

Analyzing the impact of environmental flow indices on protecting the biodiversity of macroinvertebrates

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ABSTRACT

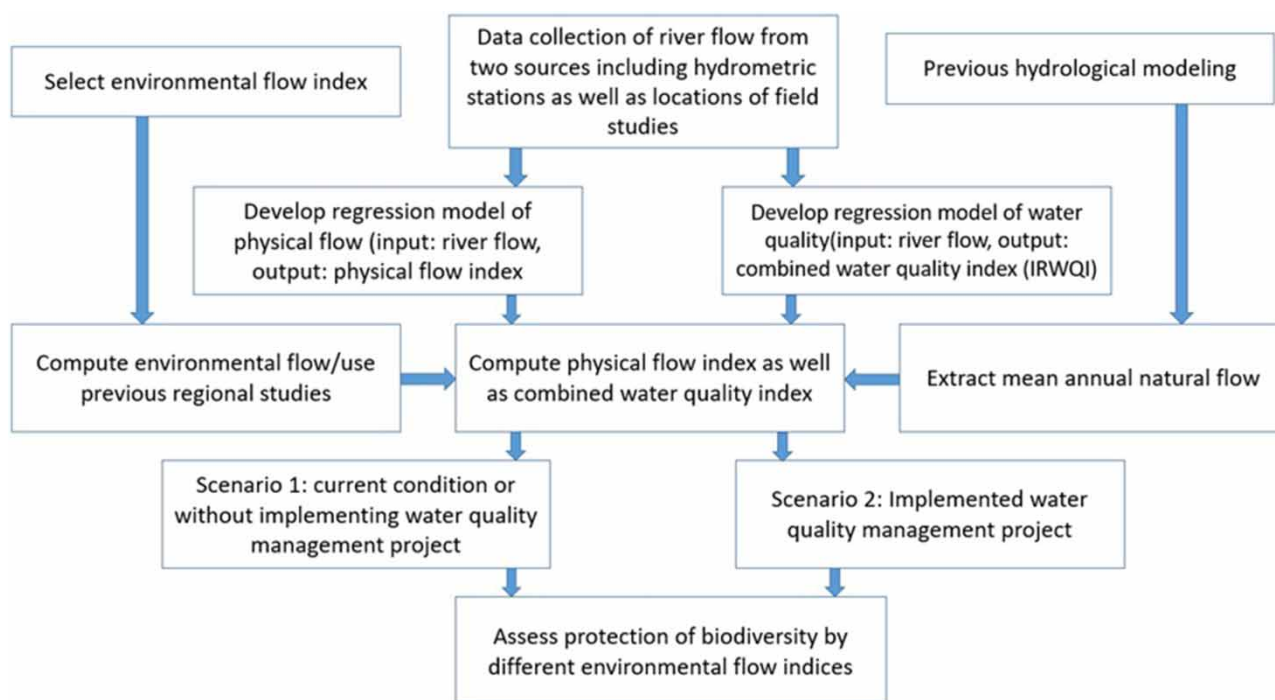
This study evaluates the impact of environmental flow regimes in the river habitats on the biodiversity index of macroinvertebrates. A multiple linear regression model was developed to simulate the biodiversity index of macroinvertebrates in which two combined indicators were considered as the inputs. A combined water quality index that can integrate the impacts of all key water quality parameters as well as a combined physical flow index were considered as the inputs of the biodiversity model. Based on the case study results, some hydrological indices of environmental flows such as 10% of mean annual flow would remarkably weaken the biodiversity of macroinvertebrates. By contrast, some environmental flow indices such as the physical habitat index can mitigate the impacts of changing flow regimes by minimizing the differences between the biodiversity index in the natural flow and environmental flow regimes. Furthermore, some hydrological indicators such as 60% of mean annual flow performed similarly to physical habitat methods. However, the results demonstrated that the degradation of water quality due to human activities has considerably weakened the biodiversity even in the natural flow regime, which means implementing an environmental flow regime without water quality improvement might worsen biodiversity. This study highlights that environmental flow studies should be incorporated within the biodiversity modeling of macroinvertebrates.

Key words: biodiversity, environmental flows, macroinvertebrates, mean annual flow, physical habitats, wetted perimeter

HIGHLIGHTS

- A novel method for assessing the impact of environmental flows.
- A focus on biodiversity of aquatics.
- Integrating water quality and quantity.
- Considering several environmental flow indices.
- Highlighting the deficiencies of environmental flow methods.

GRAPHICAL ABSTRACT



INTRODUCTION

The concept of environmental flows was defined a few decades ago to protect the environmental values of river ecosystems (Pastor *et al.* 2014). Due to the significant withdrawal of water from river networks to supply urban as well as agricultural demands, the survival of aquatic species as well as dependent terrestrial species is being threatened, which necessitates limiting water abstraction by defining some rules for protecting instream flow (Palmer & Ruhi 2019; Pal & Talukdar 2020). Furthermore, draining water pollutants into the river systems is another threat to the aquatic species that might destroy them or obstruct the biological activities including searching for food or reproduction. In fact, the environmental flow in the rivers should be defined with the following two objectives: (1) reducing the impact of insufficient water in the river ecosystem and (2) mitigating the impact of water pollutants on the aquatic species, which might be escalated due to lack of enough water as well as increasing pollutant sources. Different criteria have been considered in defining the environmental flows in previous studies. For example, some research works have studied the environmental flow impacts with a focus on recorded historical flows, which means in-depth environmental analysis has not been highlighted. By contrast, some methods such as physical habitat simulation highlighted the importance of physical flow factors only, while some other studies defined the environmental flow regime considering water quality purposes. As a general and comprehensive definition, the environmental flow should be able to protect the river ecosystem and guarantee the sustainable environmental status of rivers for overcoming freshwater ecosystem challenges (Arthington *et al.* 2018; Chen *et al.* 2020). Environmental flow studies are a hot research topic in the environmental studies of rivers due to the challenges of defining a right instream flow regime (Bayat *et al.* 2019; Jones *et al.* 2023).

As a brief review of environmental flow methods to mitigate the effects of water abstraction projects such as dams and reservoirs or pumping stations, the initial methods of assessing environmental flow were mainly based on hydrological indicators, in which a percentage of the recorded river flows is considered as the environmental flow regime (Kuriqi *et al.* 2019). These hydrological indicators such as the Tennant method have been developed only based on limited field studies conducted in a few specific watersheds, which is recommended for use in all other river basins (more details of hydrological methods by Książek *et al.* 2019). Therefore, these methods are not based on regional environmental field studies. However, the considerable impact of dams on the biodiversity is highlighted in the literature (Wu *et al.* 2019). Hence, the reliability of these methods has always been doubtful for ecologists because these methods do not pay attention to

the environmental values in a watershed. However, these methods are still widely in use (Ibáñez *et al.* 2020) due to two significant reasons. First, there are conflicting reports regarding the effects of these methods in different river ecosystems. For example, some studies highlighted that hydrological methods, which are also called desktop methods, can protect the river habitat and provide adequate flow for sustaining the environmental status of the river ecosystems. Conversely, some studies claimed that using these methods cannot provide adequate environmental suitability in river habitats, which means applying desktop methods to determine environmental flows is not recommended. Considering the challenges of using hydrological indicators for assessing environmental flow, a wide range of environmental approaches from simple habitat simulation to integrated environmental assessment has been proposed to assess environmental flow regimes. For example, physical habitat simulation is one of the first attempts to determine the environmental flow based on the habitat suitability criteria (Ahmadi-Nedushan *et al.* 2006). In fact, one or more target species are selected for simulating the suitability of the physical habitats in a river reach in this method (Im *et al.* 2018). Holistic methods for assessing the environmental flow regime claim taking into account all aspects affecting the river habitats, such as the building block methodology (BBM) (Ćosić-Flajsig *et al.* 2020; King *et al.* 2000). However, ecologists might be disappointed by all these methods because vital environmental indices such as the biodiversity index are not defined in these approaches or no clear approach for including biodiversity is stated.

Due to the importance of water quality for assessing the aquatic ecosystem health, some recent studies have focused on estimating the water quality parameters with novel methods. It is demonstrated that using improved regression models can increase the accuracy of the water quality model for estimating some key water quality parameters such as biological oxygen demand (Najafzadeh & Niazmardi 2021). Using data-driven models such as Polynomial Regression (EPR), M5 Model Tree (MT), Gene-Expression Programming (GEP), and Multivariate Adaptive Regression Spline (MARS) to predict the water quality index has been addressed in the literature, which indicates the different performances of the various data-driven models in water quality assessment (Najafzadeh *et al.* 2021). According to the cited previous studies, this research work considers a combined water quality index to assess the health of river ecosystem in terms of biodiversity protection considering river flow alteration.

The question is how can the environmental flow regimes claimed by all the available methods protect the environmental processes in the river ecosystem? For example, macroinvertebrates' biodiversity is one of the important environmental indicators in each river due to the role of these species in the food web (Aguiar & Ferreira 2002). In fact, the biodiversity index of these species can be a key indicator for measuring the environmental health of a river, which means using biodiversity models can be important in the environmental assessment of the catchments (Everaert *et al.* 2010). If the biodiversity in a disturbed system is close to the natural flow regime of the river, it will mean that the available flow regime in the river is able to provide balance among the population of different species. Due to more water abstraction projects as a consequence of increasing population, as well as alterations in the hydrological cycle of the catchments due to climate change, aquatic biodiversity is seriously under threat. The destruction of aquatic biodiversity is reported in many rivers.

One of the important weaknesses of the existing methods for assessing environmental flow is that the biodiversity of macroinvertebrates has not been highlighted as one of the important environmental indicators in river ecosystems. This research gap was the main motivation for this study. In other words, the research question is how can the existing known methods of environmental flow assessment, including the hydrological desktop method, wetted perimeter method, and physical habitat simulation, protect the biodiversity of macroinvertebrates, which is one of the important ecological indices in river habitats? Based on this research gap, the objective of this study is to develop a hydroecological model that can assess the biodiversity index of macroinvertebrates considering changing the environmental parameters of the flow consisting of physical hydraulic parameters (depth and velocity) as well as water quality parameters. Then, this model will be applied to assess some major environmental flow indices consisting of the mean annual flow (MAF), wetted perimeter (WP), and physical habitat indices in terms of protecting the biodiversity of macroinvertebrates. This study can significantly contribute to improving the available environmental flow methods in future as well. In other words, the outcomes of this study will help the researchers to rethink environmental flow assessment methods considering biodiversity protection. It should be highlighted that extensive surveying of habitats in the catchment scale for sampling macroinvertebrates as well as water quality and quantity parameters were carried out to develop a novel biodiversity model, which means this study provides a practical guideline to understand the steps for assessing the biodiversity consistent with changing of the river flow regime.

MATERIALS AND METHODS

Case study and field studies

The Jajrood River, with a length of 139 km, is one of the most important rivers in the north of Iran. It originates from the Alborz Mountains and finally flows into the Ghom Lake located at downstream of Tehran Province. Due to the importance of this river in terms of supplying drinking and agricultural water in the Tehran province as well as environmental values, protecting the ecosystem of this river has been one of the important challenges for the regional department of environment. Hence, this river basin is classified as a protected catchment. However, because of the significant water abstraction as well as low water quality resulting from significant discharge of pollutants, river habitats at downstream and upstream of the basin have been destroyed, which means the population and biodiversity of the aquatics is under threat. Environmental threats in this river basin are undeniable, which means there is a need to manage river flows for minimizing environmental impacts. In recent years, an extensive study has been carried out for assessing environmental flow regimes in this catchment, which can be used as the reference of environmental flows for further environmental assessments. According to this study, environmental flow regimes have been assessed in different tributaries by some known methods. According to our field observations, available river flow in some tributaries is close to the assessed environmental flow, while in some tributaries, the available flow regime is not consistent with the assessed environmental flow regime. All used methods for assessing environmental flow regimes are unable to integrate the biodiversity of macroinvertebrates, which raises the question of how the recommended environmental flow regimes in different tributaries of this river can guarantee aquatic biodiversity. In fact, the environmental flow regimes are not designed for protecting aquatic biodiversity in previous studies. Hence, environmentalists believe that environmental flow may not be able to address the stable environmental status of the river ecosystem. Field studies have been carried out in more than 10 locations, from upstream to downstream, in which aquatic observations have been carried out along with the measurement of water quantity and water quality parameters of the river flow. The most important challenges of the study area are the disposal of garbage and waste materials in the river, because it is a known recreational area of the capital territory in Iran. A high population, especially during summer, and wastewater from the houses and some industrial units have increased the pollutants' concentration, posing a big threat to aquatic life in this river. [Figure 1](#) shows the Jajrood catchment and its river network in which the selected stations for assessing environmental flow are shown.

In this study, the biodiversity of macroinvertebrates was taken into consideration as an environmental indicator for assessing how environmental flow regimes are able to address biodiversity as a sensitive environmental index. Due to the need for sampling the benthic population, our team carried out sampling in the shown locations using a sampler with the area of 900 cm² (30 cm × 30 cm) with the mesh size of 250 μm. The field studies were carried out in different seasons by three repetitions in each season. Furthermore, various water quality parameters and physical flow parameters of the stream were measured simultaneously. To measure water quality parameters, a portable water quality measuring device was used, which was able to measure a wide range of water quality parameters by displaying the values on the monitor. Also, a metal ruler and a flow meter were used to measure the flow depth and velocity, respectively. Due to the changing depth between zero and 1.5 m in all the locations of the field studies, it was possible to walk in the river during the field studies, which means using the metal ruler and flow meter to measure depth and velocity was not difficult. More details regarding the sampling method as well as the measurement of abiotic factors have been addressed in the literature ([Harby *et al.* 2004](#); [Bouchard & Paul 2012](#); [Couceiro *et al.* 2012](#)). The details of the case study are provided in [Table 1](#).

Biodiversity index modeling

Different biodiversity indices have been proposed in the literature that might be useful in assessing the biodiversity of the aquatic and terrestrial species. Among these indices, the Shannon index is broadly applied in the aquatic environmental studies. Equation (3) shows this index, which can evaluate the biodiversity of the river habitats. In this equation, SI is the Shannon index, P_i is the proportion of the i th species to the total number of individuals, and S is total number of existing species. [Figure 2](#) shows the workflow of computing the biodiversity index.

$$SI = - \sum_{i=1}^S P_i \ln P_i \quad (1)$$

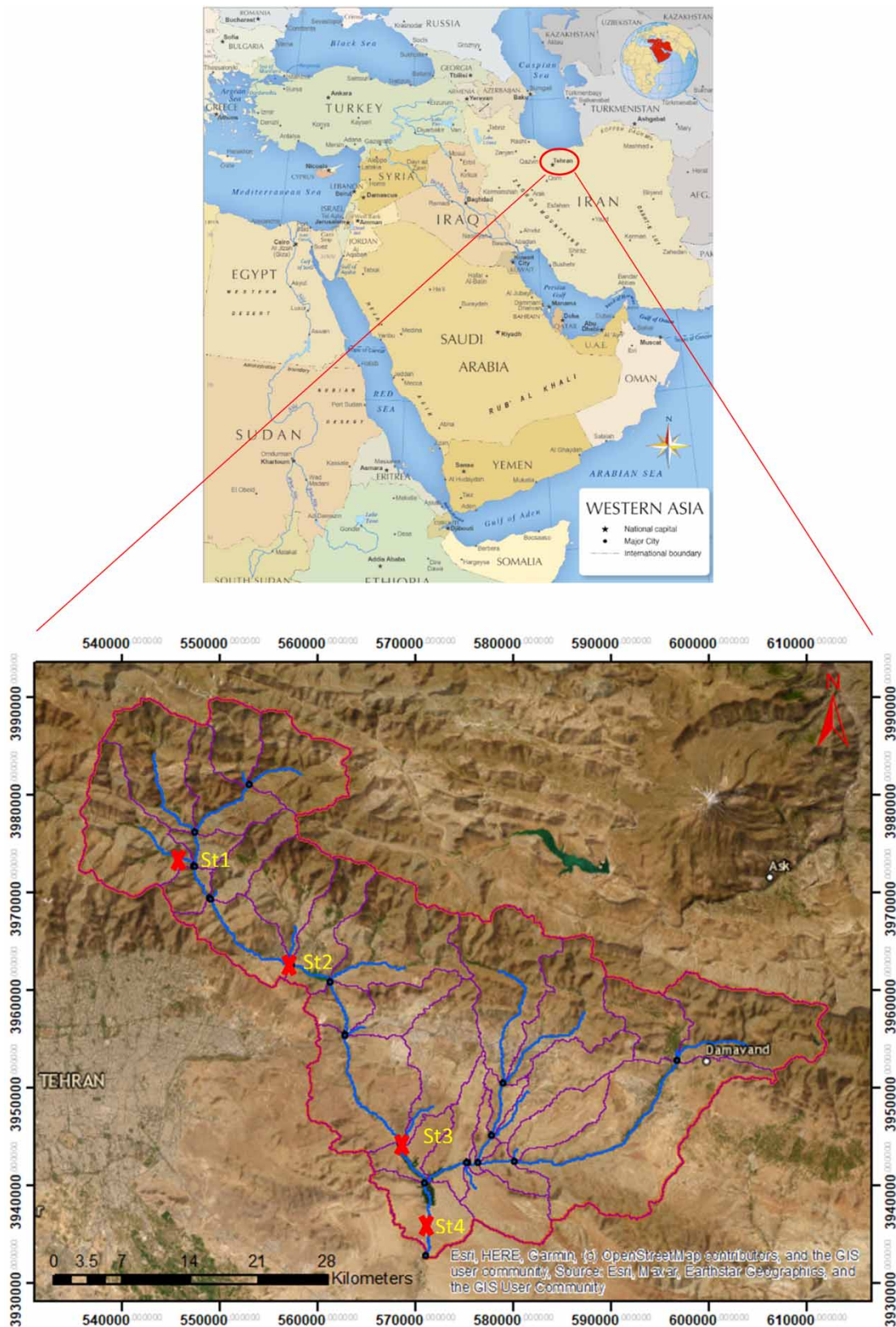
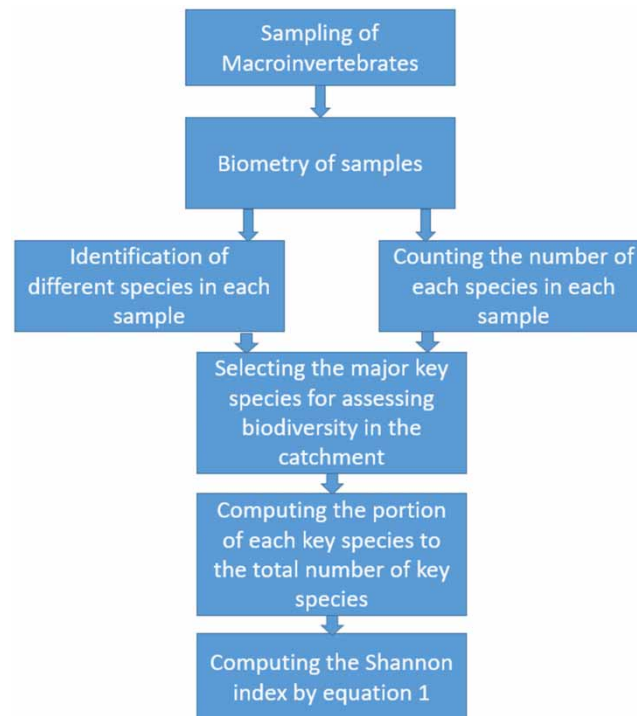


Figure 1 | Location of the study area and stations for studying an environmental flow regime.

Table 1 | Some key characteristics of the Jajrood catchment

Characteristic	Description
Latitude and longitude	558,840.15 m E, 3,963,799.52 m N
Length of the main river reach	Approximately 62 km
Catchment area	1461.7 km ²
Annual rainfall	259 mm
Climate	Warm humid summer, mild winter
Soil type	Varies across the catchment, no main soil type is identifiable
Aquatic species	Different species of fish and macroinvertebrate species as well as riparian plants across the catchment. The <i>Brown trout</i> is one of the known fish species upstream of the catchment. The <i>Elmidae</i> is one of the known macroinvertebrate species in the catchment
Land use/infrastructures	Some residential areas upstream of the catchment as well as natural terrestrial habitats downstream of the catchment. Some agricultural lands and industrial areas, particularly downstream are observable. Some major hydraulic structures such as two dams have been constructed for drinking water supply as well as agricultural water supply through the catchment and outside of the catchment
Ecological challenges	Low water quality in many tributaries of the catchment due to the draining of pollutants by the residential areas as well as industrial areas or fish farms. Reducing available instream water in river network due to water abstraction especially through the constructed reservoirs.

**Figure 2** | The workflow of computing biodiversity index.

Considering the influence of several water quality and physical flow parameters on the biodiversity of aquatic species, it was beneficial to use composite indicators for the development of the biodiversity regression model. Two composite indicators were applied for integrating the impacts of water quality and physical flow parameters on the biodiversity of the macroinvertebrate species.

The first composite index is IRWQI as a combined water quality index, which is mainly used for integrated assessment of water quality proposed by the department of environment in Iran (Ebraheim *et al.* 2020). This index takes into account multiple parameters of water quality that can give a general picture of the water quality conditions by classifying them from very weak to excellent. The defined classes and methodology for computing this index are shown in Figure 3. In this study, the samples from the field studies were used to compute IRWQI, by which water quality variables (listed in Figure 3) had been measured. Each water quality variable has a conversion graph (as shown in the sample in Figure 3) that converts the value of water quality parameter to I . In the next step, IRWQI will be computed for each sample considering equal weight of importance for all variables. We considered the equal weight of importance for all parameters based on initial ecological studies that demonstrated the importance of all parameters. However, this can be changed case by case, which means the weight of importance of each parameter should be defined based on the initial ecological studies of the impact of water quality on the aquatic species. Based on the definition of IRWQI, if the value is more than 70, it indicates excellent water quality. By contrast, an IRWQI less than 15 means the water quality is very low and consequently a considerable threat for the survival of the aquatic species is predictable.

Physical flow features like water quality factors can be effective on the population of aquatic species especially in river habitats. Many previous studies demonstrated the impacts of physical flow factors on the aquatic population as well as the suitability of the river habitat (Naman *et al.* 2020). Hence, we applied another index to include the overall impacts of physical flow features on the biodiversity of macroinvertebrates. Flow velocity to depth (as a composite physical flow index) can be used to investigate the hydraulic effect of the stream on the aquatic life, which has been widely used in the previous studies (Wang *et al.* 2023). By calculating these indices in all the samples taken, a complete database was provided to develop a regression model of biodiversity assessment in which the two described indices and the SI were inputs and the output, respectively. Finally, a correlation between the physical and water quality characteristics of the stream and the biodiversity index of the invertebrates was developed based on using the multiple linear regression model (MLR). Two indices (Equations (2) and (3)) were applied to evaluate the performance of the model compared with the observations. The Nash–Sutcliffe efficiency (NSE) is a known index proposed in hydrological and environmental studies for evaluating the models (Knoben *et al.* 2019). Moreover, the root mean square error (RMSE) is broadly used in many previous studies to evaluate the model in terms of mean error. Two other indices including the Scatter Index (STI) and Mean Absolute Error (MAE) were used as well to assess the accuracy of the biodiversity model. In Equations (2)–(5), M is simulated or modeled data and O is the observed

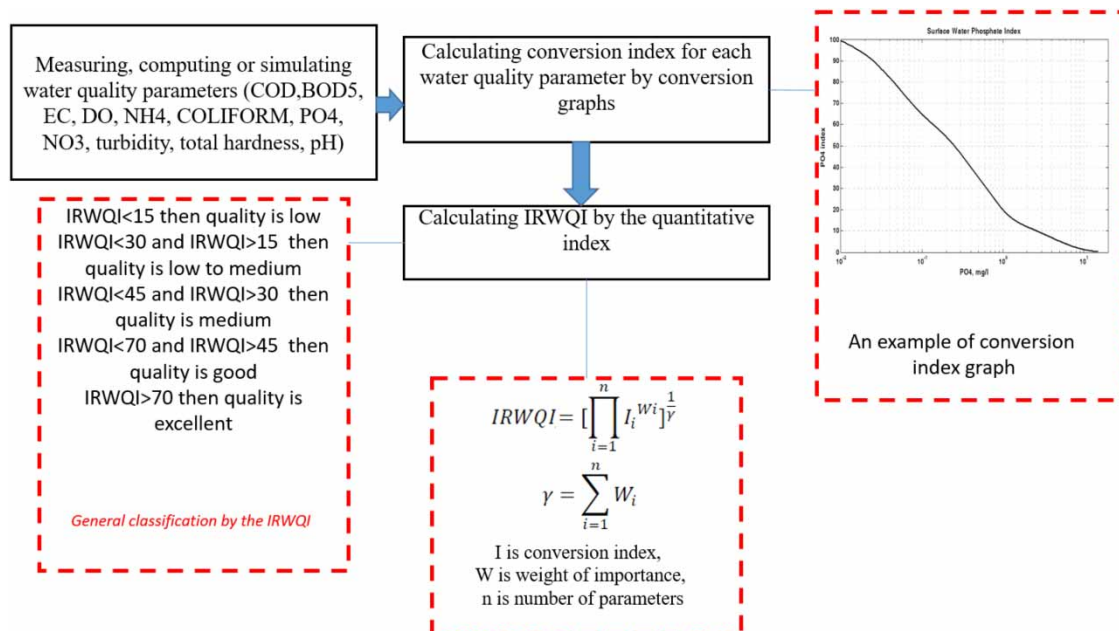


Figure 3 | IRWQI as a combined index for the integrated assessment of water quality.

data. T is the total number of samples.

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

$$RMSE = \sqrt{\frac{\sum_{t=1}^T (M_t - O_t)^2}{T}} \quad (3)$$

$$MAE = \frac{\sum_{t=1}^T |M_t - O_t|}{T} \quad (4)$$

$$STI = \sqrt{\frac{\sum_{t=1}^T [(M_t - M_m) - (O_t - O_m)]^2}{\sum_{t=1}^T (O_t)^2}} \quad (5)$$

Assessing environmental flow impacts on biodiversity

We applied a wide range of environmental flow indices in the case study to assess the environmental flow regimes to investigate how they can address the biodiversity of macroinvertebrates. In other words, the question is whether available known environmental flow methods are able to protect the biodiversity of the macroinvertebrates. Figure 4 shows the workflow of assessing the impacts of environmental flows on the biodiversity index. Furthermore, Table 2 displays the list of environmental flow indices used in this study.

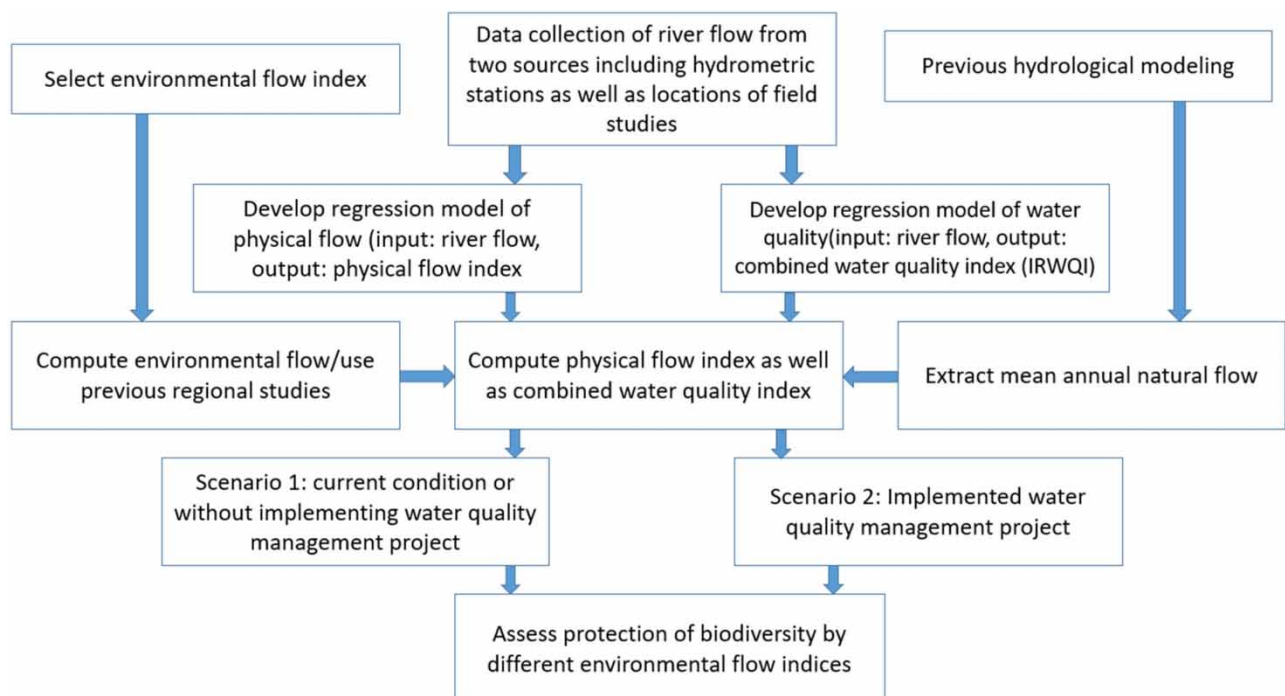


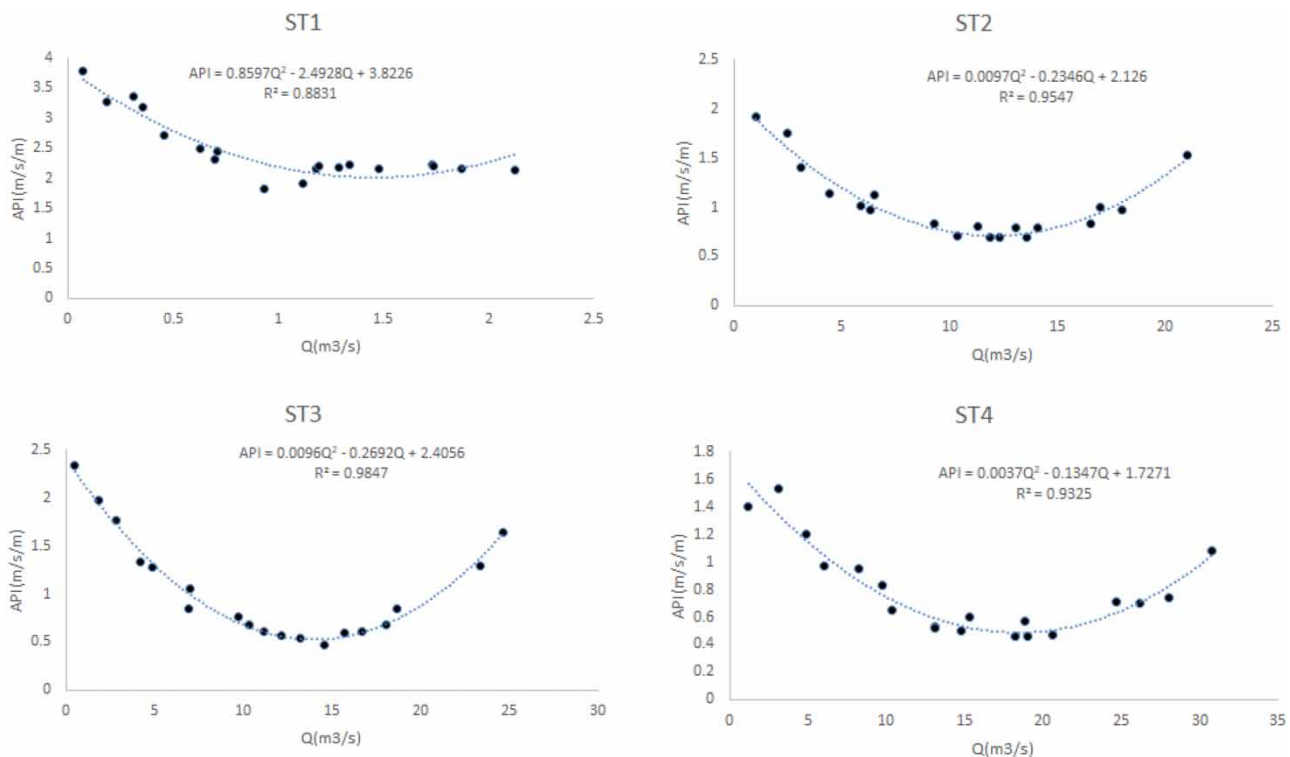
Figure 4 | Workflow of biodiversity assessment in different environmental flow scenarios.

Table 2 | Workflow of biodiversity assessment in different environmental flow scenarios

Environmental flow index	Description
10% of MAF index	This hydrological index is recommended for minimum required protection of aquatic habitats by the Iranian department of environment. More details by Karimi et al. (2012)
40% of MAF index	This hydrological index is recommended for good protection of aquatic habitats by the Iranian department of environment. More details by Karimi et al. (2012)
60% of MAF index	This hydrological index is recommended for outstanding protection of aquatic habitats by the Iranian department of environment. More details by Karimi et al. (2012)
Wetted perimeter index	This index can define minimum environmental flow regime using hydraulic rating method. More details by Sedighkia et al. (2021)
Physical habitat simulation index	This index can define minimum environmental flow regime through physical habitat simulation. More details by Sedighkia et al. (2023)

RESULTS AND DISCUSSION

First, it is necessary to show the results of the developing relationships between the river flow and the combined indicators of physical flow and water quality, as shown in [Figure 5](#). In four stations selected for environmental flow analysis, the relationship between the river flow and the average physical index (API) or average velocity to average depth was developed. According to the regression models in different stations, in low flows, due to the increase in the flow velocity and reduction of the depth, riffle habitats and rapid water habitats are increased, which means the ration of riffle habitats to pool habitats might be imbalanced. Thus, more energy consumption by the aquatic species might be a consequence of increasing rapid water habitats in the river. Meanwhile, the flow velocity decreases due to increasing river flow, which indicates the balance between the riffle and pool habitats. However, in high flows or flood flows, the flow velocity increases more than the depth of

**Figure 5** | Regression models of API in different stations of environmental flow analysis.

the flow, which means a further imbalance in the ratio of riffle to pool habitats can be predicted. In other words, it will be unfavorable for aquatic species, especially in terms of energy consumption.

Based on the collected field data as well as the data collected from the hydrometric stations, it can be concluded that the river flow affects the water quality in the catchment area remarkably. Many factors may affect water quality in a river network. However, one or more factors might have major impacts on the combined water quality indices in the catchments. In our case study, since a significant amount of pollution is continuously drained into the river through industrial units or constructed houses, especially upstream and midstream of the catchment, the changing river flow has a significant effect on the concentration of pollutants, which means other effective parameters such as the air temperature or time can be excluded in the development of regression models. However, it might not be the same in other case studies, which means the multiple regression model might be required in other case studies as well. Therefore, in this case study, it was possible to develop a relationship between the river flow and the composite water quality index, as shown in Figure 6. According to this figure, for all the selected stations in the catchment, the combined water quality index increases significantly with a rising river flow, which demonstrates providing a favorable environmental flow regime in the Jajrood River might reduce risks to the aquatic species and consequently improve important environmental indicators such as the biodiversity index of Benthic species through alleviating water quality challenges.

Based on the field studies, different genus of macroinvertebrates were identified, upstream through downstream of the Jajrood River, as displayed in Table 3. Considering that the aim of this study was to investigate the general impact of environmental flows on the biodiversity index in all considered stations upstream, midstream, and downstream, we selected some species for the development of the biodiversity index, which were mainly observed in all stations. In fact, due to the existence of different environmental zones in the catchment, it is not expected to be able to observe all macroinvertebrates species in all stations. Moreover, we selected those genus that are highly dependent on the water quality as well as physical index of flow in accordance with previous qualitative observations. The observations made in our field studies as well as

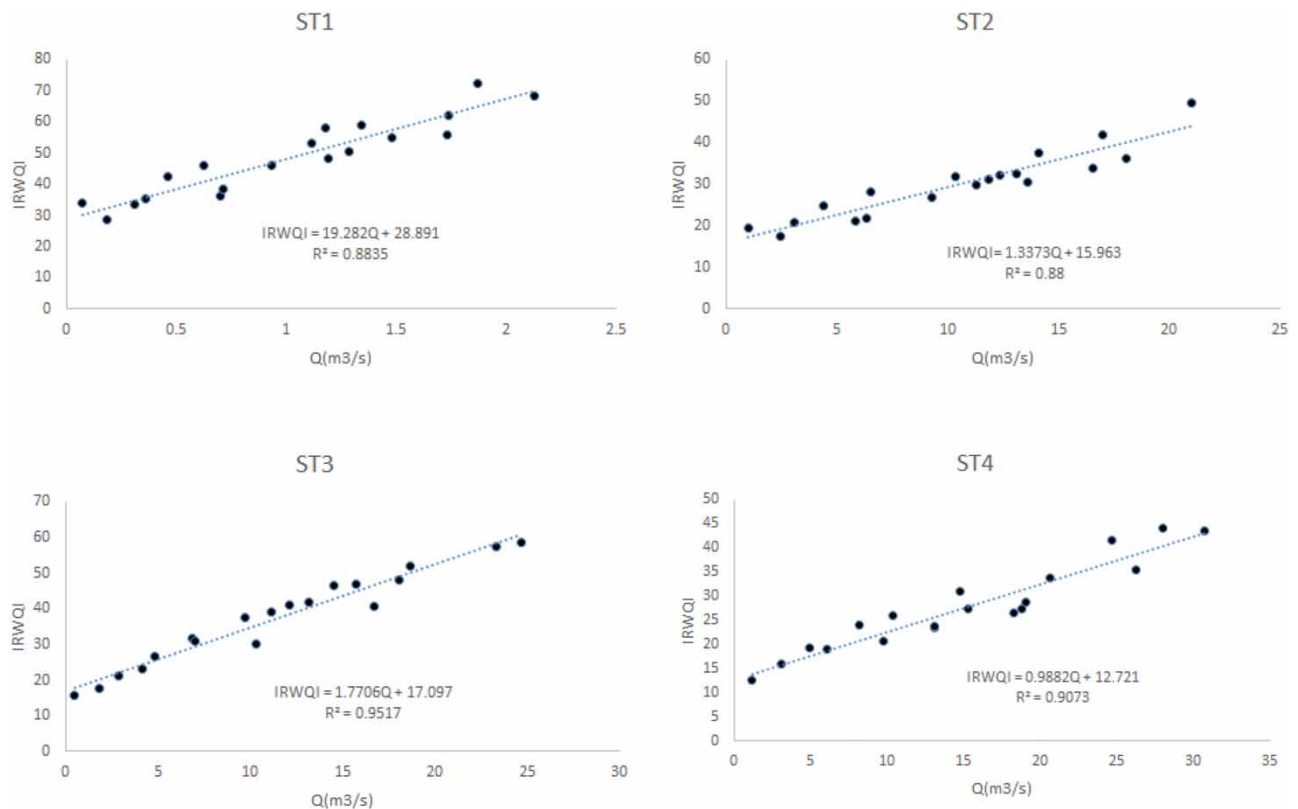


Figure 6 | Regression models of IRWQI in different stations of environmental flow analysis.

Table 3 | Identification of macroinvertebrates in the Jajrood catchment

Order	Family	Genus	Comments
Ephemeroptera	Baetidae	<i>Baetis</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow in the catchment scale
	Heptageniidae	<i>Epeorus</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow in the catchment scale
		<i>Rhithrogena</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow in the catchment scale
	Caenidae	<i>Caenis</i>	Observed in all stations from upstream to downstream and selected for developing the biodiversity index at the catchment scale
Coleoptera	Elmidae	<i>Elmidae</i>	Observed in all stations from upstream to downstream and selected for developing the biodiversity index at the catchment scale
Diptera	Chironomidae	<i>Chironomus</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
	Simuliidae		Observed in all stations from upstream to downstream and selected for developing the biodiversity index at the catchment scale
	Tipulidae	<i>Tipulidae</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
	Psychodidae		Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
	Empididae	<i>Hemerodromiinae</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow in the catchment scale
	Limoniidae	<i>Pesdiciini</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
		<i>Limoniini</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
Oligochaeta	Lumbricidae		Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale
Trichoptera	Hydropsychidae	<i>Hydropsyche</i>	Observed in some stations, which means it is not a good environmental indicator for developing a general biodiversity index for analyzing the impacts of environmental flow at the catchment scale

other long-term observations by the department of environment indicated that three genera, as highlighted in Table 3, in all habitats of the Jajrood River can be observed. Therefore, these three genera were used to develop the biodiversity index and evaluate the impact of the environmental flow on the biodiversity. Figure 7 shows a picture of the genera observed in the river habitats for the development of the biodiversity index in the present study. Moreover, Figure 8 shows the results of assessing the biodiversity index in two samples from the Jajrood River basin for the selected genera. Populations 1–3 are *Elmidae*, *Caenis*, and *Simuliidae*, respectively.

According to the indicators selected to assess the minimum environmental flow regime, Figure 9 displays the minimum environmental flow regime assessed by different indicators including 10–60% of natural MAF, the hydraulic index by the WP method, and physical habitat index (PHI) by physical habitat simulation. Based on this figure, due to the changing geometry of the river habitats as well as river flow in different stations, the various environmental indices do not have the same performance. For example, in some stations, the hydraulic index (WP) provides much more minimum environmental flow compared with other environmental flow indices. While in some other stations, the physical habitat index allocated the

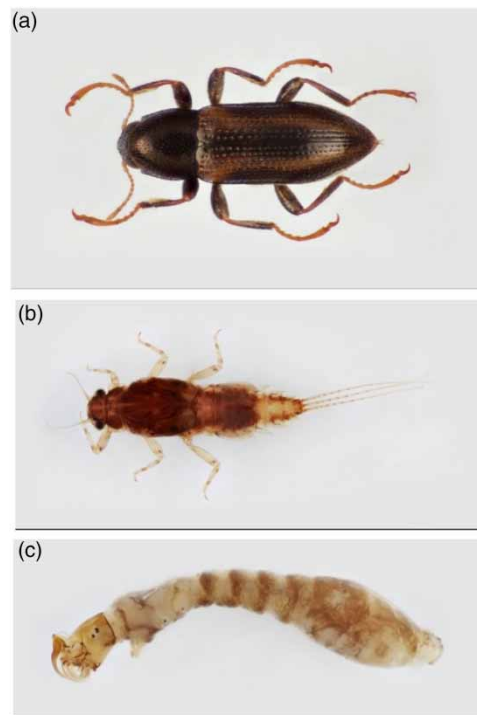


Figure 7 | Selected genera for developing a biodiversity index in the Jajrood River basin ((a) *Elmidae*, (b) *Caenis*, and (c) *Simuliidae*).

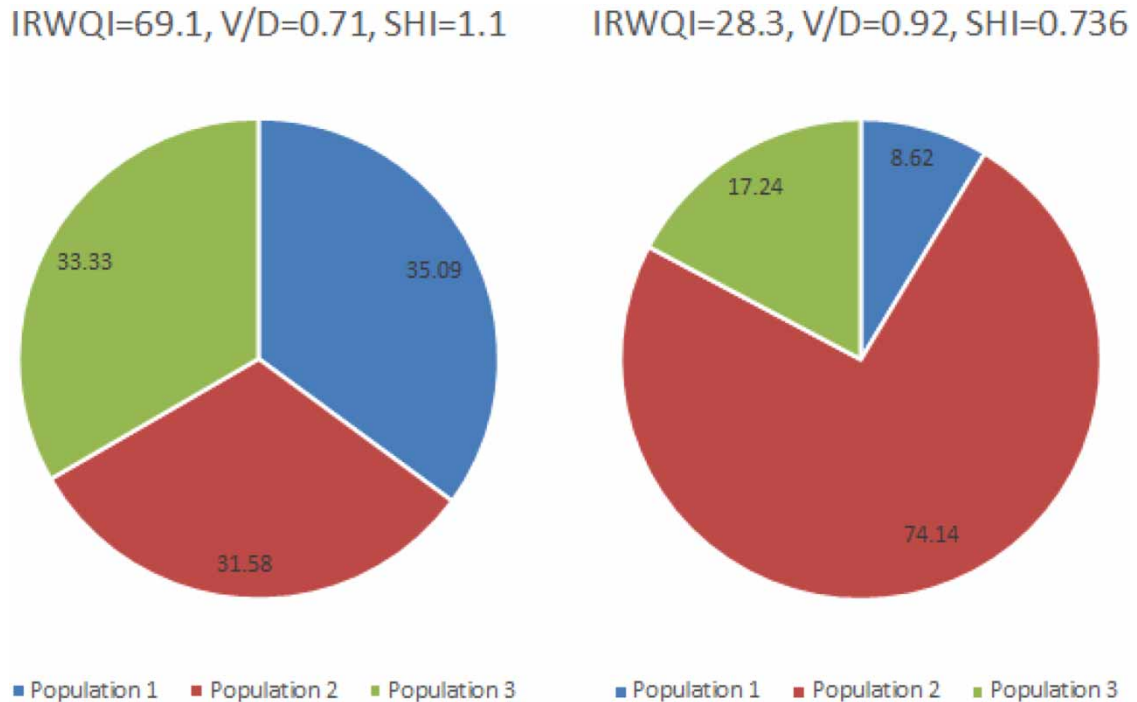


Figure 8 | Biodiversity assessment in two samples from the Jajrood River basin.

highest amount of minimum environmental flow to the river. Furthermore, the hydrological indicators that assess minimum environmental flow using the MAF of the natural flow outperformed in some stations in terms of allocating more water to the environment compared with the hydraulic and physical habitat indices. For example, in ST3, 60% of the MAF provides a

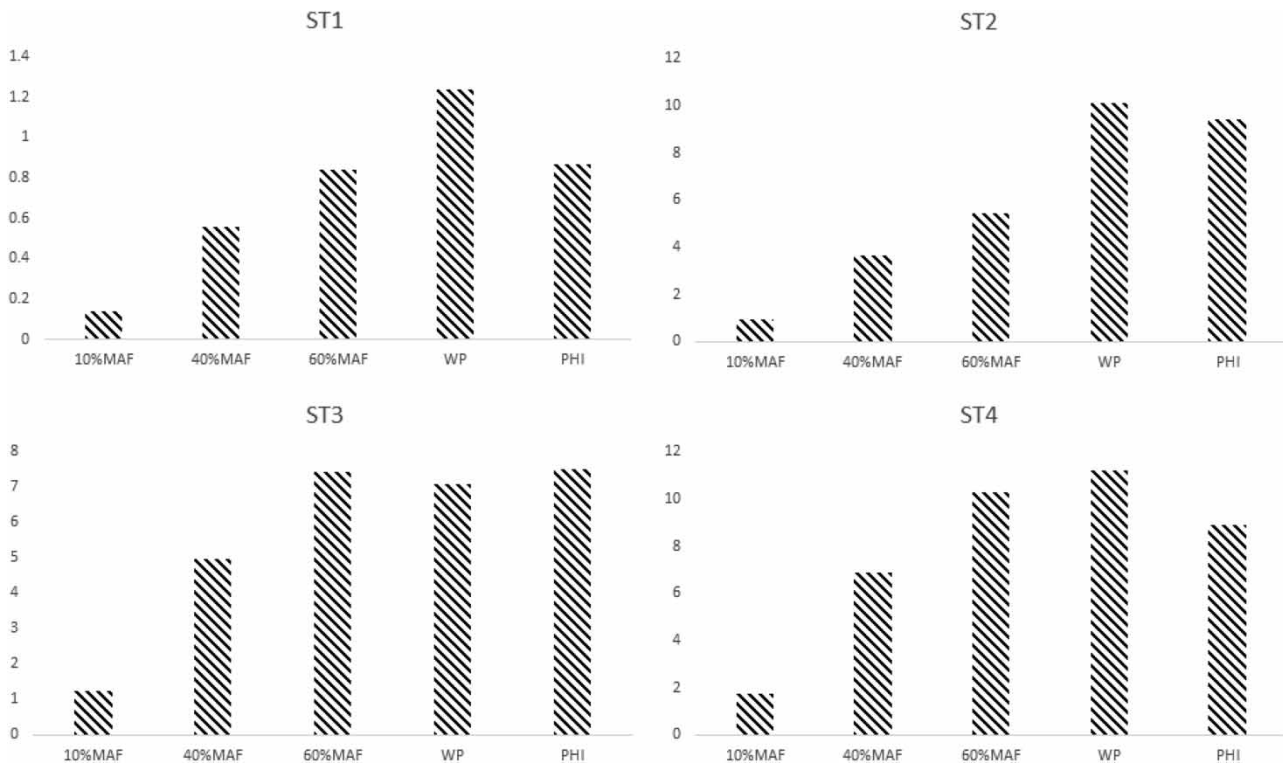


Figure 9 | Minimum environmental flow assessment in different stations.

significant amount of minimum environmental flow in the river compared with other indices. In contrast, 60% of the MAF is allocated much less water to the river ecosystem than wetted perimeter method in ST1.

In the next step, it is necessary to display the results of the biodiversity model. The combined index of water quality as well as physical flow (IRWQI and API) was considered as the input of the model, while the biodiversity index was the output of the model. Based on the extensive field studies, the results of developing this model are shown in Figure 10. The API has changed in the range of 0.4–2, which means a wide range of situations was considered in terms of changing the physical flow characteristics including velocity and depth in the habitats. For example, if the API is in the range of 0.5–0.75, it indicates that there is a proper balance between the different Meso-habitats or ratio of riffle to pool habitats. By contrast, if the API increases significantly, it indicates that there is no balance between the availability of physical habitats in the river. Therefore, it can be claimed that the impact of physical flow index on the biodiversity index of the macroinvertebrates has been investigated within an acceptable range.

Moreover, the range of changes in the water quality index indicates that a wide range of different water quality statuses has been considered in the development of the biodiversity model and consequently the environmental flow analysis. The field studies by the research team in the Jajrood River have been carried out over a long-term period, which means several observations have been made in the dry and wet seasons. Hence, the effect of changing water quality on the biodiversity is investigated meticulously. Based on the observations, due to the increase in the river flow in the wet seasons, biodiversity increases significantly, as has been confirmed by quantitative measurements. By contrast, the combined water quality index decreases significantly in droughts, which can weaken biodiversity. Hence, field observations are satisfactory for developing a reliable model to estimate the biodiversity index in unseen scenarios. Figure 10(c) also shows the results of the observations and the simulation of the SI. It seems that the difference between the observations and the model is not considerable based on observing the data in the graph. However, it is necessary to use evaluation indices as presented in this regard. Based on the two selected indices including NSE and RMSE shown on the graph, the model has an acceptable performance. According to the literature, if the NSE is more than 0.6, the results of the model can be considered acceptable. Furthermore, the RMSE index shows that the average error to simulate the SI is low. Also, MAE is low, which means the

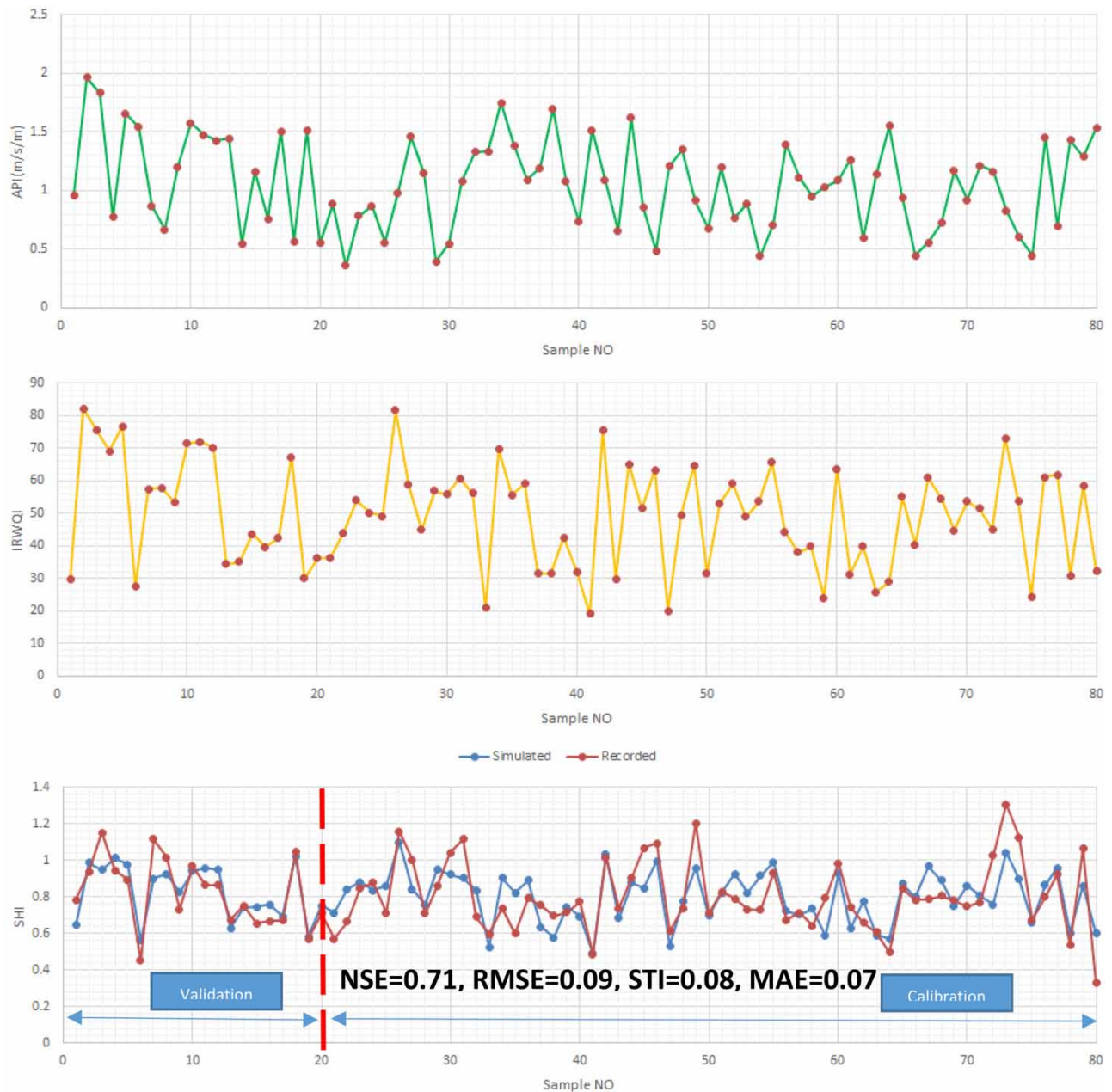


Figure 10 | Results of developing a biodiversity model ((a) API, (b) IRWQI, and (c) SI).

average absolute error is acceptable. According to the literature, an STI range less than 0.2 means the accuracy of the model can be acceptable for further applications (Howard *et al.* 2009). According to the results, STI is 0.08, which means this index corroborates the robustness of the biodiversity model as well. Therefore, it can be claimed that the biodiversity model is reliable for further applications. Equation (4) displays the biodiversity regression model of the case study in which IRWQI as well as API are inputs, while the Shannon index is the output.

$$\text{SHI} = 0.4979 + (-0.1161 \times \text{API}) + (0.008752 \times \text{IRWQI}) \quad (6)$$

Tables 4–7 display the evaluation of the impacts of environmental flows by different indices on the inputs and the output of the biodiversity model. Table 4 provides the API, which indicates this index is different in various stations. For example, the

Table 4 | API in different environmental flow regimes of various stations in the current condition

Type	Index	API			
		ST1	ST2	ST3	ST4
Annual mean of natural flow regime indices	MAF	2.02	0.79	0.54	0.50
	10%MAF	3.49	1.92	2.09	1.51
	40%MAF	2.70	1.40	1.30	0.98
	60%MAF	2.34	1.13	0.93	0.73
	WP	2.05	0.75	0.98	0.68
	PHI	2.30	0.78	0.92	0.82

Table 5 | IRWQI in different environmental flow regimes of various stations in the current condition

Type	Index	IRWQI			
		ST1	ST2	ST3	ST4
Annual mean of natural flow regime	MAF	55.89	28.13	39.11	29.72
Environmental flow indices	10%MAF	31.59	17.18	19.30	14.42
	40%MAF	39.69	20.83	25.90	19.52
	60%MAF	45.09	23.26	30.30	22.92
	WP	52.80	29.47	29.67	23.79
	PHI	45.67	28.53	30.43	21.52

Table 6 | Index in different environmental flow regimes of various stations in the current condition

Type	Index	SI			
		ST1	ST2	ST3	ST4
Annual mean of natural flow regime	MAF	0.75	0.65	0.78	0.70
Environmental flow indices	10%MAF	0.37	0.43	0.42	0.45
	40%MAF	0.53	0.52	0.57	0.56
	60%MAF	0.62	0.57	0.65	0.61
	WP	0.72	0.67	0.64	0.63
	PHI	0.63	0.66	0.66	0.59

Table 7 | Shannon index in different environmental flow regimes of various stations assuming improved water quality

Type	Index	SI			
		ST1	ST2	ST3	ST4
Annual mean of natural flow regime	MAF	0.88	1.02	1.05	1.05
Environmental flow indices	10%MAF	0.71	0.89	0.87	0.94
	40%MAF	0.80	0.95	0.96	1.00
	60%MAF	0.84	0.98	1.00	1.03
	WP	0.87	1.02	1.00	1.03
	PHI	0.84	1.02	1.00	1.02

API in ST1 is higher than in other stations due to being located in mountainous habitats and more inclined compared with other stations. In some environmental flow scenarios, such as one using an index of 10% MAF, the API may increase significantly, which indicates an imbalance between the riffle and pool habitats. By contrast, by applying the PHI, it can be observed

that the API in the natural flow regime and environmental flow regime are very close to each other. The environmental flow regime should be able to minimize the difference in the API between the natural flow and altered flow regimes. In Table 5, the combined water quality index for various environmental flow regimes can be observed derived using the regression model of IRWQI. According to this table, water quality in the natural flow regime is not in a favorable condition due to the draining of significant amounts of pollutants into the river. The results show that by implementing some environmental regimes, the unsuitability of the water quality may be intensified remarkably. For example, in ST2 and ST4, if 10% of the average annual flow is utilized as the minimum environmental flow, the water quality index will be very low. In fact, the stations will be fully unsuitable in terms of water quality for the biological activities of the aquatic species and the danger to the aquatic creatures is a potentiality. In ST1, using the hydraulic rating index (WP) to determine the minimum environmental flow regime has enabled the combined water quality index to be significantly increased compared with some other environmental flow indices. In other words, there is a significant difference between the water quality index by this method and 10% MAF. However, due to the significant volume of pollutants drained into the river in the current condition, the water quality index is not very suitable, which means even the natural flow regime cannot provide highly suitable habitats. Obviously, the water quality index will be weakened moving downstream due to the significant increase in pollutant concentrations.

Table 6 shows the results of assessing the biodiversity index in the current situation (i.e., significant draining of the pollutants to the river ecosystem) for the mean natural flow as well as the use of various environmental flow indices. In ST1, by increasing the environmental flow regime, the difference in the biodiversity index between the natural flow and the environmental flow is not significant, which means appropriate environmental indices such as WP can mitigate the impacts of water abstraction on the biodiversity index of macroinvertebrates. However, the biodiversity index in the natural flow regime is not satisfactory in terms of sustainable environmental status. Based on the long-term evaluations in some limited healthy habitats in the Jajrood River network, if the biological diversity index in the habitats is higher than 1, the balance of population of different species is deemed suitable. Currently, due to the significant pollutants in the river ecosystem of the studied stations, the biodiversity index for all habitats is significantly far from the desired value defined by regional ecologists. The results confirm that using physical habitat simulation can be reliable for assessing environmental flow regimes due to taking into consideration the needs of fish habitat suitability and minimizing the difference between natural flow and environmental flow in terms of the biodiversity index of macroinvertebrates, although utilizing 60% of the MAF can provide favorable conditions as well. In contrast, other hydrological indices such as 10% of the MAF are highly unreliable for providing suitable biodiversity in the river habitats. To sum up, it is better to use methods such as physical habitat simulation as the minimum environmental flow for maximizing protection in the habitats. However, this recommendation is only applicable for the case study because physical habitat simulation is not inherently able to integrate biodiversity modeling for assessing environmental flow regimes.

Table 7 displays the biodiversity indices in which improved water quality index is assumed. In other words, we assumed that the water quality management project is implemented successfully to investigate how it can affect the biodiversity index. In this scenario, IRWQI is equal to 70, or the water quality is fully suitable for biological activities of different aquatic species, considering existing API in each station. In ST1, due to the high slope of the river and consequently high API, even improving the water quality cannot increase the SI by more than 1. In other words, we cannot expect high biodiversity in mountainous habitats of the Jajrood River due to the physical tensions in the flow velocity. Therefore, the biodiversity index is not as high as in other stations. By contrast, the SI is more than 1 in other stations, which means improving the water quality can alleviate environmental challenges remarkably. Three indices including hydraulic rating (WP), physical habitat index, and the 60% MAF can provide sustainable environmental statuses in terms of the biodiversity of macroinvertebrates. Therefore, in general, whether in the state of improvement of water quality conditions or in the state of non-improvement of water quality, using the mentioned environmental flow indices is recommendable. Improving the conditions of the water quality is one of the important requirements before implementing environmental flow.

A full discussion regarding the results and examining the outputs compared with previous works can be useful for understanding the future research direction and key messages from this study. It is also necessary to discuss the strengths and weaknesses of the proposed approach. The results of this study showed that there are serious challenges in assessing environmental flow in river basins due to the lack of profound focus on the environmental processes. Many previous studies emphasized the use of methods such as hydrological indicators or physical habitat simulation, which can be reliable for assessing environmental flows. However, the results of this study highlighted that sustainable biodiversity cannot be guaranteed through these methods. One of the weaknesses of all available methods is no focus on the biodiversity index of the

macroinvertebrates. The biodiversity of invertebrates plays a very important role in river ecosystems because these species are a source of food for many fishes, which means they play an important role in the food web of the entire watershed (more details by [An et al. 2002](#); [Bouchard & Paul 2012](#); [Sundermann et al. 2013](#)). Therefore, determining the environmental flow without taking into account the biodiversity of benthic invertebrates can cause irreparable damage to the environmental sustainability of the watershed. Holistic methods such as BBM can provide better assessment by taking into account many factors. However, the application of these models is practically limited due to their restrictions in the current form. First, a specific modeling framework has not been proposed in these methods for environmental processes such as biodiversity assessment, which causes many uncertainties in the application of this method. Second, considerable field studies are needed, which requires a lot of budget. Thus, using these types of methods is not possible in many cases. Therefore, holistic methods are not reliable to integrate the environmental processes in the current form especially due to the lack of clear environmental modeling. Hence, modifying these methods is recommendable toward integrating environmental processes modeling in the environmental flow assessment.

The previous studies emphasized the weaknesses of some hydrological indices for assessing minimum environmental flow regimes. However, some studies have highlighted that these methods may be useful for evaluating instream flow regime. Therefore, due to the uncertainty of applying these methods, it is necessary to investigate the effects of the assessed flow regime by these methods on the environmental indicators and processes such as biodiversity in the watershed scale. In fact, hydrological or desktop indices do consist of no environmental simulation, which implies uncertainty of these indices might be high. Thus, these methods cannot be generally recommendable for environmental flow assessment though the outputs of our case study demonstrated that 60% MAF can be adequate to supply environmental water requirement. Adding environmental components to the available hydrological indices might reduce the uncertainties, which is recommendable for future studies. According to the present study, ignoring the biodiversity of benthic invertebrates in using the hydrological index can damage the biodiversity significantly. Therefore, there is ample room to add environmental processes to the current hydrological indices of environmental flow assessment.

Another important recommendation is to modify the physical habitat simulation method considering the biodiversity index of macroinvertebrates. The original method of physical habitat simulation only considers the effect of the river flow on the physical habitat suitability for fish, while not considering the biodiversity index of benthic invertebrates, which can ultimately lead to significant damage to fish communities because the main source of nutrition for different fish species is macroinvertebrates. In the case study, Brown trout as one of the endangered fish species is seen as highly dependent on the benthic species as the food source ([Esteve et al. 2018](#)). Reducing food sources causes a significant impact on the fish population. It should be noted that some fish species migrate upstream for reproduction, which raises the requirement for proper food sources due to the biological stresses and energy consumption. We selected the methods of field studies based on requirements of the case study. However, changing field studies methods is required by changing the features of the case study. For example, increasing depth of the river would change the methodology of measuring the physical flow features such as depth and velocity. Furthermore, if the depth of the river is considerable, it might be needed to measure the water quality parameters at different depths of each cross section. The current study demonstrated that the environmental flow should not highlight river habitat suitability only. In fact, it might ignore the destruction of macroinvertebrates' biodiversity due to the lack of biodiversity modelling in the approach. In our case study, it was observed that even the natural flow regime cannot protect the biodiversity values due to the weakened water quality in different stations. Therefore, implementing environmental flow in highly polluted rivers such as our case study is not meaningful for protecting the biodiversity of macroinvertebrates. In other words, it is necessary to focus on the water quality management in the catchment scale before negotiations among stakeholders for water abstraction projects. In the case study, the first practical recommendation is to improve the water quality by diminishing pollutants' concentration, which is possible through reducing the number of point sources and non-point sources of pollutions.

The present study applied two combined indicators of water quality and quantity as the inputs (API and IRWQI) of the biodiversity model. It should be kept in mind that other indicators can also be useful in this regard ([Ebraheim et al. 2020](#)). For example, several composite indices of water quality have been developed in the literature that may alter the performance of the model ([Gad et al. 2020](#)). Hence, it is recommendable to utilize other composite indices in the development of biodiversity models as a future research field. Furthermore, we used the SI as a known biodiversity index that has been used in many previous studies. However, a large number of other indices have been recommended for biodiversity assessment, which can be used as well. Therefore, applying other indicators of biodiversity might be helpful for understanding how changing the

biodiversity index might alter the outputs of environmental flow analysis. Finally, it seems that environmental flow assessment is not deeply linked with environmental processes, which is one of the significant weaknesses in the environmental management of river basins. In fact, environmental flow studies as an interdisciplinary major has not been sufficiently considered through analyzing environmental indices such as biodiversity index. There is a need for extensive studies for integrating environmental processes in environmental flow assessment. For example, using physical habitat simulation to assess the environmental flow is not generally recommendable because it only considers the physical parameters of the flow without highlighting the complex environmental processes, which means it might not protect important environmental indicators such as the biodiversity index of macroinvertebrates. It was able to minimize the difference among biodiversity indices though it might be changed in other case studies. Owing to the effects of climate change on the biodiversity and population growth, future studies should focus on the integration of environmental flow indicators and environmental processes to be able to truly protect the environmental values, such as the biodiversity in the watersheds. The present study demonstrated that some environmental flow indicators might not protect the biodiversity of invertebrates. Therefore, modifying available methods might be required to minimize uncertainties in terms of providing sustainable environmental statuses in the catchments.

CONCLUDING REMARKS

- Environmental flows should be able to protect the biodiversity of the macroinvertebrates due to the importance of these species in the food web of the catchments.
- This study proposed a novel methodology to assess how some known environmental flow indices are able to address the protection of biodiversity.
- Some hydrological indices of environmental flow assessment such as 10% of the MAF are not able to protect the biodiversity even by improving water quality in the case study.
- Due to the weakening of water quality by the draining of water pollutants into the river, even the natural flow regime cannot provide suitable environments in the river habitats for protecting the biodiversity of aquatic species. Hence, improving water quality through water quality management projects is a prerequisite for sustainable water abstraction per the case study.
- Physical habitat simulation and wetted perimeter methods are able to minimize the differences between the biodiversity indexes of the natural flow and environmental flow regimes in the case study. However, it might be changed case by case, which means this is not a general conclusion.
- Integrating biodiversity models with environmental flow assessment is a serious need in future studies of freshwater ecology.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Aguiar, F. C. & Ferreira, M. T. 2002 [Relative influence of environmental variables on macro invertebrates assemblages](#). *Journal of North American Benthological Society* **21** (1), 43–53.
- Ahmadi-Nedushan, B., St-Hilaire, A., Bérubé, M., Robichaud, É., Thiémonge, N. & Bobée, B. 2006 [A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment](#). *River Research and Applications* **22** (5), 503–523.
- An, K. G., Park, S. S. & Shin, J. Y. 2002 [An evaluation of a river health using the index of biological integrity along with relations to chemical and habitat conditions](#). *Environment International* **28**, 411–420.
- Arthington, A. H., Kennen, J. G., Stein, E. D. & Webb, J. A. 2018 [Recent advances in environmental flows science and water management – innovation in the Anthropocene](#). *Freshwater Biology* **63** (8), 1022–1034.
- Bayat, S., Ebrahimi, K., Araghinejad, S. & Mahdi, Y. 2019 [Comparison of the environmental flow assessment methods involving case studies of Karaj and Talar Rivers](#). *Iranian Journal of Watershed Management Science and Engineering* **13** (45), 77–86.

- Bouchard, R. W. & Paul, J. S. 2012 *Guide to Aquatic Invertebrate Families of Mongolia, Identification Manual for Students, Citizen Monitors, and Aquatic Resource Professionals*. Minnesota, USA.
- Chen, Y., Qu, X., Xiong, F., Lu, Y., Wang, L. & Hughes, R. M. 2020 Challenges to saving China's freshwater biodiversity: fishery exploitation and landscape pressures. *Ambio* **49** (4), 926–938.
- Ćosić-Flajsig, G., Vučković, I. & Karleuša, B. 2020 An innovative holistic approach to an E-flow assessment model. *Civil Engineering Journal* **6** (11), 2188–2202.
- Couceiro, S. R. M., Hamada, N., Forsberg, B. R., Pimentel, T. P. & Luz, S. L. B. 2012 A macroinvertebrate multimetric index to evaluate the biological condition of streams in the central Amazon region of Brazil. *Environmental Indicators* **18**, 118–125.
- Ebraheim, G., Zonoozi, M. H. & Saeedi, M. 2020 A comparative study on the performance of NSFQIm and IRWQIsc in water quality assessment of Sefidroud River in northern Iran. *Environmental Monitoring and Assessment* **192** (11), 1–13.
- Esteve, M., Abdoli, A., Hashemzadeh Segherloo, I., Golzarianpour, K. & Ahmadi, A. A. 2018 Observation of male choice in brown trout (*Salmo trutta*) from Lar National Park, Iran. In: *Brown Trout: Biology, Ecology and Management* (Lobón-Cerviá, J. & Sanz, N. eds.). John Wiley & Sons, Hoboken, pp. 165–178.
- Everaert, G., Pauwels, I. S. & Goethals, P. L. M. 2010 Development of data-driven models for the Assessment of macroinvertebrates in rivers in Flanders. In *International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting*, Ottawa, Canada.
- Gad, M., Elsayed, S., Moghanm, F. S., Almarshadi, M. H., Alshammari, A. S., Khedher, K. M., Eid, E. M. & Hussein, H. 2020 Combining water quality indices and multivariate modeling to assess surface water quality in the Northern Nile Delta, Egypt. *Water* **12** (8), 2142.
- Harby, A., Baptist, M., Dunbar, M. J. & Schmutz, S. 2004 State-of-the-art in data sampling, modelling analysis and applications of river habitat modelling. In *COST Action*, Vol. 626, pp. 1–313.
- Howard, K., Zarillo, G., Splitt, M., Lazarus, S., Chiao, S., Santos, P. & Sharp, D. 2009 The impact of atmospheric model resolution on a coupled wind/wave forecast system. In *Preprints, 16th Conf. on Air–Sea Interaction*, Vol. 9. Phoenix, AZ, Amer. Meteor. Soc.
- Ibáñez, C., Caiola, N. & Belmar, O. 2020 Environmental flows in the lower Ebro River and Delta: current status and guidelines for a holistic approach. *Water* **12** (10), 2670.
- Im, D., Choi, S. U. & Choi, B. 2018 Physical habitat simulation for a fish community using the ANFIS method. *Environmental Informatics* **43**, 73–83.
- Jones, G. J., Hillman, T. J., Kingsford, R., McMahon, T., Walker, K. F., Arthington, A. H., Whittington, J. & Cartwright, S. 2023 Independent Report of the Expert Reference Panel on Environmental Flows and Water Quality Requirements for the River Murray System.
- Karimi, S. S., Yasi, M. & Eslamian, S. 2012 Use of hydrological methods for assessment of environmental flow in a river reach. *International Journal of Environmental Science and Technology* **9** (3), 549–558.
- King, J. M., Tharme, R. E. & De Villiers, M. S. 2000 *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*. Water Research Commission, Pretoria, p. 340.
- Knoben, W. J., Freer, J. E. & Woods, R. A. 2019 Inherent benchmark or not? comparing Nash–Sutcliffe and Kling–Gupta efficiency scores. *Hydrology and Earth System Sciences* **23** (10), 4323–4331.
- Książek, L., Woś, A., Florek, J., Wyrebeck, M., Młyński, D. & Wałęga, A. 2019 Combined use of the hydraulic and hydrological methods to calculate the environmental flow: Wisłoka river, Poland: case study. *Environmental Monitoring and Assessment* **191** (4), 1–17.
- Kurqi, A., Pinheiro, A. N., Sordo-Ward, A. & Garrote, L. 2019 Influence of hydrologically based environmental flow methods on flow alteration and energy production in a run-of-river hydropower plant. *Journal of Cleaner Production* **232**, 1028–1042.
- Najafzadeh, M. & Niazmardi, S. 2021 A novel multiple-kernel support vector regression algorithm for estimation of water quality parameters. *Natural Resources Research* **30** (5), 3761–3775.
- Najafzadeh, M., Homaei, F. & Farhadi, H. 2021 Reliability assessment of water quality index based on guidelines of national sanitation foundation in natural streams: integration of remote sensing and data-driven models. *Artificial Intelligence Review* **54** (6), 4619–4651.
- Naman, S. M., Rosenfeld, J. S., Neuswanger, J. R., Enders, E. C., Hayes, J. W., Goodwin, E. O., Jowett, I. G. & Eaton, B. C. 2020 Bioenergetic habitat suitability curves for instream flow modeling: introducing user-friendly software and its potential applications. *Fisheries* **45** (11), 605–613.
- Pal, S. & Talukdar, S. 2020 Modelling seasonal flow regime and environmental flow in Punarbhaba river of India and Bangladesh. *Journal of Cleaner Production* **252**, 119724.
- Palmer, M. & Ruhi, A. 2019 Linkages between flow regime, biota, and ecosystem processes: implications for river restoration. *Science* **365** (6459), eaaw2087.
- Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H. & Kabat, P. 2014 Accounting for environmental flow requirements in global water assessments. *Hydrology and Earth System Sciences* **18** (12), 5041–5059.
- Sedighkia, M., Datta, B. & Abdoli, A. 2021 Design of optimal environmental flow regime at downstream of reservoirs using wetted perimeter-optimization method. *Journal of Hydro-Environment Research* **39**, 1–14.
- Sedighkia, M., Jahanshahloo, M. & Datta, B. 2023 Evaluating minimum environmental flow requirements in rivers: a combined decision-Tree approach integrating hydrological, physical habitat, and water quality indexes. *Journal of Sustainable Water in the Built Environment* **9** (4), 04023006.
- Sundermann, A., Gerhardt, M., Kappes, H. & Haase, P. 2013 Stressor prioritisation in riverine ecosystems: which environmental factors shape benthic invertebrate assemblage metrics? *Environmental Indicators* **27**, 83–96.

- Wang, N., Yang, G., Bao, M., Kattel, G., Li, P., Xi, Y. & Yao, W. 2023 [Evaluating the physical habitat of riffle-pool design in support of river habitat protection and rehabilitation](#). *Ecohydrology* **16** (7), e2579.
- Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q., Yin, Z., Dai, J., Yin, D., Liang, J. & Ye, S. 2019 [Effects of dam construction on biodiversity: a review](#). *Journal of Cleaner Production* **221**, 480–489.

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