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Multi-objective particle swarm optimization model for conjunctive use of treated wastewater and groundwater

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ABSTRACT

In this research, cropping pattern optimization models have been developed to maximize the benefits and minimize the potential negative effects of quantitative-qualitative conjunctive use of unconventional surface water (treated wastewater) and groundwater in agricultural irrigation. Three objective functions were considered: maximizing the benefits from crop patterns, reducing nitrogen leaching, and improving the rate of aquifer recharge. The developed models use particle swarm optimization (PSO) integrated with an additive weighting method and a multi-objective particle swarm optimization (MOPSO) algorithm for different single- and three-objective optimization scenarios in the Varamin irrigation network in Iran, and then the results of the models were compared. The solutions resulting from the three-objective model using the PSO algorithm with the additive weighting method indicated that the benefits obtained from optimizing cropping patterns, water consumption productivity, and aquifer recharge were increased by 7%, 49%, and 20%, respectively. Meanwhile, the conjunctive use of treated wastewater and groundwater and the consumption of nitrogen fertilizer were decreased by 35% and 88%, respectively. The solutions resulting from the three-objective model using the MOPSO algorithm, forming Pareto front, and then using TOPSIS to select the optimal solution from among the non-dominated solutions showed that the benefits obtained from optimizing cropping patterns, water consumption productivity, and aquifer recharge were increased by 7%, 47% and 15%, respectively. The objectives of conjunctive use of treated wastewater and groundwater and the consumption of nitrogen fertilizer were decreased by 36% and 89%, respectively. The difference between the objective function values of the two algorithms is about 0.4% to 4%, which shows the proximity of the models in finding the optimal solution. The results of this research can be used to optimize the use of water resources, increase farmers' benefits, and decrease nitrogen leaching from irrigation and drainage networks.

1. Introduction

In recent years, treated wastewater has been considered for use as a supplementary water supply for irrigation, and thus the potentially higher rate of nitrogen leaching into soil and aquifer from chemical fertilizers and treated wastewater needs to be decreased. While nitrogen is one of the most important nutrients for crop production, its overuse increases the risk of greenhouse gases and groundwater contamination. The amount of applied nitrogen fertilizer should be determined based on the existing nitrogen quantity in water resources and soil and the plant requirements during the growing season. However, many farmers use high levels of water and nitrogen to make sure they meet the plant requirements, thus soil becomes vulnerable to leaching and transferring nitrogen to groundwater resources (Ramos et al., 2012). The United States Environmental Protection Agency (USEPA, 1997) has stated that one of the most important sources of nitrate contamination is the use of nitrogen fertilizers in agricultural lands. These fertilizers have the potential to contaminate groundwater by leaching and cause adverse health effects on consumers. Meanwhile, many previous research studies show the benefits of using treated wastewater in agricultural irrigation. For example, Oron et al. (2007); Metcalf et al. (2007), and Ghasemi et al. (2011) reported that the using treated wastewater for irrigation provides a cheap and permanent source of water, reduces the costs of treatment, reserves water resources with good quality for other uses, reduces the cost of chemical fertilizers, and reduces the adverse effects of treated wastewater disposal on other water resources. The World Health Organization (WHO, 2006) reported that treated wastewater irrigation at a rate of 5.1 cubic meters per year provides 225 kg of

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nitrogen per hectare for irrigated lands, which could minimize or completely eliminate the use of organic and chemical fertilizers.

Singh et al. (2001) proposed a linear programming model to determine the optimal crop pattern in a region in India that would maximize the net benefit from available water. Khare and Jat (2006) developed a linear economic-engineering optimization model to evaluate the conjunctive use of surface and groundwater in Indonesia using different hydrological and management constraints. Their results showed that the conjunctive use options can increase the benefits from agriculture. Davijani et al. (2016a) and Davijani et al. (2016b) presented a multi-objective optimization model to allocate water resources in arid regions of Iran for maximizing job creation in industrial, agricultural, and municipal water sectors using a PSO algorithm. Results indicated that optimal allocation of water resources increased the employment rate and benefit by 13% and 54%, respectively. Banihabib et al. (2015) developed a non-linear programming model of water allocation and cropping patterns for deficit irrigation condition in the Tehran and Alborz provinces in Iran. The results of the optimization model showed that, in the most optimal state, changing the cultivated area and using deficit irrigation methods can improve the economic benefits of the agricultural sector by 36% compared to the current situation. Karamouz et al. (2005) proposed a methodology for conjunctive use of surface and groundwater resources using genetic algorithms (GAs) and artificial neural networks (ANNs) with an emphasis on water quality issues and applied this method in southern Tehran (Capital of Iran). Later, Karamouz et al. (2010) developed and used a GA model to optimize the cropping pattern of eight irrigation networks in Tehran Province according to water allocation priorities and water availability. The results showed that significant changes must be made in the cultivated area of different crops to achieve maximum economic benefit. Alizade et al. (2012) performed a cropping pattern optimization in a 10-year planning period for balancing water resources in the Mashhad-Chenaran Plain in Iran. Al Khamisi et al. (2013) studied conjunctive use of groundwater and reclaimed water (RW) in cropping rotations. The results indicated that conjunctive use can increase cropping areas compared to using RW only. Joodavi et al. (2015) developed an optimization model for the Firouzabad aquifer in Iran by considering crop patterns and conjunctive use for groundwater management. The results showed that the optimal cropping pattern is different from the current cropping pattern and that the cultivated areas of some crops should be reduced. Singh (2012) applied a linear optimization model for land and water resources to maximize net agricultural benefits in an area in India. Using production functions, Singh estimated the crop yield under different salinity levels in irrigation water. The results indicated that optimizing land and water resources would increase groundwater use and decrease the problems of waterlogging and salinity in the study area. Singh and Panda (2013) developed a linear programming optimization model for a region in India that allocates land and water resources to maximize the annual net benefit by eliminating salinity problems. Using the results of the optimization model, they implemented a groundwater simulation model to determine the long-term impacts of different water management strategies on the aquifer balance. Based on the results, a change in cropping patterns and an increase in groundwater withdrawals were suggested. Moghadasi et al. (2008) used non-linear programming (NLP), a genetic algorithm (GA) and particle swarm optimization (PSO) approaches to maximize income in the Zayanderud irrigation system in Esfahan, Iran. Davijani et al. (2012) developed an optimizing water resource allocation model in the agricultural, industrial and service sectors using the GAPSO algorithm, which is a combination of GA and PSO algorithms. According to the results, employing deficit irrigation patterns, changing cropping patterns, eliminating the cultivated area of some products, and using water resources in the industrial sector could raise revenues in Iran's central desert by 56% compared to the current situation. Mehdipour and Hadad (2011) evaluated the optimal operation of reservoirs with various objectives such as hydroelectric power generation, downstream demands, and flood control purposes. They used NLP and multi-objective particle swarm optimization (MOPSO) methods, and the comparison of results showed that the MOPSO algorithm has more capability to obtain an optimum solution. Reddy and Kumar (2007) presented an optimization model for water consumption to maximize the economic benefit by allocating irrigation water within a certain period and for multiple crops. They used PSO to solve this problem. Rezaei et al. (2017) developed a combination of MOPSO and fuzzy system (F-MOPSO) for conjunctive use of surface and groundwater in the Najafabad plain in Iran. The comparison of the results indicated that the fuzzy multi-objective particle swarm optimization performed better than MOPSO.

The previous studies on the application of MOPSO algorithm in reservoir operation problems, models for water resources allocation, and conjunctive use of surface and groundwater management showed the capability and effectiveness of this algorithm for solving multi-objective and complex optimization problems. The ability of this algorithm to optimize the quantitative-qualitative conjunctive use of treated wastewater and groundwater has not been addressed in previous research, but it was investigated in this study.

In all of the above mentioned research, cropping pattern optimizations were performed with quantitative objectives such as an increase in benefit or groundwater balance, and the groundwater salinity was controlled by the constraints of the optimization models. Given the importance of reducing the amount of nitrogen entering to the soil and groundwater, research that optimizes the amount of nitrogen leaching to soil and aquifers from the use of treated wastewater and nitrogen fertilizers is essential. Previous research only considered economic and water resources aspects in cropping pattern optimization, but we need to consider environmental aspects of controlling the nitrogen leaching as well. This study has two main goals: (1) develop and apply the three-objective cropping pattern optimization model for quantitative-qualitative conjunctive use of treated wastewater and groundwater to maximize benefits from crop patterns, reduce nitrogen leaching, and improve the rate of aquifer recharge in irrigation and drainage networks and (2) compare the single-objective PSO algorithm using the additive weighting method and the MOPSO algorithm in solving the problem of optimizing the conjunctive use of water resources.

2. Materials and methods

2.1. Case study

The Varamin Plain is in northern Iran on the southern slopes of the Alborz Mountains, south-east of Tehran Province. The average annual precipitation in this plain is about 145 mm. The Varamin irrigation network covers an area of 52 ha. The main channel, named OABC, has nine secondary channels that branch from the points O, A, B and C. This research considers the land served by the secondary channel, AU, which has an area of 3053 ha. Fig. 1 shows the Varamin irrigation network and channel locations.

2.1.1. Water resources of the Varamin network

Table 1 shows the water resources in the area covered by the AU channel in the 2012–2013 water year.

2.1.2. Soil properties

In order to determine soil nitrogen balance, the soil texture, salinity, nitrate, nitrogen, and soil organic matters were tested by random sampling in two stages, at the beginning and end of the 2015–2016 growing season. The results are presented in Table 2.

2.1.3. Measuring treated wastewater and groundwater properties

The amount of nitrate and total nitrogen in treated wastewater and groundwater was determined by samples taken at the upstream of the network, and the amount of nitrate in groundwater was obtained by