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Dynamic equilibrium strategy for drought emergency temporary water transfer and allocation management

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SUMMARY

Efficient water transfer and allocation are critical for disaster mitigation in drought emergencies. This is especially important when the different interests of the multiple decision makers and the fluctuating water resource supply and demand simultaneously cause space and time conflicts. To achieve more effective and efficient water transfers and allocations, this paper proposes a novel optimization method with an integrated bi-level structure and a dynamic strategy, in which the bi-level structure works to deal with space dimension conflicts in drought emergencies, and the dynamic strategy is used to deal with time dimension conflicts. Combining these two optimization methods, however, makes calculation complex, so an integrated interactive fuzzy program and a PSO-POA are combined to develop a hybrid-heuristic algorithm. The successful application of the proposed model in a real world case region demonstrates its practicality and efficiency. Dynamic cooperation between multiple reservoirs under the coordination of a global regulator reflects the model's efficiency and effectiveness in drought emergency water transfer and allocation, especially in a fluctuating environment. On this basis, some corresponding management recommendations are proposed to improve practical operations.

1. Introduction

Drought can be a disastrous environmental disaster (Dai, 2011; Van Loon and Laaha, 2015) which in turn can lead to significant economic losses (e.g. crop failure and reduced productivity Riebsame et al., 1991), societal problems (e.g. increased mortality and conflicts Hsiang et al., 2013) and ecological impacts (e.g. forest diebacks and impact on aquatic ecosystems Choat et al., 2012). Due to population growth and expansion in the agricultural, energy and industrial sectors, the demand for water has increased dramatically over the last few decades, so water scarcity has become as major problem in many parts of the world (Mishra and Singh, 2010). To mitigate disaster and damages, water drought emergency resource operations are needed. The 2012 drought in Russia had a major effect on agricultural production with grain harvests down almost 25 per cent, higher food prices, and significant economic damage to farmers in 22 regions, all of which could have been reduced with the guidance and support from regional and federal governments Bobylev and Kiselev (2012). The Salton Sea, California's largest lake, is shrinking due to long-term urban water transfers. In 2014, southeast Brazil suffered a severe drought, with conflict arising between water users in the Sao Paulo region, which relies on inter-basin water transfers from the neighboring Piracicaba, Capivari, and Jundiai river basins to supply nearly half its drinking water. From these examples, it can be seen that for effective drought mitigation, the efficiency, equity and sustainability of water management operations in drought conditions still need to be improved.

Many studies have focused on solving drought emergency problems through rational water allocation. Randall et al. (1990) developed a multi-objective linear program to study the operation of a metropolitan water supply system during drought. Michelsen and Young (1993) built an integrated hydrologic-economic model for optional agricultural water rights for urban water supplies during drought. Shih and ReVelle (1994, 1995) respectively described a linear continuous hedging rule and a discrete hedging rule for water demand management during drought or impending drought and built a mixed integer programming model that controlled the reservoir water supply through discrete rationing phases. Lund (2006) developed a simple drought storage allocation rule to minimize evaporative and seepage water losses from a system of reservoirs. Wang et al. (2012) proposed a water resources management

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strategy for adaptation to droughts in China and developed a typical relationship between socio-economic development and water resources management strategies to attain water management sustainability. Chang and Wang (2013) proposed a systematic water allocation scheme, which integrated systems analysis with artificial intelligence techniques to mitigate drought threats. The above studies have tended to focus on optimal water allocation under a closed-loop environment. However, relying on internal self-regulation is not effective when a drought is so severe that the water resources are unable to meet local minimum demand, production or daily living requirements, thereby putting human lives and health at risk. Under these circumstances, water transfers can significantly mitigate the drought effect (Guo et al., 2012). Therefore, severe drought emergency management requires a rational water transfer and allocation strategy for drought mitigation. With this focus in mind, in this paper, a drought emergency water transfer and allocation problem (DEWTAP) is studied and solutions developed.

In the DEWTAP, two kinds of reservoirs need to be considered: donor reservoirs, which supply water resources to drought areas, and recipient reservoirs, which are in the areas affected by the drought. This paper mainly focuses on the problem of multi-donor reservoirs and one recipient reservoir because of the complexity of the practical problems and the difficulty in finding a solution. Multi-reservoir water transfer operations involve a hierarchical relationship between decision makers on two distinct levels (Guo et al., 2012). The decision process involves two decision makers (DMs): the multi-reservoir manager (MRM) responsible for water transfer, and the individual reservoir managers (IRMs) responsible for water allocation in response to the MRM's decision. In these circumstances, there is a water transfer space conflict due to the different interests of the multiple DMs, whereby the MRM pursues optimization in the overall interest and the IRMs each seek to maximize their own interests. Cooperative bi-level programming (BLP) with multi-objective programming to seek the equilibrium in the space dimension is able to solve this DM conflict based on the leader–follower relationship (Vicente and Calamai, 1994; Chang and Mackett, 2006; Sun et al., 2008). Further, water transfers differ under normal circumstances and under the DEWTAP, because of the disaster relief objective that there are strict water supply times and water transfer efficiency requirements for the recipient reservoirs. However, substantial reservoir storage level fluctuations are not conducive to daily reservoir management for the donor reservoirs and, in practice, reservoir storage levels are influenced by the external environment: climatic changes and stream flow fluctuations. Managers, therefore, need to adjust the transfer and allocation plans to ensure the reservoirs maintain a reasonable storage level and guarantee the daily water supply. To effectively control the water transfer and allocation operations to guarantee timely water supplies to the drought affected recipient reservoir and ensure the stability of the donor reservoirs, this paper adopts dynamic programming (DP) to solve the time conflicts.

Based on the above description, this paper builds a bi-level dynamic multi-objective model to solve the DEWTAP, which encompasses both space and time dimensions. As the mathematical model is intrinsically difficult and the model is nonlinear and nondifferentiable, traditional exact methods are not suitable. Lai (1996) and Shih et al. (1996) proposed a solution for problems where the decisions on all levels are sequential and all DMs essentially cooperate with each other, which was different from the Stackelberg solution concept. The method was based on the idea that the DMs on the lower level optimize their objective function and take the goals or preferences of the upper level into consideration. This method has been further developed for two level linear (Sakawa et al., 1998) and linear fractional programming problems (Sakawa and Nishizaki, 2001) and has been successfully applied to practical problems (Sakawa et al., 2001). Shih and Lee (2000) further extended Lai's concept by introducing a compensatory fuzzy operator for solving multi-level programming problems. Sinha (2003a,b) studied an alternative BLP technique based on fuzzy mathematical programming. Pramanik and Roy (2007) extended goal programming multi-objective decision making problems introduced by Mohamed (1997) to solve MLPPs. In Shi and Xia (1997), an interactive algorithm for bi-level multi-objective programming was presented and explained using the satisfactoriness concept. Basu (2004) presented an interactive fuzzy satisfying method based on an evolutionary programming technique for short-term multi-objective hydrothermal scheduling. Sakawa and Nishizaki (2009) developed the interactive fuzzy programming to solve multi-objective two-level linear programming. Therefore, this paper applies interactive fuzzy programming to convert the bi-level multi-objective problem into a single level and a single objective model. Then, because the transferred model is still complex and difficult to calculate using an exact algorithm, a Particle Swarm Optimization (PSO) integrated with a Progressive Optimality Algorithm (POA) is adopted to solve the nonlinear dynamic model.

Based on the above discussion, this paper proposes an optimization model that integrates a water transfer strategy and corresponding water allocation strategies to mitigate sudden drought. In Section 2, the methodology reservoir managers use to mitigate drought through water transfer and water allocation, the water transfer space conflict due to the multiple decision makers, and the water transfer and allocation time conflicts due to the fluctuant environment are explained in preparation for the establishment of the mathematical model. Then, as an abstraction of the real problem, a bi-level dynamic multi-objective model is built based on the discussion and a PSO-POA based on the interactive fuzzy programming is applied in Section 3. In Section 4, a case study is presented to demonstrate the significance of the proposed model and solution method. A comparative study and some management recommendations are given in Section 5. Conclusions and future research directions are given in Section 6.

2. Methodology

2.1. Description for the key problem of DEWTAP

The DEWTAP aims to find an optimal water resource transfer and allocation plan for drought affected areas to mitigate drought damage. There are two conflicts in this DEWTAP that need to be solved: the water transfer space conflict and the water transfer and allocation time conflict (see Fig. 1). Firstly, this paper considers a multi-reservoir system which has an MRM in charge of developing the water transfer strategy to mitigate drought and IRMs in charge of deciding on their own water allocations. Water transfer is required to supply adequate water resources for drought-affected areas to mitigate damage, but donor reservoirs also need adequate water resources to maintain normal production. However, as the water resources are limited, the MRM cannot give special treatment to only one reservoir over the others as total losses are comprised of all losses from each individual reservoir. Therefore, the MRM water transfer has a space conflict.

Effective drought mitigation of drought affected reservoir depends on a continuous water supply during the drought. Reservoir storage stability and continuous donor reservoir daily water supplies must also be guaranteed. However, the stream flow in each basin changes significantly from the wet season to the dry season. For the MRM, transferring the same water resources early would give timely drought relief, but could bring risks to the donor