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Research article

Developing a methodology for real-time trading of water withdrawal and waste load discharge permits in rivers

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ABSTRACT

In this paper, a new methodology is proposed for the real-time trading of water withdrawal and waste load discharge permits in agricultural areas along the rivers. Total Dissolved Solids (TDS) is chosen as an indicator of river water quality and the TDS load that agricultural water users discharge to the river are controlled by storing a part of return flows in some evaporation ponds. Available surface water withdrawal and waste load discharge permits are determined using a non-linear multi-objective optimization model. Total available permits are then fairly reallocated among agricultural water users, proportional to their arable lands. Water users can trade their water withdrawal and waste load discharge permits simultaneously, in a bilateral, step by step framework, which takes advantage of differences in their water use efficiencies and agricultural return flow rates. A trade that would take place at each time step results in either more benefit or less diverted return flow. The Nucleolus cooperative game is used to redistribute the benefits generated through trades in different time steps. The proposed methodology is applied to PayePol region in the Karkheh River catchment, southwest Iran. Predicting that 1922.7 Million Cubic Meters (MCM) of annual flow is available to agricultural lands at the beginning of the cultivation year, the real-time optimization model estimates the total annual benefit to reach 46.07 million US Dollars (USD), which requires 6.31 MCM of return flow to be diverted to the evaporation ponds. Fair reallocation of the permits, changes these values to 35.38 million USD and 13.69 MCM, respectively. Results illustrate the effectiveness of the proposed methodology in the real-time water and waste load allocation and simultaneous trading of permits.

1. Introduction

Return flows from agricultural lands are significant sources of pollution for neighboring water bodies such as rivers, which are usually the main sources of irrigation water for these lands. Such intertwined relationship has made allocating limited sources of water while preserving acceptable water quality levels, a complicated and challenging task which is in need of new approaches. Numerous studies have focused on the application of optimization-simulation frameworks for water and waste load allocations (e.g. Burn and McBean, 1986; Chang et al., 1997; Dai and Labadie, 2001; Kerachian and Karamouz, 2005; Yamout et al., 2007; Nikoo et al., 2012; Tavakoli et al., 2014, 2015; Soltani et al., 2016). In the past decades, market-based approaches have been advocated as a cost-effective way of water allocation by allowing the trade among users with different water productivities. Similarly, Tradable Discharge Permit (TDP) has been proposed as an economic incentive for users with different efficiency levels in pollution reduction to comply with environmental standards (Jarvie and Solomon, 1998; Nguyen et al., 2013; de Lange et al., 2016). While some studies have applied approaches developed for air pollution trade (e.g. Pollution Offset System used by Prabodanie et al., 2010), others have developed systems specific to water pollution permits (Weber, 2001; Ning and Chang, 2007; Voora et al., 2012; Nguyen et al., 2013). One notable example of such frameworks is the Trading-Ratio System (TRS), which takes advantage of uni-directionality of the water flow (Hung and Shaw, 2005). There have also been efforts to extend the scope of TDP to include multiple water quality indicators, either using a simple weighting approach to aggregate

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multiple pollutant permits (Sarang et al., 2008) or applying an Extended Trading Ratio System (ETRS) as a modification to TRS that can integrate two water quality indicators (Mesbah et al., 2009; Nikoo et al., 2016).

In theory, TDP can yield to the least-cost allocation of the pollution permits. However, transaction costs and the uncertainties associated with permit allocations may cause the system to significantly deviate from its optimum conditions (Ning and Chang, 2007; Nguyen et al., 2013; Zhou et al., 2016). Multiple tools including inexact stochastic programming (Luo et al., 2005; Zhang et al., 2015), and fuzzy programming (Niksokhan et al., 2008; Nikoo et al., 2011; Zhang et al., 2015) have been used to integrate the uncertainties of allocation and trading of the pollution permits. TDP decreases agricultural pollution while increasing system benefit (Zhang et al., 2015). This extra benefit can then be distributed among dischargers which have participated in the trade, using, for example, the game theory concepts (Niksokhan et al., 2009; Nikoo et al., 2011).

Review of the previous works reveals that the proposed models for water and waste load allocation are only applicable for sizing the required infrastructures in the planning stage. In this paper, a new bilateral, step by step methodology is developed for the real-time trading of water use and waste load discharge permits. The proposed framework determines the real-time water and waste load permits and trading policies for various agricultural water users with multiple crops. To accurately estimate the quantity and quality of agricultural return flows, SWAP agro-hydrologic model is utilized. Moreover, diverting a part of return flows to the evaporation ponds is considered as the Best Management Practice (BMP) for controlling the amount of TDS load which is discharged to the river.

2. Methodology

A flowchart of the methodology developed for the real-time and simultaneous trading of water withdrawal and waste load discharge permits is presented in Fig. 1. The proposed methodology consists of three steps. In the first step, the data needed for different parts of the model is gathered; which includes locations, types and demands of water users; environmental water demands; arable area and crop patterns, crop value for unit water applied by each agricultural water user, records of river flow (surface water) and groundwater quantity and quality; and meteorological data (temperature, rain, solar radiation, wind speed, etc).

In the second step, an Artificial Neural Network (ANN) is trained to use hydrologic records of river flow and large-scale climate signals for real-time forecasting of the surface water that will be available during the upcoming months in a one-year cultivation period. Quantity and TDS concentration of agricultural return flows (RFs) from cultivated lands, as well as relative crop productions, are estimated using the SWAP agro-hydrologic model. Kroes and van Dam (2003), Singh (2004) and Soltani et al. (2016) provide more information on SWAP and its applications. The results of ANN and SWAP are integrated into a non-linear multi-objective optimization model to determine the amount of water withdrawal and waste load discharge permits that will be available for allocating to agricultural water users. Since surface water might be controlled by dams that are usually located upstream of agricultural areas, a simple optimization model is developed in this step for reservoir operation.

The total water withdrawal and waste load discharge permits which are calculated using the optimization model are then fairly reallocated to agricultural water users, proportional to their arable land area. Since this fair allocation will not achieve optimum system objectives, in the third step, water users are allowed to trade water withdrawal and/or waste load discharge permits, using a step-by-step, bilateral scheme, which will be discussed in following sections. In every step of the trade, benefits of trading permits are redistributed using a Nucleolus cooperative game. Data gathered in step 1 is updated as necessary and results of steps 2 and 3 are revised at assumed intervals, improving the accuracy of the real-time water and waste load allocation and trade at each interval within the one-year period.

2.1. The multi-objective non-linear optimization model for real-time allocation of water withdrawal and waste load discharge permits

The non-linear multi-objective optimization is utilized to estimate the available water and waste load discharge permits in real-time. Maximizing total agricultural benefit and minimizing total return flow that should be diverted to evaporation ponds during a one-year planning period are selected as objectives of the optimization model. Assuming relative weights for objectives, the weighted sum of their dimensionless values forms a single objective; which is easier to be solved by reduced gradient methods. For simplicity in the presented methodology, it is assumed that real-time revisions are done on a monthly basis. Therefore, monthly water allocated to each agricultural user, the amount of return flow that each user discharges to the river or diverts to the evaporation ponds per month, and each user's cultivated area are main decision variables of the proposed optimization model. Agricultural benefits are calculated by subtracting the costs of groundwater pumping and return flow diversion from the value of produced crop. Since the actual amount of river flow during the upcoming months in a one-year cultivation period might vary significantly compared to the forecasted value, ANN-based streamflow forecasting models are developed for each real-time interval (monthly in this paper). By updating the forecasted surface water flow at each interval, the real-time optimization model is also run and permits are revised if necessary. The optimization model formulation is as follows:

$$Max\ Obj = w_1 \frac{\sum_{i,s} P_s Ben_{is}}{\sum_i Ben_{pot,i}} + w_2 \left(1 - \frac{\sum_{i,c,t} div_{ict}}{\sum_{i,c,t} div_{pot,ict}}\right) \quad (1)$$

Subject to:

$$Ben_i = \sum_{c,t} (cw_{ic} * wa_{ict} * yr_{ic} - gwc_{ict} - cw_{ic} * div_{ict}) \quad (2)$$

$$Ben_{pot,i} = \sum_{c,t} cw_{ic} * pwd_{ict} * yr_{ic} \quad (3)$$

$$gwc_{ict} = ecost_t * \left(\frac{gw_{ict}}{eff}\right) * gwd_i * \frac{const}{0.102 * eff_{pump}} \quad (4)$$

$$wa_{ict} = d_{ict} * a_{ic} \quad (5)$$

$$wa_{ict} = sw_{ict} + gw_{ict} \quad (6)$$

$$pwd_{ict} = d_{ict} * acult_{ic} \quad (7)$$

$$div_{pot,ict} = (1 + ar) * crp_{ic} * rf_{ict} * acult_i \quad (8)$$

$$drain_{ict} = rf_{ict} * a_{ic} \quad (9)$$