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Minimal adverse impact of discharging polluted effluents to rivers with selective locations

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ABSTRACT

The disposal of sewage from human activities remains a challenge in developing countries due to relatively high treatment costs. Untreated or poorly treated sewage is therefore commonly discharged to streams, lakes, and coastal oceanic waters. The location of discharges of polluted effluents to rivers can be managed to reduce adverse environmental impacts. This study presents a relative-preference method for siting sewage discharge locations on a river considering biochemical oxygen demand (BOD) impacts. River water quality is simulated for different levels of BOD concentration using the QUAL-2 K water-quality model. Results of these simulations are compared to each other with a relative-preference function that selects polluted-effluent discharge locations to lessen the degradation of riverine water quality. The selection of the discharge locations takes into account input from regulatory agencies and other pertinent environmental organizations to achieve the least damage to receiving waters. The relative-preference method is applied to the Karoon river between Gotvand dam and Shooshtar city, Iran. The results show the best locations for discharging the new polluted effluent are at the upstream and downstream portions of the considered river reach. Locations at kilometer 35 and its vicinity had the lowest values of the relative preference function making them the most unsuitable points for discharging the sewage effluent.

1. Introduction

Rivers are one of the most important sources of water for agriculture, industry, and municipal use. Their water quality is commonly degraded by untreated or poorly untreated sewage of various origins, amounts, and composition that exceed a river's self-healing or carrying capacity. The impact of sewage disposal to river can be lessened by choosing the locations of discharges of polluted effluent properly. Melching and Yoon (1996) reviewed methods of reducing uncertainty in water-quality models. Their method was applied to the Passaic river in New Jersey using QUAL-2E. Drolc and Koncan (1999) tested the effects of wastewater released into Sava river in Slovenia and applied QUAL-2E in their simulation of river quality. Kivaisi (2001) summarized information on methods used for sewage treatment, and examined the potential of wetlands for treatment and reuse in developing countries by looking at the results of research towards implementation of the technology. Park and Lee (2002) evaluated the efficiency of QUAL-2E and QUAL-2 K models. They calculated water-quality parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD), coliforms, phosphate, and nitrate in the Nakdong river (South Korea) with these models. Goldar and Banerjee (2004) assessed the impact of informal regulation of water pollution on water quality by carrying out an econometric analysis of determinants of water quality using water quality data for monitoring points on important rivers. Azzellino, Salvetti, Vismara, and Bonomo, (2006) combined the QUAL-2E model with factor analysis to arrive at a better understanding of the role that pollution sources have on river pollution. Kashefipour, Lin, and Falconer, (2006) studied the fate of total coliforms (TC) and fecal coliforms (FC) of the Irvine river in England. Park, Choi, Wang, and Park, (2006) developed an integrated technique which used a genetic algorithm (GA) and a geographic information system (GIS) for the design methodology for an effective water quality monitoring network in a large river system. Kannel, Lee, Lee, Kanel, and Pelletier, (2007) studied factors improving the water quality of the Bagmati river in Nepal using

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with of the QUAL-2 K model. Chang (2008) evaluated spatial patterns of water quality trends for 118 sites in the Han River basin of South Korea for eight parameters, and recommended spatial analysis of watershed data at different scales should be a vital part of identifying the fundamental spatio-temporal distribution of water quality. Fan, Ko, and Wang, (2009) combined the Qual2 K with the HEC-RAS to assess the water quality of a tidal river in which various contaminated loads were discharging. Eheart (1980) studied the BOD in river water considering four scenarios for transferable wastewater discharge permits in the Willamete river in the U.S. Mannina and Viviani (2010) presented a simplified river water quality model to assess the ecological status of small rivers and predict and interpret water quality field data. Kannel, Kanel, Lee, Lee, and Gan, (2011) investigated the strengths and weaknesses of popular models for simulating the water quality of rivers. Their results showed that the QUAL-2 KW model had a better performance compared to QUAL-2 KU simulating carbonaceous BOD. Chen, Wu, Blanckaert, Ma, and Huang, (2012) examined the effects of water-quality monitoring in river basins of China. Wu and Chen (2013) employed the soil and water assessment tool (SWAT) to estimate the influence of point source and nonpoint source pollution on the water quality of a river. Rashed and El-Sayed (2014) evaluated a number of drainage water mixing projects, applying QUAL2 K to evaluate potential water quality improvement programs, particularly on salinity and water quality parameters. Momblanch et al. (2015) reported a methodology consisting of two coordinated models that combined water resource allocation and water quality assessment, and assessed the effects of water management and quality alternatives in a river basin. Parsaie and Haghiabi (2016) developed a numerical model by solving the fractional advection-dispersion equation for the simulation of pollution transmission in rivers with stagnant zones. Lai, Chien, Yang, Surampalli, and Kao, (2017) proposed a modeling tool for the river water quality and pollutant transport. The integrated tool was field-tested to assess pollutant loadings and their impacts on the riverine environment.

The standard approach to reduce contaminants discharges to rivers is by treatment of effluents prior to discharge. In many regions with limited resources, however, there are not many facilities available for sewage treatment and this is attributed to the high cost of the treatment processes (Kivaisi, 2001). Therefore, managing contaminant's discharges to rivers without the intervention of treatment plants is in that instance pertinent. This approach relies on the self-healing capacity of rivers and the natural decay of many organic contaminants, in which case finding suitable discharge locations of polluted effluents and frequencies of discharge can be optimized to preserve river water quality to the extent possible. This study presents a method for choosing polluted-effluent discharge locations to a river considering its current water-quality condition to produce minimal adverse impacts on the river's water quality. The method relies on a relative preference function that selects suitable discharge points of polluted effluents. The water-quality of the Karoon river was simulated between Gotvand dam and Shooshtar city, Iran, for different levels of BOD concentrations discharge using the QUAL-2 K model. The method applies the water-quality simulation results to select alternative contaminant-discharge locations along the river minimizing adverse water-quality impacts.

2. Materials and methods

2.1. Discharges of polluted effluents to rivers

Sewage contamination remains the primary water quality threat to the water quality of rivers, especially in many developing countries where human and animal wastes are not yet adequately collected and treated (Chapman & World Health Organization, 1996; Li et al., 2017). The discharge of polluted effluent to rivers can be classified into sudden or permanent by the duration of the release. For example, the release of materials from a fuel tanker into a river because of a road accident is a sudden release, whereas the discharge of a city's sewage to a river is considered a permanent discharge. In terms of the spatial extent of the release, pollution discharge is classified as point or nonpoint. For instance, industrial pollution is a point source of pollution. Runoff from neighboring farms entering a river is a type of nonpoint source pollution (Santhi et al., 2001).

Several factors must be considered when determining the amount and type of discharges of polluted effluents to a river. These factors include the nature of discharged wastewater (point or nonpoint, its chemical/biological/physical and decay characteristics), the self-healing capacity of a river (hydraulic features, aquatic organisms, the nature of the riverine habitat), and the total masses of pollution entering at different points along a river. The World Health Organization (WHO) has proposed various standards to reduce surface-water pollution. The Environmental Protection Organization regulates pollutants in surface waters in Iran.

2.2. The QUAL-2K model

Water quality modeling is a valuable tool for water management because it can simulate possible responses of the aquatic system to such changes as variations in sewage treatment implementations (Chapman & World Health Organization, 1996). There are several mathematical and computer models for simulating riverine water quality. The QUAL-2 K model is the most recent of the QUAL model series, and was adopted in this work for simulating riverine water quality. QUAL-2 K is a thorough model for simulating riverine water quality (Chapra & Pelletier, 2003). It can simulate many indicators such as DO, BOD, temperature, acidity, suspended materials, phosphorus, nitrogenous compounds, and algal content.

QUAL-2 K is a one-dimensional (1D) simulation model of riverine water quality (Fan et al., 2009). 1D simulation of this type assumes complete mixing of dissolved substances or properties with river depth and width. The river, however, can be divided into multiple reaches each with its own model parameters and balanced hydraulic and water-quality characteristics to allow variation with stream length. In this manner, QUAL-2 K can handle uniform and non-uniform flow conditions, point and non-point sources, multiple pollutants, and sewage discharges in primary and secondary branches of a river (Ning, Chang, Yang, Chen, & Hsu, 2001). In addition, QUAL-2 K performs uncertainty analyses and some level of optimization.

2.3. Methods

Once polluting substances are discharged into a river they are transported and transformed by physical, chemical, biological and biochemical processes. It is important to understand these various pathways in order to determine the impact of the substance on the water system and the rates at which elimination may occur (Chapman & World Health Organization, 1996). A major role of water quality management is to find out whether water quality standards are being violated and, if so, where and how often the violations occur (Park et al., 2006). Furthermore, the relation between the concentration of river pollution and its damage to river ecosystem is of a nonlinear nature. Therefore, this paper defines a relative-preference method that applies a penalty function to the BOD in river water to prioritize and select stream reaches for the purpose of polluted-effluent discharge. The penalty function equals the sum of squared pollution concentration deviations from a baseline BOD equal to 1 mg/L. The use of a quadratic function as a penalty function captures some level of nonlinearity and augments the penalty with increasing BOD. The applied penalty function is expressed by Eqs. (1) and (2):

$$c'_i = \begin{cases} c_i \textit{ if } c_i \geq 1 \\ 0 \textit{ else} \end{cases} \tag{1}$$

$$F_j(c') = \sum_{i=1}^{n} (c'_i)^2 \tag{2}$$

in which c' = BOD larger than 1 mg/L; i = counter of points (locations along a river) where BOD is calculated; c = BOD concentration (mg/L); j = counter of points where pollution enters the river (there are $F = 18$); and n = the number of points where BOD is calculated (for each F there are 102 points along the river of this paper's example).

The penalty function for each location j where pollution is discharged into the river is calculated. The value of each penalty function is divided by the smallest value among the penalty functions. Thereafter, the inverse of each value of the normalized functions is calculated, which produces the relative preference function. The values of the relative preference function ranges between zero and one. Normalized quantities so calculated are easily compared with each other and suitable polluted-effluent discharge points are identified quickly. The equation of relative preference function for a location j (M_j) is given by Eq. (3). The closer to 1 a value of the relative preference function for a location of pollution discharge to a river is, the more suitable that location is for discharging pollution, and vice versa:

$$M_j = \frac{1}{\frac{F_j(c')}{F_{\min(c')}}} \tag{3}$$

in which M = relative preference function, and: F_{min}

$$F_{\min}(c') = Min\,[F_j(c')] \tag{4}$$

2.4. Case study

This paper's method was applied to a reach of the Karoon river between Gotvand dam and Shooshtar city, Iran. The Karoon river is the longest and largest river in Iran. Numerous industrial centers, farms, and small and large cities lie near this river and discharge polluted effluents to it. Fig. 1 depicts the study area.

Considering the importance of BOD in terms of environment and the sufficiency of available data from case study, BOD was chosen as the water-quality indicator for this study. BOD is the amount of oxygen required by aerobic microorganisms to decompose the organic matter in a sample of water, such as that polluted by sewage. It is used as a measure of the degree of water pollution and is a common pollution monitoring indicator of water quality in rivers and other waters. Low (high) BOD indicates low (high) organic pollution in a water body. Low (high) BOD correlates with high (low) DO in streams. The DO is a key water-quality characteristic that determines the suitability of river water to support aerobic aquatic life. Oxygen shortage, even if it occurs merely occasionally and for short times, causes a rapid reduction in the number of aquatic aerobic organisms present, especially the clean water species that rely on high oxygen levels and most fish (Chapman & World Health Organization, 1996).

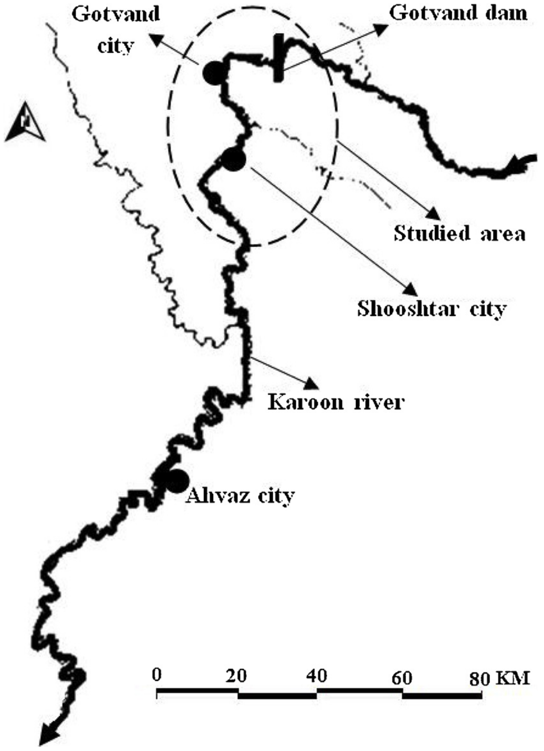

Fig. 1. The schematic of the study area.

The maximum BOD allowed in discharge to rivers in Iran is set at 30 mg/L. This study used the data on the Karoon river's water resources collected by the Khozestan's Environmental Protection Organization in 1996. The main sources of BOD discharge in the Karoon river within the study area are listed in Table 1. These sources are all permanent pollution sources and some of them have been discharging pollution with concentration over than 30 mg/l without license. Among these sources, the wastewaters of Gotvand and Shooshtar are nonpoint pollution sources for which an entry interval to the river has been determined, and the rest are point sources of pollution.

Gotvand dam is located at the upstream point of the study area. From analysis of the water released from Gotvand dam between 2011 and 2014 (when it began its operations) it was found that the minimum, average, and maximum released flows were 13.7, 247.7, and 458 m^3/s, respectively. Thus, the 13.7 m^3/s flow was chosen as the amount of river flow for river's water-quality simulation, which would produce the most severe stress on the river's water quality (that is, under minimum streamflow). Other necessary information for river's water-quality simulation is listed in Table 2. Fig. 2 depicts a schematic of the Karoon river and its pollution sources.

3. Results and discussion

3.1. Simulating riverine water quality with background water-quality

BOD simulations were made for the reach comprised between stations at zero (at Gotvad dam) and 200 km downstream from Gotvad dam. The input data corresponds to background discharges of BOD-laden discharges. The simulation results are graphed in Fig. 3, where L denotes the distance downstream from Gotvad dam. The BOD depicted in Fig. 3 demonstrates that the river's water quality in the study interval falls in a suitable range (less than 30 mg/L) when the effect of upstream discharge of BOD-laden discharge is not taken into account. The pollution entering upstream was ignored because its sources were distant from the study area and the amount of discharge is small. It is clear from Fig. 3 that BOD decreases with increasing distance from a discharge point until the next discharge location is encountered, where BOD rises anew.

3.2. Simulating riverine water quality with new pollution discharge

In this section new pollution discharge (in addition to current one) was input as BOD ranging between 10 and 30 mg/Lin increments of 5 mg/L. The discharge flow was set at 2 m^3/s. Choosing this range of new BOD pollution discharge takes into account that BOD less than 10 mg/L has a small effect on river's water quality, and discharge with BOD larger than 30 mg/L exceeds the regulatory standard. The discharge flow of 2 m^3/s was chosen from typical value of discharges in the study area.

Each level of BOD concentrations discharge (10, 15, 20, 25, and 30 mg/L) was input, one at a time, at 18 equally spaced discharge locations in a 85-km long river reach, and river's water quality was simulated with QUAL-2 K for each level of BOD concentrations input at

Table 1
The pollution sources within the study area.

Pollution discharger	Release flow (m^3/s)	BOD concentration (mg/L)	Distance from Gotvand dam (km)
Gotvand's wastewater	3.51	6.27	15 to 20
Gotvand slaughter house	0.0001	18000	25
Aghili's farm drainage	5	8.8	35
Shooshtar's wastewater	6.36	6.27	50 to 60
Khatam Alanbia hospital	0.5	40	55
Alhadi hospital	0.5	36	57
Shooshtar Azin company	1	50	60
Kharoon sugar farm	8.9	9.2	70

Table 2
Data for river's water-quality simulation.

Parameter	value	unit
River width	60	m
River length	300	km
River gradient	0.0003	–
Manning's roughness coefficient	0.03	–
BOD decay coefficient	0.3	day^{-1}

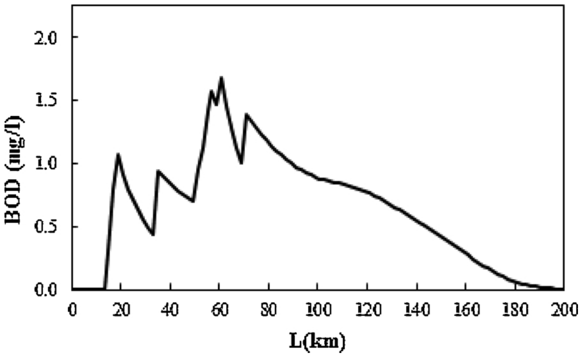

Fig. 3. The current concentration of river BOD in the study reach in an average flow. (BOD: Biological oxygen demand; L: Distance downstream from Gotvad dam).

each location, for a total of 90 simulations. Figs. 4 and 5 show the calculated results for input of new BOD equal to 10 and 30 mg/L, respectively. Figs. 4 and 5 depict the simulated BOD concentrations for discharges of polluted effluent at locations 0, 40, and 85 km of their corresponding BOD (10 mg/L for Fig. 4, and 30 mg/L for Fig. 5). The simulated BOD for other discharge concentrations (15, 20, 25 mg/L) falls between those corresponding to 10 and 30 mg/L.

Figs. 4 and 5 establish that changing the location of discharges of polluted effluent modifies the BOD diagrams. These changes are more patently clear by comparing the peaks in BOD. The differences in calculated BOD corresponding to the various input concentrations (10, 15, 20, 25, and 30 mg/L) cause varying degrees of environmental consequences that can be assessed using penalty functions. Therefore, because the intensity of environmental damage is a nonlinear function of the BOD in river water, the importance of choosing a suitable location for releasing polluted effluent is evident and is highlighted by Figs. 4 and 5.

3.3. *Calculating the relative-preference function*

The relative preference function was calculated for BOD ranging from 10 to 30 mg/L in 5 mg/L increments (that is, 10, 15, 20, 25, and 30 mg/L). Fig. 6 presents the results of the calculations. The horizontal axis represents the BOD discharge locations and the vertical axis denotes the relative preference function. The relative preference functions for different BODs exhibit similar trends. Recall that the closer to 1 the value of relative preference function is, the more suitable it is for the discharge of polluted effluent. This means that, based on Fig. 6, the closer the BOD discharge is to the start (upstream section) and end (downstream section) of the river reach, the better the river's water quality achieved. This is so because the two extreme points of the reach are about 15 km from the nearest pollution source, creating sufficient distance over which BOD decays. The general trend of the relative preference function seen in Fig. 6 indicates that the closer to the middle of a reach interval a new BOD discharge is chosen, the worse the quality of river water becomes.

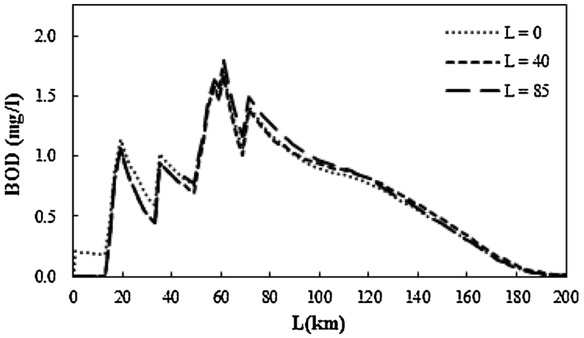

Fig. 4. Simulation of pollution discharge with concentration 10 mg/L at three locations. (BOD: Biological oxygen demand; L: Distance downstream from Gotvad dam).

River's water quality improves when the locations of new discharges of polluted effluents are toward the extremities of the river reach. In

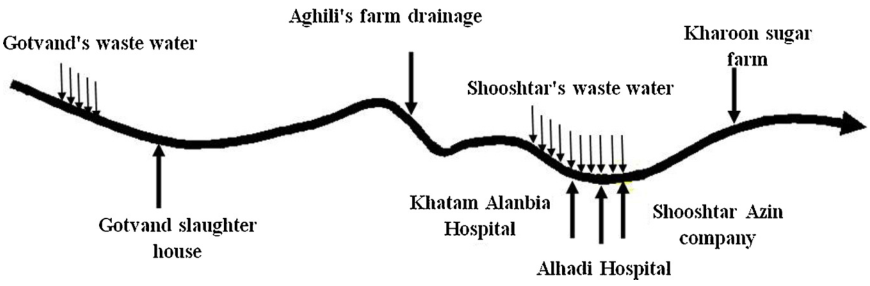

Fig. 2. A schematic illustration of the Karoon river and pollution sources in the study area.

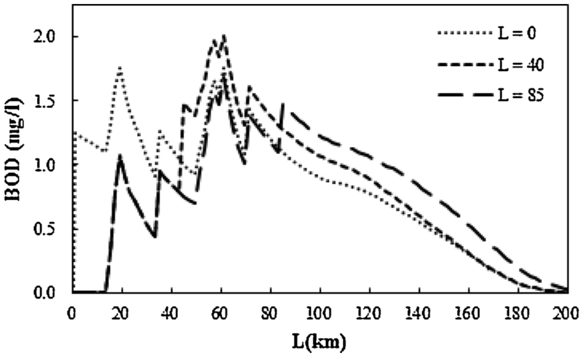

Fig. 5. Simulation of pollution discharge with concentration 30 mg/L at three locations. (BOD: Biological oxygen demand; L: Distance downstream from Gotvad dam).

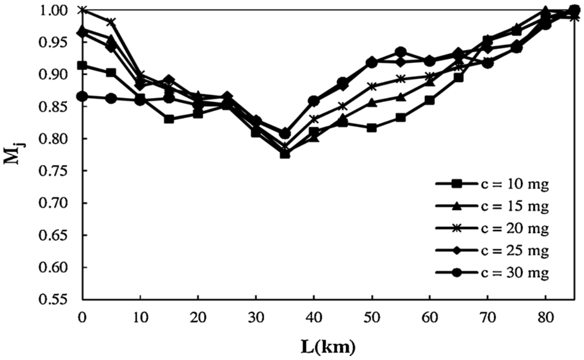

Fig. 6. Relative preference function for location *j* (M_j) between 0 and 85 km corresponding to BOD discharge ranging from 10 to 30 mg/L. (M: Relative preference function; L: Distance downstream from Gotvad dam).

contrast, kilometer 35 is the most unsuitable location for discharging new polluted effluent because of the accumulation of pollution at that location and downstream from it. Kilometer 35 coincides with the main entrance to Shooshtar city; therefore, it is appropriate that discharges of new polluted effluent be moved sufficiently downstream and upstream from kilometer 35.

The relative-preference function was calculated by applying different penalty functions to assess the effect that the penalty functions had on the choice of new discharge points. Two additional penalty functions similar to that given by Eqs. (1) and (2) were tried, one based on the sum of the third power of the deviations of BOD larger than 1 mg/L and the other on the sum of the fourth power of the deviations of BOD larger than 1 mg/L. Recall that Eqs. (1) and (2) were based on the sum of the squared of the deviations of BOD larger than 1 mg/L. Figs. 7 and 8 graph the relative preference function for penalties of BOD larger than 1 based on the sums of the third and the fourth powers of the deviations, respectively. Figs. 7 and 8 establish that the difference between the relative preference of BOD discharge locations increases with increasing power of the deviations. All things considered, it seems appropriate to use the sum of the squared deviations to establish the relative preference function for new discharge locations.

The various relative preference functions shown in Fig. 6 were averaged to derive a comprehensive relative preference function. Fig. 9 depicts the averaged relative preference function. Fig. 9 shows that the average relative preference function reaches an absolute minimum at km 35, as was concluded earlier when evaluating individual relative preference functions. Concerning Fig. 9, it is essential to carry out a sufficient number of simulations for new pollution discharges to determine the effects of accumulation, dispersion, and decay along a river. Thus, with comprehensive evaluation of discharge location, amount of discharge, and discharge flow through river simulations it is possible to determine suitable locations for new discharges of polluted effluent in a way that minimizes environmental degradation.

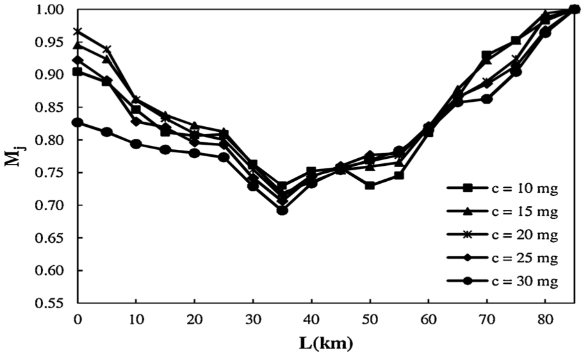

Fig. 7. Relative preference function for location *j* (M_j) between 0 and 85 km with third power penalty function for discharge concentrations between 10 and 30 mg/L. (M: Relative preference function; L: Distance downstream from Gotvad dam).

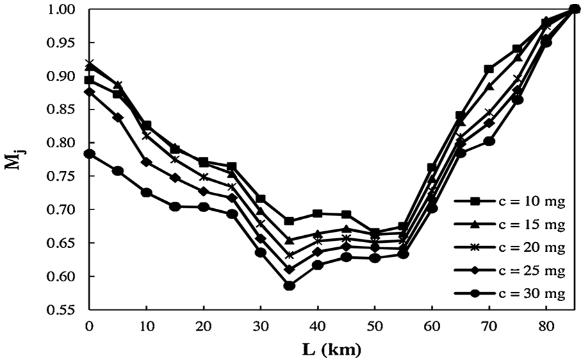

Fig. 8. Relative preference function for location *j* (M_j) between 0 and 85 km with fourth power penalty function for discharge concentrations between 10 and 30 mg/L. (M: Relative preference function; L: Distance downstream from Gotvad dam).

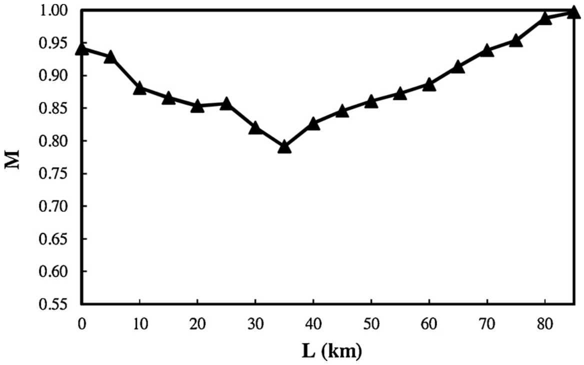

Fig. 9. The averaged relative preference function (M) as a function of distance L. (M: Relative preference function; L: Distance downstream from Gotvad dam).

4. Concluding remarks

The problem of finding suitable locations for discharges of polluted effluent in rivers involves many factors and can be solved in various ways. Yet, the most important issue that must be considered when locating new discharges of polluted effluent to rivers is the change in the amount of pollution concentration. It is possible by suitable simulation to determine the capacity of a river of accepting new polluted effluent and to find suitable locations for its discharge. This paper presented a method for locating suitable points along the river for discharging polluted effluent according to riverine water quality and river's conditions. The method first simulates riverine water quality under different BOD loadings and discharge locations using QUAL-2 K.Then, a relative preference function was calculated to compare different discharge locations of polluted effluent with BOD ranging from 10 to 30 mg. The presented method was applied to the Karoon river between Gotvand Dam and downtown Shooshtar city.

The results of the proposed model show that the most suitable locations for discharging new polluted effluent into the Karoon river in the study area are at the beginning (upstream river section) and end (downstream river section) of the considered river reach and the suitability of discharge points decreases with decreasing distance from the middle of the reach. Locations at kilometer 35 and its vicinity are the most unsuitable points for discharging BOD judged by the lowest values attained by the relative preference function sat and near km 35. This is due to the large accumulation of BOD in the vicinity of km 35.

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