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Equitable and reasonable freshwater allocation based on a multi-criteria decision making approach with hydrologically constrained bankruptcy rules

Yong Zeng[a,b], Jiangbin Li[b], Yanpeng Cai[c,d,e,*], Qian Tan[f]

[a] State Key Laboratory of Petroleum Resource and Prospecting, College of Geosciences, China Petroleum University, Beijing, 102249, China
[b] UNBC, University of North British Columbia, V2N 4Z9, Canada
[c] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing, 100875, China
[d] Institute for Energy, Environment and Sustainable Communities, University of Regina, 120, 2 Research Drive, Regina, Saskatchewan, S4S 7H9, Canada
[e] Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, School of Environment, Beijing Normal University, Beijing 100875, China
[f] School of Water Resources & Civil Engineering, China Agriculture University, Beijing 100083, China

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ABSTRACT

Effective water allocation among multiple jurisdictions is a key instrument to improve water use efficiency within the basin scale. To achieve equitable and reasonable water allocation, natural, socio-economic, and ecological conditions within a specific basin need to be systematically considered. Based on the main principles of equitable and reasonable water allocation that were defined by UN Watercourses Convention, an integrated multi-criteria decision making (MCDM) with bankruptcy rules (IMCDM-BR) under multiple hydrological constraints were proposed to allocate trans-jurisdiction water resources in Guanting reservoir basin (GRB), a shared basin between Zhangjiakou and Beijing in China. Projection pursuit (PP), as one of an effective MCDM approach, was employed to synthesize values of the related principles, which were ranked as weights for the corresponding water claims by relevant agents. Then, the weighted bankruptcy rules (BR) with multiple hydrological constraints were applied to allocate water among the related agents of the studying basin. The results of ordinary bankruptcy rules, bankruptcy rules with regular and hydrological constraints, and the proposed methods were compared and discussed. Among them, the proposed IMCDM-BR was recommended as an effective tool to support practical water allocation. Moreover, factors of equitable and reasonable water allocation were comprehensively considered. The results can thus be used for facilitating negotiation in trans-jurisdiction water allocation among agents within basins.

1. Introduction

In the past decades, rapid population growth, intensive urbanization, and increasing agricultural activities, as well as climate change disturbance are posing continuous challenges to sustainable water resources supply across the world. At the same time, freshwater is inherently a public resource that does not respect any human-defined boundaries (Cai et al., 2009a,b, 2010; Wei et al., 2010). Thus, water shortage together with uneven distribution within a watershed are causing intensive conflicts, endangering water utilization sustainability. For instance, in 1997, the Yellow River, the second largest river in China, was dried up for 227 days and no water reached the sea for over 330 days due to increasing freshwater consumptions and decreasing runoff (Liu and Zhang, 2002; Tan et al., 2011). Obviously, water shortage, mainly due to uncontrolled water withdraw and increasing freshwater demands, has emerged as a main limiting factor for economic development and ecological protection (Tang et al., 2015). Therefore, it is desired to propose effective tools for dealing with water resources allocation in an equitable and reasonable manner, particularly in many water-scarcity regions of countries with recent economic prosperity such as China.

Over the last few decades, many demand management policies involving water pricing, water right assignment, and water market establishment have received increasing attention to alleviate

* Corresponding author at: State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China.
E-mail address: yanpeng.cai@bnu.edu.cn (Y. Cai).

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potential water conflicts among multi-level governmental jurisdictions (Dinar and Subramanian, 1997). Among them, water right assignment and allocation is considered as an effective measure to deal with water shortage and the associated conflicts. It is also regarded as a prerequisite for the formation of a water market with a variety of cooperative game solutions, which is a key water management instrument to improve water use efficiency (Zheng et al., 2012). Well-defined water rights could effectively help allocate water resources to multiple stakeholders within and/or across boundaries (Kucukmehetoglu, 2009). Generally, there are three major ways to define and introduce water rights within a specific watershed or region, covering riparian, prior (appropriative), and public rights (Van der Zaag et al., 2002). The former two ways were originally initiated in UK and western US (Wurbs, 1997). At the same time, many countries in addition to UK and US took the public right as an alternative, in which water can be defined as a public property with states or basins as its owner. Normally, such water rights were administratively allocated to users through water permits from the up-level governments. Wang et al. (2003, 2007) proposed three methods for supporting water right allocation, including priority-based maximal multi-period network flow programming, modified riparian water rights allocation approach, and lexicographic mini-max water shortage ratios for initial water rights allocation.

The weakness of previous principles adopted in water rights allocation lay in the fact that there were no internationally accepted attributes and mechanisms for equitable allocation of public shared water resources (Wolf, 1999). Normally, each agent would prefer the criteria or principles that the most supported his claims, causing many potential conflicts. Previously, there were many principles in assessing public water right allocation policies, including principles originating from international environmental and water resources laws, such as a) absolute sovereignty, b) absolute riverine integrity, c) limited territorial sovereignty, and d) economic criteria (Wolf, 1999; Giordano and Wolf, 2001). Besides, principles of equity, efficiency and sustainability for water use were issued in the 1992 report of the United Nations Conference on Environment and Development. Sandoval-Solis et al. (2011) presented a water resources sustainability index, which included Performance Criteria, such as Reliability, Resilience, Vulnerability, Standard Deviation, and Maximum Deficit, to evaluate different water management policies with respect to their sustainability. Sustainability indices formulation strategy, scaling, normalization, weighting and aggregation methodology can be seen in a review of sustainability assessment methodologies by Rajesh et al. (2012).The other principles similar to sustainable water use came from international water laws as the Helsinki Rules according to the UN Watercourses Convention (1997), and the Berlin Rules (Mianabadi et al., 2015). These rules all accepted that utilization of public shared water resources should be undertaken in an "equitable" and "reasonable" manner that would take into account of relevant geographic, hydrological, climatic, demographic, social and economic factors. According to the UN Watercourses Convention (1997), equitable and reasonable utilization can be achieved taking into account the factors that define the needs and the natural conditions of the studied basin. Contrasting to sustainable water allocation, Equitable and reasonable water allocation has been addressed merely in recent years for its convenience in interpreting the selected factors in a quantitative way. Mimi and Sawalhi (2003) analyzed criteria of international water laws through the adoption of multi-criteria decision making (MCDM) methods and estimated each country's entitlement to water by the weight and the value of each indicator in water allocation of Jordan River Basin. Based on their works, Kampragou et al. (2007) included water quality and ecological criteria within the indicator system to enhance its credibility and integration. Advantage of the applied tools was the their applicability, but the calculated allocation was sensitive to changes to indicators values and their weights.

At the same time, a number of studies were conducted based on game theory. There were a lot of published literatures for supporting the allocation of water resources to achieve maximal economic benefits in a river basin based on cooperative game theory and the existing water right agreements (Becker and Easter 1997; Hu et al., 2014; Wu and Whittington 2006; Wang et al., 2008; Eleftheriadou and Mylopoulos, 2008). For example, Wu and Whittington (2006) proposed a concept of cooperative games to solve Nile water conflicts and identify incentive-compatible cooperative results. Kucukmehetoglu (2009, 2012), Kucukmehmetoglu and Guldmann (2010) conducted research on the Euphrates and the Tigris River to identify grand coalitions for dealing with water conflicts through the employment of multi-objective programming approaches, and cooperative game theory. Yang et al. (2008) recommended status quo water use of each involved agent as initial water right allocation in Guanting Reservoir basin. In their study, water uses of non-cooperative strategies were normally considered as initial water rights, where water uses for relevant agents were subsequently satisfied. A similar theory is the negotiation game theory since cooperative solution concepts can be considered as outcomes of a negotiating process. Particularly, the Nash bargaining, Kalai-Smorodinsky, area monotonic, and equal loss solutions were widely employed to identify cooperative solutions (Raquel et al., 2007; Wang et al., 2013). A summary of commonly used non-cooperative and cooperative game theory methods in water resources management was presented by Madani (2010). Though cooperative game theory methods can maximize social welfare of an entire basin, most of research reports neglected "equitable" and "reasonable" for water allocation. This may put many stakeholders in unfair positions especially for the downstream since the upstream may have advantages in accessing the shared water resources. Another problem is that maximizing the net monetary benefits from utilizing water for economic activities does not fully reflect equitable and reasonable in many cases (Mianabadi et al., 2015). The third problem lies in difficulties in constructing and solving water allocation models during a cooperative allocation, in which lots of hydrological, economic and ecological data are necessarily required. The third category is bankruptcy rules methods, which originated from a fundamental research by O'Neill (1982). It represents a fair division of asset or a common resource (E) among many creditors (C) when their claims exceed assets (E) (Mianabadi et al., 2015). Over the past years, a number of division rules, extensions and generalizations have been developed (Thomson 2003; Sechi and Zucca 2015; Oftadeh et al., 2016). The mostly used rules were proportional (PRO), constrained equal losses (CEL), and constrained equal awards (CEA) rules. An overview of bankruptcy rules were documented by Thomson (2003). Generally, such bankruptcy rules could also be considered as a form of cooperative games (Aumann and Maschler 1985; Olvera-Lopez et al., 2014). It could provide solutions that were more useful than solutions of conventional cooperative game theory when the information about utilities of the related agents or their endowments were missing or unreliable (Zarezadeh et al., 2012).

A water share problem may differ from an ordinary bankruptcy one, where geographical positions of the involved agents are of major concerns. Besides, the agent's contribution to runoff within its terrestrial domains should be considered in the final allocation. Ansink and Weikard (2012) proposed sequential sharing rules for river sharing problems. Mianabadi et al. (2014) developed bankruptcy rules that considered agents' contribution to the total resources as well as their corresponding claims. However, it is not appropriate if the agents did not have upstream and downstream positions, such as in the case of reallocation of lake of water or reservoirs within a shared area of a specific water-