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Assimilative Capacity and Flow Dilution for Water Quality Protection in Rivers

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Abstract: Industrial and urban development is a common cause of increased pollution. Pollutants are in many instances discharged untreated to rivers due to lack of adequate treatment facilities and high treatment cost. In many cases, the detriment of pollution discharge to a river exceeds its self-purification capacity, and it may cause irreparable damages to the riverine environment. In this regard, water flow in a river is an effective characteristic behind its assimilative capacity that can be used to decrease pollution damages. Determining a river's assimilation capacity and the flow necessary for dilution of pollutants are important tasks. In this paper, pollution damage to a riverine environment is a function of the pollutant's concentration and the contact duration with river water. Pollutant transport in a river is simulated based on mathematical equations of pollutant advection-dispersion. The optimum values of a river's assimilation capacity and the dilution flow required in a river to mitigate pollution are determined using a nonlinear programming (NLP) method and the nondominated sorting genetic algorithms II (NSGA-II). The optimum assimilation capacity of a river was calculated in an application example for different reservoir releases. The results show that the magnitude of river flow can improve the total riverine assimilation capacity by up to 80%. Optimal Pareto boundaries were obtained for pollutant concentration and the duration of pollutant contact by means of river flow adjustment. **DOI: 10.1061/(ASCE)HZ.2153-5515.0000234.** *© 2014 American Society of Civil Engineers.*

Author keywords: Assimilation capacity; Dilution flow; Optimization; River flow.

Introduction

Rivers provide an important water supply for human activities. Population growth, economic development, and water demand increase, encouraging humans to construct dams on rivers and build human settlements nearby. Human settlements near rivers cause pollution in rivers through multiple sources, such as industrial and municipal wastes, impairing river water quality. Using the rivers' self-purification capacity for pollution treatment can be an effective and low-cost method. There are numerous examples of pollutant discharges to rivers that have caused irreparable damages to plant and animal species, and posed risks to humans. Therefore, assessing a river's capacity to assimilate pollutants through adjustment of its flow is an important water-quality management tool.

Recently, many techniques have been developed and applied in all aspects of water resources systems such as reservoir operation (Afshar et al. 2010; Bozorg Haddad et al. 2008a, b, 2009, 2011a; Fallah-Mehdipour et al. 2011a, 2012a), cultivation rules (Moradi-Jalal et al. 2007; Noory et al. 2012), pumping scheduling (Bozorg Haddad and Mariño 2007; Bozorg Haddad et al. 2011b; Rasoulzadeh-Gharibdousti et al. 2011), water distribution networks (Bozorg Haddad et al. 2008c; Soltanjalili et al. 2010; Fallah-Mehdipour et al. 2011b; Seifollahi-Aghmiuni et al. 2011; Ghajarnia et al. 2011; Sabbaghpour et al. 2012), operation of aquifer systems (Bozorg Haddad and Mariño 2011), and site selection of infrastructures (Karimi-Hosseini et al. 2011). Only a few of these works dealt with the assimilative capacity and flow dilution for water-quality protection of surface water resources systems.

Several studies have dealt with pollution control methods in rivers. Chang et al. (1997) used fuzzy and gray programming to minimize existing uncertainties in the riverine pollution control systems. Jobson (1997) proposed an approach for the quick estimation of the pollution travel time along the river.

Seo and Cheong (1998) proposed a method estimating the dispersion coefficient in rivers using a nonlinear regression approach, and hydraulic and geometric data. Wen and Lee (1998) presented a neural network-based multiobjective optimization of water quality management within river basins and applied it for the Tou-Chen River Basin in Taiwan.

Karamouz et al. (2003) developed an optimization model for river water quality management using a sequential dynamic genetic algorithm (SDGA). Their proposed model was applied to manage water quality of the Karoon River in Iran. Meuleman et al. (2004) assessed pollution reduction along a river before achieving the De Meije wetland in The Netherlands. They evaluated high pollution concentrations of chloride, sulfate, calcium, and bicarbonate, and showed that a ditch system with aquatic vegetation could successfully remove nutrients from polluted river water.

Kerachian et al. (2005) presented a stochastic genetic algorithm (GA)-based optimization model that exploits the stochastic dynamic programming principle for pollution load allocation within a river system. To solve existing disagreements among river-using

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stakeholders, they used the Nash conflict resolution theory (Nash 1950). Yandamuri et al. (2006) proposed a multiobjective optimization framework for optimal pollution load allocation in rivers, considering (1) the total treatment cost, (2) the equity among the pollution dischargers, and (3) the dissolved oxygen (DO) in the water characteristics.

Kerachain and Karamouz (2007) developed optimal operating rules for water quality management in reservoir-river systems using a methodology combining a water quality simulation model and a stochastic GA-based conflict resolution technique. The proposed model, which is called stochastic varying chromosome length genetic algorithm with water quality constraints (SVLGAQ), was successfully applied to the Ghomrud reservoir-river system in the central part of Iran. The present river pollution situation in China was analyzed by Meng (2009). The causes of water pollution were attributed to the extensive economic developments, poor wastewater treatment, and a lack of nonpoint pollution control. To cope with this blight, they proposed establishing water pollution control systems at the watershed level, preserving healthy aquatic ecosystems, conducting risk management, and using comprehensive methods for water-quality protection. Chen et al. (2012) identified monitoring networks and water quality information as essential factors in the sustainable management of water resources and pollution control. Their monitoring and management method had been applied to optimize the water quality monitoring network on the Heilongjiang River in northeast China.

De Andrade et al. (2013) proposed a river-pollution protection model using the simulated annealing (SA) algorithm and the enhanced stream water quality simulation model (QUAL2E). This approach was applied to determine the required oxygen concentration for biochemical activities in the Santa Maria da Vitória River watershed of Brazil.

Poorsepahy-Samian et al. (2012) presented a game theory for water and pollution allocation in rivers. The suggested approach was applied to the Karoon-Dez river system in the southwest part of Iran. Obtained results showed a 300% increase in the total system benefits for various stake-holding coalitions. Wu et al. (2013) assessed ecological engineering methods for nonpoint pollution resources control due to use of chemical fertilizers and pesticides. Their findings identified several helpful strategies for sustainable agriculture.

This paper presents a method for river pollution control that relies on river flow control to tackle various levels of pollution hazards. The preservation of environmental quality is considered a top priority in the presented method, which relies on simulation of pollutant transport and optimization to achieve water quality goals.

Simulation of Pollutant Transport in Rivers

The factors that govern the transport of river pollutants include (1) advection, which makes the pollution mass move in a downstream direction; (2) longitudinal dispersion, which causes the pollution mass to disperse in the water; and (3) decay, which makes the pollution to dissipate or convert to harmful forms and reduces the pollution mass over time. Considering these factor effects, the pollution mass creates a chemograph (concentration versus time) moving through measurement points. The area and peaks of the chemograph decrease due to dispersion and decay processes as the pollutant travels downstream, as shown in Fig. 1. The x-axis represents the distance between the measuring point and the pollution discharge point, the t-axis denotes the time elapsed since pollution occurrence in the river, and the c-axis depicts the pollution concentration.

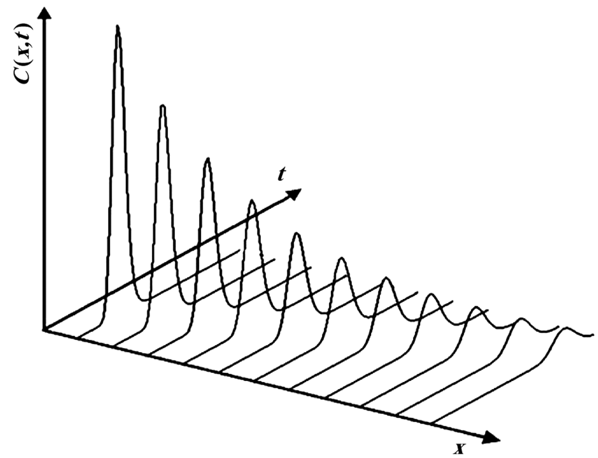

Fig. 1. Pollutant concentration-time (chemograph) movement along a river

The mathematical equations of pollution propagation in a river provide the basis for simulation methods of riverine transport. Eq. (1) indicates the one-dimension differential equation of pollution transportation and dispersion (Van Genuchten and Alves 1982)

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} - kc \tag{1}$$

in which c = pollutant concentration (mg/L); x = distance between measuring and pollution discharge points (m); t = time elapsed since pollution occurrence in the river (s); D = dispersion coefficient of the pollutant (m^2/s); u = river water flow velocity (m/s), and k = coefficient of pollution decay (1/s). In this equation, it is assumed that the river flows, the river cross-section, the dispersion and decay coefficients are constant, there is no input and output of pollution along the river, and there is a complete mixing of pollution over the depth and width of the river.

Eq. (2) shows the analytical solution of Eq. (1) for the case of sudden pollutant release into river water

$$c(x,t) = \frac{M}{2A\sqrt{\pi Dt}}\exp\left[\frac{-(x-ut)^2}{4Dt} - kt\right] \tag{2}$$

in which $c(x,t)$ = pollution concentration at distance x and at time t (mg/L); M = sudden pollutant mass at the discharge point (kg), and A = area of the river cross-section (m^2).

There are many experimental equations for calculating D. Eq. (3) has been used to calculate the value of D by Fischer (1975)

$$D = 0.011\frac{u^2w^2}{hv} \tag{3}$$

in which w = width of the flow section (m), h = flow depth (m), and v = shear velocity (m/s). v is calculated using Eq. (4)

$$v = \sqrt{gRs} \tag{4}$$

in which g = acceleration gravity (9.81 m/s^2); R = hydraulic radius of the river calculated as A/P [A = cross-section area of the river flow (m^2) and P = wet perimeter of the river flow cross-section (m)]; and s = hydraulic slope of the river (m/m).

Pollution Assessment Criteria

The damages of the pollution occurrence in the river have been assessed considering two factors in this study: (1) pollutant with concentration higher than the allowable limit along the river and (2) the duration that such pollution is in contact with the riverine environment. According to Eq. (2), these factors have conflicting traits, including: (1) to reduce the high pollutant concentration along the river, the flow velocity should decrease, so the pollutant has enough time to disperse and decay, and, then, its concentration would decrease; and (2) to reduce the duration that the pollutant with high concentration is in contact with the river environment, the flow velocity must increase, so the pollutant has a smaller contact time with the riverine environment. Both factors should be considered in a river's environment protection. Therefore, according to the purposes of this study, these factors have been considered in terms of an *allowable concentration* constraint, and the two objectives of *mean unallowable concentration* and *duration of contact* to determine the assimilation capacity and the dilution of river flow.

The allowable limit of the pollution concentration along the river, defined by environment protection agencies, is called the *allowable concentration*. This constraint has been used to control the pollution concentration to determine the river assimilation capacity. Thus, once the allowable concentration is defined, one must check whether or not the pollution concentration at each downstream point is higher than the allowable limit. For this purpose, the peak of the pollutant chemograph is determined at each point downstream of the discharge point. In general, if the peak of the chemograph at each downstream point is less than the allowable concentration, all values of the chemograph will also be less than the allowable limit. To determine the peak value of a pollutant's chemograph at each downstream point, the derivative of Eq. (2) is taken and the resulting expression is set equal to zero and solved for the time of peak value

$$t = \frac{-D + \sqrt{D^2 + u^2x^2 + 4kDx^2}}{u^2 + 4kD} \tag{5}$$

Inserting Eq. (5) into Eq. (2) yields Eq. (6) for the maximum concentration

$$c_{\max}(x) = \frac{M}{2A\sqrt{\pi D\left(\frac{-D+\sqrt{D^2+u^2x^2+4kDx^2}}{u^2+4kD}\right)}} \times \exp\left\{\frac{-\left[x - u\left(\frac{-D+\sqrt{D^2+u^2x^2+4kDx^2}}{u^2+4kD}\right)\right]^2}{4D\left(\frac{-D+\sqrt{D^2+u^2x^2+4kDx^2}}{u^2+4kD}\right)} - k\left(\frac{-D + \sqrt{D^2 + u^2x^2 + 4kDx^2}}{u^2 + 4kD}\right)\right\} \tag{6}$$

in which $c_{\max}(x)$ = maximum concentration of the pollutant at location x. The purpose of Eq. (6) is to determine the peak value of the pollutant chemograph at each point (or river station) with specified distance x from the discharge point, regardless to the chemograph passing time. The allowable concentration constraint, $c_{\max i}$ (x) at all downstream points becomes

$$c_{\max i}(x) \le c_s \tag{7}$$

in which i = index for the points and c_s = value of the allowable concentration.

Taking into account Eq. (6), the unallowable concentration is defined as follows:

$$c_d = \begin{cases} \sum_{i=1}^{n}(c_{\max i}(x) - c_s) & c_{\max i} > c_s \\ 0 & c_{\max i} \le c_s \end{cases} \tag{8}$$

in which c_d = unallowable concentration (mg/L) and n = total number of points with concentration higher than the allowable ones. Dividing c_d by n produces the *mean unallowable concentration*

$$\bar{c_d} = \frac{c_d}{n} \tag{9}$$

The duration of contact is defined as the interval from the time of pollution occurrence until the time at which the pollution concentration becomes equal to the allowable concentration. To determine the duration of contact, the points (stations) on the river with concentration higher than the allowable limit are identified using Eq. (6). Then, the point most distant from the point of pollution occurrence is chosen. The duration between the pollution occurrence time and the time of occurrence of the chosen chemograph peak is the duration of contact (T), which can be expressed mathematically as follows:

$$T = \max(t_i) \qquad i = 1, 2, \ldots, n \tag{10}$$

in which T = duration of contact (s) and t_i = time for the ith chemograph peak.

The allowable concentration constraint and the two objectives expressed by $\bar{c_d}$ and T are considered to determine the assimilation capacity and the dilution flow, respectively. Fig. 2 shows this situation, where the x-axis represents the distance, the t-axis is the time, and the x-axis is shown with the same direction as the t-axis.

Assimilation Capacity

Consideration of a river's self-purification capacity for pollution treatment is an economic necessity given scarce resources to build and operate conventional treatment facilities. The management of pollution discharge to rivers by their natural assimilation has its economic benefits, provided that the level of pollution does not exceed the river's natural treatment capacity. Therefore, the control of pollution discharge by rivers requires the setting of constraints.

The allowable concentration constraint, defined in the previous section, is used to determine the assimilation capacity of a river. It can be implemented because the discharged pollution mass can be controlled by pollution dischargers. The maximum input pollution mass to the river can be determined using this constraint and one can be assured that the input pollution concentration would be less than the allowable value.

If there is a regulating structure (reservoir) upstream of the pollution occurrence point, the water release from the reservoir in the river can be changed. Thus, one can calculate a maximum pollution

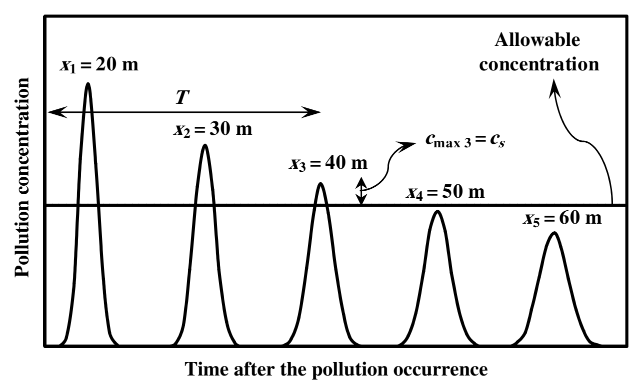

Fig. 2. Approach for checking the concentration constraint and determining the objectives of the problem

mass corresponding to the value of each release that would result in a pollutant concentration less than the *allowable concentration*. Therefore, for each value of river flow, the maximum pollution allocation can be determined and reported to the pollution dischargers. If there are no regulating structures (reservoirs) in the upstream of the pollution occurrence point, the river flow is not a control variable.

Dilution Flow

When the pollution is accidental or uncontrolled, such as sudden pollution discharge of factories near a river without a permit or fall of a tanker of petroleum to the river due to a road accident, one of the practical remedial actions is to release the release upstream of the pollution discharge point. In this circumstance, the release is adjusted to minimize the damages to the environment. This can be achieved only by construction of regulating reservoirs.

As mentioned earlier, river flow adjustment is a practical and easy method to reduce the damages caused by pollution of a riverine environment. In this situation, one can only regulate the river flow to reduce the pollution damages because the input pollution mass is uncontrollable and it cannot be changed. It should be noted that the reservoir release allocation to control the pollution or to supply other objectives, such as domestic, agricultural, and industrial demands, is made by decision makers according to each objective's importance.

Optimization Method and the Model

In determining the river assimilation capacity, the optimization objective is to control the value of the dischargeable pollution mass. The allowable concentration is the constraint imposed using Eq. (7). Before calculating the allowable concentration constraint, the maximum pollution concentration at each downstream point is calculated using Eq. (6). The unallowable concentration constraint is nonlinear due to the nonlinearity of Eq. (6). Thus, the nonlinear programming (NLP) method, which is a single-objective optimization approach, is used to determine the maximum river assimilation capacity.

When any equation (objective functions or constraints) in an optimization problem is nonlinear, the optimization problem is nonlinear. To find the optimum solution in these problems, one can use the NLP method. According to this method, the optimum solution is determined by calculating the gradient at each point of the objective function space using mathematical differentiation. The derivative of the maximum and minimum points of the functions is set equal to zero, considering the boundaries imposed by constraints, and NLP methods use this concept to find the optimum solution. However, calculating the derivative of the objective function is a time-consuming process that can become insurmountable. Nevertheless, due to its easy programming and frequently satisfactory performance, the NLP method is used to determine the maximum assimilation capacity of rivers.

The volume of dilution flow is determined when the input pollution mass to a river is higher than its assimilation capacity. In this situation, the allowable concentration constraint is violated. It is necessary to minimize the violation of this constraint to reduce the damages to the environment, because larger violations cause larger damages. In addition, the duration of pollution in a river with concentration higher than the allowable limit is important due to reduction of dissolved oxygen in the stream. Thus, minimizing the mean unallowable concentration and the duration of contact, defined in the previous sections, is the objective function used to determine the reservoir release needed for pollutant dilution and reduction of the damages to the riverine environment. The simultaneous achievement of both objectives requires a multiobjective optimization method.

One of the two-objective optimization methods is the NSGA-II, which has performed well in previous water quality studies. The NSGA-II is a search and optimization method based on the GA (Shokri et al. 2014; Fallah-Mehdipour et al. 2011a, 2012b).

A series of N primary solutions is considered as the parent population in the NSGA-II. The child population is generated based on the parent population with the same size. Then, the parent and child populations synthesize and a new population is generated with the size equal to $2N$. The members of this new population are sorted and prioritized based on their nondominant characteristics. Then, a population of size N is selected according to the nondominant characteristics from the new population. The selected population is considered as the parent population in the next iteration.

The nondominant solutions for two conflicting objectives in the NSGA-II are collected into a population called parents. This population creates a new population with the same size called offspring population. Combining these two populations, a new population is created and then sorted based on the nondominant sorting. The solutions that are superior over the others are selected from the combined population by selection operators, and they are saved in a new set. This new set, in which the number of solutions is equal to the number of them in the parent population, forms the new parent population for the next iteration. This process continues until the most nondominant solutions are saved in the last population, and the process stops.

Case Study

The described optimization method was implemented for a hypothetical river with a sudden pollution discharge. Fig. 3 shows the schematic of the hypothetical river. Table 1 contains the assumed characteristics of the river and pollution. These values are hypothetical, but they have been selected in the range of the real values for these characteristics. In Table 1, s is the hydraulic slope of the river and the other parameters have been defined in the previous

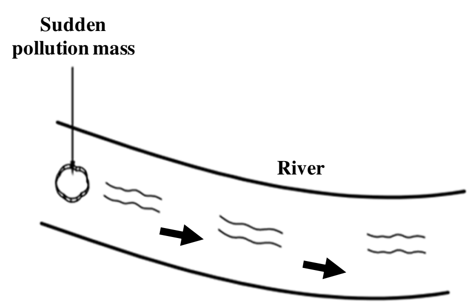

Fig. 3. Schematic of the hypothetical river and the pollution occurrence in it

Table 1. Required Parameters in Determining the Assimilation Capacity

Parameter	Value	Dimension
A	5	m^2
w	5	m
h	1	m
s	0.005	m/m
k	0.03	1/s
c_s	5, 10, 15	mg/L

Note: A = area; w = width; h = water depth; s = hydraulic slope; k = coefficient of pollution decay; c_s = concentration limit.

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sections. The river reach length has been assumed equal to 1,100 m. Because the calculated peak concentration of the pollution is smaller than the allowable limit over distances greater than 1,100 m, the chosen reach length is deemed adequate.

To calculate the peak concentration of pollution, the primary mixing length of the pollutant in the river flow was calculated using Eq. (11) (Fischer et al. 1979)

$$L = 0.1\frac{uw^2}{\varepsilon_z} \quad (11)$$

in which L = primary mixing length of a pollutant in river flow (m) and ε_z = cross-dispersion coefficient, which is determined by Eq. (12)

$$\varepsilon_z = 0.6hv \quad (12)$$

According to the preceding equations, the range 0.01–1.5 m^3/s was used for the flow discharge along with the assumed values in Table 1; the primary mixing length of the pollutant was 34 m. Therefore, the first calculation point of the peak concentration of pollution was made equal to 100 m below the discharge point, well in excess of the primary mixing length.

Three scenarios were assumed for c_s to determine the assimilation capacity. The purpose of these scenarios is to determine the discharged pollution mass, for which a maximum value will be calculated for each river flow discharge. The *Lingo11.0* software (Lindo Systems 2004), which is based on NLP methods, was used to determine the assimilation capacity. The mathematical simulation equations, explained in the previous sections, were programmed in *Lingo11.0* and the maximum value of the discharged pollution was determined based on the input information. Because there is a global optimum solution for the assimilation capacity, the *Lingo11.0* was run only once for each scenario value of c_s.

Three scenarios were assumed for the c_s values (5, 10, and 15 mg/L), to determine the dilution flow and the discharged pollution mass in the river. Thus, there were nine scenarios to evaluate for three values of the input pollution mass to the river (20, 30, and 40 t). The mathematical simulation equations explained in the previous sections were programmed in the *MATLAB* software and the NSGA-II was used for optimization. This optimization algorithm was run five times for each scenario value of c_s The discharge value (due to its direct relation with the flow velocity) was considered as the decision variable to determine the dilution flow according to Eq. (2), which is the main equation for simulating pollution transport.

Results and Conclusions

In this section, the results obtained with the described case study for the assimilation capacity and the dilution flow are summarized.

Determination of the Maximum Assimilation Capacity

If water release from the reservoir is regulated, the river flow is adjustable, in addition to the pollution mass. Thus, there would be a maximum discharged pollution mass for each value of reservoir release. The determined maximum mass of the discharged pollution to the river should be such that the pollution concentration is less than the allowable concentration along the river. The proposed procedure reduces the peak concentrations of the pollutant's chemograph by adjusting the release. This situation occurs by increasing the pollutant's chemograph passing time without reducing the value of the discharged pollution mass.

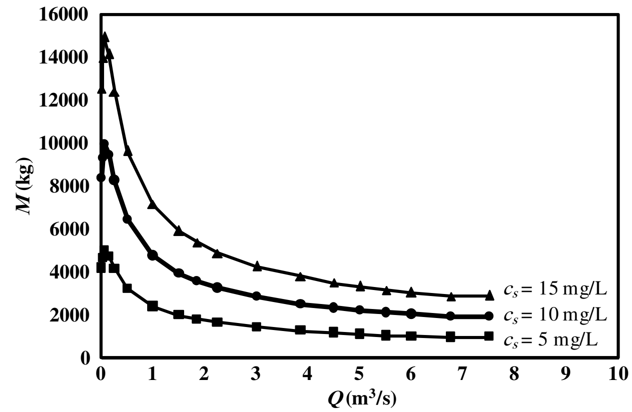

Fig. 4. Maximum discharged pollution mass corresponding to the reservoir release for the different values of the allowable concentration equal to 5, 10, and 15 mg/L

The maximum discharged pollution mass for different values of release and for three values of the allowable concentration (5, 10, and 15 mg/L) in the case study is shown in Fig. 4 using the *Lingo11.0* software.

Fig. 4 shows the increase in the assimilation capacity by increasing the value of the allowable concentration. It also shows that increasing the release does not always increase the maximum discharged pollution mass. Instead, increasing the flow over a certain amount reduces the maximum discharged pollution mass. This happens because the increase in the reservoir release increases the velocity considering a constant river area. The increase in the velocity causes rapid pollution transmission from its occurrence point toward the downstream and decreases the time of the pollution dispersion and decay. Therefore, the peaks of the pollutant concentration-time are increased downstream, and the model is forced to decrease the maximum discharged pollution mass to decrease the peaks in the hydrograph to the allowable concentration limit.

Determining the Dilution Flow

As discussed earlier, *mean unallowable concentration* and *duration of contact* are the objective functions for minimization, which have conflicting behavior, so that if one of them decreases the other one will increase and vice versa. Thus, minimizing these functions requires a two-objective optimization algorithm. Due to the desirable performance of the NSGA-II algorithm in two-objective optimization problems dealing with water quality, and easy access to it, this algorithm was used as the optimization algorithm.

Using the two-objective optimization to protect the environment against the pollution to the river, the river flow is adjusted so that the mean unallowable concentration and the duration of contact become minima. For this purpose, the pollution movement simulation in the river was programmed in the *MATLAB* software and the optimum flow, which causes the minimum damages to the environment, was determined. The input pollution mass to the river was set to 20, 30, and 40 t in the model. The river discharge was considered as the decision variable of the optimization problem in the range of 0.05–7.5 m^3/s. Considering two objectives of $\bar{c_d}$ and T, the obtained Pareto boundary for the allowable concentrations equal to 5, 10, and 15 mg/L is shown in Figs. 5, 6, and 7, respectively.

As shown in Figs. 5–7, the best solutions cover a large range of the mean unallowable concentration, and the duration of this large range has different effects on the river environment and organisms. The unallowable concentration in the Pareto boundary is equal

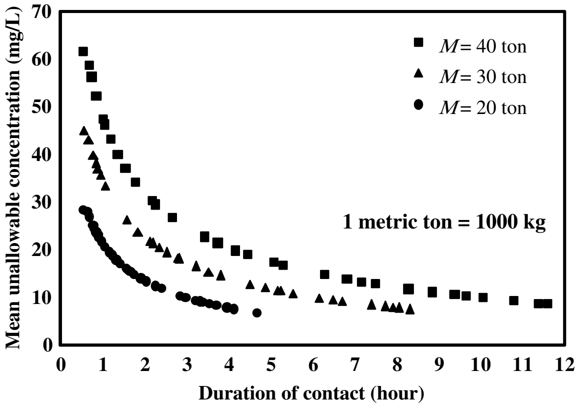

Fig. 5. The obtained Pareto boundary of the objective functions for the allowable concentration equal to 5 mg/L

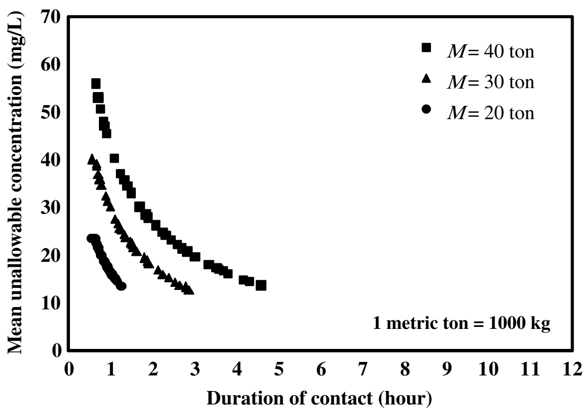

Fig. 6. The obtained Pareto boundary of the objective functions for the allowable concentration equal to 10 mg/L

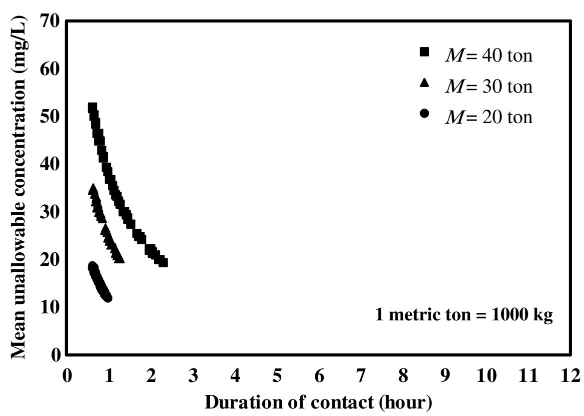

Fig. 7. The obtained Pareto boundary of the objective functions for the allowable concentration equal to 15 mg/L

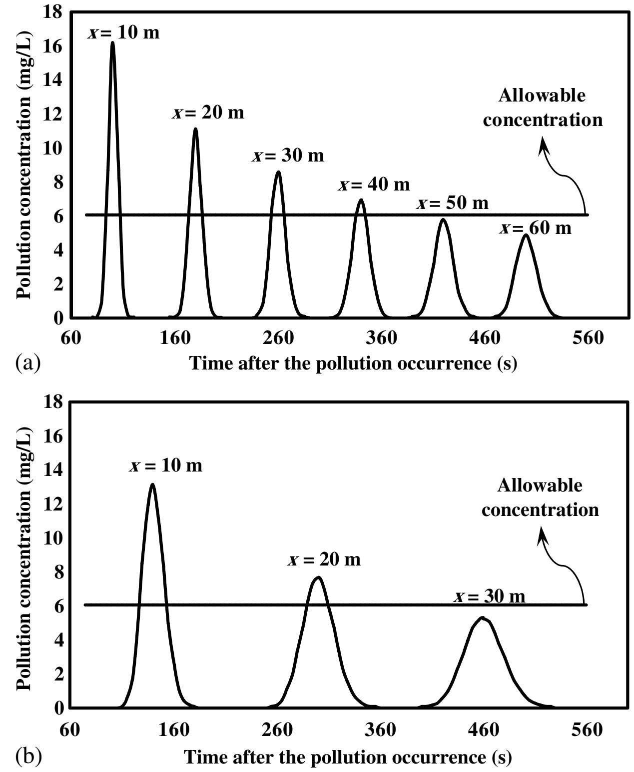

Fig. 8. The reduction of the river distance affected by the pollution concentration in terms of flow velocity changes: (a) the velocity = 0.1 m/s; (b) the velocity = 0.05 m/s

to several times the allowable concentration, and the duration of contact changes by up to several hours.

One of the results of determining the dilution flow is reduction of the distance with unallowable pollution concentration in the river. When the uncontrollable pollution occurs in the river, reduction of the affected distance in the river is one of the important objectives that should be minimized, in addition to the *unallowable concentration* and the *duration of contact*. However, because of the direct relation between the pollution concentration and the affected distance in the river, minimization of the unallowable concentration causes minimization of the affected distance automatically, and there is no reason to consider this objective in the calculations separately. This situation is shown in Fig. 8.

In Fig. 8, the location axis (x) has been pictured on the time axis (t). At the time of 560 s after the pollution occurrence, the pollution mass has traveled a distance of 60 m in Fig. 8(a) due to the high velocity of the river flow and it has traveled 30 m in Fig. 8(b) due to the low velocity of the river flow. Therefore, it was found that the pollution concentration at four points in Fig. 8(a) is higher than the allowable limit and the affected distance of the river is 60 m, while the pollution concentration in Fig. 8(b) is higher than the allowable limit only at two points on the river, and the affected distance of the river is 30 m. This situation shows the direct relation between the affected distance of the river and the unallowable concentration. Thus, minimizing the unallowable concentration can simultaneously minimize the affected distance of the river without needinh to consider another objective function in determining the dilution flow.

Concluding Remarks

This paper determined the assimilation capacity when river pollution is controllable, and the dilution flow when the pollution is uncontrollable. The simulation of the pollution movement in the river was based on the mathematical equations of pollution transport, and the optimization was accomplished using the NLP and NSGA-II methods. The proposed procedure was applied in a hypothetical case study and the obtained results were presented in terms of the assimilation capacity and the dilution river flow.

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The obtained results of applying the proposed method in determining the assimilation capacity showed that the river flow changes in the range 0.05–7.5 m^3/s can cause accentuated changes in the assimilation capacity. The change in assimilation capacity ranges from 948 to 4,965 kg for the pollution allowable limit equal to 5 mg/L, in the range 1,896–9,930 kg for the pollution allowable limit equal to 10 mg/L, and in the range 2,844–14,895 kg for the pollution allowable limit equal to 15 mg/L. Also, the increase of the river flow cannot always increase the maximum assimilation capacity; instead, increasing the river discharge over a certain amount caused a reduction in the river's assimilation capacity.

The results obtained for three pollution allowable limits (5, 10, and 15 mg/L) and the three values of pollution mass (20, 30, and 40 t) in determining the dilution flow showed that the value of the dilution flow could present various Pareto solutions for different unallowable concentrations and durations of contact. These solutions were in the range of 0–60 mg/L for the pollution concentration, and in the range of 0.5–10 h for the duration of contact. Therefore, there are values in these ranges of pollution concentration and duration of contact that correspond to required river flows for pollution dilution. These corresponding values are vital for the river environment and its organisms. Thus, when uncontrollable pollution occurs, one can adjust the release from the upstream regulating structure so that minimal damages to the environment occur, considering the importance of each aspect of the unallowable concentration and the duration of contact.

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