



An Ecological Expert System Optimization for Assessing Environmental Water Requirements of Hypersaline Lakes

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Abstract

The present study proposes an applicable methodology to optimize environmental water requirement of hypersaline lakes with a focus on Urmia lake as the case study in which remote sensing analysis, machine learning model and fuzzy expert system are linked. A machine learning model was developed to simulate effective abiotic parameters in which bands of operational land imager (Landsat 8) were inputs and depth and total dissolved solids were the outputs of the model. Moreover, an ecological expert system using Mamadani fuzzy inference system was developed to generate the habitat suitability map for the selected target species. Then, a multivariate linear model was developed to assess unit habitat suitability in which water level and total inflow of the lake were the variables of the model. An optimization model was developed to assess environmental water requirement in which habitat suitability between natural and regulated flows and water supply loss was minimized. The multivariate linear model was applied to assess habitat suitability in the optimization model. Based on the results in the case study, the proposed combined model is able to balance the ecological requirements and water demand by allocating 60% and 40% of total inflow to environmental water requirement and water demand respectively. Average habitat loss proposed by the optimal environmental water requirement was less than 20% which implies the robustness of the model. Generating habitat suitability maps of the lake by a reliable method which is used in the environmental flow optimization might be the significance of the proposed method.

Keywords Environmental water requirement · Hypersaline lakes · Remote sensing · Expert systems · Optimization

Introduction

Inland water bodies such as rivers and lakes are valuable ecosystems where have extensively been addressed in the literature in terms of their importance and role in the earth planet ecosystem (Karpatne et al. 2016). Hence, protecting river and lake habitats have been highlighted as a critical task for environmental engineers. The concept of environmental flow has been defined to protect habitats in rivers as well as lakes (Anderson et al. 2019). However, environmental water requirement might be a better term for defining required ecological water in the wetlands or lakes. Initial studies have proposed many methods for assessing environmental flow in rivers. Generally, four methods have been

proposed including historic flow methods, hydraulic rating methods, habitat simulation methods and holistic methods. Previous studies highlight strengths and shortcomings of different approaches (Tharme 2003). Some methods such as historic flow methods are not able to reflect the response of the organisms which means they might not be reliable. Conversely, implementing the holistic methods might be expensive in the river basin which implies using these methods might not be logical in many river basins. It sounds that habitat simulation methods could be efficient to assess environmental flow due to focusing on the organisms and logical costs of field studies and simulations (Sedighkia et al. 2022). The habitat simulation method might be useable in the lakes as well. Some previous studies focused on the assessing environmental water requirements of the lakes, which should be reviewed.

Some studies proposed simple ecological indices to assess the environmental water requirements of the lakes in which the indices have been developed based on water quality parameters and biological and ecological characteristics of

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the inhabited organisms (Abbaspour and Nazarioust 2007). However, these methods are not reliable due to inaccurate annual assessment of ecological water requirement. Some studies indicated that using ecological approach might provide sustainable solutions for assessing environmental water requirement in the lakes (e.g. Sajedipour et al. 2017). Recent studies developed the simulation–optimization approaches for managing environmental water requirement which seems an efficacious solution in the lake ecosystems (e.g. Goorani and Shabanlou 2021). However, the proposed frameworks in the literature have not been able to come to picture the ecological complexities in the structure of the optimization models. Hence, more studies and developing new frameworks are necessary in which complexities of ecological suitability should be simulated. It should be noted that using optimization methods is recommendable in water resource management and planning. Some previous studies applied conventional optimization method such as linear and non-linear programming to manage water resources or reservoirs (e.g. Zhou et al. 2018; Yue et al. 2020). However, due to complexities of the objective functions, evolutionary algorithms have been used and introduced as the efficient methods for optimization in water resources management (Janga Reddy and Nagesh Kumar 2020). Due to using remote sensing analysis and ecological modelling in the present study, it is needed to review them briefly in this section.

Remote sensing data processing is an applicable tool for civil studies which is able to reduce time and cost of field studies considerably (Wang and Yang 2019). Several previous studies highlighted the application of remote sensing analysis for simulating water quality parameters in the lakes and coastal regions which corroborate the efficiency and outstanding advantages of this method (e.g. Maliki et al. 2020; Pizani et al. 2020; Topp et al. 2020). Two aspects matter for simulating water quality by remote sensing analysis including data acquisition and useable models to convert the remote sensing data to the water quality parameters. More details regarding data acquisition methods and statistical and artificial intelligence methods to convert the remote sensing data to water quality parameters have been addressed in the literature (e.g. Zhu et al. 2018; Forkuor et al. 2017; Maxwell et al. 2018).

Ecological modelling is an effective method to simulate the response of the environment due to changing abiotic factors in terrestrial and aquatic ecosystems. Simple statistical methods have initially been applied to model the ecological status of the ecosystems (Tredennick et al. 2021). However, they were not robust and reliable in all the cases due to complexities of habitat selection by disparate organisms. Hence, advanced methods have been recommended and utilized in recent decades. For example, machine learning models have successfully been applied to simulate the ecological status (e.g. Meyer et al. 2018). However, they might not be useable

for all the cases due to difficulties for recognizing effective inputs of the machine learning model and need for extensive field studies. The previous studies corroborated the conventional mathematical models might not be applicable in ecological modelling of aquatic habitats due to complex interactions between effective abiotic parameters (Noack et al. 2013). Expert opinions might be applicable in this regard because their observations could make clear the unknown interactions of parameters. Fuzzy approach has been recommended for simulating aquatic habitats (Noack et al. 2013).

Due to increasing population and water abstraction from the inland water ecosystems, allocating an appropriate environmental flow regime to the wetlands is crucial for sustainable ecological management of the wetlands. Using advanced ecological methods is essential to assess environmental water requirement of the wetlands. The previous studies did not apply advanced ecological models in the assessment of the environmental water requirement. In fact, developing the suitability distribution maps of the wetland ecosystem in the assessment of the environmental water requirement is needed. However, the previous studies did not develop an integrated method in this regard in which habitat suitability distributions are linked to the environmental flow method. Moreover, Management of water resources in the wetland basins needs an optimization framework to balance the humans' needs and environmental requirements. These research gaps were the main motivation of the present research work to develop a novel method to assess and optimize the environmental water requirement in the wetland ecosystems. Hence, the present study proposes a novel simulation–optimization approach to assess the environmental water requirement of the wetlands in which habitat suitability distributions are linked with the optimization model of water resources management. A novel method was developed to generate the habitat suitability maps in the wetland in which linkage of remote sensing and expert systems was applied. Then, the results of habitat suitability modelling were utilized in the optimization model in which environmental water requirements and water supply are balanced. Not only the proposed method enriches the application of habitat suitability models of wetlands in the environmental water assessment by presenting a novel method for generating habitat suitability maps of the wetlands, but also this method is able to improve the environmental water requirement models to the advanced optimization models of the water resources management. In this study, we focus on hypersaline lakes as one of the important saline ecosystems in the world. The Urmia lake as one of the largest hypersaline lakes is threatened in recent years due to lack of enough inflow. Hence, we applied the developed framework in this wetland. However, the proposed method is useable in all types of wetlands with some limited changes in data collection and modelling procedure.

Methods and Materials

Study Area

The proposed method was implemented in the Urmia Lake in Iran, this hypersaline lake is threatened due to environmental challenges of the ecosystem. On the one hand, consequences of climate warming and severe droughts are a jeopardy, which cause considerable reduction of natural inflow to the wetland and increasing evaporation from the surface of the lake. On the other hand, remarkable water abstraction from the upstream rivers has reduced the inflow of the wetland, which means outflow is much more than inflow in the current condition. These current challenges indicate that using a simulation–optimization system is necessary to balance the ecological requirements and humans' needs. Figure 2 displays the location of the Urmia Lake. Moreover, Table 1 shows the meteorologic information of the study area. It is helpful to present more details on climate zone, the ecological problem, hydrological characteristics and importance of key species in the study area. This lake is located in a temperate region in which average precipitation is more than other regions in Iran. However, it experienced more dry years in recent decades which has increased challenges of environmental management. Apart from more dry years in recent decades, the natural flow regime in rivers as the inflow of the lake has been drastically changed due to increasing population and consequently cultivated areas. In other words, considerable amount of available water in the rivers is abstracted by different water diversion projects or dams at upstream of the rivers. Hence, lack of enough inflow has reduced the water level in most areas of the lake which is a significant environmental challenge. In fact, the available habitats for the aquatic and terrestrial species are seriously threatened in the current condition. Based on the regional ecological studies, two significant species who are dependent on the ecological status of the lake are Artemia as the aquatic species and Penguin as the terrestrial species. However, Penguins are migratory who lives in the lake habitats for a limited time in each year and the only aquatic specie who is a good environmental index for assessing environmental water requirement. of the lake is Artemia. In other

Table 1 Meteorologic information of the study area in different hydrological conditions

Status	Average annual temperature(°C)	Average annual precipitation (mm)	Average annual evaporation (mm)
Dry years	12.9	493	1241
Normal years	11.4	704	947
Wet years	10.8	936	824

words, Artemia is sensitive to alteration of key physical and water quality factors (TDS and depth) which means it could be applied as a ecological index in assessing environmental water requirements.

We simulated 40 months for showing the capabilities of the developed method to assess the environmental water requirement. It was needed to have the natural inflow of the lake in the simulated period. However, it is not in the scope of the present study. Natural inflow was estimated in the present study using rainfall-runoff modelling by regional studies. Moreover, evaporation from surface of the reservoir was estimated based on previous studies and collected data from the local weather station. It should be noted that agricultural water demand in the Urmia wetland basin is high which means the farmers have requested more than available flow. Hence, we did not consider the water demand time series for the study area. Furthermore, other needed relationship between geomorphological parameters of the lake such as volume, surface area and water level were developed based on the previous regional and scientific studies. The present study develops an ecological model to assess environmental water requirement. Hence, it was needed to focus on the organisms in the study area. Based on the opinions by and experienced ecologist and recommendations of the previous studies, Artemia is the most important aquatic species who inhabits in all the available habitats of this Salt Lake. Hence, Artemia was selected as the target species in the present study.

Model Description and Construction

Model description

It might be helpful to review the workflow of the proposed method and location of the case study as displayed in the Figs. 1 and 2. Remote sensing analysis, ecological expert system and environmental water optimization are integrated in the method. Remote sensing analysis was applied to simulate the physical and water quality effective parameters using an artificial intelligence model. Moreover, ecological expert system was developed based on the expert opinions by a panel in the structure of a Mamdani fuzzy inference system. Then, a multivariate linear model was developed to assess unit suitability habitat index (USH). The developed linear model was utilized in the structure of the optimization model in which difference between natural and optimal USH is minimized, while water supply is maximized. More details regarding each part will be presented in the next sections.

Data Collection

Data acquisition is one of the prerequisites to analyse the environment by remote sensing. In the present study, we

Fig. 1 Flowchart of proposed method

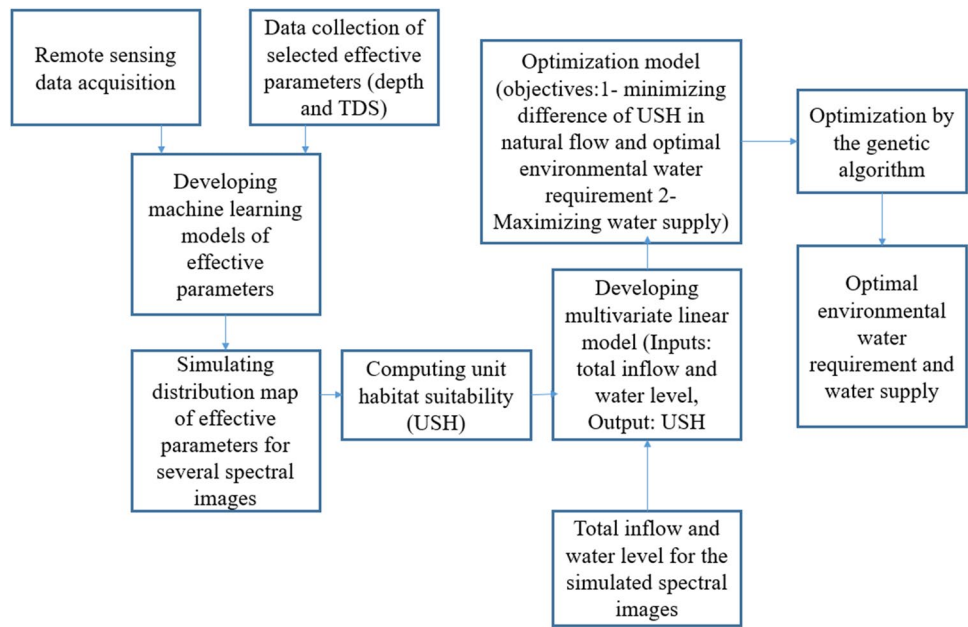


Fig. 2 Location of Urmia Lake in Iran

applied the captured spectral images by Landsat 8, which is one of the recommended satellites for studying the abiotic factors in the water bodies. Hence, 20 spectral images were utilized to develop the data driven model in which measured depth and TDS were available. Figure 3 shows the band 1 of one of the spectral images as the sample of downloaded data. 18 points in which TDS and depths were measured were selected for 20 spectral images which means 360 points in different spatial and temporal scales were applied to develop the data driven model. We used 80% of available data for training and rest of them for testing the model.

Model Construction

According to the literature, the abiotic factors are effective on the suitability of aquatic habitats. Hence, it seems logical to focus on the effective abiotic factors to simulate the ecological status of the lake. Many factors might be effective on the suitability of habitats. However, using all the factors might not be reasonable due to need for extensive field studies and computational costs. Hence, it is required to highlight the most important effective factors for simulating the ecological status.

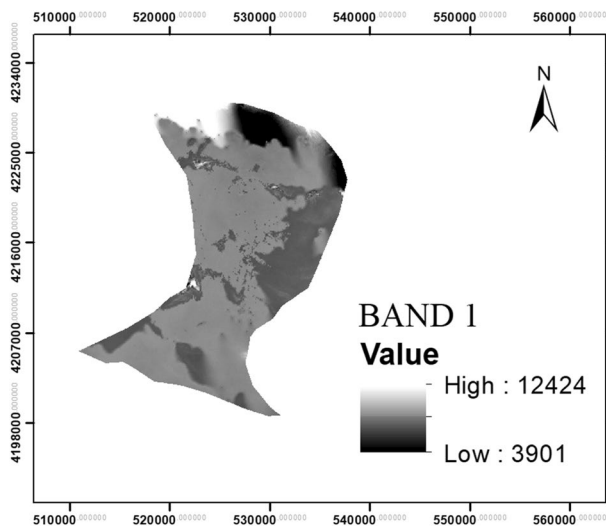


Fig. 3 A sample of collected spectral images from Landsat 8 data set (Band 1- imagery date: March, 2013)

The Previous studies demonstrated the key role of total dissolved solids (TDS) and water level in the suitability of *Atrémia*'s habitats in this lake (e.g. Sima et al. 2021). Water level could be mentioned by changing depth in the lake as the physical factor. In fact, depth is an important physical factor, which might provide safe habitats for the target species. In contrast, high concentration of TDS might threaten the survival of the target species. In other words, a combined suitability might be needed to sustain the ecological status of the lake. Field studies by the previous studies and the present study was applied for development of model in which depth, and TDS concentration was measured in different spatiotemporal scales. Four hundreds measured points were used in the present study to develop the data driven models in which the remote sensing data was inputs and depth and TDS concentration were the outputs of the model.

The inputs of the model include Band1 to Band 7 of operational land imager of Landsat 8. Moreover, output of model 1 and model 2 were depth and TDS respectively. A hybrid machine-learning model was used to simulate

effective factors through the remote sensing data. A feed-forward neural network was developed as the core of the model. Moreover, particle swarm optimization was used to train the machine learning model (more details by Sengupta et al. 2018). To increase the accuracy of the model, an optimization process was considered to find the best number of hidden layers in the model. More details regarding the structure and role of hidden layers in the feed forward neural network (FNN) have been reviewed in the literature (Thakur and Konde 2021). Root Means Square Error (RMSE) was applied to find the best FNN model. Table 2 displays more details on the data driven models. The Nash–Sutcliffe efficiency and RMSE were applied to evaluate the robustness of the data driven models (More details regarding these indices by Chai and Draxler 2014 and Gupta et al. 2009).

Model Verification

In the testing process of model, we evaluated the performance of the model using two indices. First, The Nash–Sutcliffe model efficiency coefficient (NSE) was used as the measurement index (Gupta and Kling 2011) displayed in the Eq. 1 in which M is simulated by model and O is observation or recorded data. m means mean or average observed data in the simulated points. T is number of simulated points. Moreover, root means square error (RMSE) was used as well displayed in the Eq. 2

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

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

Ecological Expert System

The Mamadani fuzzy inference system was applied to develop the ecological expert system in which membership

Table 2 Characteristics of data driven model

Inputs	Output	Number of Hidden layers	Training methods
Band 1 Visible (0.43—0.45 μm) 30 m	Model 1: Depth, Model 2: TDS	Optimization of number of hidden layers (between 1 and 100 hidden layers)	Particle swarm optimization
Band 2 Visible (0.450—0.51 μm) 30 m			
Band 3 Visible (0.53—0.59 μm) 30 m			
Band 4 Red (0.64—0.67 μm) 30 m			
Band 5 Near-Infrared (0.85—0.88 μm) 30 m			
Band 6 SWIR 1(1.57—1.65 μm) 30 m			
Band 7 SWIR 2 (2.11—2.29 μm) 30 m			

functions and fuzzy rules were proposed by an expert panel. Figure 4 displays the workflow of the expert panel to develop fuzzy rules. An experienced ecologist who was familiar with the regional ecological characteristics contributed as the chief of the panel. Two other members including a water resource engineer and one of the regional environmental managers were involved in the panel. At the first glance, it might sound that increasing number of the members would increase the accuracy of the developed rules. However, some points should be considered in this regard. First, each main member of the panel might have an expert network who contributes in the development of the fuzzy rules indirectly. Furthermore, two external reviewers are engaged in the panel who their comments might change the developed fuzzy rules. However, reviewers' comments would not directly alter the rules. In other words, chief of the panel makes the final decision on the rules. The graph of developed rules will be displayed in the next section. Habitat suitability is defined between zero and one. Zero means the unsuitable habitats for the target species, while $HS = 1$ means the most suitable habitat for the species. A sample of verbal fuzzy rules developed in the present study is presented as follows:

“If depth is medium AND TDS is high, THEN habitat suitability is MEDIUM”

Optimization System

The present study developed a novel environmental objective function in which difference between natural and optimal habitat suitability of the lake as well as difference between total inflow and optimal water supply. In other words, the

optimization model might balance the ecological requirements and humans' needs which is able to provide an optimal ecological water requirement for the lake. Equation 3 displays the objective function of the proposed framework, where $NUSH_t$ is unit habitat suitability in the natural flow, $OUSH_t$ is unit habitat suitability in the optimal environmental flow, TI_t is total inflow to the lake and TW_t is total water supply. $P1_t$ is a penalty function, which was added to the function due to considering a constraint in the optimization model. More details will be presented in this regard.

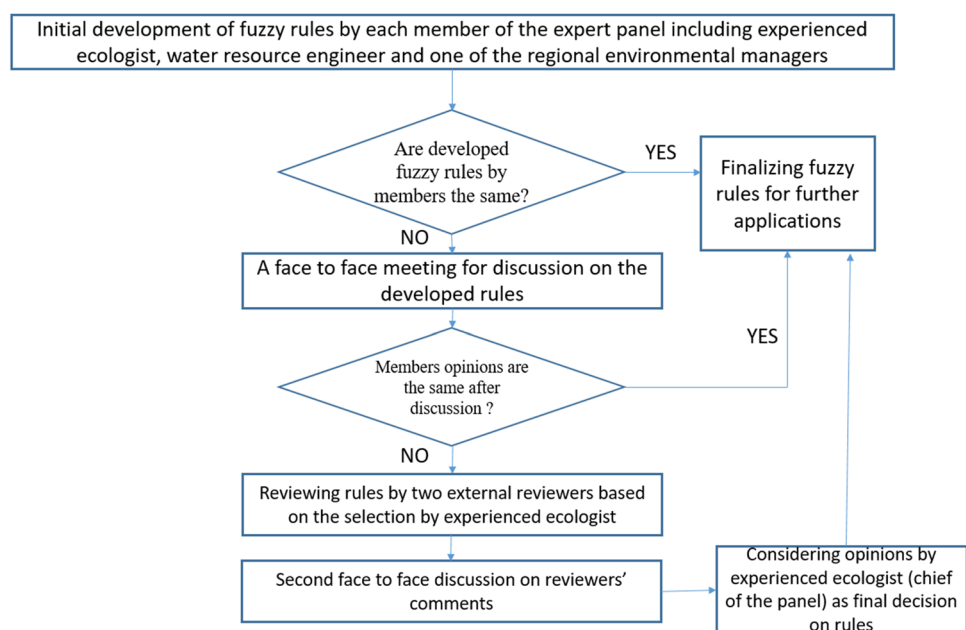
$$\text{Minimize}(OF) = \sum_{t=1}^T \left(\frac{NUSH_t - OUSH_t}{NUSH_t} \right)^2 + \left(\frac{TI_t - TW_t}{TI_t} \right)^2 + P1_t \quad (3)$$

It matters to explain how to compute the unit habitat suitability (USH) in the natural flow as well as optimal environmental flow. Equation 4 displays computational relation to estimate unit habitat suitability where SI_n is suitability index in the cell, a_n is area of the cell and A is total area of the simulated domain.

$$USH = \frac{\sum_{n=1}^N (SI_n * a_n)}{A} \quad (4)$$

Optimal water supply or optimal off stream flow will be calculated based on difference between optimal environmental flow and total inflow in each time step. Adding constraints might be essential in each optimization system. In the proposed optimization model, we considered a constraint in the model which is helpful to have minimum environmental flow in the river. According to the hydrological studies in the rivers, 10% of mean monthly flow should be available in the rivers

Fig. 4 Workflow of using expert opinions for developing fuzzy rules



to sustain the ecological status of the rivers (More details on Tessman method by Karimi et al. 2017). However, it might not be enough to sustain the ecological status of the lake. Hence, minimum environmental water requirement in each time step should not be less than 10% of mean monthly inflow to the lake. It should be noted that optimization model might increase the needed flow to the lake due to ecological needs of the lake compared with the assessed minimum environmental flow in rivers. The penalty function is a known method to add constraints in the optimization model which is recommended in many previous water resources studies. Thus, we applied this method in the present study in which the Eq. 5 was developed as the penalty function and added to the objective function. It was needed to update the storage of the lake in each time step which was carried out by Eq. 6. As presented, developed relationships in the previous studies were applied to convert the storage to the water level or surface area of the lake, if needed. The genetic algorithm as a known and classic evolutionary algorithm was utilized to optimize environmental water requirement in present study (more details on this algorithm by Katoch et al. 2021). In the Eqs. 5 and 6, S is storage of the lake, V is evaporation from the surface and AL is area of the lake. Moreover, ENV is environmental water requirement and $Minenv$ is minimum water requirement defined in the optimization model.

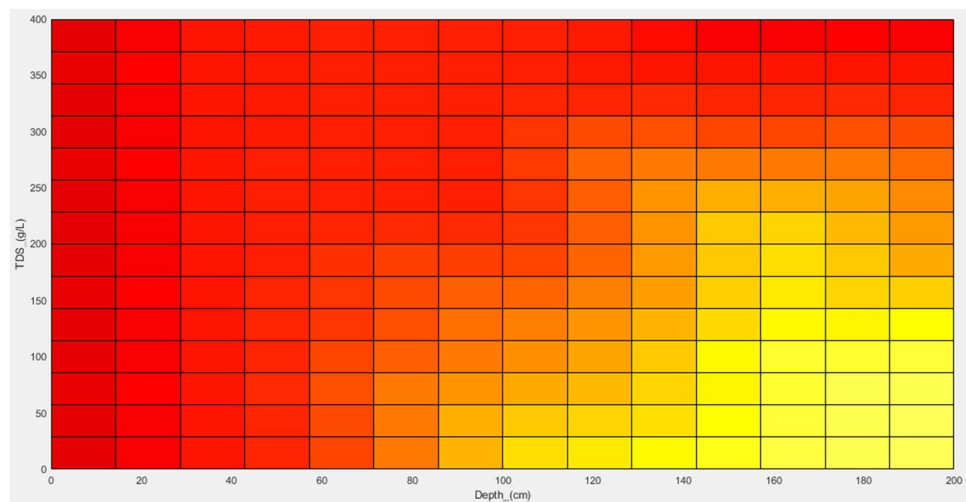
$$if ENV_t < Minenv_t \rightarrow P1_t = c3 \left(\frac{ENV_t - Minenv_t}{Minenv_t} \right)^2 \quad (5)$$

$$S_{t+1} = S_t + TI_t - TW_t - \left(\frac{V_t * AL_t}{1000} \right), t = 1, 2, \dots, T \quad (6)$$

Results

First, it is required to display the results of developing fuzzy habitat rules for the target species. Figure 5 displays the pseudo-colour plot of the fuzzy rules in which inputs are the axes and habitat suitability are shown by changing colour in the plot. Dark red means the lowest suitability, while the yellow colour means the highest suitability of the habitats. Low depth and high TDS provide the lowest habitat suitability in the study area, which seems logical. In fact, environmental tensions are high in this condition. Conversely, high depth and low TDS is able to maximize the suitability in the Artemia's habitats. Developed rules were applied to generate the suitability maps in the study area. In the next step, results of model development should be presented. Figure 6 displays the results of testing process of the model in which NSE is shown as well. It should be noted that the optimal number of hidden layer for depth and TDS models were 24 layers and 9 layers respectively. It seems that the performance of depth model is robust and reliable because NSE is 0.9. The highest value of NSE is 1 which means the model and observations are completely similar. According to the literature, when NSE is more than 0.5, the model is robust for further applications. Thus, depth model is reliable to generate distribution map in the lake. RMSE is low which implies the model is reliable in terms of mean error as well. In contrast, the outputs of testing process indicate that TDS might not be as robust as the depth model, which might be reasonable. In fact, more unknown factors might be effective on the TDS that might weaken the robustness of the model. However, NSE of TDS model is close to 0.5 which means the performance of the model is acceptable in terms of predictive skills. Moreover, RMSE of TDS is more or less low compared with the range of recorded data in the lake. Hence, TDS model could be used for further applications as well.

Fig. 5 Pseudo-colour plot of the fuzzy rules



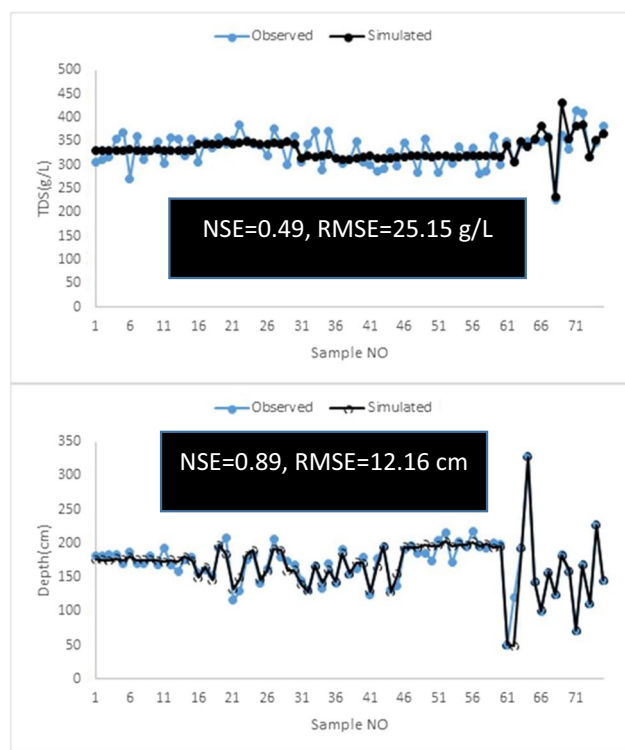


Fig. 6 Results of testing process of two data driven models (Up: TDS model, Down: depth model)

In the next step, it is necessary to present the results of simulating the distribution map of depth and TDS as well as generated habitats suitability map in the simulated region of the lake. As presented, twenty spectral images were used to simulate the ecological status in different water level of lake and total inflow of the lake. It should be noted that we considered these two factors to develop multivariate linear model. In other words, available storage in the lake or water level and inflow were considered as the variables in the regression model which was applied in the optimization model. As a sample of results simulated depth and TDS distribution map and habitat suitability map for one of the used spectral images are displayed in Fig. 7. Moreover, Fig. 8 shows the multivariate linear regression in which USH in different water level and inflow could be modelled. NSE and RMSE were utilized to evaluate the multivariate linear model as well. As displayed in the Fig. 8 and based on previous explanations on these indices, the multivariate linear model is robust and reliable for using in the structure of the optimization model.

In the next step, the outputs of the optimization model as the main results of this study should be presented. Figure 9 displays the direct results of optimization model in which flow time series, water level time series and USH time series are observable. It seems that considerable portion of inflow should be allocated to the environmental water requirement,

which implies minimum environmental flow defined in the rivers is not adequate to sustain the ecological status of the lake. However, off stream flow is remarkable in some time steps, which means the optimization model is able to balance the water demand and environmental demand in the lake ecosystem. Water level time series demonstrate that the available water level might be reduced considerably due to having the optimal environmental flow in the lake. The difference between average water level in the natural flow and the optimal environmental water requirement is 1.49 m which implies the impact of optimal water abstraction might be significant on the water level. However, water level might not be an appropriate criterion to assess the environmental suitability of the lake. Based on the results, the optimization model is able to minimize difference between habitats suitability for the natural flow and the optimal environmental flow which indicates the robustness and capability of the model to optimize environmental water requirement. Mean difference between habitat suitability in the natural flow and the optimal is less than 0.2 which indicates how the optimization model is able to mitigate environmental impacts in the lake, while the water supply is maximized.

Discussion

The optimization model allocated the 60% of total inflow in the simulated period to environmental water requirement, while 40% was allocated for supplying potential demands in the study area. It seems that the optimization model is able to balance ecological needs and humans' needs in the lake basin. It should be noted that the current environmental flow regime in the rivers is lower than proposed environmental water requirement by the present study. Hence, using the proposed method is recommendable due to integrating lake and river in the environmental flow assessment.

The water level has been considered as the key parameter in many previous studies to assess the environmental water requirement in the lake. However, the outputs of the present study indicated that this parameter creates a misconception regarding the real environmental needs of the lake. In other words, rate of inflow is important which should be highlighted on the future studies of environmental water requirement in the lakes. In fact, the inflow changes the rate of pollutant in the lake which is effective for changing distribution of water quality factors such as TDS. This study presented an approach based on computing of habitat suitability map in the lake in which change of water level is one of the effective factors to alter the habitat suitability in the lake habitats. Thus, it is recommendable to apply the habitat suitability maps in the future studies for assessing real ecological needs of the lakes. Generally, hydrological models have extensively been utilized to assess the ecological

Fig. 7 Simulated ecological status by proposed method (March, 2013)

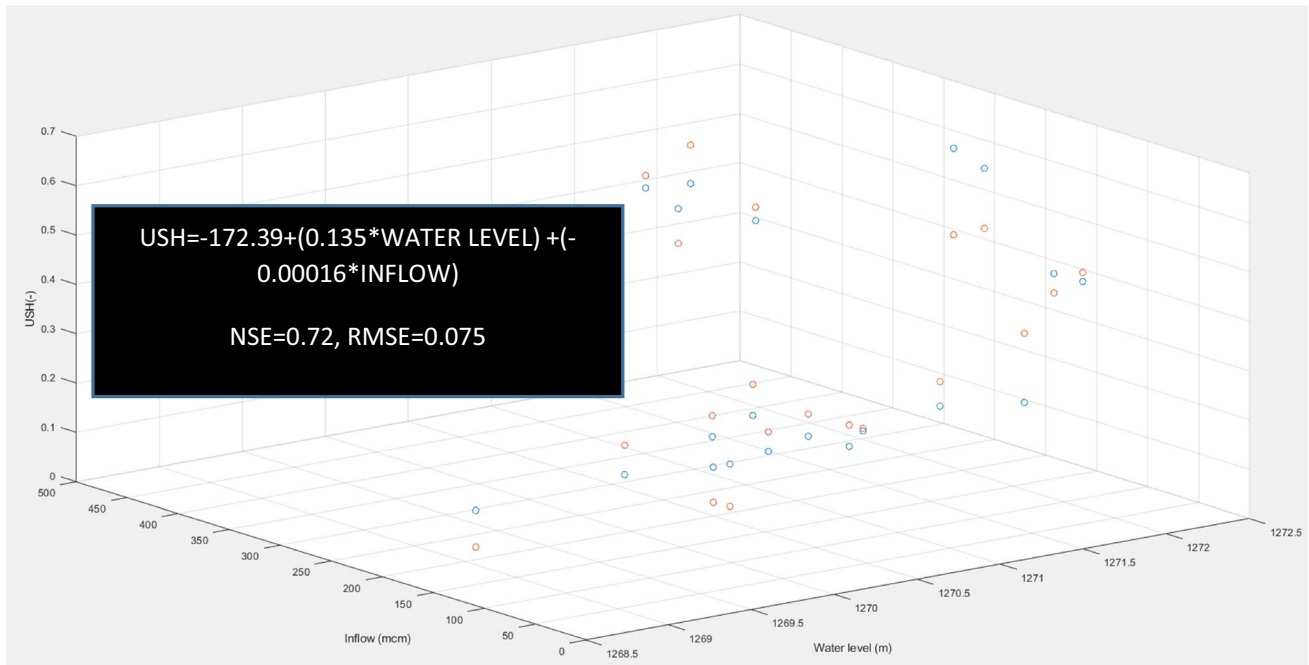
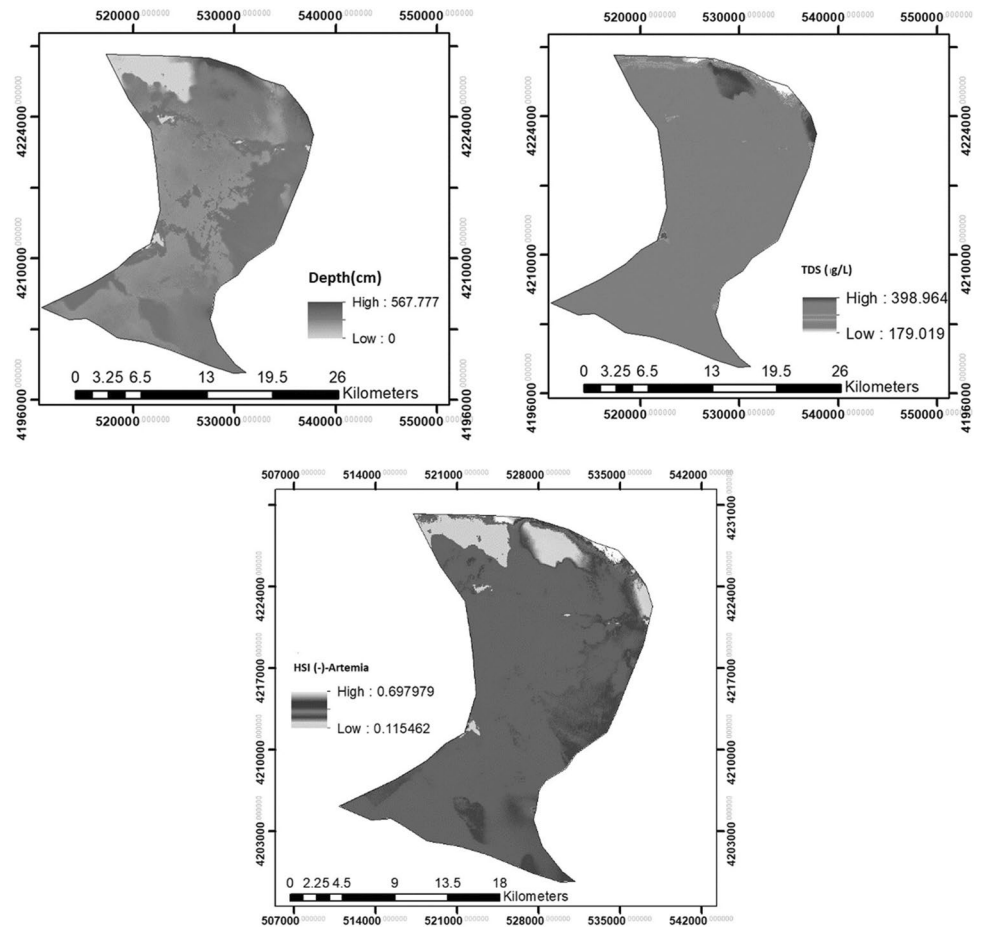


Fig. 8 Multivariate linear model of habitat suitability assessment (Blue points: linear model, Red points: computed by Eq. 2)

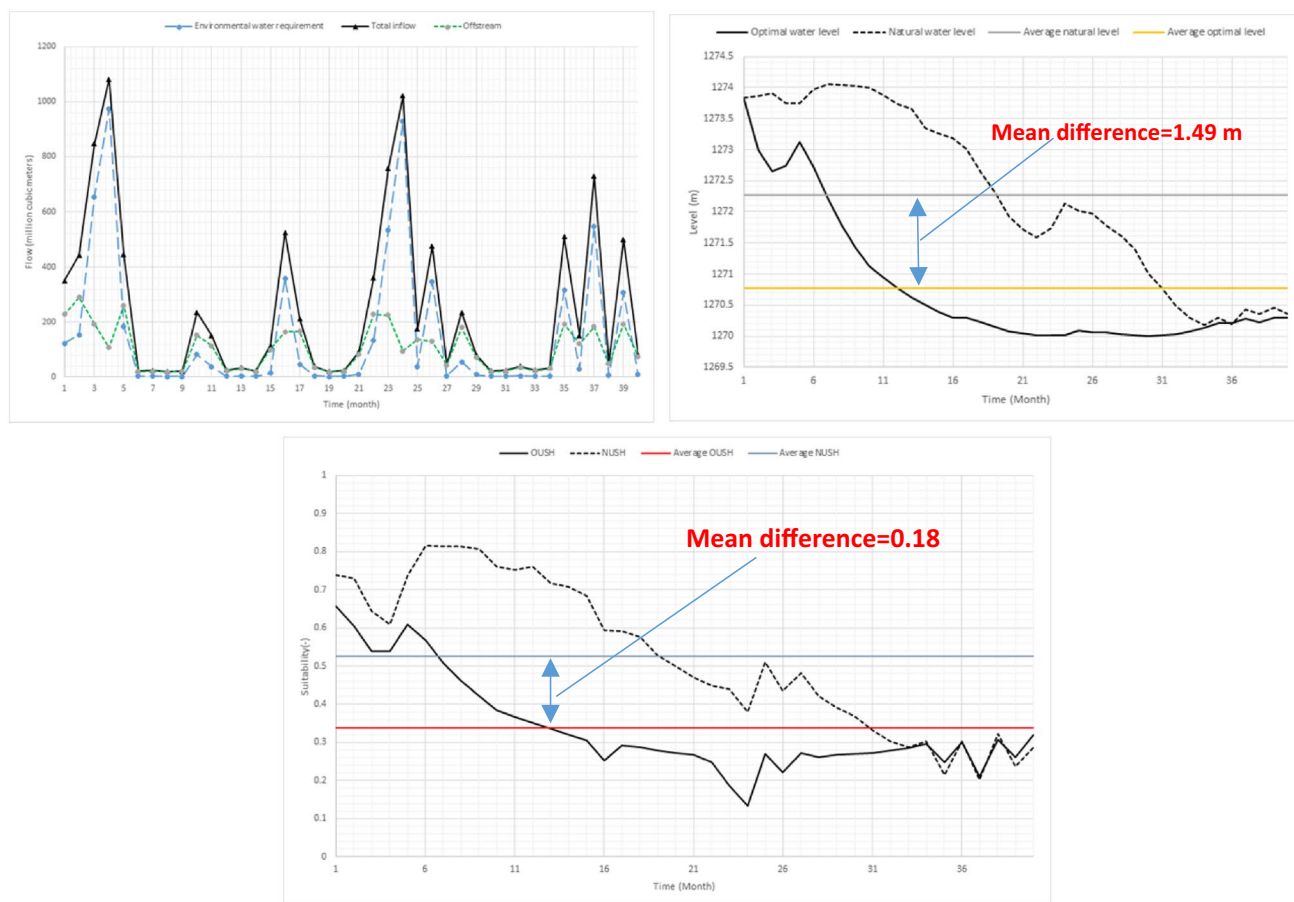


Fig. 9 Results of assessing environmental water requirement

flow in many previous studies. However, the present study demonstrated that using hydrological factors might increase the negotiations between environmental managers and stakeholders because underestimation and overestimation of the environmental water requirement is a significant weakness of the hydrological indices. Moreover, most of the previous studies in which the ecological indices have been applied to assess environmental water requirement were not able to generate the habitat suitability map of the lake linked with the environmental flow optimization.

The proposed method applied remote sensing in the assessment of the environmental water requirement which is a helpful and novel step to improve the environmental flow models. It should be noted that remote sensing is the most applicable available tool to simulate the suitability distribution map in the lakes which implies current methodology is recommendable to assess environmental water requirement in other case studies. Furthermore, an ecological expert system based on fuzzy approach was developed in this study which would have considerable strengths compared with other machine learning and statistical methods. Given the complexities of habitat selection by aquatics which is

influenced by different and unknown parameters, utilizing expert opinions is a favourite method in many cases. In fact, observations by ecologists or environmentalists accompanied by recognizing the most effective abiotic factors would be able to cover the weaknesses of absence of identifying unknown effective parameters in the habitats. It seems that using fuzzy expert system is advantageous compared with the conventional methods of machine learning in terms of technical and economic aspects. First, using machine learning models need extensive field studies in which measuring many abiotic factors is expensive and time consuming. Furthermore, these field studies are carried out in a limited time which means the historical observation in the lake habitats could not come to picture in the modelling process. Conversely, applying expert opinions is able to apply the old and qualitative observations in the habitats.

Two main limitations should be discussed regarding the proposed method. First, lack of experienced experts who are skilled and familiar with regional ecological status is a problem in many regions of the world, which means using the proposed method is not possible in these regions. Moreover, the present framework needs to simulate suitability

maps through remote sensing analysis, which increases the computational cost including time and memory for the large regions. It should be noted that numerous simulations are needed to develop an accurate model.

It is required to analyse the outputs of the present study compared with the previous studies. Some previous studies applied the environmental flow models of the river such as wetted perimeter method to assess the environmental needs of the wetland (e.g. Gholami et al. 2020). However, these methods are not reliable method to assess environmental water requirements of the wetland due to incapability to generate the habitat suitability maps of the wetland ecosystem itself, which is a significant weakness for these types of methods. Ecohydrological methods have been recommended in the literature as well (e.g. Modaberi and Shokoohi 2019). However, lack of direct relationship between changes of habitat suitability in different regions of wetlands and assessment process of the environmental water requirement is an important shortcoming in these methods. Some recent studies applied ecological indices for assessing environmental water requirement. However, the average indices for the wetland was used which means accurate ecological assessment throughout the wetland ecosystem was not considered due to lack of using robust methods such as remote sensing techniques. A general drawback of all previous studies in the assessment of environmental water requirement of the wetlands is lack of optimization framework of the water resource management, which would weaken the applicability of the models in practice. The current method covers these two drawbacks including direct use of suitability maps of wetland and applying a water resources optimization model in the assessment process of the environmental water requirement of wetlands.

It also matters to highlight the main advantage of the developed method, which is helpful for further applications of this novel method. The wetland or lake ecosystem are complex ecosystem, which are not easily assessable. In fact, suitability of the habitats is spatially different which means assessing ecological indices by simulating suitability in some limited points is not reliable. Hence, generating habitat suitability maps in the wetlands is essential to assess ecological requirement in advanced assessment. The present study steps toward the accurate ecological assessment of the wetlands by generating habitat suitability maps in which key factors such as depth and TDS are considered. We applied remote sensing methods to assess effective factors, which is able to cover whole surface of the wetlands using satellite images. In fact, using remote sensing data processing is one of the strengths of the present study which makes it possible to assess the whole surface of the wetland. Furthermore, expert system was applied to overcome the complexities of interactions between parameters for estimating ecological suitability for target species. Mentioned points are the ecological advantages of the proposed method. However,

we proposed a method for improving the available methods not only in terms of ecological models but also in terms of water resources management. The results of the habitat suitability maps were used in the water resources optimization, which is able to balance the environmental needs and humans' needs. Hence, the proposed method could be attractive either for ecologist or water resources engineers for improving environmental management of the wetlands.

It is needed to clarify the application of the proposed model in this study. We developed a novel model which is applicable for a wider context which means the proposed model is useable for all wetlands. However, some changes in the structure of the model is needed based on the environmental requirement of the case study. In the present study, we customized the proposed method for hypersaline lakes as one of the important inland water bodies. The Urmia lake is currently under environmental stress due to lack of inflow. Hence, it is needed to reassess the environmental water requirement based on real needs of the habitats. The proposed method provides a scientific framework to assess environmental water demand of the lake for having a sustainable ecological status. Inflow to the lake is currently much less than assessed environmental water by the proposed method which means using old methods of environmental flow assessment is not able to provide sustainable ecological status for the aquatic species especially *Artemia* as an important environmental indicator in the lake. Hence, it is recommendable that regional environmental managers replace the old methods of environmental water assessment with the proposed method to balance environmental requirement and water demands.

Some points are recommendable for the future studies, which should be highlighted as the future research needs. Economic consequences of applying optimal environmental water requirements proposed by the present study should be investigated to clarify limitations in the development of the regional communities. Moreover, habitat based model of the rivers could be linked to the ecological model of the lake. However, it increases the complexities of the model remarkably. Using combination of different target species would be recommendable in some cases due to simultaneous importance of different species for ecological manage of the lake. Finally, it is generally recommendable to change the view of assessing environmental water requirements from simple statistical methods to advanced remote sensing based methods for improving the ecological management of the lakes.

Conclusions

The present study developed a novel method to optimize environmental water requirement in the lakes in which remote sensing data processing and ecological expert

systems are linked. The main advantage of this method is to generate habitat suitability maps in the lake coupled with the environmental water optimization model. Based on the results in the case study, this method is able to balance the ecological needs and water supply by reducing habitat loss to less than 20% compared with the natural inflow. 60% of total inflow in the simulated period was allocated to the environmental water requirements and rest of the available inflow was allocated to supply the water demand. The proposed method is able to minimize negotiations between stakeholders and environmental managers by effective use of advanced modelling methods.

Authors Contributions MS is responsible for writing of the manuscript and related programming and calculations. AA is responsible for data collection and reviewing the research work.

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Data Availability Some or all data and materials that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests Not applicable.

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