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Bilevel model for multi-reservoir operating policy in inter-basin water transfer-supply project

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ABSTRACT

The purpose of this paper is to propose a bilevel model and a set of water-transfer rule to solve the multi-reservoir operation problem in inter-basin water transfer-supply project. At present, there is very little literature on multi-reservoir operating policy taking water transfer and water supply into consideration at the same time, especially very little study on water-transfer rule. In this study, a bilevel model is presented to consider water transfer and water supply together, in view of the hierarchical structure of the problem, which renders this problem unsuitable for modeling by conventional method. The multi-reservoir system manager, at the upper level of the hierarchy, optimizes water-transfer rule curves to allocate trans-boundary water resources spatially. And the individual reservoir manager, at the lower level, pursues the best water supply accompanying the action of water transfer by optimizing hedging rule curves. The East-to-West inter-basin water transfer project of Liaoning province in China is taken as a case study. The results indicate that the proposed bilevel model and water-transfer rule are reasonable and suitable to deal with the multi-reservoir water transfer-supply operation problem.

1. Introduction

The uneven distribution of water resources and imbalanced water demand in different regions make it inevitable to construct an inter-basin water transfer (IBWT) project across regional boundaries. Creation of storage and inter-basin transfer of water from surplus to deficit regions are rational options to overcome the problems caused by the mismatch of supply and demands, which can increase the resilience of the water system and decrease the risk of shortages (Jain et al., 2007).

Presently, the research on IBWT mainly focuses on optimal allocation of transferable water resources (Sadegh et al., 2010), alternative evaluation (Matete and Hassan, 2006; Li et al., 2009), uncertainty analysis (Dosi and Moretto, 1994; Chen and Chang, 2010), strategic choice methodology in conflicts over water resources management by IBWT (Carvalho and Magrini, 2006), hydrological impact (Bonacci and Andric, 2010) and inter-basin water transfer-supply model (Xi et al., 2010). For example, Sadegh et al. (2010) developed a new methodology based on crisp and fuzzy Shapley games for optimal allocation of inter-basin water resources. Matete and Hassan (2006) proposed a generalized analytical framework that can be applied to integrate environmental sustainability aspects into economic development planning in the case of exploiting water resources through IBWT. Li et al. (2009) presented a new optimization method using fuzzy pattern recognition to appraise the water-supply decision schemes in inter-basin diversion systems. Dosi and Moretto (1994) investigated the storage capacity and optimal guaranteed deliveries in IBWT, taking into account the uncertain nature of water surplus. Chen and Chang (2010) used fuzzy sets for incorporating objective and subjective uncertainties to address the complexity in determining water resources redistribution alternatives in a trans-boundary channel-reservoir system. Carvalho and Magrini (2006) analyzed the application of the strategic choice methodology in a dispute over transferring water between two river basins. Bonacci and Andric (2010) described the hydrological changes of two rivers caused by IBWT and reservoir development. Xi et al. (2010) developed a new inter-basin water transfer-supply and risk assessment model with consideration of rainfall forecast information.

As the most important facilities in IBWT project, reservoirs play an important role in storing and regulating water resources to meet certain requirements. The above review of previous work indicates that the interest of researchers on IBWT has spread widely throughout many respects, but there has been limited study on multi-reservoir operating policy in IBWT project, especially on the water-transfer rule. In this paper, a set of water-transfer rule is proposed to direct the system manager under what condition to transfer water from the abundant to scare regions.

Regarding the reservoir operating rule for water supply, there has been much research and several types of reservoir operating

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rules have been proposed and discussed. Among these policies, the Standard Operating Policy (SOP) is a simple and the most often used operating policy. According to the SOP, reservoirs release as much water as they can provide to meet the target delivery. The SOP is the optimal operating policy with an objective to minimize the total deficit over the time horizon (Stedinger, 1984). Besides, different forms of the Linear Decision Rule (LDR) are also applied widely in the practical operation of reservoirs. The LDR is formulated to assume the releases linearly related to storage and decision parameters and is usually optimized with linear programming (ReVelle et al., 1969). Hedging rule, normally used for rationing the water supply during droughts, distributes deficits over a longer horizon to improve the efficiency of reservoir operation (Shih and ReVelle, 1994; Neelakantan and Pundarikanthan, 2000). During periods of drought, system managers would rather incur a sequence of smaller shortages in water supply than one potential catastrophic shortage (Lund and Reed, 1995). Due to its good ability to deal with reservoir operation problem during droughts, hedging rule has attracted much attention of researchers. (You and Cai, 2008a,b; Bayazit and Unal, 1990; Shiau, 2011; Draper and Lund, 2004). In this paper, hedging rule is adopted in the form of hedging rule curves for individual reservoirs in IBWT project to control their releases.

About multi-reservoir operation model, many advances in this area have been made during recent years. A lot of optimization methods are designed and applied to prevail over the high-dimension, dynamic, nonlinear, multi-objective and stochastic characteristics of reservoir systems (Labadie, 2004), which include implicit stochastic optimization, explicit stochastic optimization, real-time control with forecasting, and heuristic programming models. Increased application of heuristic programming to be linked directly with trusted simulation models is a great advantage. Fuzzy rule-based systems and neural networks may alleviate the difficulty in inferring operating policies from implicit stochastic optimization models. The detailed work and recent advancement on optimal operation of multi-reservoir system are scrutinized by Labadie (2004).

Despite great advances on the study of reservoir operation, it can be observed, from the above review, that the problems of multi-reservoir water supply and water transfer in IBWT project have seldom been taken into consideration together. This may influence the utilization efficiency of water resources, because an improper water transfer will not only bring negative effect on the water supply of the reservoir(s) in water-exporting region but also can increase water spills of the reservoir(s) in water-importing region. Therefore, the water-supply rule in IBWT project should match up with the water-transfer rule and both of them are ought to be considered at the same time.

For multi-reservoir operation problem in inter-basin water transfer-supply project, it involves decision makers at two distinct levels with a hierarchical relationship between them. The decision process involves two different decision makers, who represent the multi-reservoir system manager in charge of water transfer and the individual reservoir manager in charge of water supply, respectively. The system manager, which is at the upper level of the hierarchy, controls the distribution of water resources among water exporting and importing regions using a set of water-transfer rule. The individual reservoir manager, at the lower level of the hierarchy, controls the water-supply process by hedging rule, which is influenced by the decision of the upper decision-maker. Both, in general, do not cooperate because of different optimization purposes. These characteristics make this problem unsuitable for modeling by standard mathematical programming. They are more likely to be modeled using bilevel programming (BLP), which has been proposed in the literature as an appropriate model for hierarchical decision processes with two non-cooperative decision makers, the leader at the upper level of the hierarchy and the follower at the lower level (Calvete et al., 2011).

This paper proposes a bilevel programming model for multi-reservoir operating policy in inter-basin water transfer-supply project. And a set of water-transfer rule based on the storage of individual reservoir in the system is presented in this study. In this bilevel programming model, the leader wants to allocate trans-boundary water resources in accordance with the planned water transfer amount to satisfy water demand in every region and to reduce water spills of the system. The follower pursues the best water supply; meanwhile, the action of water transfer occurs. In other words, the objective of the leader is to minimize both the system water spills and the deviation of the actual transferred water from the water-transfer target. The objective of the follower is to minimize water shortage or maximize the amount of water supply. The water-transfer rule curves are decision variables of the leader in the hierarchical process, which determine the conditions to start water transfer or not. Besides, hedging rule curves are decision variables of the follower, which relate to some indexes reflecting water-supply efficiency. An improved particle swarm optimization algorithm (IPSO) proposed by Jiang et al. (2007) is adopted in this paper to solve the bilevel model. The East-to-West inter-basin water transfer project of Liaoning province in China is taken as a case study to verify the reasonability and efficiency of the proposed bilevel model and the water-transfer rule.

2. Bilevel optimization model

Decision-making in most real life problems fits within the framework of a leader–follower or Stackelberg game (Stackelberg, 1952). Such a game can be expressed mathematically by bilevel model, which has been proposed for dealing with decision process involving two decision makers with a hierarchical structure, the leader at the upper level and the follower at the lower level. Each decision maker controls a set of variables subject to a set of constraints and seeks to optimize his own objective function. Once the leader sets the value of his variables, the follower reacts by providing the value of his controlled variables and optimizes his objective function. In general, the leader can influence but can not control the behaviors of the follower. The goal of the leader is to optimize his objective function and incorporate the reaction of the follower to the leader's course of action within the optimization scheme. In other words, the leader optimizes his objective function taking into account his own constraints and the reaction of the follower, who has the freedom of choosing his best decision (Calvete et al., 2011). General bilevel optimization model can be formulated as

$$\begin{aligned} &\min_{x} \quad F(x,y) \\ &s.t. \quad G(x,y) \leqslant 0 \\ &\min_{y} \quad f(x,y) \\ &s.t. \quad g(x,y) \leqslant 0 \end{aligned} \tag{1}$$

where F is objective function of the upper-level decision maker (system manger); x is decision vector of the upper-level decision maker; G is constraint set of the upper-level decision vector; f is objective function of the lower-level decision maker; y is decision vector of the lower-level decision maker; g is constraint set of the lower-level decision vector.

It can be observed that many decision-making problems in real life can be described as Stackelberg game. Therefore, bilevel programming model has been widely used to deal with such practical problems as transportation control and management (Yang and Bell, 2001), production–distribution planning (Calvete et al., 2011), pricing control (Marcotte et al., 2009) and aid in specification