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Journal
Water and Environment Journal, 35(2)

ISSN
0951-7359

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Publication Date
2021-05-01

DOI
10.1111/wej.12645

Peer reviewed

Water and Environment Journal
Promoting Sustainable Solutions
CIWEM
Water and Environment Journal. Print ISSN 1747-6585

Fulfillment of river environmental flow: applying Nash theory for quantitative-qualitative conflict resolution in reservoir operation

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Keywords
conflict resolution; environmental flow; Nash theory; reservior release; riverine ecosystem conservation; water quality control.

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doi:10.1111/wej.12645

Abstract

The construction of reservoirs for water supply alters the riverine ecology and changes water quality. It is, therefore, imperative to estimate and provide the riverine environmental flow requirement to prevent irreversible environmental damage and to maintain suitable water quality. Water releases from reservoirs constitute the means for meeting environmental flow and water quality requirements downstream from reservoirs. These requirements can be realized through the modification of the reservoir operation programmes by reallocating a percentage of the reservoir releases otherwise dedicated to quantitative objectives. This is performed in this study by considering the qualitative (i.e. pertaining to water quality) objectives alongside quantitative objectives of reservoir releases in order to achieve a general coverage for an operating programme that balances in the most rational manner the interests of riverine environmental protection and quantitative functions. The case study area is located in the river reach between the Gotvand reservoir and Shooshtar city in the Gotvand-Karoon reservoir-river system in Iran. The range of riverine environmental flow is calculated in the study river reach with hydrologic methods. Water quality is simulated and included reservoir operation with the QUAL-2K simulation model. The existing quantitative and qualitative objectives for reservoir operation are determined and classified. The best reservoir releases corresponding to three scenarios are determined by the Nash theory considering all possible objectives in the reservoir-river system. These scenarios allocate relative weights to defined objectives and releases were determined to be equal to 183.8, 141.8 and 206.8 m^3/s for three scenarios.

Introduction

An initial step in how best to use water resources is understanding the connection between various allocation mechanisms and the associations in terms of ability to target specific aspects of the flow regime, management flexibility and system requirements (Horne *et al*., 2018a). Significant progress in environmental flow management has occurred in recent years due to several factors including governments committing to environmental flow programmes, progress in scientific knowledge and assessment methods that involve stakeholder cooperation and co-design (Horne *et al*., 2017a). However, the operation of shared water resources frequently causes conflicts between stakeholders due to differing priorities and goals. In addition, economic and social developments in river basins reduce water flow and augments pollutants discharged to rivers, thus leading to the degradation of riverine ecosystems.

The key objective of this study is to provide a method for reservoir operation that minimizes adverse riverine environmental damages considering environmental flow and water quality requirements along with other traditional water functions (municipal, industrial and agricultural water supplies). This study focuses on leading functions of reservoir operation, especially water quality objectives (qualitative objectives) that are frequently underrated in comparison with water supply and other revenue-generating purposes. A few relevant bibliographical citations are succinctly reviewed next.

Melching and Yoon (1996) assessed the uncertainties of the QUAL-2E model by applying it in the Passaic river of New Jersey in the United States. Dussaillant *et al*. (1997) simulated the water quality of the Mapocho river in Chile with the QUAL-2E model. They predicted the lowering of river water quality levels due to sewage discharges. Park and Lee (2002) evaluated the efficiency of quality simulation models in the Nakdong river of Korea. They employed the QUAL-2K and QUAL-2E models for simulating the river water quality. Azzellino *et al*. (2006) combined the QUAL-2E model with factor analysis to determine the portion of each pollutant discharge source in decreasing the river water quality in two rivers in Italy. Kerachian and Karamouz (2007) combined a water quality simulation model and conflict resolution theory for managing the quality of reservoir-river systems. They introduced a random variety of the Nash conflicting resolution theory to solve existing conflicts between stakeholders and decision-makers in the Ghomrud reservoir-river system. The genetic algorithm (GA) was employed for optimising the operation rule of the reservoir and its initial solutions were generated with a varying chromosome length GA (VLGA). Hughes and Louw (2010) presented a flexible method to determine the environmental flow requirement considering different management scenarios in a river basin in South Africa. Yang (2011) reported a multi-objective optimisation model for allocating the environmental flow requirement in the Yellow river of China. That model considered the health of the ecosystem and the economic benefits to downstream lands' stakeholders. De Andrade *et al*. (2012) determined the effective factors governing pollutant loads to the Santa Maria da Vitoria river in Brazil. A simulator-optimizer model was presented combining the QUAL-2E model with the simulated annealing (SA) algorithm for solving the problem of pollutant loading to the river. Shiau and Wu (2013) defined a reservoir operation rule to provide the environmental flow requirement for the Feitsui reservoir of Taiwan. The results showed that providing environmental flow does not necessarily diminish other reservoir functions. Zhang *et al*. (2014) assessed the hydrological and ecosystem changes in the East River in China applying indicators of hydrological alteration (IHA). Elhatip and Hinis (2015) determined the environmental flow requirement of the Euphrates river in Turkey employing hydraulic methods and a river analysis system software (HEC-RAS) and several hydrological methods. Farhadian *et al*. (2014) presented a method to determine the assimilation capacity of pollutants in rivers when the pollution source is controllable and the dilution flow to reduces the damages to the ecosystems when the pollution is not controllable. Analytical equations were used to simulate the river water quality and two optimisation methods were employed to accomplish such purposes. Zhang *et al*. (2015) assessed the causes of water quality reduction in the Taihu lake, China, applying the QUAL-2K model. The maximum allowable pollutant discharge was determined for four pollution indexes, including total nitrogen, total phosphorus, ammonia and chemical oxygen demand (COD). Bozorg-Haddad *et al*. (2017) employed two data-driven methods for modelling water-quality parameters. The methods are the least-squares support vector regression and genetic programming similar to that developed by Fallah-Mehdipour *et al*. (2014). They analysed the efficiency of employed models in water quality modelling by statistical evaluations of the results. Sarzaeim *et al*. (2017a) assessed the climate change effects on the environmental water demand and its temporal variation and concluded that climate change might affect the environmental water demand regime, which makes it necessary to consider the environmental assessment for riverine ecosystems. Sarzaeim *et al*. (2017b) evaluated several plans in using available water in the Karkheh river basin of Iran and predict that due to agricultural expansions, vulnerable aquatic ecosystems would be severely impacted in the future. Morid *et al*. (2019) assessed the impact of climate change in hydrological indicators and environmental components and the water temperature in the Kikuchi River basin, Japan and concluded that more extreme hydrological events in the future would pose a high risk for riverine ecosystems through increasing water temperatures. Soleimani *et al*. (2019) modelled the thermal stratification of the Karkhe Reservoir, Iran, in the period 1981–1995. They used meteorological, chemical, hydrological and discharge time series in order to predict the water temperature of reservoir releases. Bejarano *et al*. (2019) applied various scenarios for environmental flow regimes to show that flows can significantly affect the environmental costs and hydropower production, which proves the need for providing the best water-regulation operational programmes. A review of previous research indicates the topic of providing environmental flow and considering that water quality has not received as much attention as other topics in the reservoir operation literature or in studies dealing with other hydrosystems (Soltanjalili *et al*., 2011; Sabbaghpour *et al*., 2012). However, due to their effects, the environmental flow and water quality deserve heightened attention in water resources management. It is best practice to consider all the objectives of a reservoir operation programme simultaneously, including traditional and environmental ones, as they are all related through the scarcity of water and the impacts that water works have on the environment. This study provides a method provide environmental flow requirement and meet water quality control and traditional reservoir functions, although detailed reservoir operation is not pursued in this work. This work first determines the suitable range of riverine environmental flow.The riverine water quality is simulated to calculate the range of downstream reservoir water releases. Last, the optimal reservoir release is calculated based on the Nash theory and by allocating relative weights to the reservoir functions. Figure 1 depicts a flowchart of this paper's methodology.

The environmental flow requirement

The problem of optimal water allocation has received considerable attention in the literature; however, most of the previous investigations have focused on allocating

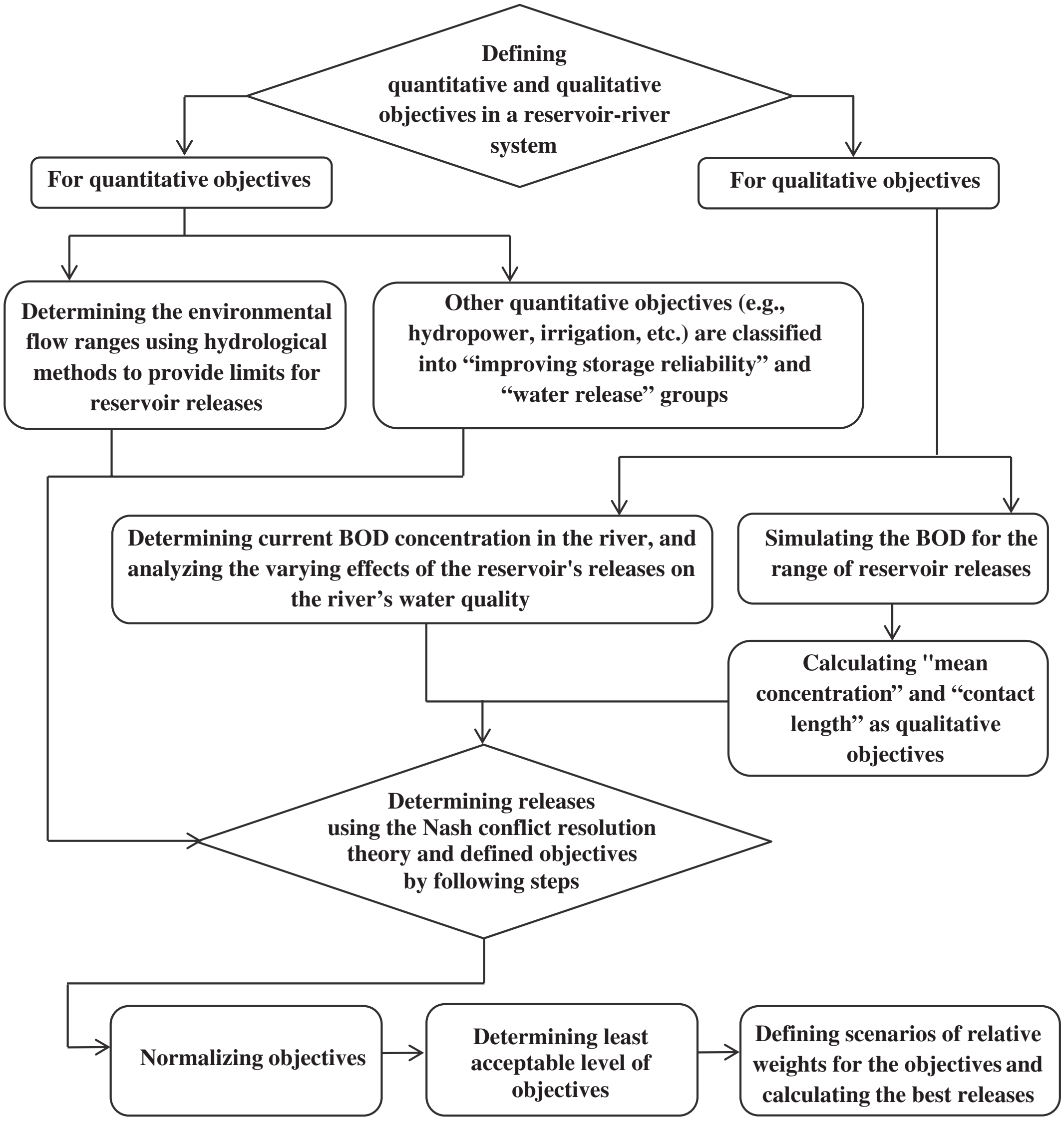

Fig. 1. Flowchart of the main methodology steps.

water amongst human demands and not ecological flow needs (Homa et al., 2005). Where water quantities are limited not all flow elements can be provided for all environmental needs (Horne *et al*., 2010). Implementing sustainable river flows requires understanding the responses of riverine ecosystems to stresses (Horne *et al*., 2019). In recent years, there has been considerable effort dedicated to improve methods for estimating environmental flow requirements; however, few studies have considered how to operate water programmes to supply flow requirements effectively (Harman and Stewardson, 2005). Streamflow regulation by reservoirs alters the downstream flow regime in quantity and quality, which more often than not has adverse effects on river sediment transport and the riverine ecosystem.

The magnitude of flow required to maintain healthy riverine ecosystems is called the environmental flow requirement, or environmental flow, in short. There are several methods for estimating environmental flows. They can be classified into four categories that are (1) hydraulic methods, (2) hydrologic methods, (3) ecosystem simulation and (4) comprehensive methods (Tharme and King, 1998). The hydrologic methods apply hydrological data including river daily, monthly and annual natural flows. This study relies on hydrologic methods for determining environmental flow. This choice is primarily justified by the paucity of river data and the conditions in the study area, located in Iran, that fits well with the application of hydrologic methods. The most common hydrologic methods are the Tennant (1976) and aquatic baseflow (Arthington *et al*., 2006) methods, which are applied in this study and briefly introduced in the following sections.

Tennant (1976) presented a method for calculating the environmental flow in several rivers in the United States. This method relies on natural streamflow not impacted by human actions. The average annual natural flow is calculated and a percentage of the average value is set equal to the environmental flow. This environmental flow is constant over the course of a year. Tennant (1976) identified three threshold percentages of natural river flow, or 10% as the minimum level, 30% as a relatively favourable level and 60% as the most favourable and maximum needed level for ecosystem support. The Tennant method uses relatively simple data and sets a minimum of 10% of average natural streamflow as the minimum threshold for the environmental flow. Its main disadvantages are relying upon the average annual natural flow, which ignores inter-seasonal flow variations.

The aquatic baseflow method considers that the minimum average monthly natural flow is the minimum threshold that can support the riverine ecosystem. This method is of straightforward implementation, but it cannot be applied to rivers whose streamflow may cease during dry seasons. Hydrologic methods yield approximate estimates of the environmental flow and they are easily implementable as shown in this work.

General objectives of flow regulation by reservoirs

The management of environmental water must achieve the best possible outcomes in a transparent and defensible manner (Horne *et al*., 2016) to gain public support in securing the environmental flow. Reservoirs are operated to meet various objectives. Also, the protection of ecosystems downstream from reservoirs requires operation programmes to satisfy environmental requirements, which in practice, often involves re-regulating river flows within the water resources constraints (Yin *et al*., 2012). This study focuses on the environmental flow and water quality control besides other operation purposes in determining the best reservoir releases. Thus, the main objective of this work is supplying water for the environmental flow.

In allocating the environmental flow decisions must be made on how to distribute water between the environmental and traditional users, which is a long-term planning issue (Horne *et al*., 2010). However, managing operation alternatives to provide the environmental flow is a difficult task, because there are generally multiple water demands and many management options to be considered (Szemis *et al*, 2013). Reservoirs serve many functions including hydropower generation, flood control, agricultural water supply, municipal water supply, recreation, fish farming and navigation. These functions may be considered as quantitative objectives and are met by properly determining reservoir water releases. Accordingly, these functions can be divided into two groups. The first group incorporates those functions that prioritize water storage in the reservoir and include recreation, fish farming and shipping. In this work, the first group is defined as those ‘improving storage reliability’. Other functions that rely on water releases from the reservoir for downstream uses form the second group herein called objectives by ‘releasing water’. The second group includes hydropower generation, flood control, agricultural water supply and municipal water supply (Jahandideh-Tehrani *et al*., 2015). This classification is such that the intra-group functions are not conflicting, but inter-group functions might be. The cited objectives have been divided into these two groups based on their preference to release water from or store water in the reservoir and from this point of view, hydropower is put in the ‘releasing water’ group as water release is necessary to generate power. But from another point of view, hydropower must ensure the storage level to provide an adequate hydraulic head for hydropower generation; therefore, it is possible for it to be placed in the first group. The same duality holds for flood control, which aims in creating reservoir storage capacity to accommodate large floods, while relies on water releases from the reservoir to avoid exceeding the reservoir capacity leading to spillway overflow and possible dam failure. The two groups form quantitative functions. The two alternative groups are necessary for applying the Nash theory in the context of this paper’s objectives.

Contaminants discharge to rivers is the primary reason of freshwater pollution (Farhadian *et al*., 2016). Flow regulation is an effective tool to improve water quality (Sun *et al*., 2018). Streamflow downstream a reservoir is sustained in whole or in part by its water release and must be of suitable quantity and quality. The provision of water with suitable quality for downstream use relies in this work on the ‘average of BOD concentrations’ and the ‘contact length’ (Farhadian *et al*., 2014; Seifollahi-Aghmiuni *et al*., 2015). The riverine biochemical oxygen demand (BOD) measures the amount of dissolved oxygen in water consumed by micro-organisms and organic substances in the oxidation of organic matter (Brenniman, 1999). There are many other water quality parameters; yet, sufficient data are available for BOD analysis in the case study of this paper and that is why this parameter is chosen to measure aquatic pollution. BOD is affected by the downstream distance travelled from a pollution source (Loucks and Van Beek, 2017) and, therefore, the reliance on the ‘contact length’, which describes the distance of the river that is polluted by BOD.

BOD in river water in excess of 1 mg/L is herein considered as the threshold above which is potentially harmful to aquatic ecosystems. The average BOD concentration is given by Eqs (1) and (2):

$$C_{E,i} = \begin{cases} C_i \; C_i \geq 1 \\ 0 \; C_i < 1 \end{cases} \quad (1)$$

$$C_{ave} = \frac{1}{TP} \sum_{i=1}^{TP} C_{E,i} \quad (2)$$

in which $C_{E,i}$ = the BOD concentration at point (or station) i along a river reach that exceeds 1 (mg/L); i = the counter of points for calculating the pollution concentration; C_i = the BOD concentration at the point i (mg/L); C_{ave} = the average of BOD concentrations larger than 1 mg/L and TP = the total number of points used for calculating the average BOD concentration and equals the number of points such that $C_i \geq 1$.

The second qualitative objective concerns the distance (or contact length, *CL*) that streamflow must traverse for BOD to be reduced below the threshold equal to 1 mg/L is given by Eq. (3):

$$CL = \max(L_{C_{E,i}}) \quad (3)$$

where CL = the contact length (km) and $L_{C_{E,i}}$ = the distance along the river where the pollution concentration is larger than 1 mg/L. Riverine water quality is improved by reducing the contact length, *CL*.

In summary, the objectives of reservoir operation considered in this work are: (1) supplying the environmental flow; (2) improving storage reliability; (3) suppying water to meet human demands; (4) reducing the average BOD concentration; and (5) reducing the contact length.

The QUAL-2K model

The QUAL-2K model is employed for water-quality simulation in this study. This model has desirable traits including: (1) it simulates conditions caused by point and nonpoint sources of pollution; (2) its implementation is relatively straightforward; (3) it has been applied for water quality simulation extensively and successfully, which provides many references with guidance about its application; (4) and it is an open-source model which can be improved by users.

The QUAL-2K model simulates the river in one dimension, where the river is well-mixed vertically and laterally. The system has a main-stem river with branched tributaries divided into reaches and elements of various sizes. Also, multiple loadings and withdrawals are input to any system element and non-uniform and steady flow is simulated (Chapra *et al*., 2008).

The Nash conflict-resolution theory

Rivers must be protected as their natural conditions have been altered due to human activities (Szemis *et al*., 2012). Reallocating water between demands and ecosystems is integral to river management policy and emerging frameworks make it possible to consider multiple uses in rivers, even though balancing various priorities remains challenging (Chen and Olden, 2017). While there have been significant gains in river management there remain challenges in linking this knowledge to inform environmental management decisions (Horne *et al*., 2018b). Management of environmental flows to obtain the best ecological outcomes in river systems has been recognized as an active area of research, with several decision support tools available for this purpose (Kaur *et al*., 2017). Decision making amongst stakeholders commonly generates conflict due to diverging objectives, viewpoints and priorities (Akbari *et al*., 2014). There are decision support tools that can be applied to achieve environmental flow requirements (Horne *et al*., 2017b).

The Nash theory is applied to solve conflictive situations (Farhadian *et al*., 2017). Nash presented a set of conditions that must be met by an optimal solution to a conflict situation involving multiple stakeholders (Madani and Hipel, 2011). These conditions are: (1) the stakeholders can only resort to existing available resources because new resources are unattainable; (2) each stakeholder accepts agreements in which the utility function is equal to or higher than his/her minimum acceptable utility; and (3) there are no other better solutions for the stakeholders.

The Nash conflicting resolution theory was initially developed for solving conflicts between two stakeholders. Harsanyi (1958) expanded this theory to consider more than two stakeholders as an optimisation model described by Eq. (4):

$$\max \prod_{i=1}^{N} \left(f_i - d_i\right)^{w_{ei}} \; f_i \geq d_i \quad (4)$$

in which i = the counter for stakeholders; N = the total number of stakeholders; f_i = the utility function of stakeholder i, d_i = the least acceptable utility level of stakeholder i; and w_{ei} = the relative weight for stakeholder i (Asgharpour, 2003). Solving conflicts between two or more stakeholders applying the Nash theory begins with the identification of stakeholders, establishing their minimum utilities and relative weights. The best solution for the existing problem is found with Eq. (4).

Case study

This work mainly seeks to determine the environmental flow of the Karoon River in the reach located between the Gotvand reservoir and downstream city of Shooshtar. The Gotvand reservoir is constructed on the Karoon River, Iran. It serves the functions of hydropower generation, flood control, agricultural water supply, municipal water supply and recreation. This reservoir has a capacity of 4.67 billion cubic metres and in addition to generating 4000 gigawatts hydropower, helps to maintain the stability of the country's electricity network. The Karoon River is the largest river in Iran. Its length equals 800 km and its average annual flow in the vicinity of the Gotvand reservoir is equal to 453 m^3/s. Its average annual volume flowing through this location exceeds 14×10^9 m^3. However, average monthly inflows and outflows for the period Jully 2011 to June 2015 are depicted in Fig. 2. The average monthly inflows also will be used in the following to determine environmental flow using the aquatic baseflow method.

The required hydraulic characteristics for modelling the water quality of the Karoon River are adapted from Farhadian *et al*. (2019) and are listed in Table 1. Also, Table 2 lists the pollutant (BOD) characteristics in the study area, including point and nonpoint sources, discharge volume and BOD concentration of discharges to the river, which are adapted from Farhadian *et al*. (2019) and completed. Figure 3 depicts the studied area including the Gotvand reservoir, the Karoon River and existing BOD sources.

Preserving the environment and water quality in the Karoon River is essential in the area as it passes through many large and small residential zones, such as the metropolitan area of Ahwaz. Therefore, domestic demands, recreational activities, fishing and natural landscapes are dependent on this river. Also, water quality in the Karoon River takes heightened relevance given that it is the main source of water supply for domestic demands in the area, and, also, due to large agricultural water demands which imply an everlasting impetus to increase river water diversion that reduce the environment share of streamflow. Most of the landscape and ecology of the area rely on the Karron River, and thus, reducing the environment share will vanish them. Therefore, environmental flow with a suitable quantity and quality to preserve Karoons' environment is necessary.

Results and conclusions

The current BOD concentration in the river

The BOD concentration in the river was calculated with the QUAL-2K model setting the minimum and maximum reservoir daily releases equal to 13.7 and 458 m^3/s, respectively. The data of daily releases are not presented here due to large size. For the purpose of water quality modelling using daily flows results in much more accurate results than employing average monthly flows. The calculated BOD concentrations as a function of location along the river reach are depicted in Fig. 4. It is seen in Fig. 4 that the BOD concentration in the Karoon River downstream of the Gotvand reservoir corresponding to the minimum release is much higher than that associated with the maximum release. This is due to the high dilution of pollutant discharge affected by the larger level of reservoir release. Figure 4 conveys a general understanding of current water

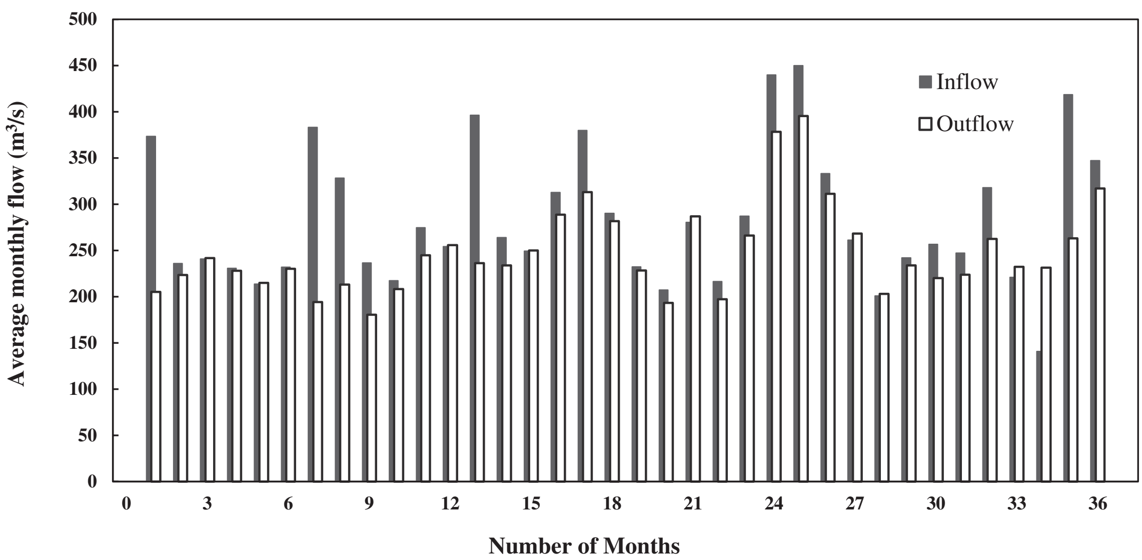

Fig. 2. Average monthly inflows and outflows of the Gotvand reservoir during the study period.

quality status and also shows the opposite effects of the flow rate on the C_{ave} and CL. These opposite effects can be perceived better in Fig. 4 where at a kilometre of 162.5, which is defined as the 'turning point', the two curves for BOD concentrations intersect each other. The differentiation in BOD concentrations corresponding to the two sets of reservoir releases is associated with the different times that are required to dissolve pollution by advection and dispersion processes (Farhadian *et al*., 2018). The BOD concentration is calculated for all of the possible reservoir daily releases, as explained below, in addition to minimum and maximum reservoir daily releases.

Determining the river's environmental flow range

Based on the available data, the Tennant and aquatic baseflow methods were applied to calculate the Karoon River's environmental flow in the study area.

The average annual natural river flow before reservoir construction was equal to 453.9 m^3/s. Tennant (1976) argued that the environmental flow ranges between 10 and 60% of the average annual natural river flow. Therefore, the value of the environmental flow in the Karoon River would be in the range of 45.4 to 272 m^3/s based on these percentages. The value of 45.4 m^3/s is herein considered as the minimum possible environmental flow, under which the riverine ecosystems would be severely impacted. The flow equal to 272 m^3/s is considered as the maximum environmental flow, above which releasing additional water would be unnecessary for ecosystem support.

Table 1 The river hydraulic characteristics

Characteristic	Value	Dimension
Degradation rate	0.3	day^{-1}
River average slope	0.0003	%
River average width	60	m
Manning's coefficient	0.03	none

The environmental flow by the aquatic base flow method is equal to the minimum average monthly natural river flow. The average monthly inflow to the Gotvand reservoir is graphed in Fig. 2 for the period July 2011 through June 2015, and its minimum represents the environmental flow of the Karoon River (140.75 m^3/s). These average monthly inflows are calculated from average daily inflows. It is shown in Fig. 2 that the minimum monthly average inflow equals 140.75 m^3/s, which occurred in April 2014, and is shown as the number 34 month in this Fig. 2. The Gotvand reservoir started operating in 2012 and at the time this study was done there was little available data.

It is noteworthy that the range of the environmental flow obtained with the Tennant method includes the estimate by the aquatic baseflow method. Therefore, the flow range herein determined by the Tennant method is used in the conflict resolution section.

Simulating the BOD for the range of reservoir releases

Each BOD simulation is required to be continued until the pollution concentration reaches equilibrium in the river. This is so because alongside the river pollutants are released into the river, and, therefore, cumulative BOD typically increases in a downstream sense from the location of the first pollution source to the last one along the river. The required time for the river water to travel from the first source of pollutant discharge (Gotvand's sewage in this instance) to the most downstream point of simulation constitutes the minimum required time for conducting a simulation. This required time was calculated equal to 2 days based on the flow velocity calculated with Manning's equation available in the QUAL-2K model.

BOD simulation was carried out with the QUAL-2K model for flows in the range of 13.7 to 458 m^3/s with steps of 1 m^3/s (which are the minimum and maximum allowable volumes of daily reservoir releases, respectively). New codes were added to the QUAL-2K model to run a large number

Table 2 The BOD sources in the study area

Contaminant source	Point (P) or Non-Point (NP) source	Distance from Gotvand reservoir (km)	BOD concentration (mg/L)	Discharge Rate (m^3/s)
Gotvand's sewage	NP	15–20	6.27	3.51
Gotvand slaughter-house wastewater	P	25	18 000	0.0006
Aghili farmstead drainage	P	35	8.8	5
Khatam-Alanbia hospital wastewater	P	55	40	0.5
Alhadi hospital wastewater	P	57	36	0.5
Shooshtar-Azin company wastewater	P	60	50	1
Shooshtar's sewage	NP	50–60	6.27	6.36
Shooshtar slauther-house wastewater	P	65	9.2	0.0008
Karoon sugarcane farmstead drainage	P	70	9.2	8.9

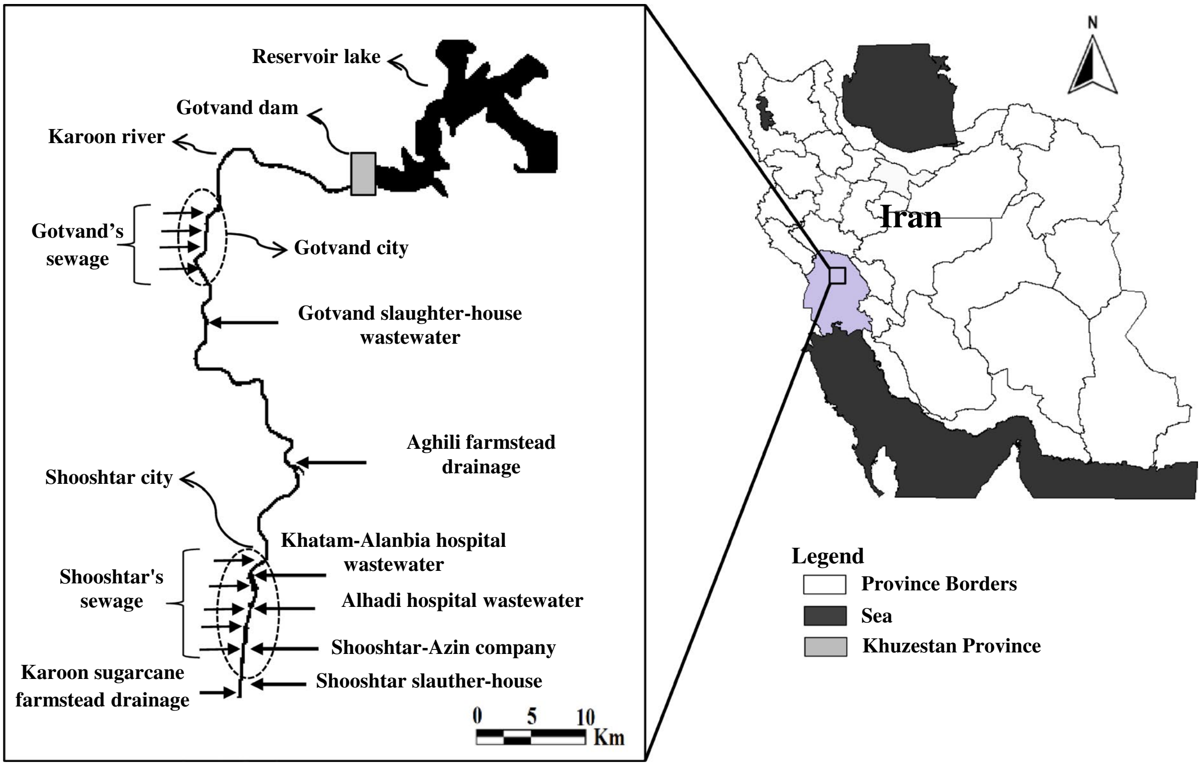

Fig. 3. Location of the study area. [Colour figure can be viewed at wileyonlinelibrary.com]

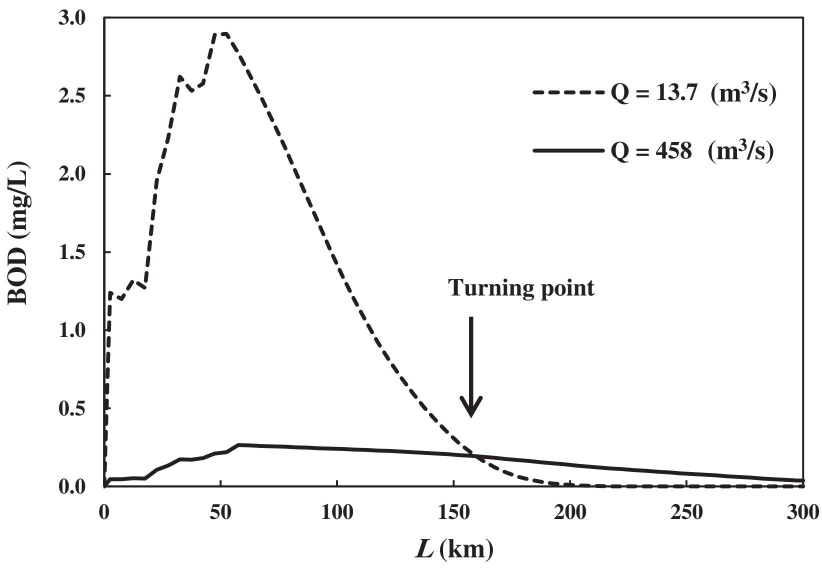

Fig. 4. Simulation of BOD corresponding to minimum and maximum reservoir releases.

of BOD simulations with long simulation time and the range of reservoir releases. In addition to the total time span of simulation which is 2 days and release flows as the decision variable, there are other important criteria worth mentioning including a simulation time step equal to 0.09 hours and the number of simulation reaches being equal to 3.

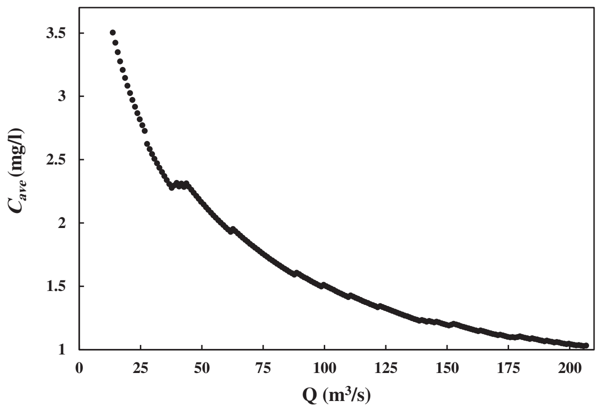

Fig. 5. The mean BOD concentration (C_{ave}) for different values of reservoir release (Q).

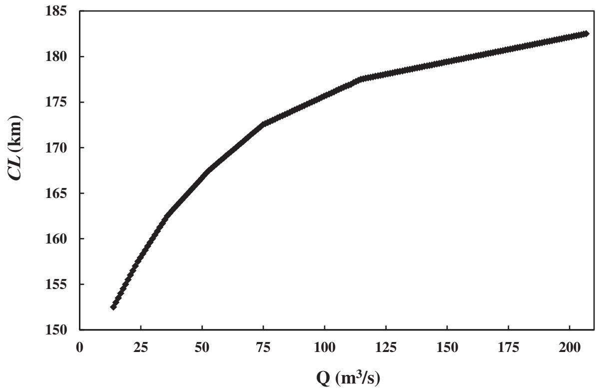

Fig. 6. The contact length (CL) for different values of reservoir release (Q).

Calculating the mean concentration and the contact length

Figures 5 and 6 show the calculated mean BOD concentration and the contact length, respectively. The simulation results establish that the mean concentration for releases larger than 206.8 m^3/s is less than 1 mg/L. Therefore, according to the Eqs (1) and (2), calculation of the mean concentration and contact length for releases larger than 206.8 m^3/s is not necessary because the BOD concentration reaches below 1 mg/L and assumed as not pollution here anymore. This being the reason why they are not shown in Figs 5 and 6. Figure 5 indicates that the mean concentration decreases with increasing reservoir release due to the volume of water and BOD dilution, and vice versa. Also, increasing flow velocity increases the contact length, which is seen in Fig. 6. These results determine the suitable reaches to withdraw water with good quality from the river, especially on the downstream reaches of the studied area where water is withdrawn for municipal and agricultural uses. Many villages and cities, such as Ahwaz city, are located on this downstream reach and the reservoir release must be determined to achieve allowable levels of pollution concentrations at the use points.

The mean concentration and contact length for various values of reservoir release are depicted in Fig. 7, where it is seen that the C_{ave} and CL vary in a manner contrary to the variation of reservoir water release Q. This forced varying the C_{ave} from its highest value to its lowest value to construct the BOD graph shown in Fig. 7. The results in Fig. 7 determine the contact length that achieves the desired BOD concentration and the amount of river flow necessary to meet the environmental flow requirement. Figures 5–7 in this section reveal the effects of release flows on the objectives concerning mean BOD concentration and the contact length, but not on all the five defined objectives.

Determining the releases employing the Nash theory for conflict resolution

There is a divergence of viewpoints concerning actions needed to meet the stated reservoir objectives. The maximum possible water release from the reservoir is desirable to meet the environmental flow, releasing water and BOD concentrations. Conversely, a minimum possible value of reservoir release is suitable for assuring storage reliability and achieving desirable contact length. The Nash theory is useful in this case to solve the existent conflict between the five objectives.

Normalisation of objectives

The Nash optimisation function employs normalized data for each objective. Eq. (5) normalizes each function data as follows:

$$y_{n,i,j} = \frac{x_{i,j} - \bar{x}_j}{sd_j} \quad (5)$$

in which j = the counter of objectives (values of 1 to 5); i = the counter of data for the objective j; $x_{i,j}$ = the data i for the objective j; $\bar{x}_j$ = the mean value of objective j; $y_{n,i,j}$ = the normalized data i for the objective j; and sd_j = standard deviation value for the objective j.

The least acceptable level of objectives

The least acceptable level of the five objectives of reservoir operation is required to determine the utility of that objective corresponding to the values of water release based on the Nash theory. The least acceptable level of environmental flow is the calculated minimum flow from

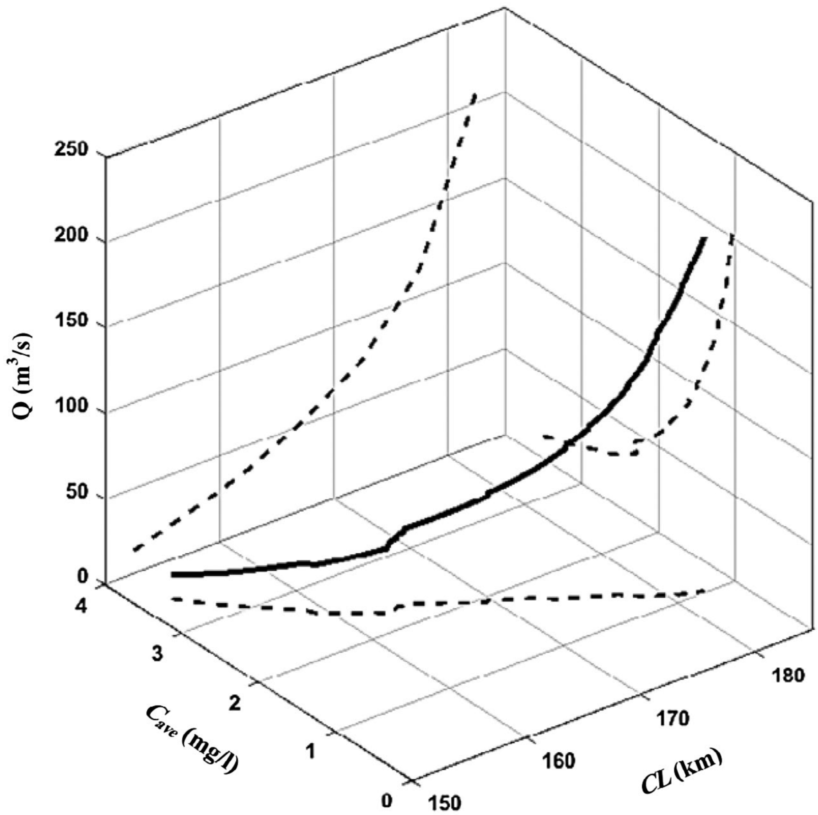

Fig. 7. The BOD concentration as a function of the contact length (*CL*), the average concentration (C_{ave}) and the reservoir release (*Q*). The solid line shows the BOD concentration and the dashed curves show the projections of the curved lines on the planar sides.

the Tennant method (45.4 m^3/s). In fact, 45.4 m^3/s is the most undesirable possible value for the riverine ecosystem in the range of environmental flow, which ranges from 45.4 to 272 m^3/s. The least acceptable level for the reservoir storage reliability objective corresponds to a reservoir release equal to the average inflow to the reservoir (or 453.9 m^3/s). This magnitude of release would not allow sustaining reservoir storage given that the average inflow would equal the average release, and therefore, reduce the reliability. The least acceptable level for releasing water objective is equal to the minimum reservoir release (13.7 m^3/s) needed to produce a desirable volume and quality of river water. By selecting the minimum reservoir release as the minimum acceptable level for this objective, none of the quantitative and qualitative downstream water demands would be met. The least acceptable levels for the C_{ave} and *CL* contact length equal their maximum possible values. Their maximum possible values would cause the most damages to the riverine ecosystem. However, this maxima may not reflect the possible damages. The C_{ave} and *CL* were calculated as stated in the previous sections for various magnitudes of release. Accordingly, one unit of standard deviation is added to the maximum value of C_{ave} and *CL* to calculate their least acceptable levels. The standard deviation (SD) for the C_{ave} and *CL* data is calculated with Eq. (6) as follows:

$$SD_j = \sqrt{\frac{1}{N_j}\sum_{i=1}^{N_j}(x_{i,j} - \bar{x}_j)} \quad (6)$$

in which SD_j = standard deviation for objective *j*; *j* = the counter of objectives (values of 1 and 2); N_j = the number of data for objective *j*; and other parameters have been defined before.

Scenarios of relative weights for the objectives

Nash theory requires relative weights for each objective. Relative weights are set based on the importance of each objective. This study implemented three scenarios whose weights vary according to quantitative and qualitative issues that affect the objectives. The results of the Nash optimisation were calculated for each scenario.

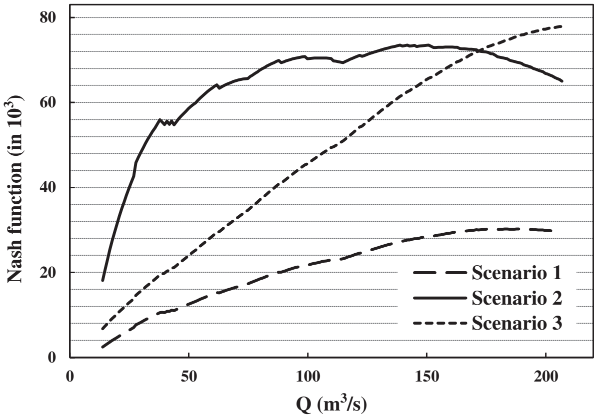

Fig. 8. The Nash optimisation functions in terms of the reservoir release (*Q*).

Scenario 1: Equal relative weights for all objectives

This scenario sets the relative weights of all objectives equal to one. The Nash optimisation function for various values of release is shown in Fig. 8 for this scenario. It is seen in Fig. 8 that the release associated with the maximum calculated value of the Nash function is selected as the optimal release for this scenario, which is equal to 183.8 m^3/s.

The selected value supplies the environmental flow of the studied area almost completely based on the values presented by the Tennant method. Thus, this value of release is appropriate for supplying the environmental demand flow. Also, the flow equal to 183.8 m^3/s is about 40% of the average natural river flow, which appears to be a relatively desirable value for the reservoir storage reliability objective. Yet, it would not be suitable for the releasing water objective. The mean BOD concentration and contact length objectives for this value of reservoir release equal 1.08 mg/L and 181.25 km, respectively, which must be taken into account when withdrawing water or releasing more pollution into the river.

Scenario 2: Increasing the relative weights of the quantitative objectives

The objectives of supplying the environmental flow, releasing water and achieving reservoir storage reliability constitute the quantitative objectives amongst the five considered objectives. The second scenario prescribes relative weights of the quantitative objectives that are twice as large as those of the qualitative ones. This means the quantitative objectives the power of two in the Nash function, while the qualitative objectives stay with the power of one. The corresponding calculated Nash optimization function is displayed in Fig. 8.

The value of optimal release in this scenario equals 141.8 m^3/s based on the calculated Nash function. This value would supply the environmental flow to some extent, but not completely, according to the values from the Tennant method. Also, this magnitude of reservoir release would be about 30% of the average natural river flow, which would improve the storage reliability objective compared to Scenario 1. Yet, meeting the releasing water objective with this release would be challenging. The mean BOD concentration and contact length objectives for this value of release equal 1.22 mg/L and 178.9 km, respectively, that are larger and smaller, respectively, than those of Scenario 1.

Scenario 3: Increasing the relative weights of the qualitative objectives

The two mean BOD concentration and contact length objectives relate to riverine water quality. The third scenario prescribes relative weights that are twice as large as those of the quantitative objectives. This means in this scenario, the qualitative objectives receive the power of two in the Nash function, while the quantitative objectives remain with the power of one. The calculated Nash optimisation function is graphed in Fig. 8.

The calculated value of optimal release in this scenario equals 206.8 m^3/s. This level of reservoir release is about 46% of the average natural river flow, which would supply the environmental flow completely, according to the values presented by the Tennant method. Also, this level of release decreases the utility of the reservoir storage reliability objective and improves the objective of releasing water compared with the two previous scenarios. The mean BOD concentration and contact length objectives for this value of release equal 1.03 mg/L and 182.5 km, respectively, which are smaller and larger, respectively, compared with those of Scenarios 1 and 2.

Concluding remarks

(1) Reservoirs supply water to achieve several objectives. In many cases, these objectives may conflict with each other, and, therefore, there is a need to solve the conflicts in the best possible manner. This study considered several reservoir objectives simultaneously, including water quality and environmental flow, which are rarely considered in reservoir operation studies. The aim of this paper is to provide a general quantitative, qualitative and environmental approach for determining reservoir releases that support the riverine ecosystem.

(2) This work determined the best reservoir releases for the Karoon River considering several water resources objectives in the study area with the objective of reaching a comprehensive agreement between stakeholders (objectives). In doing so, first, the required environmental flow was determined. Pollutant sources in the Karoon River downstream of the Gotvand reservoir were identified. The current water quality of the Karoon River was assessed in the study area and river BOD concentrations were simulated for the range of reservoir releases applied in the QUAL-2K model. The key quantitative and qualitative objectives were defined in this study together with three scenarios for the relative weights of reservoir-operation objectives. These three scenarios included (1) equal relative weights for all stakeholders (objectives), (2) relative weights for quantitative objectives equal to twice the values of qualitative ones and (3) vice versa of (2). The reservoir releases were determined under scenarios 1, 2 and 3 by means of the Nash conflict resolution theory, whose values equalled 183.8, 141.8 and 206.8 m^3/s, respectively.

(3) Supplying the environmental flow with a proper water quality, which is the principal purpose of reservoir operation considered in this study, under scenario 3 leads to the most desirable results and the optimal release would equal 206.8 m^3/s. This means to operate optimally for the downstream environment a large portion of the average inflow must be released, which, in turn, reduces the possibility of supplying water for other reservoir functions. It was herein demonstrated that 206.8 m^3/s would be the upper limit of reservoir release into the downstream river in a way that the maximum needed level for ecosystem support is fulfiled and excess water could be stored for other purposes. Releasing less than 206.8 m^3/s down to the lower limit, which equals 45.4 m^3/s, is possible, which provides storage to supply water for other purposes. However, damage to the riverine environment increases with decreasing reservoir release.

Acknowledgement

The authors thank Iran's National Science Foundation (INSF) for its financial support of this research.

Conflict of interests

None.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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