

# Water Quality Planning in Rivers: Assimilative Capacity and Dilution Flow

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**Abstract** Population growth, urbanization and industrial expansion are consequentially linked to increasing pollution around the world. The sources of pollution are so vast and also include point and nonpoint sources, with intrinsic challenge for control and abatement. This paper focuses on pollutant concentrations and also the distance that the pollution is in contact with the river water as objective functions to determine two main necessary characteristics for water quality management in the river. These two necessary characteristics are named assimilative capacity and dilution flow. The

mean area of unacceptable concentration ( $\bar{c}_a$ ) and affected distance (X) are considered as two objective functions to determine the dilution flow by a non-dominated sorting genetic algorithm II (NSGA-II) optimization algorithm. The results demonstrate that the variation of river flow discharge in different seasons can modify the assimilation capacity up to 97%. Moreover, when using dilution flow as a water quality management tool, results reveal that the content of ( $\bar{c}_a$ ) and X change up to 97% and 93%, respectively.

**Keywords** Assimilation capacity · Water quality · Dilution flow · Optimization · River

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Surface water and rivers are the most important human water resources. Unfortunately, pollutants originating from untreated industrial, agricultural, and domestic wastewater disposal reduce the water quality of these crucial and critical human resources and sometimes lead to irreparable damage to the environment. In these circumstances, the high costs of water treatment often prohibit reaching the minimum acceptable quality parameters of drinking water and other water uses. One of the most cost-effective ways for controlling pollution is considering the water flow adjustment. Two important tools for managing water pollution in a river are assimilative capacity and dilution flow (Farhadian et al. 2014). Assimilative capacity is categorized as controllable pollution entrance for each water flow in the river and dilution flow is considered for uncontrollable entered pollution which is obviously higher than assimilative capacity. On the other hand, assessment of the content of acceptable pollution concentration entering the river considering water flow is an applicable and economical solution for water quality management (Farhadian et al. 2014).

The expression of the assimilative capacity of the environment for the first time was presented by the 1972 Stockholm conference. The assimilative capacity refers to the natural ability of waters to dilute and disperse wastes and pollution without harm to the aquatic environment, and it has been adapted in the context of marine pollution (GESAMP 1986). Use of the assimilative capacity concept as an environmental threshold in various environmental management processes and techniques was generally founded on the premise of developing an essential framework for the subsequent design of appropriate environmental standards and land-use regulations (Glasoe et al. 1990).

Assimilative capacity is defined completely different in various regions around the world and the best definition has developed a regulatory application which is known as total maximum daily load (TMDL) by the United States. Assimilative capacity is the maximum amount of a pollutant that can be existed in an impaired water system regardless of pollutant source (Landis 2008). It is a branch of the object-oriented approach that has been developed for the analysis of point-source pollution control in river basins (Spanou and Chen 2000). Moreover, assimilative capacity is an offshoot of the stressor-based monitoring approach and in various projects has been used to illustrate how biomonitoring techniques can be used to quantify biological condition over time (Maruya et al. 2014). It is important to note that, besides these different definitions, the same concept has been used in many investigations. Several governments have employed many different procedures to reduce the detrimental effects of non-point source pollution entrance including sediment and nutrient loads in the Xiangxi catchment, China. The eco-hydrological model and water evaluation tool are the available solutions to confront with these destructive effects and were used to mitigate the hazards in prior investigations (Strehmel et al. 2016; Wu et al. 2013). Furthermore, utilization of assimilative capacity must ensure a specific reference minimum flow condition associated with a particular risk level (Abbasi and Abbasi 2012). A probabilistic evaluation of risk of human health against the hazard of metal pollution entered in a river is investigated (Saha et al. 2017). Therefore, it is crucial to employ a comprehensive definition for this important parameter (assimilative capacity) of river, in researches to avoid any misunderstanding. Assimilative capacity is typically very limited when dealing with toxic substances and it means that toxic substances have a much lower assimilation capacity (Abbasi and Abbasi 2012). In 1994, two studies showed that paper mills using chlorine dioxide in their bleaching process were capable of producing effluents, which after realistic dilution in the receiving water, were not found harmful or only caused very little effects in the aquatic ecosystem (Landner et al. 1994; Tana et al. 1994). The main reasons for this low impact are probably because of the effective procedure inspection in

pioneer mills, eschewing extreme dosage of chemicals, precarious production situation and accidental spills (Landner 1994). Moreover, the assimilative capacity is generally very restricted when confronting poisonous material that are resistant and tend to condense in the environment and aggregate in aquatic biota (Abbasi 1976; Abbasi and Soni 1983, 1984).

Due to the significant role of assimilation capacity as a water quality index, many researchers determine water quality management tool experimentally (Joardar 1998; Clarke et al. 1980; GESAMP 1986, Murray and Beak 1990; Glasoe et al. 1990; Wang 1991; Spanou and Chen 2000).

Water flow adjustment to minimize the damages caused by unallowable pollution entrance is a practical aspect of water quality indices which is a remedial action in pollution crisis management in real cases. An analysis of the assimilative capacity of the St. Lawrence river was done to specify suitable effluent ranges for a promotion to the Brockville Water Pollution Control Center (WPCC), which discharges treated effluent into the St. Lawrence river (Brockville Water Pollution Control Center 2004). Also, assimilation capacity and dilution flow are practical concepts that are used in many water quality management contexts. The aim of an economical drainage design, with respect to pollution, is to balance the effects of continuous and intermittent discharges against the assimilation capacity of the water (Loucks and Van beek 2005). Real-time water quality management was utilized within the San Joaquin Basin (SJR) to determine safe discharge of contaminant loads (Nigel and Quinn 2005). The Province of Ontario, via the ministry of the environment, funded in the Assimilative Capacity Studies (ACS) to be engaged as a contribution with the conservation authority to protect the Nottawasaga valley and lake Simcoe region (Executive Summary 2006). Oceanographers have framed pollution control in terms of assimilative capacity as the ability of natural waters to dilute, disperse and absorb industrial wastes without harm to valuable commercial fish species (Keeling 2007).

However, in all of these researches assimilation capacity is determined using experimental data and only for one specific river. So if the case study changes or the experimental data was not available for another river, it is not possible to calculate assimilation capacity. This problem arose because of the lack of modeling techniques for calculating assimilation capacity. Therefore, acquiring a suitable model to calculate assimilation capacity for various rivers based on the hydraulic parameters of flow and the amount of pollution entrance to the river is crucial. Several studies were developed for simulation of the assimilation capacity which requires having pollution transport equation to be solved. An analytical scheme of a model of pollution transport in the advective area of rivers has been extended and evaluated (Schmalle and Rehmann 2014). Additionally, some

analytical and numerical studies were focused on finding the most convenient description of transport and transformation of dissolved and suspended substances by the advection–dispersion formulas which are used for calculation of water quality indices (assimilative capacity and dilution flow) (Hashemi Monfared and Dehghani Darmian. 2016; Hashemi Monfared et al. 2016).

Considering the fact that the assimilation capacity of various rivers is different (Abbasi and Abbasi 2012) and as mentioned the importance of a reliable simulation model, researchers tried to present a convenient model to determine water quality management tools (assimilative capacity and dilution flow). Wen and Lee (1998) proposed a multi-objective optimization method based on neural network for water quality management in rivers and then employed the model in the Tou-Chen basin in Taiwan. An optimization model to manage water quality of the Karoon river in Iran is extended with sequential dynamic genetic algorithm (Karamouz et al. 2003). Smedt et al. (2005) investigated simulation and optimization techniques to enable estimation of the temporal and spatial evaluation of pollution using an injected tracer. The procedure was successfully applied to the Chilla'n river, Chile. Their results demonstrated good agreement between the observed data and modeling outputs. Gillibrand's report (2006) described progress towards achieving the development of modeling techniques to improve predictions of assimilative capacity of water bodies which is utilized for marine aquaculture. Yandamuri et al. (2006) proposed a multi-objective optimization framework for determining optimal pollution load in rivers, due to (1) the total treatment cost, (2) the equity among the pollution dischargers, and (3) the dissolved oxygen (DO) concentration. Monitoring and controlling schemes are employed to evaluate the quality management of water networks. The ability of the ecosystem to adsorb and assimilate pollution is defined by the hydrodynamic and biological specifics of the water bodies, in order to reduce the pollution hazard and conserve water and environmental quality (ACWG 2004; Tett et al. 2007). Chen et al. (2012) identified monitoring networks and water quality information as essential factors in the pollution control methods and applied their method for water network on the Heilongjiang river in northeast China.

A scheme was extended using a volume-equivalent equation for aluminum dilution identification and discovering sources of aluminum from surface water, groundwater and filter-backwash wastewater, along with losses created by spill discharge, sedimentation and water withdrawal from the reservoir. The method was implemented to 13 reservoirs and data on aluminum and DOC concentrations in reservoirs and influent water were evaluated (Colman et al. 2011). De Andrade et al. (2013) presented a model based on the simulated annealing (SA) algorithm and the raised flow water

quality simulation model (QUAL2E) for river-pollution conservation. This approach was applied to determine the required oxygen concentration for biological activity in the Santa Maria da Vitoria river watershed of Brazil. The allocation of drinking and agricultural water of the Karaj dam in Iran was accomplished by use of the CE-QUAL-W2 simulation model. The results showed that, for abrupt pollution conditions, the developed quality-quantity model was more suitable with the inclusion of water allocation (Bozorg Haddad et al. 2014; Mahmoudi et al. 2016; Aboutalebi et al. 2016).

In one of the recent modeling studies, nonlinear programming model (NLP) was used to determine assimilation capacity (Farhadian et al. 2014), although this model (NLP) to determine the assimilation capacity faced (1) High runtime and (2) In some cases the problem is insurmountable. Furthermore, in their research when the input concentration of the pollutant is higher than the assimilative capacity, this was treated by optimizing the dilution flow using specified objective functions; mean unallowable concentration ( $\bar{c}_d$ ) and duration of contact (T). However, these two objective functions are not accurate enough so that dilution flow cannot be simulated accurately which is modified in the present study.

Also Zhang et al. (2017) investigated the practical vision of dilution flow as a natural ability of the ecosystem to treat the hazard. In their study, three Heavy metal concentrations in three different seasons including wet, dry and medium in the Hun River in china was measured. They found that concentration of pollutant in wet season is much lower than dry season along the river. Their results prove the natural ability of environment to dilute the incoming hazard (pollution). These practical and theoretical researches addressed to the dilution flow as a solution scenario for water quality management.

However, none of the above investigations have addressed the impact of input pollution (controllable and uncontrollable) on water quality management equipment. When the pollution input is controllable, the water quality management tool that has been proposed uses the assimilation capacity of the river and when the pollution entrance is uncontrollable and higher than river's assimilation capacity, dilution flow is suggested as economical water quality management tool.

The first practical novelty of this research is to provide a fast simple model to calculate assimilation capacity of various rivers under different pollution entrance. The advantages of this model are (1) low runtime process and (2) the performance of the model in compare with the previous researches is so better and never be insurmountable. Since convenient selection of objective functions is hugely affect optimum dilution flow, for acquiring better accuracy, new objective functions are introduced in this study. Owe to many flaws of ( $\bar{c}_d$ ) calculation, mean area of unallowable concentration ( $\bar{c}_a$ ) is presented in

this study instead of  $(\bar{c}_d)$  to overcome problems.  $(\bar{c}_a)$  is presented to calculate unallowable concentration along the river, existence of a parameter that measures affected distance of unallowable concentration in the river is necessary. So, the second objective function that is introduced in this study is the affected distance ( $X$ ). Finally, the proposed objective functions are selected to be optimized by non-dominated sorting genetic algorithm II (NSGA-II) which leads to find the optimum dilution flow.

## Materials and Methods

### Simulation of Pollutant Transport

The mathematical equations of pollution propagation in a river without turbulent flow and at a specified velocity are the foundation for simulation methods of riverine transport. Equation (1) indicates the one-dimension differential advection–dispersion equation of pollution transport. (Van Genuchten and Alves 1982; Hashemi Monfared. et al. 2014)

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

In which  $c$  = the pollutant concentration (mg/L) in time ( $t$ ) and downstream distance ( $x$ ).  $x$  = distance from a pollution source entrance (m);  $t$  = time elapsed since a pollutant enters the river (s);  $D$  = diffusion coefficient ( $m^2/s$ );  $u$  = mean velocity of the river (m/s), and  $k$  = coefficient of pollution decay (1/s).

Equation (2) indicates the analytical solution of Eq. (1) when abrupt pollutant releases into river water (Hashemi Monfared and Deghani Darmian 2016).

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

$c(x, t)$  = pollutant concentration at each distance and each time (mg/L);  $M$  = sudden pollutant mass at the discharge point (kg);  $A$  = area of the river cross-section ( $m^2$ ). Other parameters are as previously defined.

There are many experimental methods for calculating dispersion coefficient (Seo and Cheong 1998). In this paper, the Fischer method has been used to calculate the value of  $D$  (1975).

$$D = 0.011 \frac{u^2 w^2}{h\nu} \quad (3)$$

In which  $w$  = width of the river section (m);  $h$  = water depth (m); and  $\nu$  = shear velocity (m/s).  $\nu$  is calculated using bellow equation:

$$\nu = \sqrt{gRs} \quad (4)$$

$g$  = Gravitational acceleration ( $9.81 \text{ m/s}^2$ );  $R$  = hydraulic radius computed as  $A/P$  [ $A$  = area of the river cross-section ( $m^2$ );  $P$  = wet perimeter of the water stream ( $m$ )]; and  $s$  = hydraulic slope of the river (m/m).

### Pollution Evaluation Criteria

The pollution damages in the river have been evaluated with considering two factors from previous studies: (1) a pollutant with concentration higher than the acceptable limit along the river, and (2) the time interval that such pollution is in contact with the riverine environment (Farhadian et al. 2014). In this paper, a new factor is also considered to determine the damage of the pollution incidence in the river, which indicates the distance that contaminant, is in contact with the river water flow and is called affected distance. According to the Eq. (2), these factors are related to each other in order to: (1) reduce the duration of high pollutant concentration contact with the riverine environment by increasing water velocity so the pollutant which has a smaller contact time with the river environment; and (2) reduce the high pollutant concentration and affected distance by decreasing the flow velocity to provide time for pollutant diffusion and decay. Therefore, the concentration will decrease and also the affected distance becomes minima.

The current study demonstrates practical mechanisms to reduce unallowable pollutant concentration to a permissible concentration through the above scenarios. The main question that is answered by this study is: what is the river velocity, duration of contact, and affected distance, for treating the unallowable pollutant concentration in a specified river. To answer this question, two water quality indices are necessary to be defined:

1. Assimilation capacity
2. Dilution flow.

### Assimilation Capacity

A branch of stressor-based monitoring approaches is the concept of carrying capacity or assimilative capacity. The concept was formulated around the use of the freshwater and marine environments for the disposal of mainly organic wastes and associated effluents. In this context, Cairns (1977) had propounded that the assimilative capacity may be defined as the ability of an ecosystem to be exposed to certain concentrations of (organic) wastewater and effluents without suffering considerable damage to biological agents. Consideration of a river's self-purification capacity (assimilation capacity) for pollution treatment is an economic necessity which leads to design of optimized conventional treatment facilities to decrease costs.

If there are reservoirs upstream of the pollution occurrence point, and if the pollutant source is controllable, there are two scenarios for considering assimilative capacity of the river. To investigate these scenarios it is important to consider the maximum assimilation capacity of the river which occurs in low velocity of water flow, because as discussed earlier (Eq. 2), the flow velocity must decrease to reduce the high pollutant concentration. Thus, by decreasing the water flow velocity, the assimilative capacity will increase and vice versa. In addition, there are some water demands that may occur in downstream, such as: domestic, recreational, agricultural, and industrial water demands. In these circumstances, water managers and decision makers should decide which scenario is more important. Scenario A), reservoir release allocation to control the pollution, or scenario B) water allocation to supply downstream demands. Due to the direct relation between the water release from upstream reservoir and water flow velocity in the river, to satisfy scenario A, the flow velocity must be decreased and for scenario B, the flow velocity should be increased. Therefore, these two available scenarios have conflicting behaviors. In this paper, scenario B has been considered for calculation of the assimilative capacity for each water reservoir release to supply the downstream demands.

If there are no regulating structures upstream of the pollution occurrence point, the river flow cannot be a control variable. In this situation, the assimilative capacity depends on the location of water withdrawal, to satisfy water demands. This means that in a constant downstream allowable concentration, by increasing the water withdrawal location from pollution occurrence point, the assimilative capacity increases.

**Dilution Flow**

When the pollution entrance to the river is accidental or uncontrollable, such as abrupt pollution discharge of industrial factories near a river without permission, or an accident such as the spill of a tanker of chemicals (like petroleum) into the river, if the input concentration of the pollutant is higher than the assimilative capacity, the high pollution concentration in the river should be decreased. One practical remedial action is to release a volume of water from upstream of the pollution entrance point, which is called dilution flow. In this situation, the release is adjusted to minimize the damage to the environment. This can be attained only by using, or construction, of regulating structures.

In these circumstances, the pollution mass is uncontrollable, therefore one can only regulate the river flow (the base flow plus dilution flow) to reduce the pollution damages to the riverine environment.

According to prior studies, some factors have been considered in a river’s environment protection in terms of an

allowable concentration constraint, and the two objectives of duration of contact and mean unallowable concentration to calculate the assimilation capacity and the essential dilution flow respectively, are defined as follows:

The unallowable concentration (mg/L) has been given as bellow:

$$c_d = \begin{cases} \sum_{i=1}^n (c_{\max i}(x) - c_s) & c_{\max i} > c_s \\ 0 & c_{\max i} \leq c_s \end{cases} \tag{5}$$

In which  $c_{\max i}$  = maximum concentration of the pollutant at location  $x$  (mg/L),  $c_s$  = the allowable limit of the pollution concentration along the river, often defined by Environmental Protection Agencies (EPA), is called the allowable concentration (mg/L) and  $c_d$  = unallowable concentration (mg/L).

Dividing  $c_d$  by  $n$  produces the mean unallowable concentration.

$$\overline{c_d} = \frac{c_d}{n} \tag{6}$$

$n$  = Total number of points with concentration higher than the allowable ones.

The duration of contact was defined as the interval from the time of pollution occurrence until the time at which the pollution concentration becomes equal to the allowable concentration, represented as:

$$T = \max(t_i) \quad i = 1, 2, \dots, n \tag{7}$$

In which  $T$  = duration of contact (s),  $t_i$  = time for the  $i$ th chemograph peak and  $i$  = index for the points.

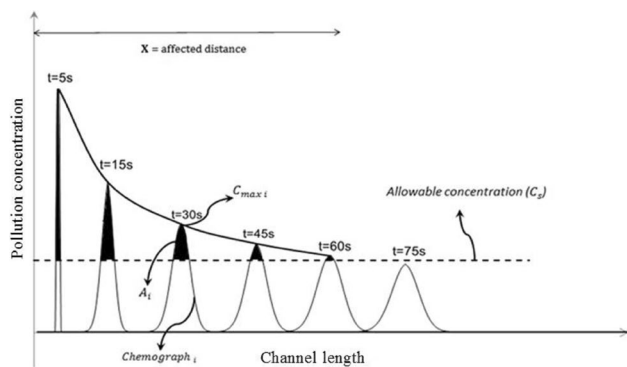
$c_d$  is the total of differences between maximum and allowable concentration. In other words,  $\overline{c_d}$  considered only the peak value of the unallowable pollutant chemograph at each point for calculating mean unallowable concentration. In the present study  $c_a$ , instead of  $c_d$ , is introduced as bellow:

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

In which  $A_i$  is the area of unallowable concentration at each downstream pollutant chemograph (Fig. 1). In this figure the  $x$ -axis represents the distance, the  $t$ -axis is the time, and the  $t$ -axis is shown with the same direction as the  $x$ -axis.

Dividing  $c_a$  by  $\sum_{i=1}^n A_i$  produces the mean area of unallowable concentration.

$$\overline{c_a} = \frac{c_a}{\sum_{i=1}^n A_i} \tag{9}$$



**Fig. 1** Schematic diagram of  $\bar{c}_a$  and  $\bar{c}_d$  by considering  $c_s$

The mean area of unallowable concentration ( $\bar{c}_a$ ) seems more like a realistic objective function than the mean unallowable concentration ( $\bar{c}_d$ ). The first reason is described in Fig. 1,  $\bar{c}_a$  considers not only the peak value of the unallowable pollutant chemograph at each point, but also all the values of unallowable concentration. The second reason is the weighted average; pollutant chemograph at each point is given weight of value to arrive at a certain answer.

To clarify the difference between  $\bar{c}_a$  and  $\bar{c}_d$ , the benchmark case study that is considered by Farhadian et al. (2014) is simulated with Eq. (2) in MATLAB software and the obtained results are shown in Fig. S1.

The affected distance is defined as the interval from the location of pollution occurrence until the place at which the pollution concentration becomes equal to the allowable concentration. To specify the affected distance, the farthest point (station) on the river with concentration higher than the allowable limit is identified using MATLAB. This objective can be expressed mathematically as the followings:

$$X = \max(x_i) \quad i = 1, 2, \dots, n \quad (10)$$

In which  $X$ =affected distance (m) and  $x_i$  = location for the  $i$ th chemograph peak river with concentration higher than the allowable limit. In Fig. S1 the required parameters are defined as follow:  $c_{s_{\min}} = 15$  mg/l,  $c_{s_{\max}} = 130$  mg/l and  $\Delta c = 1$  mg/l.

Therefore, in this study three factors have been considered including ( $c_s$ ) to determine the assimilation capacity and two objective functions, ( $\bar{c}_a$ ) and ( $X$ ) to calculate the required river flow to dilute the high pollution entrance.

### Model Formulation and Optimization Method

In a recent investigation, the nonlinear programming (NLP) method was used to control and calculate the value of the maximum assimilation capacity (Farhadian et al. 2014). According to the NLP method, the optimum solution is

identified by computing the gradient of the objective function at each point using mathematical differentiation which is a time-consuming procedure and may become insurmountable. Therefore, in the current study the assimilation capacity is simulated by Eq. 2 in MATLAB software with the specified steps (Fig. S2) to solve these problems.

To calculate the maximum assimilative capacity due to the variable downstream water demands in different seasons of the year, water release from upstream reservoir to meet the water demands is assumed to correspond. The purpose of this simulation is that for any water release from the reservoir, the maximum assimilative capacity is determined.

For each water flow velocity (due to direct relation with water reservoir release), each specified affected distance and each downstream allowable concentration constraint, the maximum assimilative capacity is calculated in the modeling process. The runtime of the applied MATLAB program is rapid and the obtained answers are comparable with the calculation of assimilation capacity in former investigations. Figure S2 shows the flowchart of the written code with MATLAB software for this approach and pervious methods to determine the assimilation capacity simultaneously.

Furthermore, the volume of dilution flow is determined when two conditions are satisfied simultaneously. First, when pollution entering into the river is uncontrollable and without permission, and second, when pollution mass to a river is higher than its assimilation capacity. In these conditions, the allowable concentration constraint in a specified affected distance is violated. To reduce the detrimental impact to the environment, the effects caused by abrupt pollution entrance should be minimized. These effects are calculated by:  $1 - (\bar{c}_a)$ ;  $2 - (X)$ ;  $3 - (T)$  Eqs. (7, 9, 10). Minimization of ( $X$ ) and ( $T$ ) are important due to the impact of reduced dissolved oxygen in the stream and subsequent damage to the aquatic ecosystem. ( $\bar{c}_a$ ) and ( $X$ ) are considered as two objective functions to determine the pollutant dilution and reduction of the damage to the riverine environment. This is a mathematical optimization problem involving more than one objective function to be optimized simultaneously. Therefore, multi objective optimization approaches should be applied. In the previous water quality studies, NSGA-II has performed well. NSGA-II is an extension of the Genetic Algorithm for multiple objective function optimization. The mechanism of this optimization algorithm is described in previous investigations (Shokri et al. 2014; Deb et al. 2002; Fallah-Mehdipour et al. 2012a, b; Seifollahi Aghmiani et al. 2015; Fallah-Mehdipour 2015). Figure S3 shows the flowchart to determine the dilution flow.

### Case Study

The case study which has been evaluated in this research is a benchmark problem in the field of water quality management

which was solved in a former investigation and is used for comparison between both works. A river with a sudden pollution discharge is considered with the specified characteristics. The pollutant entrance into the river is shown in Fig. S4. Table S1 contains characteristics of benchmark problem of the river (Farhadian et al. 2014). In Table S1,  $w$  = width;  $A$  = area;  $h$  = water depth;  $s$  = hydraulic slope;  $k$  = coefficient of pollution decay;  $c_s$  = allowable concentration.

The distance between water withdrawal and pollution occurrence point has been assumed to be 200 m with water flow velocity in the range of 0.07–1 m/s. Two values have been assumed for  $c_s$  to determine the maximum assimilation capacity for each water flow discharge. It should be noted that due to the constant river area, there is a direct relation between water flow velocity and water flow discharge. Figure S5 demonstrates a schematic view for determination of the river's assimilation capacity with the simulation process which is explained in Fig. S2.

To determine the dilution flow, two values have been applied for the  $c_s$  (0.5 and 1 mg/L) and two values have been considered for the input pollution mass (10 and 20 tons). Thus, there were four scenarios to evaluate the water flow discharge. It must be noted that the discharge value (due to its direct relation with the flow velocity) was assumed as the decision variable to determine the optimum dilution flow by the NSGA-II. Figure S6 shows the problem view of determining the dilution flow.

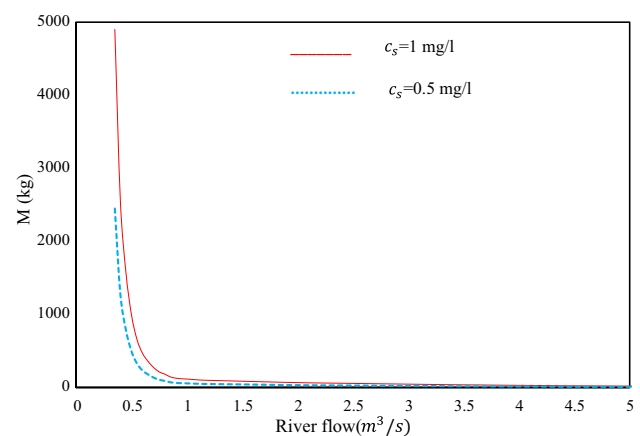
The differences between the assimilation capacity and dilution flow were identified following careful examination of (Figs. S2, S3) and (Figs. S5, S6), which is very important in the modeling process.

## Results and Discussion

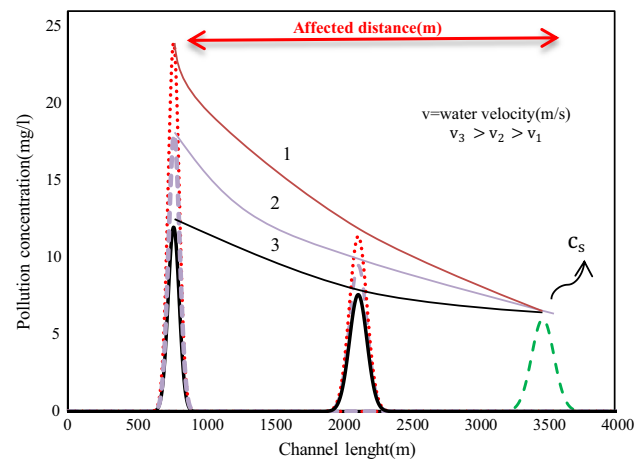
### Calculation of the Maximum Assimilation Capacity

To determine the maximum assimilative capacity, the water release from the upstream reservoir and the pollution entrance in the river are adjustable. Thus, there is a maximum assimilative capacity for each amount of water that is released. Since assimilative capacity is the maximum value of pollution mass that could be entered into the river, the pollution concentration is less than the allowable limit after the water withdrawal location [Affected distance ( $X$ )]. According to Fig. S5, the assimilation capacity increases by increasing the location of water withdrawal from the pollution occurrence point ( $X$ ) in a constant water flow velocity and invariant allowable concentration constraint.

Figure 2 shows the maximum assimilation capacity of the river, which is represented in the case study due to several reservoir releases for both values of the allowable concentration equal to 0.5 and 1 mg/L using MATLAB software.



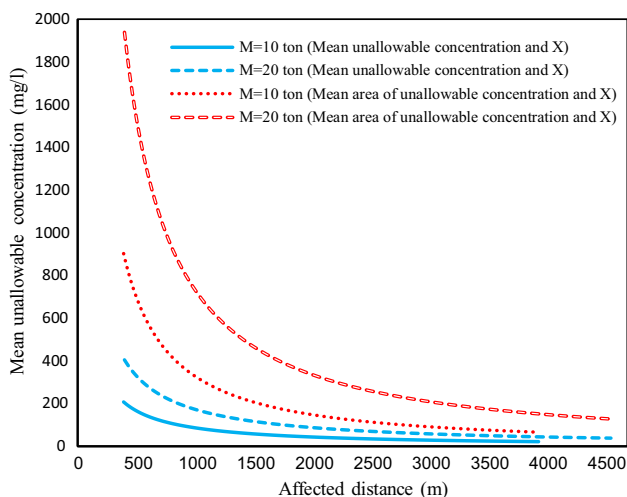
**Fig. 2** Maximum assimilation capacity corresponding to the several reservoir releases for the different values of the downstream allowable limit equal to 0.5 and 1 mg/L



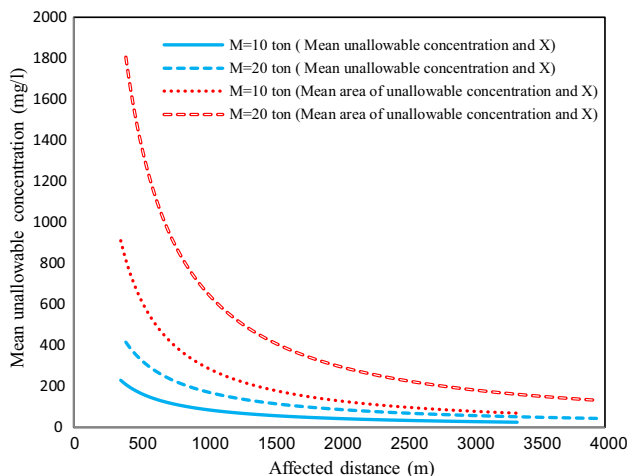
**Fig. 3** Relation between water flow velocity of river and its assimilative capacity

According to Fig. 2, two results could be concluded:

1. Increasing the water flow velocity (due to direct relation with water discharge) causes a decrease in the assimilative capacity. By increasing water flow velocity, the duration of pollution contact is reduced and the time for pollution decay and dispersion is also decreased. The peaks of the pollutant chemographs increase in the downstream position and the model is forced to reduce the pollution entrance to reach the allowable limit. This concept is illustrated in Fig. 3.



**Fig. 4** Obtained Pareto boundary of the objective functions for  $c_s = 0.5$  mg/L



**Fig. 5** Obtained Pareto boundary of the objective functions for  $c_s = 1$  mg/L

**Determining the Dilution Flow**

Both  $(\bar{c}_d)$  and (T) have been considered as objective functions for optimization (Farhadian et al. 2014). In the current work, first  $(\bar{c}_d)$  and (X), then  $(\bar{c}_a)$  and (X) have been considered to be minimized and were compared. Note that the  $(\bar{c}_a)$  and (X) are the main objective functions and have been used for optimization in this study.

For this aim, the pollution movement in the river has been simulated in MATLAB software and the optimum water flow, which causes minimum damage to the environment, has been calculated. The river discharge was considered as a decision variable of the optimization process in the range of 0.07–8 m<sup>3</sup>/s. Figures 4 and 5 indicate the Pareto fronts,

considering two series objectives of  $(\bar{c}_a, X)$  and  $(\bar{c}_d, X)$  for the  $c_s$  equal to 0.5 and 1 mg/L, and the input pollution mass equal to 10 and 20 tons.

The general form of the optimization problem is as follows:

$$\text{Minimize } \left\{ \frac{\bar{c}_a}{X} \text{ and } \left\{ \frac{\bar{c}_d}{X} \right. \right. \tag{11}$$

s.t.

$$c_s = 0.5 \text{ and } 1 \text{ mg/L}$$

Sudden pollution entrance = 10 and 20 tons

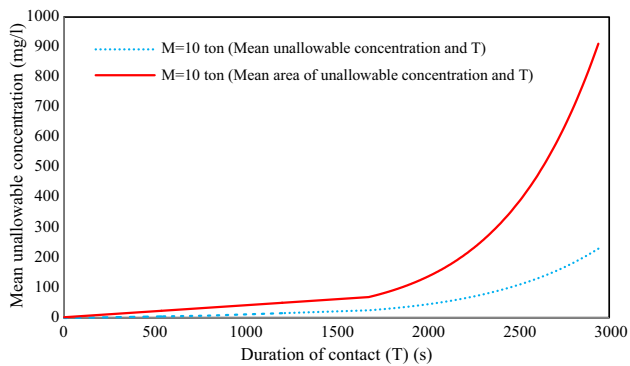
$$\text{Decision variable} = \text{River discharge (base flow + dilution flow)} \\ = 0.07 \text{ until } 8 \text{ m}^3/\text{s}$$

As shown in Figs. 4 and 5, the best solutions of the problem cover a large range of  $(\bar{c}_d)$  and  $(\bar{c}_a)$ . The affected distance (X) of these large ranges has different impacts on the riverine environment and aquatic ecosystem. The  $(\bar{c}_d)$  and  $(\bar{c}_a)$  in the Pareto fronts are equal to several times greater than  $c_s$  and the affected distance changes by several meters.

The obtained results comparing the two objectives  $(\bar{c}_d)$  and  $(\bar{c}_a)$  are as the following:

1. In constant values of affected distance, dilution flow, pollution input and downstream pollution concentration,  $\bar{c}_a$  is larger than  $\bar{c}_d$ .
2. For a constant mean unallowable concentration (for example  $\bar{c}_a$  and  $\bar{c}_d$  equal to 150 mg/L), the specified pollution entrance and downstream allowable concentration, the affected distance corresponding to  $\bar{c}_a$  is greater than  $\bar{c}_d$ . Therefore, due to the direct relation between the affected distance and the upstream water discharge, the dilution flow corresponding to  $\bar{c}_a$  is also getting bigger. Thus,  $\bar{c}_a$  is a stricter objective than  $\bar{c}_d$ , because  $\bar{c}_a$  needs more dilution flow and affected distance than  $\bar{c}_d$  to achieve the same water quality. In other words, by considering  $\bar{c}_a$  instead of  $\bar{c}_d$  in a similar situation, less pollution could be tolerated.
3. For a certain pollution input, the constant allowable concentration and stakeholders’ decision on water withdrawal locations, the optimum  $\bar{c}_a$  and dilution flow could be determined.
4. Under constant pollution loading, decreasing the downstream allowable concentration (from 1 to 0.5 mg/L in this study), increases the range of  $\bar{c}_a$  and  $\bar{c}_d$ , as well as the affected distance.
5. According to Figs. 4 and 5, in the large affected distance (for example after the 1500 m in this study), the change rate of  $\bar{c}_a$  and  $\bar{c}_d$  are decreased and also the value of  $\bar{c}_d$  becomes closer to  $\bar{c}_a$ .





**Fig. 6** Demonstration the relation between  $\bar{c}_a$  and T for the  $c_s = 1$  mg/L

6. From the Figs. 4 and 5, it is clear that in a constant and specified downstream allowable concentration, by increasing the content of pollution entrance (from 10 to 20 tons in this case study),  $\bar{c}_a$  and  $\bar{c}_d$  are also increased by the same proportion.

Due to the simulation process, one of the important results of determining dilution flow is reduction of (T) in addition to reduction of  $\bar{c}_a$ . In the case of a sudden pollution entrance to the river, reduction of (T) is important due to the potential decline in dissolved oxygen. However, because of the direct relation between the  $\bar{c}_a$  and (T), minimization of  $\bar{c}_a$  leads to the automatic minimization of (T) and does not require considering (T) separately in the calculations. This direct relation between the  $\bar{c}_a$  and T is shown in Fig. 6. Therefore, when water resource managers consider (T) as a constraint for protecting the river environment, for each (T) constraint in a specified characteristic river (M and  $c_s$ ), the optimal  $\bar{c}_a$  and dilution flow are determined.

## Conclusion

This study determined two necessary characteristics for river water quality management. The first one is Assimilative capacity when the river pollution is controllable and the second one is Dilution flow when the discharged pollution is uncontrollable and higher than the river's assimilative capacity. The presented modeling procedures calculate the assimilation capacity and the dilution flow which are based on the equation of pollution propagation in a river. For water quality protection these proposed procedures were applied in a benchmark case study which is used by previous researches.

The results indicated that river velocity changes mainly caused by an upstream reservoir release ranged from 0.07 to 1 m/s, could cause a prominent change in assimilative capacity. The assimilation capacity changes from 100 to 3460 kg

when  $c_s$  equal to 0.5 mg/L and changes in the range of 200 to 6920 kg for  $c_s$  equal to 1 mg/L in the constant affected distance of 200 m.

Water release from an upstream reservoir is a practical and cost-efficient remedial action. To determine the best dilution flow, two series of objective functions ( $\bar{c}_d, X$ ) and ( $\bar{c}_a, X$ ) were considered. The new parameter  $\bar{c}_a$ , which presented in this study was found to function better than  $\bar{c}_d$ . Also for calculating the value of dilution flow, NSGA-II, which is a multi-objective optimization algorithm, was used.

Results for the two allowable pollutant concentrations ( $c_s = 0.5$  and 1 mg/L) and two entrance pollution masses (M = 10 and 20 tons) showed that for each value of dilution flow, the contents of mean area of unallowable concentration ( $\bar{c}_a$ ), mean unallowable concentration ( $\bar{c}_d$ ), affected distance (X) and duration of contact (T) were different. These values ranged from 50 to 2000 mg/L for  $\bar{c}_a$ , 5–430 mg/L for  $\bar{c}_d$ , 300–4700 m for X, and in the range of 1500–4000 s for T. These expressed values are vital and necessary to protect the river environment, corresponding to the current and future water quality conditions. Considering the significance of each aspect of objective functions and parameters including  $\bar{c}_d$ ,  $\bar{c}_a$ , X and T, water manager can make better decisions for the reduction of the environmental damage.

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