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Integrated optimal allocation model for complex adaptive system of water resources management (I): Methodologies

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SUMMARY

Due to the adaption, dynamic and multi-objective characteristics of complex water resources system, it is a considerable challenge to manage water resources in an efficient, equitable and sustainable way. An integrated optimal allocation model is proposed for complex adaptive system of water resources management. The model consists of three modules: (1) an agent-based module for revealing evolution mechanism of complex adaptive system using agent-based, system dynamic and non-dominated sorting genetic algorithm II methods, (2) an optimal module for deriving decision set of water resources allocation using multi-objective genetic algorithm, and (3) a multi-objective evaluation module for evaluating the efficiency of the optimal module and selecting the optimal water resources allocation scheme using project pursuit method. This study has provided a theoretical framework for adaptive allocation, dynamic allocation and multi-objective optimization for a complex adaptive system of water resources management.

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1. Introduction

Water resources play an important role in the development of socioeconomic and environmental system. Because water resources are dynamic interactions and adaptations with related socioeconomic and environmental factors, water resources allocation is a complex adaptive problem involving population, economy, environment, ecology and policy, etc. (Singh, 2014). The optimal water resources allocation literature mainly treated one or more of the following three elements: (1) complex adaptive allocation of water resources, (2) dynamic allocation of water resources and (3) multi-objective optimization of water resources allocation.

The agent-based on genetic algorithm, i.e., intelligent agent or adaptive agent is one approach that can help decision makers build a complex adaptive model for water resources allocation (Galán et al., 2009; Ng et al., 2011). Zhao et al. (2004) proposed a complex adaptive model for water resources allocation based on genetic algorithm and agent-based. The model was used to analyze the rational amount of diversion water for the West Line of Water Transfer Project from South China to North China and its utilization benefit. Berger et al. (2007) applied multi-agent simulation to capture the complex adaptation of multiple users and their socio-economic implications within water resources management. Yang et al. (2009) presented a decentralized optimization algorithm for water shed management based on multi-agent simulation with outer river human agent, inner river human agent and ecological agent. Chu et al. (2009) developed an agent-based simulation to capture the complex characteristics of residential water usage. Rieker and Labadie (2012) explored an intelligent agent for optimization of complex river-reservoir system management and long-term operation. Akhbari and Grigg (2013) introduced an agent-based model to resolve and mitigate conflicts of parties participating in water resources management. Giuliani and Castelletti (2013) used multi-agent simulation to model and analyze different levels of cooperation and information exchange among multiple decision makers in order to allow the downstream agents to better adapt to the upstream behaviors in water resource system. Ni et al. (2014) applied an agent-based model to deal with water resources optimal allocation based on genetic algorithm. Yuan et al. (2014) developed an agent-based model for prediction of urban household

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water demand so as to simulate stochastic behavior and feedbacks caused by administrative agent and domestic agent.

System dynamic (SD) is a well-known methodology that supplies a theoretical framework and concepts for modelling dynamic allocation of water resources (Forrester, 1958; Ahmad and Simonovic, 2004; Feng et al., 2008; Willuweit and O'Sullivan, 2013; Hoekema and Sridhar, 2013). An overview of general dynamic allocation models for water resources has been summarized by Winz et al. (2009). Yang et al. (2008) applied SD to seek a balance between mitigating water shortages and total financial cost in water resources management. Zhang et al. (2008) developed a SD model for making decision on water resources allocation and management. Zhang et al. (2009) developed an integrated dynamic model of water consumption based on SD and water resources carrying capacity theory. Gastélum et al. (2010) explored a SD model for water right transfer with regards to the degree of complexity and uncertainty of the water right allocation process to different economic variables. Rehan et al. (2013) developed a SD model for financially sustainable management of urban water distribution networks. Akhtar et al. (2013) applied SD simulation to present comprehensive response of the society–biosphere –climate–economy–energy system by considering climate, carbon cycle, land use, population, food production, hydrologic cycle, water demand, water quality and energy–economy. Chen and Wei (2014) applied SD method to research on water security including flood security, water resources security, carrying capacity, water environment security. Wang et al. (2014) used a complex system dynamic model to study relationship among population growth, economic development, climate change, management strategies and water resources, and identify the best management strategy to adapt with the changing environment.

The multi-objective algorithm and multi-objective evaluation are alternative methods in solving multi-objective optimization of water resources allocation (Nicklow et al., 2009; Singh, 2014). Nayak and Panda (2001) used multi-objective evaluation to solving water resources allocation for water manager and decision-makers. Srdjevic et al. (2004) used an integrated simulation operation, system performance indices and multi-objective evaluation model to simulate operation of reservoir system. Castelletti et al. (2008) used multi-objective decision to cope with the preference and subjective aspects of the water resources allocation. Shourian et al. (2008) used a multi-objective model to allocate water resources optimally over time and space among competing demands based on particle swarm optimization algorithm. Chang et al. (2009) proposed an integrated multi-objective model for regional water resources allocation and planning problem based on multi-objective genetic algorithm and operating rules. Kilic and Anac (2010) developed a multi-objective planning model for large scale irrigation system in order to increase the benefit from production, increase the size of the total area irrigated and reduce the water losses. Kim and Chung (2013) developed a multi-objective evaluation model for assessing climate change vulnerability of water resources management. Hou et al. (2014) used a multi-objective optimization model for maximizing benefit to the economy, society and environment in water resources allocation. Nouiri (2014) used multi-objective genetic algorithm and Pareto optimality concept to optimize daily management schedule of hydraulic system. Roozbahani et al. (2014) proposed a multi-objective optimization model for sharing water among stakeholders of a trans boundary river by transforming the multi-objective problem to a three-step single objective problem.

This study is an integrated optimal allocation model of complex adaptive allocation, dynamic allocation and multi-objective optimization, focusing on complex adaptive management of water resources allocation. The paper is organized as follows: Section 2 describes the method adopted in this study, which comprises three parts: introduction of a general framework of integrated optimal allocation model by firstly setup an agent-based module (Section 2.1), secondly setup an optimal module (Section 2.2), and finally setup a multi-objective evaluation module (Section 2.3). The conclusions are drawn in Section 3.

2. Development of methodology

The integrated optimal allocation model (IOAM) for complex adaptive system (CAS) of water resources management consists of following three separately modules: (1) an agent-based module, (2) an optimal module including multi-objective function, constraints and algorithm, and (3) an evaluation module consisting of multi-objective evaluation indices as well as projection pursuit method. The structure of the IOAM is described in Fig. 1. The details of each module are given as follows.

2.1. Agent-based module

Due to the dynamic, multi-objective, multi-reaction and adaption characteristics of CAS of water resources management, SD, agent-based and non-dominated sorting genetic algorithm II (NSGA-II) are used to reveal evolution mechanism of CAS.

2.1.1. Evolution mechanism of CAS

The procedures of applying SD, agent-based and NSGA-II to revealing evolution mechanism of CAS are shown in Fig. 2. CAS of water resources management consists of administrative agent, water supply agent (including reservoir and hydropower station agent), water user agent (including industrial production water agent, agricultural production water agent, domestic water agent, reservoir and hydropower station agent as well as ecological water agent), sewage treatment agent (Zhao et al., 2004). Because functions of reservoir and hydropower station are mainly included flood control, water supply, power generation as well as navigation, etc., reservoir is both water supplier and water user. The details of evolution mechanism of CAS are described as follows:

(1) The planning strategies of society and economy development including population, economy, agriculture and ecology are formulated by administrative agent as well as transmitted to water user agents.
(2) Water demand of water user is predicted by inner stimulus–response of agent and outer feedback relationship between agents based on SD, when the planning strategies of economic and social development are transmitted to water user agents.
(3) Preliminary water supply strategy is formulated by administrative agent and transmitted to reservoir and hydropower station agent according to feedback information of water demand simulated by SD.
(4) Water supply and storage of reservoir as well as hydropower station agent is simulated by inner stimulus–response of agent and outer feedback relationship between agents based on SD according to reservoir operating rules and storage, and then that information is fed back to administrative agent.
(5) The preliminary water supply strategies are simulated by reservoir operation and transmitted to water user agents, at the same time, utilization benefit and sewage discharge of water user agent simulated by SD is fed back to administrative agent and sewage treatment agent, respectively.
(6) Sewage treatment agent is simulated by SD and fed back to administrative agent.

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