce the related social, economic, and environmental consequences. Thus, an efficient and effective decision support system (DSS) is needed to deal with the challenges in water transfer operation, in particular, emergency planning.

DSS is an efficient tool that can effectively support transparent, informed decision and policy making. Over the past several decades, considerable work on DSS has been conducted in the fields of water resources management (Liu 2000; Fassio *et al.* 2005; Fu 2008; Zhang *et al.* 2011; Ge *et al.* 2013; Svoboda *et al.* 2015), and many successful DSSs have been developed, including WaterWare (Fedra & Jamieson 1996; Jamieson & Fedra 1996a, 1996b), RiverWare (Zagona *et al.* 2001), RiverSpill (Samuels *et al.* 2006), E2 (Argent *et al.* 2009), mDSS (Mysiak *et al.* 2005), SWQAT (Sharma *et al.* 2013), AQUATOOL (Andreu *et al.* 1996), and other DSSs (Rowan *et al.* 2012; Svoboda *et al.* 2015). These DSSs cover various aspects of water resources management, including water allocation, water quality management, water supply management, and urban water management. However, with the construction of water transfer projects, there are many changes in water resources management, especially in water supply. Decisions about water diversion and water supply should be made together, but have not been considered in previous DSSs. In particular, there are few DSSs designed to tackle the challenges in water transfer operation, in particular, emergency planning.

This paper presents a DSS which considers both multiple water sources and emergency management to help decision-makers manage water resources. The DSS was applied to the city of Dalian, northeastern China. First, the water supply of Dalian is from multiple water sources, including local surface water, underground water, reclaimed water, seawater desalination, direct seawater utilization, and transferred water. The uneven distribution of surface water, many-to-many relationships between water sources and water supply sub-areas, and trade-off among water supply sub-areas substantially increase the complexity of water supply problems. Second, this DSS is designed to tackle the challenges in case of emergency, such as severe drought, water pipe burst, and water contamination incidents. For emergency scheduling during severe droughts, this paper discusses three strategies, including strategy of allocation change, strategy of water division change, and strategy of water supply change, which produce four emergency scheduling plans for implementation. In short, by the mutual compensation of the hydrological system's and reservoir's capacity, emergency scheduling plans guarantee both the

water supply reliability and the normal operation of the reservoir.

In the rest of this paper, the DSS design and implementation (e.g., the components and models combined in the system) is dealt with in the next section. This is followed by an introduction to the data and water supply problems in the city of Dalian. The application of this DSS and a discussion of results follows and the final section discusses the benefits and shortcomings of the DSS.

SYSTEM DESIGN AND IMPLEMENTATION

System architecture

In Figure 1, the architecture of the DSS is presented, including the application layer, graphical user interface (GUI), model layer, database management, database, standards and regulations, and information security system. The application layer is used to provide operational functions for this DSS, with the emergency management being the most characteristic and core functionality. GUI is a user-friendly visualization tool for the decision-maker to inquire information, analyze the results, and make the final decision. The model layer is designed to implement model computation, and consists of five models. The data management layer includes information inquiry, user management, and parameter setting. The database holds all required data for water supply management and is composed of six sub-databases. Standards and regulations ensure that the DSS is in line with national industry standards. The information security system guarantees the safety and reliability of data stored in this DSS. The introduction of models, sources of data, standards and regulations are provided in the Supplementary material (available with the online version of this paper).

System function

Water supply and transfer scheduling

To make a scheduling plan, three questions need to be solved: water resource allocation between conventional and non-conventional water sources, the amount of water supply and water diversion, and the allocation of competing
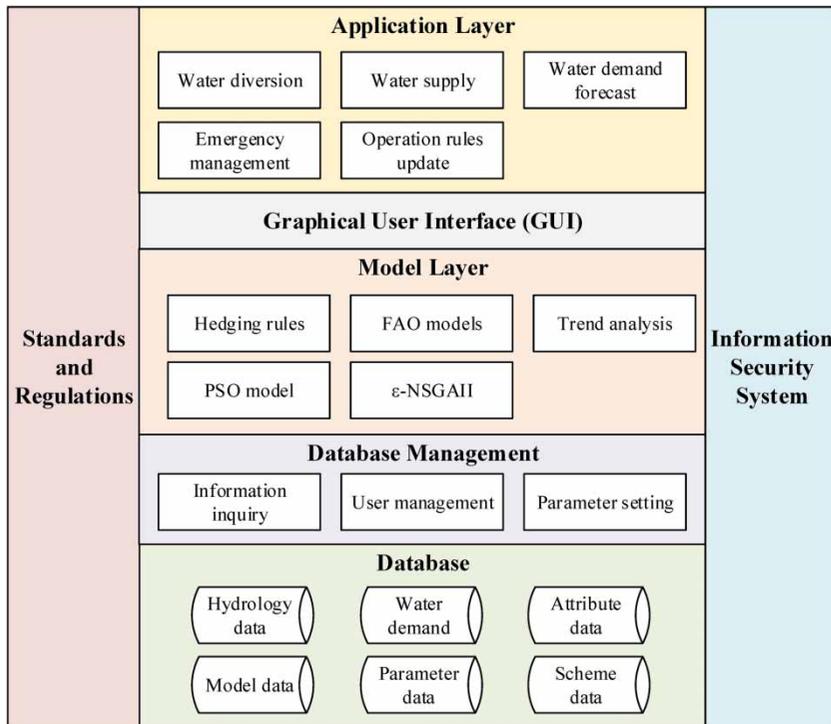
Figure 1 │ Architecture of a DSS for water supply management. FAO, Food and Agriculture Organization of the United Nations; PSO, parameterization–simulation–optimization.

demands for water from different sectors. The methods adopted in this DSS to solve these three questions are explained in detail as follows:

1. How to balance the allocation between conventional and non-conventional water sources? Two water supply schemes of different water resources are established. The amount of non-conventional water sources is almost invariant and its water users are fixed. Thus, the water supply scheme of non-conventional water sources is established in the DSS, and then the water supply scheme of conventional water sources.

2. How to determine the amount of water supply and water diversion? Water supply operation rule curves are determined by dynamic water storage and the type of water demand. Water diversion rule curves is determined by dynamic water storage. In addition, the model of hedging rules (You & Cai 2008a, 2008b; Ding *et al.* 2015) is used in making scheduling decisions. Details of reservoir operation rules and water demand forecasting are provided in the Supplementary material.

3. How to determine the allocation of competing demands for water from different sectors? When an area receives water from more than one reservoir, a water right ratio, which is determined by optimization result from historical data in advance, is given by the DSS to solve the allocation problem. Normally, in the process of the implementation stage of the scheduling plan, the actual operation result of previous periods, the latest water demand, and more precise inflow forecast can be obtained. In addition, some emergency situations may occur to impede the implementation of the original scheduling plan. For these reasons, the function of feedback adjustment is set up in the DSS. That is, users can adjust the scheduling plan at any time on the basis of the feedback of previous operation results, latest information, or fortuitous events.

In addition, the operation rules of water supply and transfer scheduling can be updated with new information to meet new requirements of water supply; and then, the original operation rules are substituted by the selected operation rules in the database. In brief, the renewal of the

scheduling plan makes this DSS more applicable and more reliable.

Emergency management

In this DSS, the emergency scheduling plans can be obtained in three kinds of emergency situations, which are severe droughts, water pipe burst, and water contamination. To improve the emergency situation, emergency management provides three strategies: strategy of allocation change, strategy of water division change, and strategy of water supply change. First of all, dynamic allocation is used to calculate the proportion of water supply allocated into each reservoir with the available water supply in each period. The allocation proportion of water supply is calculated using

$$K_{i,t} = \frac{(S_{i,t} + I_{i,t} - SD_{i,t})}{\sum_i^N (S_{i,t} + I_{i,t} - SD_{i,t})} \qquad (1)$$

where $S_{i,t}$ is the initial water storage of reservoir i at the beginning of period t; $I_{i,t}$ is the inflow of reservoir i during the period t; $SD_{i,t}$ is the side demand of reservoir i at the beginning of period t; N is the number of reservoirs with supply water to common task. Second, when the amount of water division is lower than the design capacity of water diversion, the amount of water division is increased to relieve the emergency situation. Third, by adjusting the rational coefficient λ of water supply, DSS could provide several water supply schemes, which include different groups of urban and agriculture water supply. Although water shortage situations cannot be solved completely in this strategy, different scheduling schemes with different emphases can be provided for decision-makers to choose. In brief, emergency management is designed to solve or alleviate the emergency situation in order to maintain the normal operation of reservoirs.

CASE STUDY

Dalian is a major city in the south of Liaoning Province, China. Seven large reservoirs, 16 medium reservoirs, and 240 small reservoirs provide the water supply for Dalian.

Among them, most medium and small reservoirs can serve as local alternate water sources. Then, water diversion, as a supplementary of local water resources, becomes a necessary and important water supply source. In addition, water resources of reclaimed water, seawater desalination, and direct seawater utilization have developed rapidly. These have formed a new water supply configuration for Dalian depending on multiple water sources. The new water supply configuration has the following characteristics. First, the city of Dalian is divided into seven water supply sub-areas, and the water source of each sub-area differs from one another. The relationship between reservoirs and water supply sub-areas is shown in Figure 2. Second, water supply targets of each reservoir are also different, and include industrial water demand, agricultural water demand, urban domestic water demand, and ecological environmental water demand, etc. Third, for non-conventional water resources, the amount of water supply is almost invariant, and their water supply targets are relatively fixed. Thus, the non-conventional water supply scheme is made in advance. However, the amount of local surface water and transferred water varies relatively greatly, due to the annual change of the runoff and its uneven distribution in any one year.

To investigate the feasibility and performance of the system for water resources management under multiple water sources, this system was tested to make scheduling plans for a wet year, normal year, and severe drought year. Furthermore, four emergency scheduling plans are provided to explain the coping strategies which are used to deal with emergency situations.

RESULTS AND DISCUSSION

Scheduling plan of local surface water and transferred water

Local surface water and transferred water are the main water resources for agriculture, environment, industry, and urban supplies. These water supply targets can be divided into two types: the agriculture or environment water supply target is supplied by a single reservoir; industry and urban water supply target is supplied by multiple reservoirs.
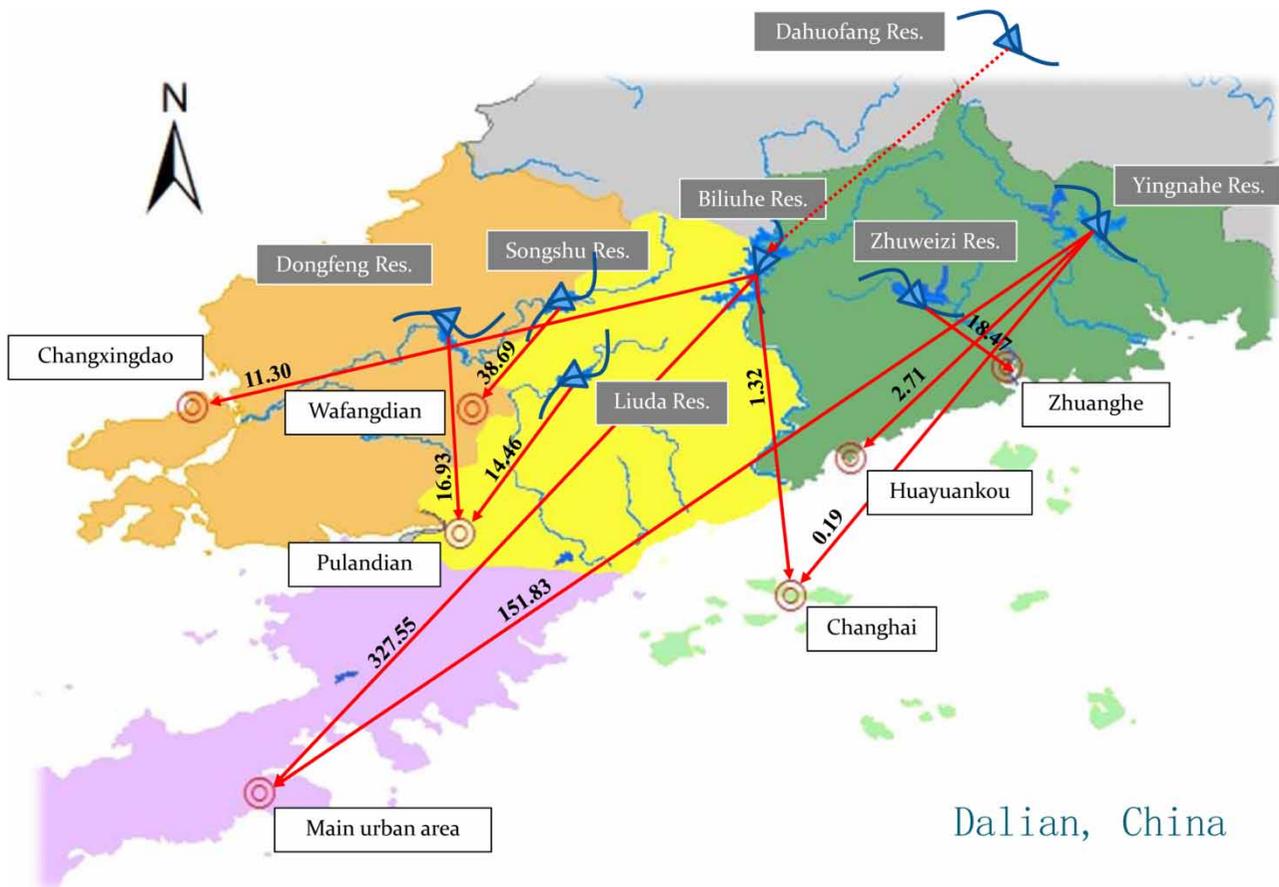
Figure 2 │ The water supply system in Dalian and the allocation of water supply in a normal year (10^6 m^3).

Compared with the former, the relationships between reservoirs and industry and urban water supply targets are more complicated. In this paper, three typical years, which respectively represent three scenarios under flow frequency of 10, 50, and 99% (i.e., 10, 50, and 99% of the study years have more inflow than this year), are chosen to show the results of their scheduling plans.

Scheduling results of normal year

First, the diversion water and total supply is determined based on the corresponding operation rules. Take the normal year under water frequency of 50% for example. The initial water storage of Biliuhe Reservoir is 200 million m^3 (M m^3) and that of Yingnahe Reservoir is 80 M m^3. The inflow of Biliuhe Reservoir is 472.71 M m^3 and that of Yingnahe Reservoir is 361.47 M m^3. According to water

diversion rules, the total water storage 280 M m^3 lies in zone II, so the amount of water diversion is 175.17 M m^3, which is calculated by multiplying a rational coefficient. Similarly, according to the reservoir water supply operation rule curves, the water demand can be fully met. The total amount of water supply is 591.53 M m^3, which is composed of 17.33 M m^3 of ecological water supply, 494.90 M m^3 of urban water supply, and 79.30 M m^3 of agricultural water supply. In addition, the total water spillage is 26.18 M m^3. The total evaporation loss is 60.55 M m^3. The ending water storage of Biliuhe Reservoir and Yingnahe Reservoir is 396.42 M m^3 and 214.68 M m^3, respectively.

Second, the allocation of water supply is determined by the water demand and water supply operation rule curve, which is the foundation of water allocation for sub-areas. Allocation of water supply in the normal year is shown in Figure 2. Taking as an example the main urban area, the

water supply of Biliuhe Reservoir and Yingnahe Reservoir is 327.55 M m^3 and 151.82 M m^3, which is 68.33 and 31.67% of the total water supply. Then, taking the example of Biliuhe Reservoir, the received water of the main urban area, Changxingdao and Changhai, is 327.55 M m^3, 11.30 M m^3, and 1.32 M m^3, which is 96.38%, 3.32%, and 0.30%, respectively. Table 1 lists the scheduling information of each reservoir in the normal year. Taking the example of Biliuhe Reservoir, the amount of 340.17 M m^3 of urban and industrial water supply equals to the sum water supply of the main urban area, Changxingdao and Changhai, in Figure 2.

Comparison of scheduling results in three scenarios

Analogously, the scheduling results of the wet year under water frequency of 10% and the severe drought year under water frequency of 99% can be obtained. The results of Biliuhe Reservoir and Yingnahe Reservoir are shown in Figure 3, which illustrates the water supply and the changing process of the water storage in 36 periods, respectively.

In Figure 3(a), the water supply of Biliuhe Reservoir in the severe drought year is the same as the normal year; whereas the water supply of Yingnahe Reservoir in severe drought is 9.79 M m^3 less than the normal year. For the diversion water, only Biliuhe Reservoir involves an inter-basin water diversion project, and water diversion of Biliuhe Reservoir increases significantly in the severe drought year. Water spillages of both reservoirs in the wet year are large, and in the severe drought year are zero. Due to the limited regulated storage capacity of

Yingnahe Reservoir, there is still a small amount of water spillage in the normal year.

In Figure 3(b), it is indicated that each reservoir water level in 36 periods of three typical years is above the dead storage water level of Biliuhe Reservoir. However, in Figure 3(c), the water level of Yingnahe Reservoir in severe drought year decreases to the dead storage water level at the 21st, 36th, and 37th periods, which present the last ten-day period of July, the last ten-day period of December, and the ending water storage, respectively. Suppose that Yingnahe Reservoir might continue to supply water even if the water level is below the dead water level, the changing process of the water storage in these three periods is shown as the dotted line, which is under the full line of dead storage in Figure 3(c). This is queried in DSS and thus the water demand of urban and agriculture are discounted from the middle ten-day period of September to the end of the year. The water rational coefficient λ is 0.9 and 0.7, respectively. It is indicated in some periods of the severe drought year that the water supply of Yingnahe Reservoir cannot meet the water demand, even though it has been discounted. Therefore, effective and efficient emergent scheduling plan should be made to deal with such an emergency situation, in order to ensure both the water supply reliability and the normal operation of the reservoir.

DISCUSSION

On further analysis and comparison of the changing process of the water storage in Figure 3(b) and 3(c), it can

Table 1 │ The scheduling information of each reservoir in normal year (10^6 m^3)

| Reservoir	Biliuhe	Yingnahe	Liuda	Songshu	Dongfeng	Zhuweizi
Initial water storage	200.00	80.00	53.64	68.81	82.12	90.00
Inflow	472.71	361.47	74.12	48.82	91.42	116.29
Water diversion	175.17	0.00	0.00	0.00	0.00	0.00
Urban and industrial water supply	340.17	154.73	17.11	43.39	21.67	20.53
Agricultural water supply	48.95	30.35	2.40	0.00	0.00	6.69
Ecological water supply	14.02	3.31	0.00	1.09	0.17	3.50
Water spillage	0.00	26.18	40.60	0.00	45.28	49.39
Evaporation loss	48.32	12.22	8.69	9.33	9.22	13.40
Ending water storage	396.42	214.68	58.96	63.82	3.20	3.78
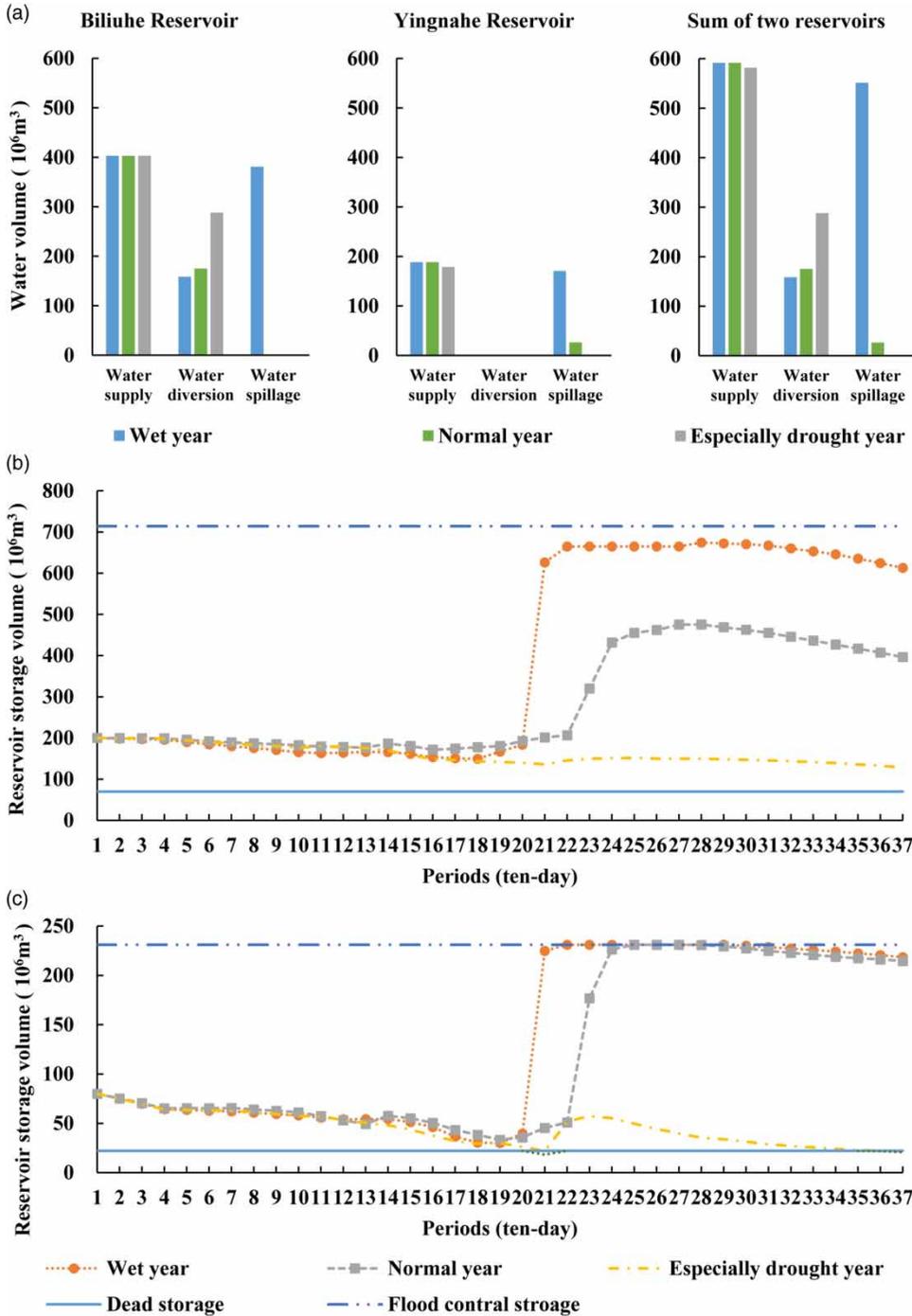
Figure 3 │ Comparison of results in three scenarios: (a) water supply, water diversion, and water spillage; (b) changing process of the water storage of Biliuhe Reservoir; (c) changing process of the water storage of Yingnahe Reservoir.

be found that in some periods Yingnahe Reservoir cannot provide enough water to meet demands, but there is redundant water in Biliuhe Reservoir. This indicates the allocation strategy of water supply between these two reservoirs is inappropriate in the severe drought year. According to the first strategy in the section on emergency
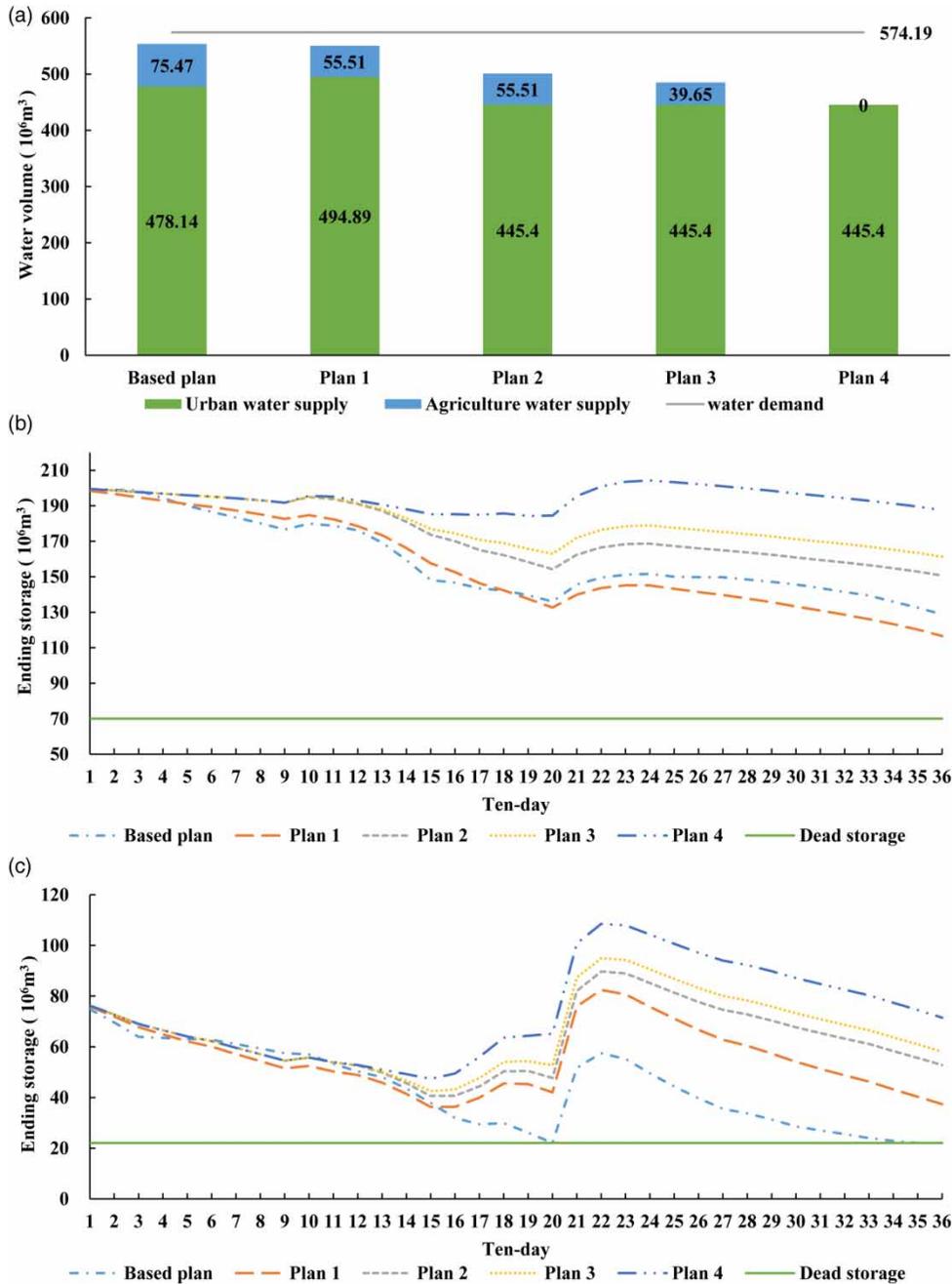
Figure 4 │ Comparison of results from emergency scheduling plans: (a) results of water supply; (b) changing process of the ending water storage of Biliuhe Reservoir; (c) changing process of the ending water storage of Yingnahe Reservoir.

management, the inappropriate situation above can be improved by dynamic allocation, and then, water diversion is fully imported in the scheduling plan. Moreover, in the scheduling plan, the water supply of urban and agriculture is not discounted until the active water storage cannot meet the water demand, whereas the water supply of emergency scheduling plans is discounted from the first period of the year on the basis of the third strategy. The rational coefficients of urban water supply and agriculture water supply of emergency scheduling plan 1 are 1.0 and 0.7. For

plan 2, plan 3, and plan 4, the rational coefficients are 0.9 and 0.7, 0.9 and 0.5, 0.9 and 0, respectively. The determination of emergency scheduling plans and emergency management processes are provided in the Supplementary material (available with the online version of this paper).

The results of the scheduling plan in severe drought year and results of the four emergency scheduling plans are shown in Figure 4. With different rational coefficients of water supply, these four emergency scheduling plans provide four groups of urban and agricultural water supply for decision-maker to choose, which is shown in Figure 4(a). The changing process of the ending water storage of Biliuhe Reservoir and Yingnahe Reservoir under different plans is shown in Figure 4(b) and 4(c).

Comparing Figure 4(a) and 4(c), it is obvious that the ending water storage of Yingnahe Reservoir is higher than dead water storage by limiting the water supply of urban and agriculture, however the water supply of urban shows no obvious decrease. In other words, the emergency scheduling plans make a trade-off between water supply and the ending water storage, in order to guarantee both the water supply reliability and the normal operation of the reservoir. In addition, the DSS can deal with other emergency situations, such as water pipe burst and water contamination incidents. Owing to space limitations, this paper only explicates the emergency situation of the severe drought year.

CONCLUSIONS

DSSs have played an increasing role in various aspects of water resources management. However, previous DSSs have focused on either water supply management or water diversion. Decisions regarding water diversion and water supply have not been considered together. Moreover, few DSSs are designed to tackle the challenges in water transfer operation, in particular, emergency planning.

In this paper, a DSS was developed to help water resources management decision-makers address emergency management of multiple water sources problems. The models utilized in the system are selected or developed according to the characteristics of multiple water sources supply, especially water diversion. The diversion water and total supply is determined based on the corresponding operation rules. The allocation of water supply is determined by the water demand and water supply operation rule curve. In addition, emergency management provides three strategies, including strategy of allocation change, strategy of water division change, and strategy of water supply change in order to deal with emergency situations. An application case was also briefly introduced. This DSS was applied in the city of Dalian in three typical years, i.e., normal year, wet year, and severe drought year.

The results obtained from the case study indicate that the water supply problems with multiple sources and high complexities, including the uneven distribution of surface water, many-to-many relationships between water sources and water supply sub-areas, and trade-off among water supply sub-areas, can be solved in the DSS, with an effective integration of diversion and allocation operations. What is more, for the severe drought year, a trade-off between water supply and the ending water storage was utilized to guarantee both the water supply reliability and the normal operation of the reservoir. The emergency scheduling highlights the fact that in water supply management with multiple sources the emergency scheduling plans become particularly important and can be produced by different strategies. DSS is an effective tool for assisting decision-makers to make informed, transparent decisions.

Although emergency scheduling plans can be obtained in case of emergency, the influences of pump stations and sluice gates on practical operation were not considered. Future work should, therefore, aim to evaluate whether water hammer or another hydrodynamic phenomenon impacts on implementation of emergency scheduling plans and also how much uncertainty it will take.

ACKNOWLEDGEMENT

REFERENCES

Aeschbach-Hertig, W. & Gleeson, T. 2012 Regional strategies for the accelerating global problem of groundwater depletion. *Nat. Geosci.* **5** (12), 853–861.

Andreu, J., Capilla, J. & Sanchís, E. 1996 AQUATOOL, a generalized decision-support system for water-resources planning and operational management. *J. Hydrol.* **177** (3–4), 269–291.

Argent, R. M., Perraud, J. M., Rahman, J. M., Grayson, R. B. & Podger, G. M. 2009 A new approach to water quality modelling and environmental decision support systems. *Environ. Modell. Softw.* **24** (7), 809–818.

Chang, J., Bai, T., Huang, Q. & Yang, D. 2013 Optimization of water resources utilization by PSO-GA. *Water Resour. Manage.* **27** (10), 3525–3540.

Ding, W., Zhang, C., Peng, Y., Zeng, R., Zhou, H. & Cai, X. 2015 An analytical framework for flood water conservation considering forecast uncertainty and acceptable risk. *Water Resour. Res.* **51** (6), 4702–4726.

Fassio, A., Giupponi, C., Hiederer, R. & Simota, C. 2005 A decision support tool for simulating the effects of alternative policies affecting water resources: an application at the European scale. *J. Hydrol.* **304** (1–4), 462–476.

Fedra, K. & Jamieson, D. G. 1996 The 'WaterWare' decision-support system for river-basin planning. 2. planning capability. *J. Hydrol.* **177** (3–4), 177–198.

Fu, G. 2008 A fuzzy optimization method for multicriteria decision making: an application to reservoir flood control operation. *Expert Syst. Appl.* **34** (1), 145–149.

Ge, Y., Li, X., Huang, C. & Nan, Z. 2013 A Decision Support System for irrigation water allocation along the middle reaches of the Heihe River Basin, Northwest China. *Environ. Modell. Softw.* **47**, 182–192.

Jamieson, D. G. & Fedra, K. 1996a The 'WaterWare' decision-support system for river-basin planning. 3. Example applications. *J. Hydrol.* **177** (3–4), 199–211.

Jamieson, D. G. & Fedra, K. 1996b The 'WaterWare' decision-support system for river-basin planning. 1. Conceptual design. *J Hydrol.* **177** (3–4), 163–175.

Liu, Z. 2000 Decision support system for water supply management in drainage basin. *Arid Land Geogr.* **23** (3), 259–263.

Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B. & Zhang, M. 2013 Water conservancy projects in China: achievements, challenges and way forward. *Global Environ. Change* **23** (3), 633–643.

Mysiak, J., Giupponi, C. & Rosato, P. 2005 Towards the development of a decision support system for water resource management. *Environ. Modell. Softw.* **20** (2), 203–214.

Rowan, J. S., Greig, S. J., Armstrong, C. T., Smith, D. C. & Tierney, D. 2012 Development of a classification and decision-support tool for assessing lake hydromorphology. *Environ. Modell. Softw.* **36**, 86–98.

Samuels, W., Amstutz, D., Bahadur, R. & Pickus, J. 2006 Riverspill: a national application for drinking water protection. *J. Hydraul. Eng.* **132** (4), 393–403.

Sharma, A., Naidu, M. & Sargaonkar, A. 2013 Development of computer automated decision support system for surface water quality assessment. *Comput. Geosci.-UK* **51**, 129–134.

Svoboda, M. D., Fuchs, B. A., Poulsen, C. C. & Nothwehr, J. R. 2015 The Drought Risk Atlas: enhancing decision support for drought risk management in the United States. *J. Hydrol.* **526**, 274–286.

You, J. & Cai, X. 2008a Hedging rule for reservoir operations: 2. A numerical model. *Water Resour. Res.* **44** (1), W1416.

You, J. & Cai, X. 2008b Hedging rule for reservoir operations: 1. A theoretical analysis. *Water Resour. Res.* **44** (1), W1415.

Yu, C. 2011 China's water crisis needs more than words. *Nature* **470** (7334), 307.

Zagona, E. A., Fulp, T. J., Shane, R., Magee, T. & Goranflo, H. M. 2001 Riverware. *J. Am. Water Resour. Assoc.* **37** (4), 913–929.

Zhang, L., Li, D. & An, X. 2011 Study on water resources optimal allocation of irrigation district and irrigation decision support system. In: *Computer and Computing Technologies in Agriculture IV* (D. Li, Y. Liu & Y. Chen, eds). Springer, Berlin, Heidelberg, pp. 716–725.