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Development of Multi-Objective Optimal Waste Model for Haraz River

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Abstract: With the rapid economic development, the water quality is getting worse in Haraz River Basin and the adjacent areas. To improve the water quality, the total inland pollutant load should be controlled effectively. Therefore, a simulation model for the prediction of the steady-state water quality in terms of BOD, based on Streeter Phelps equation, was developed. The Streeter-Phelps equation gives the response of DO concentration at each river reach to a BOD load concentration. In the next step, the optimization objective functions and water quality constraint equations were formulated and the linear programming method was used to calculate the environmental capacity. The optimization programming of minimum treatment cost produces non-uniform removal rate for pollution sources which suggest a broad range of minimum treatment cost.

Key words: Dissolved oxygen · Simulation model · Linear programming · Waste load allocation model

INTRODUCTION

Presently the quantity of the fresh water resources is the most pressing of the many environmental challenges on the national horizons. The water quality situation in developing countries is highly variable, reflecting social, economic and physical factors as well as state of development. While all of countries are not facing a crisis of water shortage, all of them have serious problems, associated with degraded water quality. The quality of the water in nature affects the condition of ecosystems and all living organisms. Moreover, water bodies are used for the disposal of domestic, industrial and agricultural wastewaters which leads to degrading the quality of those water bodies.

As to protect and save human life and the life of other living things, water quality management would be considered as one of the most important activities of mankind. Sasikumar and Mujumdar, Subbarao and *et al*., believe that the management of water quality is to describe and predict the observed and future effects of a water quality change in the river system which needs modeling the quality of the river [1, 2].

According to Tookwinas Modeling can therefore be used as a tool for making decision for resource, allocated to achieve desired water quality objectives [3]. Burn and Yulianti and Schulz *et al*., stated that the control of water quality in any river at various locations requires the determination of the optimal pollutant removal levels at a number of point and nonpoint sources locations along the river in a cost-effective, equitable and efficient manner [4, 5].

The optimal treatment levels for a given set of pollutant sources are affected by the assimilative capacity of the receiving water body which is determined in Waste Load Allocation (WLA) studies. Burn and Yulianti and Mujumdar and Subbarao believe that WLA problems address minimization of the total treatment cost and minimization of the inequity among the pollutant dischargers, subject to satisfaction of a specified standard at all the check points located along the river [4, 6].

As stated by Subbarao, Finding the optimal waste load allocation strategy requires a simulation model for the prediction of the steady-state water quality response in terms of the pollutant at specified receptor locations along a river, for various possible combinations of waste loadings [7]. Streeter and Phelps state that one of the most commonly used water quality simulation models in waste load allocation planning studies is the Streeter-Phelps equation [8].

According to Babu *et al*. and Dogan *et al*., Streeter-Phelps equation incorporates river water quality and optimization modeling generally focused on the simple negative relationship between DO and BOD [9, 10]. As stated by Rixen and *et al*. and Kedong *et al*., Dissolved oxygen (DO) is the primary indicator of the general health of a river system, since fish needs oxygen to survive [11, 12]. DO is affected by many organic pollutants.

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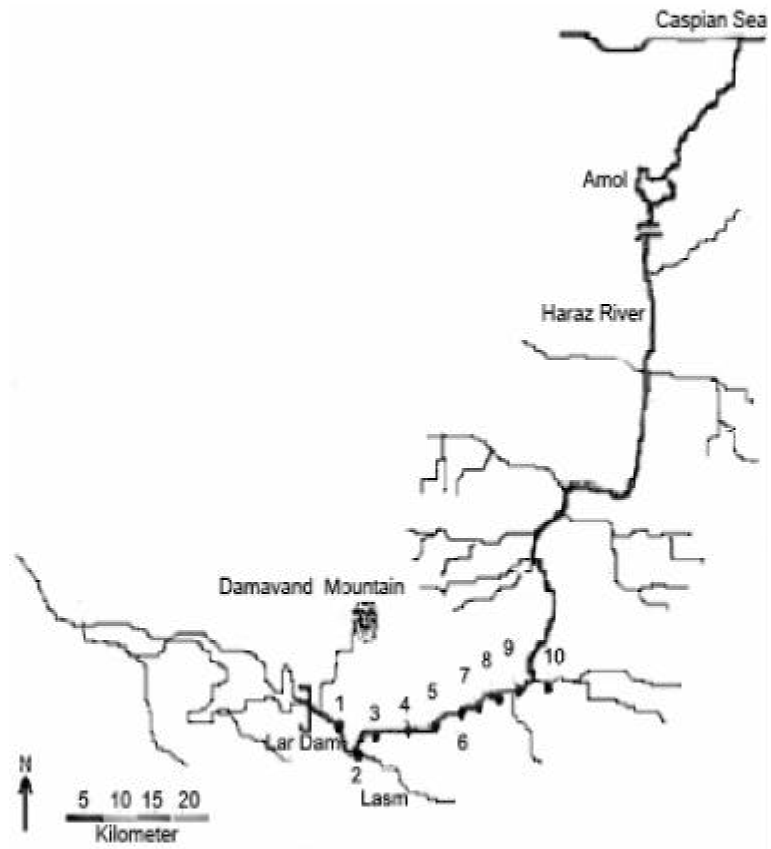

Fig. 1: The map of study area

As stated by Nakamura *et al*. and and Pang *et al*., Biological oxygen demand (BOD) is a measure of the oxygen used by microorganisms to decompose organic waste in the river [13, 14]. According to Liu and Mattiasson and Liu *et al*., BOD is generally the most common river pollutant. Its treatment processes are well known and relatively cost effective in comparison with treatment of other organic pollutants [15, 16]. It is also well used in modeling because the relationship is well known and simple. According to Babu *et al*. and Rastogi *et al*. The Streeter-Phelps equation gives the response of DO concentration at each river reach to a BOD load concentration which is described in the following [9, 17].

In this work, a multi objective optimization algorithm for optimal waste load allocation is proposed. This optimization model is a cost-equity-performance model. An overall performance measure is proposed with regard to satisfying a specific BOD standard along the river. According to Mujumdar and Subbarao, these waste load allocation models use a water quality simulation model, which considers the flow to be steady, but non-uniform [4]. Jiang studied the simulation model considering the advective, dispersive and reactive transports for BOD and DO [18]. According to Riverol and Pilipovik, the multi-objective optimization model is solved with the linear programming technique [19].

Haraz River Basin area is located in the Mazandaran Province and north region of Iran and lies between longitude of 35°52' and 45°5' and latitude of 35°45'and 36°15' and has a length of 185 km with a discharge of 940 × 106 m^3/y (in 2006)(Fig. 1). The width of river ranges from 50 to 500 m at different locations. The catchment area of river is about 4,060 Km^2 with average precipitation of 832 mm/y. Keramat Amirkolaie studied Haraz River originates from Alborz mountain ranges and flows into the southern coast of the Caspian Sea [20].

MATERIALS AND METHOD

Initially the response field of BOD was calculated through water hydraulic and quality modeling and the response relationship between the pollutant emission and water quality was built up.

In the next step the optimization objective functions and water quality constraint equations were formulated and the linear programming method was used to calculate the environmental capacity. And finally the total maximum allowable load was allocated with the fairness among the pollution sources (fish farms of Haraz basin) in consideration.

Water Quality Model: Water quality modeling in a river is based on Streeter and Phelps model that developed a balance between the dissolved oxygen supply rate from re-aeration and the dissolved oxygen consumption rate from stabilization of an organic waste. In this model the BOD-DO rate was expressed as an empirical first order reaction, producing the classic dissolved oxygen sag (DO) model. Considering the dispersion process, the governing equation becomes a partial differential equation.

DO is one of the most important constituents of natural water bodies; as fish and other aquatic animal species require oxygen. Oxygen is also important to maintain an aerobic state as the end products of chemical and biochemical reactions in anaerobic systems produce aesthetically displeasing odors, colors and taste. When biodegradable organics are discharged into a stream, microorganisms convert the organics into new cells and oxidized waste components. During this process, DO is consumed. The rate and quantity of DO consumption is dependent on the quantity of organics and the dilution capacity of the stream.

Generally all the in-stream DO models are based on the Streeter-Phelps equation. The first equation was developed by Streeter and Phelps to predict the effect of state discharges into river and is described as [8]:

$$D_t = \frac{K_D L}{K_R - K_D}\left(10^{-K_D t} - 10^{-K_R t}\right) + D_O 10^{-K_R t} \qquad (1)$$

Where D_t= Dissolved Oxygen deficit at time t, (mgL^{-1}), L= Ultimate first stage BOD at point of waste discharge (mgL^{-1}), D_o= Initial oxygen deficit, (mgL^{-1}), K_D =Deoxygenation coefficient, K_R = Reoxygenation coefficient

The time at which the minimum dissolved oxygen occurs can be obtained from equation as given:

$$t_m = \frac{1}{K_R - K_D}\log\left[\left(\frac{K_D L - K_R D_o + K_D D_O}{K_D L}\right)\frac{K_R}{K_D}\right] \qquad (2)$$

The DO curve predicts the DO concentration (DO deficit) over time or distance following the introduction of organic matter. When a biochemical oxygen demanding substance such as sewage enters a river, the organic matter provides a source of energy for aerobic decomposer microorganisms, living in the volume of water. This energy surplus leads to population growth in the decomposers and DO consumption through their respiration. As their population increases, they consume more organic material and more oxygen, leading to the critical point of downstream at which DO reaches its minimum value and river conditions are at their worst. At this critical point, following the laws of supply and demand, the microbial population peaks and then begins to decline as the food supply become limiting.

Waste Load Allocation Model: Waste load allocation refers to that amount of a stream's total permissible substance load that is allocated to one or more existing or future point source discharges. The total allowable substance load is determined by calculating the amount of substance that can be discharged while maintaining in stream guidelines under worst case conditions.

Many analytical models are documented, for example, the USEPA lists 19 allocation methods [21]. Among them, balance between cost and equity requirement are the most challenge.

$$B_i - \sum_{i=1}^{N} A_{ij} \times W_i \times r \le S_j \quad (\textit{water quality limitation}) \qquad (3)$$

$$R^L \le r \le R^U \; (\textit{constraint on treatment technology availability}) \qquad (4)$$

Nonnegative values are for all variables and parameters.

Where B_j is the *BOD* concentration at checkpoint j (mg/L), A_{ij} is the impact coefficient of source i to checkpoint j (the details and unit of this value are addressed in the next section.), *Wi* is the *BOD* load of source *i* (kg/day), S_j is the water quality standard at checkpoint j (mg/L) and N is the number of sources. (N is equal to four in this study.) R_U and R_L is the upper and lower limitation of the removal rate, respectively. *r* is the removal rate applied to all sources for attaining the water quality standard

$$\textit{Minimum}\sum_{i=1}^{N} C_i \qquad (5)$$

Where C_i is the treatment cost required for reduction of loading from source i.

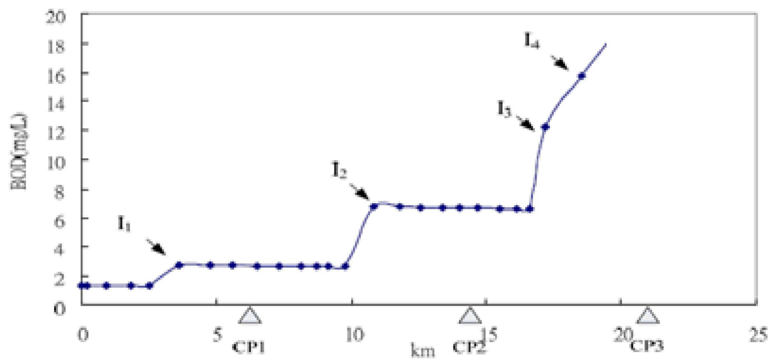

Fig. 2: Simulation of BOD concentration for current situation

Subject to constraints (3)-(5), with modification of (3) by replacing r with r_i as individual removal rate for each source and addition of cost function:

$$B_i - \sum_{i=1}^{N} A_{ij} \times W_i \times r_i \le S_j \quad (water\ quality\ limitation) \tag{6}$$

$$C_i = f(W_i, r_i, Q_i)\ (cost\ function\ for\ BOD\ discharges) \tag{7}$$

It should be noted that the results from simulation model is transferred to water impact coefficient (A_{ij}) as crucial input in optimization programming and its value indicates the change in water quality produced by pollution discharges. In the same modeling condition, a large value of A_{ij} means the corresponding pollution sources has more potential to pollute water quality. The impact characteristic on water quality of sources was firstly derived from the Streeter-Phelps equation (DO-BOD model) (Burn, 1989), such as Eq. (8). However, replacing by complex modeling, the A_{ij} is obtained by Eq. (9) without distorting its original means.

$$A_{ij} = \frac{W_i k_l^i}{Q_j \left[k_2^{ij} - (k_l^i + k_3^{ij}) \right]} \left[e^{(k_l^i + k_3^{ij}) t_{ij}} - e^{k_2^{ij} t_{ij}} \right] \tag{8}$$

Where A_{ij} is the impact coefficient, Q_j is the water flow at checkpoint j, t_{ij} represents the travel time from the source i to checkpoint j, k_l is the de-oxygenation rate coefficient, k_2 is re-aeration rate coefficient and k3 is the sedimentation-scour rate coefficient.

$$A_{ij} = \frac{\nabla C}{loadings} = \frac{BOD_{jp} - BOD_{jn}}{W_i} \quad unit: \frac{mg/L}{kg} \tag{9}$$

Where BOD_{jp} is the BOD concentration at checkpoint j when all sources are considered (mg/L) and BOD_{jn} is the BOD concentration at checkpoint j when all sources except source i are considered (mg/L).

The BOD concentration should be maintained under 4 mg/L, but the average value is over 5 mg/L (Fig 2). Cost function is required in allocation Minimum Total Cost. According to the report of the Construction and Planning Agency, the treatment cost of wastewater was suggested as:

x = 204.1q-0.3826, where x is the cost (NTD/ m^3 of wastewater) and q is the wastewater treated (m^3/day). The treatment cost of every BOD amount is obtained from the translation of the treatment cost of unit wastewater and treatment cost for each source is summarized. In addition, the treatment removal rate is set 30% to 99% according to technical achievability.

RESULTS AND DISCUSSION

The optimization programming of minimum treatment cost produces non-uniform removal rate for pollution sources based on Minimum Cost Method (MCM) as it is shown in Fig.3. Different from distributions of water quality results (similar with normal distribution), the consequences of optimization programming are not centralized on mean value but mainly distributed on both sides of boundary. For pollution sources I_1, I_2 and I_3, the distributions are distinctly concentrated on extreme values. Source I_4 is with the maximum treatment cost on BOD removal; therefore, the lower boundary of removal rate, 30%, is received in highest frequency. On the other hand, the maximum removal rate, 99%, is suggested to sources I_2 and I_3 because of their larger waste discharges (Table 1) and lower treatment cost. For source I_2, removing more waste loading is resulted due to its larger discharging loadings.

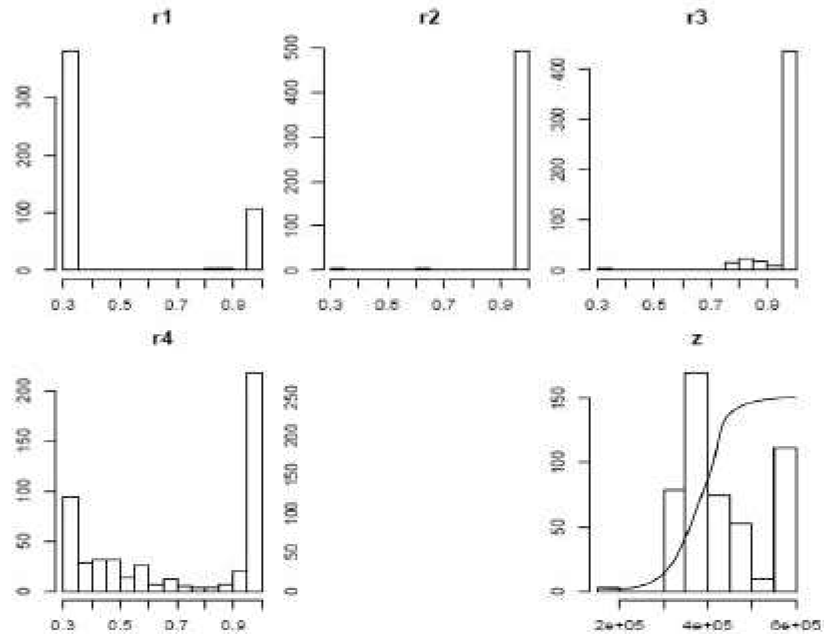

Fig. 3: Distribution of MCM programming results, including removal rates of each pollution sources and minimum treatment cost. The bars in histograms indicate frequency corresponding to removal rates (r_1 to r_4) and minimum cost (z).

Table 1: The characteristics of each farm

Farm	Location (Km)	Discharge flow(m^3/s)	BOD_5, (mg/l)	DO,(mg/l)	Temperature
I_1	6	3.24	0.7	3.2	2.9
			3.6	7.1	6.8
I_2	10	2.192	0.3	5.1	4.8
			4.1	9.2	9
I_3	25	1.71	9.2	4.1	9.9
			3.5	9.4	10.6
I_4	34	0.361	2.3	3.1	2.12
			4.1	9.5	13.2

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