

Water Quality Trading with Equitable Total Maximum Daily Loads

S. Jamshidi, E. Feizi Ashtiani, M. Ardestani

Abstract—Waste Load Allocation (WLA) strategies usually intend to find economic policies for water resource management. Water quality trading (WQT) is an approach that uses discharge permit market to reduce total environmental protection costs. This primarily requires assigning discharge limits known as total maximum daily loads (TMDLs). These are determined by monitoring organizations with respect to the receiving water quality and remediation capabilities. The purpose of this study is to compare two approaches of TMDL assignment for WQT policy in small catchment area of Haraz River, in north of Iran. At first, TMDLs are assigned uniformly for the whole point sources to keep the concentrations of BOD and dissolved oxygen (DO) at the standard level at checkpoint (terminus point). This was simply simulated and controlled by Qual2kw software. In the second scenario, TMDLs are assigned using multi objective particle swarm optimization (MOPSO) method in which the environmental violation at river basin and total treatment costs are minimized simultaneously. In both scenarios, the equity index and the WLA based on trading discharge permits (TDP) are calculated. The comparative results showed that using economically optimized TMDLs (2nd scenario) has slightly more cost savings rather than uniform TMDL approach (1st scenario). The former annually costs about 1 M\$ while the latter is 1.15 M\$. WQT can decrease these annual costs to 0.9 and 1.1 M\$, respectively. In other word, these approaches may save 35 and 45% economically in comparison with command and control policy. It means that using multi objective decision support systems (DSS) may find more economical WLA, however its outcome is not necessarily significant in comparison with uniform TMDLs. This may be due to the similar impact factors of dischargers in small catchments. Conversely, using uniform TMDLs for WQT brings more equity that makes stakeholders not feel that much envious of difference between TMDL and WQT allocation. In addition, for this case, determination of TMDLs uniformly would be much easier for monitoring. Consequently, uniform TMDL for TDP market is recommended as a sustainable approach. However, economical TMDLs can be used for larger watersheds.

Keywords—Waste load allocation (WLA), Water quality trading (WQT), Total maximum daily loads (TMDLs), Haraz River, Multi objective particle swarm optimization (MOPSO), Equity.

I. INTRODUCTION

WATER QUALITY TRADING (WQT) is a promising policy for surface water quality management. Based on an analytical decision making framework outlined by USEPA

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(2004) [1], the discharge permit can determine the interactions of emission sources in the market. This is carried out by estimation of the projected loads, environmental standard limits, the incremental and total treatment costs, and finally through an optimized waste load allocation (WLA). For better environmental management, it is obvious that the interactions of WQT should be defined in the ambient discharge framework. It means that if the pollution exceeds the limits at checkpoints or through the monitoring districts, the environmental penalty would be charged. Accordingly, the stakeholders would be more interested in cooperation for an economical waste load allocation [2].

WQT have been investigated mostly with emphasize on finding the potential market of discharge permits among different stakeholders. For example, the interactions between point and nonpoint sources were recommended for better market outcomes [3]-[5]. Furthermore, some studies have used decision support systems to make the results more accurate [6]. For instance, fuzzy logic has been used to simulate the interactions of market stakeholders and find supportive rational decision making [7]-[10]. It is also recommended that the interactions are more vigorous for parameters like phosphorus and nitrogen [11]. Moreover, Ghosh, et al. (2011) and O'grady (2011) have previously reviewed the economical and socio-political aspects and barriers of this framework in different conditions. However, the impacts of using different types of TMDLs have not been studied for WQT [12], [13].

For WQT, environmental standard limits should primarily be determined in form of total maximum daily loads (TMDLs) [14]. Two approaches may be used for this purpose. First, by simulation of river basins, a critical checkpoint is considered for monitoring. This point can be the upstream of a reservoir, water treatment plant, estuarine or an ecologically important area. The whole emission sources upstream should equally remove pollutants (%) to maintain the quality of the checkpoint within the standard limits. Therefore, the TMDLs would not be as strict as conventional methods because it considers the remediation capabilities of surface waters. In the second approach, the whole water body is considered for monitoring as critical checkpoints. It means that regulating and monitoring organizations can take samples wherever through the river and charge the districts with unsatisfied water quality. Here, simulation-optimization models are used to find economically attractive TMDLs for WLA. This may minimize total treatment costs to fulfill environmental conditions.

This paper aims to answer this question that which type of TMDLs can be addressed more effective, economical and

supportive for a discharge permits market in small catchments. In other word, whether defining uniform TMDLs can find more sustainable market? Or TMDLs defined by simulation-optimization methods are better to fulfill the demands of the stakeholders? For this purpose, WQT is considered as the basic framework for comparative study in the case of Haraz River.

II. MATERIALS AND METHODS

A. Study Area

Haraz River is located in the North of Iran, with total length of 185 km and maximum flow rate of 94 MCM/yr. It originates in Alborz Mountains and ends up to the Caspian Sea [15]. For around 40 km in upstream, it is the main receiving water body of several fish farming discharges. These can build up eight colonies that here are termed as point source polluters (Fig. 1). The overall characteristics of emission sources, such as their distance to the headwater, the average discharge flow rate, and measured initial concentrations are shown in Table I [16]. It is noteworthy that the effluents are currently monitored by command and control (C&C) policy regarding the concentrations of biochemical oxidation demand (BOD) at discharge points. This is required to be removed at least about 90%. However, monitoring dissolved oxygen (DO) may be more efficient in the whole receiving water body instead. Therefore, this study initially uses simulation methods to find appropriate and economical TMDLs based on DO concentrations.

B. Methodology

This study compares TMDLs, WLAs and their economical outcomes in two scenarios. In first step, the projected loads were estimated and river was simulated by Qual2kw [17] in which the terminus point was considered as checkpoint [2]. The biochemical oxidation demand (BOD) is assumed here to be below 2.5 mg/L for the checkpoint and through the river basin. The sensitivity analysis finds the impact factors of emission sources and a uniform WLA is considered for TMDLs (Type I). The proposed algorithm of trading by USEPA [1] is then used for WLA based on discharge permit market. This intends to minimize total abatement costs in a pre-defined environmental condition at checkpoint.

In the second step, the simulation of river was carried out by Streeter - Phelps equation in MATLAB software to achieve BOD and DO profiles. It is then optimized by multi-objective particle swarm optimization (MOPSO) method to minimize environmental violations along the streamline and total abatement costs simultaneously [16]. Here, the WLA obtained in the least cost condition may introduce economical TMDLs (Type II). Since the whole streamline is determined as critical area and the spatial variations are not significant, the sensitivity analysis is not required for this step. Finally, the outcomes of trading discharge permits market by these TMDLs (Type II) would be compared with the optimal WLA resulted by the WQT of first scenario.

It should be mentioned that the efficiency and practice of MOPSO as a meta-heuristic explanatory algorithm has been previously approved by different studies. Baltar and Fontane used MOPSO to solve a multipurpose reservoir operation problem with four objective functions [18]. Azadnia and Zahraie used the MOPSO for the operation of Sefidrud reservoir to simultaneously supply the downstream demands and sediment discharge. They also discussed about the potential of MOPSO algorithm on finding non-inferior solutions with high diversity [19]. Rahimi et al. compared the performance of the MOPSO and the NSGA-II algorithms in the reservoir operation of Doroudzan Dam. The comparative results verified the efficiency of the former for optimum solutions achievement for reservoir operation [21].

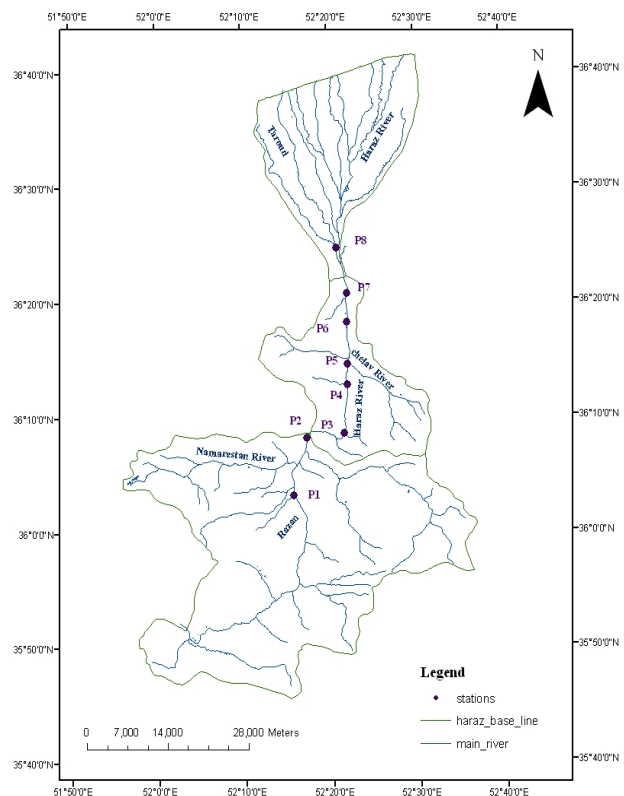


Fig. 1 Study area and location of emission sources

Here, MOPSO is used to find the set of non-dominated solutions. It shows the Pareto solutions of minimum total treatment costs (TC) versus minimum total environmental violations (EV). These functions are defined here as Z_1 and Z_2 respectively by (1), and (3) as [2], [16].

$$Z_1 = \text{Min} \sum_{i=1}^n C_i(x_i) \quad (1)$$

Z_1 is TC objective function, n is the number of point sources here equals 8, C_i is the annual capital and operating cost of wastewater treatment plants per volume ($\$/\text{m}^3$) determined by (2), x_i is the biochemical oxidation demand (BOD) removal

determined by the optimization model, and Q_i is the annual average flow rate of discharger i (m^3).

The total treatment costs of emission sources rely on the efficiency of waste load removal and the process in use. Therefore, it is defined as a function of BOD removal. Here, the capital and operating costs are included for 30 years operation and maintenance. It should be noted that the cost function is estimated by a data base of 50 wastewater treatment plants previously practiced in Iran from 2010 to 2013 [2].

$$C_i(x_i) = ax_i^2 + bx_i + c \quad (2)$$

where a , b , and c are given as 13.56, 7.25, and 0.95 respectively through a trendline attained by regression analysis.

$$z_2 = \text{Min} \sum_{j=1}^m V_j \quad (3)$$

$$V_j = D_{st} - D_{sim} \quad (4)$$

Z_2 refers to the total environmental violations where m is the number of control points, and V_j (mg/L) is the difference between the concentration of the monitoring parameter simulated (D_{sim}) and the standard limit (D_{st}) at the control point j (4). The former is calculated here by Streeter-Phelps equation for dissolved oxygen (DO) [22]. It is noteworthy that V_j relies on the remediation potential of surface waters which is estimated here by the simulation. It means that V_j is dependent on parameters such as, hydraulic conditions, waste loads discharged, the flow rates, and more important the aeration and organic degradation rates.

The TC-EV Pareto solutions determine the economical TMDLs in a condition that the environmental violation is at its minimum level. Here, for V_j , the minimum DO concentration is set on 3.2 mg/L to surely have a river with more than 3 mg/L DO concentration in optimal WLA. In addition, along

the stream line, the total standard violation (EV) is limited to 3 mg/L.

In order to have an economical and fair WLA, in addition to preserve the environmental standard limits alongside the streamline, the trading BOD discharge permit market is checked by using inequity index function (5).

$$Z_3 = \text{Min} \sum_{i=1}^n \left| \frac{x_i}{x_m} - \frac{W_i}{W_m} \right| \quad (5)$$

Z_3 shows the total inequity index in which W_i and W_m are respectively the waste load discharged by polluter i and average of waste loads discharged to the surface water. Other parameters have already been introduced. Minimization of this index means that the dischargers with high waste loads (W) are recommended to remove more organics (x) for WLA rather than polluters having a less amount of waste loads.

This index may represent the adverse emotional effects of stakeholders that are participated in the WLA policy.

III. RESULTS AND DISCUSSION

This study compares the outcomes of using two types of TMDLs assigned for WQT. The first scenario focuses on uniform TMDLs (Type I) for a specific checkpoint while the second intends to minimize TC-EV simultaneously prior to WQT.

Regarding the simulation results of Qual2kw, it is realized that if all emission sources remove BOD about 70% equally, the total BOD concentration of the checkpoint would be below the required limits. Accordingly, the TMDLs Type I are calculated based on this uniform policy (Table III). However, for Type II, the TMDLs are economically optimized through a simulation-optimization method. The former totally costs 1.15 M\$/yr and has the inequity of 3.34. The latter may have more cost savings in which it totally requires 1 M\$/yr for BOD removal. However, the inequity index increases to 4.72. Fig. 2 illustrates the TC-EV trade-off curve in which the minimum total violation is selected for TMDLs. Here, the average of BOD removal is 69% which is almost equal to Type I.

TABLE I
CHARACTERISTICS OF EIGHT POINT SOURCES USED FOR SIMULATION- OPTIMIZATION MODEL

	P1	P2	P3	P4	P5	P6	P7	P8
Distance to the Headwater (km)	1	10	11.5	14.5	15	22	26	38.5
Discharge (m^3/s)	0.08	0.33	0.09	0.1	0.16	0.07	0.07	0.03
DO (mg/L)	5.5	5.8	5.4	5.7	7	5.5	4.6	6.3
BOD (mg/L)	32	30	42	41	20	40	55	30

TABLE II
THE ESTIMATED PROJECTED LOADS AND IMPACT FACTORS OF THE EMISSION SOURCES

	Unit	D1	D2	D3	D4	D5	D6	D7	D8	C&C Total Costs (M\$/Yr.)	Inequity Index
Projected Loads	Kg/day	207	842	312	368	279	225	342	83	1.69	3.34
Impact Factors	%	11.4	18.8	11.7	11.8	11.4	11.5	11.7	11.7		

TABLE III
TYPES OF TMDLS DERIVED FOR WQT

	Units	D1	D2	D3	D4	D5	D6	D7	D8	Total Costs (M\$/Yr)	Inequity index
TMDL (Type I)	% Removal	70	70	70	70	70	70	70	70	1.15	3.34
	Kg/day	62.2	252.7	93.7	110.5	83.8	67.4	102.6	24.9		
TMDL (Type II)	% Removal	62	12	99	99	96	57	99	27	1	4.72
	Kg/day	78.8	741.3	3.1	3.7	11.2	96.6	3.4	60.6		

In Table III, it is implied that the dischargers of D1, D2, D6, and D8 would be inclined to use Type II while the other four dischargers (D3, D4, D5, and D7) are interested in Type I. If the numbers were not equal, the decision making may be more complicated. [20]

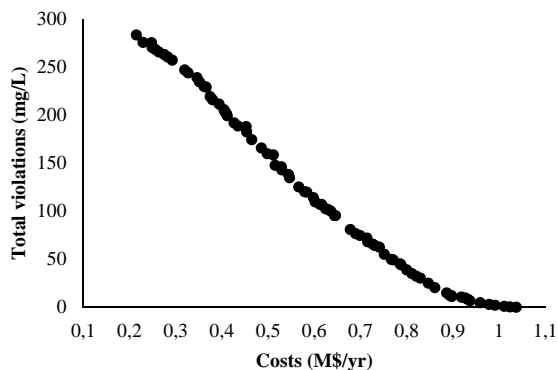


Fig. 2 Total costs - total environmental violations trade-off curve

In addition, the inequity indices indicate that TMDLs with uniform reduction have much more equity than economical TMDLs. In spite of higher economical savings of TMDLs Type II, the differences in inequity may totally increase the interests of stakeholders for participating in a market based framework established by TMDLs of Type I. Fig. 3 illustrates the probable influence of TMDL (Type II) on river DO profile.

Based on these two types of TMDLs, the discharge permit markets are calculated in regard. For Type I, the impact factors of emission sources are considered in trading discharge permit while for Type II it is neglected. The results of WLA in WQT for eight emission sources are shown in Table IV. It should be mentioned that the total allocation is implemented regarding this fact that the dealers should be interested in participating in the trading market. It means that the total cost of each emission source must be less than the total costs of the conventional system. Also, it is preferred that WQT finds less cost in comparison with TMDL approach itself. The latter can be balanced by the discount factor previously recommended [2]. Otherwise, the market would be fragile and the required deals may not be approved. Therefore, it can be concluded that using TMDLs based on Type I and Type II can respectively save 32% and 40% in comparison with the conventional emission charge framework. For the former, WQT can increase the revenues to 35% while the latter reduces total costs to 45%. The overall cost estimation of different approaches are illustrated in Fig. 2. Furthermore, WQT can also reduce the inequity index of WLAs.

The first market (Type I) will have 3.3 for inequity index while the second (Type II) may find more inequity about 4.5. This emphasize on this fact that finding robust TMDLs will lead into more satisfactory discharge permit markets. In addition to economic incentives, profits attained by stakeholders and free market for pricing permits, the equity of WLA is also critical.

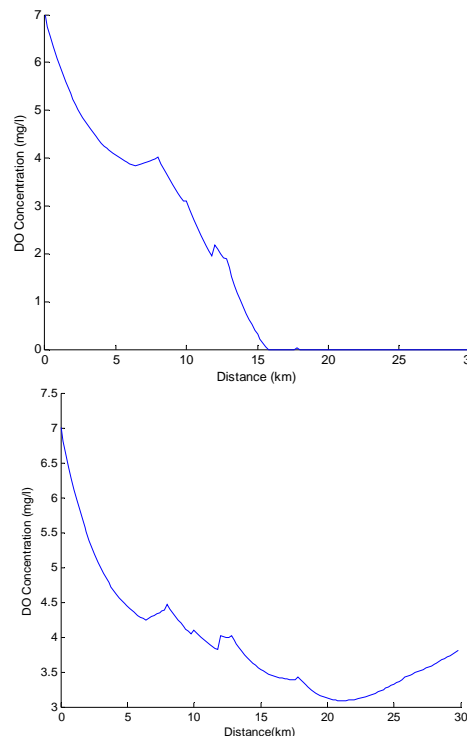


Fig. 3 DO concentrations profile before (up) and after (down) determination of TMDLs

Based on the results, it can be discussed that however the market formed for Type I, has slightly higher total costs, it has more equity for waste load allocation. The latter makes stakeholders do not be that much envious of difference between TMDL and WQT allocation. Also, for this case that includes a small vicinity of river, determination of TMDLs uniformly would be much easier for monitoring and decision making. Accordingly, the market would be much smaller in which the trades can be controlled better. The Type II is recommended to be used for cases only includes vast watersheds, required dynamic discharge permit markets without control, and those areas previously have experienced the monitoring through Type I.

TABLE IV
WASTE LOAD ALLOCATION IN WQT FOR TWO TYPES OF TMDLS

TMDL used in	BOD removal (%)								Total Costs (M\$/Yr.)	Costs Saved (M\$/Yr.)	Inequity index
	D1	D2	D3	D4	D5	D6	D7	D8			
Type I	58	75	70	70	40	66	85	59	1.09	0.59	3.3
Type II	70	20	95	95	65	75	95	40	0.93	0.75	4.5

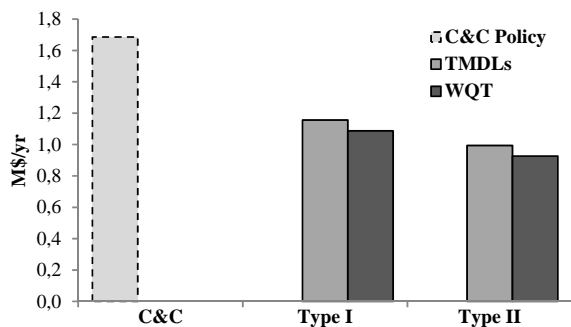


Fig. 4 The comparison of total costs in different WLAs

IV. CONCLUSION

This study shows that in small catchment areas, finding economical TMDLs for WQT with multi-objective optimization models are not necessary. Conversely, using simple simulation methods and accordingly TMDLs assignment can introduce more equal WLA. This has approximately the same revenues in comparison with economical TMDLs for WQT. It implies that finding TMDLs and optimal WLA for WQT can use simple simulation techniques and does not require severely vigilant optimizations. Consequently, it is recommended that in discharge permit markets with limited point source stakeholders, equitable TMDLs may cause more incentives for participation rather than economical TMDLs. This can ensure more sustainable discharge permit market interactions in small catchments. In addition, WLA calculations become simpler. Yet, it is recommended that this approach can be testified in other catchments for WLA and WQT framework.

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