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RESEARCH ARTICLE

Effluent trading in river systems through stochastic decision-making process: a case study

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Abstract The objective of this paper is to provide an efficient framework for effluent trading in river systems. The proposed framework consists of two pessimistic and optimistic decision-making models to increase the executability of river water quality trading programs. The models used for this purpose are (1) stochastic fallback bargaining (SFB) to reach an agreement among wastewater dischargers and (2) stochastic multi-criteria decision-making (SMCDM) to determine the optimal treatment strategy. The Monte-Carlo simulation method is used to incorporate the uncertainty into analysis. This uncertainty arises from stochastic nature and the errors in the calculation of wastewater treatment costs. The results of river water quality simulation model are used as the inputs of models. The proposed models are used in a case study on the Zarjoub River in northern Iran to determine the best solution for the pollution load allocation. The best treatment alternatives selected by each model are imported, as the initial pollution discharge permits, into an optimization model developed for trading of pollution discharge permits among pollutant sources. The results show that the SFB-based water pollution trading approach reduces the costs by US\$ 14,834 while providing a relative consensus among pollutant sources. Meanwhile, the SMCDM-based water pollution trading approach reduces the costs by US\$ 218,852, but it is less acceptable by pollutant sources. Therefore, it appears that giving due attention to stability, or in other words acceptability of

pollution trading programs for all pollutant sources, is an essential element of their success.

Introduction

Rivers water quality planning and management should be developed with due attention to efficiency, sustainability, and executability criteria. The efficiency criteria are involved primarily with economic aspects, and the sustainability criteria deal with preservation of ecosystem and meeting environmental standards. The executability criteria however are related to social aspects of programs (Zolfagharipoor and Ahmadi 2016). One of the new methods of river water quality management, which have managed to satisfy both sustainability and economic criteria, is the pollution trading (Sarang et al. 2008). There is an extensive literature dedicated to pollution trading programs, but this section only mentions the most important studies of the last decade.

Development of trading-ratio system (Hung and Shaw 2005), modeling of non-point source effluent trading (Wang et al. 2004; Luo et al. 2005), assessing the main reasons for the failure of some water quality trading programs (Shortle and Horan 2006), pollution trading with multiple pollutants (Sarang et al. 2008; Jamshidi and Niksokhan 2015), the use of conflict resolution theory to determine the agreement point on the trade-off curve between the total treatment cost and fuzzy risk of violation of water quality standards (Niksokhan et al. 2009a), real-time management of pollution trading using Bayesian networks (Mesbah et al. 2009), fair allocation of treatment costs with the use of game theory concept (Niksokhan et al. 2009b), providing several optimization

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models for simultaneous use of treatment and trading discharge permit methods (López-Villarreal et al. 2011, 2014), analyze the water pollution trading pilot programs in face of existence of overlap and conflict among policies (Zhang et al. 2012), the use of agent-based models (ABMs) to simulate the trading process and providing the structure of a virtual market (Zhang et al. 2013; Nguyen et al. 2013), simultaneous trade of reclaimed water and discharge permits (Jamshidi et al. 2014), development of a benchmark dynamic trading pattern algorithm among point and non-point sources (Caplan and Sasaki 2014), the use of best management practices (BMPs) in a pollution trading program (Zhong et al. 2016; Zaidi and deMonsabert 2015), the effect of different uncertainties on non-point pollution trading policies (Zhang et al. 2014; Li et al. 2014; Zhang et al. 2015a), the effect of artificial aeration process on pollution trading programs (Jamshidi et al. 2015), providing an economic model for the seasonal pollution trading (Jamshidi et al. 2016), an interval optimization model for multi-pollutant load allocation (Nikoo et al. 2016), considering hydrological variation for effluent trading systems (Chen et al. 2016; Corrales et al. 2017), water quality and quantity management based on water resources allocation with a pollution trading mechanism under uncertainties (Zeng et al. 2016), assessment of different factors such as trading-ratio, transaction cost, and trading cost on success of water quality trading programs (Motallebi et al. 2017), uncertainty analyses in effluent trading systems through Bayesian theory (Zhang et al. 2017), and the use of nutrient assimilation credits compared to BMPs approach in a pollution trading program (Stephenson and Shabman 2017).

Pollution load allocation in rivers through trading discharge permits has been the subject of many studies, but executability of such allocation policies has received marginal attention. Executability of pollution load allocation policies can be improved by using the decision-making approaches to take the opinions of wastewater dischargers about these policies into account.

Full cooperation and lacking cooperation of various stakeholders of a decision-making problem can be simulated with optimistic (multi-criteria decision-making methods) and pessimistic approaches (bargaining methods), respectively (Madani et al. 2014a). When there are multiple stakeholders, the possibility of full cooperation is low, as it cannot guarantee an optimal outcome for all stakeholders. In that case, the results obtained with a pessimistic approach will be more stable than optimistic solutions.

One of the pessimistic decision-making approaches that has drawn some interest from water resources and environmental managers is the fallback bargaining approach (Brams and Kilgour 2001). In this approach, which is a subset of game theory, the purpose is to reach an option that majority or all bargainers can agree on. This approach provides a certain level of desirability for all bargainers (Sheikhmohammady

et al. 2010). The literature on the use of fallback bargaining methods in water resources management is scarce. In the following, some the related studies are mentioned.

Evaluation of performance of fallback bargaining approach for reaching an agreement among 32 countries in regard to oil pollution problem (Brams et al. 2007), predicting the outcome of negotiations among the five Caspian littoral states on the division of oil and gas resources and the seabed (Sheikhmohammady et al. 2010), solving the hydro-environmental problem of Sacramento-San Joaquin Delta under certainty and uncertainty conditions (Shalikarian et al. 2011), minimizing the dissatisfaction of parties involved in the pollution load allocation problem (Mahjouri and Bizhani-Manzar 2013), reaching a consensus on the allocation of profits from the water transfer among stakeholders (Jafarzadegan et al. 2014), and water allocation over a basin (Mehrparvar et al. 2016).

Multi-criteria decision-making (MCDM) methods (optimistic approach) have long been regarded as efficient tools for determining the optimal solutions of water resource problems (Joubert et al. 2003; Hajkowicz 2007; Gomes et al. 2008; Hajkowicz and Higgins 2008; Bravo and Gonzalez 2009; Zoltay et al. 2010; Janssen et al. 2010; Madani et al. 2014b; Read et al. 2014; Abed-Elmdoust and Kerachian 2012, 2014; Mianabadi et al. 2014; Flores-Alsina et al. 2014; Molinos-Senante et al. 2014; Chen et al. 2015; Kumar et al. 2016; Ghodsi et al. 2016; Bozorg-Haddad et al. 2016; Ouyang and Guo 2016). The ordinal structure of these methods allows decision-makers to assess a large number of options, integrate a set of decision-makers into one decision-maker, and make decision based on multiple criteria.

This study presents a new framework for the pollution load allocation in river systems based on not only the efficiency and sustainability criteria but also the executability aspects of policies. Pessimistic (fallback bargaining) and optimistic (multi-criteria decision-making) decision-making approaches with elements of uncertainty are used to incorporate the role of wastewater dischargers into decision-making process and therefore increase the executability of pollution load allocation programs. In this method, each discharger ranks the wastewater treatment alternatives based on total cost of treatment and penalties of violation of water quality standards. Considering the presence of uncertainty in cost-related outcomes of treatment alternatives, the Monte-Carlo simulation method is combined with pessimistic and optimistic decision-making approaches to cover this uncertainty. Analysis of this uncertainty gives wastewater dischargers some knowledge about the risks of treatment alternatives. In the next step, different SFB and SMCDM methods are used to choose the best treatment alternative.

The group decision-making processes based on distance from the ideal solution often ignore the effect of power dynamics among stakeholders (Read et al. 2014). So

executability of outputs of these processes must be measured with stability methods. In this case, the stability index method can be used to assess the executability of choices made by each decision-making approach and compare the stable treatment alternative with these choices. After making sure of executability of chosen pollution allocation policy (its ability to reduce costs and motivate dischargers for voluntary participation in river water quality protection program), treatment alternatives selected by SMCDM and SFB models are traded as initial discharge permits among dischargers using the Extended Trading-Ratio System (ETRS).

Innovations of this study in comparison to previous works include the following: (1) Further focus on acceptability of pollution allocation policies for dischargers and assessing the impact of such focus on pollution trading approach in a real case study; (2) comparing the stability of the results of optimistic and pessimistic decision-making approaches in the pollution allocation problem; (3) incorporating the uncertainty into the decision-making process to give wastewater dischargers some knowledge about the risk of selected alternatives; (4) adopting the policy of penalty for violation of water quality standards in order to improve the river water quality with due attention to the utility of pollutant sources; and (5) fair allocation of penalties among pollutant sources. The performance of the proposed framework is assessed through a case study on the pollution load allocation for main dischargers of the Zarjoub River in northern Iran.

Methodology

Figure 1 shows the structure of the proposed model for adoption of pollution allocation polices for a river system, based on decision-making and pollution trading approaches. According to the flowchart drawn, the first step is to collect quantitative and qualitative river data for the period of 1 month with critical water quality condition. After determining the intervals and verifying the accuracy of information, the next step is to use the quality and hydraulic information as the inputs of the proposed pollution allocation model. Other inputs include qualitative, quantitative, and locational data related to pollutant sources and definition of minimum water quality. The proposed model consists of three main parts: simulation, stochastic decision-making, and optimization. In the simulation part, a water quality simulation model (QUAL2Kw) is used to determine pollution load transfer coefficients, trading-ratio coefficients, and pollution load capacity for each zone of the river. Next, a number of treatment scenarios, each covering a certain biochemical oxygen demand (BOD) removal percentage, are defined and the costs of these scenarios for each discharger are determined. These scenarios are then integrated to form treatment alternatives. Next, input data is used along with the water quality simulation model and treatment scenarios to determine dissolved oxygen (DO) concentration changes along the river. Also the penalty for violation of quality standards is calculated by the simulation model based on the extra expenses required to improve water quality.

The stochastic decision-making part determines the optimal treatment alternative based on pessimistic and optimistic decision-making approaches under uncertainty. Stochastic modeling of pessimistic and optimistic decision-making approaches is performed by coding in the MATLAB software environment. Superiority of treatment alternatives is measured with economic indicator. Economic indicator of each treatment alternative is the sum of treatment cost and the penalty of violation of quality standards. Because of presence of error and uncertainty in the cost calculations, economic indicator is considered to have a stochastic nature. So Monte-Carlo simulation model is combined with fallback bargaining and MCDM methods to develop a new stochastic decision-making framework that allows pollution allocation policies to be determined with greater precision.

The developed model runs so that, it first selects a random number for economic indicator of each treatment alternative by using the Monte-Carlo simulation method. It must be extracted the results related to analysis of the treatment costs, especially determination of the penalty function for violations of water quality standards. This is required for executing the calibrated simulation model. Therefore, in order to run the developed stochastic decision-making model, the results from running of the simulation model must be first recalled and entered to the MATLAB software environment. In the following, the procedure of selecting the best treatment alternatives using both pessimistic and optimistic decision-making approaches are implemented.

In the SFB model, the ranges of every outcome of every treatment alternatives are selected randomly and simultaneously based on economic indicator. After each random selection, every discharger prioritizes the treatment alternatives based on its outcomes, and this leads to creation of a deterministic bargaining matrix, in which the number of rows and columns are respectively the number of bargainers (dischargers) and the number of treatment alternatives.

After entering all pollutant sources into the negotiating process, different SFB methods are used to find the desirable treatment alternative. Depending on the type of fallback bargaining method, each bargaining matrix has one or more outputs. If N be the number of random selections, and n_i be the number of times treatment alternative, i is selected as the output of fallback bargaining method, the winning probability of i will be n_i/N. Next, the best treatment alternatives selected by different SFB methods are compared in terms of total cost they impose on the system, and the one with lowest cost is determined as the ultimate best alternative of SFB approach.

Fig. 1 A flowchart of the proposed methodology for effluent trading-based stochastic decision-making process in rivers
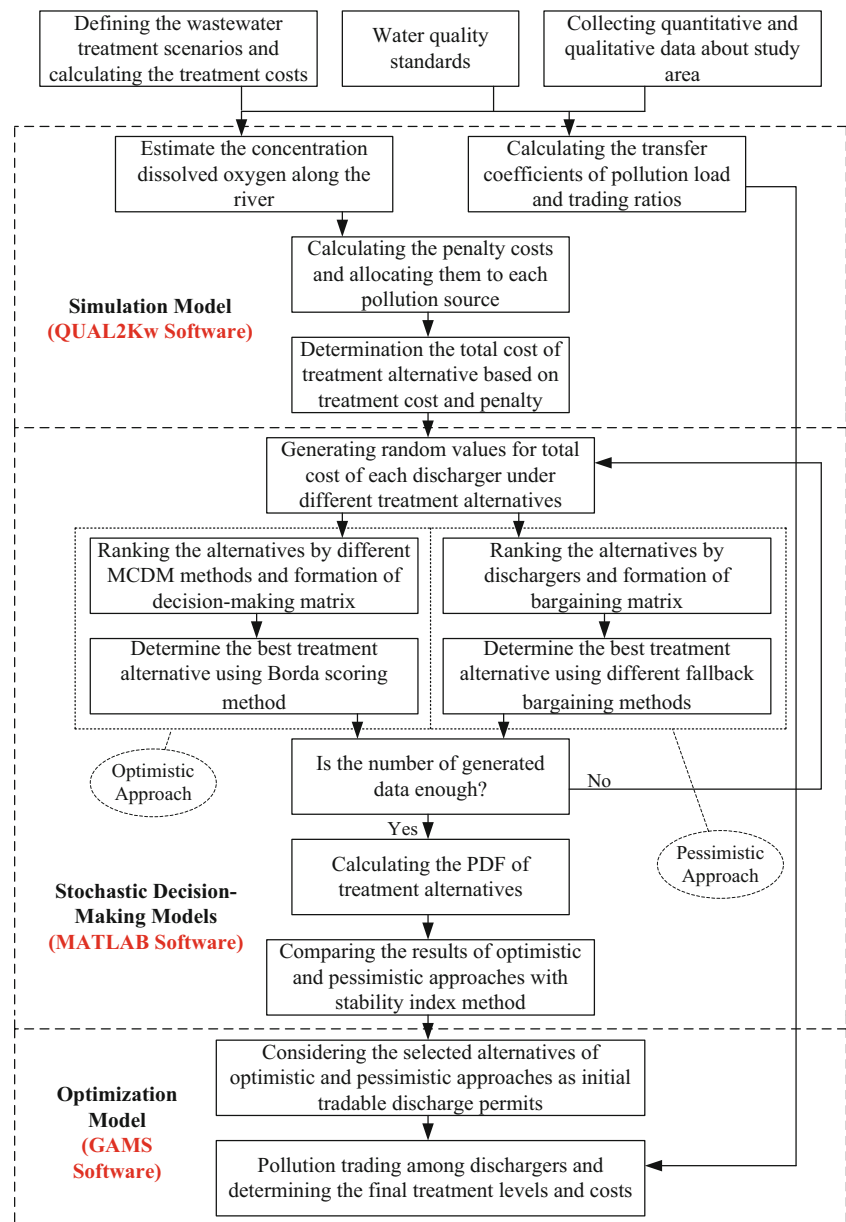
The SMCDM model also ranks treatment alternatives based on different methods. Like the previous model, each random selection leads to creation of a deterministic matrix which allows the alternatives to be evaluated. The Borda scoring method (De Borda 1781; Sheikhmohammady et al. 2010) then determines the best alternative. Here, the best alternative is the one with highest probability of winning. In the next step, the stability index method is used to assess the executability of alternatives selected by optimistic and pessimistic approaches, and the best treatment alternative is compared with the alternative selected by the stability index.

Considering the complexities involved in the determination of the best alternative by each of the pessimistic and optimistic decision-making processes as well as the large number of iteration in this process (50,000 times), the model running time will be relatively long. The model running time is different for various models ranging from several hours to a few days.

The final step is to allocate the treatment alternatives chosen by fallback bargaining and MCDM approaches as the initial pollution discharge permits. The trade of initial discharge permits among dischargers is emulated with an optimization model. The proposed optimization model calculates the pollution load removal rate of each discharger, provides the optimal trading pattern, and also incorporates the views of each discharger on optimal treatment alternatives into the decision-making process.

Fallback bargaining

Fallback bargaining (Brams and Kilgour 2001) approach is a sub-discipline of game theory. In this approach, each of the bargainers or players prioritizes the available options based on their desirability. Then players enter a bargaining process, in which they gradually shift their position from the most desirable option to less desirable ones until reaching an option that the majority or all players can agree on. Therefore this approach provides a certain level of desirability for all bargainers. The following is a brief description of different fallback bargaining methods used in this paper.

Unanimity fallback bargaining (UFB)

This method selects the option that can guarantee the satisfaction of all bargainers while achieving the highest possible level of desirability. In other words, in this method, the best option is the one that can satisfy all stakeholders while enforcing the lowest possible level of compromise (Brams and Kilgour 2001). It should be noted that this method can report more than one option as desirable.

Quota approval fallback bargaining (QAFB)

This method can also be used to select the option that satisfies the majority of bargainers (instead of complete consensus). The UFB method is a special variant of this method (Brams and Kilgour 2001; Sheikhmohammady et al. 2010).

Fallback bargaining with impasse (FBI)

In this method, each bargainer selects and prioritizes its options and then specifies the threshold below which the options lose their desirability for that bargainer (Brams and Kilgour 2001). This threshold determines the undesirable options that will be disregarded in negotiations.

Multi-criteria decision-making based on distance from the ideal solution

One of the approaches to assessment of group decision-making solutions is the use of distance concept. This concept refers to the distance from the ideal solution and can be used as a reliable indicator of the dissatisfaction level of each bargainer with its allocated share. In other words, distance-based methods seek to obtain socially acceptable solution by distributing the dissatisfaction among stakeholders as optimally as possible (Read et al. 2014).

The MCDM methods usually integrate the set of decision-makers into one decision-maker and thus ignore the effect of power dynamics among decision-makers. To address this drawback, stability measures such as stability index can be used to determine whether all decision-makers agree on the selected policy (Read et al. 2014). In this context, stable solution is the one that can satisfy all bargainers sufficiently to convince them to stay in the negotiation process and reach an agreement. In the appendix, four different MCDM methods used in this study are introduced, and then the stability index method is explained.

Water quality simulation model

Water quality simulation models must often be calibrated manually through trial and error, which is usually time-consuming. To overcome this problem, Pelletier et al. (2006) has developed the river water quality simulation model known as QUAL2Kw. This model, which also contains a genetic algorithm for automatic calibration, simulates the transfer and results of a number of constituents.

The main equations of the QUAL2Kw model are including steady-state flow balance equation, hydraulic equations, and heat balance equation and general mass balance equation for each constituents. In addition, the most important biochemical reactions of the model are including plant photosynthesis and respiration, nitrification, and denitrification. The variables, equations and the coefficients of each of them as well as more descriptions about the model are presented in (Pelletier et al. 2006; Pelletier and Chapra 2008; Chapra et al. 2012).

Data required for development of the model include physiological factors, qualitative and quantitative parameters of water, parameters and coefficients related to simulation of selected water quality variables, flow rate, slope, Manning coefficient, and hydraulic characteristics of the river, including emission factors and discharge coefficients (Zhang et al. 2015b). In this paper, this model is used to examine the impact of various pollutant sources on river water quality status.

Optimization model

Effluent trading based on one water quality index (Hung and Shaw 2005) may lead to violation of other water quality standards. For example, trading the BOD discharge permits affects the DO concentration in the river. To overcome this problem, Mesbah et al. (2009) has proposed a new pollution trading approach, in which BOD and DO are considered to be, respectively, the traded pollutant and the water quality index. The effluent trading optimization model, which determines the optimal trading policies, optimal treatment percentages of discharger units, and the treatment costs, is presented in the

following. Other details and components of the ETRS system are described in Mesbah et al. (2009).

$$\text{Min} \sum_{i=1}^{n} c_i \qquad (1)$$
$$s.t. :$$

$$e_i \leq \sum_{k=1}^{i-1} t_{ki} T_{ki} - \sum_{k>i}^{n} T_{ik} + \overline{T}_i \qquad i = 1, \ldots, n \qquad (2)$$

$$T_{ik}, T_{ki} \geq 0. \qquad \forall i, k \qquad (3)$$

$$e_i \in \left[0, e_i^0 \right]. \qquad \forall i \qquad (4)$$

Equation 1 is the objective function of the optimization model and minimizes the costs of pollution load reduction in the river. In this equation, c_i is the treatment cost of ith pollutant source, and depends on the quantity of treated effluent, and in other words, is a function of the pollution load of unit i after pollution trade (e_i).

Equation 2 gives the pollution load of each unit by taking the traded quantities into consideration. According to this equation, pollution load should be traded such that water quality at checkpoints (after trading) meets the predetermined standards. The first term on the right represents the quantity of pollution load bought by unit i from unit k. The second term on the right represents the quantity of pollution load sold by unit i to other units. In this equation, t_{ki} is the trading-ratio between zones i and k, T_{ik} is the pollution load sold by unit i to unit k, and T_i is the size of initial discharge permit of unit i (kg). It should be noted that upstream units cannot buy pollution load permits from downstream units.

Equation 3 shows that the volume of traded pollution is non-negative. Finally, Eq. 4 shows that pollution load discharged by unit i after the trade cannot exceed its initial pollution load (e_i^0). This limitation meets the lack of increase for pollution load entering the river after trading process.

Reviewing the literature (Montgomery 1972; Krupnick et al. 1983; McGartland 1988; Hung and Shaw 2005), it can be found that the trading-ration system (TRS or ETRS) is of a quite superiority compared to other trading systems in transaction costs. The transaction costs in this system are less than other ones due to the awareness of dischargers and authorities from trading-ratios and the lack of need for series trade of discharge permits related to all the influenced points (Hung and Shaw 2005). Also, in this system, in a trading process between two polluting sources, one of them is seller getting benefit, and on the contrary, the other source is purchaser and must pay cost. Hence, the total system profits and losses is equal to zero and the permit cost is not considered in the objective function of the optimization model. Therefore, the total costs in the conditions of pollution trading are only including treatment costs and it is neglected from the cost of transactions and permits.

Additionally, another positive feature of the TRS (ETRS) system is the consideration of environmental constraints at the standard limits (as limiting constraints). In the ambient-permit system (APS) method, because of providing the constraint corresponding to the maximum allowable pollution (pollution in the standard limit) at each receptor check point of pollutant in order to establish the condition of intersection of trade balance point with the least economic costs, limiting and sometimes unattainable conditions are created (Montgomery 1972; Krupnick et al. 1983). Also in the exchange-rate emission trading system (ERS) method, if environmental constraints are not among the limiting constraints (i.e., environmental conditions are not placed at the limit of violation of standards), the trading balance point is not the economical answer of the problem (Hung and Shaw 2005). Hence, generally in these two methods, given that the environmental constraints are not simultaneously the limiting constraints for all receptor check points of pollutant, having an initial allocation of tradable discharge permits is very difficult. However in the TRS system, considering one-dimensional nature for movement of pollutants in the water, the approach of capacity consideration makes the environmental constraints as the limiting constraints in each region. In other words, the environmental conditions would be simply placed in the boundary of violation of standards, for each region (Hung and Shaw 2005).

Case study

The area selected for the case study is a 24 km long section of the Zarjoub River, which starts from the outskirts of the city of Rasht and flow northward until reaching the Caspian Sea. The geographic location of the Zarjoub River is shown in Fig. 2.

The reasons for choosing the Zarjoub River as the case study can be summarized as follows (Iran Water Resources Management Company 2013; Iran Department of Environment 2005): (1) severe pollution of the Zarjoub River due to reception of industrial wastewater, agricultural effluents, and untreated sewage of all urban and rural communities in the area. (2) The major role of the Zarjoub River in agriculture and industry activities and consequently municipal services. (3) Economic importance of the Zarjoub River in terms of tourism as well as fish reproduction and pisciculture activities. (4) Considering that data available on Iran's rivers is largely limited to river water quality and information on the quality and quantity of pollutant sources is scarce, simultaneous sampling of river water quality and pollutant sources can provide valuable data.
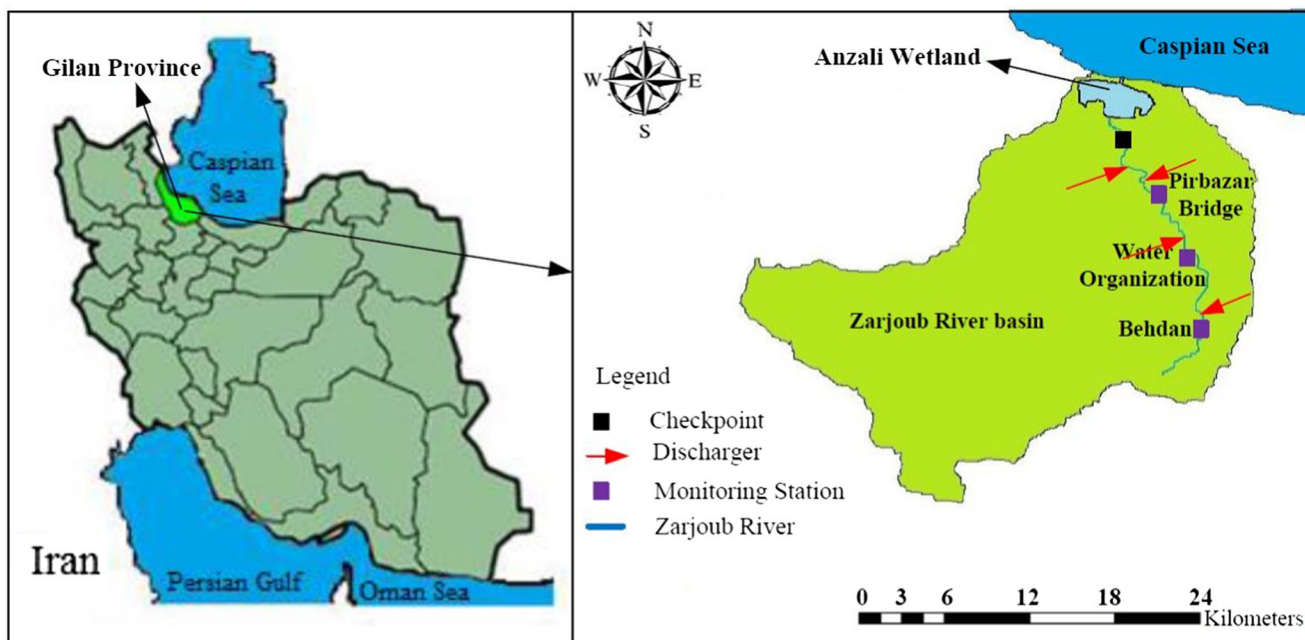
Fig. 2 The location of Zarjoub River system

Pollutant sources and treatment scenarios

Considering the lack of information on industrial and agricultural sources that discharge pollution into the studied river, this paper uses only the information on four point sources of pollution, all of which are municipal wastewater transferred separately to treatment plants. To find the optimal pattern of treatment and trading of discharge permits, the treatment of each pollutant source is defined in 4 scenarios representing different combinations of full treatment and preliminary treatment of wastewater. These four scenarios are full treatment of 0, 30, 60 and 90% of the incoming wastewater. For example, in the scenario of 60% full treatment, 40% of the wastewater entering the treatment plant undergoes preliminary treatment including pre-treatment, primary sedimentation and chlorination and then joins the remaining 60% of wastewater, which have been fully treated, and the mixture will be released in the river. In other words, the preliminary treatment removes bacteria, pathogens, and some of the solids in the wastewater, and slightly reduces the BOD of this part of the wastewater.

Table 1 shows the quantitative and qualitative information recorded at the upstream control point of the Zarjoub River and Table 2 shows the characteristics of pollutant sources and the BOD of treatment plant output in different scenarios. The BOD of treatment plant output is calculated based on the BOD concentrations and the flow rate of wastewater entering the treatment plant, and the assumption of removal of 90% of BOD in full treatment and assumption of removal of 30% of BOD in preliminary treatment.

Treatment costs

Pollutant sources of the study area are assumed to be only municipal wastewater, so the treatment costs of municipal wastewater to be entering the river is estimated through a scenario-based approach. The cost analysis of municipal wastewater treatment usually depends on plant's capacity in terms of covered population (Tsagarakis et al. 2003). The most important parts of a treatment cost are the cost of land, the cost of construction and the annual cost of operation. The cost of land and construction on which treatment plant will be constructed is usually covered by the government. On the other hand, analyzing the operational costs of the municipal wastewater treatment is performed based on the plant's capacity (the population covered) and the quality of its output wastewater (no violation of the standards for discharge into the river). Hence, the operational costs are influenced by the percentages of treatment and are paid by dischargers. Therefore, in the decision-making model, treatment costs includes only the operation costs (land and construction costs are disregarded).

Economic analysis conducted in this paper is based on municipal wastewater treatment system via activated sludge process. Such treatment plant consists of preliminary

Table 1 The quantitative and qualitative characteristics related to the upstream of the Zarjoub River (Iran Water Resource Management Company 2013)

Flow (m³/s)	Temperature (°C)	DO (mg/L)	BOD (mg/L)
0.117	24	7.51	5

Table 2 General properties of pollutant sources and the BOD concentration of treatment plants output (Iran Water Resource Management Company 2013)

Discharger	Wastewater flow (m³/s)	BOD concentration (mg/L)	Population (person)	BOD concentration of treatment plants output (mg/L)			
				Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	0.083	100	39,840	70	52	34	16
2	0.414	46	198,720	32	24	16	7
3	0.217	98	104,160	69	51	33	16
4	0.149	180	71,520	126	94	61	29

treatment, primary sedimentation, aeration, secondary sedimentation, chlorination, concentration, digestion, and mechanical dewatering (Iran Water Resource Management Company 2013). Operating costs mainly consists of four parts: personnel, energy, chemicals, and maintenance (Tsagarakis et al. 2003). In Iran, these parts constitute, respectively, about 55, 18, 8, and 10% of the annual operating cost of a municipal wastewater treatment plant.

Generally, the annual operating costs of full treatment of municipal wastewater are considered to be US$2 per person for a plant covering a population of 10,000 and 100,000 people and US$1 per person for a plant covering a population of more than 100,000 people. The annual operation cost of preliminary treatment units are estimated to be 10% of their counterparts in full treatment (Iran Water Resource Management Company 2013). The annual operational costs (APCs) of treatment can be obtained by using the following linear function:

$$APC = Ti \times (Pi \times Ci) + [(0.1 \times Pi \times Ci) + (1 - Ti)] \quad (5)$$
$$= Pi \times Ci \times (0.9 \times Ti + 0.1)$$

In this equation, the parameters *T*, *P*, and *C* respectively denote complete treatment percentage, the population covered, and the annual operational cost of per person for *i*th pollutant source. The annual operation costs (APCs) pertaining to each pollutant source in different scenarios are provided in Table 3.

Results and discussion

Treatment alternatives are formed based on the treatment scenarios assumed for the wastewater dischargers. For example, the alternative referred to as 2431, is the one resulted from assuming scenarios 2, 4, 3, and 1 for the first to fourth dischargers, respectively. The total number of treatment alternatives is 256. In the following, the broken-down and detailed results of simulation model, stochastic decision-making and optimization parts of the process are provided.

Simulation model

To investigate the changes in water quality of the Zarjoub River, the water quality of the part located between the Behdan station at the upstream side of the Rasht city and the Golsar station at the downstream side of this city is simulated. Running the QUAL2Kw model requires some qualitative and quantitative inputs; and considering that most critical qualitative condition of the Zarjoub River has been recorded on October 2005, the data pertaining to this month is used for simulation. Assessment of qualitative variables measured for this river show that BOD and DO concentration exceed the standards, so qualitative variable BOD5 and DO are considered to act as, respectively, the pollution load and the water quality control indicators. To minimize the difference between calculated and observed DO and BOD values along the river, the coefficients defining the reactions of these parameters are calibrated using the genetic algorithm provided in the simulation model. The mean required time for automatic calibration of the model and determining the coefficients and constants of the reactions by using a system with the characteristics of Intel Corei5@2.3 GHz CPU, is about 1 h.

Table 4 shows the calibrated coefficients of the model. In this table, the decay rates of DO and BOD respectively indicate that in a river system, what ratio is reduced from the concentrations of DO (due to consuming by the organisms existing in the water) and BOD, per unit of time (e.g., 1 day). The more the amount of these coefficients are, indicates the faster the chemical and biological reactions in the water and decomposition of pollutants are ongoing. Moreover, the settling and oxidation rates of BOD respectively indicate that in a river system, what ratio of the BOD concentration is reduced by sedimentation and due to reaction with oxygen and oxidation process, per unit of time (e.g., 1 day) (Bowie et al. 1985; Chapra 2008; Karamouz and Kerachian 2011). In addition, in this paper, the aeration coefficient along the river is determined by equation (O'Connor and Dobbins 1958) that is usually used in operational works and also exists in the QUAL2Kw model.

Figure 3 shows the changes in dissolved oxygen (DO). The Zarjoub River passes through urban areas with a ground surface slope lees than 1% (Iran Water Resource Management

Table 3 Treatment costs (US Dollars)

Treatment scenarios	Discharger 1	Discharger 2	Discharger 3	Discharger 4
1	7968	19,872	10,416	14,304
2	29,482	73,526	38,539	52,925
3	50,995	127,181	66,662	91,546
4	72,509	180,835	94,786	130,166

Table 4 Constant coefficients of Do and BOD reactions in the calibrated model of the Zarjoub River

BOD decay (1/day)	BOD settling (1/day)	DO decay (1/day)	BOD oxidation rate (1/day)
0.4	0	0.6	4.95

Company 2013). Therefore, the variation of the DO concentration at the upstream is not due to passing from mountain regions, but is related to the location of discharging pollution loads, along the river path (Karamouz and Kerachian 2011). The variations of DO concentration along the river (Fig. 3) is so that, the first discharger enters its pollution load at a relatively small distance from the river upstream (a distance of 0.5 km from the upstream), thus, the DO concentration strongly reduces near this location. Thereafter, by providing required opportunities of self-purification of river, the DO concentration will increase, gradually. At the middle of the river path (14-km distance from the upstream), the second discharger enters its load into the river and the DO concentration reduces with a relatively steep trend. Next, regarding that the third and fourth polluting sources discharge their pollution loads into the river in an almost small distances (respectively at 21.6 and 23.4 km from the upstream), the river does not have adequate time for self-purification and as is seen, the DO concentration continues its reducing trend with a relatively steep slope.

According to Fig. 3, the DO_{sat} concentration is increasing along the river path. This increase has a relatively steep change up to the middle of the river and thereafter, it has an almost slow increasing change. In the QUAL2Kw model, DO_{sat} concentration is considered as a function of water temperature and elevation above sea level (Chapra et al. 2012) and determined using the (APHA 1995) equations. According to these equations, the DO_{sat} concentration has an inverse relation with the water temperature and elevation above sea level.

Figure 4 shows the variation of water temperature along the river. As can be seen in the figure, the water temperature has a decreasing trend. This decrease is of relatively steep changes up to the middle of the river and an almost slow trend after that. It is therefore expected that by reducing the water temperature, the DO_{sat} concentration have an increasing trend. In addition, investigation into the data obtained from hydrometric stations (Iran Water Resource Management Company 2013) shows that the variations of elevation above sea level along the river has a relatively steep decreasing trend. Hence, the DO_{sat} concentration will increase proportional to this relatively high loss.

Also, Fig. 5 shows the changes in the observed and simulated BOD values along the river. Comparing the observed

and calculated values indicates that the coefficients used for calibration have produced good estimates of qualitative variables.

After calibrating the simulation model, transfer coefficients and trading-ratio coefficients to be used in the optimization model are determined. If a violation of water quality standards (concentration of DO less than 3.5 mg/L) occurs, the treatment alternative is assigned with a cost acting as the penalty of violation. In this paper, concerning the lack of national standards for quality evaluation of water resources in Iran (Karamouz and Kerachian 2011; Iran Water Resource Management Company 2013), it has been used from the standard of France (Krenkel and Novotny 1980) in order to determine a standard limit for DO concentration. So that, according to Iran's climatic and economic conditions, water quality of group II in the France's standard is applicable for most of rivers in Iran (Karamouz and Kerachian 2011). According to this standard, the allowable concentration of DO is placed at [3, 5]. Hence, a concentration of 3.5 (mg/L) is considered as allowed limit in this paper.

The penalty function is calculated based on a linear regression between the values of violation and the extra costs of further treatment necessary to regain that standard (Alberini 2006). Therefore, in order to determine the amounts of violation from quality standard and regarding that the pollutant in this study (BOD) is a non-conservative pollutant that its concentration will be changed along the river path under the effects of quantitative and qualitative conditions and the river self-purification capacity, it is required to implement the water quality simulation model. The QUAL2Kw model performs the qualitative simulation of the river based on its quantitative, qualitative, and hydraulic properties (such as the river slope and length). Thus, it observes the effect of self-purification capacity in assessment of river water quality condition. The amount of violations is determined by execution of quality simulation model under different BOD removal percentages (at least 30 samples). The following equation shows the proposed penalty function:

$$P = 106.1X \qquad (6)$$

In this equation, P is the penalty in US dollars and X is the degree of violation of DO from the standard at the checkpoint (mg/L). The penalty is fairly allocated to each wastewater dischargers based on its choice of treatment scenario (the

Fig. 3 DO concentration changes along the Zarjoub River (mg/L)
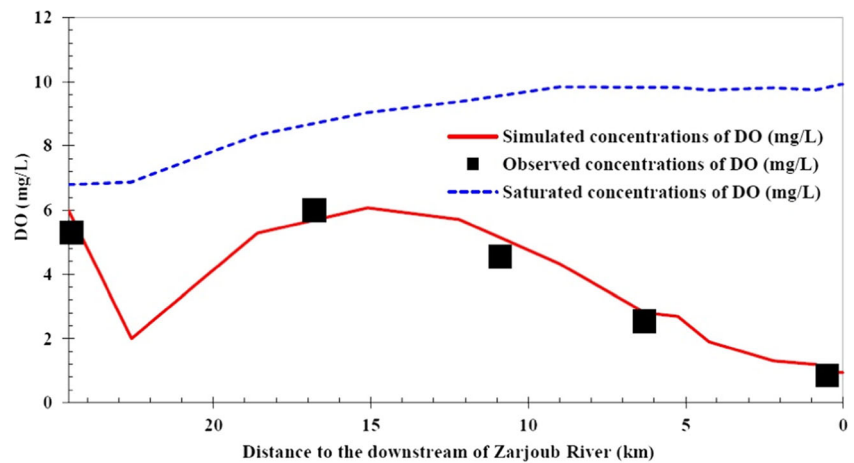
percentage of full treatment). Therefore, a discharger unit with the selection of a less extensive treatment scenario (lower percentage of full treatment) will pay a higher share of penalty, and vice versa. In this paper, it is assumed that discharger units that have chosen scenario 1, 2, 3, and 4 must pay, respectively, 4, 3, 2, and 1 share(s) of total penalty.

Stochastic decision-making model

Estimation of treatment costs and penalties is subject to error and uncertainty, so the best alternative must be selected through a stochastic decision-making process. Pessimistic stochastic decision-making model used in this paper makes simultaneous use of Monte-Carlo simulation and the fallback bargaining methods. This model makes a number of random selections in regard to the range of outcomes of each treatment alternative (sum of treatment cost and violation penalty). Each instance of random selection produces 256 numbers (outcomes of treatment alternatives). Since information about the treatment cost in Iran is quite limited, random numbers are generated based on a normal distribution function. The number of iterations for generation of random numbers is considered to be 50,000. After each random selection, each

discharger prioritizes its treatment alternatives based on their outcomes producing as a result a 4 × 256 bargaining matrix.

Next, different fallback bargaining methods are used to determine the best treatment alternative (the one with the highest probability of winning) for each of the 50,000 bargaining matrices. stochastic unanimity fallback bargaining (SUFB) method identifies, among 256 treatment alternatives, the one that can satisfy all bargainers by ensuring the least amount of fall back from their most desirable solutions. Using this method, the best alternative is determined to be the treatment alternative 4444.

In stochastic fallback bargaining with impasse (SFBI) method, each discharger is assigned with a selection threshold, which is the alternative that has a maximum cost as much as 90% of the highest cost imposed to that discharger. Applying different thresholds shows that when the maximum cost imposed on the bargainers is less than this value (90% of the highest cost imposed) negotiation goes to a stalemate (fails). In the next step, the best alternative is chosen through a bargaining process. In this case, 10 treatment alternatives are accepted into the agreement set. Using the Borda scoring method, the outcome of negotiation is determined to be the treatment alternative

Fig. 4 Water temperature variations along the Zarjoub River (^{0}C)
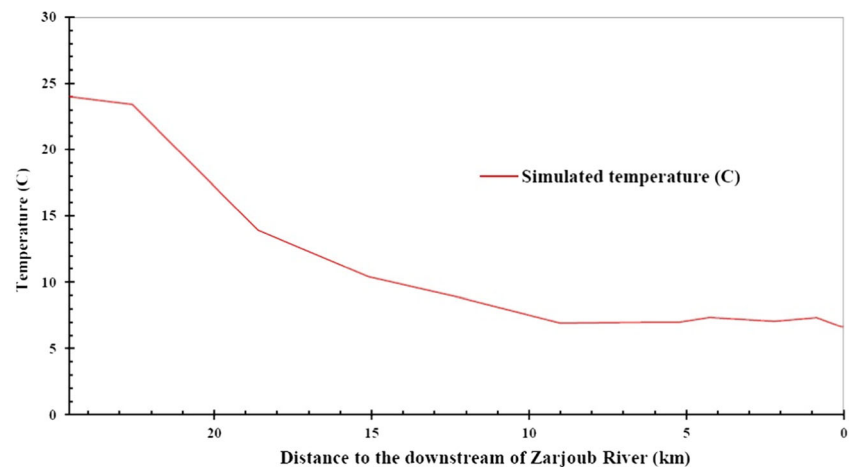
Fig. 5 BOD concentration changes along the Zarjoub River (mg/L)
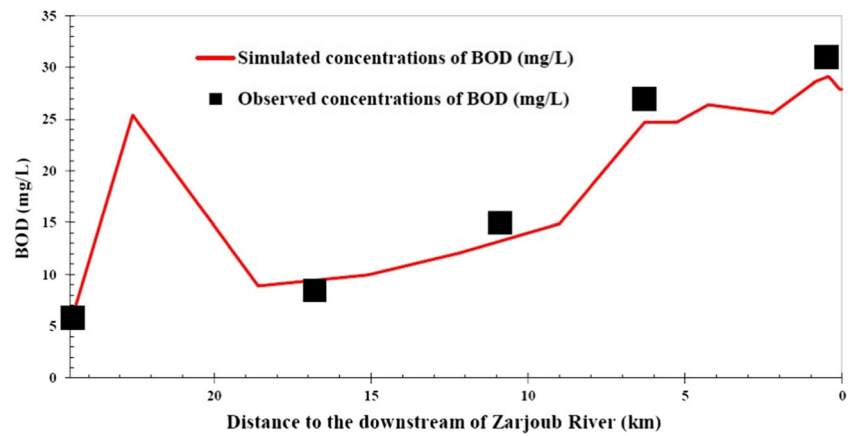
4441. In stochastic quota approval fallback bargaining (SQAFB) method, the best treatment alternative is the one that is accepted by at least 3 wastewater dischargers. The best alternative is determined in two modes: (i) with a stalemate threshold for the desirability levels and (ii) without stalemate threshold. Stalemate threshold is set to 90% of the highest cost imposed. In both modes, the outcome of negotiation is determined to be the treatment alternative 1444.

Details of alternatives chosen by different stochastic fallback bargaining methods are provided in Table 5. As can be seen, in the SUFB method, all discharger have chosen the same treatment scenario, so they must pay equal penalties. In the SFBI and SQAFB methods, dischargers 4 and 1 have chosen a less extensive treatment scenario (lower percentage of full treatment) so they have to pay greater penalties. These examples show the fairness in the allocation of penalties resulted from violations of quality standards.

Each fallback bargaining method produces a different output. The result of UFB method is the more desirable than that of QAFB, as it guarantees a level of desirability for all dischargers. With the same reasoning, if dischargers be given more freedom in choosing their desired alternatives and be able to set a minimum level for their choices, the results of FBI method will be better than the results of quota fallback bargaining with impasse (QFBI). So it seems that the choice of best fallback bargaining method for solving the pollution load allocation problem depends heavily on the problem condition. For example, if the intention is to use the fallback bargaining method for pollution allocation in a real project, the FBI method is more recommended, as it improves the executability of the quality management programs and motivates wastewater discharger to participate. However, if different importance of different dischargers need to be incorporated into the bargaining process, the use of QAFB method may be more appropriate.

The alternatives chosen by different stochastic fallback bargaining methods are compared based on their costs. The alternative that imposes the lowest cost is identified as the best alternative of the fallback bargaining approach. It should be noted that the cost defined as violation penalties (the extra cost of regaining quality standards) in each treatment alternative is a form of guarantee for the preservation of river water quality criteria, so treatment alternatives are compared based only one cost. According to Table 5, the result of the SFBI method is the ultimate result of fallback bargaining approach for pollution allocation in the river.

Optimistic stochastic decision-making model ranks the treatment alternatives based on different multi-criteria decision-making based on distance methods. Like the pessimistic model, this model uses the Borda scoring method to produce the desirable treatment alternative for each of the 50,000 4×256 decision matrices (256 treatment alternatives and 4 decision-making methods). Again, the alternative with the highest probability of winning is selected as the best one. The output of this model is treatment alternative 3333, which has 73% winning probability, imposes a US$ 637,052 cost on the system, and results in a 1.83 (mg/L) for concentration of DO at the downstream checkpoint.

At this stage of the work, the stability index method is used to evaluate the executability of treatment alternatives selected by pessimistic and optimistic approaches. To do so, the alternatives selected by these approaches are compared with the alternative selected by stability index method. The output of stability index is the treatment alternative 2222, which has a total cost of US$ 522,739.

Comparing the costs imposed on each discharger by pessimistic and optimistic solutions with stability index shows that dischargers participating in pessimistic decision-making process are more satisfied with the allocated costs. Furthermore, dischargers seem to have little regard for optimistic approach to pollution load allocation policies. So in this approach, giving due attention to the stability (stakeholders' willingness to cooperate in the negotiation process) of pollution load allocation policies is essential.

Table 5 Characteristics of each treatment alternatives selected by different stochastic fallback bargaining methods

Bargaining method	Discharger	Selected scenario	Treatment cost (USD)	Penalty cost (USD)	Total cost (USD)	DO concentration at the checkpoint (mg/L)	Winning probability (%)
Stochastic unanimity fallback bargaining (SUFB)	1	4	72,509	39,333	111,842	2.08	56
	2	4	180,835	39,333	220,168		
	3	4	94,786	39,333	134,119		
	4	4	130,166	39,333	169,499		
	Sum	–	478,296	157,332	635,628		
Stochastic fallback bargaining with impasse (SFBI)	1	4	72,509	33,700	106,209	1.64	76
	2	4	180,835	33,700	214,535		
	3	4	94,786	33,700	128,486		
	4	1	14,304	134,733	149,037		
	Sum	–	362,434	235,833	598,267		
Stochastic quota approval fallback bargaining (SQAFB)	1	1	7968	108,500	116,468	1.71	59
	2	4	180,835	27,133	207,968		
	3	4	94,786	27,133	121,919		
	4	4	130,166	27,133	157,299		
	Sum	–	413,755	189,899	603,654		

Effluent trading optimization model

Effluent trading can act as a group incentive for wastewater dischargers to maximize their total discharge while minimizing their discharge costs. This approach is also an incentive for future technological innovations aimed at reducing the volume of wastewater and consequent costs. Effluent trading optimization model developed in this paper determines not only the optimal treatment level and treatment costs of discharger units, but also the optimal pattern of trade of discharge permits among dischargers.

The effluent trading optimization model is solved in the GAMS software environment. The model is consisted of four equations (Eqs. 1 to 4) and is developed for four pollutant sources. The decision variables of the model are including the treatment percentage of each pollutant source after trading (a number of four decision variables equal to the number of pollutant sources) and the trading volume between each pair of pollutant sources. The number of decision variables of the trading volume is equal to 16 (bilateral trades between the four pollutant source). It is obvious that each discharger unit cannot enter bilateral trading with itself, thus, four decision variables have a value equal to zero (being zero the value of these variables is determined with regard to being zero the corresponding trading-ratio coefficients). Moreover, since the upstream units cannot buy pollution load from the downstream units (Eq. 2), a number of six decision variables are thus of a value equal to zero. Finally, the number of the decision variables of the model having a non-zero value will be equal to six.

Treatment alternatives chosen by the pessimistic and optimistic approaches, i.e. alternatives 4441 and 3333, are considered as the initial pollution discharge permits. Then, the effluent trading optimization model is executed and the permits are exchanged among pollutant sources. Table 6 presents the summary of results obtained from the two pollution trading models.

The results of the first model show that the optimal pattern of trade is between source 2 and sources 3 and 4. In this pattern, source 2 sells permits equivalent to 30 and 18 kg/day) of BOD discharge to sources 3 and 4, respectively (source 1 does not participate in the trade). According to this table, the total profit of implementing the pollution trading process in the studied area is US$ 14,834. Implementation of trading process increases the costs of discharger 4, which participates in trading, and decreases the costs of discharger 1, which does not participate. Dischargers 1 and 3, which receive considerable profits, can easily compensate for the increased cost of discharger 4 and even give some profit to this discharger.

The results of the second model show that the optimal pattern of trade is between source 1 and sources 2, 3, and 4, between source 2 and sources 3 and 4, and finally between source 3 and source 4. In this pattern, source 1 sells 33, 27, and 27 kg/day of BOD discharge permits to sources 2, 3, and 4, source 2 sells 80 and 76 kg/day of BOD discharge permits to sources 3 and 4, and source 3 sells 73 kg/day of BOD discharge permits to source 4. In this pattern, the total profit of implementing the pollution trading process in the studied area is US$ 218,852. Since all discharger participate in the trade, implementing the model triggers a significant cost reduction, which encourages dischargers to participate in river water quality protection program.

Table 6 The results of optimization model

Model	Discharger	Traded BOD load (kg/day)	Total cost in initial permits condition (USD)	Total cost in trading permits condition (USD)
Effluent trading with pessimistic approach	1	–	106,209	78,533
	2	48 (sales)	214,535	238,433
	3	30 (purchase)	128,486	108,700
	4	18 (purchase)	149,037	157,767
	Sum	0	598,267	583,433
Effluent trading with optimistic approach	1	87 (sales)	126,162	71,133
	2	156 (sales), 33 (purchase)	202,348	177,367
	3	73 (sales), 107 (purchase)	141,829	87,000
	4	176 (purchase)	166,713	82,700
	Sum	0	637,052	418,200

Conclusion

This paper presented a new framework for the study of executability of effluent trading policies in river systems. The two approaches of pessimistic and optimistic decision-making under uncertainty were used to determine the treatment alternative that can satisfy dischargers. By providing the possibility of direct consideration of the desirability of dischargers, these approaches could lead to increase the executability of the pollution trading programs. These pessimistic and optimistic approaches were realized with fallback bargaining and MCDM based on distance methods. Due to presence of uncertainty in the estimation of treatment costs and penalties for violations of water quality standards, they were formulated with a stochastic approach and obtained through Monte-Carlo simulation method. This approach gave each discharger a certain degree of knowledge about the risks associated with its alternatives.

In this paper, the stochastic nature was regarded only for the economical payoff resulting from the implementation of a treatment alternative and it was neglected from the uncertainty of other important variables such as the river flow, water temperature, reactions' coefficients, etc. Based on the proposed method, in the estimation of treatment costs and penalties, which are respectively influenced by the pollution load of each discharger and the concentration of the index quality variable, it is dealt with the influence of uncertainty of other parameters, indirectly and generally. In such a way that, taken into consideration the uncertainty for treatment costs indicates that, the stochastic nature is indirectly adopted for amount of pollution load. Moreover regarding that the penalty values are determined based on the concentration of the index quality variable and by the water quality simulation model that observes the effect of different factors such as the river flow and water temperature, taking uncertainty into consideration for penalty values represents the indirect attention to the stochastic nature of other important variables. Nevertheless, it is

recommending to directly consider the uncertainty of other variables in the simulation process in the future studies.

The efficiency of the proposed models was evaluated by the use of information regarding the Zarjoub River in northern Iran (Gilan Province). Treatment alternative chosen by the fallback bargaining approach and determined as the final solution provides relative satisfaction for all dischargers. While, the result from the MCDM approach is less agreed by the dischargers. The reason for such a finding must be sought in the nature of each of these approaches. In waste load allocation problem, according to the conditions, there could be the possibility of full cooperation or the lack of cooperation among different dischargers. In general, each dischargers seeks for maximizing its desirability (reducing treatment costs) and as a result, stakeholders in the decision-making process follow a non-cooperative behavior. Concerning that the possibility of cooperative behavior among dischargers is less in real conditions, it seems that the results obtained from modeling of non-cooperative behavior of the stakeholders would be more accepted due to more similarity to the real conditions. Of course, the results of the present study also confirms this conclusion.

In addition to similarity to real conditions, the mechanism existing in each of the pessimistic and optimistic decision-making approaches is significance in the best option selection. The mechanism of the best option selection in the pessimistic decision-making approach is based on prioritization of options by each of the claimants and performing the process of negotiation to reach an agreement of the majority or all. Thus, according to the theorems and theoretical concepts presented in (Brams and Kilgour 2001), such a mechanism will lead to provide the least desirability for all claimants and consequently the stability of the output of the pessimistic approach. On the other hand, the mechanism of the best option selection by the optimistic decision-making approach is based on evaluation of criteria from the view of an equivalent decision-maker. In this mechanism, in addition to optimal distribution of

dissatisfaction among the claimants, since it is attempted that the group of decision-makers become a decision-maker, the dynamic state of power existing among the group of decision-makers in the real conditions, is not considered. Thus, in this approach, being agreed a decision-making law by all of the claimants could not be guaranteed. The results of the present paper showed that the pollution load allocation policies are not so acceptable. Therefore, it is generally required that the executability of the outputs of the optimistic decision-making model be investigated by using stability testing methods.

The alternatives chosen by decision-making approaches were used as initial discharge permits, which were traded using an optimization model. The pollution trading approach not only satisfied the environmental standards but also reduced the cost of treatment.

In this paper, some of the different aspects of the pollution trading approach are considered as follows:

- One of the main advantages of the pollution trading approach is reduction in the costs imposed on the system in order to improve the river water quality, without doing structural measurements and only through exchanging of discharge permits. Similar to the previous researches (Hung and Shaw 2005; Sarang et al. 2008; Mesbah et al. 2009, 2010; Niksokhan et al. 2009a, b; Mahjouri and Bizhani-Manzar 2013; Nikoo et al. 2016; Zolfagharipoor and Ahmadi 2016), the results of this study show that the total costs of system are reduced in comparison with the case without trading.

- Based on being non-conservative of the trading pollutant, different methods have been considered for river water quality simulation. These methods are including solution of analytical equations such as the Streeter-Phelps equation (Niksokhan et al. 2009a, b; Mesbah et al. 2010) and numerical solution of diffusion, advection and deterioration equations of important quality parameters in rivers by using software such as various models of QUAL2Kw (Mahjouri and Bizhani-Manzar 2013; Nikoo et al. 2016; Zolfagharipoor and Ahmadi 2016). Also in this paper, regarding the necessity of investigating locational variation of pollutants' concentration, it has used the QUAL2Kw software.

- In the previous studies of pollution trading, using different methods such as multi-objective optimization (Mesbah et al. 2009, 2010; Niksokhan et al. 2009a), game theory (Niksokhan et al. 2009b; Nikoo et al. 2016), and bargaining approaches (Mahjouri and Bizhani-Manzar 2013), it has been dealt with conflict resolution between the parties such as the environmental organization and pollution sources about improvement of the river water quality and reduction of treatment costs. However in this study, in addition to considering economic efficiency and environmental sustainability criteria, the executability of pollution trading policies are also taken into consideration by applying pessimistic and optimistic decision-making approaches.

- In the previous studies, the analysis of uncertainty conditions corresponding to the affecting factors in the pollution trading process (such as treatment costs, quality standards, quantitative and qualitative parameters of river, coefficients related to quality reactions and pollution load transferring coefficients) has been conducted by different methods such as fuzzy theory (Niksokhan et al. 2009a, b; Mesbah et al. 2009, 2010), probabilistic models (Niksokhan et al. 2009b; Mesbah et al. 2009; Zolfagharipoor and Ahmadi 2016), and interval models (Nikoo et al. 2016). In this paper, the stochastic nature of treatment costs and violation penalties have also been taken into consideration by using probabilistic approach.

- Similar to the previous studies (Mahjouri and Bizhani-Manzar 2013; Nikoo et al. 2016; Zolfagharipoor and Ahmadi 2016), the actual conditions of each treatment plant in terms of technical and technological equipment have been considered by the use of scenario-based viewpoint of treatment rather than continuous percentages of treatment (Hung and Shaw 2005; Sarang et al. 2008; Mesbah et al. 2009, 2010; Niksokhan et al. 2009a, b).

The limitation of proposed methodology can be addressed as follows:

- By adding more pollutant sources, the number of treatment alternatives increases. Therefore, the process time for selecting the best alternative using each of the decision-making approaches will be prolonged due to increasing of the dimension of decision-making and bargaining matrixes. Also, the reality about the cooperative (optimistic decision-making) or non-cooperative (pessimistic decision-making) behaviors among pollutant sources is independent to the number of the persons involved in the decision-making process but depends on their behavioral essence. In other words, by increase in the number of pollutant sources, the general results obtained from the proposed model (stability of results) would not be changed.

- The QUAL2Kw model has the ability of considering tributaries, in such a way that it considers each of the tributaries similar to the river's main stem as a segment and for each segment, it plots the diagrams corresponding to the output results. However in this paper, the studied river does not contain significant tributaries (Iran Water Resources Management Company 2013) and thus, the influence of the presence of the tributaries on the water quality simulation process is not considered.

- In this paper, regarding that there are no adequate data about other pollution indices, the pollution trading model is developed only for the BOD pollution load. However, the method proposed is capable of being generalized to more than one pollutant. If another pollutant is added to the modeling process, the stochastic decision-making process is first run for each of the pollutants, separately. Then by entering the superior treatment policies of each pollutant into the optimization model, the trading volume and its pattern among different pollutants will be determined for each one, separately. The objective function of the model consists of the total reduction in the treatment costs of each pollutant load, regarding its pollutant source. The trading-ratios for each pollutant will be determined, separately. Also, Eq. 2, which denotes the need to preserve the environmental capacity of the river, will be written for each of the pollution loads, separately. Please refer to (Nikoo et al. 2016) for more information about details of modeling and how to formulate the pollution trading model for multiple pollutants.

Future research can be focused on providing incentives for further cooperation of dischargers in trading through fair allocation of benefits resulted from cost reduction. Furthermore, in the presence of sufficient information, the work can be extended to include not only the point sources but also the non-point sources of pollution and the interaction between groundwater and surface water. In the other hand, it is proposed that in order to consider the effectiveness of the uncertainty analysis method, it could be used from other methods such as quasi Monte-Carlo simulation, which have no problem of accumulation of samples in a part of the sampling space, comparing their results with the Monte-Carlo method.

Appendix

Minimax

The Minimax method minimizes the maximum overall dissatisfaction of all bargainers with regard to the ideal solution, assuming that they have an adequate knowledge about available solutions. This method is particularly useful for those decision-making problems in which severe dissatisfaction of a stakeholder can result in failure of negotiation process (Read et al. 2014). Thus, this method seeks to distribute dissatisfaction homogeneously and uniformly among all stakeholders to reduce the probability of

failure due to uneven distribution of dissatisfaction. The formula of this method is as follows:

$$\text{Min} \quad \text{Max} \left\{ \frac{f_{i,j} - f_i^*}{f_i^*} \right\}, \forall i, \forall j \tag{7}$$

In this equation, $f_{i,j}$ is the share allocated to bargainer i by allocation method j and f_i^* is the ideal share of bargainer i.

Maximin

In contrast to the previous method, the maximin method maximizes the minimum satisfaction of stakeholders with the decision. This method increases the executability of output decision by reducing the disparities in the distribution of dissatisfaction among bargainers (Read et al. 2014). The formula of this method is as follows:

$$\text{Max} \quad \text{Min} \left\{ \frac{f_{i,j}}{f_i^*} \right\}, \forall i, \forall j \tag{8}$$

- Compromise programming

This method (Zeleny 1973) calculates the distance of each management option from the ideal solution and identifies the one closest to this ideal point as the best option. The formula of this method is as follows:

$$\text{Min} \quad L_P = \left[\sum_{i=1}^{m} \left| \frac{f_{i,j} - f_i^*}{f_i^- - f_i^*} \right|^p \right]^{1/p}, \forall i, \forall j \tag{9}$$

In this equation, L_p is the undesirability and f_i^- is the lowest share of bargainer i. Parameter P values between 1 and infinity and expresses the importance of maximum deviation from the ideal solution. When P is 1, all distances (from the ideal point) have the same effect on L_p, but when P value increased, the greater distances have more effective on undesirability of each option (Read et al. 2014). In this paper, P is 1.

Least squares analysis

The least squares analysis method minimizes the total dissatisfaction of all stakeholders but makes no distinction between the dissatisfaction of individual stakeholders (Read et al. 2014). This method identifies the solution with the lowest overall dissatisfaction (the minimum value of sum of square

of distances from the ideal solution) as the best option. The formula of this method is as follows:

$$Min \sum_{i=1}^{m} \left(\frac{f_{i,j} - f_i^*}{f_i^*} \right)^2, \forall i, \forall j \quad (10)$$

Stability index

The stability index concept, which has extensive use in economics applications, has also been used to measure the stability in cooperative games and cost allocation problems (Loehman et al. 1979). In this paper, the stability index method is used to assess the executability of the proposed option. The formula of this method is as follows:

$$\alpha_i = \frac{\left(f_{i,j} - f_i^* \right)}{\sum_{i=1}^{m} \left(f_{i,j} - f_i^* \right)} \quad \forall i, \forall j \quad (11)$$

$$\sum_{i=1}^{m} \alpha_i = 1 \quad (12)$$

$$SI = \frac{\sigma}{\overline{\alpha}} \quad (13)$$

In the above equations, α_i is the power index of bargainer i, σ is the standard deviation of bargainers' power, $\overline{\alpha}$ is the mean value of bargainers' power, and SI is the stability index.

According to this concept, the best solution is the one that maximizes stability through uniform distribution of dissatisfaction among bargainers (Read et al. 2014). Larger values of this index signify that dissatisfaction levels of bargainers are close to each other, and there is therefore a lower probability of failure in negotiation process.

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