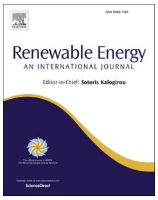
Renewable Energy 218 (2023) 119283

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



# An optimization approach for managing environmental impacts of generating hydropower on fish biodiversity

Mahdi Sedighkia [a,*], Asghar Abdoli [b]

[a] College of Science and Engineering, James Cook University, Townsville, Australia
[b] Eenvironment Science Research Institute, Tehran, Iran

ARTICLE INFO

Keywords:
Fish biodiversity
Ecological management
Hydropower
Reservoir operation
Evolutionary optimization

ABSTRACT

The present study proposes an applicable framework to mitigate the impacts of generating hydropower on the fish biodiversity in the large reservoirs considering water quality and hydraulic factors. Moreover, several data driven models were utilized for simulating effective parameters. Finally, a multivariate linear regression model was used to estimate the fish biodiversity index in which two combined hydraulic and water quality indices were the inputs of the model and the fish biodiversity index was the output of the model. Then, all the simulators were applied in the structure of the hydropower plant operation optimization for different hydrological conditions (i.e. dry years, normal years and wet years) in which two purposes were defined: 1- minimizing the fish biodiversity loss 2- minimizing the loss of generating hydropower. Based on the results in the case study, all the simulators are reliable to model the physical flow, water quality parameters and the fish biodiversity index. The optimization model is able to minimize the impacts on the fish biodiversity properly. The reliability of generating hydropower in the dry years is 30%, while it is 53% in the wet years. High computational complexities might be a limitation for the model.

## 1. Introduction

The ecological impacts of the water resources projects and hydraulic structures on the ecological values of inland waters are highlighted as the serious concern in the literature. Large dams are the most important hydraulic structures, which might have considerable role for supplying need of the communities [1]. Most dams are multipurpose which means generating hydropower and flood control are responsibilities of many dams. Many dams have been constructed around the world. The upstream and downstream environmental impacts of dams are extensively reviewed in the literature (e.g., Ref. [2]. As a brief description, the most critical ecological impacts on the aquatic habitats include weakening the suitability of the habitats for different species and impacts on the biodiversity of the aquatic species.

The concept of environmental flows has been initially defined to sustain the ecological status of the rivers. Many methods have been proposed to assess environmental flow in literature [3]. Some methods such as hydrological and desktop methods do not focus on the aquatic organisms, which means they are not fully reliable to protect river habitats [4]. In contrast, habitat-based methods highlight the organisms in the assessment of environmental flows [5,6]. The known environmental flow methods are not able to highlight the biodiversity values in the river ecosystems. However, the fish biodiversity crisis has been highlighted in many previous studies. For example, problems such as exploitation, pressures on the freshwater ecosystems due water abstraction are the main threats for fish biodiversity in China [7]. Restoration of the habitats with a focus on the fish biodiversity has been recommended to overcome degradation of the fish biodiversity. Moreover, the fish biodiversity crisis has been highlighted in Canada as well [8]. The previous studies pointed out despite of considerable investment on the restoration of the fish biodiversity, the outputs were not successful due to lack of using integrated framework for restoring fish biodiversity [8]. Many previous studies highlighted the negative role of dams on the fish biodiversity due to different and complex ecological impacts on the river ecosystems (e.g. Ref. [9]. Blocking migration routes and habitat fragmentation are the initial factors, which could affect the fish biodiversity in the river ecosystems. However, changing the river flow regime might be one of the most important impacts of the dam in the river ecosystem, which would weaken the fish biodiversity in the river ecosystems. Not only a dam might change the downstream flow regime, but also, it is able to change the water quality parameters such as water temperature at downstream. It should be noted that other humans' activities such as draining pollutants at downstream river

---

* Corresponding author.
E-mail address: mahdi.sedighkia@my.jcu.edu.au (M. Sedighkia).

https://doi.org/10.1016/j.renene.2023.119283
Received 21 May 2022; Received in revised form 30 July 2023; Accepted 7 September 2023

**List of acronyms**

| | |
|---|---|
| BOD5 | Dissolved oxygen needed for the biological degradation |
| COD | *Chemical* oxygen demand |
| EC | Electrical conductivity |
| DO | Dissolved oxygen |
| NH4 | Ammonium |
| PO4 | Phosphorus |
| NO3 | Nitrate |
| pH | A measure of how acidic/basic water is |
| W | Weight of importance |
| ϒ | Exponent |
| IRWQI | Combined water quality index |
| V | Flow velocity |
| D | Depth |
| V/D | ratio of velocity to depth |
| Q | Discharge |
| NSE | *The Nash–Sutcliffe* efficiency |
| O | Observation |
| M | Modelled (simulated) |
| RMSE | Root Mean Square Error |
| PPC | Installed capacity |
| PP | Power production |
| NS | Biodiversity index in natural flow |
| OSI | Biodiversity index in optimal release |
| P1, P2, P3 | Penalty functions |
| S | Storage |
| I | Inflow |
| R | Release from the reservoir |
| F | Overflow |
| E | Evaporation |
| A | Surface area of reservoir |
| MCM | Million Cubic Meters |
| MW | Mega Watt |
| $m^3/s$ | Cubic Meters per Second |

might exacerbate the impact of dam on the fish biodiversity. Due to lack of focus on the fish biodiversity in the environmental flow methods, it is an important research gap that should be highlighted in the studies. In other words, the ecological impacts of the dams should be beyond the assessing environmental flow with the conventional methods. It should be noted that generating hydropower might have considerable impacts on the fish biodiversity due to severe impacts on the river flow and water quality factors.

Due to role of hydropower for energy supply in some regions as clean source energy, previous studies highlighted its undeniable role in future years [10]. However, some studies have pointed out using hydropower without control on the downstream ecological impacts might have destructive effects on the aquatic habitats [11]. Using optimal environmental flow is one of the important recent recommendations for managing environmental impacts of hydropower plants [12]. Hence, it seems that focus on the complex aspects of ecological flow especially in the context of optimal operation for maximizing benefits is a serious need for better ecological management of hydropower plants.

Optimal operation of the reservoirs has been highlighted in many previous studies due to importance of maximizing the benefits of the dam for the communities (e.g. Refs. [13–15]. The optimal generating hydropower was the purpose of the reservoir operation in many previous studies (e.g. Refs. [16,17]. Some recent studies highlighted the possible challenges of the optimal operation of generating hydropower such as impacts of climate change [18,19]. Moreover, it is highlighted that using the evolutionary algorithms is an efficient solution for optimizing the reservoir operation in terms of water supply or electricity supply [20–22]. Many classic and new generation algorithms are available to optimize the reservoir operation such as particle swarm optimization and bat algorithm [23,24].

More population and consequently water demand increase the importance of the dams in water and electricity supply, which means the environmental impacts of the large dams, is a fresh research field which needs more studies to overcome the ecological challenges. Optimal operation of reservoirs has been highlighted from several decades ago due to importance of maximizing the benefits from the reservoir. Many recent studies have still focused on the conventional optimization of the reservoir operation such as hydropower plant operation. However, some studies in recent years added the environmental values to the optimization of the reservoir operation. Two aspects should be noticed in the environmental operation of the reservoirs including 1- developing an appropriate objective function and 2- using a suitable optimization method. The objective function should be developed based on the needs and purposes of the reservoir management. An appropriate loss function consistent with the purposes of the reservoir management might be able to optimize the reservoir operation properly as used in many previous studies. Furthermore, a wide range of optimization methods including simple optimization method such as linear programming and complex methods such as evolutionary optimization methods have been applied in the reservoir operation. Many previous studies highlighted the efficiency and robustness of the evolutionary optimization in the reservoir operation models.

According to the conclusions of the previous studies, adding ecological models to the reservoir operation for mitigating the downstream environmental impacts is a necessity in the current condition. It seems that adding conventional environmental flow models is not able to protect the ecological values due to lack of highlighting complex ecological interactions such as fish biodiversity. Due to this research gap, the present study proposes and evaluates a novel framework for integrating fish biodiversity models and reservoir operation optimization in which the downstream impacts of the reservoir on the fish biodiversity are mitigated, while benefits of the reservoir are maximized. In other words, the main novelty of this study is to develop a novel framework which can integrate the fish biodiversity index with the optimal operation of a hydropower plant to protect downstream ecological values or minimizing ecological impacts of hydropower on the fish biodiversity. Another novelty of this study is to develop a data-driven model for assessing fish biodiversity considering water quality as well as hydraulic parameters of flow through adaptive neuro fuzzy inference system. In fact, this study proposes a novel interdisciplinary framework for ecological operation of hydropower plants considering fish biodiversity. This study might open new windows in the environmental operation of the hydraulic structures in which complex ecological interactions between the abiotic factors and the fish communities could be added to the water resource management directly. The present study improves integration of advanced ecological models and the water resources frameworks. As a clear statement on the objectives of this research work, the following objectives were defined.

1 developing an integrated simulation-optimization framework for minimizing the impacts of changing flow regime by hydropower plants on downstream fish biodiversity
2 Using advanced data driven models for simulating downstream water quality parameters in the structure of the ecological reservoir operation model
3 Integrating water quality as well as water quantity indices for assessing fish biodiversity index which is helpful to understand and simulate the impact of abiotic factors on the fish biodiversity

4 Proposing an optimal release from the reservoir in the case study which is able to minimize losses of the hydropower plant as well as biodiversity ecological impacts

## 2. Application and methodology

### 2.1. Overview on the methodology and case study

Fig. 1 shows the overview of the methodology in which three components could be observed. The extensive field studies in the river habitats are the first step in the developed methodology in which fish sampling and simultaneous measurement of physical and water quality factors were carried out. Then, the outputs of the field studies were applied to develop a data driven model to assess the fish biodiversity, which was used in the structure of the reservoir operation optimization. In the optimization process, balancing the environmental requirements and benefits of the reservoir was the purpose of the model. More details regarding each part will be presented in the next sections.

The proposed simulation-optimization method was applied in the Rajaei reservoir located in the Tajan river basin, Mazandaran province, Iran. Generating hydropower is the main responsibility of the reservoir, which is highly important for satisfying the electricity demand for the near cities and farms. Due to generating hydropower, the downstream flow regime has considerably changed compared with the natural flow. On the one hand, regional water authority is willing to increase the release of the reservoir based on the optimal operation of the hydropower. On the other hand, the regional environmental department is seriously concerned regarding the release of the reservoir due to downstream ecological values. In fact, several fish species are living at downstream river, which need suitable environment for biological activities. Recent field studies by the regional environmental department indicated that fish biodiversity has been weakened compared with the natural flow. In other words, the number of some species has increased, while the population of some other species has remarkably reduced. The current environmental challenges in the study area especially in terms of fish biodiversity have escalated the negotiation between the reservoir managers and environmental advocators. Thus, restoration of the fish biodiversity consistent with the current condition is a requirement for protecting the freshwater ecosystems in this basin. Due to this regional requirement, the present study proposes a mew framework for restoring the fish biodiversity by changing the operation of the hydropower plant. Fig. 2 displays the location of the Rajaei reservoir in the Tajan river basin and land use map of the basin. Moreover, Table 1 shows more details on the installed hydropower plant and the features of the reservoir.

### 2.2. Fish biodiversity modeling

The extensive field studies were carried out in the study area including fish sampling or observation and measuring the abiotic factors in different types of habitats. In fact, initial survey by department of environment had demonstrated that changing abiotic factors including physical parameters of flow and water quality parameters could be highly effective on the fish biodiversity in this basin. Many previous studies highlighted the impact of abiotic factors on the river habitats (e.g. Ref. [25]. Fish sampling or observation was carried out through the electrofishing method in which different types of fishes would be observed indirectly. A limited voltage was used to recover the fish to the habitats. After sampling process in different types of meso-habitats (i.e. riffles, runs and pools), different species were identified by an experienced ecologist and available population of each species was recorded. Moreover, depth and velocity were recorded by the metal ruler and propeller in the sampled habitats. The portable device measured water quality parameters as well or collected samples were measured in the Lab for some parameters. More details regarding the methodology of field studies in the river habitats have been addressed in the literature [26].

Based on measurement of the abiotic factors, two indices including ratio of velocity to depth (V/D) as the physical index and Iran water quality index (IRWQI) as the combined water quality index were computed in each sample. The theory and application of IRWQI have been addressed in the literature. However, Fig. 3 displays more details regarding computation of IRWQI (more details on this index by Ref. [27]. Furthermore, Shannon index (SI) was used to evaluate the fish biodiversity in each sample [28]. Equation (1) shows this index, which is highly useable 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. Finally, 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.

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

Assessing SI in each time step of the reservoir operation needs to develop some models for simulating physical and water quality parameters. Hence, these models were developed based on the data

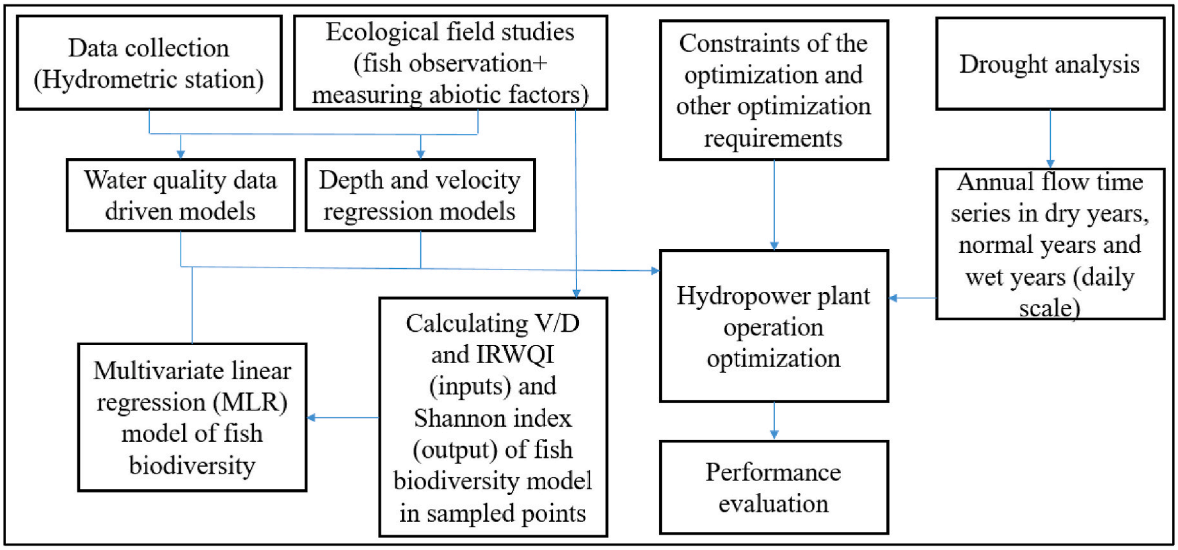


**Fig. 1.** Workflow of the proposed method.

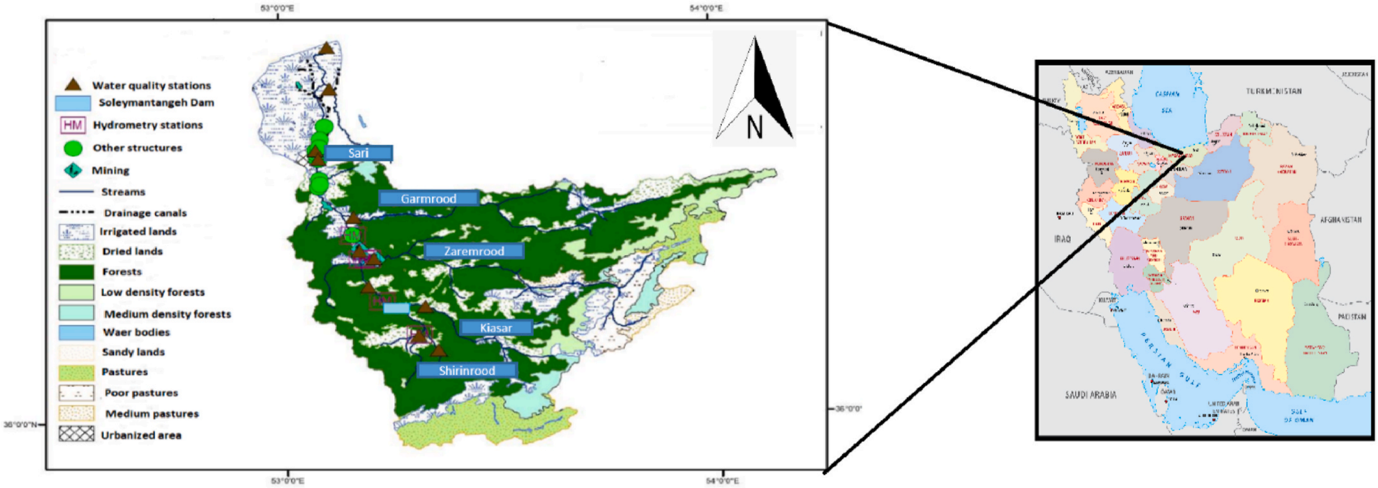


**Fig. 2.** Land use, location of the Rajaei reservoir and river network map of Tajan basin.

**Table 1**
More details on the hydropower plant and reservoir.

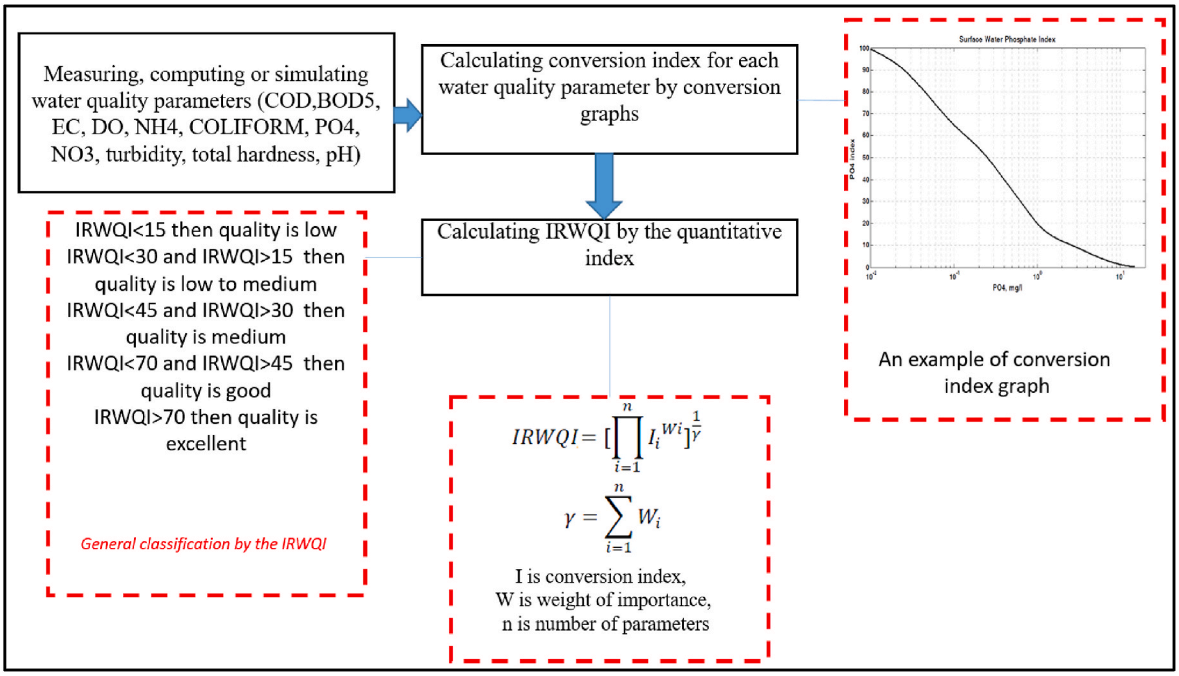
| Minimum discharge of hydropower plant | 3 $m^3/s$ |
|---|---|
| Design discharge | 15 $m^3/s$ |
| Installed capacity | 13.5 MW |
| Capacity of the reservoir | 160 MCM |
| Minimum operational storage | 15 MCM |

collection of the parameters in hydrometric stations and field studies. Two regression models were developed to simulate average depth and velocity at downstream river habitats as displayed in the following equations in which Q is discharge and V and D are velocity and depth respectively.

$$Upstream\ reach\begin{cases} V = -0.00317\left(Q^2\right) + (0.0821Q) + 0.0589 \\ D = -0.00162\left(Q^2\right) + (0.0857Q) + 0.0296 \end{cases} \tag{2}$$

Several previous studies corroborate the applicability and efficiency of neural networks or adaptive neuro fuzzy inference system (ANFIS) as a data driven model to simulate water quality parameters (e.g. Refs. [29,30]. Hence, we applied ANFIS based model to simulate water quality parameters at downstream of the reservoir. More details on the theory and application of ANFIS has been addressed in the literature [31]. However, Fig. 4 displays the simple structure of the ANFIS with two inputs. Moreover, Table 2 shows more details on the data driven models used in the presents study. Two known indices were applied to evaluate the goodness of fit the data driven model including the Nash–Sutcliffe efficiency (NSE) and root mean square error (RMSE) [32]. Equations (3) and (4) display the mathematical form of these indices where O is observed data, M is simulated data and i and m mean the sample number and average of the data respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{I}(M_i - O_i)^2}{\sum_{i=1}^{I}(O_i - O_m)^2} \tag{3}$$


Measuring, computing or simulating water quality parameters (COD,BOD5, EC, DO, NH4, COLIFORM, PO4, NO3, turbidity, total hardness, pH)

Calculating conversion index for each water quality parameter by conversion graphs

Calculating IRWQI by the quantitative index

IRWQI<15 then quality is low
IRWQI<30 and IRWQI>15 then quality is low to medium
IRWQI<45 and IRWQI>30 then quality is medium
IRWQI<70 and IRWQI>45 then quality is good
IRWQI>70 then quality is excellent

*General classification by the IRWQI*

$$IRWQI = \left[\prod_{i=1}^{n} I_i^{W_i}\right]^{\frac{1}{\gamma}}$$

$$\gamma = \sum_{i=1}^{n} W_i$$

I is conversion index,
W is weight of importance,
n is number of parameters

An example of conversion index graph

**Fig. 3.** Workflow of computing IRWQI as the combined water quality index.

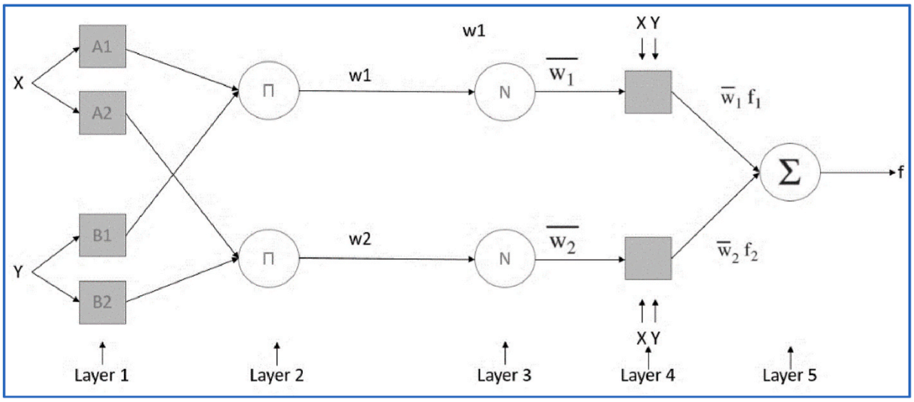


**Fig. 4.** Simple structure of ANFIS based data driven model with two inputs.

**Table 2**
Main characteristics of ANFIS based model for simulating water quality parameters at downstream of the hydropower plant.

| Inputs | Number of MFs (inputs) | Type of MFs (inputs) | Outputs | Number of MFs (Output) | Type of MFs (Output) | Methods |
|---|---|---|---|---|---|---|
| Discharge, distance from the reservoir, air temperature, top width of river | 10 | Gaussian | Water quality parameters as listed in Fig. 3 | 10 | Linear | Clustering method: subtractive<br>Training method: hybrid algorithm |

$$RMSE = \sqrt{\frac{\sum_{i=1}^{I} (M_i - O_i)^2}{I}} \tag{4}$$

Two other indices (equations (5) and (6)) were applied as well to have more accurate comparison between simulated data and observed data including mean squared error (MSE), mean absolute error (MAE) and mean absolute percentage error (MAPE) as follows:

$$MSE = \frac{\sum_{i=1}^{I} (M_i - O_i)^2}{I} \tag{5}$$

$$MAPE = \frac{\sum_{t=1}^{I} |(M_t - O_t)/O_t|}{I} \tag{6}$$

## 2.3. Optimization model

The main component of each optimization model is the objective function, which should be developed, based on the purposes of the optimization process. In the present study, balancing the benefits of generating hydropower and protecting fish biodiversity was the purpose of the optimization. Hence, a new form of objective function was developed to satisfy this requirement in the case study. Equation (7) shows the developed objective function in the present study where the PP is power production, PPC is installed capacity, NSI is biodiversity index in natural flow, OSI is biodiversity index in optimal release and P1 to P3 are penalty functions for inserting the constraints of the storage and minimum discharge of the power plant in the operation model. It should be noted that changing storage level and release are mainly effective on the power production (PP) which means generating power was defined based on changing these parameters in each time step. Other coefficients of the hydropower plant were considered as constant. Based on equations (8)–(10), storage should not be more than capacity (Smax) of the reservoir and less than minimum operational storage (Smin). Moreover, release should not be less than minimum discharge (Qmin). It should be noted that maximum release was not defined due to possibility of needed flow for protecting biodiversity.

$$Minimize(OF) = \sum_{t=1}^{T} \left(\frac{PPC - PP_t}{PPC}\right)^2 + \left(\frac{NSI_t - OSI_t}{NSI_t}\right)^2 + P1_t + P2_t + P3_t \tag{7}$$

$$ifS_i > S_{max} \rightarrow P1 = c1\left(\frac{S_t - S_{max}}{S_{max}}\right)^2 \tag{8}$$

$$ifS_i < S_{min} \rightarrow P2 = c2\left(\frac{S_{min} - S_t}{S_{min}}\right)^2 \tag{9}$$

$$if\ R_t < Qmin \rightarrow P3 = c3\left(\frac{R_t - Qmin}{Qmin}\right)^2 \tag{10}$$

It was needed to update the storage in each time step, which carried out, by equation (11).

$$S_{t+1} = S_t + I_t - R_t - F_t - \left(\frac{E_t \times A_t}{1000}\right), t = 1, 2, \ldots, T \tag{11}$$

where S is storage, I is inflow of the reservoir, E is evaporation from the surface, A is area of the reservoir surface, R is release, and F is overflow calculated by equation (12).

$$\begin{cases} if\left(S_t + I_t - \left(\frac{E_t \times A_t}{1000}\right)\right) \geq S_{max} \rightarrow F_t = S_t + I_t - \left(\frac{E_t \times A_t}{1000}\right) - S_{max} \\ if\left(S_t + I_t - \left(\frac{E_t \times A_t}{1000}\right)\right) < S_{max} \rightarrow F_t = 0 \end{cases} \tag{12}$$

We simulated the operation of the hydropower in different hydrological conditions including dry years, normal years and wet years. The average daily flow time series in these conditions were computed based on stream drought index. More details raging the drought analysis by this method have been addressed in the literature [33]. Hence, we do not present more details in the manuscript. Moreover, three indices were applied in the evaluation of the performance of the optimization model. Reliability index was used to measure the performance in terms for electricity supply as displayed in equation (11). We also applied RMSE and NSE for evaluating the optimization model in terms of protecting fish biodiversity. It should be noted that the purpose of the model is to emulate the fish biodiversity in the natural flow. Thus, the developed equations (14) and (15) were utilized in this regard. It should be noted that biogeography-based optimization as one of the new generation evolutionary algorithms was applied to optimize the release of the reservoir in the present study (More details by Ref. [34].

$$RI = \frac{\sum_{t=1}^{T} PP_t}{PPC * T} \tag{13}$$

$$NSE(opt) = 1 - \frac{\sum_{t=1}^{T} (OSI_t - NSI_t)^2}{\sum_{t=1}^{T} (NSI_t - NSI_m)^2} \tag{14}$$

$$RMSE(opt) = \sqrt{\frac{\sum_{t=1}^{T} (OSI_t - NSI_t)^2}{T}} \tag{15}$$

## 3. Results and discussion

In the first steps, it is essential to report the results of the simulations in the case study. As presented, fish observations in many points (120 points) were carried out throughout the Tajan river basin. It should be noted both natural habitats with the minimum environmental impacts and impacted habitats by humans' activities were considered in the field study, which means the outputs were reliable for developing a robust model to assess the fish biodiversity due to changing abiotic factors. Fig. 5 displays results of some sampled habitats by the electrofishing method and simultaneous measurement of the abiotic factors for calculating V/D and IRWQI. Five fish species who were available in all the samples were taken into account in the fish biodiversity assessment. SP1 to SP5 are Capoerta, Squalius, Luciobarbus, Alburnoides and Carrassius species respectively. It sounds that changing the water quality and physical indices affects the biodiversity considerably. For example, simultaneous reduction of IRWQI and V/D increased the population of the SP4 remarkably which means the fish biodiversity has been weakened. Hence, the field studies corroborate the necessity of fish biodiversity studies due to altering flow regime in the rivers.

Several data driven models were applied to assess water quality and fish biodiversity in the present study. Thus, it is necessary to present the goodness of fit of these models in the results. In other words, it should be presented how the developed models would be reliable to assess the abiotic and fish biodiversity. Fig. 6 shows the training and testing process of DO model as the sample of water quality models. Moreover, Table 3 displays the evaluation indices of all water quality models in which NSE and RMSE of the models are calculated. According to the literature, if NSE is more than 0.5, the developed model might be reliable. The maximum value of NSE is 1 that means the model and the observations are identical. However, developing a perfect model is not possible practically. Based on this threshold, all the water quality models are reliable for using in the further steps. Moreover, RMSEs of all models are low which corroborate the applicability of the data driven model for water quality simulation in the case study. MAPEs and MSEs of all water quality models corroborate the robustness of the models as well. As presented, a multivariate linear model was developed to calculate the fish biodiversity index (SI) in which IRWQI and V/D are inputs and the SI is the output of the model. Fig. 7 displays the inputs and the output of this model in a 3d graph. Based on the measurement indices displayed on the graph, the fish biodiversity model is highly reliable which can confirm the right selection of two physical and water quality indices in the present study.

In the next step, the results of the optimization model should be presented. We simulated the hydropower operation in three different hydrological condition including dry years, normal years and wet years. Hence, the outputs including the generating hydropower, release and the fish biodiversity index in these statuses should be described in this step. Fig. 8 shows the normalized generating hydropower in all the time steps in three simulated conditions. It seems that chaotic changes of hydropower production in the simulations is due to altering the inflow of the reservoirs and available storage in the reservoir. Generally, less generating hydropower in the dry years could be observed. However, it is not identifiable how much it is reduced compared with the normal or

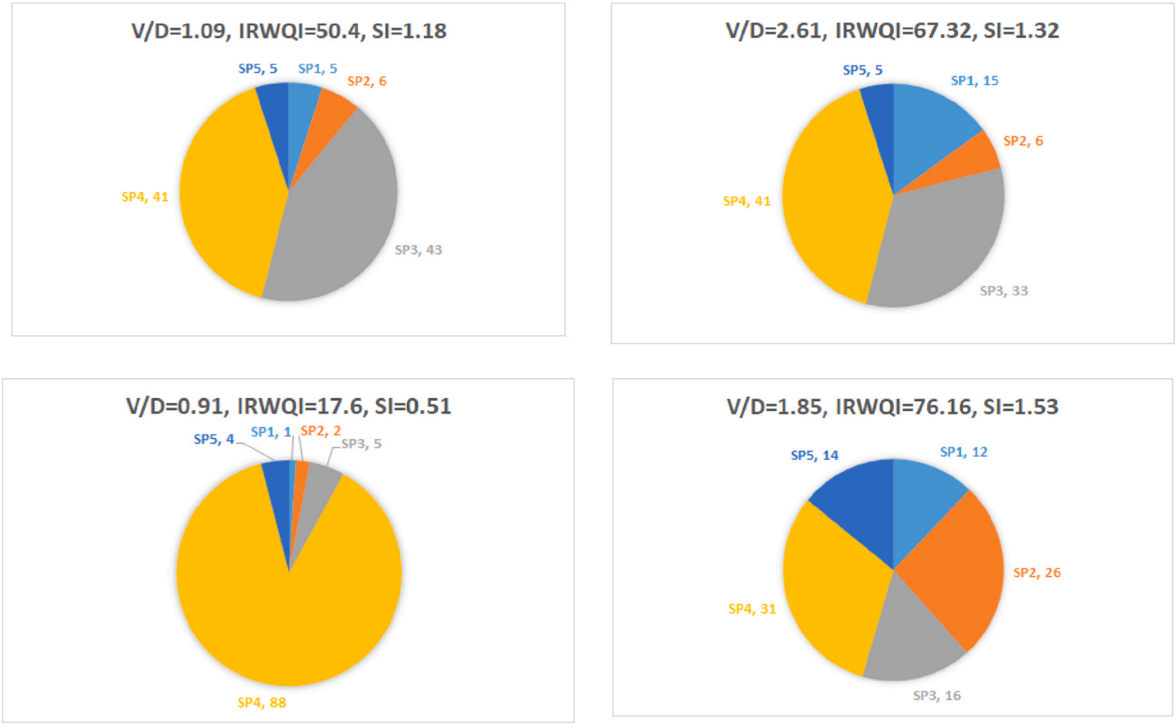


**Fig. 5.** Results of fish biodiversity assessment in for samples of field studies.

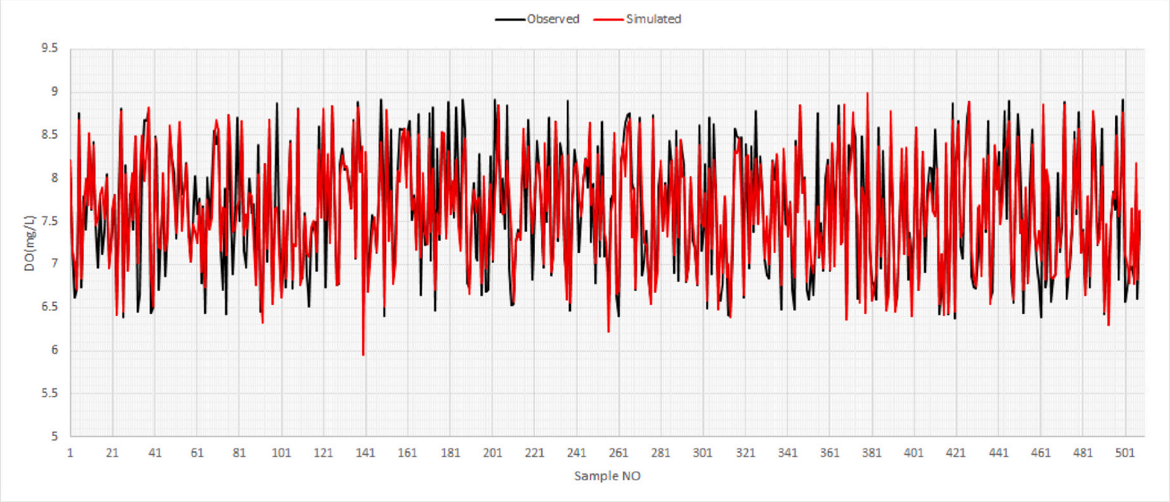


**Fig. 6.** Results of training and testing process of the dissolved oxygen (DO) model as the sample of data driven models.

**Table 3**
Measurement indices of water quality models.

| Model | NSE | MAPE | RMSE | MSE |
|---|---|---|---|---|
| COD | 0.78 | 0.12 | 0.28 | 0.08 |
| BOD5 | 0.76 | 0.13 | 0.29 | 0.08 |
| EC | 0.63 | 0.18 | 47 | 2209.00 |
| DO | 0.81 | 0.09 | 0.32 | 0.10 |
| NH4 | 0.65 | 0.17 | 0.03 | 0.00 |
| COLIFORM | 0.53 | 0.24 | 9.6 | 92.16 |
| PO4 | 0.49 | 0.37 | 0.5 | 0.25 |
| NO3 | 0.73 | 0.14 | 2.1 | 4.41 |
| turbidity | 0.84 | 0.07 | 4.4 | 19.36 |
| total hardness | 0.55 | 0.29 | 15.3 | 234.09 |
| pH | 0.52 | 0.33 | 0.34 | 0.12 |

wet years. Thus, using a measurement index is essential. Table 4 shows all the measurement indices of the optimization system in which reliability index of hydropower production is available. Reliability of generating hydropower in dry years is highly lower than wet years which means electricity supply in the dry years might be challenging. It should be noted that we defined the reliability index of hydropower considering the maximum possible generating hydropower. In fact, based on the recommendations by the regional water authority, the real need of the urban and non-urban area of the case study is much more than the installed capacity of the Rajaei reservoir. Hence, the maximum possible supply of electricity demand by the hydropower was aimed. Thus, defining reliability index of electricity supply considering installed capacity of the plant seems logical in the case study. However, it might be needed to define the reliability index of hydropower using the predefined maximum demand of electricity in other cases. The reliability index of hydropower in dry years, normal and wet years are 30%, 43% and 53% respectively. Low reliability in the dry years demonstrates the considerable challenges of balancing the benefits of the reservoir and environmental requirements. Furthermore, the storage time series in three hydrological statuses are shown in this figure as well. Generally, the available storage of the reservoir in dry years is lower than normal and wet years. However, the storage management in the last days of the simulated period might be challenging in all the hydrological statuses. In other words, the optimization model releases high volume of water which might be a need due to satisfying ecological requirements of the reservoir management. It seems that the role of storage in the environmental management should be considered in the design of the future reservoirs. More discussion will be presented in the next section.

In the next step, the results of the optimization model in terms of fish biodiversity should be explained for investigating how the optimization model is able to balance the benefits of the reservoir and the ecological impacts. Fig. 9 shows the full results of the optimization model in terms of environmental issues including release and biodiversity index in the natural flow and the downstream optimal release. It sounds that the

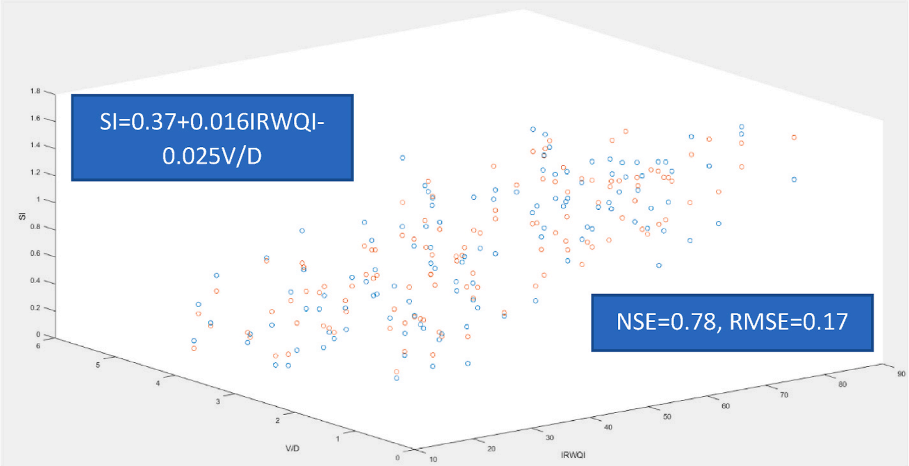


**Fig. 7.** The multivariate linear model of simulating fish biodiversity index in the study area (Blue circles: observations and orange circles: simulations.

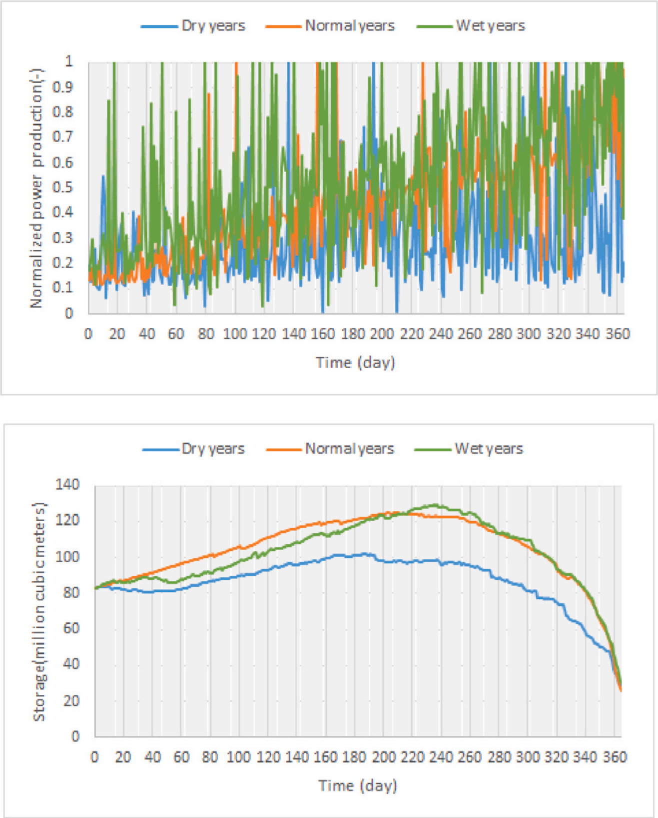


**Fig. 8.** The result of reservoir operation optimization including storage and generating power time series.

**Table 4**
Measurement indices of the optimization system.

| Index | Dry years | Normal years | Wet years |
|---|---|---|---|
| Reliability index of generating power | 30% | 43% | 53% |
| NSE of biodiversity | 0.9 | 0.88 | 0.89 |
| RMSE of biodiversity | 0.1 | 0.11 | 0.13 |

optimization model is able to balance the fish biodiversity in the natural flow and optimal operation of the hydropower plant because the biodiversity index time series in dry years, normal years and wet years are close to the biodiversity time series in the natural flow. Hence, the developed model is efficient in terms of reducing the ecological impacts on the fish biodiversity. However, the accurate assessment of the performance needs to apply measurement index. Based on Table 4, NSE and RMSE of the optimization model in terms of biodiversity assessment are approximately 0.9 and 0.1 in all the hydrological conditions which means the optimization model is highly robust for reducing the ecological impacts in the case study. However, the performance of the optimization model might be changed case by case due to altering the inputs parameters of the reservoir system. The mots interesting result of the optimization model is release of the reservoir because the release is highly different from the natural flow. The optimization model increases the release in many time steps compared with the natural flow, which indicates the complex management of the reservoir to satisfy the ecological requirements of the fish biodiversity. More discussion will be presented in the next section in this regard.

It matters to discuss on the results in the case study for providing technical recommendations to improve management of the reservoir and hydropower plant. Fig. 9 demonstrates that modifying the operation of hydropower plant consistent with the proposed method can mitigate the potential downstream impacts on the fish biodiversity remarkably. In other words, Table 4 indicates that finding an optimal environmental solution is possible as a great news for the environmentalist in the case study. However, Fig. 8 indicates that changing available storage in the simulated period is inevitable which might not be positive in terms of having strategic storage in the reservoir. Moreover, Fig. 8 highlights the challenges of generating hydropower in the dry years which might escalate negotiations between stakeholders.

Importance, mechanism, advantages and shortcomings of the proposed model in terms of technical and computational aspects should be discussed. The results of the presents study demonstrate that not only integrating the ecological impacts in the reservoir operation model is necessary, but also defining the ecological impacts in the structure of optimization model might be challenging. Some previous studies defined the ecological degradations by some non-ecological indices which might be highly deleterious for the aquatic habitats due to lack of a model to integrate the real needs of the environment. For example, most recent studies applied hydrological or desktop methods to assess the ecological impacts in the reservoir operation models which are not able to simulate the environmental requirements of the available organism in the study area. Conversely, some limited studies considered the needs of the aquatic organisms in the model. However, they are not fully reliable for perfect ecological management of the reservoirs because they had considerable simplifications in the ecological assessment of the aquatic habitats. In other words, the previous methods are not able to reflect the ecological complexities of the ecosystem in the water management model. The fish biodiversity is an important criterion to assess the health of the river ecosystems which might need a complex environmental model. The proposed method is highly advantageous regarding applying advanced ecological models in the reservoir management, which is a serious need in the current condition. According to the literature, destruction of biodiversity is a big problem in many freshwater ecosystems due to water supply and draining pollutant to the inland water bodies. It should be noted that these impacts might be exacerbated in the future years due to increasing the population and global warming impacts. Thus, utilizing the proposed method is highly helpful for reducing the destructive effects of generating hydropower in the rivers.

The outputs of applying model in the case study revealed that it is needed to increase release of the reservoir in many time steps compared with the natural flow. This issue should be noticed in terms of two aspects. First, generating hydropower might need higher release compared with natural flow which might be generally reasonable. Secondly, satisfying environmental requirements in terms of fish biodiversity might be changed the needed flow regime compared with the natural flow. At the first glance, it seems that minimizing difference between the optimal release and the natural flow might be enough for having sustainable environmental condition in the downstream aquatic habitats. However, not only a hydropower plant might change the water quantity (i.e., flow regime) at downstream, but also it might alter the water quality at downstream habitats. Many previous studies have discussed on the impacts of hydropower on the water quality parameters at downstream of the reservoirs. Many environmental flow methods such as hydrological methods aim to minimize the difference between instream flow and natural flow. However, the present study indicated that assessing environmental flow at downstream of hydropower plant should be beyond the comparison of natural flow and optimal environmental flow due to complex impacts on the water quality and consequently the biodiversity of the aquatics. It should be noted that the behavior of the model is not linear in different hydrological conditions which means release in dry years, normal years and wet years could not be forecasted without using a biodiversity data driven model in three statuses.

Another technical issue, which is highly important in the ecological reservoir management considering the fish biodiversity, is the available storage in the reservoir. According to the results in the case study, the optimization model released much more water in some time steps which

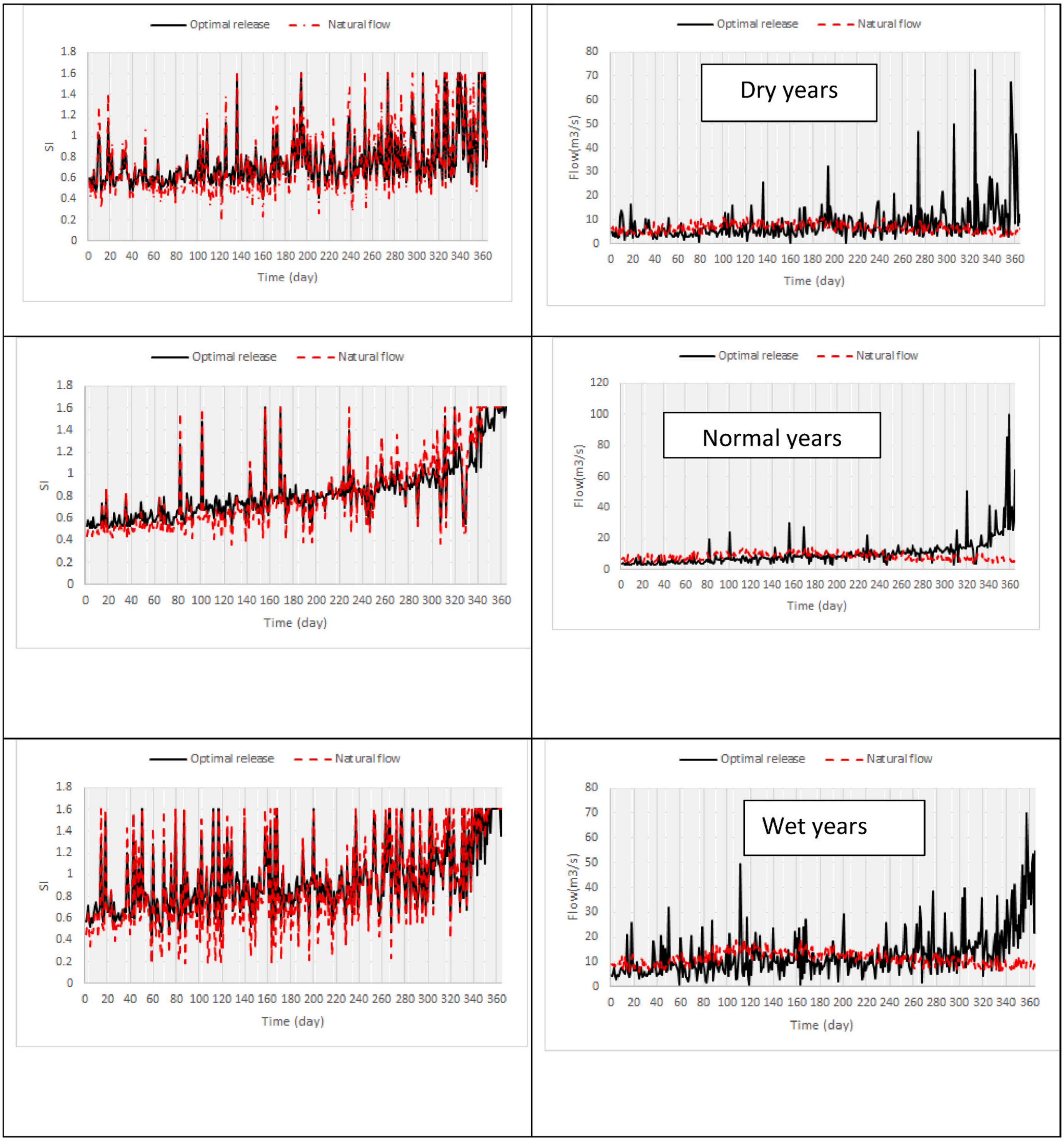


Fig. 9. The result of reservoir operation optimization including SI and release of the reservoir.

reduced the available storage considerably. It is not favorite for the reservoir managers not to have in sufficient storage in the reservoir. For example, managers might define a strategic level of the storage in the reservoir. Hence, mitigating the ecological impacts by the proposed method might be challenging for the reservoir managers in terms of having more storage in different time steps. In fact, the operator should release high amount of water beyond the hydropower plant need in some time steps to mitigate the ecological impacts on the fish biodiversity. Many solutions for overcoming this challenge are not available in the constructed reservoirs. In the single reservoirs, no solution is available which means reducing the storage of the reservoir is inevitable. In contrast, in multi-reservoir systems, utilizing the total available storage by all reservoirs might be a solution for overcoming this problem. In other words, several reservoirs might have contribution for mitigating the ecological impacts in the river ecosystem. However, flexibility in the construction of new reservoirs or modifying the structure of the reservoir is accessible. In other words, it is recommendable to design the new reservoirs or modify the structure of the existing reservoir based on the ecological requirement of the fish biodiversity. It should be noted that an open loop was considered in the reservoir operation of the proposed model. In other words, release was directly optimized in this model. Another solution is to determine the operation rules in the optimization of the reservoir. We recommend utilizing other strategies of the reservoir operation in the future studies in which the fish biodiversity is integrated in the optimization model of the reservoirs.

Adding the impact of climate change matters in the future studies because the climate change might alter all the inputs of the simulation-optimization model. The climate change might alter the total flow of the river and the air temperature, which might be effective on the simulation and optimization models. In other words, changing precipitation and consequently river flow might change the reservoir management plan as well as the fish biodiversity in the natural flow. Moreover, changing the air temperature might alter the water quality parameters due to impact of water temperature on the simulation of the water quality factors. Furthermore, it is recommendable to add the population and development considerations in some cases in which the highest electricity demand might be changed due to the regional development.

Main findings of this study should be analysed in the context of the broader scientific literature by addressing limitations of the study and conflict with other published works. This study corroborated the results of previous studies on downstream ecological flow management of hydropower plants regarding critical ecological impacts of hydropower plants on the downstream habitats [35]. Some previous studies addressed the environmental flow in the context of optimal operation of hydropower plants (e.g, Refs. [11,12]. However, a serious drawback in these studies was lack of addressing the fish biodiversity as an important ecological index which will not be generally considered in the environmental flow assessment. This study covers this shortcoming by proposing a novel simulation-optimization framework for minimizing downstream ecological impacts on the fish biodiversity. We applied Shannon index as a known biodiversity index. However, other biodiversity indices have been proposed in the literature which can be used in future studies for extending the proposed framework (more details on biodiversity indices by Ref. [36]. Some key technical limitations of the proposed method should be noted. First, we only used one biodiversity index which might not be able to reflect all aspects of fish biodiversity. As recommended, using other indices will be helpful for covering this limitation. Furthermore, it is recommendable to combine previous frameworks of optimal environmental flow with the proposed framework for covering unseen ecological impacts. Another limitation of the proposed method is inability to consider cascade of the reservoirs which might make the system much more complex.

Apart from the technical aspects of the model, computational aspects matter to apply the model effectively. The computational complexities are key criteria for assessing the applicability of the model practically. As a brief description on this term, it is defined as the required time and memory for convergence of the optimization model. Clearly, the managers and experts are not willing to use a complex reservoir operation model in which much time and memory might be needed to find the best solution. Covering a long-term period and huge number simulations might be needed in the practical management of the reservoirs. The proposed model has some advantages and disadvantages in this regard. Utilizing a regression model to assess the depth and velocity at downstream of the reservoir as well as multivariate linear model of the fish biodiversity index reduced the computational complexities. However, applying the ANFIS based model to simulate water quality remarkably increased the complexities of the model. Hence, the developed model is averagely a complex model due to applying several ANFIS based water quality models, which might be a drawback of the framework. Brainstorm on diminishing the computational complexities in the future studies might be a great help for increasing the applicability of the proposed method.

Discussing on optimization algorithm is required as well. The proposed optimization model is a multipurpose model, which means two objectives were simultaneously considered in the model including generating hydropower and fish biodiversity. At the first glance, using a multi-objective optimization algorithm might seem logical which is used in many multi-objective optimization problems. However, we applied a single objective optimization in the present study due to some advantages compared with the multi-objective algorithms. As discussed, the computational complexities are a real hindrance for applying the simulation-optimization in practice. The multi-objective algorithms are inherently more complex than single objective algorithms which means they need more time and memory to find the best solution. In the proposed model, several ANFIS based model was implemented in the structure of the model which increased the computational complexities. Thus, using a multi-objective optimization algorithm is not recommendable due to augmenting needed time and memory in the optimization process. The results of the case study indicated that a single objective algorithm is able to balance the benefits and environmental requirements of the hydropower production.

## 4. Conclusions

The present study developed a novel simulation-optimization model for minimizing the impacts of generating hydropower by the reservoirs on the downstream fish biodiversity considering water quality as well as water quantity indices. Several data driven models were applied to simulate water quantity and quality indices as well as the fish biodiversity index in the structure of the reservoir operation optimization. Results showed robust performance of water quality models due to having NSE more than 0.5 in all the models. Moreover, optimization model successfully modified release from the reservoir to minimize difference between biodiversity index in the natural flow and optimal release. Reliability index of generating hydropower in the dry years is 30% which means protecting ecological values reduces hydropower production considerably. Computational complexities might be one of the limitations of the proposed framework. Moreover, it is recommendable to use other biodiversity indices in future research works.

## Availability of data and materials

Some or all data and materials that support the findings of this study are available from the corresponding author upon reasonable request. However, it is not free of charge.

## CRediT authorship contribution statement

**Mahdi Sedighkia:** Conceptualization, Methodology, Software, Writing – original draft. **Asghar Abdoli:** Field studies, reviewing research work, Data curation, collection.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: There is no conflict of interests.

## References

[1] A. Afshar, M. Shafii, O.B. Haddad, Optimizing multi-reservoir operation rules: an improved HBMO approach, J. Hydroinf. 13 (1) (2011) 121–139.
[2] M. Heydari, F. Othman, M. Noori, A review of the environmental impact of large dams in Iran, International Journal of Advancements Civil Structural and Environmental Engineering, IJACSE 1 (1) (2013) 4.
[3] A.H. Arthington, J.G. Kennen, E.D. Stein, J.A. Webb, Recent advances in environmental flows science and water management—innovation in the Anthropocene, Freshw. Biol. 63 (8) (2018) 1022–1034.
[4] M. Sedighkia, S.A. Ayyoubzadeh, M. Haji Esmaeili, Habitat simulation technique as a powerful tool for instream flow needs assessment and river ecosystem management, Environmental Energy and Economic Research 1 (2) (2017) 171–182.

[5] M. Noack, M. Schneider, S. Wieprecht, The Habitat Modelling System CASiMiR: A Multivariate Fuzzy-Approach and its Applications, in: Ecohydraulics: an Integrated Approach, 2013, pp. 75–91.
[6] S.F. Railsback, Why it is time to put PHABSIM out to pasture, Fisheries 41 (12) (2016) 720–725.
[7] Y. Chen, X. Qu, F. Xiong, Y. Lu, L. Wang, R.M. Hughes, Challenges to saving China's freshwater biodiversity: fishery exploitation and landscape pressures, Ambio 49 (4) (2020) 926–938.
[8] J.C. Ray, J. Grimm, A. Olive, The biodiversity crisis in Canada: failures and challenges of federal and sub-national strategic and legal frameworks, FACETS 6 (1) (2021) 1044–1068.
[9] H. Wu, J. Chen, J. Xu, G. Zeng, L. Sang, Q. Liu, Z. Yin, J. Dai, D. Yin, J. Liang, S. Ye, Effects of dam construction on biodiversity: a review, J. Clean. Prod. 221 (2019) 480–489.
[10] X.Z. Li, Z.J. Chen, X.C. Fan, Z.J. Cheng, Hydropower development situation and prospects in China, Renew. Sustain. Energy Rev. 82 (2018) 232–239.
[11] S. Sichilalu, F. Wamalwa, E.T. Akinlabi, Optimal control of wind-hydrokinetic pumpback hydropower plant constrained with ecological water flows, Renew. Energy 138 (2019) 54–69.
[12] N. Suwal, X. Huang, A. Kuriqi, Y. Chen, K.P. Pandey, K.P. Bhattarai, Optimisation of cascade reservoir operation considering environmental flows for different environmental management classes, Renew. Energy 158 (2020) 453–464.
[13] A. Afshar, O.B. Haddad, M.A. Mariño, B.J. Adams, Honey-bee mating optimization (HBMO) algorithm for optimal reservoir operation, J. Franklin Inst. 344 (5) (2007) 452–462.
[14] S.M. Choong, A. El-Shafie, State-of-the-art for modelling reservoir inflows and management optimization, Water Resour. Manag. 29 (4) (2015) 1267–1282.
[15] J.W. Labadie, Optimal operation of multireservoir systems: state-of-the-art review, J. Water Resour. Plann. Manag. 130 (2) (2004) 93–111.
[16] R. Afzali, S.J. Mousavi, A. Ghaheri, Reliability-based simulation-optimization model for multireservoir hydropower systems operations: khersan experience, J. Water Resour. Plann. Manag. 134 (1) (2008) 24–33.
[17] R. Arunkumar, V. Jothiprakash, Optimal reservoir operation for hydropower generation using non-linear programming model, J. Inst. Eng.: Series A 93 (2) (2012) 111–120.
[18] M. Jahandideh-Tehrani, O.B. Haddad, H.A. Loáiciga, Hydropower reservoir management under climate change: the Karoon reservoir system, Water Resour. Manag. 29 (3) (2015) 749–770.
[19] J. Chang, X. Wang, Y. Li, Y. Wang, H. Zhang, Hydropower plant operation rules optimization response to climate change, Energy 160 (2018) 886–897.
[20] M. Ehteram, H. Karami, S.F. Mousavi, S. Farzin, A.B. Celeste, A.E. Shafie, Reservoir operation by a new evolutionary algorithm: kidney algorithm, Water Resour. Manag. 32 (14) (2018) 4681–4706.
[21] O.B. Haddad, A. Afshar, M.A. Mariño, Design-operation of multi-hydropower reservoirs: HBMO approach, Water Resour. Manag. 22 (12) (2008) 1709–1722.
[22] Z.M. Yaseen, M.F. Allawi, H. Karami, M. Ehteram, S. Farzin, A.N. Ahmed, S. B. Koting, N.S. Mohd, W.Z.B. Jaafar, H.A. Afan, A. El-Shafie, A hybrid bat–swarm algorithm for optimizing dam and reservoir operation, Neural Comput. Appl. 31 (12) (2019) 8807–8821.
[23] X.S. Yang, A.H. Gandomi, Bat Algorithm: a Novel Approach for Global Engineering Optimization, Engineering computations, 2012.
[24] R. Eberhart, J. Kennedy, Particle swarm optimization, in: Proceedings of the IEEE International Conference on Neural Networks, vol. 4, 1995, November, pp. 1942–1948 (Citeseer).
[25] Q. Quan, S. Gao, Y. Shang, B. Wang, Assessment of the sustainability of Gymnocypris eckloni habitat under river damming in the source region of the Yellow River, Sci. Total Environ. 778 (2021), 146312.
[26] C.J. Macnaughton, S. Harvey-Lavoie, C. Senay, G. Lanthier, G. Bourque, P. Legendre, D. Boisclair, A comparison of electrofishing and visual surveying methods for estimating fish community structure in temperate rivers, River Res. Appl. 31 (8) (2015) 1040–1051.
[27] G. Ebraheim, M.H. Zonoozi, M. Saeedi, A comparative study on the performance of NSFWQIm and IRWQIsc in water quality assessment of Sefidroud River in northern Iran, Environ. Monit. Assess. 192 (11) (2020) 1–13.
[28] J.H. Hu, W.P. Tsai, S.T. Cheng, F.J. Chang, Explore the relationship between fish community and environmental factors by machine learning techniques, Environ. Res. 184 (2020), 109262.
[29] S. Palani, S.Y. Liong, P. Tkalich, An ANN application for water quality forecasting, Mar. Pollut. Bull. 56 (9) (2008) 1586–1597.
[30] A. Azad, H. Karami, S. Farzin, A. Saeedian, H. Kashi, F. Sayyahi, Prediction of water quality parameters using ANFIS optimized by intelligence algorithms (case study: gorganrood River), KSCE J. Civ. Eng. 22 (7) (2018) 2206–2213.
[31] J.S. Jang, ANFIS: adaptive-network-based fuzzy inference system, IEEE transactions on systems, man, and cybernetics 23 (3) (1993) 665–685.
[32] W.J. Knoben, J.E. Freer, R.A. Woods, Inherent benchmark or not? Comparing nash–sutcliffe and kling–gupta efficiency scores, Hydrol. Earth Syst. Sci. 23 (10) (2019) 4323–4331.
[33] H. Akbari, G. Rakhshandehroo, A.H. Sharifloo, E. Ostadzadeh, Drought Analysis Based on Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) in Chenar Rahdar River Basin, Southern Iran. Southern Iran, American Society of Civil Engineers, 2015, pp. 11–22.
[34] D. Simon, Biogeography-based optimization, IEEE Trans. Evol. Comput. 12 (6) (2008) 702–713.
[35] J. Petrie, P. Diplas, M. Gutierrez, S. Nam, Characterizing the mean flow field in rivers for resource and environmental impact assessments of hydrokinetic energy generation sites, Renew. Energy 69 (2014) 393–401.
[36] P. Fedor, M. Zvaríková, Biodiversity indices, Encycl. Ecol 2 (2019) 337–346.