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Optimization of Pollutant Discharge Permits, Using the Trading Ratio System: A Case Study

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Abstract: Water quality management of rivers is one of the challenges in the analysis of water resource systems. The optimal operation of the pollutant carrying capacity of these systems provides significant economic value and could reduce treatment costs. In this study, the application of the trading ratio system is investigated to control the cost of pollutants in a river and make a fair deal. In this regard, transfer coefficients between pollution sources, along with the trade coefficients, are determined, considering the system limitations and each pollutant's contaminant impact. To provide allowable limits of river water quality concentrations, the total cost of all sources and the system is minimized, using the linear programming method. Finally, the new trading discharge permits are calculated for each source. The proposed method is successfully applied to Dez River as a case study. Results show that using a trading ratio system could maintain water quality at a standard level containing economic benefits for the participants of this program.

Keywords: discharge permits; trading ratio system; optimization

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1. Introduction

Rivers, as one of the most important sources of water supply and transfer in industrial, agricultural, and urban sectors, are critically important in water resource management. Development of agricultural and industrial activities and increasing the volume of urban sewage cause contamination of water resources, especially rivers [1]. Optimal utilization of the capacity of pollution reception and reducing the cost of pollutant filtration in water resources systems is one of the important issues in water quality management of water resources [2,3]. Pollutant trading is an effective solution to pollution load allocation, which is based on transferable discharge permits between different stakeholders and river self-purification. This approach could create incentives to reduce pollution by exchanging additional discharge permits. A discharge permit is a transferable property right, which is mandatory for pollutant discharge units, and is issued by environmental authorities. In a discharge permit system, in addition to reducing the cost, the total amount of sewage discharge could stay constant or even reduced, which provides incentives for discharging units to reach a combination of minimum cost and total drainage.

The idea of pollutant trading was first introduced by Dales (1968) for wastewater discharge [4]. A few years later, Montgomery (1972) proposed the theoretical basis of discharge permit trading for nonpoint pollutant sources [5]. In 1980, Eheart used a cost-efficiency method to control the biochemical oxygen demand (BOD) discharges and formulated the trading discharge permit as a multi-objective optimization model [6]. In another study, in 1984, Brill et al. investigated the water quality under pollutant discharge permit trading system based on the BOD index [7]. Meanwhile, many research studies are reported on different subjects such as time-variable discharge permits [8], discharge permits with variable flow [9], discharge permits for two different pollutants [10], discharge permits for two different pollutants in different seasons [11], and discharge permit between point and nonpoint sources [12,13].

Despite the mentioned research studies, McCabe (1991) modeled the groundwater flow and pollutant transfer using ModFlow and MT3D and developed smart markets to allocate discharge permits for nonpoint sources of pollutants in groundwater resources [14]. Later on, in the year 2000, Morgan et al. presented a new method for nitrate discharge permit trading in nonpoint sources of pollutants, by linking nitrate leaching from nitrogen fertilizer applied to crops at a farm to nitrate levels measured at a drinking water well [15]. Subsequently, Horan et al. (2002) developed a method to trade nitrogen in agricultural point and nonpoint sources in a trading system in the Susquehanna River basin in Pennsylvania [13]. Additionally, the effect of sewage discharge permits on maximum daily pollutant load was studied by Eheart and Ng (2004) [16]. They confirmed that the permit trading system could be a powerful tool to reach an optimal balance between economic efficiency and water quality. Furthermore, Ng and Eheart (2005) extended the mean-value first-order second-moment (MFOSM) method to demonstrate how changes, due to discharge permit trading, in the environmental quality mean and/or variance of a system will cause the environmental quality reliability of the system to either decrease, increase, or remain unchanged. In this regard, they used the Willamette River in Oregon and the Athabasca River in Alberta, Canada, as example case studies, and investigated the effect of pollutant discharge permit trading on preserving reliable water quality, using a stochastic approach [17].

In another study in 2005, Hung and Shaw introduced the trading ratio system (TRS) for pollutant discharge permit trading [18]. This system could provide optimal trading permits, considering both economic aspects and environmental standards. Moreover, Ning and Chang (2007) used the QUAL2E model to simulate both BOD and NH_3 in a dynamic pollutant trading system for point sources, to present an integrated simulation and optimization analysis for generating spatially varied trading ratios and evaluating seasonal transaction prices accordingly [19].

Later, in 2008, Niksokhan et al. developed a stochastic method for trading pollutant discharge permits in river systems, considering a conflict resolution model [20]. Following that, Niksokhan et al. (2009) admitted that the game theoretic approach could be applicable for trading discharge permits in rivers [21]. Meanwhile, Mesbah et al. (2009) extended the TRS method to be applicable to BOD and dissolved oxygen (D.O.) management in river systems. They proposed a real-time model for pollutant discharge permits and investigated its application in the Zarjub River, Iran [22]. Moreover, they showed that using Bayesian networks and game theory, the optimal discharge permit in a trading system could be achieved. Thereupon, Mesbah et al. (2010) utilized an extended version of TRS and presented a new model for pollutant discharge permit trading based on TRS and fuzzy nonlinear cost functions [23].

In another study, a trading system for nonpoint sources was studied by Prabodanie et al. (2010) based on allowable nitrate entering the groundwater [24]. Later, in 2012, Poorsepahy-Samian et al. introduced a new method to allocate discharge permits for agricultural areas in sheared rivers, using game theory [25]. Furthermore, Jamshidi et al. (2014) investigated the nitrogen-based pollution trading between point sources and nonpoint sources of the Gharasoo River in the west of Iran, as a sustainable and efficient approach for surface water quality management [26].

More recently, Jamshidi and Niksokhan (2016) focused on the challenge of using a multiple pollutant transferable discharge permit market for operating wastewater treatment plants. They explored the trading discharge permits for the Sefidrud River in Iran, based on controlling BOD and total nitrogen [27]. In another study in 2016, Zolfagharipoor and Ahmadi used Monte-Carlo and QUAL2Kw to develop a new decision-making method called 'stochastic social choice rules' (SSCR), for wastewater discharge trading [28]. In 2017, Kumar and Kotecha presented an optimal pollution-trading model based on the genetic algorithm [29]. Moreover, Zolfagharipoor and Ahmadi (2017) developed a stochastic decision-making framework for effluent trading in river systems [30]. In another study, Soltani and Kerachian (2018) proposed a multi-objective model for real-time trading waste load discharge permits in rivers [31].

Furthermore, Zhang et al. (2019) introduced a new method called Bayesian risk-induced interval stochastic modeling framework (BRISF) for trading programs between different sources under system risk [32]. Later, Wang et al. (2022) developed two-dimensional water trading (2DWT) approach to unify both the quantity and quality of water [33]. Their findings show that the method could reduce the risk cost and water deficit. In another study, Xu et al. (2022) created a Bayesian simulation-based multi-watershed effluent trading designing model (BS-METM) for water quality simulation, uncertainty analysis, and optimal trading [34]. The application of their model was investigated in a real case study which showed the model's effectiveness for nonpoint source pollution management.

In this study, the TRS method is implemented to allocate pollutant discharge permits in the Dez River in Iran. A linear-based optimization approach is implemented to minimize the total cost. Using a trading ratio coefficient based on a transferable discharge permit, a local market between different stakeholders is created. This model aims to maintain river water quality while minimizing pollutant control costs. Therefore, pollutant sources could use the maximum amount of their allocated discharge permit issued by the environmental authorities or even sell extra permits.

2. Materials and Methods

Nowadays, the quality management of river systems is extremely important due to the significant increase in pollution and the diversity of urban, agricultural, and industrial pollutants. The pollutant discharge permit trading system is an efficient tool to handle qualitative management of rivers, which could consider economic aspects and water quality together. In this method, pollutant discharge units could transfer their discharge permit to reduce pollutant filtration costs. The units that can remove contamination more than necessary could sell their extra permit to other units. TRS is based on transfer coefficients:

$$t_{ij} = \frac{\Delta L_j}{\Delta L_i} \tag{1}$$

where ΔL_i and ΔL_j are the changes in pollutant discharge for upstream and downstream units, respectively; t_{ij} is a number between zero and one which represents the ratio of the discharge of the upstream and downstream pollutant units. Typically, the transfer coefficients are determined by environmental authorities, based on the river quality model and available quantitative and qualitative standards.

Generally, the allowable discharge quality for every pollutant unit depends on water quality in the relevant zone. In this case, QUAL2K is a tool to simulate water quality in a river. It is based on one-dimensional mass transfer and diffusion equations, which are numerically solved with respect to space and time (Chapra and Pelletier 2003) [35].

According to Hung and Shaw (2005), the tradable discharge permit for each unit could be calculated as [18]:

$$TDP_j = E_j - \sum_{k=1}^{j-1} t_{kj} TDP_k \text{ , } k < j \tag{2}$$

where TDP_j and E_j are the tradable discharge permit and the total load standard issued by environmental authorities for the unit j, respectively.

In certain conditions, where the value of the multiplication of the upstream total load standard and the transfer coefficient is more than the value of the total load standard downstream (i.e., $t_{(j-1)} E_{j-1} > E_j$), this area is defined as a critical zone and the TDP_j could be calculated as:

$$TDP_j = 0 \tag{3}$$

$$TDP_{j-1} = \frac{E_j}{t_{(j-1)j}} - \sum_{k=1}^{j-2} t_{kj} TDP_k \tag{4}$$

The trading ratio, r_{kj}, is the amount of increased pollutant discharge of j, according to buying one unit discharge permit from k, which could be determined as:

$$r_{kj} = \frac{1}{t_{kj}} \tag{5}$$

The pollutant sources are based on the trading ratio. These trades are constrained to satisfy river quality standards in control points after trading.

The objective function (Z) to minimize the total pollutant discharge in the system is defined as Equation (6), restricted by the constraints represented in Equations (7)–(15):

$$Z = Min\left(\sum_{i=1}^{n} C_i\left(x_i^0 - x_i\right)\right) \tag{6}$$

$$x_i \le TDP_i + \sum_{k\le i} T_{ik} - \sum_{k\ge i}^{n} r_{ki}T_{ki} \tag{7}$$

where x_i is the optimal permitted discharge for unit i after trading. T_{ik} and T_{ki} are the trading discharge permits bought by i from k and the trading discharge permits that i sells to k, respectively. It should be mentioned that the upstream units could not buy discharge permits from downstream units because the trading ratio is equal to zero when $i < k$. C_i is the cost of reducing pollutant discharge and x_i^0 is the primary pollutant discharge for unit i.

Equations (1)–(15) are linear and could be solved with the linear programming method. It should be noted that the values of parameters are restricted as $0 < x_i < x_i^0$ and $T_{ik}, T_{ki} \ge 0$. Based on Equations (2)–(4)), the following constraints are added to the optimization model for the case study of the Dez River:

$$TDP_1 = E_1 \tag{8}$$

$$TDP_2 = E_2 - t_{12}TDP_1 \tag{9}$$

$$TDP_3 = E_3 - t_{13}TDP_1 - t_{23}TDP_2 \tag{10}$$

$$TDP_4 = E_4 - t_{14}TDP_1 - t_{24}TDP_2 - t_{34}TDP_3 \tag{11}$$

$$TDP_5 = E_5 - t_{15}TDP_1 - t_{25}TDP_2 - t_{35}TDP_3 - t_{45}TDP_4 \tag{12}$$

$$TDP_6 = E_7/E_6 \tag{13}$$

$$TDP_7 = 0 \tag{14}$$

$$TDP_8 = E_8 - t_{18}TDP_1 - t_{28}TDP_2 - t_{38}TDP_3 - t_{48}TDP_4 - t_{58}TDP_5 - t_{68}TDP_6 - t_{78}TDP_7 \tag{15}$$

The developed method is presented in the flowing flowchart in Figure 1. Herein, Lingo is used to solve the linear programming problem. Lingo is a well-known computer software for optimization. A detailed description of this model can be found in its manual.

2.1. Case Study

In this study, the Dez River is investigated as the case study. This river originates from the southwestern highlands of Iran and, after joining the Karoon River, it flows into the Persian Gulf. The basins of the Dez and Karoon rivers are in latitudes 30 and 34 degrees. These rivers originate from areas with a height of more than 4000 m with cold and humid air and downstream they are located in warm and semi-arid plains. The catchment areas of the Dez and Karoon rivers are 23,500 and 17,523 km^2, respectively (Figure 2). Based on historical data, the maximum river flow in this area is in April, and the minimum is in

September, which are 647 and 110 $\frac{m^3}{s}$, respectively. The average flow discharge of the river is 368 $\frac{m^3}{s}$ throughout the year.

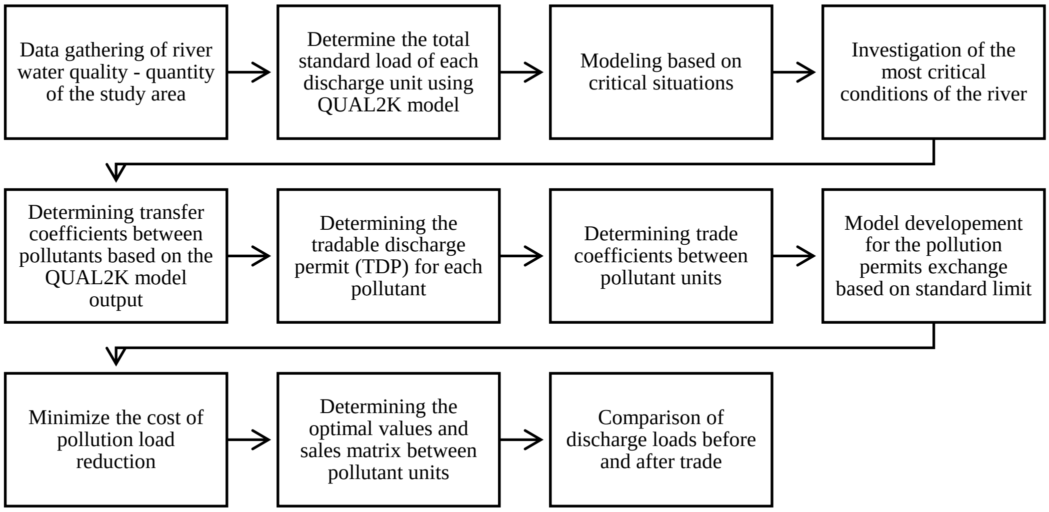

Figure 1. The flowchart of the developed method.

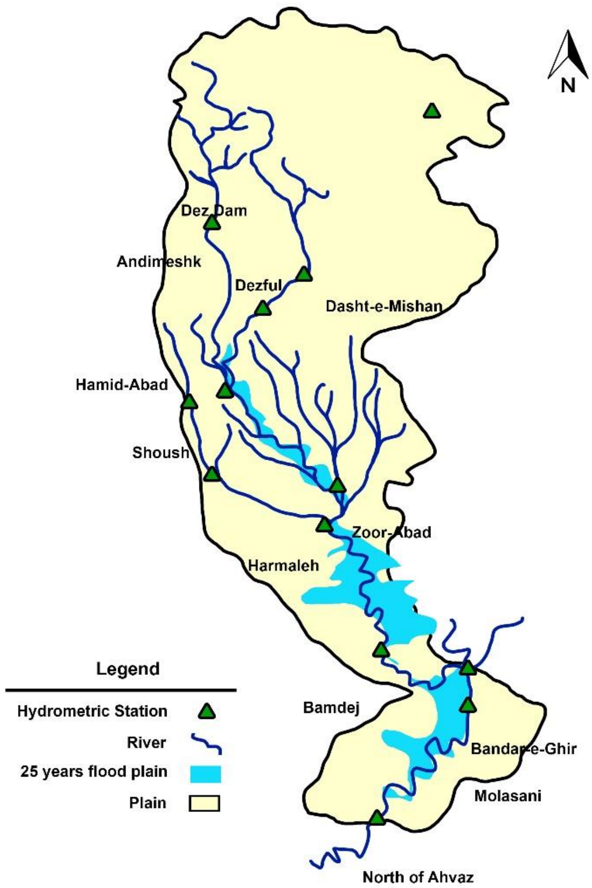

Figure 2. The catchment area of the Dez and Karoon rivers.

The study area is a part of the Dez River, one of the branches of the Karoon River, which covers the Dez Dam to Band-e-Ghir with a length of 153 km. It contains eight pollutant sources as presented in Figure 3 and Table 1. The pollutant discharges of all these units enter the river as point sources. According to observed data, measuring values from hydrometric stations, and available reports, the study area was modeled and calibrated in QUAL2K.

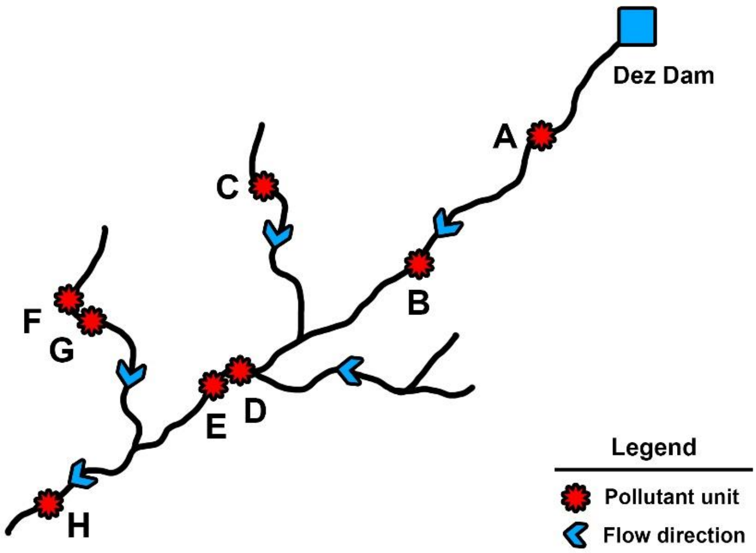

Figure 3. The schematic view of the study area.

Table 1. The specification of the pollutant units in the study area.

Pollution Source		Distance to the Start Point (km)	Total Discharge (m^3/day)	BOD_5 (mg/L)	Pollutant Discharge (tons/year)	Total Load Standard (tons/year)
ID	Name					
A	Dezful City	152	69,261	75	1896	474
B	Sugar Factory	109	30,000	321	3515	879
C	Andimeshk City	94	35,096	139	1780	445
D	Haft-Tapeh Sugar Cane Mill	79	156,384	105	5993	1498
E	Pars Paper Company	64	45,000	423	6948	1735
F	Shoush City	59	16,920	100	618	154
G	Pasteurized Dairy Products Company	58	250	400	37	9
H	Karoon Cane Company	30	52,704	62	1183	296

It should be mentioned that all data are based on official reports and information received from the competent authorities and are available upon request.

2.2. *QUAL2K*

The QUAL2K model is a 1D water quality simulation model composed of various subroutines, each responsible for solving the corresponding equations. This model considers the main reactions of the food cycle, algal production, oxygen demand of floor sediments, carbon dioxide consumption, atmospheric exhalation, nitrification, denitrification, and their effects on dissolved oxygen. The information and data required for the model include kinetic coefficients, meteorological data, geographical data, discharge values, effluent concentrations, and river water withdrawals, which are obtained using meteorological, hydrological, and water resources planning and management [36]. This model contains an auto-calibration module that is based on a genetic algorithm. More details about the calibration method can be found in Pelletier et al. (2006) [37].

3. Results and Discussion

In this paper, the permitted pollutant discharge is based on BOD_5 and is limited to 5 mg/lit in the study area. The BOD_5 is common between all units and could reduce D.O. in the river. In addition, this criterion is highly appropriate for fair trading among units. Firstly, the transfer coefficients are calculated as follows:

1. The primary value of BOD of a point source pollutant is changed in QUAL2K and new results are executed.
2. By changing the pollutant concentration of a source, the concentration of the downstream is affected, which is detected and recorded.
3. Considering the maximum allowable dissolved oxygen, the above procedure iterated for two-by-two units.
4. The changes in concentrations are depicted in a linear chart for every two units. The gradient of the graph will be the transfer coefficient.

Figure 4 represents QUAL2K calibration results for both D.O. and BOD. Table 2 represents the calculated transfer coefficients and the trading ratio matrix.

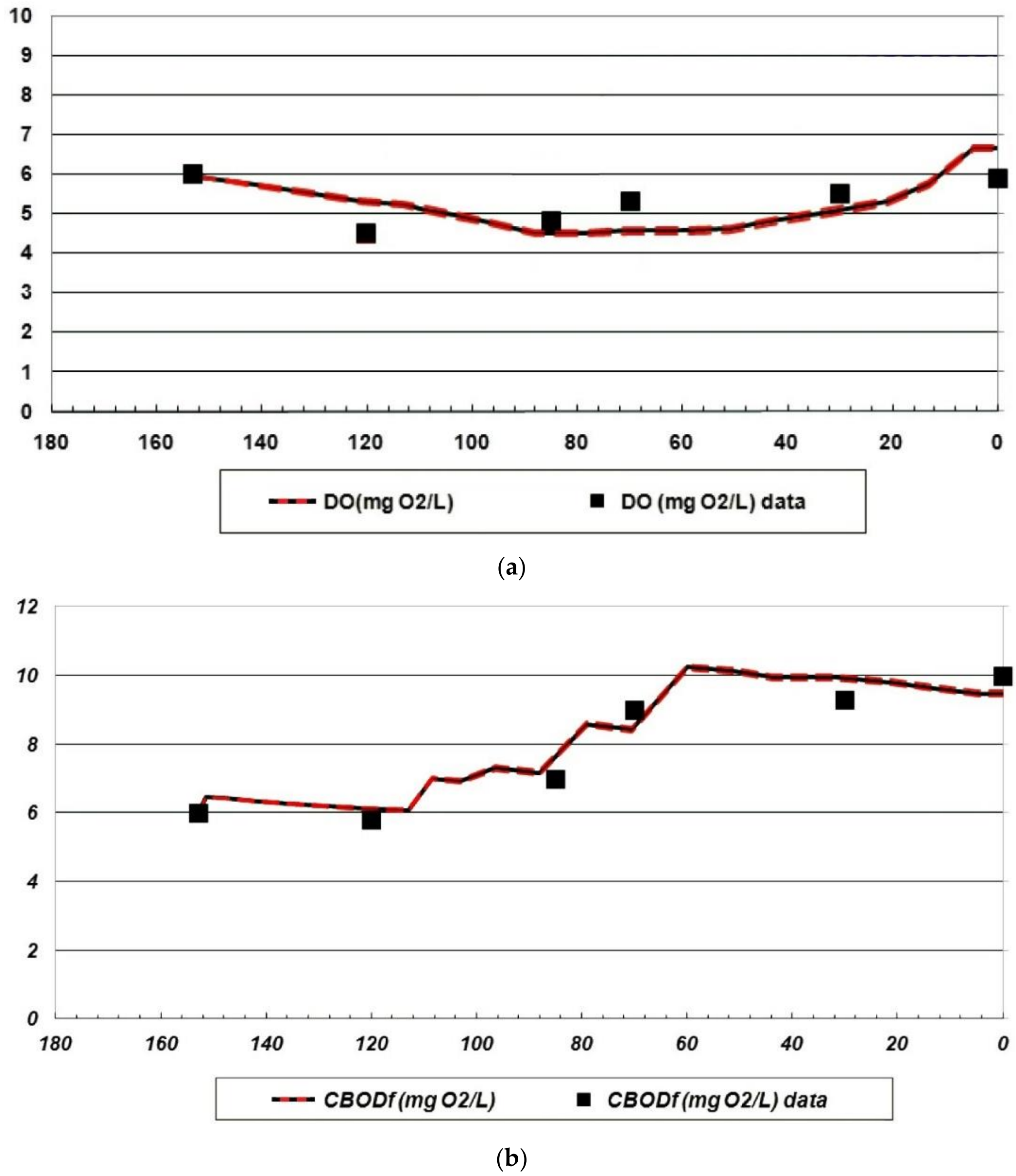

Figure 4. QUAL2K calibration results: (**a**) D.O. and (**b**) BOD.

Table 2. The transfer coefficients matrix.

	The Pollutant Unit	A	B	C	D	E	F	G	H
The transfer coefficients matrix	A	1	0.862	0	0.782	0.769	0	0	0.702
	B	0	1	0	0.906	0.89	0	0	0.804
	C	0	0	1	0.944	0.923	0	0	0.838
	D	0	0	0	1	0.979	0	0	0.888
	E	0	0	0	0	1	0	0	0.92
	F	0	0	0	0	0	1	0.95	0.87
	G	0	0	0	0	0	0	1	0.666
The trading ratio matrix	H	0	0	0	0	0	0	0	1
	A	1	1.159	0	1.278	1.300	0	0	1.424
	B	0	1	0	1.104	1.123	0	0	1.243
	C	0	0	1	1.059	1.083	0	0	1.193
	D	0	0	0	1	1.021	0	0	1.126
	E	0	0	0	0	1	0	0	1.087
	F	0	0	0	0	0	1	1.052	1.149
	G	0	0	0	0	0	0	1	1.501
	H	0	0	0	0	0	0	0	1

Solving the optimization problem, the following results are obtained (Table 3). Consequently, the value of each pollutant discharge is calculated (Table 4).

Table 3. The optimal value of trading discharge permits (tons/year).

The Pollutant Unit	A	B	C	D	E	F	G	H
A	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0
C	309.59	141.67	0	0	0	0	0	0
D	0	0	445	0	0	0	0	0
E	0	0	0	0	0	0	0	0
F	155.41	0	0	0	0	0	0	0
G	9	0	0	0	0	0	0	0
H	0	0	0	0	0	9.47	0	0

Table 4. Pollutant discharge (tons/year).

The Pollutant Unit	*TDP* before Trading	*TDP* after Trading	Buy	Sell
A	474	474	0	0
B	469.9	469.9	0	0
C	445	425	451.255	451.255
D	281.6	726.6	445	0
E	265.9	265.9	0	0
F	9.47	154	155.411	10.88
G	0	9	9	0
H	0	9.47	9.47	0

Unit A is in the upstream and could not buy any discharge from downstream units. Unit C could sell 20 tons/year and compensate for part of its costs. Unit D is obliged to buy 445 tons/year from upstream to be competitive in the market. It is recommended to use a treatment facility and not enter the market for this unit, because the amount of sold discharge is more than the bought value. Conversely, the amount of bought discharge is more than sold for units F, G, and H. Therefore, it is reasonable to buy the pollutant and reduce their pollution to be in the market.

The total cost of reducing 21,970 tons of pollutants in a year is 67 billion IRR (Iranian Rial). In other words, the cost of reducing the pollution for every ton is 3,050,000 IRR, which could be the basis of an initial pollutant discharge permit. Correspondingly, the cost of trading for each unit is presented in Table 5.

Table 5. Trading cost for units (IRR*/year).

The Pollutant Unit	A	B	C	D	E	F	G	H
A	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0
C	9,442,464,450	432,081,300	0	0	0	0	0	0
D	0	0	1,357,250,000	0	0	0	0	0
E	0	0	0	0	0	0	0	0
F	474,003,550	0	0	0	0	0	0	0
G	27,450,000	0	0	0	0	0	0	0
H	0	0	0	0	0	28,883,500	0	0

* 1 USD is approximately equal to 300,000 IRR.

4. Conclusions

In this paper, the application of the TRS was investigated in the economic water quality management of the Dez River. The significant feature of this method is the ability to obtain an economic solution, which yields allowable quality standards based on environmental law. A total discharge permit could provide a new atmosphere for stakeholders to ignore their classic approach and use a market with a simple trading system. In TRS, the permitted discharge could be transferred between different units, represented by transfer coefficients. Furthermore, trading ratios are computed and, finally, a trading system is performed to control the water quality and pollution control costs. Results show that this method could meet an economical solution and yield an appropriate quality of the river. The efficiency of this method depends on the number and amount of possible exchanges in each area and the whole study area. Most exchanges will be between large sources of pollutants as a seller and sources of small pollutants as buyers.

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