

Use of multi-objective analysis to reveal the benefits of a water transfer project

Rong Tang, Chi Zhang, Wei Ding, Yu Li and Huicheng Zhou

ABSTRACT

This paper employs the multi-objective analysis to evaluate the benefits and feasibility of a local water transfer project between two water supply reservoirs in China. Firstly, the multi-objective simulation optimization model of reservoir operation for three scenarios, including no connection, virtual connection, and pipeline connection, are set up considering the compensation role of hydrology and the storage capacity of relevant reservoirs. Secondly, the Pareto-optimal solutions and the selected operation solutions for the three scenarios are analyzed to evaluate the benefits of the transfer project. And visual analytics is used to show and analyze the relation of the three scenarios' Pareto-optimal solutions intuitively. Lastly, the results show building a pipeline can attain more benefits in reducing the amount of diverted water and water spills for the water supply system, but with some issues such as additional engineering cost and low utilization rate of the diversion pipeline. This study demonstrates that conducting a holistic multi-objective analysis for water transfer options can reveal the full trade-offs between competing objectives, show the relation of different scenarios' Pareto-optimal solutions and provide support for informed decision-making on water diversion project planning.

Key words | multi-objective analysis, reservoir operation, trade off, visual analytics, water transfer

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INTRODUCTION

With economic development, population growth, and climate change, water supply has become a pressing issue in many regions (Zhang *et al.* 2014). Water diversion projects are increasingly used to solve the problem of water scarcity, increase water security and reduce the risk of water shortages (Grant *et al.* 2012). For example, the South–North Water Transfer Project in China aims to transfer water from the Yangtze River to meet the increasing demands in Beijing, Tianjin and other cities in the north (Zhang 2009).

Water transfer, diverting water from areas with surplus to those with shortage, makes use of compensations between different hydrological regions, basins or rivers (Davies *et al.* 1992). The compensation benefits depend on hydrological difference, and an ideal situation is that water deficit in the importing region always occurs concurrently with a

significant water surplus in the exporting region (Liu & Zheng 2002). To date, the feasibility of a water transfer project is usually analyzed using asynchronism-synchronism analysis of flow to calculate the hydrological difference and compensation efficiency, which is based on the dryness or wetness assessment of the flow series for pairing regions (Liu & Zheng 2002). This method is used in the feasibility study of the South-to-North Water Transfer Projects in China (Liu & Zheng 2002; Zhang 2009; Kang & He 2011). However, this method considers only natural flows and ignores the function of reservoirs, which play an important role in storing and regulating water resources and contribute to the compensation benefits in a water transfer project (Guo *et al.* 2012; Li *et al.* 2014; Zhao & Zhao 2014). There might exist compensation potential in the regions with limited hydrological

compensation capacity but sufficient storage compensation (Guo *et al.* 2011; Zhou *et al.* 2015). Thus, this paper proposes the use of multi-objective analysis combined with reservoir operation to reveal the benefits and feasibility of a water transfer project, not only considering the compensation of hydrology but also the compensation benefits of the relevant reservoirs in the water transfer project.

The operation problem of multi-reservoirs involved in water transfer is typically a multi-objective optimization problem. Multi-objective evolutionary algorithms (MOEAs) perform well in solving such a problem, with high complexity and dimensionality (Fu *et al.* 2008; Hurford *et al.* 2014). They exploit their population-based search to provide Pareto-optimal solutions on which solutions cannot be improved for any of the objectives considered, without disadvantaging one or more of the others (Kasprzyk *et al.* 2009). To provide analytical information in a more intuitive way, visual analytics can be used to explore the Pareto-optimal trade-offs with holistic pictures (Fu *et al.* 2012; Hurford *et al.* 2014). This helps to make informed decisions.

This paper investigates the use of multi-objective analysis to reveal the feasibility study of a water diversion project between Biliuhe reservoir and Yingnahe reservoir in Dalian, China. Firstly, the multi-objective optimization model, with three objectives as water supply reliability, water spills and diverted water is established for three scenarios including the base scenario (no connection), virtual connection, and pipeline connection. And the Pareto-optimal solutions are obtained with the epsilon non-dominated sorting genetic algorithm II (ϵ -NSGAI) and displayed with Visual analytics. Additionally, selected solutions with the same reliability are compared to further reveal the benefits of such a water transfer project.

CASE STUDY

Biliuhe reservoir and Yingnahe reservoir are two important water sources for Dalian, which lies in a semi-arid river basin with annual average rainfall of 675.6 mm in Northeast China. Biliuhe reservoir's active storage is $644 \times 10^6 \text{ m}^3$ with an average inflow of $556 \times 10^6 \text{ m}^3$ per year, while Yingnahe reservoir's active storage is $209 \times 10^6 \text{ m}^3$ with an average inflow of $330 \times 10^6 \text{ m}^3$ per year. As can be seen, the ability of

Biliuhe reservoir to regulate flow is higher than that of Yingnahe reservoir. According to the plan of water resources sustainable utilization of Dalian, in the middle term, Biliuhe reservoir needs to meet an annual local water demand of $54 \times 10^6 \text{ m}^3$ and Yingnahe reservoir needs to meet a local demand of $23 \times 10^6 \text{ m}^3$ due to population growth and city development. Additionally, they need to jointly supply the water demand of the main city zones, with an annual amount of $526 \times 10^6 \text{ m}^3$, which is referred to as the joint demand in this paper.

For alleviating local water supply pressure, an inter-basin water transfer project from Dahuofang reservoir to Biliuhe reservoir, was constructed, as shown in Figure 1. This regional water transfer project is called as D-B water transfer project and is a long distance water transfer project. To reduce the high cost of the long distance water transfer and make full use of local water resources, constructing a bidirectional water pipeline between Biliuhe reservoir and Yingnahe reservoir, called the B-Y water transfer project, has been considered in the last several years and the benefits of the project are to be evaluated. Therefore, this paper evaluates the benefits and feasibility of such a local water transfer project from the point of water amount using multi-objective analysis.

METHODOLOGY

Scenario definition

This study aims at revealing the benefits of the proposed local project between Biliuhe reservoir and Yingnahe reservoir. The approach used is multi-objective analysis for scenario comparison based on reservoir operation. Correspondingly, this study defines three operational scenarios as follows.

Scenario 1: This is the base scenario without diversion pipelines between the two reservoirs. In this scenario, Biliuhe reservoir undertakes three-fourths of the joint demand and the rest is supplied by Yingnahe reservoir.

Scenario 2: This scenario is referred to as the virtual connection scenario. In this scenario, there is no diversion pipelines between the two reservoirs and the joint demand is met by the two reservoirs according to different allocation proportions in each period through existing water supply networks in the water supply region. The allocation proportions are generated by the optimization scheduling model.

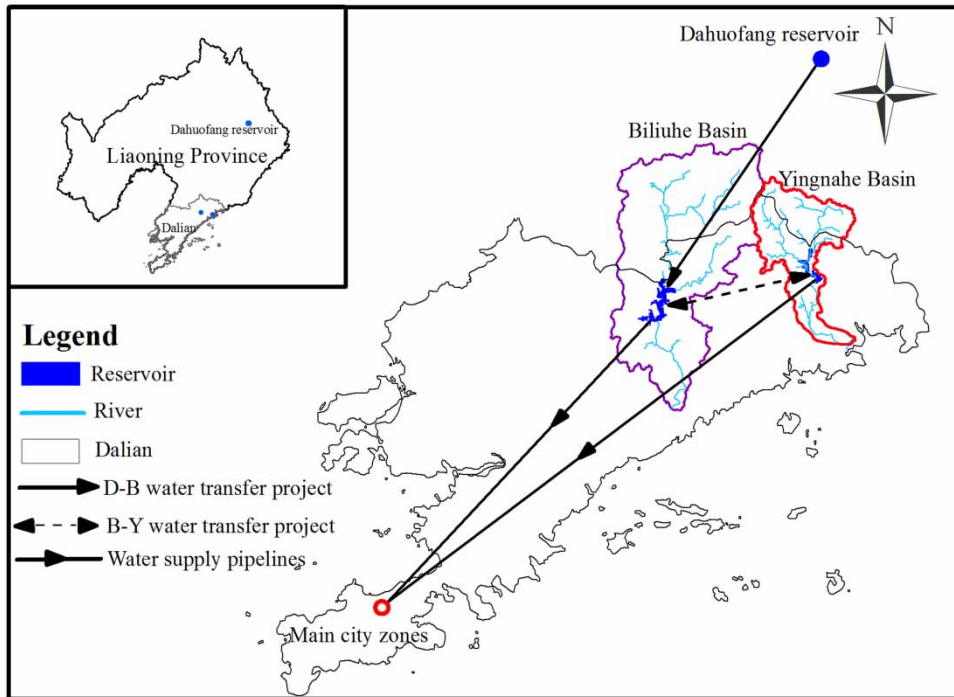


Figure 1 | Study area.

Scenario 3: This scenario is the pipeline connection scenario. In this scenario, there is a water diversion pipeline (there is no limitation in this water pipeline when optimized) between the two reservoirs, which allows water to be diverted in both directions in order to fully utilize the storages of the two reservoirs for water supply. In this scenario, the joint demand is also undertaken by the two reservoirs according to different allocation proportions which are also optimized similarly to scenario 2.

Optimization problem formulation

The benefit analysis of such a water transfer project using scenarios' comparison based on multi-reservoir operation can be regarded as a multi-objective optimization problem. Simulation optimization, which is an effective tool to determine optimal decision variables that result in maximization or minimization of objective functions, is used to solve this problem. Objective functions, decision variables, the optimization method and the way to show optimal solutions that are involved with the simulation optimization are formulated as below, and some details are provided in the Supplementary material (available with the online version of this paper).

Objective functions

The reservoir operation performance of the three scenarios will be compared using three indicators. One is water supply reliability (*WSR*). For domestic water supply, improving water supply reliability is one of the most important regulation goals. Another is the volume of average annual diverted water from Dahuofang reservoir (*DW*). This case study focuses on the benefits of the B-Y water transfer project, and in addition Biliuhe reservoir can transfer water from Dahuofang reservoir. Reducing the volume of water diverted from Dahuofang reservoir can avoid the high cost of long distance water transfer and make full use of local water. Another indicator is the volume of average annual water spills (*SP*). *SP* is an indicator widely used in reservoir operation as one criterion to evaluate the reservoir operation performance. Reducing the volume of average annual water spills can confirm more water could be supplied. Therefore, each scenario is designed as an optimization problem seeking to maximize *WSR*, minimize *SP*, and minimize *DW*. The formulations of the objective functions and constraints involved are provided in the Supplementary material.

Decision variables

In an optimization problem, it manipulates decision variables in search of values that produce the optimal value for the objective function. For the reservoir operation in the three scenarios, the same decision variables optimized are the water storage volumes at different operation periods on reservoir operation rule curves of water supply and water diversion, which are widely applied to reservoir operation (Liu *et al.* 2011). Details of how reservoir operation rules divide the reservoir storage volume into different zones against time where different water demands are met fully or partially are provided in the Supplementary material. Additionally, different allocation proportions to allocate the joint demand also need to be optimized in scenarios 2 and 3. More details of the decision variables are provided in the Supplementary material.

Optimization method

Recent studies show ϵ -NSGAI is one of the promising MOEAs and widely used to obtain the optimal solutions of water resources problems (Zhang *et al.* 2008). It is an extension of the original NSGA-II by adding ϵ -Domination archiving and automatic parameterization to enhance the solution of high-order Pareto optimization problems (i.e., problems with three or more objectives) (Deb *et al.* 2002; Laumanns *et al.* 2002; Zhang *et al.* 2008). ϵ -Domination requires users to specify the precision with which they wish to quantify each objective. This algorithm can balance convergence speed and diversity. Due to the stochastic of ϵ -NSGAI, 20 random algorithm runs are carried out for each scenario. The Pareto-optimal solutions of each run are put together and then the Pareto-optimal approximations are determined.

Visual analytics

Visual analytics is an emerging tool in the fields of scientific and information visualization (Andrienko *et al.* 2007; Sweetapple *et al.* 2014; Meng *et al.* 2016). It can provide a holistic picture of the multiple objectives by visualizing the trade-offs (Hurford *et al.* 2014). We use it to compare the Pareto-optimal approximations of three scenarios.

RESULTS AND DISCUSSION

Pareto-optimal trade-offs

With the simulation optimization model, the Pareto-optimal solutions of three scenarios are obtained and presented as three trade-off surfaces in three dimensions shown in Figure 2(a). This allows visualization of how performance across all the objectives is distributed for each scenario

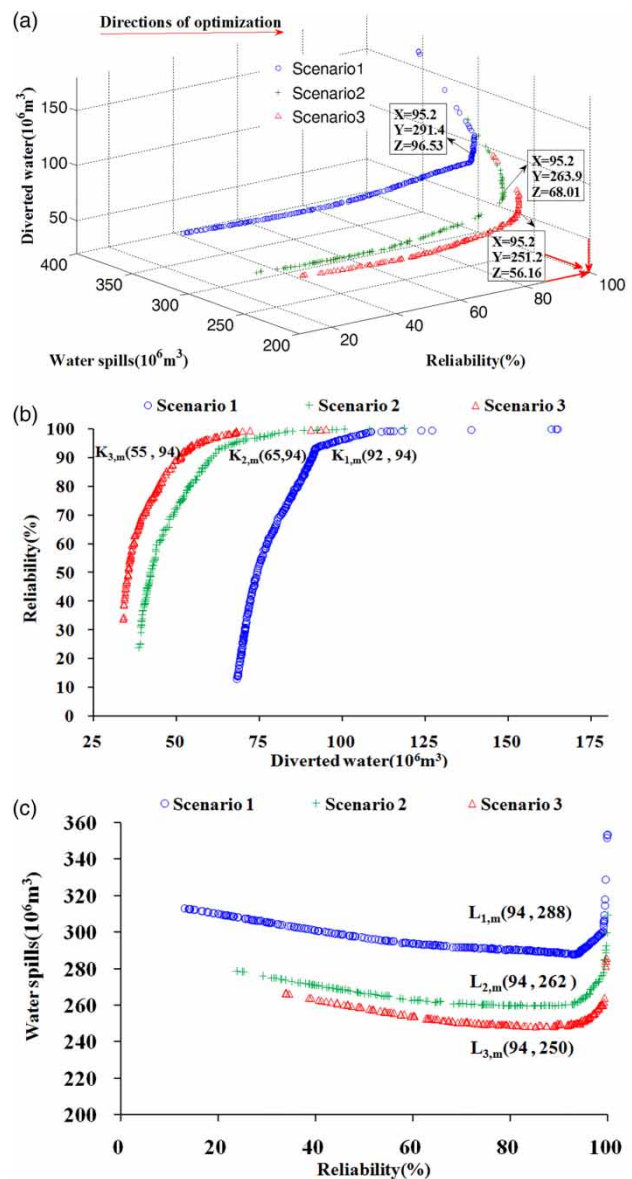


Figure 2 | Pareto-optimal solutions of three scenarios.

and show the relation of the three scenarios' Pareto-optimal solutions.

As can be seen from Figure 2(a), the three trade-off surfaces of scenarios 1, 2 and 3 have a similar trend: the reliability increases with an increasing amount of diverted water; with the reliability increasing, the amount of water spills decreases and then increases. This is because raising the amount of diverted water makes water available for supply increase, and thus, water demands can be satisfied in more operation periods, which leads to the increase in water supply reliability and water supply amount. More water is supplied and less water is spilled. So water spills reduce accordingly. However, the water spills cannot decrease all the time. To further improve the water supply reliability, it has to satisfy water demand even in those extremely dry periods. For this, it has to manipulate water diversion rules to add the amount of diversion for those periods in the optimization. The water diversion rules are universal, which results in a great quantity of diversion even in wet periods. But so much water isn't needed in wet periods, and this leads to larger water spills.

From Figure 2(a), we can see clearly that the trade-off surfaces of the virtual connection scenario and pipeline connection scenario are much better than that of the no connection scenario. This is because both the virtual connection scenario and pipeline connection scenario can manipulate allocation proportions of joint water demand between Biliuhe reservoir and Yingnahe reservoir reasonably at different operation periods of a year according to the two reservoirs' different hydrological conditions, project conditions, and storage difference. For example, when one reservoir stores a little water while the other one stores abundant water, then the latter one can undertake more of the joint demand. And thus, more joint water demand can be satisfied, less water spills come out, and less water needs to be diverted from Dahuofang reservoir. So the virtual connection scenario and pipeline connection scenario can indirectly make use of hydrological compensation and capacity compensation between different reservoirs to improve the utilization of water resources.

What's more, it is also apparent from the two closer trade-off surfaces of the three in Figure 2(a) that the pipeline connection scenario has a better performance over the virtual connection scenario in reducing the amount of water transferred over long distances and water spills. In the pipeline connection scenario, the water diversion pipeline could

have allowed transfer of water from one reservoir when it has some surplus water while another does not. However, there is only a small amount of water transfer between the two reservoirs. This is mainly because Biliuhe and Yingnahe reservoirs are in the same hydrological region and have similar hydrological characteristics, i.e., they are wet and dry at the same time.

Pairwise comparisons of Pareto-optimal trade-offs

This part mainly compares objectives from two dimensions of three scenarios. Figure 2(b) shows the relationship between the amount of diversion and water supply reliability, while Figure 2(c) shows the relationship between reliability and the amount of water spills. From pairwise comparisons, we can obtain the relation of three scenarios' Pareto-optimal solutions more clearly. It is similar to what is described in the section Pareto-optimal trade-offs. When given a reliability, the diverted water satisfies $K_1 > K_2 > K_3$ (K_k represents the diverted water of scenario k , $k = 1, 2, 3$) and water spills satisfies $L_1 > L_2 > L_3$ (L_k represents the water spills of scenario k). Especially, when the water supply reliability is up to 94%, the growth rate of reliability changes slowly and gradually and water spills begin to increase sharply. In this paper, we regard the point of this reliability as a turning point. At this point, we can also see $K_{1,m} > K_{2,m} > K_{3,m}$ ($K_{k,m}$ represents the turning point's diverted water of scenario k) and $L_{1,m} > L_{2,m} > L_{3,m}$ ($L_{k,m}$ represents the turning point's water spills of scenario k). Comparing the value of $K_{k,m}$ and $L_{k,m}$, both the pipeline connection scenario and virtual connection scenario can reduce at least $27 \times 10^6 \text{ m}^3$ diverted water and $26 \times 10^6 \text{ m}^3$ water spills compared with the no connection scenario. These data further support that both the pipeline connection scenario and virtual connection scenario can obtain better benefits. Additionally, $K_{2,m}$ is $10 \times 10^6 \text{ m}^3$ more than $K_{3,m}$, and $L_{2,m}$ is $12 \times 10^6 \text{ m}^3$ more than $L_{3,m}$. These data show fewer benefits obtained in the virtual connection scenario compared to the pipeline connection scenario in reducing the amount of diverted water from Dahuofang reservoir, and water spills.

Comparison of simulated operation rules

To compare the differences between the three scenarios in greater detail, we selected one solution with the same

water supply reliability value from the Pareto set of each scenario (shown in Figure 2(a)). As the common minimum of water supply reliability value for domestic water supply is 95%, this paper selects 95.2% as the same reliability value. The operation results under each scenario are shown in Figure 3(a), which also presents the values of the three objectives and the amount of the local diversion between Biliuhe reservoir and Yingnahe reservoir.

Because of the water supply reliability, there is no difference in water supply and water shortage, as can be seen in Figure 3(a). Additionally, the water diversion from Dahuofang reservoir is $96.53 \times 10^6 \text{ m}^3$, $68.01 \times 10^6 \text{ m}^3$ and $56.16 \times 10^6 \text{ m}^3$ for the no connection, virtual connection and pipeline connection scenarios, respectively. For water spills, it is $291.42 \times 10^6 \text{ m}^3$ for the no connection scenario, $263.91 \times 10^6 \text{ m}^3$ for the virtual connection scenario, and $251.17 \times 10^6 \text{ m}^3$ for the pipeline connection scenario. These results further illustrate that both the virtual connection scenario and pipeline connection scenario can reduce

water diversion from Dahuofang reservoir and water spills compared with the no connection scenario. Moreover, the pipeline connection scenario can reduce water transfer by $11.85 \times 10^6 \text{ m}^3$ and water spills by $12.74 \times 10^6 \text{ m}^3$ compared to the virtual connection scenario. Building a pipeline as assumed in the pipeline connection scenario can attain relatively more benefits in reducing the amount of diverted water and water spills than only doing the joint operation in the virtual connection scenario.

On the other hand, the pipeline connection scenario has the following issues that have to be considered by the decision maker. First, there is a significant capital cost for the pipeline, which might have associated environmental and social impacts. Second, as is shown in Figure 3(a), there is an increase in local diversion, $44.80 \times 10^6 \text{ m}^3$, which is the total volume transferred from both directions, thus inevitably there is an operating cost to pump the water in one direction. Third, as shown in Figure 3(b), diversion between Biliuhe reservoir and Yingnahe reservoir

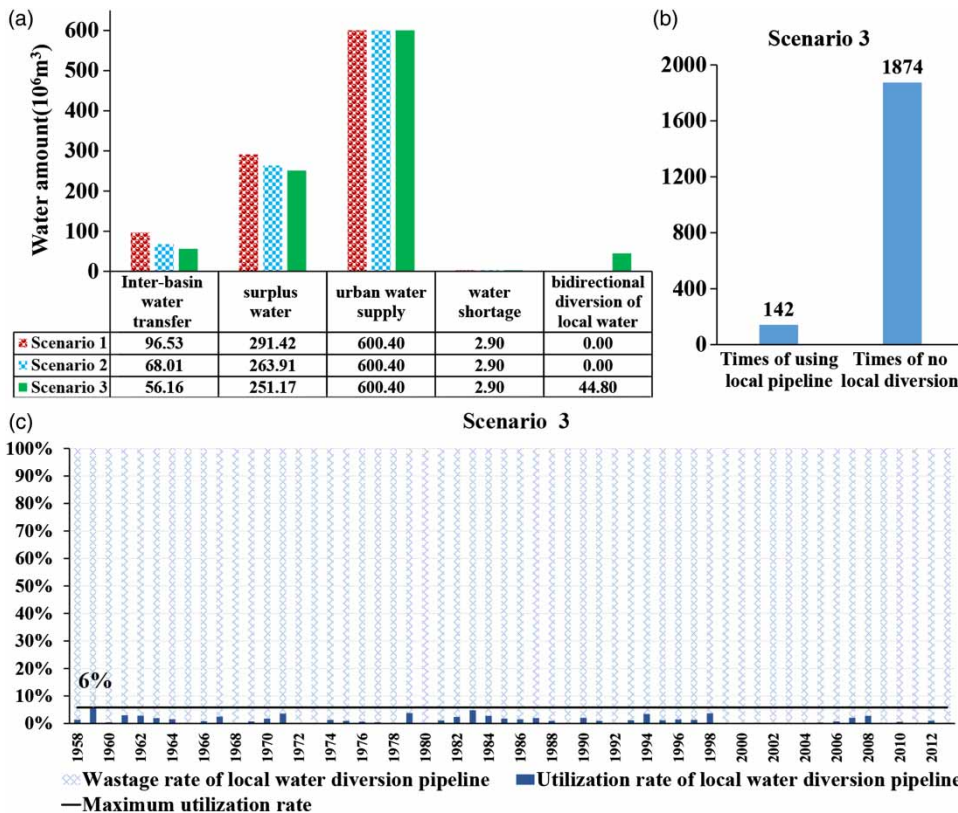


Figure 3 | Comparison of simulating operation results.

occurs in 142 periods, accounting for 7.04% of all operation periods (2016 periods). (From Figure 3(c), we can see clearly that the annual utilization rate of each year's diversion pipeline between Biliuhe reservoir and Yingnahe reservoir is no more than 6% in terms of water volume). Remarks: The maximum water diversion 95.94 m³/s derived from the simulation optimization process is assumed as the pipeline delivery capability in calculating the utilization rate of local water diversion pipeline. The benefits achieved by building the pipeline have to be taken into consideration in the trade-off analysis with the issues described above.

CONCLUSIONS

This paper proposes the use of the multi-objective analysis approach for analyzing the benefits of water transfer between Biliuhe reservoir and Yingnahe reservoir. Multi-objective analysis is based on reservoir operation considering the role of the storage capacity of reservoirs through a joint operation of relevant reservoirs. And this approach mainly uses interactive visual analytics to compare the Pareto-optimal trade-offs under three scenarios, i.e., a scenario with no connection, virtual connection, and pipeline connection between two reservoirs. The results show that: (1) the virtual connection and pipeline connection scenarios can reduce the amount of diverted water from other regions, and decrease water spills compared with the no connection scenario; (2) the pipeline connection scenario can attain relatively more benefits than the virtual connection scenario for the two reservoirs in reducing the amount of diverted water and water spills; (3) the pipeline connection scenario has some issues such as additional engineering cost and low utilization rate of the diversion pipeline.

The approach applied in this paper is a new way to analyze the benefits of water transfers. It considers the role of the storage capacity of reservoirs through a joint operation of relevant reservoirs. This approach could be used at the planning stage of water transfer projects for informed decision making. However, this approach has shortcomings as it puts the emphasis upon feasibility study from water amount, instead of cost, which is always discussed in a feasibility study. Thus, future work will involve further analysis with cost considered.

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