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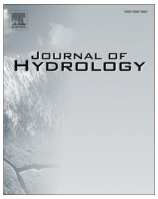

Hydroeconomic optimization of reservoir management under downstream water quality constraints

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SUMMARY

A hydroeconomic optimization approach is used to guide water management in a Chinese river basin with the objectives of meeting water quantity and water quality constraints, in line with the China 2011 No. 1 Policy Document and 2015 Ten-point Water Plan. The proposed modeling framework couples water quantity and water quality management and minimizes the total costs over a planning period assuming stochastic future runoff. The outcome includes cost-optimal reservoir releases, groundwater pumping, water allocation, wastewater treatments and water curtailments. The optimization model uses a variant of stochastic dynamic programming known as the water value method. Nonlinearity arising from the water quality constraints is handled with an effective hybrid method combining genetic algorithms and linear programming. Untreated pollutant loads are represented by biochemical oxygen demand (BOD), and the resulting minimum dissolved oxygen (DO) concentration is computed with the Streeter–Phelps equation and constrained to match Chinese water quality targets. The baseline water scarcity and operational costs are estimated to 15.6 billion CNY/year. Compliance to water quality grade III causes a relatively low increase to 16.4 billion CNY/year. Dilution plays an important role and increases the share of surface water allocations to users situated furthest downstream in the system. The modeling framework generates decision rules that result in the economically efficient strategy for complying with both water quantity and water quality constraints.

1. Introduction

The North China Plain (NCP) has experienced severe water scarcity and water quality challenges over the past decades as a result of the economic development, population growth and regional climate change (Liu and Xia, 2004; Mo et al., 2013; Zheng et al., 2010). Consequently, the surface water resources are fully utilized, the groundwater aquifers are heavily overexploited to cover the annual deficit in the water budget and the rivers are used as waste water recipients (Brown, 2001; Liu et al., 2001; Xia et al., 2006; Zheng et al., 2010).

In 2011, the Government of P.R. China launched the China 2011 No. 1 Central Policy Document (No. 1 Document, CPC Central Committee and State Council, 2010) and the 2015 Ten-point Water Plan (State Council, 2015), which target the increasing challenges of sustainable management of the Chinese water resources. The implementation of the so-called Strictest Water Resource Management System (SWRMS) is divided into three focus areas known as the Three Red Lines (Ministry of Water Resources, 2012). The Three Red Lines set objectives for (1) reduction of overexploitation of the water resources, (2) efficient use and control of the growing water demands and (3) water quality and pollution control (Ministry of Water Resources, 2012). Similarly to the European Water Framework Directive in the European Union, the No. 1 Document is regarded as one of the most important water policy documents produced by China, and it is expected to significantly change water management in China (Griffiths et al., 2013). Introduction of water markets, water right trading schemes and scarcity-dependent water pricing are suggested as tools to meet the objectives set by

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the No. 1 Document, but no clear-cut guidelines are enforced so far (Griffiths et al., 2013; Yang et al., 2013). Yang et al. (2013) underlined the need for an integrated approach to solve the complex water issues, because focus on a single sector, technology or policy will be insufficient.

In integrated water resources management, the overall objective is to promote coordinated optimal management of the resources, while ensuring economic and ecological sustainability and social equity (Loucks and van Beek, 2005). In this context, hydroeconomic analysis provides a consistent framework for assessing conflicts among competing water uses, by representing the various interests using a common monetary unit (Harou et al., 2009). While hydroeconomic optimization models have been widely applied to water quantity management problems (e.g. Heinz et al., 2007; Pulido-Velázquez et al., 2006; Tilmant et al., 2012) and water quality management problems (e.g. Cools et al., 2011; Hasler et al., 2014), only few studies have addressed optimization of coupled water quantity–quality problems (Ahmadi et al., 2012; Karamouz et al., 2008).

Ejaz and Peralta (1995) presented an optimization–simulation approach based on the response matrix approach. The model framework maximized allocations of surface water and groundwater and waste loads from a sewerage treatment plant to a river, while complying with water quality constraints, such as dissolved oxygen and nutrients. A coupled water allocation (MODSIM) and water quality routing (QUAL2E-UNCAS) simulation-based decision support tool was developed by de Azevedo et al. (2000). Performance measures for water allocation (e.g. reliability) and water quality (e.g. compliance to stream standard) was used to assess performance planning alternatives. Cardwell and Ellis (1993) used stochastic dynamic programming (SDP) to minimize waste water treatment costs, while complying with dissolved oxygen (DO) water quality constraints, in a setup with river reaches as stages, water quality parameters as state variables and water treatment as decision variables. A few studies, such as Hayes et al. (1998) and Kerachian and Karamouz (2007) also include reservoirs, which leads to coupling of decisions in time. Hayes et al. (1998) assessed the impacts of upstream water management changes on river water quality downstream of reservoirs. In this study the hydropower revenue was maximized while the DO concentration, computed from the biochemical oxygen demand (BOD) with the Streeter–Phelps equation, was used as water quality constraint. Cai et al. (2003) applied a hydroeconomic optimization approach, based on a simple decomposition approach, to maximize the sum of irrigation, hydropower and ecological benefit subject to salinity control, for a complex multi-reservoir basin. Kerachian and Karamouz (2007) used a simplified SDP framework based on genetic algorithms (GA) to resolve water conflicts from water demands, water quality and waste load allocations, summarized in a Nash bargaining setup. Total dissolved solids (TDS) and temperature were selected as the most critical water quality parameters. Later, Ahmadi et al. (2012) used a fuzzy multi-objective GA approach to guide quality and quantity management, while determining the land uses that maximize agricultural production in an upstream region.

This study builds on previous efforts to solve complex water management problems in China on the basis of rational economic decisions (Davidsen et al., 2015, submitted for publication). In Davidsen et al. (2015) an integrated hydroeconomic optimization approach was used to solve a water allocation problem. A variant of SDP known as the water value method (Stedinger et al., 1984) was used to guide long term sustainable management of the water resources. The discrete sub-problems of the SDP framework were strictly linear, and the future cost function was convex and thus solvable with linear programming (LP). In Davidsen et al. (submitted for publication), a second state variable was introduced, which allowed inclusion of a more realistic representation of the groundwater aquifer. Non-convexity arising from head-dependent groundwater pumping costs required use of a nonlinear global solver. A hybrid GA–LP implementation developed by Cai et al. (2001) was applied. The overall objectives are (i) to couple water quality decisions and water allocation decisions within the framework of the water value method, (ii) to demonstrate how complex non-linear water quality constraints can be used to enforce good water quality in the rivers and (iii) estimate the additional costs of meeting minimum water quality in the rivers.

2. Methods

2.1. Case study area

The Ziya River is a medium-sized river formed in the Taihang Mountains in the eastern Shanxi Province of China (see Fig. 1). The natural river routes in the lower basin on the NCP in the Hebei Province have been modified extensively as part of flood control projects more than 50 years ago. Originally, the Hutuo and Fuyang rivers joined the Hai River but today New Ziya River, a large floodwater spillway, generally denoted the “Ziya River Basin” by the Hai River Commission, leads the remaining non-diverted water directly to the Bohai Gulf. The 52,000 km^2 basin has a population of 25 million people (2007) with the majority located on the NCP (Bright et al., 2008). Reservoirs on all the natural mountain tributaries allow almost full utilization of the surface water resources. Some of the NCP river channels are mostly carrying untreated wastewater, while others provide occasional irrigation water from the reservoirs. Farmers along the rivers without access to groundwater sometimes pump wastewater for irrigation directly to their fields.

According to Chinese legislation (HRB WRPB, 2008), surface water quality is divided into 6 grades as shown in Table 1. Grade I represents natural water quality, while water that does not meet the requirements of Grade V is considered heavily polluted. The major pollutants include chemical oxygen demand (COD), BOD and ammonia (Ministry of Environmental Protection, 2010). In 2009, 42% of the river sections in the Hai River Basin failed to meet the Grade V standard (Ministry of Environmental Protection, 2010), which is also supported by our field observations. In the northern part of the Ziya River Basin, significant natural attenuation of pollutants is observed as the river flows from Xinzhou city through the Taihang Mountains and into the reservoirs located close to Shijiazhuang city. The main water quality challenges are therefore in the lower part of the catchment, and water quality in the upstream catchment is not considered in this study.

Simulation models can handle a high number of pollutants and are capable of simulating complex physical processes, whereas optimization models are, often computationally, limited to simpler representations of the real world problems (Harou et al., 2009). Davidsen et al. (2015) formalized the management problem as a simplified optimization as illustrated in Fig. 2A with water users in three sectors irrigated agriculture, domestic and industries, upstream and downstream of a central reservoir. This central surface water reservoir is an aggregation of the five major reservoirs in the basin (see Davidsen et al., 2015) and it receives the combined runoff from the sub basins upstream these reservoirs. It is assumed that reservoir releases can be moved to any point downstream this central reservoir, an assumption which is realistic given high connectivity of the downstream rivers and channels. Runoff from both the Hutuo and Fuyang rivers is included in the aggregated reservoir model. The water values from the aggregated optimization model can be used with a much more detailed simulation model with multiple smaller reservoirs, within the suggested framework.