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An agent-based-nash modeling framework for sustainable groundwater management: A case study

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ABSTRACT

An agent-based-Nash modeling framework has been developed to find a sustainable solution for groundwater management in Daryan Aquifer, Fars Province, Iran. This framework also includes a MODFLOW simulation model, an Artificial Neural Network (ANN), and a Non-dominated Sorting Genetic Algorithm-II (NSGA-II) optimization model. Groundwater state was simulated using MODFLOW and it was calibrated based on the measured data provided by Regional Water Organization (RWO) of Fars Province. In order to reduce the computational time, an ANN was trained and validated based on the input-output data of the MODFLOW model to estimate groundwater level. The validated ANN was linked to a nonhomogeneous elitist NSGA-II multi-objective optimization model to find a Pareto optimal front among the three objectives of reducing irrigation water deficit, increasing equity in water allocation, and reducing groundwater drawdown, as the objectives of the three main groundwater resource stakeholders; farmers, the government executive sector, and the environmental protection institutes. The Nash bargaining model was applied to the optimal solutions in order to find a compromise among the stakeholders. Social influential factors in the study environment, and policy mechanisms to encourage agents to cooperate with the management decisions were implemented in the agent-based model. These factors include training, incentives, penalties, and social norming (neighbors' impacts), as well as considering the executive and judicial systems. After application of the agent-based model, computed optimum solutions were modified according to social conditions. Finally, the Nash bargaining model was used again to find a compromise among modified optimal objectives of the stakeholders. Implementation of this solution led to 58.3% less water extraction and approximately 3 m water level uplift.

1. Introduction

Growing human population, consumption, and using advanced technologies have led to a rising groundwater overuse (Dietz et al., 2003; Grimble, 1999) which should be controlled by appropriate groundwater management. Numerous groundwater management methods have already been proposed. Their evaluation has proven that sustainable groundwater withdrawals are achievable provided that the social behavior, preferences, dislikes of water users and their interactions with the environment are implemented in the method (Akhbari and Grigg, 2014; Berglund, 2015; Gleick, 2000; Liu et al., 2007; Pahl-Wostl, 2002, 2007).

Recently, different approaches have been developed for incorporation of the interaction of humans and the groundwater extractions. Pahl-Wostl (2002) showed that social factors are more influential than deterministic physical parameters in adaptive groundwater management. Schreinemachers and Berger (2011) introduced an agent-based software package, Mathematical Programming-based Multi-Agent Systems (MP-MAS), which builds on constrained optimization to simulate the decision-making of farmers in agricultural systems. Agricultural technologies, market dynamics, environmental changes, and policy interventions were incorporated in this model. However, the conflicting interests of the non-farmers, such as policy mechanisms and social normings, were excluded in this decision-making process. The influence of farmers' characteristics on land-use change and the corresponding groundwater overuse was studied also by Holtz and Pahl-Wostl (2012). They employed an agent-based model to investigate the history of irrigated agriculture in the Upper Guadiana Basin, Spain. The effects

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of gross margin, risk, labor (work) load, and illegal behavior of the farmers were considered as Cobb-Douglas function to compute the utility of land-use pattern. This study also lacked investigating the impacts of policy mechanisms to reduce water exploitation. Kelly et al. (2013) investigated five common approaches for integrated environmental assessment and management that have the capacity to accommodate multiple issues, values, scales, uncertainties, and stakeholder engagements. These approaches were system dynamics, Bayesian networks, coupled component, agent-based, and knowledge-based models. They corroborated that the agent-based models are of high utility for implementing social conditions in management of complex systems. Nikolic et al. (2013) integrated geographic information system, system dynamics, agent-based model, and hydrologic simulation tools to manage groundwater abstractions in Thames River Basin, Southern Ontario, Canada. The spatial and temporal variability of agricultural, industrial, and municipal water demands, harvest yield, and population growth were considered in the integrated decision-making framework, but the effects of social norming were not included. In order to discover the water users' roles in the management process, Zhao et al. (2013) compared their behavior under administered and market-based water allocation systems through an agent-based modeling framework. A penalty-based decentralized optimization framework provided by Inalhan et al. (2002) was used in this study to formulate the agents' behavior.

For social structures, the whole set of economic, social and environmental institutions, rules and social arrangements regulate individual and collective behavior of the water users (Pahl-Wostl, 2007). In complex systems, stakeholders' behavior and their interactions could be incorporated into decision-making procedures using agent-based models (Bandini et al., 2009; Reeves and Zelner, 2010), which requires close collaboration between researchers and stakeholders involved in the arenas of collective choice (Mazzega et al., 2014). Akhbari and Grigg (2013) developed a framework for a conflict management tool to simulate institutional interactions among competing parties in California's San Joaquin River watershed. They developed this framework using an agent-based modeling approach to find practical ways to increase agents' cooperation. Mulligan et al. (2014) used a multi-agent system simulation to evaluate the efficiency of different policy mechanisms, such as caps and tax, in the Republican River Basin, central United States. The comparison of the results with their proposed optimization model represented that more water would be consumed when more realistic, heterogeneous, myopic, and self-interested agents were considered in the multi-agent model. The individual benefits of each agent were maximized subject to some policy mechanisms, but the social interactions among water users were not involved in the decision-making process.

In the present study, a decentralized non-homogeneous groundwater management approach is proposed. This approach integrates groundwater simulation, Artificial Neural Network (ANN), Non-dominated Sorting Genetic Algorithm-II (NSGA-II) multi-objective optimization, the Nash bargaining, and agent-based models to find a practical optimal groundwater management decision which is respected by the stakeholders. Social factors and policy mechanisms such as training, incentives, penalties, and social norming (neighbors' impacts), as well as the executive and judicial systems are considered in the proposed framework and it was applied to Daryan aquifer in southwest Iran that is prone to severe depletion due to agricultural overuse of groundwater.

2. Methods

In the modeling of low-water management, the agents' rationality progressively leads to the adoption of a sociological position in which the agents' strategies could be far from rules and norms (Mazzega et al., 2014). In order to consider social properties in groundwater management, an integrated model is proposed, which implements the preferences of stakeholders. In the proposed framework, whose step-by-step flowchart is presented in Fig. 1, first, necessary data regarding hydrological and hydrogeological characteristics of the study area, social properties of the agents and the study environment, the agents' water demands, and the governmental regulations and plans were gathered. Then, a groundwater simulation model was developed and calibrated, using MODFLOW. To allocate the optimum amount of groundwater to water users, a multi-objective optimization model was employed and the calibrated groundwater simulation model was iteratively run to reach the optimum solution. But the large number of water users caused a long computational time. Therefore, to reduce the computational time and also to implement management mechanisms of the government, the study area was divided into managerial subregions, occupied by agents. Therefore, in this study, an agent is defined as farmers within a subregion. The calibrated MODFLOW groundwater simulation model was iteratively run for different possible groundwater allocation scenarios to the agents in order to reach an appropriate database for training an ANN metamodel. This metamodel was trained and validated based on the provided input-output database to substitute the MODFLOW groundwater simulation model and decrease computational time.

The ANN model was linked to an NSGA-II multi-objective optimization model in order to compute the optimized groundwater allocation to each agent while the objectives of the main stakeholders of the groundwater resource were addressed in the model. The stakeholders were considered as the society of farmers, i.e., the agents, with the objective of a maximum profit, the executive government sector with the objective of maximum groundwater distribution equity, and environmental protection institutions with the goal of having a sustainable groundwater abstraction, i.e. a minimum groundwater drawdown. The multi-objective optimization model resulted in many sets of optimal solutions that comprise an optimal Pareto front among the objectives. For any optimal set of solutions, which implies certain water allocations to the agents, different levels of each objective were satisfied. Choosing any of these optimal allocation scenarios could raise conflicts among the principal stakeholders who have different preferences. A Nash bargaining conflict-resolution model was therefore applied to the optimal Pareto front to find a theoretical compromised solution among all stakeholders. This solution is derived from the results of the NSGA-II multi-objective optimization model. Although, this model has been developed based on stakeholder's preferences to find the optimal solution, it does not consider social properties of the study area and especially the agents, as the groundwater extractors. Therefore, the resulted solutions might not be accepted by the agents, resulting in their non-cooperation.

To incorporate the human-environment interactions into the proposed framework for groundwater resource management with a sustainable approach, an agent-based model was developed and the social properties of agents and also the study environment were considered to test the agent's reactions to all optimal solutions. A modified optimal Pareto front was then derived. Each point on this modified optimal set of solutions specifies the water demand of each agent influenced by societal conditions.

To reach a consensus and find a compromise solution that is acceptable by the agents while it addresses all principal objectives, i.e. sustainability of groundwater, equity in water withdrawals and economic benefits of stakeholders, once again the Nash bargaining model was employed. Indeed, Nash model seeks a solution based on each stakeholder's individual preferences, while the agent-based model provides an opportunity to consider the societal impacts on the agents' reactions to governmental policy mechanisms, and