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A fish biodiversity protection based approach for assessing environmental flow regime in rivers

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ABSTRACT

Available environmental flow assessment methods are not able to integrate the impacts of flow regime on the fish biodiversity which means improving these methods is necessary. This study proposes a novel approach to assess environmental flow regime in which the fish biodiversity index is simulated in the structure of the environmental flow assessment for protecting the fish biodiversity values in the case study. Due to considerable impact of water quality parameters as well as physical flow parameters, two combined physical flow and water quality indices were considered as the inputs of simulating fish biodiversity index. Adaptive neuro fuzzy inference system (ANFIS) as well as hydraulic simulation were applied to simulate combined indices of physical flow and water quality. Moreover, a multiple linear regression (MLR) model was utilized for simulating the fish biodiversity index. Due to necessity of simulating natural flow regime in the representative river reach, soil and water assessment tool as a known hydrological tool was applied as well. According to evaluation indices of the case study, ANFIS model as well as SWAT and MLR are reliable to assess environmental flow considering the fish biodiversity. The minimum environmental flow in the study area was assessed 40% of mean annual flow in which the difference between fish biodiversity index between the natural flow and environmental flow is less than 10%. However, significant improvement of water quality is a prerequisite before implementing the proposed environmental flow regime. High computational complexities is one of the weaknesses of the proposed method.

1. Introduction

Rivers are one of the most productive ecosystems in the world, which can support many aquatic as well as terrestrial species. In fact, rivers are the habitats of various aquatic species including fish, macroinvertebrates and Macrophytes. Moreover, a large number of terrestrial species such as birds are highly dependent on the river ecosystems. According to the previous studies, rivers play a key role in biological activities of aquatic species (Palmer and Ruhi, 2019). For example, many fish species need to migrate to the upstream habitats of rivers for reproduction. Furthermore, many aquatic and terrestrial species depend on rivers for finding foods which means if no suitable habitat is available in rivers, the life of many species will be jeopardized. Rivers are an important resource of water supply for human societies as well (Brunner et al., 2019). Apart from water supply by rivers, due to human activities in river basins, many types of pollutants may be discharged into rivers. Therefore, water quantity and quality are at risk due to human activities in river networks. Hence, the concept of environmental flow has been proposed from several decades ago in the literature, which means the amount of flow required to protect river habitats.

According to the defined purposes of environmental flow, this flow regime may guarantee sustainable ecological activities in the river ecosystems. While this general definition has a simple concept, there are many ecological complexities in environmental flow assessment, which has made environmental flow simulation as a hot research field in the ecological and water resources engineering (Arthington et al., 2018; Ibáñez et al., 2020). Several methods for assessing the environmental flow in rivers have been proposed which apply different indices (Książek et al., 2019). Simpler methods that might not take into account the ecological complexity were developed in the early years of using this concept. For example, hydrological or desktop methods cannot consider the ecological values of the study area which means hydrological indices of river flow such as mean annual flow (MAF) might be only considered in environmental flow assessment (Pastor et al., 2014). The Tennant method is one of the oldest and known methods which uses MAF in assessing flow regime. This method and other similar methods were

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widely used in previous works. However, due to the lack of considering the habitat suitability of the aquatic species, these methods might not be reliable for assessing environmental flow. More details regarding these methods have been addressed in the literature (Karimi et al., 2012; Bayat et al., 2019; Pal and Talukdar, 2020).

Due to weaknesses of hydrological or desktop methods, other methods have been developed based on the habitat suitability assessment since decades ago. For example, the habitat simulation method is one of these methods developed by the US Wildlife Service to consider habitat suitability of target species for assessing environmental flows (Jorde et al., 2001). This method has several advantages compared to hydrological methods. More details regarding habitat simulation models have been reviewed in the literature (Ahmadi-Nedushan et al., 2006). However, due to the lack of highlighting complex ecological processes such as impacts of water quality and biodiversity assessment, it cannot provide a correct assessment of the environmental flow. Some studies developed holistic values in which more ecological features have been added in the assessment process (Jones et al., 2023; Ćosić-Flajsig et al., 2020). However, lack of clarity and vague simulation process such as absence of robust water quality as well as hydrodynamic modelling are major weaknesses of the holistic methods. In fact, environmental flow should address the complex ecological indicators such as biodiversity. According to available methods, habitat simulation or even holistic methods such as building block methodology (BBM) cannot address important ecological indicators such as biodiversity properly and methodically (more details regarding BBM by King et al., 2000). It should be noted that a long list of environmental flow methods exists in the literature. The purpose of this study is not to review all of these methods which means only some key methods have been critically reviewed. Some previous studies have provided a more comprehensive review of the methods (Młyński et al., 2020; Suwal et al., 2020).

Biodiversity is a key indicator in river habitats which can be affected by changes in physical parameters such as depth, velocity, or changes in water quality parameters. Biodiversity refers to the variety of species in the river habitats. In other words, a variety of native species may be observed in riverine habitats which depend on the river flow for their biological activities (Chen et al., 2020). Changing water quality as well as available flow can be highly effective on the population of these species. Therefore, changing environmental features of a river ecosystem due to water resources and agricultural projects might have a significant impact on biodiversity. Hence, not only environmental flows should provide the suitable habitat for one species, but it should be also able to balance the population of all kinds of species compared to the natural flow regime. In other words, environmental flow should be able to protect the biodiversity index. The construction of large hydraulic structures such as dams as well as impacts of climate changes are challenging factors that can affect the biodiversity of the aquatic species in rivers (Wu et al., 2019). Accordingly, the environmental flow should minimize these impacts to preserve the biodiversity of species.

It is necessary to state the research gap, objectives and novelties of the present study. Lack of addressing the fish biodiversity is one of the weaknesses of available environmental flow methods which was the main motivation of this research work. Based on this research gap, it is needed to modify the environmental flow methods for addressing fish biodiversity in the structure of simulating ecological flow. The following objectives were considered.

1. A novel method for assessing environmental flow in rivers considering protecting fish biodiversity
2. Using combined water quality as well as water quantity indices in simulating and evaluating fish biodiversity index

2. Application and methodology

2.1. Overview of the method

Fig. 1 shows the workflow of the proposed method for assessing environmental flow considering fish biodiversity. In the first step, field studies should be carried out on study area including fish sampling as well as measuring hydraulic parameters and water quality parameters simultaneously. More details regarding the sampling method or the observation of fish in the habitat as well as technical issues of devices and tools are provided in the following sections. Two combined indices were considered to evaluate the water quality as well as the hydraulic parameters of the river flow. To calculate these indices in the simulated period, it was necessary to use water quality models as well as the hydraulic model in the simulated river reach. Furthermore, using the fish observations and computing the combined indices of water quality as well as hydraulic parameters of water in the sampled points, a linear multivariate model was developed to estimate the fish biodiversity index. In the next step, it was necessary to simulate the natural flow in the simulated river reach to assess the biodiversity index in the natural condition. Finally, the environmental flow regime was assessed considering changing the fish biodiversity index in the natural condition compared with altered flow regime. More details regarding necessities and methodology of the simulations will be presented in the next sections.

2.2. Case study, field studies and catchment hydrological modelling by SWAT

The proposed framework was implemented in the Jajrud River, which is one of the protected and important rivers in the northern region of Iran. This river plays a significant role in providing drinking water as well as supplying agricultural water demand in the capital territory of Iran. Due to available population living in this catchment as well as seasonal migration and climate change impacts, environmental challenges are considerable. Owing to the importance of water supply in this catchment, two major dams including Latian and Mamloo have been constructed in this area, which play a critical role in water supply. Based on rough estimations, the population living in the region is around 40,000 people which might be doubled in summers. The direct effect of more population is to increase water abstraction in the catchment. Moreover, the indirect effects of population should be considered as well. Land use change as well as construction of access roads have increased the potential erosion and water quality deterioration. Due to these challenges, the river habitats are severely threatened especially downstream of the dams. Hence, it is necessary to have a suitable environmental flow to protect ecological processes and biodiversity.

The ecological threats are especially evident downstream of the Mamloo Dam because the impacts of pollution and water abstraction are maximized. Therefore, it is necessary to have a favourable environmental flow in this river reach so that it can guarantee the ecological sustainability of the river ecosystem (Kuriqi et al., 2019). Due to the ecological values and endangered fish species, this river is a protected river which means the regional environment department has maximum effort to preserve the existing aquatic species and suitable habitats in all river networks in this catchment. Based on the initial observations in river habitats, three major native fish species need environmental protection in this river. Hence, preserving the biodiversity of these fish species is considered as one of the environmental purposes in the environmental planning of this catchment. In fact, preliminary local studies have shown that fish biodiversity can be an important environmental indicator which means protecting fish biodiversity might guarantee other ecological process in this catchment. Therefore, redefining the environmental flow regime considering the fish biodiversity index in the critical river reaches such as downstream of Mamloo dam is essential. Previously, the environmental flow in the river has been defined

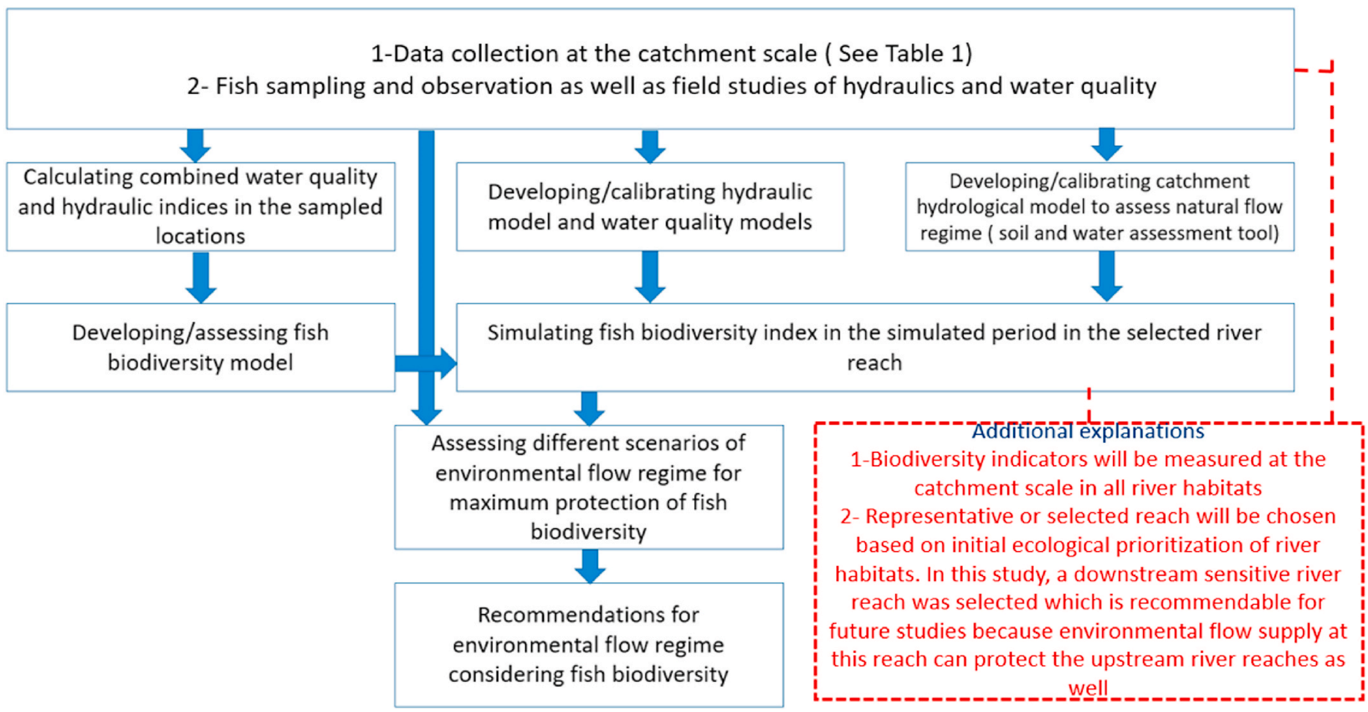


Fig. 1. Workflow of the proposed method.

according to the hydrological indices or physical habitat simulation of one species, which were not able to address the fish biodiversity. In other words, the previously defined environmental flow cannot guarantee to preserve the biodiversity in the river because the protection of biodiversity is a complex process which may be affected by different environmental factors including water quality and quantity. Simulation of the natural flow regime in the simulated river reach is a requirement in this study. In fact, it should be noted that due to the different hydraulic structures and water abstraction projects the recorded flow in the hydrometric stations is not the same with the natural flow regime. Therefore, it is necessary to simulate the natural water flow regime in the study area. Hence, one of the known hydrological model (soil and water assessment tool, SWAT) used in many previous studies was applied in this regard. SWAT is capable of simulating the river flow at the outlet of sub-catchments on a daily or monthly scale. More details regarding the theory and application of this model have been addressed in the literature (Abbaspour et al., 2015). Fig. 2 shows the flowchart of the SWAT model simulating river flow in the outlet of a catchment. The key raster inputs of SWAT includes the digital elevation model, the soil map as well as the land use map. It is necessary to insert the rainfall data as the main driver of the flow in the catchment into the model as well.

One of the most challenging steps in the development of a hydrological model in the catchment scale is the calibration and validation of the model using observational data. This trial and error process is not easy. Hence, a standalone software has been developed in this regard called SWAT-CUP (Abbaspour et al., 2015). Four calibration parameters are generally considered in the SWAT-CUP including CN2.mgt (Initial SCS runoff curve number for moisture condition II), ALPHA_BF.gw (Alpha factor for groundwater recession curve of the deep aquifer (1/days)), GW_DELAY.gw (Ground water delay time) and GWQMN.gw (Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O)) as the calibration factors. It is essential to evaluate

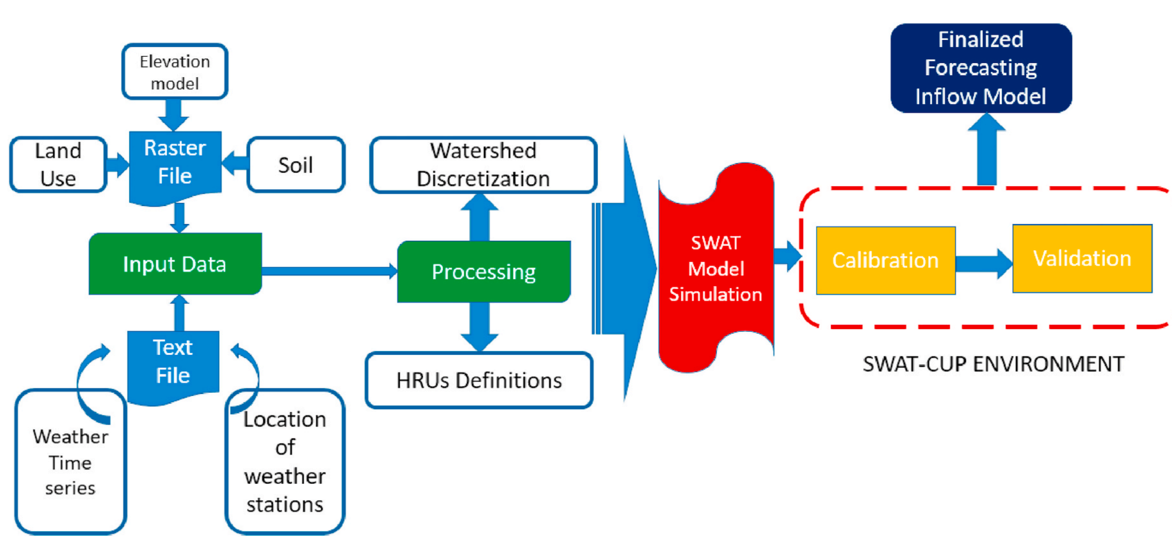
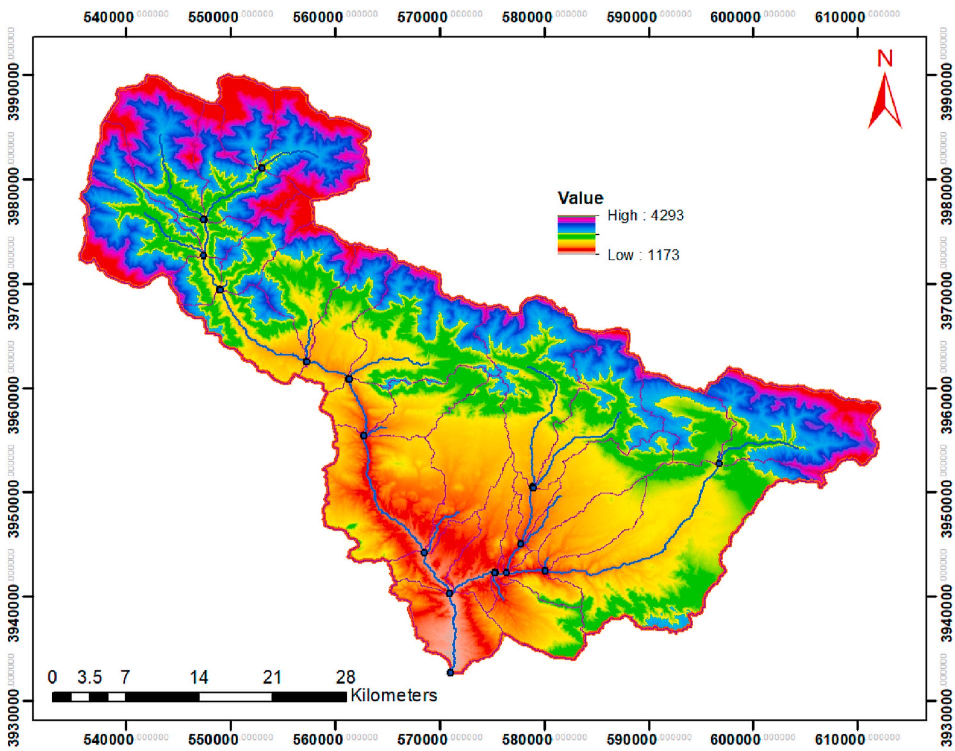


Fig. 2. Flowchart of coupled SWAT and SWAT-CUP to simulate inflow of the simulated river reach for assessing environmental flow regime.

the results of the model in the case study which means the results can be acceptable, if evaluation indices corroborate it. Thus, we used two evaluation indices recommended in the previous studies for evaluating the robustness of the SWAT's results as shown in equations (1) and (2) (Abbaspour et al., 2015). More details regarding the Nash- Sutcliffe efficiency (NSE) have been addressed in the literature (Knoben et al., 2019). The NSE changes between minus infinite and one. NSE = 1 means the simulation performance is fully consistent with the observations, which is not possible in practice. In fact, the development of a perfect model is practically not possible which means NSE = 1 is not expected.



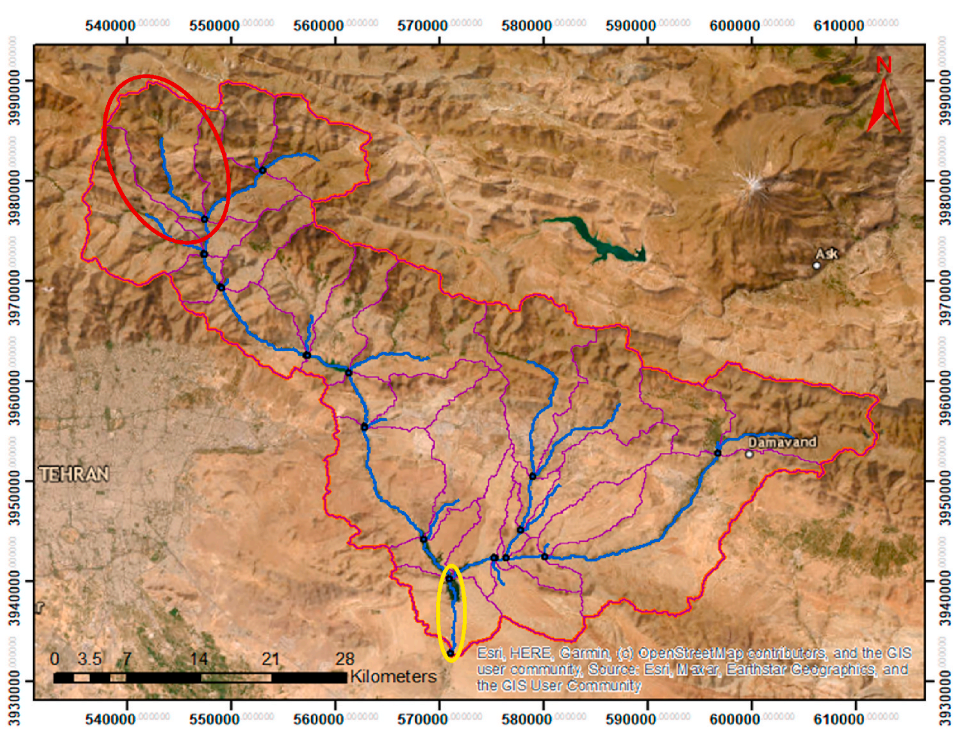


Fig. 3. a) Digital elevation model (DEM) of the Jajrood river basin b) Location of simulated river reach (yellow) and sub-basin used for calibrating SWAT (Red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$NSE = 1 - \frac{\sum_{t=1}^{T} (M_t - O_t)^2}{\sum_{t=1}^{T} (O_t - O_m)^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T} (M_t - O_t)^2}{\mathrm{T}}} \quad (2)$$

where Mt is forecasted inflow by model in each time step, Ot is observed or recorded inflow in each time step and Om is mean observed or recorded inflows in the simulated period. Fig. 3 displays the location of the Jajrood river basin as well as the digital elevation model. This figure shows the boundary of the watershed as well as the boundaries of the sub-basins and the river network. A river reach was selected to study environmental flow or to simulate the fish biodiversity located downstream of the Mamloo dam as a destructed river habitat in the river basin. It should be noted that field studies and fish observations have been carried out throughout the river. However, the modelling of environmental flow was carried out downstream of the Mamloo dam. Table 1 displays the description of data used in this study.

2.3. Combined water quality index and its modelling

Water quality variables significantly affect the ecological process in river habitats. In other words, the abundance of aquatic species as well as the biodiversity of the species is influenced by the water quality variables (Teurlincx et al., 2019). Unsuitable water quality can deteriorate the fish population as well as their biodiversity. Therefore, it is necessary to consider the effect of water quality parameters in biodiversity modelling and consequently environmental flow assessment. Due to the effect of numerous water quality parameters, using combined water quality indicators has been recommended in some previous studies, which is a smart solution to integrate the overall impact of water quality parameters (Parween et al., 2022). In this study, according to the requirements of the study area, a known combined water quality index customized for Iran was used, which is able to indicate the overall effect of water quality on the fish population as well as biodiversity index. More details regarding this index (IRWQI) have been provided in the literature (Ebraheim et al., 2020; Gad et al., 2020). Fig. 4 displays the workflow of assessing IRWQI.

Table 1
Description of data used in the case study.

Type of data	Description and source of data
Land use map	Application: Used in the hydrological model for simulating the natural flow, Source: regional department of environment
Soil map	Application: Used in the hydrological model for simulating the natural flow, Source: FAO database with some additional data from regional department of agriculture
Weather data	Application: Used in the hydrological model for simulating the natural flow, Source: Weather stations installed by regional weather forecasting organization in several point of the catchment
Hydrological data (river flow)	Application: Used in the hydrological/hydraulic models, Source: Hydrometric stations installed by regional water authority throughout the catchment and field studies by the team
Water quality	Application: Used in the water quality modelling, Source: Hydrometric stations installed by regional water authority throughout the catchment as well as databank of regional department of environment and field studies for identifying the sources of pollutants
Digital elevation model for the catchment scale	Application: Used in the hydrological model with the resolution of 25*25 m, Source: NASA database
Digital elevation model of the representative reach	Application: Used in the hydraulic model with the resolution of 5*5 m, Source: Generated based on surveying cross sections by the team as well as previous surveyed cross sections by the regional department of the environment

Several water quality parameters can play a role in determining this index which means it can be an appropriate expression of water quality condition in the surface water evaluation. Generally, if this index is higher than 70, it will show very suitable water quality. In contrast, if this index is less than 15, it will mean unsuitable water quality. First, we applied this combined index in the sampled points or observed locations in the field studies in which we computed the index considering measured water quality parameters for further application in development of fish biodiversity model. Moreover, the combined index was used to assess the water quality for assessing environmental flow. In other words, IRWQI was simulated (daily scale) in the simulated river reach downstream of Mamloo dam. The long-term quality data collected in the simulated river reach were used to develop a model for assessing IRWQI. Based on previous studies, data-driven models have been widely used to evaluate water quality parameters which means using data driven models such as machine learning models is generally recommendable. Neuro fuzzy inference systems, which are among the known machine models, have been used to simulate water quality indices widely (Azad et al., 2018). Due to the successful application of this model in previous studies, we applied this framework to simulate IRWQI in the representative river reach downstream of Mamloo dam. Table 2 shows the details of the model to assess combined water quality index, in which the inputs and output as well as details of adaptive neuro fuzzy inference system (ANFIS) are displayed. The ANFIS based water quality model in this study has five layers. The first layer consists of the input membership functions including inputs displayed in Table 2. The second layer includes the fixed nodes to give the product of all incoming signals. The fixed nodes in layer 3 calculate the normalized firing strength of each rule. Layer 4 consists of tuning parameters. Finally, a single node calculates the overall output. Gaussian function was applied as the membership function with ten functions from very low to very high. Moreover, subtractive clustering was used for clustering which is advantageous compared to the partitioning method especially in term of computational complexities. More details regarding the architecture of ANFIS based models as well as advantages of subtractive clustering method have been addressed in the literature (Im et al., 2018; Awan and Bae, 2014). Total load of each day in the simulated period was estimated through previous surveys of source pollutant in the study area carried out by department of environment. NSE and RMSE was applied for evaluating the performance of water quality models as well.

2.4. Combined hydraulic index and its modelling

The depth and velocity of the river flow are the most important hydraulic parameters which can highly affect the biological activities of the fish and consequently their biodiversity. Numerous studies have proven either the effect of the velocity on the energy consumption by different fish species (e.g., Ahmadi-Nedushan et al., 2006). Moreover, the role of depth on biological activities such as feeding and sheltering is demonstrated which means depth and velocity are key hydraulic factors effective on the fish biodiversity. Therefore, it is necessary to consider the effect of habitat hydraulic parameters on fish biodiversity to assess environmental flows.

The combined index of depth and velocity (ratio of velocity to depth) is one of the indices used to identify the impact of hydraulic factors (Jowett, I.G., 1993; Maddock et al., 2013). In fact, this index can evaluate the impact of turbulence and the appropriateness of the physical environment for surviving different fish species. In our field studies and further analysis, this index was calculated at the locations where fish species were observed, which were utilized in the developing the fish biodiversity model. It was also necessary to compute average V/D in the

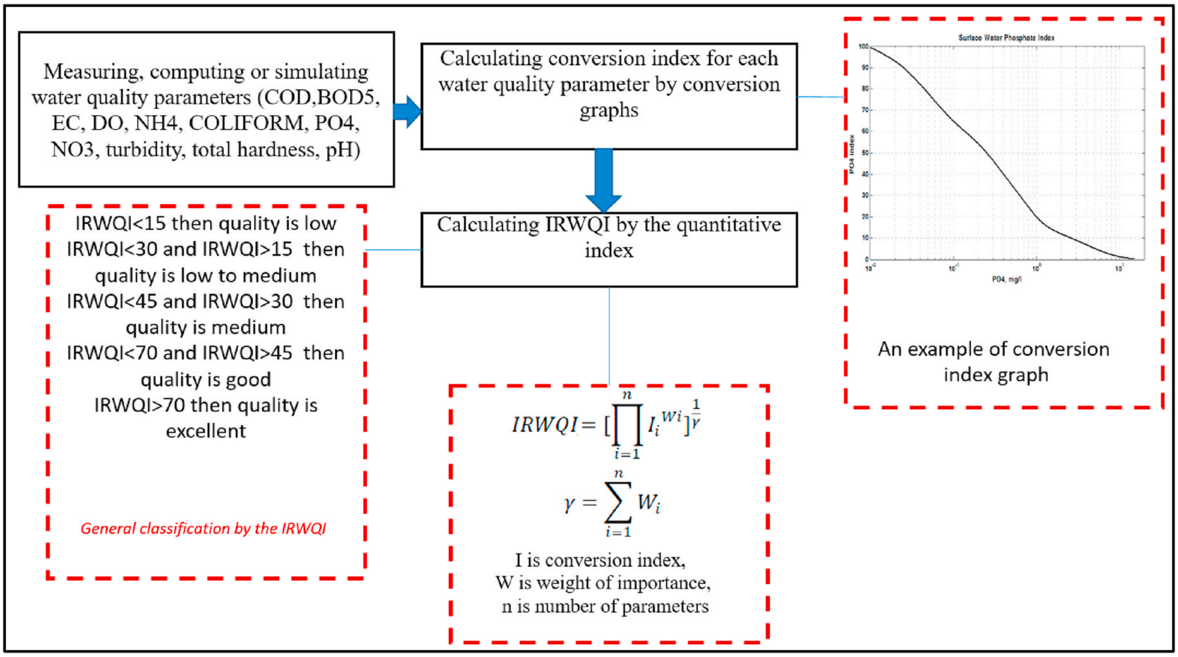


Fig. 4. Workflow of computing IRWQI as the combined water quality index.

Table 2
Main features of ANFIS based model to assess IRWQI in the representative river reach.

Inputs	Number of member ship functions (MFs) (inputs)	Type of membership functions (MFs) (inputs)	Outputs	Number of MFs (Output)	Type of MFs (Output)	Clustering method
Daily average river flow (m^3/s)	10	Gaussian	Daily average IRWQI	10	Linear	Subtractive Clustering
Daily average air temperature (Centigrade)	10	Gaussian				
Daily average total estimated pollutant load (%)- zero means no pollutant and 100% means maximum estimated pollutant	10	Gaussian				

representative river reach selected for assessing environmental flow (downstream of the Mamloo dam). In fact, it was needed to simulate hydraulic of the river flow in this reach for the simulated period in the daily scale. Due to using HEC-RAS 1D in many previous studies of environmental flow assessment, it is adopted for simulating depth and velocity in different cross sections of the representative river reach. Fig. 5 shows the flowchart of this model to simulate depth and velocity in different cross section in the main flow direction (Merwade, 2012).

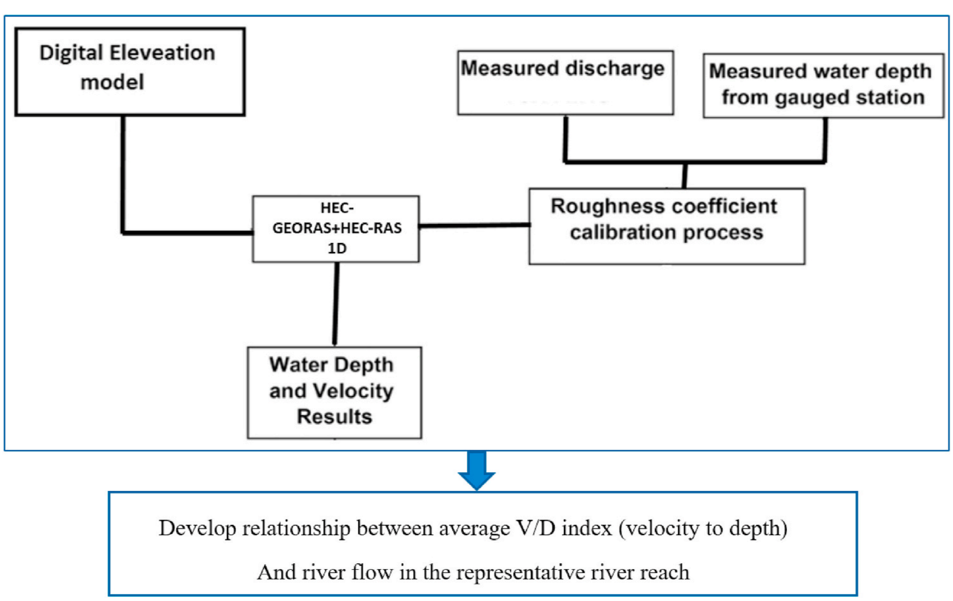


Fig. 5. Flowchart of hydraulic simulation to determine average physical index (V/D) in the representative river reach.

Average section depth and velocity was used to compute ratio of velocity to depth.

2.5. Ecological field studies and fish biodiversity modelling

The present study was carried out based on long-term ecological field studies in the catchment scale. In other words, our observations have been made in different river tributaries during several years which means intensive field studies were carried out in different seasons especially during highly wet and dry seasons. The biodiversity model was developed based on the observation of fish throughout the catchment in which water quality and hydraulic parameters were measured simultaneously, while the environmental flow was assessed in a representative reach. In fact, the biodiversity model was developed based on the observed data in the catchment scale because available data in one river reach is not enough to develop a robust biodiversity model. It should be noted that there is no problem about scale mismatch of field studies and simulations because initial ecological studies demonstrated that the main native fish species involved in the biodiversity model are existing in the tributaries and rivers of the catchment. Hence, the biodiversity model can be used in the representative river reach for assessing environmental flow as well. Regarding fish observation, various methods have been recommended in the literature, which are generally classified into two groups including direct and indirect methods. In the direct methods such as video telemetry, a fish will be actually observed in the habitat. In contrast, the indirect methods use devices such as electrical shockers (electro-fishing) for sampling different fish species (Esteve et al., 2018). Direct and indirect methods of observing fish in river habitats each have their advantages and disadvantages (Macnaughton et al., 2015; Harby et al., 2004). In the present study, due to the long-term experience of the team for using electro-fishing method as well as the advantages, this method was applied in the fish sampling. Each fish observation was repeated at least twice to mitigate the potential impact of false absence, with a considerable delay of at least one day between two samplings at the same site.

In our study, a limited voltage was used in the electro-fishing, which helped survival of the sampled fish and returning them to the habitats. Therefore, most of the shocked aquatic species were returned to the original habitat after the biometric measurements which means and fish losses were minimized. Also, water quality parameters and hydraulic parameters were measured simultaneously with the observation of fishes. A metal ruler was used to measure the flow depth. It should be noted that the depth of the flow was mainly less than 1.5 m which means it was possible to use a metal ruler to measure the depth of the flow. Furthermore, the flow velocity was measured using a flow meter (Simab electronic flow meter with 0.1 m/s precision), which is a common device in hydraulic field studies. A three point method was applied in which the flow velocity in three points (near to surface, mid depth and near to the bed) were measured in the 1 m horizontal distances in each cross-sections All water quality parameters of the river, including dissolved oxygen temperature, etc., were measured by a portable water quality measuring device.

Different biodiversity indices have been proposed in the literature. Among these indices, the Shannon index is widely used in the aquatic ecological studies (Türkmen and Kazanci, 2010). Equation (3) shows this index, which is applicable for evaluating biodiversity in the river habitats. In this equation, SI is Shannon index, P is the proportion of the ith species to the total number of individuals and S is total number of existing species. In the next step, a multivariate linear regression (MLR) was applied to simulate the fish biodiversity index (SI) in which V/D and IRWQI were inputs and SI was the output of the model.

$$SI = -\sum_{i=1}^{S} P_i \ln P_i \tag{3}$$

3. Results

In this section, all the results obtained from the simulations, as well as assessment of the environmental flow, will be presented. Moreover, advantages and drawback of the proposed method along with comparing the outputs of this study with previous environmental flow studies will be discussed which is helpful for the readers to apply the proposed new method for assessing environmental flows in rivers.

3.1. Natural flow regime simulation

First of all, it is necessary to show the results of natural flow simulation using the hydrological model (SWAT) in the representative river reach. As shown in Fig. 6. Hydrological modelling was carried out at upstream sub-catchment in which the outflow was close the natural flow. In the calibration and validation of the model, 80% of the available data was used for calibration which means 20% of the available data were used to validate the capabilities of the model to simulate natural flow regime. Based on the evaluation indices to assess the model shown on the figure, NSE and RMSE of the validation period are 0.6 and 0.1 m^3/s respectively. According to the existing recommendations, if NSE is more than 0.6, the results of the model can be considered reliable. If this index is more than the suggested threshold, the results of the model can be considered acceptable and used for further applications. Also, RMSE is a known index in statistical studies to compare the model and observations. Generally, if this index is as minimal as possible, the results of the studies can be considered acceptable. In the current research, RMSE is around 0.1 m^3/s, which means the average modelling error of the river flow in the study area is acceptable because the average flow in the simulated period of the sun-basin used for calibration is approximately 2 m^3/s (Fig. 6). Due to robust performance of the hydrological model, this model was used to simulate the natural flow regime in the representative river reach at downstream of the Mamloo Dam. It should be noted that the simulation of the environmental flow needs simulating natural flow when recorded flow in the representative reach is far from the natural flow due to water abstraction projects. Therefore recorded data in the representative reach could not be directly used in the proposed environmental flow assessment framework. Fig. 7 displays the natural flow in the simulated flow in the representative reach.

3.2. Hydraulic modelling

In the next step, it is necessary to present the results of the hydrodynamic modelling used to determine the average physical flow index (V/D) in the representative river reach. First, it is needed to show the outputs of verification of the HEC-RAS 1D in different cross-sections of the representative reach in various river flows recorded in the field studies. According to Fig. 8, the hydrodynamic model is reliable for further applications because NSE is close to 1 and RMSE is low for both hydraulic parameters.

Fig. 9 shows the relationship between river flow and average physical index. Changing river flow is highly effective on the physical index which means the impact of changing velocity to depth would alter the balance of meso-habitats. Hence, an appropriate environmental flow regime should be able to minimize the impact of flow on the fish biodiversity by mitigating the impact of physical index on the fish biodiversity index. In other words, there must be a physically balanced condition of the flow in the river. It is necessary to mention that the details of the hydraulic simulation are not shown due to needs for showing many graphs in the results and discussion.

3.3. Water quality modelling

In the next step, the results of calibration and validation of the model to simulate combined water quality index (IRWQI) should be presented. The same indices including RMSE and NSE were applied to evaluate

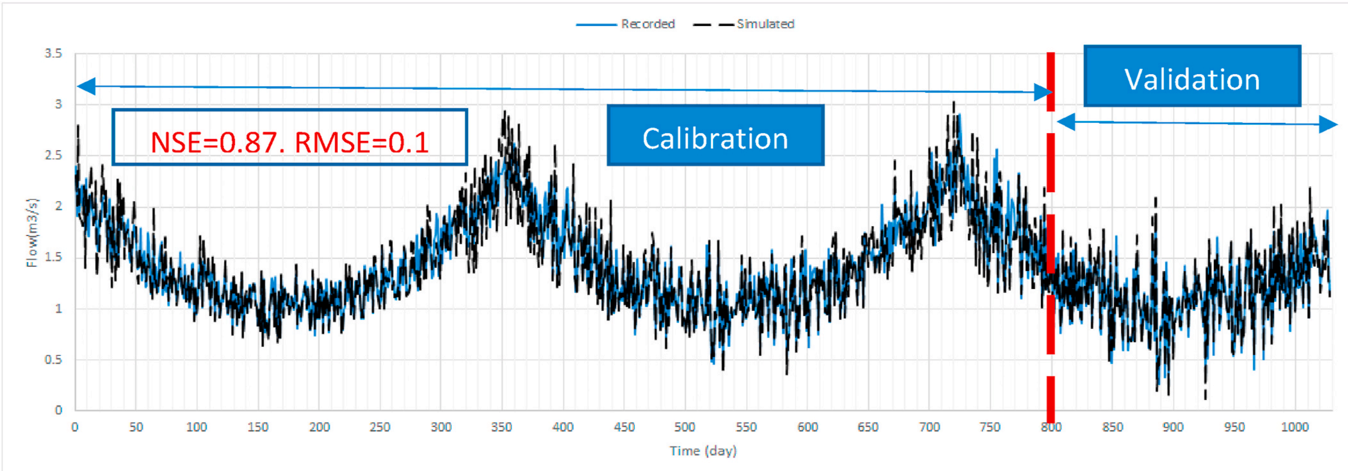


Fig. 6. Simulation of natural flow regime-calibration and validation results at upstream sub-catchment.

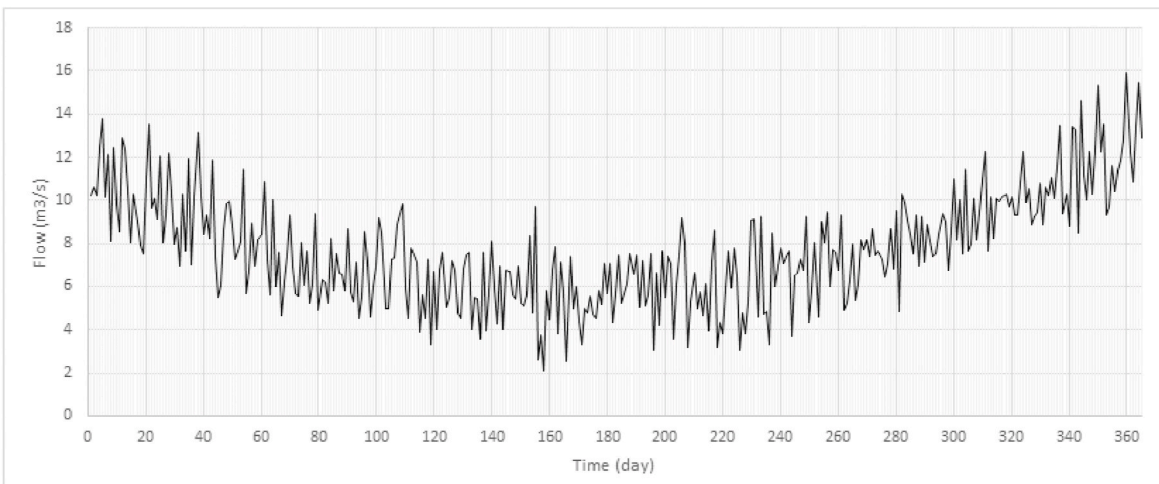


Fig. 7. Simulated natural flow regime in the representative river reach.

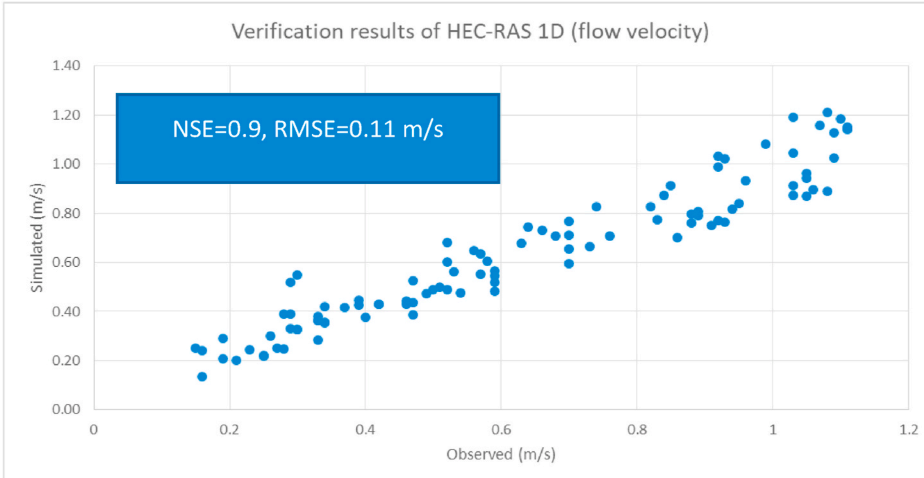
water quality model as well. Fig. 10 shows the observed and simulated IRWQI in the sampled river habitats of the Jajrood river basin. According to the evaluation index displayed on Fig. 10, the performance of this model is acceptable. However, it is not very robust which means the developed model should be used cautiously. It should be noted that the development of the water quality model based on the recorded data is a complex process, because some unknown parameters may affect water quality parameters and consequently combined water quality index.

3.4. Biodiversity index simulation

Our long-term field studies in the Jajrood river basin indicated that three main fish species including Nemacheilus (SP1), Vimba vimba (SP2) and Capoeta capoeta (SP3) at the downstream of Jajrood river basin can be observed which means the biodiversity assessment was carried out based on these species. Fig. 11 displays two samples from the field studies for assessing biodiversity index. Furthermore, Fig. 12 shows the regression model for simulating Shannon index in which V/D and IRWQI are the inputs of the model. Based on this figure, NSE is more than the acceptable threshold suggested in the literature which means the performance of the multiple linear regression (MLR) for predicting the biodiversity index can be reliable for further applications. Based on the field observations, biodiversity index will be increased by improving water quality as well as appropriateness of ratio of velocity to depth. In other words, if adequate flow can be available to improve physical and water quality factors, increasing biodiversity will be expected. In contrast, weakened water quality as well as increasing energy consumption due to the increase in the flow velocity can imbalance the population of the fish species.

3.5. Environmental flow assessment

Fig. 13 shows the simulated time series of average physical indicator as well as average combined water quality index of the representative river reach in the simulated period. Based on Figs. 9 and 13, it can be seen that with the decrease in the daily flow of the river, IRWQI will increase significantly, while V/D might reduce in higher river flows. A suitable environmental flow regime should be able to keep the physical index (V/D) at the optimal level so that the species are able to use meso-habitats including riffles, runs and pools efficiently. In other words, too low or high V/D can be destructive either in terms of energy consumption or biological impacts such as sheltering. Furthermore, results of simulating combined water quality index corroborate that this index (in the current condition of draining water pollutants) even in the natural flow is not favourable, which has happened due to the draining of industrial and urban pollutants as well as extensive land use changes for agricultural development in the study area. In other words, even in the natural flow of the river, it is not possible to provide favourable water



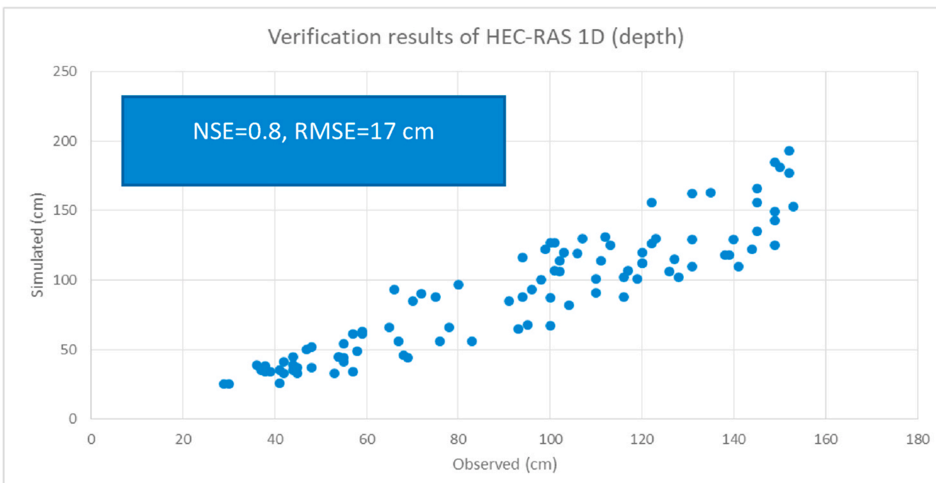


Fig. 8. Verification of HEC-RAS 1D.

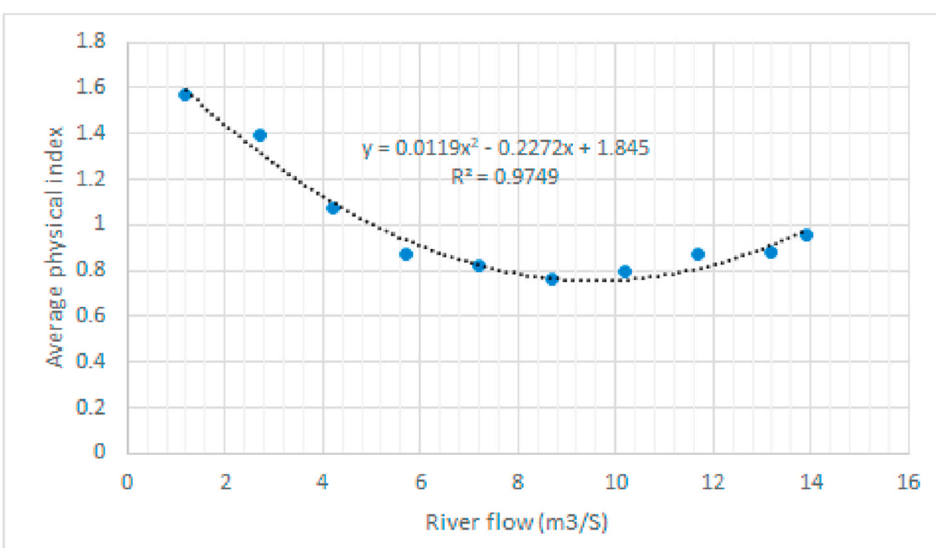


Fig. 9. Physical habitat index function in the representative river reach.

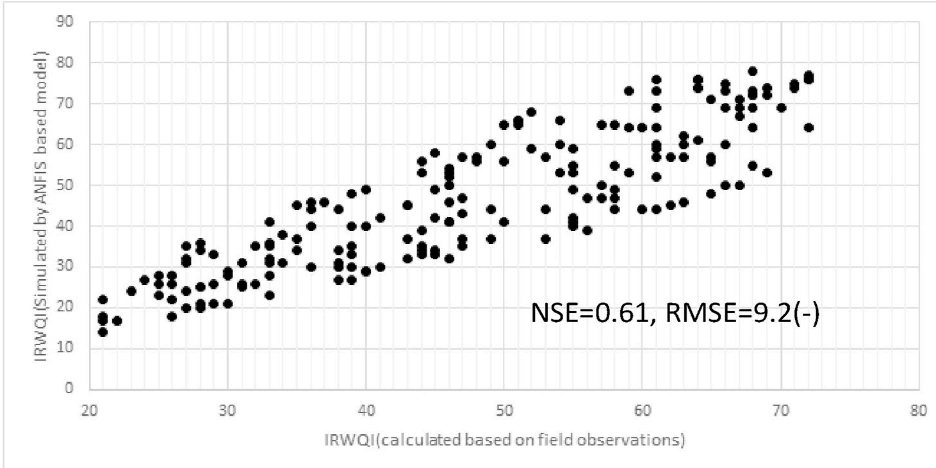


Fig. 10. Calibration/validation of water quality model for simulating IRWQI (IRWQI is a dimensionless index which means RMSE will be dimensionless in this case as well).

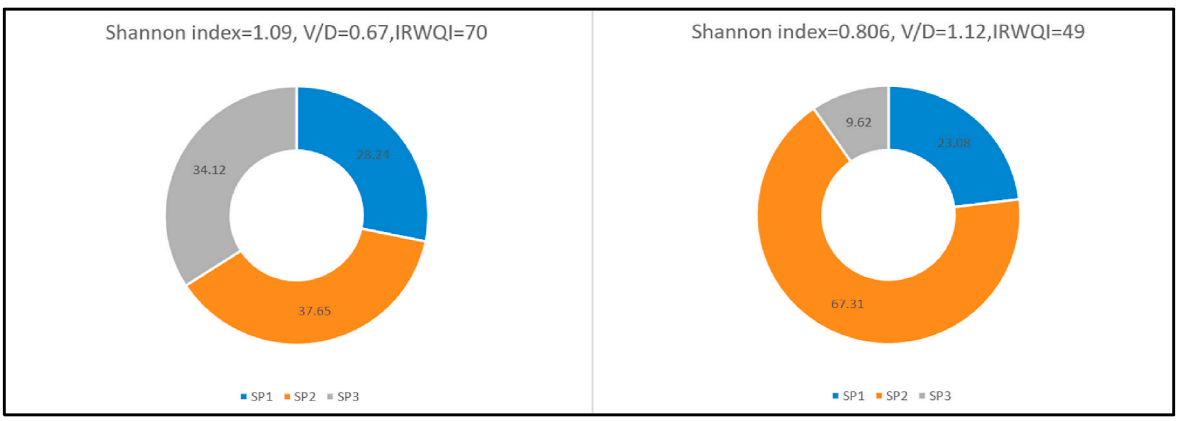


Fig. 11. Two samples of the field ecological observations (population percentage). In our case study, three major native fish species exist in the catchment which means the biodiversity index was developed based on these species. In the displayed all three species were existing.

quality for protecting fish biodiversity. It is necessary to calculate the biodiversity index of the natural flow regime in the current condition of weakening water quality due to draining water pollutants for having a better view on fish biodiversity protection challenges. Fig. 14 shows the changes of the biodiversity index of the natural flow regime in the current conditions are such that, due to the significant pollution drained to the river, the biodiversity index is not suitable which means water abstraction can worsen the fish biodiversity. Hence, improving water quality or reducing sources of the pollutants is necessary before any planning regarding water abstraction or environmental flow.

Due to water quality challenges in the study area, it was necessary to assume that water quality is improved in assessing environmental flow. In other words, we assumed that water quality management project as a necessary prerequisite of water abstraction in the study area has been carried out. Hence, we considered IRWQI = 70 in all days of the simulated period which means water quality is close to the ideal condition. Then, the biodiversity index was recalculated. Fig. 14 displays the fish biodiversity index in the favourite water quality as well. Based on this figure, a significant increase in the biodiversity index can be observed. In fact, the balance between the populations of species will be possible, if water quality is improved in the natural flow regime. Therefore, it can be concluded that in the current situation, due to the significant decrease in the combined water quality index and consequently the fish biodiversity index, it is practically not possible to abstract water from the river. In other words, even the natural flow regime is not able to provide suitable environmental conditions to preserve the biodiversity of fish species.

According to discussed environmental requirements in terms of water quality, assessing the environmental flow regime in the representative river reach was carried out by assuming average IRWQI = 70 in the river reach. Different hydrological indices have been proposed and investigated to determine the environmental flow regime though these hydrological indicators are inherently unable for consider the ecological requirements in the context of assessing environmental flow regime which implies linking hydrological indicators and ecological simulations can be used as an effective method for environmental flow assessment. In other words, hydrological indicators can be used to define hydrological scenarios of environmental flow management. Mean annual flow (MAF) has been proposed as one of the known hydrological indices for assessing ecological flow regime. On this basis, we used MAF index to define hydrological scenarios of defining fixed environmental flow regime. In other words, different percentages of MAF were considered as different possible scenarios of environmental flow. Table 3 shows the result of evaluating the environmental flow regime, in which five scenarios of environmental flow were considered based on the mean annual flow index. In these scenarios, the amount of flow is changed from 10% to 80% of MAF. Based on simulating biodiversity index in the simulated period due to natural flow and ideal water quality condition, it is 0.99 which means the balance of the population of different fish species. As a marginal acceptable change, we considered 10% difference of fish biodiversity index between the natural flow and environmental

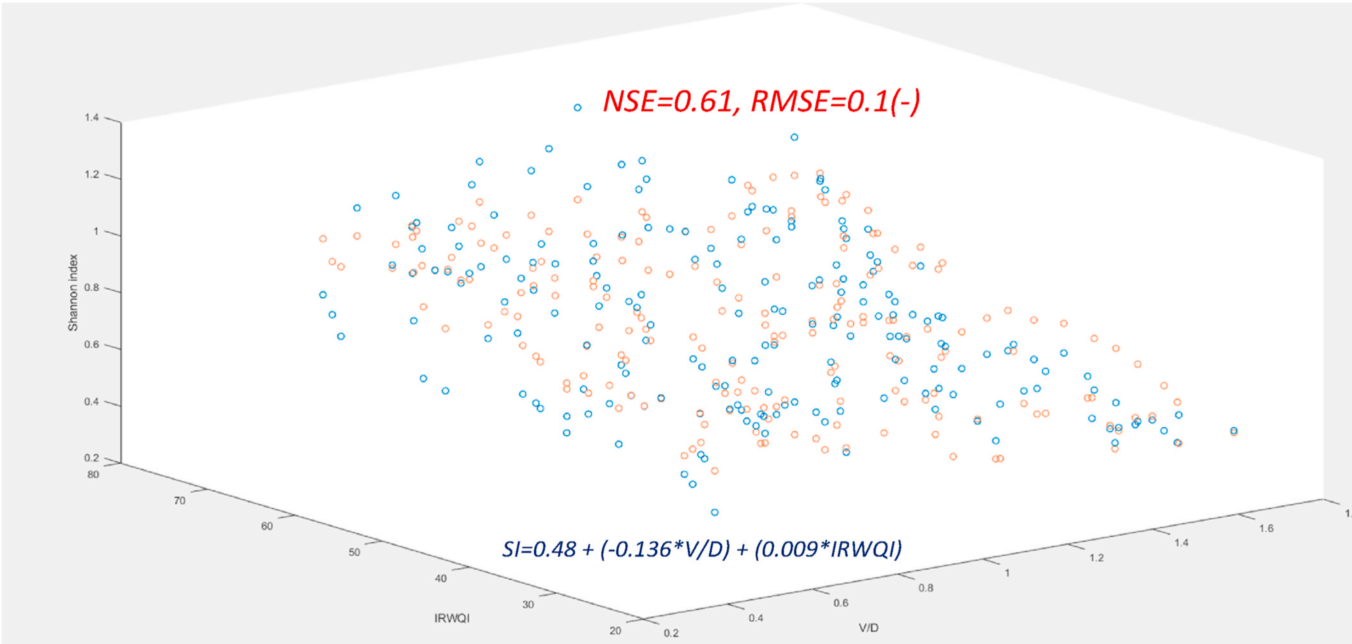


Fig. 12. Multiple linear regression model for simulating fish biodiversity index (Blue: observations, Orange: simulations). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

flow regime. Based on Table 3, 40% MAF is acceptable as the minimum environmental flow regime in the representative river reach. However, 80% MAF can be defined as the optimal environmental flow regime in which the difference between biodiversity index in the natural flow regime and environmental flow regime is less than 5%. Hence, 40%–80% MAF can be defined as the environmental flow regime for protecting the fish biodiversity considering improved water quality.

4. Discussion

Discussing the technical and computational aspects of the framework can be helpful for the readers of the present research work so that they can effectively apply the novel proposed method to assess environmental flow regime in rivers. It is also necessary to discuss on the limitations and strengths of the proposed framework which can open new windows for further environmental flow studies by considering important ecological indices such as biodiversity index.

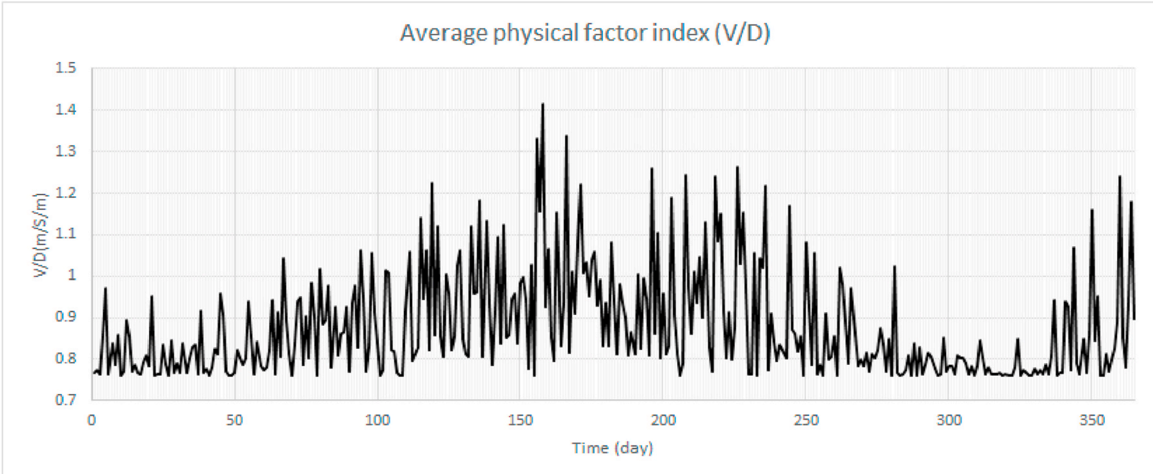
The old methods of environmental flow in rivers have only applied hydrological indicators without any link to the ecological simulations. In fact, these methods used hydrological indicators or historical flow studies to assess ecological flow. Due to the lack of focus on the ecological values of the study area, these methods are not practically reliable which means they should be excluded from advanced studies of environmental flow. However, they might be useable for initial studies of environmental flow to have a better understanding on historical flow changes in each case study. Moreover, the proposed hydrological indicators such as MAF can be used to define ecological protection scenarios as used in this study.

4.1. Technical advantages compared to previous environmental flow studies

During the last two decades, using ecological based methods has been developed which means new ecological based methods have been proposed to assess environmental flow regimes. Physical habitat simulation method as a known ecological based methods utilizes physical habitat suitability for the target species to generate weighted useable area function which can be applied for assessing environmental flow assessment considering some further steps (Sedighkia et al., 2023). However, it should be noted that physical habitat simulations or other similar methods, which focus on a target species, are practically unable to consider the complexity of the ecological status such as biodiversity. In fact, the key ecological indicators such as biodiversity index should be considered in simulating environmental flow regime. Furthermore, original physical habitat simulation does not take into account water quality indices in the simulation as well which is another shortcoming of this approach. The proposed approach integrated physical habitat index due to impacts of physical parameters on the fish biodiversity which means available background of meso-habitat simulations was applied. Holistic approaches such as building block methodology (BBM) take into account water quality considerations in assessing environmental flow (King et al., 2000). However, lack of robust ecological simulation frameworks as well as lack of using biodiversity indices are the main drawback of these approach which weaken their application. It is necessary to improve available holistic frameworks considering the proposed ecological method to add the fish biodiversity index in the structure of the methods.

Our main motivation of this research work was how available flow in a stream can preserve the fish biodiversity because abiotic factors such as physical parameters of the flow as well as water quality indices play an effective role in preserving the biodiversity of aquatic creatures and such fish. To ensure the conditions of ecological stability in the river ecosystem. The proposed approach should be added to the available water resources planning approaches in the river basins. Some past studies have shown that the use of advanced ecological frameworks is an important need in the water resources planning and management especially at downstream of hydraulic structures such as dams, which has been neglected in many studies ((Kuriqi et al., 2021). Some studies have proposed using ecological simulation in the context of water resources management (Sedighkia and Abdoli, 2022). However, complex ecological indicators such as biodiversity indices have not been added to the water resources modelling. On the one hand, the simulation of these indicators is complex and multidisciplinary studies are required in this regard. On the other hand, field studies are essential which might be expensive in some cases.

In the data-driven model of water quality, we applied 10



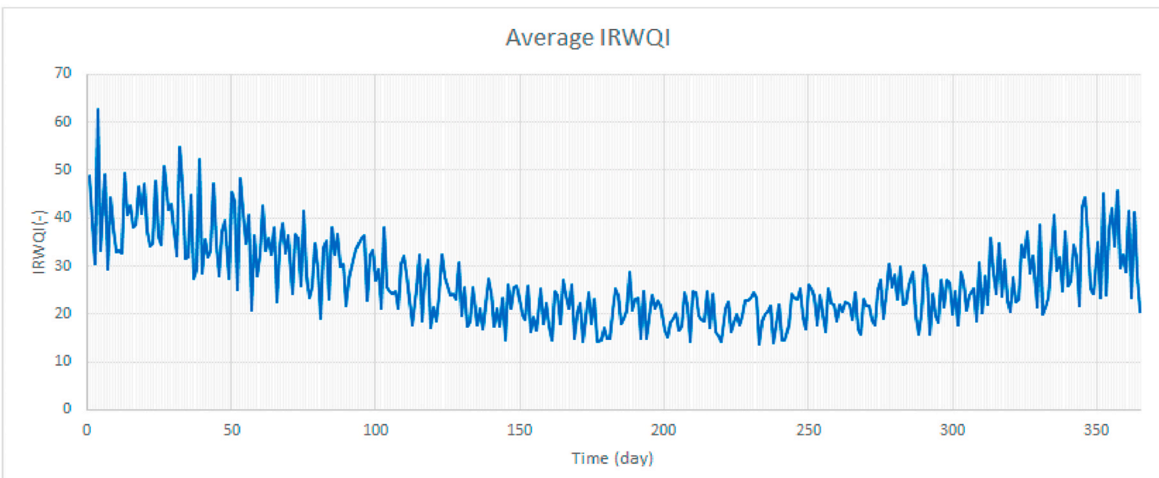


Fig. 13. Time series of average combined water quality index and physical factor index in the simulated representative river reach.

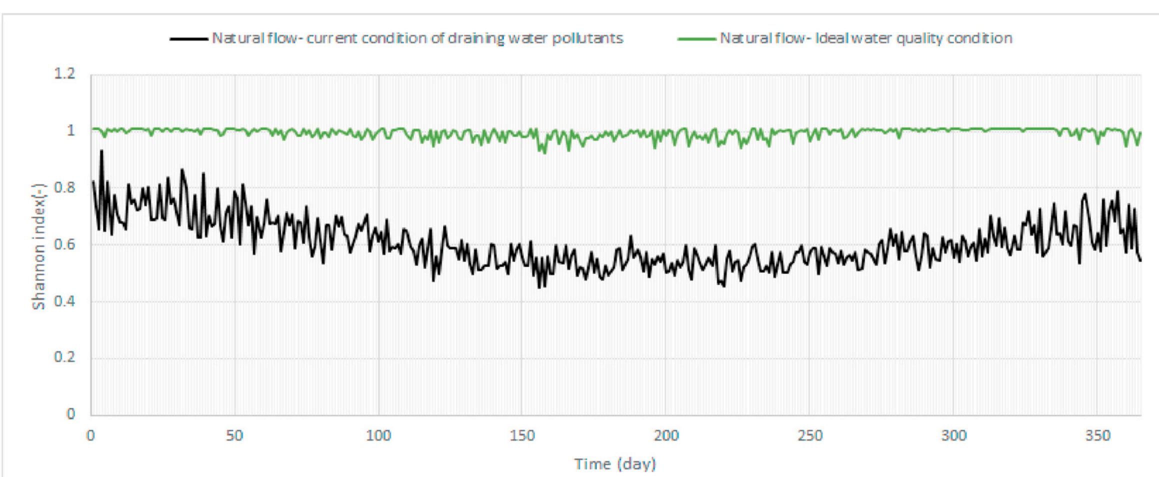


Fig. 14. Time series of Shannon index in current condition of draining water pollutants and ideal water quality condition (IRWQI = 70) in the simulated representative river reach.

membership functions for inputs and outputs, resulting in a total of 1000 fuzzy rules. This extensive set of rules contributes to the complexity of the model, especially in terms of computational time. However, reducing the number of membership functions could significantly compromise the accuracy of the model. Therefore, it is advisable to experiment with various numbers of rules to optimize the balance between model complexity and accuracy. In our study, we tested different numbers of membership functions and ultimately determined that 10

Table 3
Environmental flow assessment in the representative river reach considering protecting fish biodiversity.

Hydrological scenarios of environmental flow regime (considering natural flow regime in the calculation)	Environmental flow (Cubic meters per second)	V/D	IRWQI	Average shannon index due to environmental flow and IRWQI = 70	Average shannon index in the simulated period due to natural flow and IRWQI = 70	Recommendations
10% MAF	0.44	1.75	70	0.877	0.99	**10% MAF is not adequate for environmental flow due to difference between shannon indices more than 10%**
20% MAF	0.88	1.65	70	0.889		**20% MAF is not adequate for environmental flow due to difference between shannon indices more than 10%**
40% MAF	1.76	1.48	70	0.913		**40% MAF is recommendable as the minimum environmental flow**
60% MAF	2.64	1.33	70	0.934		**60% MAF is recommendable as the fair environmental flow**
80% MAF	3.52	1.19	70	0.953		**80% MAF is recommendable as the optimal environmental flow**

membership functions provided the best performance.

4.2. Ecological considerations/limitations

It is needed to justify why we selected Shannon index as an appropriate biodiversity index in the study area. First, we have not applied it as an absolute index because defining absolute appropriate value for the Shannon index is not meaningful. For example, it is not clear the equal proportion of different species is good or bad. Thus, we applied this index for comparing the natural flow regime and environmental flow regime. In fact, the proportion of different species in the natural flow regime was defined as the target of ecological management. Then, if the ecological flow method is able to provide maximum proximity between the natural flow regime and the ecological flow regime, it can be an appropriate assessed ecological flow regime. In our case study, we only used three fish species which seems all the fish species are not considered at the first glance. However, these three fish species are the major native fish species in the case study which means adding rare population of some other species which may be observed only in some points of the river does not make sense. In other words, we defined the biodiversity index reliably based on the major identified native fish species with remarkable population. Based on the initial ecological studies, these species in the case study were not predator of each other which means they only have competition for occupying the best habitats for biological activities as well as the food sources. The initial ecological studies corroborated that the ecological flow regime due to impacts on water quantity as well as water quality is highly effective on finding the best habitats and the food sources. Thus, it can change the balance of the population of these species unfavourably because we assumed that the Shannon index in the natural flow regime is the equilibrium point of the proportion of the different species' population. However, it can be different case by case and the number of fish species and the appropriateness of the biodiversity index should be determined case by case. Another point is why we did not consider the number of individual of each species in the assessment process. As discussed, the balance of fish population in the natural flow regime is considered as the ideal condition which means any change in the flow regime can alter the population of each species and consequently the Shannon index will be changed because these species are competitors for obtaining the best habitats as well as the food sources. Hence, Shannon index can be a good ecological index to assess the impacts of the flow regime on the proportion of each species compared to the natural condition.

It is required to discuss on the immigration of the species related to the proposed framework. In the case study, the three fish species are not migratory which means they spend the lifetime in the river habitats because the Jajrood river basin is an inland basin with no connection to a sea or a great lake as the secondary habitats of the fish species. Thus, defining the proposed framework for assessing minimum ecological flow regime is logical because it can show the impact of humans' activities on the flow regime. However, using the proposed framework in the river basin in which the fish species are migratory should be cautiously. In fact, the natural process of the immigration of the species can be effective on the biodiversity index in different tributaries. Applying the biodiversity index in each tributary seasonally can be a solution for these cases. Hence, modifying the proposed framework for these basin can be one of the future research needs.

The research team simulated the natural flow for a year in the representative river reach (Fig. 8) as a testing period to define the ecological flow. However, the MAF should not be defined only based on the one year because MAF is a hydrological index for defining the ecological flow in all years. If engineers only consider one year such as simulated period (in the case study, it was a normal year), it cannot be logical because the river flow will be reduced in the dry years which means the proposed ecological flow might not be suppliable during the droughts. Hence, the research team defined MAF as a fair index based on the simulation of natural flow regime for a long-term period (30 years), which can be suppliable in all the hydrological conditions. Defining the ecological flow based on the long-term MAF can assure the community regarding overcoming the ecological challenges of the river ecosystem for all hydrological conditions. The computed MAF (4.4 m^3/s) is the result of assessing MAF in a long-term period including dry years, normal years and wet years.

The proposed methodology is a general approach applicable to all river basins. Three main species, observed from upstream to downstream, were considered to calculate the Shannon index in the case study. However, the number of fish species may exceed ten due to the ecological characteristics of a river basin. Therefore, employing a biodiversity index is crucial within the methodology. Additionally, modelling changes in the biodiversity index can help capture unknown biological interactions.

Initially, selecting only three species for the case study may seem insufficient, suggesting the need to augment density data. However, it's important to note that no other significant fish species were identified, and the population of other species was scarce. Incorporating these rare species into the biodiversity index at the catchment scale may not be feasible. Furthermore, there are no limitations on applying the Shannon index in ecological studies in terms of the number of species. In essence, the ecological characteristics of a catchment will dictate the number of species used in the biodiversity index.

The selection of a biodiversity index sparks considerable debate within the literature, necessitating thorough discussion. It has been emphasized in the literature that there is no universally superior or most reliable biodiversity index suitable for all ecological studies. Rather, the choice of a biodiversity index depends on the specific aspects of diversity and objectives within the study area that require investigation (Gatti et al., 2020).Comprehensive studies on biodiversity indices in freshwater ecosystems suggest that indices such as Shannon index, functional diversity, and rarefied species richness can offer similar insights into ecosystem conditions, particularly regarding species number and dominance. While, measures like size diversity and distinctness can provide supplementary information on ecosystem quality (Gallardo et al., 2011). Konopiński (2020) advocates for the use of an improved biodiversity index in population genetic studies, as opposed to the original Shannon index.

It is important to clarify that the objective of our study is to assess the balance of fish population, focusing on the number of observed species in the samples. Thus, employing the Shannon index suffices, as neither ecosystem quality nor population genetic studies are the primary aims of our research. Our methodology and field studies are specifically designed to address the balance of native or introduced fish species in their habitats. Conversely, other ecological studies, such as population genetic research aimed at identifying alleles associated with disease risk or assessing ecosystem quality, may require the utilization of alternative, improved biodiversity indices.

Our developed approach represents the first method for assessing environmental flow based on fish biodiversity, employing a simpler ecological indicator, namely, the balance of fish species in habitats, for easier application. It is worth noting that the intended end users of our method may include water resources engineers, and the use of complex biodiversity indices, which integrate species number and ecosystem quality, could complicate the method's application for interdisciplinary purposes. Nevertheless, future ecological studies have the potential to enhance our proposed method by incorporating additional biodiversity indices, thus facilitating both the assessment of species balance and ecosystem quality. However, the field studies as well as computational approach should be modified accordingly.

4.3. Technical limitations

The present research work combines extensive field studies as well as complex data-driven and hydraulic modelling to link the environmental flow regime and biodiversity index, in which hydrological models of the catchment as well as hydrological indices were used. However, each new method has some limitations which should be noted in the further applications. Two limitations regarding the application of the developed framework should be considered. First, the developed framework for environmental flow simulation considering the biodiversity index is complex in terms of used disciplines which means several types of modelling approaches including catchment models as well as hydraulic modelling and data driven models should be used. The lack of necessary experts in many case studies especially in the developing countries as well as the computational complexity might be a hindrance for applying the proposed method practically. Therefore, it is recommendable that this framework should be applied by a team in which experts of different disciplines are present. In fact, the framework provides an interdisciplinary environment that can combine ecological field studies with environmental considerations as well as ecological modelling to propose environmental flow regime. Another hindrance for using the proposed method is the need for extensive field studies. In fact, fish observations should be carried out broadly by measuring the environmental parameters simultaneously which may increase the costs of the environmental flow assessment. Therefore, the proposed method can only be used if field studies can be possible in the acceptable level to develop data-driven water quality model as well as biodiversity regression model and hydraulic model.

4.4. Computational aspects of modelling

One of the important requirements of the proposed method is necessity of estimating the natural flow regime in many cases. In fact, in many case studies, recorded historical flow differs from the natural flow of the river due to water abstraction projects. Hence, it is necessary to estimate the natural flow of the river with catchment hydrological models. In this study, soil and water assessment tool (SWAT) was used though other models may also be used in future studies. However, due to successful use of SWAT in previous studies to simulate the flow regime, it is recommendable to apply this model in future practical applications to simulate the natural flow of the river because this model is able to consider the key parameters such as soil map and land use map as the direct inputs. Moreover, due to the possibility of automatic calibration by SWAT-CUP, this model can be a reliable option.

Examining the computational complexities of the proposed framework compared to other methods can also be essential. The proposed method is a complex one compared to the available environmental flow methods, because the computational complexity of data-driven models as well as the computational complexity of hydraulic and hydrological modelling can be significant. Considerable time might be required to train the data-driven model, which can increase the computational complexities. Besides, calibration of SWAT can be time-consuming because a lot of trial and error is required to achieve the optimal coefficients. We used SUFI2 optimization method in the SWAT-CUP which may take a significant time to carry out iterations (Abbaspour et al., 2015). In contrast, hydrological desktop methods are very simple with minimum computational complexities. Furthermore, although the habitat simulation method seems more complex than the hydrological desktop methods, the complexity of this approach is still not high compared to our method (if 1D hydraulic model uses in the simulation similar to the proposed framework) because there is no need to develop data-driven models or watershed models in the habitat simulation method. Therefore, in cases where biodiversity ecological is of great importance, the proposed method should be applied though more computational complexities. The impact of climate change on the biodiversity index in watersheds is undeniable. Therefore, one of the problems which should be investigated in future is the combination of climate change models with the proposed method to analyse the environmental flow. Moreover, using other hydrological indices such as monthly mean flow or flow duration curve is linked with the proposed biodiversity modelling is recommendable to explore applicability of these hydrological indices. Applying other data-driven models for water quality modelling is another recommendation for future research works (more details regarding potential options by Palani et al., 2008).

5. Conclusion

Applying the biodiversity indices for assessing environmental flows is a research need in many case studies. Due to this research gap as the motivation of this research work, a novel method was developed to assess environmental flow regime in which protecting the fish biodiversity is aimed. This novel method is able to integrate impacts of water quantity and quality on the fish biodiversity in the structure of the environmental flow assessment. Different modelling approaches were applied to simulate combined indices of water quality and physical habitat as the inputs of the fish biodiversity regression model. Based on the results, the proposed method is able to protect the fish biodiversity properly by proposing an appropriate environmental flow regime. However, significant improvement of water quality is a prerequisite before implementing the proposed environmental flow regime. 40% of mean annual flow regime is the minimum required environmental flow in the case study. Many improvements will be possible in future studies including using other biodiversity indices or combining biodiversity indices as well as using other types of data driven and hydraulic models in the structure of the environmental flow assessment. Moreover, the proposed method should be integrated in the structure of catchment planning in future studies.

CRediT authorship contribution statement

Mahdi Sedighkia: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Asghar Abdoli:** Writing – review & editing, Supervision, Resources, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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