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Research article

Simulation-based optimization framework for reuse of agricultural drainage water in irrigation

A. Allam [a, b, *], A. Tawfik [b], C. Yoshimura [c], A. Fleifle [d]

[a] Civil Engineering Department, Faculty of Engineering, Kafr Elsheikh University, Egypt
[b] Environmental Engineering Department, Egypt-Japan University of Science and Technology, (E-JUST), P.O. Box 179, New Borg Al-Arab City, 21934, Alexandria, Egypt
[c] Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Meguro-ku, Tokyo, 152-8552, Japan
[d] Irrigation Engineering and Hydraulics Department, Faculty of Engineering, Alexandria University, El-Horia St., 21544 Alexandria, Egypt

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ABSTRACT

A simulation-based optimization framework for agricultural drainage water (ADW) reuse has been developed through the integration of a water quality model (QUAL2Kw) and a genetic algorithm. This framework was applied to the Gharbia drain in the Nile Delta, Egypt, in summer and winter 2012. First, the water quantity and quality of the drain was simulated using the QUAL2Kw model. Second, uncertainty analysis and sensitivity analysis based on Monte Carlo simulation were performed to assess QUAL2Kw's performance and to identify the most critical variables for determination of water quality, respectively. Finally, a genetic algorithm was applied to maximize the total reuse quantity from seven reuse locations with the condition not to violate the standards for using mixed water in irrigation. The water quality simulations showed that organic matter concentrations are critical management variables in the Gharbia drain. The uncertainty analysis showed the reliability of QUAL2Kw to simulate water quality and quantity along the drain. Furthermore, the sensitivity analysis showed that the 5-day biochemical oxygen demand, chemical oxygen demand, total dissolved solids, total nitrogen and total phosphorous are highly sensitive to point source flow and quality. Additionally, the optimization results revealed that the reuse quantities of ADW can reach 36.3% and 40.4% of the available ADW in the drain during summer and winter, respectively. These quantities meet 30.8% and 29.1% of the drainage basin requirements for fresh irrigation water in the respective seasons.

1. Introduction

Water scarcity is among the major problems in many countries around the world. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of water scarcity, and 500 million people are approaching this situation (UN-Water, 2007; World Health Organization, 2002). Among them, Egypt is one of the countries facing great challenges due to its limited water resources, represented mainly by its fixed share of water from the Nile River, and its general aridity (Allam et al., 2015). Traditionally, the Egyptian Ministry of Water Resources and Irrigation (MWRI) has adopted different strategies aimed at increasing the use of agricultural drainage water (ADW) to confront the prevailing water scarcity (Flifle et al., 2013). However, increasingly widespread pollution in the drainage system threatens these reuse strategies (Allam et al., 2014; MWRI, 2002; Shabaan et al., 2010). Unfortunately, drainage networks in Egypt receive a large amount of domestic and industrial wastewater and the majority of this wastewater is dumped into the drainage system without any treatment (Abdel-Azim and Allam, 2005; MWRI, 2003; Nagy and Salem, 2003). Therefore, as in other arid areas, optimizing the quantity and quality of reused drainage water is the main concern of any strategic planning for better water resource management in Egypt.

Over the years, surface water quality models (WQMs) have been increasingly recognized to assist decision making and water quality management. Recently, several WQMs have been developed for evaluating and predicting water quality in streams. In this context, QUAL2K and its updated version QUAL2Kw are well-known models

* Corresponding author. Civil Engineering Department, Faculty of Engineering, Kafr Elsheikh University, Egypt.
E-mail addresses: ayman_allam@eng.kfs.edu.eg, aymanallam82@gmail.com (A. Allam).

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for flexible and applicable simulation of water quantity and quality in different settings with different parameters (Kalburgi et al., 2010; Vasudevan et al., 2011; Gikas, 2014). The complex relationships between waste loads from different sources and the resulting water quality in the receiving bodies of water are best described with the QUAL2Kw model (Fliefle et al., 2014; Rashed and El-Sayed, 2014).

WQMs are useful for evaluating single hypothetical scenarios and testing potential management alternatives. They are, however, unable to automatically solve multi-criteria optimization problems. Metaheuristic algorithms such as genetic algorithms (GAs), simulated annealing and ant colony algorithms have been employed to deal with multi-criteria problems (Fliefle et al., 2013; Yandamuri et al., 2006). GAs are a powerful optimization technique that has successfully been applied to water quality management (Fliefle et al., 2013; Karamouz et al., 2003; Kerachian and Karamouz, 2005; Saadatpour and Afshar, 2007). Yet, these studies limited the considered water quality variables to 5-day biochemical oxygen demand (BOD_5), total dissolved solids (TDS) and dissolved oxygen (DO) in the optimization process. Furthermore, the WQMs used in these studies cannot be effectively used to model complex drainage systems. In this regard, there is a considerable need to use a more comprehensive WQM that can be applied to any complicated drainage system. Furthermore, more water quality variables should be included in the simulation-based optimization framework to identify reasonable reuse decisions.

Recently, several studies concluded that even the best-calibrated WQM with good agreement between its results and observed field data may contain some uncertainties (Fang et al., 2008; Hanfeng et al., 2013; Kannel et al., 2007; Kim and Je, 2006; McIntyre et al., 2003; Tao, 2008). When modeling a drain, varied and inescapable irregularities in data collection result in making assumptions about the model parameters, which leads to the magnification of errors in the model outputs (Paliwal et al., 2007; Sharma et al., 2015). Uncertainty in WQM predictions is inevitably high due to model equation errors, parameter errors and limited definitions of boundary conditions and management objectives (Paliwal et al., 2007; Hanfeng et al., 2013). These uncertainties in the model simulation space will also propagate into the decision space. Thus, an uncertainty analysis helps to demonstrate the reliability of simulated results (Paliwal et al., 2007; Hanfeng et al., 2013). Furthermore, sensitivity analysis enables modelers to identify the most critical variables for the determination of water quality (Sharma et al., 2015; Tao, 2008; Paliwal et al., 2007).

In this study, a simulation-based optimization framework for ADW reuse through the integration of a WQM (QULA2Kw) and a GA was proposed. First, uncertainty and sensitivity analyses were conducted to ensure the reliability in simulation of the ADW quality and quantity using QUAL2Kw. Given such results, the GA technique was then applied as an optimization tool for determining the optimum ADW reuse quantities at specific points of withdrawal. The practical utility of the proposed framework in decision-making is illustrated through its application to the Gharbia drain in the Nile Delta, Egypt.

2. Study area

The study area was the catchment of the Gharbia drainage canal in the Nile Delta, Egypt. The Gharbia drain is the largest drain in the middle of the Nile Delta. It has a catchment area of 2940 km^2 and a length of 59 km (EL-Gammal et al., 2009). It originates in the Gharbia Governorate and extends north through the Kafr el-Sheikh Governorate until it reaches the Mediterranean Sea at Baltim. It is noteworthy that the drain receives the discharge of six major polluted branch drains by pump stations. These drains are the Samatay and Segaaya drains and Drains 3, 4, 5 and 6 (Fig. 1). The Khashaa weir at the downstream end of the drain was built in 1990 to stop the drainage water from flowing into the Mediterranean Sea and to meet the demand for irrigation water.

The Gharbia drain catchment area covers a heavily populated area in Gharbia and Kafr el-Sheikh Governorates. Fully irrigated agriculture is the major activity in this area. It has two main seasons: summer and winter. The cropping pattern is completely different between the two seasons: rice, maize and cotton are the main crops in summer while wheat, beans and berseem are grown in winter. The drain also passes through industrial cities such as Tanta and El-Mahalla El-Kubra. Consequently, it collects industrial and domestic sewage in addition to agriculture drainage. The discharges from agricultural drainage, domestic sewage and industrial wastewater represent 75%, 23% and 2% of the total drainage water, respectively (EL-Gammal et al., 2009).

The main source of irrigation water in the study area is drainage water reuse, in which Gharbia drainage water is mixed with fresh Nile irrigation water. The drainage water is reused in three ways: 1) official reuse at Hamoul and Boteita reuse pump stations, and at Khashaa weir (Table A1); 2) emergency pump stations which were constructed by the local irrigation districts at the ends of irrigation networks; 3) unofficial reuse which can be seen along the drain, in which farmers who receive inadequate fresh irrigation water pump the drainage water to directly irrigate their fields without permission.

In this study, the average monthly records of water quantity and quality from August 2011 to July 2012 were collected for 10 locations: 4 sites (MG28, MG15, MG08 and MG11) along the main stream of the drain and 6 sites (MG02, MG04, MG05, MG07, MG09 and MG10) along branch drains (DRI, 2012). The average monthly records of DO, temperature, pH, BOD_5, TDS, chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP) and total suspended solids (TSS) were measured according to APHA (1998). Table 1 summarizes the average water quality variables for the 10 monitoring locations of Gharbia drain from August 2011 to July 2012 and Egyptian standards for drainage water reuse in irrigation according to Law 48/1982 (DRI, 2012).

3. Methods

The simulation-based optimization framework for ADW reuse includes three phases: 1) the application of a QUAL2Kw model for the simulation of water quality and quantity changes in a drain, 2) conducting uncertainty and sensitivity analyses based on MCS to assess the uncertainties associated with the input variables and to estimate the correlation between forecasted output variables and each assumed input variable, respectively, and 3) the application of a GA as an optimization tool to maximize the total reuse quantity at the proposed reuse locations with the condition that the standards for using mixed water in irrigation are not violated.

3.1. Water quality modeling

We used the modeling tool QUAL2Kw (Pelletier and Chapra, 2005). It is a stationary and one-dimensional stream WQM that is an upgraded version of the QUAL2K model. A complete discussion of the model theory is described in the QUAL2K Documentation and User's Manual (Pelletier and Chapra, 2005). The Gharbia drain was divided into 5 reaches with various lengths and further subdivided into a total of 59 elements of 0.997 km length (Fig. 2). The main criterion for this division was the similarity of hydraulic characteristics, such as width and slope, in a canal reach. The measured geometries and water velocities were used to determine the hydraulic characteristics at each sampling location. Manning's