AQUA
Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 71 No 2, 229 doi: 10.2166/aqua.2022.104

Linking ecohydraulic simulation and optimization system for mitigating economic and environmental losses of reservoirs

Mahdi Sedighkia[a,*], Bithin Datta[a] and Zeynab Fathi[b]
[a] College of Science and Engineering, James Cook University, Townsville, QLD, Australia
[b] University of Kurdistan, Sanandaj, Iran
*Corresponding author. E-mail: mahdi.sedighkia@my.jcu.edu.au

ABSTRACT

Balancing the benefits and environmental degradations of the reservoirs is a challenging issue in the reservoir management. The present study proposes and evaluates an integrated framework to optimize reservoir operation in which hydropower loss and economic loss of irrigation supply are minimized while ecological degradations at downstream river are alleviated. The ecohydraulic simulation was utilized in the structure of the reservoir operation optimization. Reservoir operation losses and environmental degradations were minimized in three hydrological conditions including dry years, normal years and wet years. Moreover, the cropping pattern optimization was applied to mitigate the economic loss of irrigation supply as the main responsibility of the reservoir in the study area. Particle swarm optimization was applied in the reservoir operation optimization. Based on the results in the case study, reliability indices of hydropower production and farmers' revenue are 15–25 and 30–60%, respectively. Moreover, the physical habitat loss is considerably reduced in all hydrologic conditions by proposing optimal environmental flow. The proposed method is able to provide a fair balance between downstream environmental degradations and economic benefits of the reservoir including farmers' revenue and hydropower production. Low computational complexities are the most important strength point for the developed model.

Key words: cropping pattern, ecohydraulic simulation, hydropower, particle swarm optimization, reservoir operation

HIGHLIGHTS

- A novel optimization method for reservoir operation.
- Linking ecological impacts and energy and food production in an integrated model.
- Ecohydraulic simulation was carried out by fuzzy approach.
- Cropping pattern model was applied to maximize net revenue.

NOMENCLATURE

Symbol	Meaning
A	surface area of the reservoir
CO	cost of the cultivation for the crop
D	water demand
E	generation efficiency
EV	evaporation rate from the reservoir
F	overflow
FE	price of the crop
H	reservoir water level
I	inflow of the reservoir
MaxCA	maximum cultivated area
MinCA	minimum cultivated area
NNWUA	normalized weighted useable area in the natural flow
ONWUA	normalized weighted useable area in the optimal release by the reservoir
PF	plant factor
PP	produced power
RMSE	root mean square error

Q	monthly stream flow
$Q_{\max}$	maximum or design discharge of hydropower plant
$Q_{\min}$	minimum allowed discharge for hydropower plant
R	release from the reservoir for water demand
RE	release from the reservoir to the downstream
S	storage of the reservoir in each time step
SDI	stream drought index
$S_{\max}$	maximum storage or capacity of the reservoir
$S_{\min}$	minimum operational storage of the reservoir
T	time horizon
TR	total release from the reservoir
TW	outlet water level
V	cumulative stream flow
X	area of the cultivated crop
Y	yield of the crop

1. INTRODUCTION

The supply of necessary resources for the successful functioning of the communities is a serious challenge in recent decades due to the increasing population in the developed and developing countries (Asgari *et al.* 2016). Water, energy and food are the essential resources that should be supplied properly. Hence, resources management in the river basins is a key responsibility for the managers. On the one hand, previous studies highlighted the challenges for supplying these essential resources in future decades (Bizikova *et al.* 2013; El Gafy *et al.* 2017). On the other hand, the instream flow of the rivers has been decreased due to increasing water demand (Postel 1998). It seems that we face a complex problem in the management of the water resources in the river basins. The water–energy–food nexus approach is an interdisciplinary approach that has been defined to produce more with fewer resources. The water–energy–food nexus approach in a perfect form integrates planning of the infrastructures to maximize benefits regarding water, food and energy that might contain economic, social and political factors (Zarei *et al.* 2021). The present study focuses on the downstream environmental degradations and economic benefits of irrigation supply and hydropower production in the reservoirs. One of the significant hydraulic structures in the river basins are large dams that might be responsible for supplying water and electrical energy in the basins. As a description on the environmental issues associated with the water–energy–food nexus in the river ecosystems, the main purpose of the food–energy nexus approach is to maximize food and energy production using available water in the river. Hence, reducing the instream flow of the river and changing flow regime of the river that might be remarkably detrimental for the aquatics are the main environmental impacts associated with the food–energy nexus approach in the river ecosystems. Thus, we need an optimal operation for the reservoirs to minimize losses of the food and energy production and environmental impacts simultaneously. The optimal operation of the reservoirs has been highlighted in the literature (Stretch & Adeyemo 2018). The food production revenue has not been considered in many previous studies of the reservoir operation. However, it has rarely been addressed in recent studies. For example, the previous studies investigated the synergistic benefits of water–food–energy nexus in a multiobjective reservoir optimization model (Uen *et al.* 2018).

It is essential to review reservoir operation studies briefly. The initial loss function of the reservoir operation was defined based on the minimizing difference between target and release from the reservoir. Target might be defined as the water demand (Hashimoto *et al.* 1982; Datta & Burges 1984). This basic reservoir operation function has been used in many recent studies (e.g., Ehteram *et al.* 2017). However, this loss function lacks hydropower component in the structure that is a main responsibility for many reservoirs. Some previous studies focused on the maximizing hydropower production in the large-scale hydropower plants in the reservoirs (Taghian & Ahmadianfar 2018; Raso *et al.* 2020; Xu *et al.* 2021). Considering water and energy supply is a requirement to maximize benefits from the large dams. Other factors might be important in the reservoir operation models as well. For example, analysing and simulating stream flow is effective for developing a robust model (more details by Oo *et al.* (2020)). Moreover, analysis of evaporation and effective parameters on the evaporation might be helpful to develop an accurate reservoir operation model (more details regarding evaporation analysis by Obianyo (2019)). Using water stress mitigation models has also been recommended in the river basins that might be helpful for improving the reservoir operation (Tsanov *et al.* 2020).

Another aspect in the reservoir operation is optimization methods that might have a significant impact on the outputs of the optimization system. The linear programming (LP) methods are the simplest method regarding reservoir operation (Reis *et al.* 2005). However, they are not reliable for the reservoir operation due to the non-linear nature of the objective function in the reservoirs (Ahmad *et al.* 2014). Hence, non-linear programming (NLP) and dynamic programming (DP) are highlighted as other options to improve the optimal solutions (e.g., Birhanu *et al.* 2014). Due to the complexities of the objective function, evolutionary algorithms have been recommended in the literature for the reservoir operation optimization (Adeyemo 2011). The classic and new generation algorithms could be used in the optimization of the reservoir operation (classified by Dokeroglu *et al.* (2019)). The classic evolutionary algorithms such as genetic algorithm and particle swarm optimization (PSO) have been utilized for many optimization problems in different branches of engineering (more details by Marini & Walczak (2015) and Mirjalili (2019)). The new generation algorithms such as bat algorithm have been developed to improve the optimal solutions (Yang & He 2013). Generally, metaheuristic algorithms have been classified as the animal and non-animal inspired algorithms in which social behaviour of animals and natural laws might be imitated, respectively (Jahandideh-Tehrani *et al.* 2021). Many algorithms have been utilized in the reservoir operation optimization that demonstrates the applicability and efficiency of the metaheuristic optimization (e.g., Ehteram *et al.* 2018; Yaseen *et al.* 2019). It seems that adding environmental aspects to the optimization system of the reservoir operation is necessary as well. The environmental aspects have rarely been addressed in the literature (e.g., Suwal *et al.* 2020). However, more studies are needed due to complexities in the environmental management.

It should be noted that construction of dams might have significant environmental impacts in the river basins at upstream and downstream. Thus, alleviating environmental impacts and maximizing benefits should be integrated in the optimization system. Changing natural flow regime at downstream of the reservoirs is the main threat for the aquatic habitats. Hence, the concept of environmental flow has been defined to protect aquatic habitats at downstream of the reservoirs. In other words, the environmental flow regime might guarantee the sustainable ecological status in the rivers. It is required to present more details regarding the concept of environmental flow. Water diversion projects reduce the instream flow of the river that means decreasing the instream flow is inevitable due to water demand by the communities. Considerable reduction of available water in the river might terminate the biological activities of the aquatics such as fishes. For example, reproduction or searching for food might need suitable depth and velocity that means water diversion should be carried out considering the environmental impacts to sustain the ecological status of the river ecosystem. The environmental flow is able to protect habitats by proposing instream flow regime that should be available in the river for minimizing environmental impacts of the water diversion.

Different simple and complex methods have been proposed to assess environmental flow (reviewed by Richter *et al.* (2012)). For example, hydrologic desktop methods are the simple and inexpensive methods to assess environmental flow in which ecological values are not highlighted (Sedighkia *et al.* 2017). Thus, they might not be reliable to assess the environmental flow regime. In contrast, holistic methods are considerably expensive that means they are not implementable in many rivers. It sounds that habitat simulation methods might be logical for utilizing in many cases. This method highlights the ecological values in the study area by focusing on the target species. Moreover, it does not need extensive ecological field studies that means costs are not as much as holistic approaches. The habitat simulation approach was developed in the structure of the instream flow incremental methodology (IFIM) in which PHABISM software is used to simulate physical habitats (Stalnaker 1995). IFIM proposed univariate habitat model that has been utilized in many previous studies. Physical habitat simulation is applied as the standalone method to assess environmental flow (Nestler *et al.* 2018). However, this method has been criticized due to inabilities for simulating the interactions between physical parameters including depth, velocity and substrate (Noack *et al.* 2013). Multivariate fuzzy approach is one of the robust methods regarding the simulation of physical habitats in which verbal fuzzy rules are developed (Jorde *et al.* 2020). Two advantages should be noted for using fuzzy approach in the physical habitat simulation. First, it is able to consider interactions between physical factors on the habitat selection by the fishes. Moreover, expert opinions could be utilized in the development of the verbal fuzzy rules that might be a significant advantage. According to the literature, habitat selection is a complex process that means using expert opinions might be helpful for improving the accuracy of the physical habitat simulation. Fuzzy physical habitat simulation has been used as a robust method to assess the environmental flow regime in the rivers (e.g., Sedighkia *et al.* 2021a). Physical habitat simulation is classified as an ecohydraulic simulation method in the literature (Maddock *et al.* 2013).

The reservoirs have a significant role for electricity and water supply in the river basins. On the one hand, stakeholders such as farmers would like to maximize the economic benefits from the reservoir without considering environmental degradations.

On the other hand, environmentalists have serious concerns regarding the downstream environmental degradations due to inappropriate reservoir operation. Recent studies developed models in which ecohydraulic simulation has been used as the ecological impact model to optimize environmental flow (e.g., Sedighkia *et al.* 2021b). However, robust models for optimizing economic benefits of the reservoir such as hydropower production and farmers' revenue are not incorporated in an integrated optimization system. In other words, environmental management of the water resources should be carried out in the structure of the water–energy–food nexus approach that is the main contribution of this study. On the one hand, most of the previous studies developed the reservoir operation model considering water supply or hydropower production without considering advanced ecological models in the structure of the model (Azad *et al.* 2020). On the other hand, some recent studies in which environmental flows are considered, agricultural economic benefits component of the reservoir operation have not been added to the system (e.g., Cai *et al.* 2013). Moreover, when the reservoir responsibility is supply of irrigation demand, it is necessary to add the economic models of the agriculture such as cropping pattern optimization to the optimization system. The proposed method of the present study integrates all these necessary components in one optimization model. In other words, the present study develops a novel optimization framework for the operation of the reservoirs in which economic benefits of irrigation supply and hydropower production is linked with the ecohdyraulic assessment of the environmental flow to minimize reservoir operation losses and ecological impacts at downstream. The main advantage of the proposed method is to minimize negotiations between farmers, reservoir managers and environmentalists in the managing large dams. The proposed method opens new windows regarding environmental sustainability in the reservoir operation. In other words, the proposed method is able to integrate benefits of the reservoir in terms of food and energy and environmental degradations at downstream. The main output of the developed optimization system is to maximize hydropower production and food production revenue by the reservoir while alleviating ecological degradations at downstream river habitats.

2. APPLICATION AND METHODOLOGY

2.1. Overview of the methodology

Due to the complexities of the proposed framework, it might be helpful to have an overview of the methodology that is displayed in Figure 1. As the summary of the methodology, the environmental optimization model of the reservoir operation and cropping pattern optimization are linked to maximize economic benefits of the reservoir including hydropower production and food production revenue. The proposed method converts a conventional reservoir operation optimization to a novel

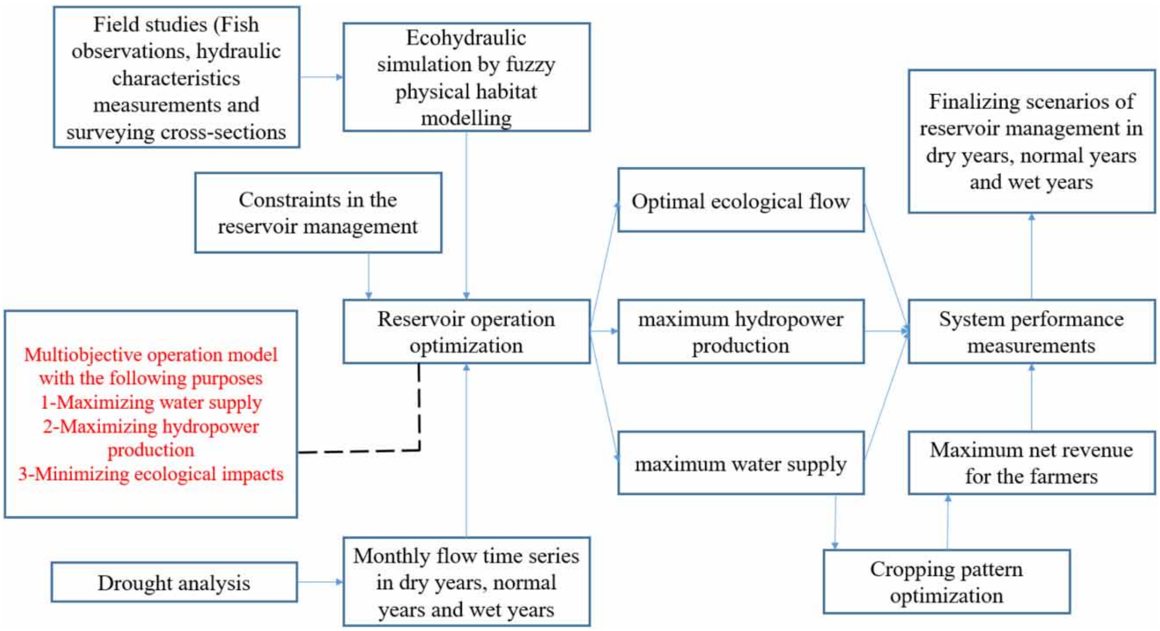

Figure 1 | Workflow of the proposed method.

optimization model of the reservoir operation in which the food production revenue, hydropower production and ecological modelling of the river ecosystem are linked. The design of the study, methodology and data analysis are presented in this section. The study was designed based on an actual project of the reservoir operation in which environmental management needs an integrated optimization system. This system should be able to provide interest of the farmers, electrical energy users and environmental managers simultaneously. The study was carried out by field studies in the river ecosystem, defining a proper objective function and solving the optimization system by the appropriate optimization methods. Different indices were utilized to measure the performance of the optimization model.

Ecohydraulic simulation is one of the requirements in the developed model in which using results of the field studies might be essential. Moreover, drought analysis is carried out to develop monthly flow time series in the dry years, normal years and wet years. Three outputs of the optimization model include optimal ecological flow, maximum hydropower production and maximum food production revenue. The cropping pattern optimization was utilized to maximize food production revenue. Finally, some indices were applied to measure the performance of the optimization system. More details regarding each section of the framework are presented in the next sections.

2.2. Ecohydraulic simulation

We applied the fuzzy physical habitat simulation as the efficient method for ecohydraulic simulation in which three main tasks should be carried out. In the first step, a combination of fish observations and expert opinions were applied to develop verbal fuzzy rules for the habitat suitability of the selected target species in the study area. Then, 1D hydraulic simulation by the HEC-RAS 1D was used to simulate depth and velocity distribution for different flows in the representative reach. Finally, results of the hydraulic simulation and verbal fuzzy rules were combined to compute weighted useable area in different flows. The normalized weighted useable area (NWUA) function was applied as the environmental impact function in the reservoir operation model. Figure 2 displays the workflow of the ecohydraulic simulation in the present study. More details regarding the physical habitat simulation have been addressed in the literature.

It is required to describe the field studies in the case study as well. The field studies include fish observations and hydraulic studies in which fish sampling and measuring hydraulic characteristics might be carried out. Several direct and indirect methods have been proposed for fish sampling in the literature (Harby *et al.* 2004). Each method might have some advantages and disadvantages. We applied the electrofishing method that is a known method for fish sampling. One of the drawbacks of this method might be high voltage that is detrimental for the fishes. However, we reduced the voltage as much as possible for recovering the fishes. As a full description on the on-site survey, the following steps were carried out.

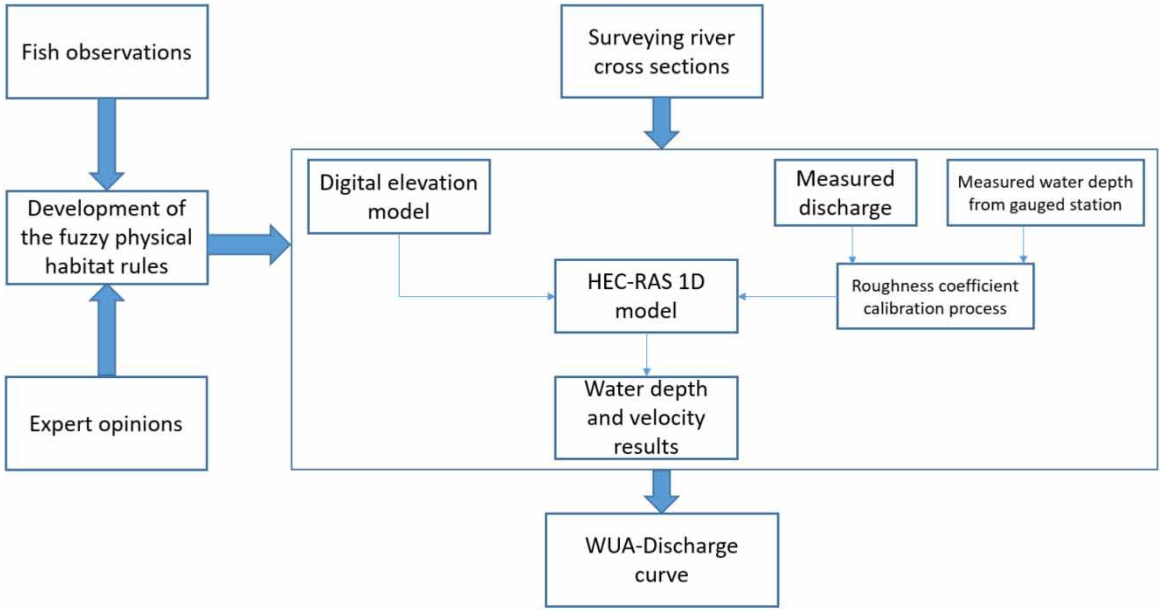

Figure 2 | Flowchart of the physical habitat simulation in the proposed framework.

- The cross-sections were surveyed by the conventional methods in which cross-section profile was plotted that were applied in the 1D hydraulic simulation of the representative river reach to obtain depth and velocity distribution.
- Electrofishing was used in different points of the river reach in which shocked fishes were collected and biometry process was done out of the water for the selected target species.
- Depth was measured by the metal ruler for the habitats in which electrofishing was used.
- Moreover, velocity was measured by the propeller using two-points method (measurement of velocity in 20 and 80% of the depth).
- Substrate (bed particle size) was measured based on the sampling of the bed particles. Mean diameter was determined based on the image processing for the coarser particles and sieve analysis for the finer particles.

Results of biometry were utilized to develop verbal fuzzy rules of physical habitat suitability for the target species considering expert opinions. As a description on the development of the verbal fuzzy rules, an experienced hydroecologist developed fuzzy rules based on previous studies regarding the target species in other rivers. If each rule is compatible with the field observations, it could be used as the final rule. If the rule is not compatible with the field studies, then that rule could be changed based on the observations. As an example, one of the rules was defined as follows. Total number of rules was 27.

'If depth is high, velocity is high, and substrate is low then habitat suitability is low'.

2.3. Drought analysis

Hydrologic condition might remarkably be effective on the water supply and hydropower or food production revenue by the reservoirs. Thus, a smart management of the reservoir should consider hydrological conditions in the scenarios of the reservoir operation. Generally, three hydrological conditions are identified in the river basins including dry years, normal years and wet years. In the present study, we used drought analysis to identify hydrological conditions in a long-term period at the upstream catchment of the reservoir. Then, monthly flow time series were computed in dry years, normal years and wet years as the input of the optimization model. More details regarding the drought analysis are presented as follows.

We utilized the stream drought index (SDI) that is a known index to analyse drought condition in the streams. First, it is necessary to collect data for generating time series of monthly flow. Then cumulative stream flow volume should be calculated as displayed in Equation (1).

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j}, \quad i = 1, 2, \ldots, 12, \; k = 1, 2, 3, 4 \tag{1}$$

where K means the period of drought analysis (3–12 months). In the next step, it is required to utilize Equation (2) for computing SDI.

$$SDI_{i,k} = \frac{v_{i,k} - V_k}{S_K}, \quad i = 1, 2, \ldots, 12, \; k = 1, 2, 3, 4 \tag{2}$$

where V and S are the mean and standard deviation of cumulative stream flow volume, respectively. More details regarding the SDI have been addressed in the literature (Akbari *et al.* 2015). Table 1 displays defined criteria to determine a year as non-drought to extreme drought (Akbari *et al.* 2015).

Table 1 | Criteria for definition of SDI

State	Description	Criterion of SDI
0	Non-drought	=<0.0
1	Mild drought	−1.0 => and <0.0
2	Moderate drought	−1.5 => and <−1.0
3	Severe drought	−2.0 => and <−1.5
4	Extreme drought	<−2.0

We utilized 12 months SDI to determine hydrological status in the river including dry years, normal years and wet years. Then, we considered years with the status of moderate to extreme drought as the dry years, and mild drought as the normal years and other values as the wet years.

2.4. Reservoir operation optimization

The objective function is the main component in each optimization model that should be defined based on the initial purposes of the model. In the present study, three purposes were considered including maximizing irrigation supply, maximizing hydropower production and minimizing ecological degradations at downstream river habitats. Equation (3) displays the novel objective function of the reservoir operation developed in the present study where D_t is maximum water demand, R_t is release for water supply, PP_t is hydropower production. Moreover, PPC is maximum hydropower production based on the capacity of the installed power plant, NNWUA_t is the normalized weighted useable area in the natural flow and ONWUA_t is the normalized weighted useable area in the optimal environmental flow.

$$\mathrm{Minimize(OF)} = \sum_{t=1}^{T} \left(\frac{D_t - R_t}{D_t}\right)^2 + \left(\frac{\mathrm{PP}_t - \mathrm{PPC}}{\mathrm{PPC}}\right)^2 + \left(\frac{\mathrm{NNWUA}_t - \mathrm{ONWUA}_t}{\mathrm{NNWUA}_t}\right)^2 \tag{3}$$

Hydropower production in each time step is computed based on Equation (4). As could be observed, release to the downstream and available head in the reservoir are mainly effective on the hydropower production. In Equation (4), E is the generation efficiency of the reservoir, H_t is the reservoir water level at the upstream of the turbine, TW_t is the outlet water level, PF is the plant factor of the reservoir and RE_t is release to the downstream. It should be noted that if PP_t is greater than PPC as the installed capacity, PPC will be considered as the hydropower production in the time step t.

$$\mathrm{PP}_t = \frac{\mathrm{RE}_t \cdot g \cdot E \cdot (H_t - \mathrm{TW}_t)}{\mathrm{PF} \cdot 1000} \tag{4}$$

Each optimization system might require some constraints in the optimization process. In the reservoir operation problems, constraints of the reservoir management should be considered in the optimization model. Three technical constraints were inserted to the optimization model including release for hydropower production, release for water demand and storage constraints of the reservoir. Using the penalty function method is one of the appropriate methods in the metaheuristic optimization in which a constrained optimization problem could be converted to the unconstrained optimization problem. Some penalty functions should be added to the optimization model that increases the penalty of the system due to violation of the defined constraints. The following penalty functions were added to the optimization system. $Q_{\max}$ and $Q_{\min}$ are maximum and minimum discharge for the power plant based on the initial design. $c1$–$c5$ are constant coefficients that were determined based on the initial sensitivity analysis of the optimization model.

$$\text{if } S_t > S_{\max} \rightarrow P1 = c1\left(\frac{S_t - S_{\max}}{S_{\max}}\right)^2 \tag{5}$$

$$\text{if } S_t < S_{\min} \rightarrow P2 = c2\left(\frac{S_{\min} - S_t}{S_{\min}}\right)^2 \tag{6}$$

$$\text{if } R_t > D_t \rightarrow P3 = c3\left(\frac{R_t - D_t}{D_t}\right)^2 \tag{7}$$

$$\text{if } \mathrm{RE}_t > Q_{\max} \rightarrow P1 = c4\left(\frac{\mathrm{RE}_t - Q_{\max}}{Q_{\max}}\right)^2 \tag{8}$$

$$\text{if } \mathrm{RE}_t < Q_{\min} \rightarrow P1 = c5\left(\frac{Q_{\min} - \mathrm{RE}_t}{Q_{\min}}\right)^2 \tag{9}$$

Storage should be updated in each time step (Monthly time step). Equation (10) carried out this responsibility in the proposed method. Moreover, overflow was computed by Equation (11). It should be noted that we used the PSO in the optimization process of the reservoir operation. More details regarding this evolutionary algorithm have been addressed in the literature. However, Figure 3 displays the flowchart of this algorithm to find the best solution. In Equation (10), TR is total release, S is storage, F is overflow, A is the area of the reservoir and EV is evaporation from the surface of the reservoir.

$$S_{t+1} = S_t + I_t - \mathrm{TR}_t - F_t - \left(\frac{\mathrm{EV}_t \times A_t}{1000}\right), \quad t = 1, 2, \ldots, T \tag{10}$$

$$\begin{cases} \text{if}\left(S_t + I_t - \left(\frac{\mathrm{EV}_t \times A_t}{1000}\right)\right) \geq S_{\max} \rightarrow F_t = S_t + I_t - \left(\frac{\mathrm{EV}_t \times A_t}{1000}\right) - S_{\max} \\ if\left(S_t + I_t - \left(\frac{\mathrm{EV}_t \times A_t}{1000}\right)\right) < S_{\max} \rightarrow F_t = 0 \end{cases} \tag{11}$$

2.5. Cropping pattern optimization

As presented, the reservoir operation model might maximize the water supply at the downstream of the reservoir. However, maximizing water supply might not be able to maximize the food production revenue. In the case study, supplied water is consumed to grow the crops at the downstream farms of the reservoir. Different strategies might be applicable regarding maximizing food production revenue in agriculture. One of the applicable solutions that might be helpful is the cropping pattern optimization. Linear programming is one of the appropriate methods in the cropping pattern optimization. The previous studies demonstrated high efficiency for this approach (Osama *et al.* 2017). It should be noted that linear programming might not be efficient in the water resources problems such as reservoir operation due to the complexities of the function. However, the cropping pattern might not have complex objective function in a simple form. Equations (12) and (13) display the objective function of the cropping pattern optimization and required constraints, respectively. It should be noted that we defined objective function based on maximizing net revenue for the farmers. In other words, maximizing the net revenue is the most favourite scenario for the farmers. Hence, defining the food production revenue optimization based on maximizing

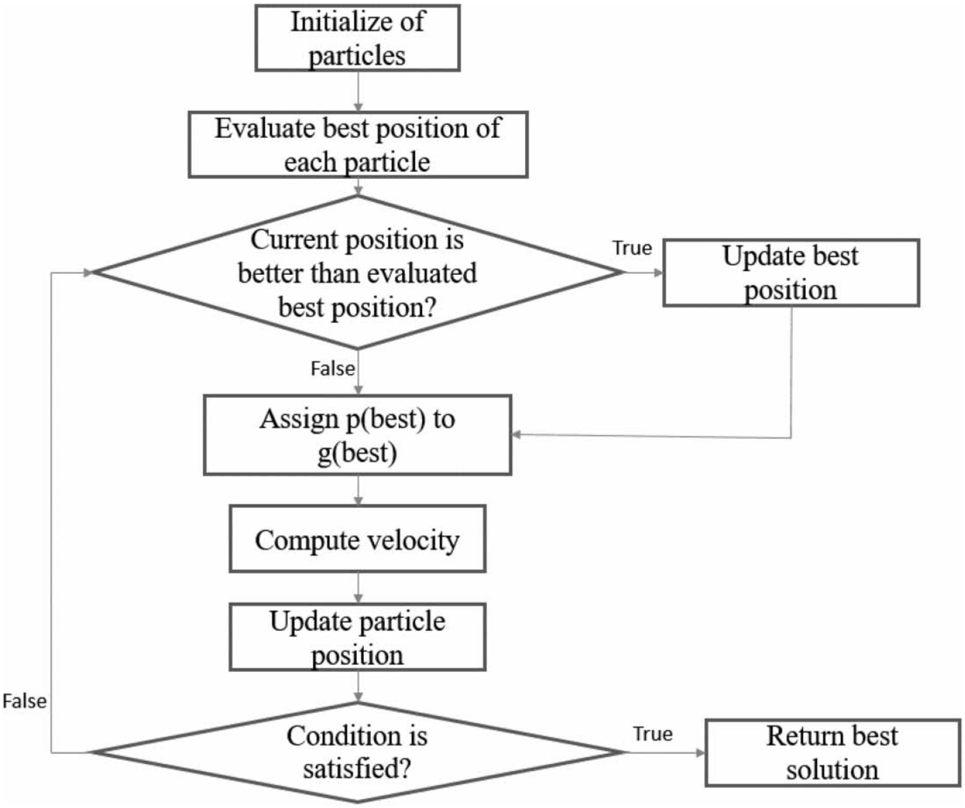

Figure 3 | Particle swarm optimization (PSO) flowchart.

net revenue in the cropping pattern seems logical. In Equation (12), x is the area of the cultivated crop (Ha) as the main variable in the optimization model. Y is the yield of the crop in the study area (kg/Ha), FE is the price of the crop ($) and CO is the cost of the cultivation for the crop ($/Ha) and J is the number of the selected crops. In Equation (13), MinCA is the minimum cultivated area for the crop and MaxCA is the maximum cultivated crop.

$$\text{Maximize (net revenue)} = \sum_{j=1}^{J} (x_j \cdot Y_j \cdot \text{FE}_j) - (x_j \cdot \text{CO}_j) \tag{12}$$

$$\begin{aligned} &\text{Cons1} \rightarrow \text{MinCA}_j \leq x_j \leq \text{MaxCA}_j \\ &\text{Cons2} \rightarrow \text{Sum}(x) \leq \text{Total area} \\ &\text{Cons3} \rightarrow \text{Total irrigation demand} \approx \text{Total available water} \end{aligned} \tag{13}$$

2.6. Measuring the system performance

Each optimization model needs some indices to measure the performance of the system. It is essential to investigate how the optimization system is able to support the defined purposes. These indices should be defined based on the requirements and technical consideration in the case studies. Based on the technical issues in the case study, three indices were considered to measure the performance of the optimization system. Reliability index was utilized to measure the performance of the system in terms of hydropower production. Moreover, RMSE was utilized to measure the robustness of the optimization system in terms of physical habitat loss. It should be noted water is mainly utilized for irrigation in the farms. Hence, measuring the performance of the cropping pattern model was applied for assessing food production revenue. Reliability index was used in this regard as well. The following equations show the defined indices to measure the performance of the optimization system.

$$\text{RMSE}_{\text{Physical habitat loss}} = \sqrt{\frac{\sum_{t=1}^{T} (\text{NNWUA}_t - \text{ONWUA}_t)^2}{T}} \tag{14}$$

$$\text{Relibility index}_{\text{Hydropower}} = \frac{\text{Total hydropower production by the reservoir}}{\text{Total power demand in the study area}} \tag{15}$$

$$\text{Relibility index}_{\text{Net revenue}} = \frac{\text{Net revenue by the optimization model}}{\text{Maximum possible net revunue for the farmers}} \tag{16}$$

2.7. Case study

We implemented the novel optimization system at the Garan dam as one of the reservoirs in the Kurdistan province, Iran. The main economic activity at the downstream of this reservoir is agriculture. This constructed dam is mainly responsible to supply irrigation demand in the study area. Moreover, hydropower plant is installed in the reservoir for hydropower production. Due to the importance and sensitivity of water and energy supply in the study area, regional water authority needs to maximize benefits of the reservoir. In contrast, the department of environment is willing to maximize environmental flow to minimize ecological impacts at the downstream of the reservoir. Based on the initial ecological studies, several native fish species have been identified at downstream river of the reservoir that means protecting river habitats is essential. Figure 4 displays the upstream river basin of the reservoir location of the dam and part of agricultural lands at downstream.

Figure 5 displays price, yield, irrigation demand and the minimum and maximum cultivated area for the selected crop in the study area.

3. RESULTS AND DISCUSSION

Figure 6 displays drought analysis results in which the SDI in a long-term period has been assessed. It should be noted that SDI was computed based on the inflow of the reservoirs. It seems that the study area might experience dry and wet years irregularly. According to the described methodology, mean monthly flows in dry, normal and wet years were calculated as displayed in Figure 7. The difference between dry years and wet years is considerable in some months. However, it is limited

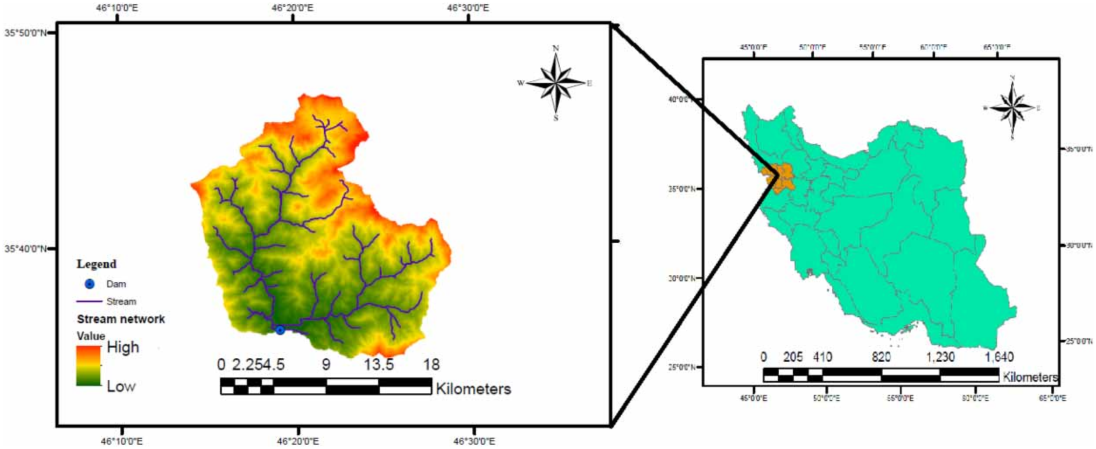

Figure 4 | Study area, location of the Garan dam and upstream river basin.

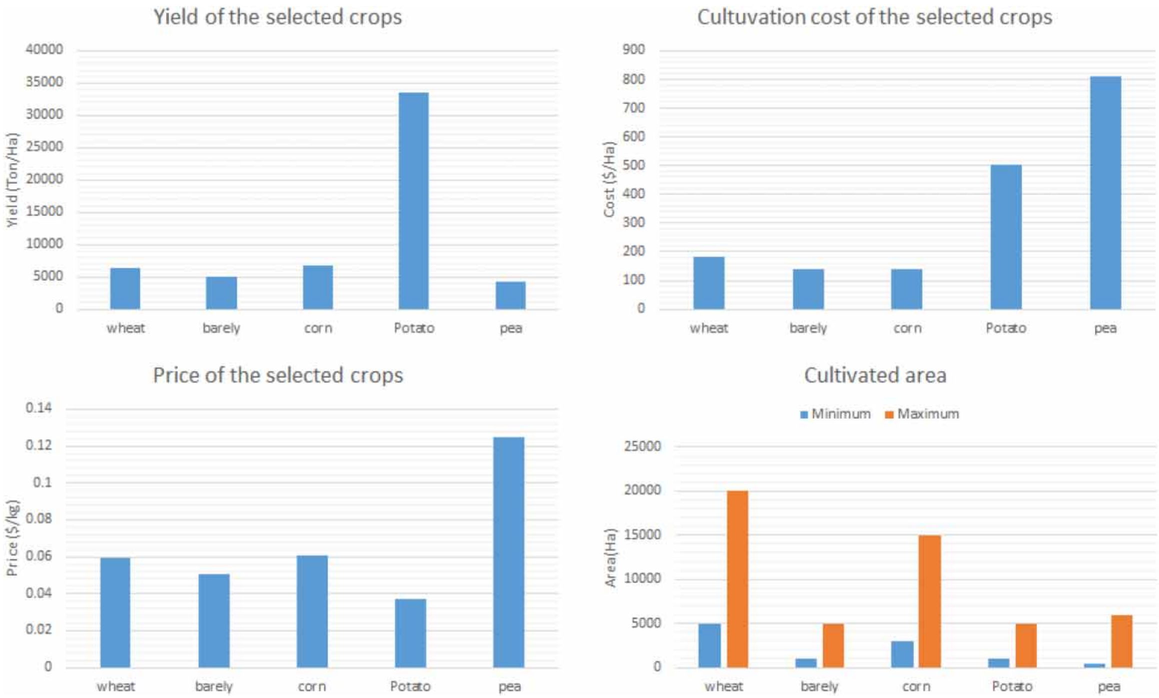

Figure 5 | More details on the selected crops in the optimization model.

in other months. It sounds that the impact of hydrological condition on the available water in the reservoir is remarkable. Hence, assessing the role of the reservoir in the water–energy–food security nexus should be incorporating drought analysis to determine reservoir inflow in different hydrological conditions including dry years, normal years and wet years. In other words, we face a dynamic hydrological condition in the river basins that might be able to change loss of the reservoir operation as well as ecological condition at downstream river.

The NWUA function is another output of the developed method. The final output of the fuzzy physical habitat simulation is the NWUA function that could be utilized in the structure of the reservoir operation optimization to mitigate ecological impacts at the downstream of the reservoir. A regression model was applied to finalize the development of the ecological impact function as displayed in Figure 8. NWUA could be considered as the biological response of the river ecosystem for changing river flow. The biological response of the river ecosystem is not linear that means using ecohydraulic simulation is essential in the environmental assessment at the downstream of the reservoir. Old methods of the environmental flow

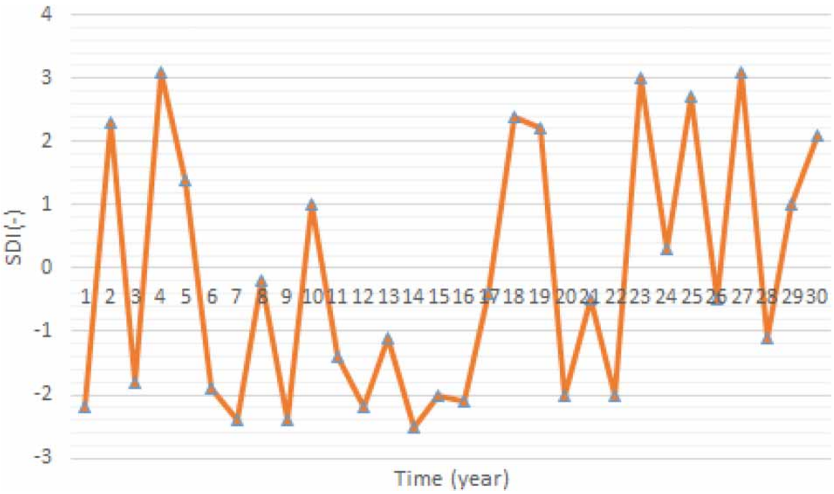

Figure 6 | Drought analysis results.

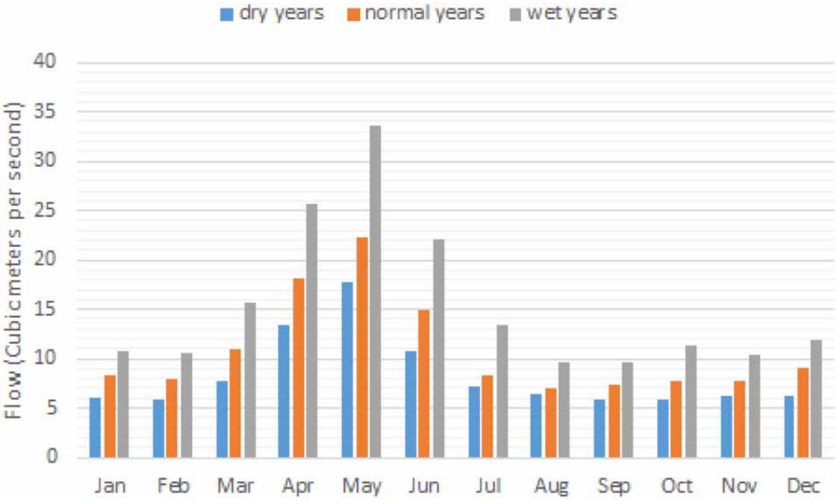

Figure 7 | Mean reservoir inflow in three hydrological conditions including dry years, normal years and wet years.

assessment such as hydrologic desktop methods considered a linear and direct relationship between the river flow and the biological response. In these methods, increasing river flow would enhance the habitat suitability in the river ecosystem. However, the output of the case study demonstrates that this assumption is not correct ecologically. Hence, we recommend utilizing ecohydraulic simulations as the reliable method to assess ecological impacts at the downstream of the reservoir. It should be noted that the correct assessment of the environmental degradation associated with the water–energy–food nexus might be very important due to its significant impact on the production in the river basins. The main purpose of this method is to maximize production by applying fewer resources. Hence, the incorrect assessment of the ecological impacts might negatively or positively affect the benefits from the reservoir. For example, if the required environmental flow is assessed more than the actual need of the river ecosystem, the irrigation supply might be considerably decreased which would lead to reduce benefits for the farmers as the stakeholders. Conversely, if the environmental flow is ecologically assessed less than actual need, the farmers' revenue will be increased. However, environmental degradation of the river ecosystem will be increased as well. One of the advantages of the proposed method is to provide a correct ecological impact assessment in the simulation of the reservoir operation.

In the next step, it is necessary to present results of the optimization model as the main output of the present study. Figure 9 displays total instream flow (environmental flow) and offstream flow (water supply) for dry years, normal years and wet years

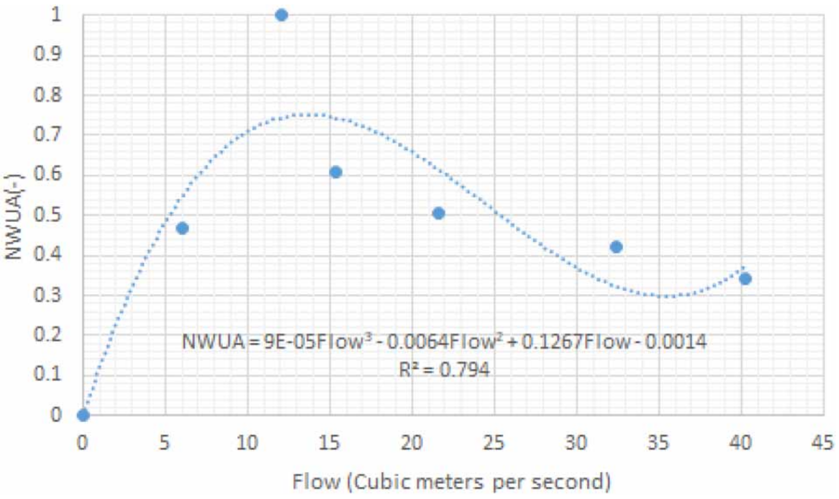

Figure 8 | Normalized useable area function as the main output of the fuzzy physical habitat simulation.

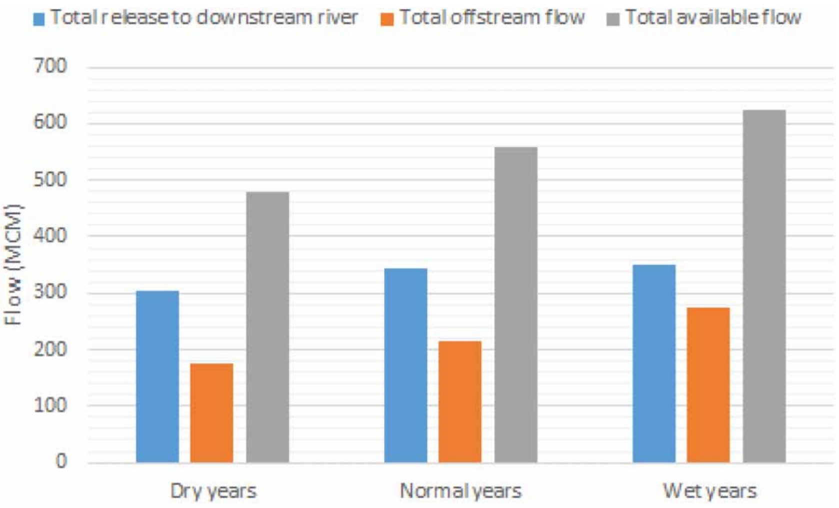

Figure 9 | Total offstream and release in the dry years, normal years and wet years.

proposed by the optimization model of the reservoir operation. It seems that environmental flow in different conditions is between 40 and 50% of the available flow in the river that means more than 50% of the available water could be utilized to supply water demand in the study area. It should be noted that instream flow in the case study could be used for either supply of environmental demand or hydropower production. Conversely, offstream flow is being pumped directly from the reservoir. Hence, allocated water as the instream flow and offstream flow is able to minimize ecological impacts at downstream river and maximize food and energy production by the reservoir. However, maximizing food production revenue might need cropping pattern optimization as the additional model to the proposed method.

In the next step, it is necessary to assess the performance of the optimization model in terms of physical habitat loss. We applied the NWUA function as the ecological impact function that means assessing physical habitat loss might be helpful to investigate how the optimization model is able to mitigate ecological impacts at the downstream of the reservoir as one of the main purposes for the optimization system. Figure 10 displays NWUA in the natural flow and optimal environmental flow at downstream river of the reservoir. It should be noted that minimizing the difference between NWUA for the natural flow and NWUA for optimal environmental flow was considered as the purpose in the optimization system. If the available suitable habitat area in the optimal environmental flow is close to the natural flow, it might guarantee the appropriate ecological status in the river. Based on the results, the proposed method is robust in terms of minimizing physical habitat loss in the

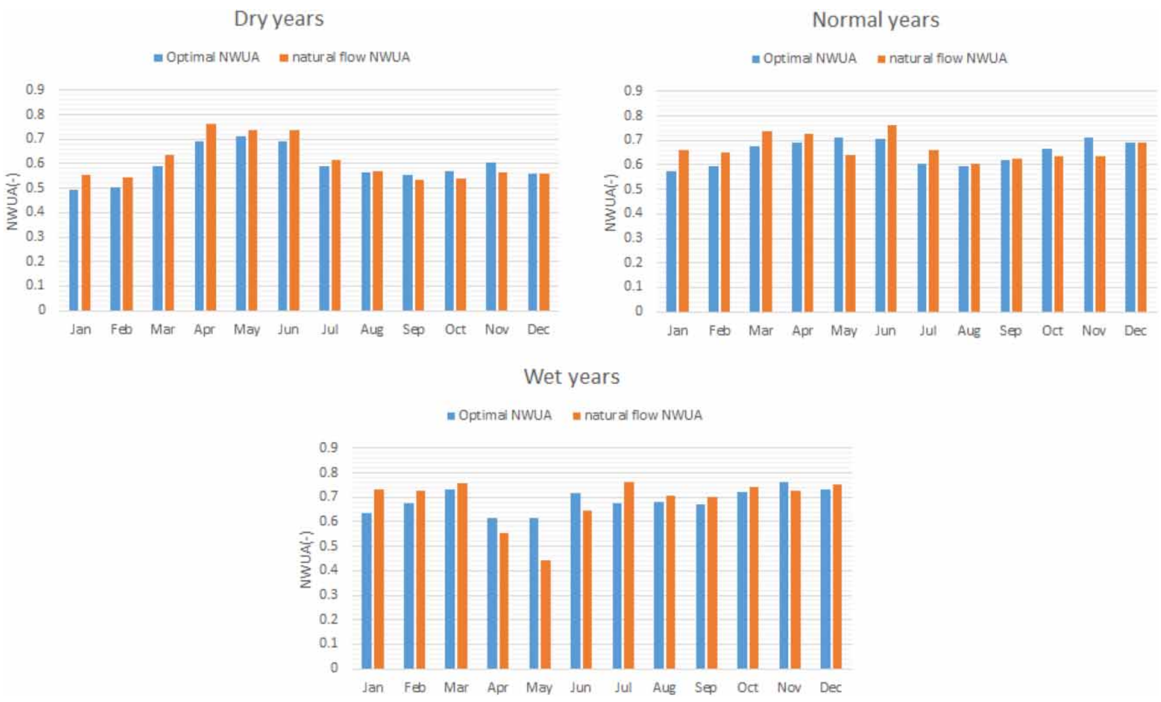

Figure 10 | Normalized weighted useable area in the natural flow and optimal environmental flow.

study area. Interestingly, the optimization model is able to provide a more suitable habitat area compared with the natural flow in the wet years due to the non-linear relationship between flow and biological response. Moreover, the optimization model is able to minimize physical habitat losses in the dry years that might be a critical condition in the management of the reservoir. In the dry years, the inflow of the reservoir will drastically be decreased that means supply of environmental flow might be challenging in this period. In other words, the conflict between supply of water demand and environmental flow is considerable in the dry years. It seems that robust performance of the optimization model in terms of physical habitat loss in the droughts could corroborate the applicability of the ecohydrualic simulation in the optimal management of the reservoirs.

In the next step, it is essential to investigate the output of the optimization system in terms of the hydropower production. Figure 11 displays the optimal normalized hydropower production in different hydrological conditions including dry years,

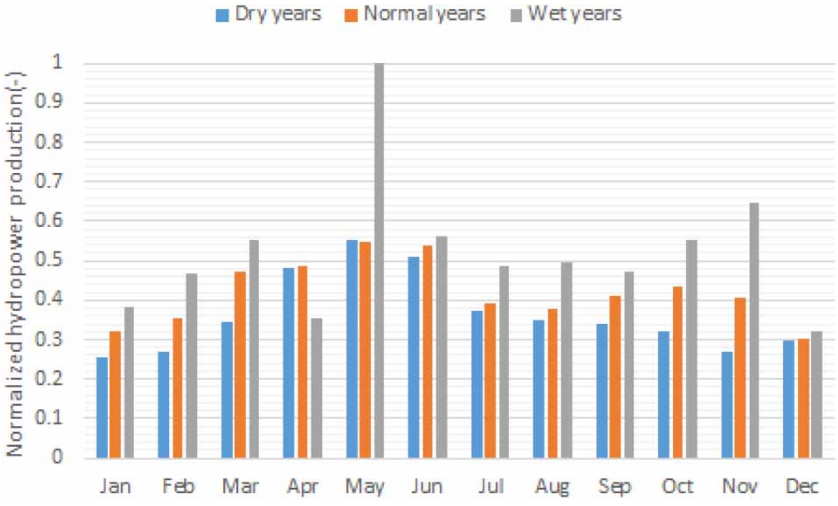

Figure 11 | Normalized hydropower production in dry years, normal years and wet years proposed by the optimization model.

normal years and wet years. It should be noted that we utilized the normalized hydropower production for better comparison of the impact of the hydrological condition on the optimal hydropower production in the case study. Clearly, the reservoir is able to provide the highest hydropower production in the wet years due to much available water in the river. In some months, the reduction of hydropower production in the dry years is considerable that means droughts might be a serious threat for the hydropower production in the study area. However, the difference between dry years and wet years is not remarkable in some other months. Hydropower production is reduced 15% approximately in the normal years compared with the wet years. Furthermore, the hydropower production is decreased more than 30% in the dry years.

In the next step, the result of the cropping pattern optimization should be presented. It should be noted that maximizing the food production is a purpose in the water–energy–food nexus approach. However, we considered the maximum net revenue in the cropping pattern optimization. At the first glance, it might be logical for considering the maximization of the food production revenue in the optimization model. However, it is not an efficient method, because costs of the cultivation should be taken into account in the optimal planning of the agriculture in the study area. In other words, if we ignore the costs of the cultivation, the proposed solution is not applicable. Hence, we recommend using the maximum net revenue in the optimization models of the food production revenue at the downstream of the reservoirs. Figure 12 displays the optimal cropping pattern in the dry years, normal years and wet years. It should be noted that we considered the minimum and maximum cultivation area for different crops based on the recommendations by the regional agricultural department. It seems that the optimization model was able to find the optimal solution based on defined constraints. The optimization model mainly increases the area of the wheat in the available agricultural lands. However, the cultivated area of the corn is increased in the wet years as well. It seems that we should consider a dynamic cropping pattern in the study area. We considered some main crops in the optimization model. However, it is recommendable to simulate other types of the crops in the practical projects.

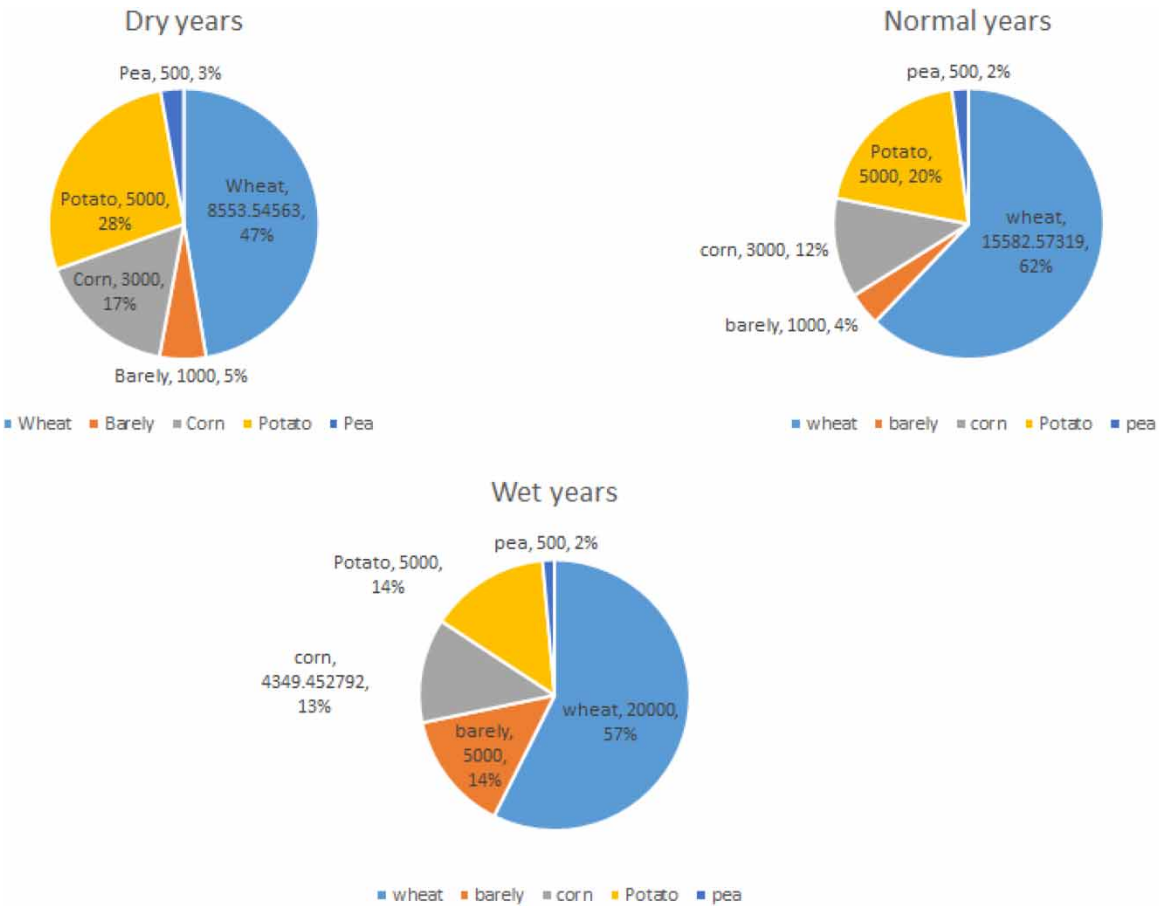

Figure 12 | Optimal cropping pattern in dry years, normal years and wet years proposed by the optimization system.

Measuring the performance of the optimization system is needed as well. As presented, we utilized three indices including reliability index for cropping pattern in terms of net revenue, reliability index for hydropower reproduction and RSME for physical habitat loss in the study area. Figure 13 displays these indices in the case study. It should be noted that reliability of the cropping pattern was compared with the maximum possible net revenue in the study area. The ideal net revenue means available net revenue for the farmers in the current condition without considering the environmental flow regime at the downstream of the reservoir. In other words, downstream release is used for other available agricultural lands and zero flow is available at downstream river habitats. Reliability index in the wet years is more than 50% that seems proper in the study area. It should be noted that supply of environmental flow would reduce the water supply that means considerable reduction of the food production revenue is predictable. However, the proposed optimization system is able to protect more than 50% of the revenue. In contrast, RMSE for the physical habitat loss is very low in all the hydrological conditions that means the optimization system is able to mitigate losses of food production revenue and ecological impacts simultaneously. At the first glance, it does not seem a fair balance between the environmental flow and water supply. However, it should be noted that sensitivity of the river habitats is much more important than the supply of the water demand or the food production revenue. The food production revenue could be enhanced using other available water resources in the study area such as groundwater resources while alleviating environmental impacts in the river ecosystem is only possible by the instream flow that means other alternative water resources are not available to mitigate ecological impacts. Hence, we claim that the proposed optimal solution would provide a fair balance between the environmental requirement and water supply in the study area. Moreover, hydropower production was compared with the maximum needed electrical power in the study area. In the best condition (wet years), the reservoir is able to supply 25% of the needed power that means hydropower is not a reliable source for the energy supply in the study area. The reliability index of the hydropower reduces to 15% approximately in the dry years that means hydropower production might be critical in dry years.

A full discussion on different aspects of the developed model is essential as well. Each optimization system might have limitations, strengths and drawbacks that should be noted in the applications. Moreover, it is essential to discuss the future research fields in this regard. We discuss the developed model based on the technical view and computational view. In the present study, fuzzy physical habitat simulation was utilized as the ecological impact model that demonstrates the robust performance. However, this method might not be useable in all the case studies. For example, the absence of robust expert opinions regarding the target species might be a hindrance to using the fuzzy physical habitat simulation in

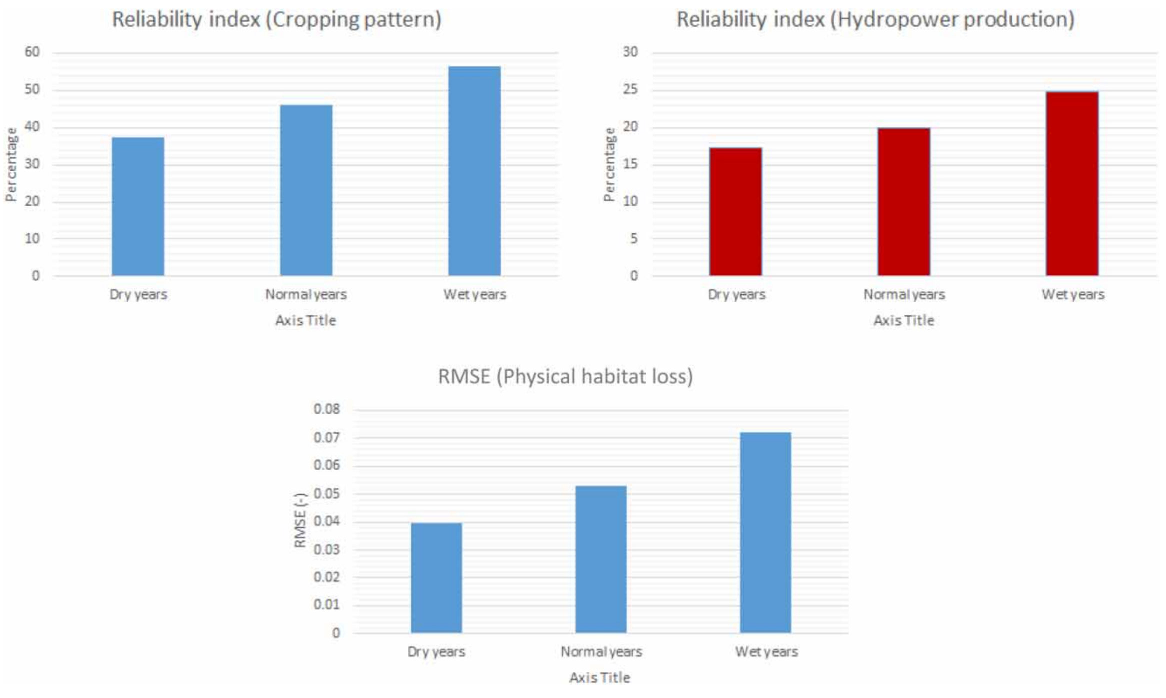

Figure 13 | Measurement indices for the optimal solutions in the case study.

other cases. Other methods might be available in this regard. For instance, the data-driven models have been proposed as the robust alterative for the physical habitat simulation in the rivers. Utilizing the artificial neural networks in the simple form or improved form such as adaptive neuro fuzzy inference systems (ANFISs) are recommended in the literature (Sedighkia *et al.* 2021b). This method is useable when sufficient information is not available regarding the fish species in the study area. However, it might be effective on the efficiency of the optimization model in terms of the computational aspects.

We applied the cropping pattern optimization combined with the reservoir operation optimization to minimize loss of the food and energy production and ecological impact at the downstream of the reservoirs. However, other strategies might be useable in the agriculture planning of the lands. For example, deficit irrigation is one of the effective strategies in agriculture that is able to reduce water consumption. However, it might decrease the yield of the farms. It seems that using the combined strategies such as coupled deficit irrigation-cropping pattern model could be highlighted in the future studies.

Computational aspects are very effective in the successful application of the optimization systems. Computational complexities might reduce the efficiency of the optimization model drastically. As a definition on this term, it has been defined as the required time and memory to find the optimal solution in the simulated domain. The proposed method is considerably advantageous that means low computational complexities are the most important strength point for the system. It should be noted that the importance of the computational complexities might be highlighted in the practical projects. We need to carry out numerous simulations in practice that implies the high computational complexities might be a serious limitation. The engineers are not willing to apply the complex optimization system due to significant limitations such as considerable running time or required memory. As discussed, other types of ecohydraulic simulations such as data-driven models of the physical habitat suitability are useable in the proposed method. However, direct using of the data-driven model such as ANFIS-based models in the structure of the optimization system might increase the computational complexities. Thus, changing the method of the ecohydraulic simulation should be based on computational considerations in the optimization model.

We utilized the PSO as the optimization algorithm in the present study by the single objective function. In fact, we aggregated all the losses in a single objective function. However, using multiobjective algorithms such as MOPSO might be another option as well. In other words, each term of the optimization model could be used as an independent function in the optimization model. However, some disadvantages might confine its applications. First, multiobjective optimization algorithms have the higher computational complexities compared with the single objective algorithms. It might be a serious problem for applying data-driven models in the structure of the optimization model. Thus, we proposed an aggregated objective function in which all the terms are available in the objective function. This form of the objective function increases the upgradability of the model for the future studies. Moreover, global optimization is another problem for using a multiobjective algorithm in practice. One of the important weaknesses of the evolutionary algorithms is inability to guarantee the global optimization for the complex objective functions. The proposed method is a complex objective function that might need using different algorithms in the practical projects. However, we used one algorithm as a test of the model. Unfortunately, a limited number of the multiobjective algorithms have been developed in the literature. Thus, using a single objective function is advantageous for using different evolutionary algorithms including classic and new generation algorithms.

One of the recommendations for the future studies is to add the climate change model in the structure of the optimization model. The climate change might affect the inflow of the reservoir drastically that means efficiency of the reservoir in terms of food and energy production and mitigating ecological impact might be changed in the future periods. We recommend utilizing the proposed method in the reservoir operation instead of the available methods that are not able to mitigate loss of the reservoirs in terms of food and energy production and environmental impacts. The conventional form of the reservoir operation optimization is not efficient to overcome the complexities in the river basins. The proposed method provides an upgradeable environment that means other components or improved models could be added to the system.

We selected a particular set of parameters in the present study. It is required to explain the rationale on the choice of the set of parameters in this study. The set of the parameters in the present study was considered based on the technical issues in the reservoir of the case study. In fact, each reservoir might need a specific set of parameters that might not be the same as the other case studies. We did not test other sets of the parameters in the present study. Because it was not compatible with the technical considerations of the case study, and it is an unrealistic condition that might not be evaluable. However, it is recommendable to apply the proposed framework in other case studies and change the set of parameters based on the needs of the case study. Moreover, some key assumptions were considered in the present study. For example, physical habitat suitability was the main effective parameter on the habitat suitability of the river. This assumption was highly correct in the case study. Because other effective parameters such as water quality were not problematic. However, other case studies might need water quality assessment as well. Moreover, power plants coefficients such as PF were considered as the constant due to recommendations by the regional water authority that was logical in the case study. Furthermore, maximum irrigation demand and maximum revenue were defined based on the current cultivation pattern and area in the case study. This assumption helped us to compare the abilities of the optimization model to provide the local requirement of the cultivation in the case study. Justifications on other assumptions are explained in the related section.

4. CONCLUSION

The present study developed a novel form of the optimization system in which hydropower and food production revenue by the reservoir are maximized while ecological degradations at downstream river is minimized. According to the results in the case study, the proposed method is able to optimize reservoir operation in terms of defined purposes in the objective functions. The ecological impact at the downstream of the reservoir were minimized perfectly. The RMSE of physical habitat suitability is less than 01. In all hydrological conditions that means the proposed method is highly advantageous in terms of mitigating environmental impacts. Moreover, the impact of the hydrological condition on the hydropower production is considerable. The reliability index of hydropower production is between 15 and 25% in different hydrological conditions. Hence, the supply of environmental flow might considerably reduce the hydropower production. Furthermore, the developed method proposed dynamic optimal cropping patterns in dry years, normal years, and wet years. The cropping pattern optimization model associated with the reservoir operation model is averagely able to protect more than 40% of the maximum net revenue. The optimization model balances the benefits and environmental impacts that means negotiations between stakeholders and environmental managers could be minimized. Using the proposed framework is highly helpful for sustainability in the operation of the reservoirs. Hence, we recommend using the proposed method to optimize reservoir operation in the future studies for improving sustainable management of the reservoirs.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Adeyemo, J. A. 2011 *Reservoir Operation Using Multi-Objective Evolutionary Algorithms - A Review*.

Ahmad, A., El-Shafie, A., Razali, S. F. M. & Mohamad, Z. S. 2014 Reservoir optimization in water resources: a review. *Water Resources Management* **28** (11), 3391–3405. https://doi.org/10.1007/s11269-014-0700-5.

Akbari, H., Rakhshandehroo, G., Sharifloo, A. H. & Ostadzadeh, E. 2015 Drought analysis based on standardized precipitation index (SPI) and streamflow drought index (SDI) in Chenar Rahdar river basin, Southern Iran. *American Society of Civil Engineers* 11–22. https://doi.org/10.1061/9780784479322.

Asgari, H.-R., Bozorg-Haddad, O., Pazoki, M. & Loáiciga, H. A. 2016 Weed optimization algorithm for optimal reservoir operation. *Journal of Irrigation and Drainage Engineering* **142** (2), 04015055. doi:10.1061/(ASCE)IR.1943-4774.0000963.

Azad, A. S., Rahaman, M. S. A., Watada, J., Vasant, P. & Vintaned, J. A. G. 2020 Optimization of the hydropower energy generation using meta-heuristic approaches: a review. *Energy Reports* **6**, 2230–2248.

Birhanu, K., Alamirew, T., Dinka, M. O., Ayalew, S. & Aklog, D. 2014 Optimizing reservoir operation policy using chance constraint nonlinear programming for Koga irrigation Dam, Ethiopia. *Water Resources Management* **28** (14), 4957–4970. https://doi.org/10.1007/s11269-014-0770-4.

Bizikova, L., Roy, D., Swanson, D., Venema, H. D. & McCandless, M. 2013 *The Water-Energy-Food Security Nexus: Towards a Practical Planning and Decision-Support Framework for Landscape Investment and Risk Management*. International Institute for Sustainable Development, Winnipeg, Manitoba, Canada.

Cai, W., Zhang, L., Zhu, X., Zhang, A., Yin, J. & Wang, H. 2013 Optimized reservoir operation to balance human and environmental requirements: a case study for the Three Gorges and Gezhouba Dams, Yangtze River basin, China. *Ecological Informatics* **18**, 40–48.

Datta, B. & Burges, S. J. 1984 Short-term, single, multiple-purpose reservoir operation: importance of loss functions and forecast errors. *Water Resources Research* **20** (9), 1167–1176. https://doi.org/10.1029/WR020i009p01167.

Dokeroglu, T., Sevinc, E., Kucukyilmaz, T. & Cosar, A. 2019 A survey on new generation metaheuristic algorithms. *Computers & Industrial Engineering* **137**, 106040. https://doi.org/10.1016/j.cie.2019.106040.

Ehteram, M., Karami, H., Mousavi, S. F., El-Shafie, A. & Amini, Z. 2017 Optimizing dam and reservoirs operation based model utilizing shark algorithm approach. *Knowledge-Based Systems* **122**, 26–38. https://doi.org/10.1016/j.knosys.2017.01.026.

Ehteram, M., Karami, H., Mousavi, S. F., Farzin, S. & Kisi, O. 2018 Evaluation of contemporary evolutionary algorithms for optimization in reservoir operation and water supply. *Journal of Water Supply: Research and Technology – AQUA* **67** (1), 54–67. https://doi.org/10.2166/aqua.2017.109.

El Gafy, I., Grigg, N. & Reagan, W. 2017 Water-food-energy nexus index to maximize the economic water and energy productivity in an optimal cropping pattern. *Water International* **42** (4), 495–503. https://doi.org/10.1080/02508060.2017.1309630.

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: COST Action 626 Report. Doctoral Dissertation*, Univerza v Ljubljani, Naravoslovnotehniška fakulteta.

Hashimoto, T., Stedinger, J. R. & Loucks, D. P. 1982 Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research* **18** (1), 14–20. https://doi.org/10.1029/WR018i001p00014.

Jahandideh-Tehrani, M., Bozorg-Haddad, O. & Loáiciga, H. A. 2021 A review of applications of animal-inspired evolutionary algorithms in reservoir operation modelling. *Water and Environment Journal* **35** (2), 628–646. https://doi.org/10.1111/wej.12657.

Jorde, K., Schneider, M. & Zöllner, F. 2020 Invited lecture: analysis of instream habitat quality–preference functions and fuzzy models. In: Z.-Y. Wang & S.-X. Hu, eds. *Stochastic Hydraulics 2000*. CRC Press, London, pp. 671–680.

Maddock, I., Harby, A., Kemp, P. & Wood, P. J. 2013 *Ecohydraulics: An Integrated Approach*. John Wiley & Sons.

Marini, F. & Walczak, B. 2015 Particle swarm optimization (PSO). A tutorial. *Chemometrics and Intelligent Laboratory Systems* **149**, 153–165. https://doi.org/10.1016/j.chemolab.2015.08.020.

Mirjalili, S. 2019 Genetic algorithm. In: J. Kacprzyk, ed. *Evolutionary Algorithms and Neural Networks*. Springer, Cham, pp. 43–55.

Nestler, J. M., Milhous, R. T. & Layzer, J. B. 2018 Instream habitat modeling techniques. In: J. A. Gore & G. E. Petts, eds. *Alternatives in Regulated River Management*. CRC Press, Boca Raton, pp. 295–314.

Noack, M., Schneider, M. & Wieprecht, S. 2013 The habitat modelling system CASiMiR: a multivariate fuzzy-approach and its applications. In: I. Maddock, A. Harby, P. Kemp & P. Wood, eds. *Ecohydraulics: An Integrated Approach*, John Wiley & Sons Ltd, pp. 75–91.

Obianyo, J. I. 2019 Effect of salinity on evaporation and the water cycle. *Emerging Science Journal* **3** (4), 255–262. http://dx.doi.org/10.28991/esj-2019-01188.

Oo, H. T., Zin, W. W. & Kyi, C. T. 2020 Analysis of streamflow response to changing climate conditions using SWAT model. *Civil Engineering Journal* **6** (2), 194–209. http://dx.doi.org/10.28991/cej-2020-03091464.

Osama, S., Elkholy, M. & Kansoh, R. M. 2017 Optimization of the cropping pattern in Egypt. *Alexandria Engineering Journal* **56** (4), 557–566. https://doi.org/10.1016/j.aej.2017.04.015.

Postel, S. L. 1998 Water for food production revenue: will there be enough in 2025? *BioScience* **48** (8), 629–637.

Raso, L., Bader, J. C. & Weijs, S. 2020 Reservoir operation optimized for hydropower production reduces conflict with traditional water uses in the Senegal River. *Journal of Water Resources Planning and Management* **146** (4), 05020003.

Reis, L. F. R., Walters, G. A., Savic, D. & Chaudhry, F. H. 2005 Multi-reservoir operation planning using hybrid genetic algorithm and linear programming (GA-LP): an alternative stochastic approach. *Water Resources Management* **19** (6), 831–848. https://doi.org/10.1007/s11269-005-6813-0.

Richter, B. D., Davis, M. M., Apse, C. & Konrad, C. 2012 A presumptive standard for environmental flow protection. *River Research and Applications* **28** (8), 1312–1321. https://doi.org/10.1002/rra.1511.

Sedighkia, M., Ayyoubzadeh, S. A. & Hajiesmaeli, M. 2017 Modification of tennant and wetted perimeter methods in Simindasht basin, Tehran Province. *Civil Engineering Infrastructures Journal* **50** (2), 221–231. doi:10.7508/ceij.2017.02.002.

Sedighkia, M., Abdoli, A. & Datta, B. 2021a Optimizing monthly ecological flow regime by a coupled fuzzy physical habitat simulation–genetic algorithm method. *Environment Systems and Decisions*, 1–12. https://doi.org/10.1007/s10669-021-09809-z.

Sedighkia, M., Datta, B. & Abdoli, A. 2021b Minimizing physical habitat impacts at downstream of diversion dams by a multiobjective optimization of environmental flow regime. *Environmental Modelling & Software* **140**, 105029. https://doi.org/10.1016/j.envsoft.2021.105029.

Stalnaker, C. B. 1995 *The Instream Flow Incremental Methodology: A Primer for IFIM*, Vol. 29. US Department of the Interior, National Biological Service.

Stretch, D. & Adeyemo, J. 2018 Review of hybrid evolutionary algorithms for optimizing a reservoir. *South African Journal of Chemical Engineering* **25** (1), 22–31. https://doi.org/10.1016/j.sajce.2017.11.004.

Suwal, N., Huang, X., Kuriqi, A., Chen, Y., Pandey, K. P. & Bhattarai, K. P. 2020 Optimisation of cascade reservoir operation considering environmental flows for different environmental management classes. *Renewable Energy* **158**, 453–464. https://doi.org/10.1016/j.renene.2020.05.161.

Taghian, M. & Ahmadianfar, I. 2018 Maximizing the firm energy yield preserving total energy generation via an optimal reservoir operation. *Water Resources Management* **32** (1), 141–154. https://doi.org/10.1007/s11269-017-1800-9.

Tsanov, E., Ribarova, I., Dimova, G., Ninov, P., Kossida, M. & Makropoulos, C. 2020 Water stress mitigation in the Vit River Basin based on WEAP and MatLab simulation. *Civil Engineering Journal* **6** (11), 2058–2071. http://dx.doi.org/10.28991/cej-2020-03091602.

Uen, T. S., Chang, F. J., Zhou, Y. & Tsai, W. P. 2018 Exploring synergistic benefits of Water-Food-Energy Nexus through multi-objective reservoir optimization schemes. *Science of the Total Environment* **633**, 341–351. https://doi.org/10.1016/j.scitotenv.2018.03.172.

Xu, W., Liu, P., Guo, S., Cheng, L., Ming, B. & Gong, Y. 2021 Optimizing the reservoir operation for hydropower generation by using the flexibility index to consider inflow uncertainty. *Journal of Water Resources Planning and Management* **147** (8), 06021008.

Yang, X. S. & He, X. 2013 Bat algorithm: literature review and applications. *International Journal of Bio-Inspired Computation* **5** (3), 141–149. https://doi.org/10.1504/IJBIC.2013.055093.

Yaseen, Z. M., Allawi, M. F., Karami, H., Ehteram, M., Farzin, S., Ahmed, A. N., Koting, S. B., Mohd, N. S., Jaafar, W. Z. B., Afan, H. A. & El-Shafie, A. 2019 A hybrid bat–swarm algorithm for optimizing dam and reservoir operation. *Neural Computing and Applications* **31** (12), 8807–8821. https://doi.org/10.1007/s00521-018-3952-9.

Zarei, S., Bozorg-Haddad, O., Kheirinejad, S. & Loáiciga, H. A. 2021 Environmental sustainability: a review of the water–energy–food nexus. *AQUA – Water Infrastructure, Ecosystems and Society* **70** (2), 138–154. https://doi.org/10.2166/aqua.2020.058.

First received 4 August 2021; accepted in revised form 3 January 2022. Available online 19 January 2022