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Linking catchment and hydrodynamic models for environmental flow analysis in hypersaline lakes

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ABSTRACT

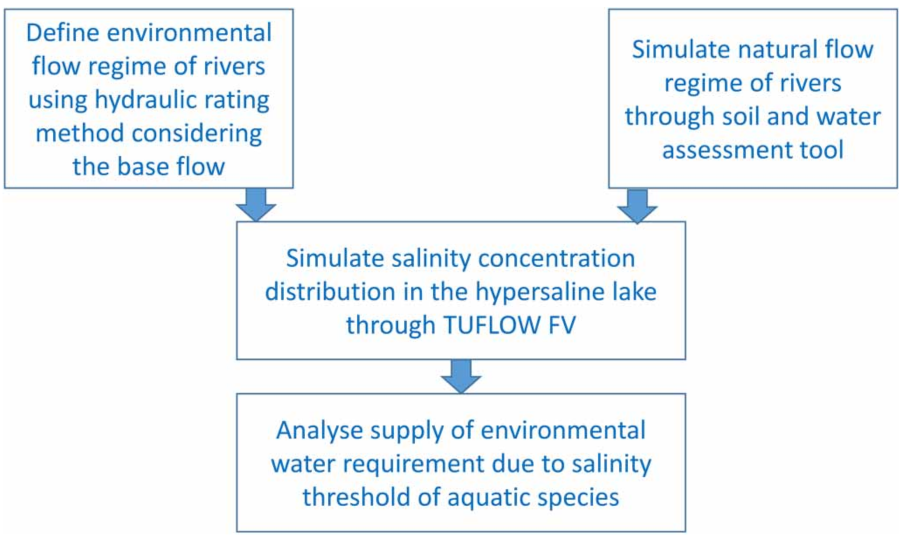
This research work proposes a novel method of environmental flow analysis in hypersaline lakes in which the outputs of the hydraulic rating method considering the base flow as a known approach for environmental flow assessment in rivers are analyzed in terms of providing suitable aquatic habitats in the lake by linking a continuous hydrological model and a hydrodynamic model of salinity simulation. Soil and Water Assessment Tool (SWAT) as a hydrological model was applied to simulate the natural inflow of the lake's ecosystem in the simulated period. Moreover, a hydrodynamic model was applied to simulate the salinity distribution of the lake in the same simulated period. Based on the results of the models and monthly analysis of the environmental flows, both models are robust for simulations. The Nash–Sutcliffe Efficiency (NSE) of both hydrological and hydrodynamic models average more than 0.5, which means that they are reliable for simulating the natural inflow and salinity distribution respectively. Furthermore, outputs indicated that using the hydraulic rating method considering the base flow for assessing the environmental flow of rivers is not able to provide environmental requirements in the lake's ecosystem of the case study.

Key words: environmental flow analysis, hydrodynamic modelling, hypersaline lakes, salinity simulation, Soil and Water Assessment Tool

HIGHLIGHTS

- New method for environmental flow analysis.
- Linking catchment model and hydrodynamic model.
- Assessing environmental flow supply.

GRAPHICAL ABSTRACT



INTRODUCTION

Population growth, development and climate change are significant environmental threats to inland water bodies' habitats which probably escalate in future years (Chen *et al.* 2020). These threats cause the loss of suitable habitats for both aquatic and terrestrial species which are dependent on the ecosystem of rivers or lakes. Due to the importance of protecting these habitats, the concept of environmental flow has been defined, which refers to the amount of required flow to provide sustainable ecological status (Kumar & Jayakumar 2021). Many methods have been proposed to assess environmental flows in rivers (reviewed by Williams *et al.* 2019). Some simple methods such as hydrological or desktop ones use the historical flow of the river to assess the environmental flow regime. In contrast, other complex methods such as physical habitat simulation apply ecological impact functions. It should be noted that desktop methods are much cheaper than complex ecological methods (more details by Książek *et al.* 2019). However, they might not be fully reliable due to simplifications in the structure of the method. Some studies highlighted the importance of environmental flow downstream of dams (Yin *et al.* 2012; Cai *et al.* 2013). Apart from rivers, lakes' habitats should be protected in which concept of environmental water requirement has been defined as well. In general, defining an appropriate water level in the lake called ecological level is used to assess environmental water requirements (Yang *et al.* 2020). As a description of this method, if the water level in a lake is higher than the predefined minimum level, the sustainable ecological status might be guaranteed. It should be noted that lakes and rivers are interdependent habitats in some cases, so environmental flow assessment in rivers should be based on the ecological requirements of the lakes. In other words, integrated assessment in rivers and lakes is necessary.

The hypersaline lakes are one of the important ecosystems with their special environmental requirements (Anufriieva 2018). Due to high salinity concentration, some certain species can live in these lakes and the protection of these lakes might require application of some specific methods and models. Based on the nature of hypersaline lakes, salinity concentration is one of the most important parameters for evaluating ecosystem health. In other words, a huge increase in salinity concentration might destroy suitable habitats. Based on previous studies, different methods and models are applicable to simulate the water quality of lakes and estuaries. It should be noted that water quality parameters are the most important factors in assessing ecosystem health in terms of the impact of abiotic factors. The hydrodynamic models are popular methods to simulate water quality parameters in lakes, which have been successfully developed in many previous studies. The distribution of water quality parameters in lakes is of great importance for evaluating the health of an ecosystem. Hence, hydrodynamic models can be used as one of the reliable tools to analyze water quality distribution.

Due to the focus of this study on using a hydrodynamic model, it is essential to have a brief review of their applications in the water bodies. Hydrodynamic models have been conventionally applied for the simulation of water quality in the freshwater and saltwater water bodies (Wu *et al.* 2019). Due to changing geomorphological features, the hydrodynamic processes and the water quality distribution might be different case by case in the lake or estuary ecosystems. According to the literature, interior freshwater lakes have been highlighted, while the hydrodynamic models of saltwater lakes have not been broadly addressed. The complexities of the interactions between freshwater and saltwater ecosystems might be a significant challenge in the modelling of coastal lakes (Jones *et al.* 2016). The previous studies indicated that the ecological models in the lakes are highly sensitive to the hydrodynamics of the water bodies, which implies the importance of identifying hydrodynamic processes to simulate the ecological interactions (Toffolon *et al.* 2006; Khojasteh *et al.* 2021). Several models have been applied or recommended in the literature to simulate hydrodynamics of the lakes or estuaries. For example, the ocean model (FVCOM) has been used to simulate the hydrodynamic of the flows in lake El-Manzala, Egypt (Bek *et al.* 2010). Some commercial models are known and popular in the world in this regard. MIKE package is one of the known commercial models, which might be useable in the lake or estuaries for simulating hydrodynamics of pollutant transfer (more details by Li *et al.* 2020). Moreover, EFDC + or Delft3D are other useful packages, which have been developed and applied in recent years (e.g. Baracchini *et al.* 2020; Madani *et al.* 2022). It should be noted that selecting an appropriate hydrodynamic model is a location-based task, which means that all different regional and managerial factors might be effective in selecting the best model for each study. TUFLOW FV is another option to simulate hydrodynamic processes in saline water habitats. The TUFLOW FV is useable in a wide range of problems from hydraulic modelling of rivers to hydrodynamic modelling of lakes or estuaries. This model, which was originally developed and supported by the environmental protection agency of the US, is able to solve the turbulent equations of motion for an incompressible and variable density fluid. This model uses the basic concept of conservation laws of energy, mass and momentum for the flows. Using this model has been addressed in previous studies to solve a wide range of problems in the management of saltwater and freshwater ecosystems and complex interactions between these water bodies. Due to the need for reliable tools for numerical modelling and visualizing the results, the TUFLOW FV might be a powerful option to simulate the hydrodynamics of hypersaline lakes.

According to the literature, on the one hand, the environmental flow models of rivers and lakes are not integrated. On the other hand, many known environmental flow methods of rivers estimate the instream flow regime ignoring impacts of water quality parameters at downstream lakes, which might destroy suitable habitats. This problem should be highlighted in hypersaline lakes because the usual environmental flow methods of rivers as the lake inflow do not analyze the secondary impacts on the salinity concentration in the lake. Thus, environmental flow analysis in the hypersaline lakes is necessary to assess the appropriateness of the flow regime in terms of protecting saltwater habitats. In other words, designing new methods for environmental flow analysis of hypersaline lakes is helpful in estimating how assessed environmental flow regimes in rivers connected to the lake are able to protect saltwater habitats. Due to this research gap, this study presents a novel method of environmental flow analysis in which the outputs of the hydraulic rating method considering the base flow as a known method for environmental flow assessment in rivers are analyzed using a linked continuous hydrologic model- hydrodynamic model in a hypersaline lake's ecosystem. In other words, the present study applies TUFLOW FV to simulate the distribution of salinity concentration in a hypersaline lake. In salinity simulation, the natural flow regime simulated by the Soil and Water Assessment Tool (SWAT) and the environmental flow assessed by the hydraulic rating method considering the base flow are considered as the boundary conditions. Based on the outputs, we are able to investigate the effectiveness of the proposed environmental flow regime in rivers to protect the lake's habitats. This research might broaden the horizon of applying hydrodynamic models to analyze the ecosystem's health of hypersaline lakes.

METHODS

Case study and overview of the methodology

The Urmia Lake is one of the largest hypersaline lakes in the world located in the northwest of Iran between the West and East Azerbaijan provinces. This lake matters in terms of tourist attractions and environmental values in the northwest of Iran. In recent years, due to population growth and increasing irrigation demand, the lake inflow has decreased drastically which consequently causes exceeding the salinity of the lake compared with the natural condition. Some areas have been dried up by considerable reduction of the inflow. The natural outflow of the lake is evaporation currently. Undeniably, the frequency and intensity of droughts have increased in recent decades. However, water abstraction projects in rivers are the main culprit to reduce inflow and consequent environmental impacts. All these threats have caused significant damage to both aquatic and terrestrial species which need suitable habitats for the lake. Figure 1 shows the location of the Urmia Lake.

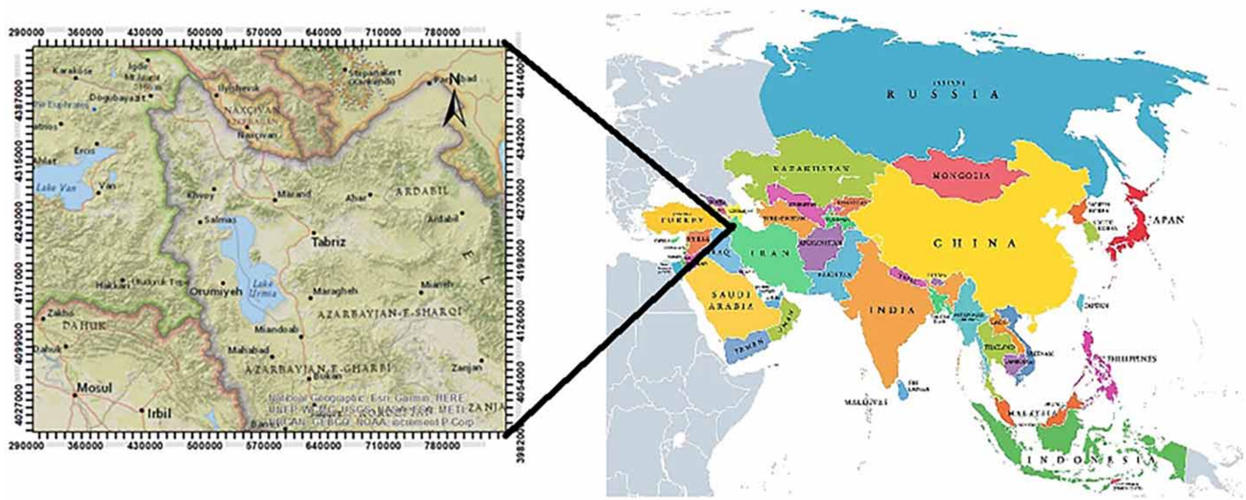


Figure 1 | Location of the Urmia Lake in northwest of Iran.

According to the initial ecological surveys in the Urmia Lake, *Artemia* is a known species in this lake that can live in high salinity. This valuable species can be a suitable environmental indicator to evaluate the ecosystem health of the Urmia Lake or ecological assessment of the habitats. *Artemia* lives in this lake throughout the year which means that it could be selected as a reliable environmental indicator in this study. Figure 1 shows the location of the lake in the northwest of Iran. Based on hydrological and field studies, eight rivers are the main suppliers of the Urmia Lake as shown in Table 1. The assessment of the environmental flow is carried out in these rivers. In contrast, due to high temperatures especially in summer, a significant amount of water is evaporated from the lake annually. Agricultural activities are of great importance for people living in the catchment of the lake. All cultivated areas are highly dependent on river flow which means that reducing the inflow of the lake is currently a serious challenge for either the environment or farmers. Some rivers due to larger catchment size have more contribution to satisfying environmental water demand. However, each river has its own ecological values, which means that supplying environmental flow is essential in the rivers. Currently, there is a serious challenge to assess the environmental water demand of the lake. Some experts and regional managers point out that providing a predefined ecological level is sufficient to sustain the ecological status of the lake. In contrast, some ecologists believe that providing a predefined ecological level cannot guarantee the ecological suitability of the lake's habitats. In other words, abiotic factors especially the water quality of the lake should be simulated in the analysis of environmental water requirements. Hence, it is needed to develop an integrated method for environmental flow analysis in this hypersaline lake. The present study focuses on developing a novel method for analysing whether released water for the environment in the rivers is able to provide suitable habitats for the aquatics in the lake.

We used a hybrid method in which the hydrodynamic model plays a key role in simulating salinity as displayed in Figure 2. The environmental flow regimes of rivers were defined based on previous studies by the hydraulic rating method considering

Table 1 | Main sub-basins of the lake

Name of the river	Code	Total length (km)	Catchment area (km^2)
Zarrinehrood	R1	340	11,897
Siminehrood	R2	145	3,656
Mahabadchai	R3	80	152
Gadarchai	R4	100	2,137
Baranduzchai	R5	72	1,318
Shahrchai	R6	70	720
Nazloochai	R7	85	2,267
Rozechai	R8	51	453

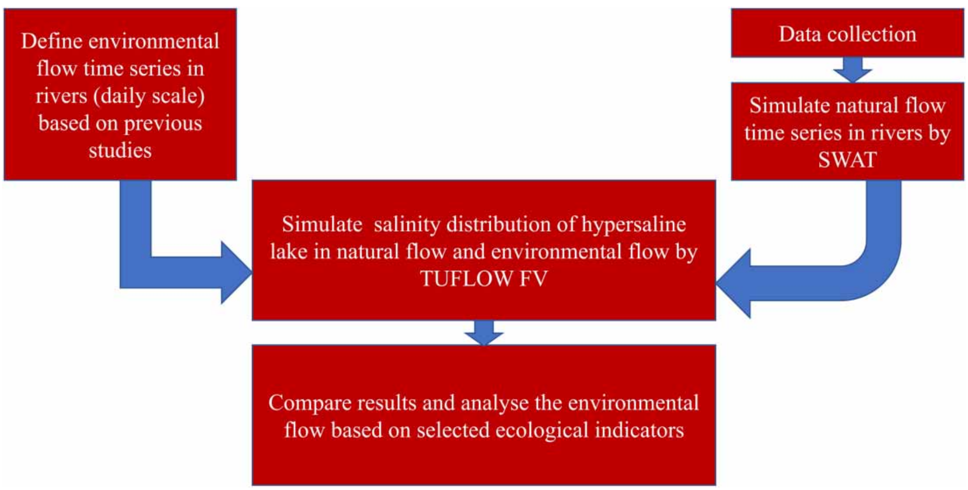


Figure 2 | Workflow of the proposed method.

the base flow. The environmental flow time series were used as the boundary conditions of the hydrodynamic model. The purpose of this study is to compare the environmental flow with the natural flow to assess the health of the lake's ecosystem for the selected target species as an environmental indicator. Hence, it is necessary to estimate the natural flow regime in the rivers as well. It should be noted that due to the construction of many hydraulic structures such as large dams and diversion dams, regulated inflow recorded at downstream hydrometric stations is considerably different from natural inflow. Hence, it is necessary to use a reliable hydrological method to estimate the natural inflow regime of the lake. In this study, a continuous hydrological model (SWAT) was used to estimate the natural inflow of the lake. The natural flow regimes were used as the boundary conditions in the hydrodynamic model as well. By hydrodynamic modelling in two statuses (i.e. natural flow regime and environmental flow regime), salinity distributions were compared and ecological flows were analyzed.

Environmental flow assessment in rivers

Different methods are available for assessing the environmental flow regime in rivers. One of the known methods for assessing environmental flow method is the hydraulic rating method, which applies the wetted perimeter concept to assess minimum environmental flow regime. In fact, this method considers the equivalent flow of the break point of the wetted perimeter curve in the graph of the wetted perimeter with respect to the river flow as the minimum environmental flow requirement. More details regarding this method have been addressed in the literature (Prakasam *et al.* 2021; Sedighkia *et al.* 2021). In this study, based on long-term environmental flow studies by the research team in the rivers as the inflow of the lake, minimum environmental flow by hydraulic rating method was not enough for providing minimum ecological suitability in rivers. Hence, 10% of the mean monthly flow was added to the minimum environmental flow of each month as the base environmental flow considering long-term hydrological analysis of the river flow regimes. Thus, the hydraulic rating method considering base environmental flow was applied to assess the environmental flow regime in rivers. Finally, the assessed environmental flow regime was used as the inflow of the lake in the hydrodynamic model.

Simulating natural flow using SWAT

The SWAT is one of the powerful hydrological models, which has been widely applied in previous studies (fundamentals of this model reviewed by Gassman *et al.* 2007 and Neitsch *et al.* 2009). This model is a continuous and physically based semi-distributed hydrological model in which daily data could be inserted and the output data could be generated on either a daily or monthly scale. Due to the extensive use of this model in previous studies, more details on the theoretical background are available in the literature.

SWAT includes several sub-models and components that can be used in different types of simulation in the catchment scale. In this study, we applied a continuous hydrological sub-model for simulating river flow in which the Green and Ampt Mein Larson (GAML) excess rainfall method (Mein & Larson 1973) is utilized for assessing infiltration in the daily step. SWAT version 2012 was applied in this study linked with ARCGIS/QGIS. Figure 3 shows the workflow for simulating the outlet of the catchment. Outputs should be calibrated and validated which is doable by SWAT CUP as a standalone software. A wide range of input data is required for simulation using this model including meteorological data (daily temperature and daily rainfall), spatial data (Digital Elevation Model-DEM), land use data, and the soil map of the water basin. In this study, the SWAT was applied for all 8 catchments which means that the natural inflow was simulated in the daily scale for a year as the selected simulated period. As the sample of input spatial data, the DEM and slope map for one of the river basins are shown in Figure 4. Using a suitable method for calibration and validation plays a key role in the modelling process by SWAT. SUFI 2 was applied for calibration and validation, which is one of the used methods in SWAT CUP. More details have been addressed in the literature (Abbaspour 2013; Abbaspour *et al.* 2015).

As presented, the natural flows are not available at downstream or immediately before the lake. In fact, we developed a hydrological model to simulate the natural inflow. However, it is needed to have a natural flow regime or close regime to the natural status for calibration and validation of the model in each catchment. Hence, we applied some recorded time series at upstream of the catchments in which the flow was close to the natural flow in the calibration process. Then, calibrated coefficients were adopted for simulating the downstream outflow of the catchments. More details on the main calibration coefficients by SWAT CUP have been addressed in the literature (Abbaspour 2013).

It is necessary to use appropriate indices to measure the performance of the hydrological models. In this study, Root Mean Square Error (RMSE) and Nash–Sutcliffe Efficiency (NSE) were used, which are shown in Equations (1) and (2). NSE is one of the most known indices for evaluating hydrological models, ranging from negative infinity to 1. NSE = 1 means that the

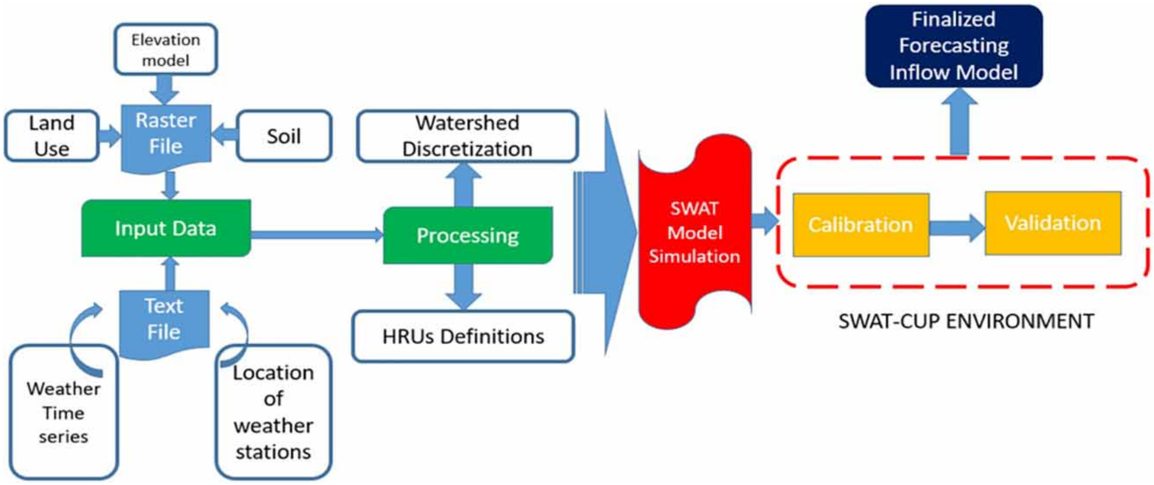


Figure 3 | Workflow of SWAT in the present study.

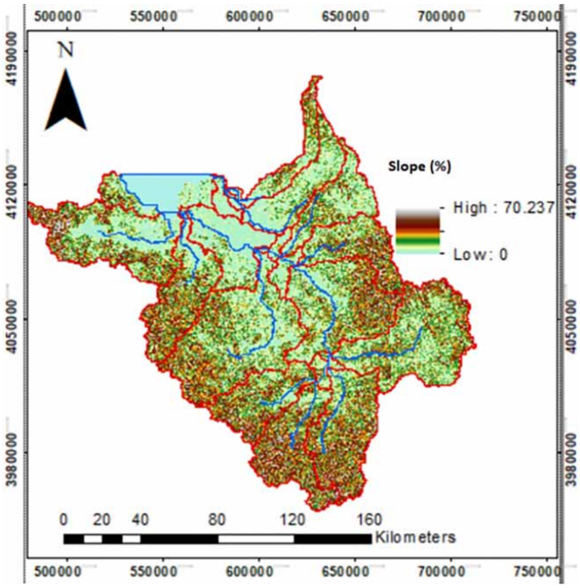


Figure 4 | Sample of spatial input data in SWAT, slope map of the Zarrinehrood basin.

model is perfect which is impossible practically. According to the recommendations in the literature, if the NSE of a hydrologic model is more than 0.5, the performance is robust, which means it can be used for further simulations. RMSE is another important index as well. A lower RMSE means a lower average error, which means that the model could be more acceptable. More details on these indices have been addressed in the literature (Gupta & Kling 2011).

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

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

where M_t is forecasted inflow by model in each time step, O_t is observed or recorded inflow in each time step and O_m is mean observed or recorded inflows in the simulated period and N is the number of data in the time series.

Salinity modelling by TUFLOW FV

The TUFLOW FV was applied to simulate salinity concentration in the present study. It should be noted that the hydrodynamic model by TUFLOW FV was calibrated in the selected area of the lake. More details regarding the background, theory and procedure for using this hydrodynamic model have been addressed in the literature (Armandei *et al.* 2021). However, Figure 5 shows the workflow of TUFLOW FV in this study. Moreover, Figure 6 displays the simulated area in the Urmia Lake in which the location of boundary conditions (rivers) and calibration points are displayed. Table 2 shows more details on the generated hydrodynamic model to simulate salinity distribution in the lake. It should be noted that we applied this model in two stages. First, the model was used for simulating one year in which inflows are known and salinity in some points of the lake was measured. By having acceptable results in the calibration/validation period, the model was applied to simulate another year in which natural flow and environmental flow by wetted perimeter method considering the base flow were applied to analyze the environmental flow. As a short description of the scientific methodology of TUFLOW FV, this mathematical model solves non-linear shallow water equations, which are a system of equations describing the conservation of fluid mass/volume and momentum in an incompressible fluid. The governed equations in this model conserve three variables including volume (depth), x-momentum and y-momentum. This fundamental system of flow modelling can be used for simulating hydraulic characteristics of river flow two-dimensionally (depth-averaged). Different modules have been developed which can be linked with the core model of TUFLOW FV to simulate other parameters. Advection-Dispersion module (AD module) is a module that allows users to assess the fate and transport of dissolved quantities, salt, temperature and all water quality constituents. The AD module can be applied to simulate the time evolution of salinity, temperature, suspended sediment, passive tracers and water quality constituents which deploys an Eulerian scheme to compute (numerical) cell average dissolved quantities. More details on the scientific method of TUFLOW FV are freely available in the scientific manual of this model (TUFLOW FV science manual 2013).

RESULTS AND DISCUSSION

It is necessary to present the results of the calibration of SWAT. Figure 7 shows the calibration results of SWAT in one of the rivers. As mentioned, two indices (RMSE and NSE) were used to measure the performance of the model as displayed in the Figure. Moreover, Table 3 shows these indices in other rivers. Based on the defined threshold of NSE in the previous section, it can be claimed that the generated hydrologic model is reliable to simulate the downstream natural flow regime or natural

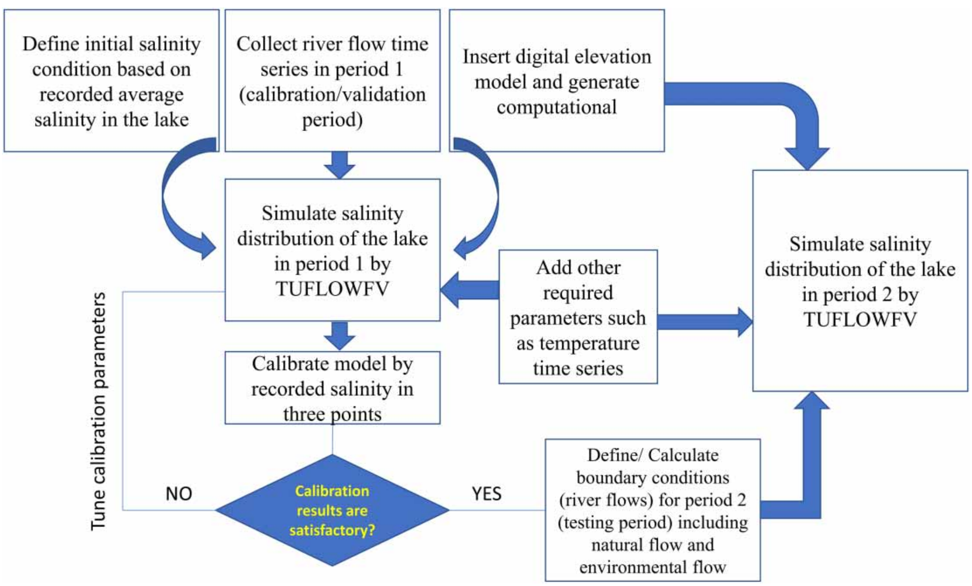


Figure 5 | Workflow of TUFLOW FV in the present study.

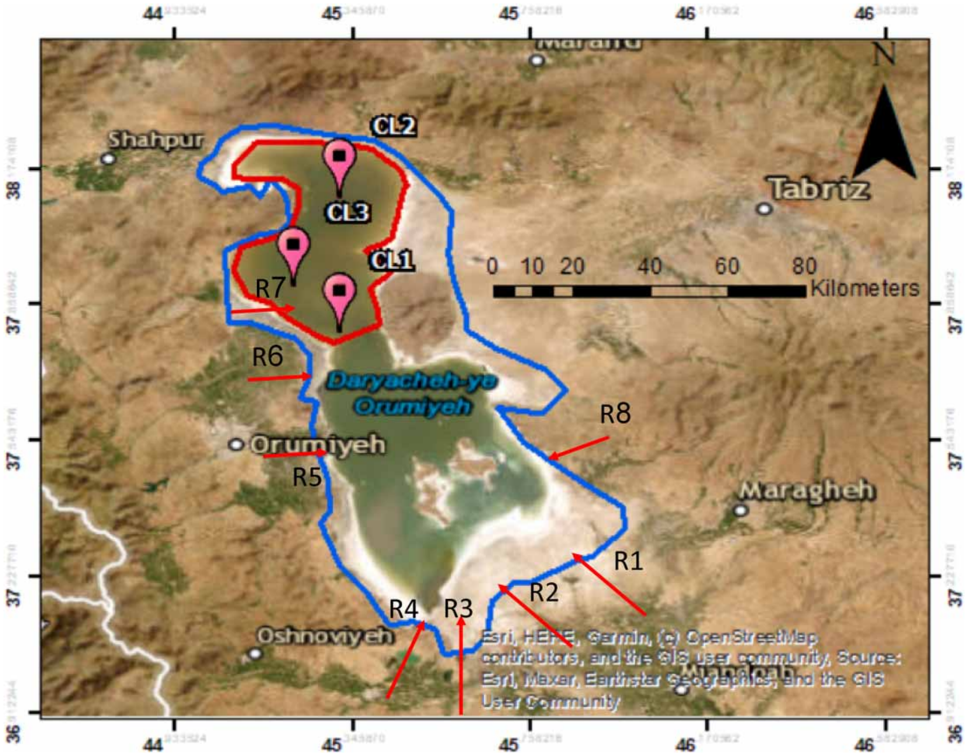


Figure 6 | Simulated area and location of boundary conditions (blue line: historic borders of the lake, red line: focused area in calibration/validation) – CL1 to CL3 are available points for recordings salinity in calibration of TUFLOW FV.

Table 2 | More details on generated hydrodynamic model for salinity distribution simulation in the Urmia Lake

Simulated periods	Period 1: 365 days for calibrating the hydrodynamic model of salinity Period 2: 365 days in the testing period for analysis of environmental flow (average monthly salinity distribution map was generated)
Initial condition (salinity)	Defined based on average salinity in CL1, CL2 and CL3 in the first day of simulation in each period
Initial condition (water temperature)	Defined based on average temperature in CL1, CL2 and CL3 in the first day of simulation in each period
Initial condition (water level)	Defined based on average water level in CL1, CL2 and CL3 in the first day of simulation in each period
Grid type	Curvilinear
Number of grid cells	21,725
Focused area	1,210 km²
Time step	5 s
External forcing data (flow)	Flow time series in 8 points of the boundary conditions (displayed in Figure 6)
External forcing data (wind speed)	One time series was used in the simulated period
External forcing data (including rainfall time series, evaporation time series etc.)	One time series was used in the simulated period

inflow of the lake. However, the accuracy of the model is more robust in some basins. Moreover, computed RMSEs show that low mean errors in all rivers provide several reliable models to simulate the natural inflow of the lake.

It is necessary to present the verification results of the hydrodynamic model as well. NSE and RMSE were applied for the hydrodynamic model. Figure 8 shows the observations and the simulated values by the modelling in three verification points as displayed in Figure 6. Moreover, Table 4 displays the NSE and RMSE in the verification points of the lake. The results show

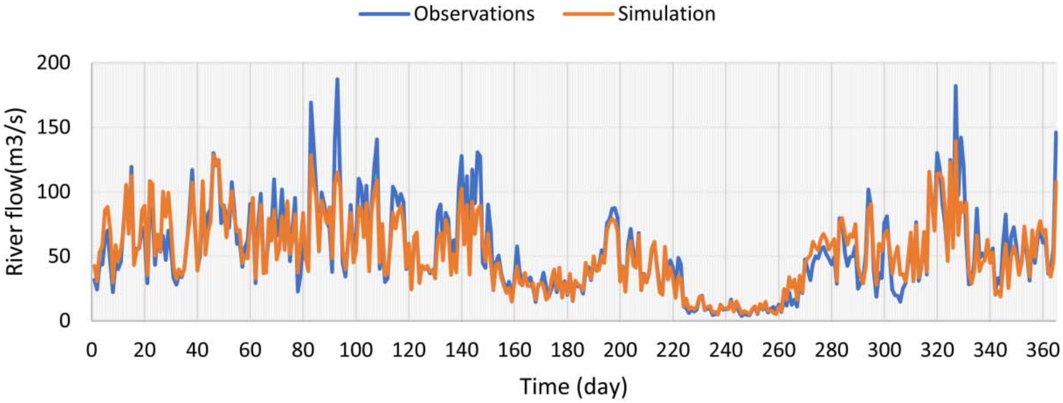


Figure 7 | Calibration/validation of SWAT at an upstream sub-basin of the Zarrinehrood River where the river flow is close to the natural flow.

Table 3 | Calibration/validation of SWAT in eight simulated river basins

Name of the river	NSE	RMSE (m^3/s)
Zarrinehrood	0.85	12.89
Siminehrood	0.74	1.52
Mahabadchai	0.58	0.41
Gadarchai	0.71	1.34
Baranduzchai	0.52	0.24
Shahrchai	0.65	1.1
Nazloochai	0.63	0.91
Rozechai	0.61	0.88

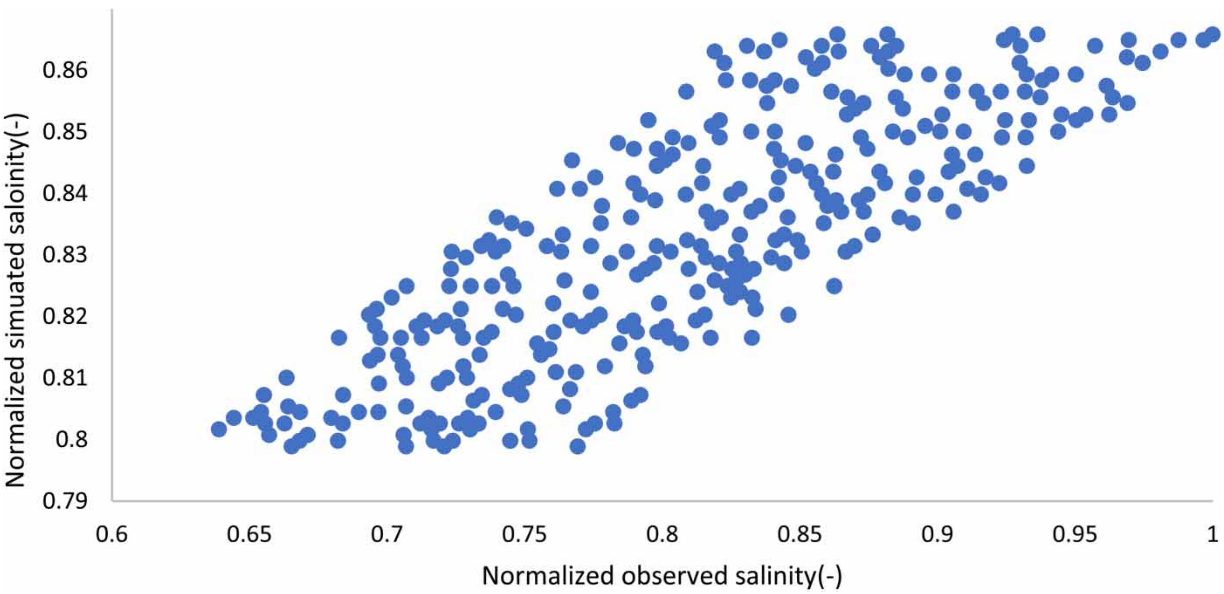


Figure 8 | Verification results of the hydrodynamic model in CL1.

Table 4 | Results of TUFLOW FV verification for simulating salinity concentration in three points

Verification points	NSE	RMSE (g/L)
CL1	0.421	15.3
CL2	0.534	10.2
CL3	0.506	13.4

that the NSE is more than 0.5 in two points, which means that the performance of the salinity model is acceptable for further applications. It is less than 0.5 in one point, which means that the performance of the model is not perfect. However, it should be noted that generating an accurate hydrodynamic model is an arduous task. In CL1, NSE is close to 0.5 which means that it could be acceptable. These results were obtained after several tries and errors by tuning the calibration parameters used in the model. An important point is the definition of the initial condition in the model. We defined an initial condition based on average salinity in some measured points of the lake in the first of the simulations in period 1. However, if recorded data in many points are available, the initial salinity distribution could be considered. In the case study, the lack of recorded data at many points was a problem in developing the very accurate model.

It matters that the results of this study could be useable practically. Thus, we applied a monthly scale in all environmental flow analysis because the environmental flow management in the Urmia Lake basin is monthly. In other words, environmental flow management in the daily scale is not practically possible which means that all environmental flow analysis should be carried out in the monthly scale. It is needed to discuss why managing environmental flow on a daily scale is not practically possible in the case study. First, flow measurement devices and tools are not accurate enough to control the flow regime of the rivers on a daily scale. Second, there is a monthly-based contract for delivering water to the farmers, which means that the farmers are authorized to manage daily flow by themselves based on permitted monthly water abstraction. Third, the long-term operation of the reservoirs in the catchment is monthly scale. All these requirements mean that the environmental flow management plan should be on a monthly scale. Hence, all daily results regarding environmental flow analysis were converted to the monthly scale in this section by arithmetic averaging. Due to the accuracy of SWAT in all rivers, this model was applied in the simulation of the natural inflow as shown in Figure 9. The proposed monthly environmental flow regimes are displayed in this Figure as well (proposed by Abdoli *et al.* 2018). In the present study, we defined a threshold of salinity for the selected environmental indicator or species. As presented, Artemia was selected as the target species which can live in salt waters without biological tension, if the salinity concentration is less than 270 g/L based on the expert opinions in this case, the habitats will be suitable. Increasing salinity will raise biological tensions for the target species. We applied this threshold in all the environmental analysis.

Next, the simulation results using the TUFLOW FV should be displayed. Figures 10 and 11 show the salinity distribution in the Urmia Lake for different months in two different statuses including natural and environmental inflow regimes. The results show that reducing inflow has a significant impact on the distribution of salinity in the lake, compared with the natural flow in some months. It should be noted that we simulated one of recent years in which a mild drought was experienced which means that biological tensions might be occurred in the natural flow as well. Based on Figures 10 and 11, salinity concentration in the natural flow in some months at least in some parts of the lake, especially summer is higher than the predefined threshold which means that some habitats are not suitable naturally. Hence, it is critical not to increase the biological tensions by the environmental flows. However, results indicate that the proposed environmental flow regimes in rivers are not satisfactory in terms of protecting the habitat suitability of the Urmia Lake because the minimum salinity in the lake in spring and winter is higher than the salinity threshold, while the natural flow regime is able to keep the salinity concentration lower than the predefined salinity concentration for the target species. In other words, the excessive increase in the salinity is one of the important problems in the proposed environmental flow regimes which weakens the applicability of the proposed environmental flow regime in terms of sustaining the ecological status of the lake. In fact, the assessed environmental flow of the rivers might be effective for the survival of the aquatic species in the rivers. However, hydrodynamic simulations demonstrated that it is not able to provide suitable habitats in the lake because the minimum salinity concentration is higher than the predefined threshold, especially in the winter and spring. We did not consider the entire lake in the hydrodynamic

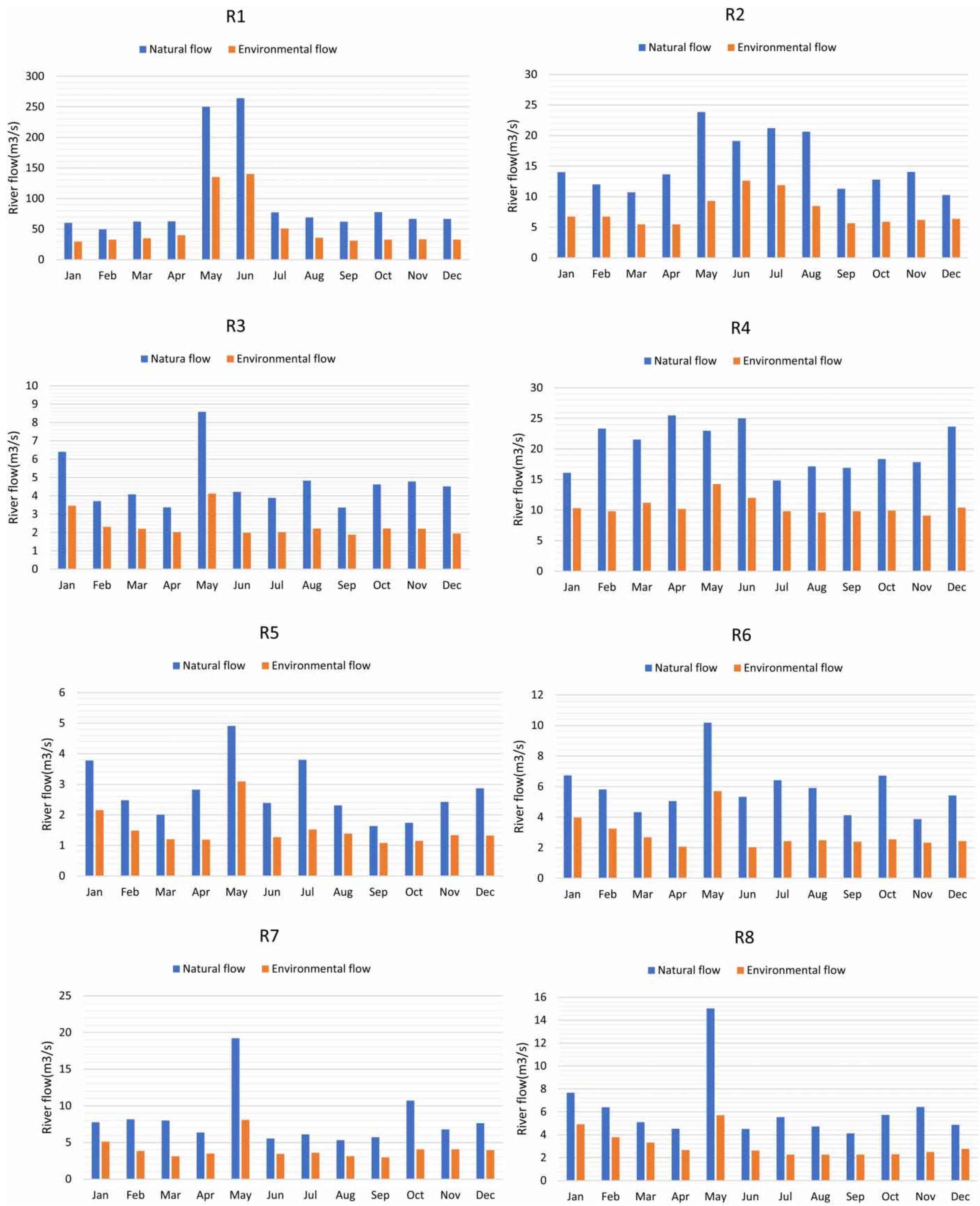


Figure 9 | Natural flow simulated by SWAT and environmental flow assessed by the hydraulic rating method considering base flow.

simulations, which might be questionable. Currently, part of the lake's regions are not active habitats due to a lack of enough inflow and reliable measurements of salinity were not available. Hence, we only considered active habitats in the verification and displayed results in which recorded data was available.

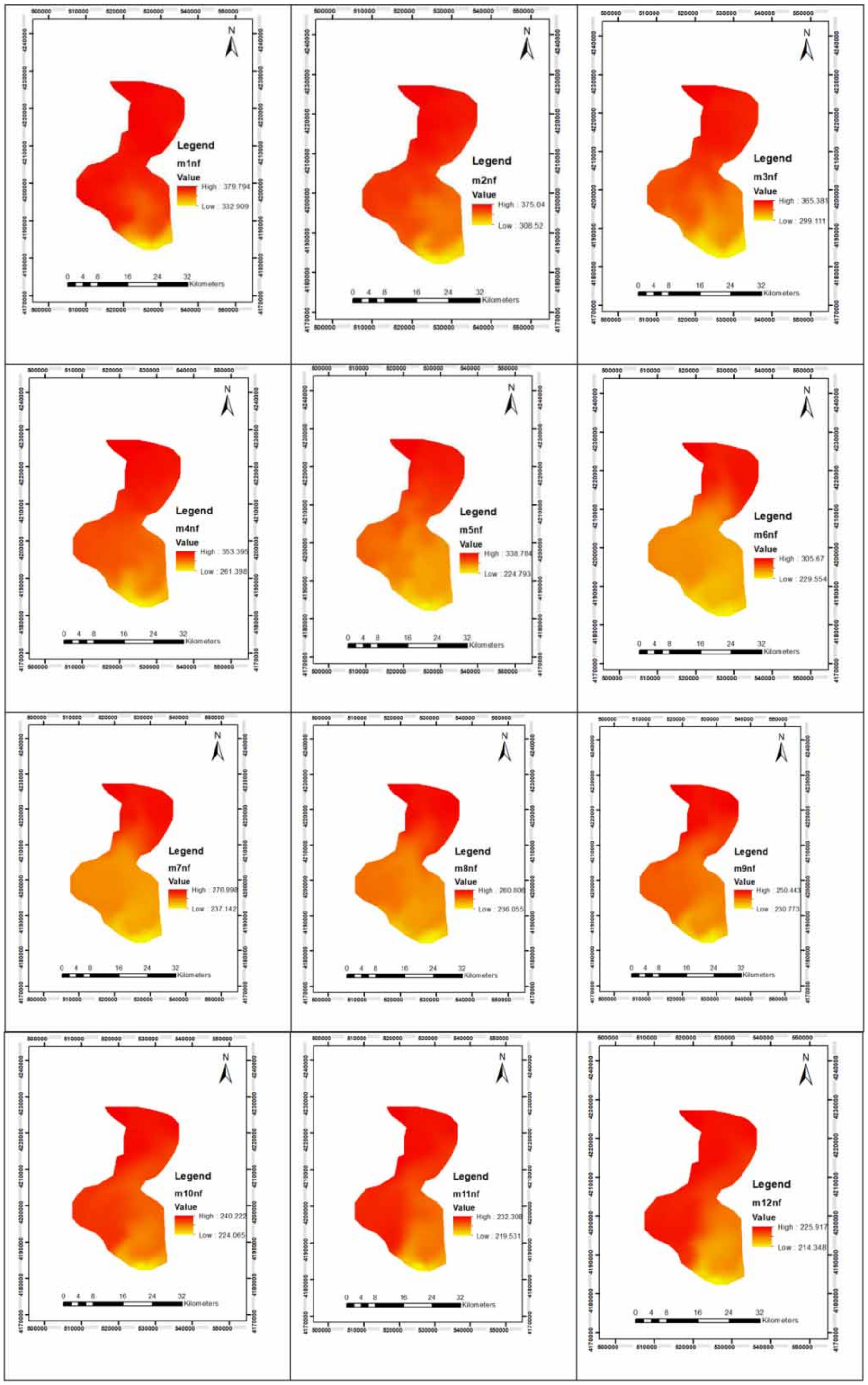


Figure 10 | Simulated salinity distribution by TUFLOW FV in the natural inflow regime (m1nf to m12nf mean simulation results in the natural flow from first month of simulation (July) to last months of simulation (June)).

This research work investigates one of the research gaps for assessing the environmental water requirement of the hypersaline lakes. The existing methods of environmental flow assessment do not integrate river and lake habitats in one model. In other words, it is ambiguous in the available methods for the rivers how the assessed regime is able to environmental water requirement of the downstream wetlands. We proposed to use the linked SWAT-TUFLOW FV model to analyze the proposed

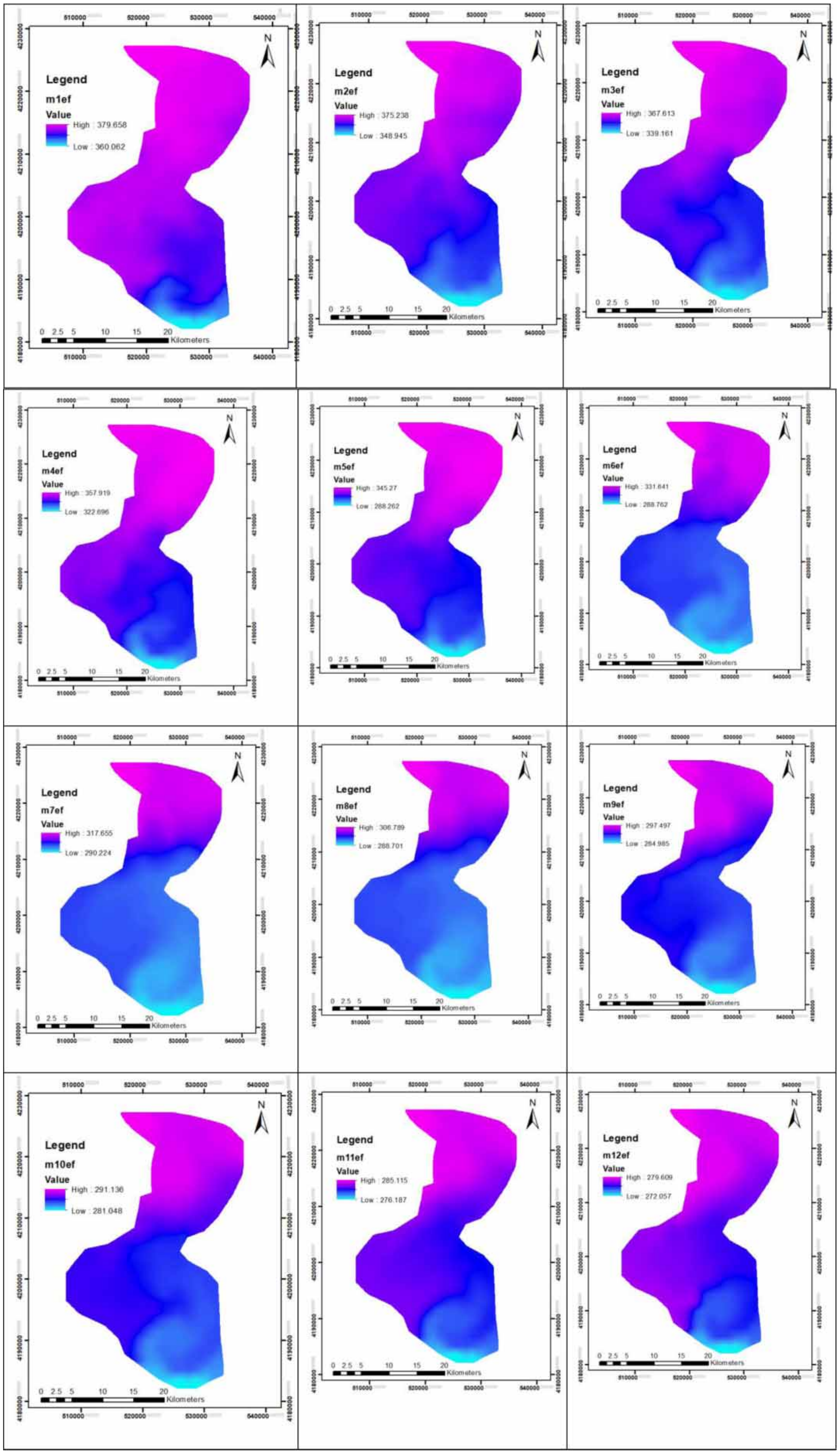


Figure 11 | Simulated salinity distribution by TUFLOW FV in the assessed environmental flow regime (m1ef to m12ef mean simulation results in the environmental flow from first month of simulation (July) to last month of simulation (June)).

environmental flow regimes of rivers at downstream wetlands in terms of minimizing biological tension. We applied salinity as the water quality indicator in a hypersaline lake. However, water quality indicators might be changed in freshwater lakes. The proposed method is helpful in terms of environmental management of hypersaline lakes. Generally, there is a misconception that available environmental flow models in the rivers are able to protect the basin ecosystem. However, the results of this study indicated that the results of an environmental flow model might not be defensible, which means that it is not able to mitigate downstream environmental challenges in the lake's habitats. The lack of using a framework of environmental analysis like the proposed one causes environmental degradation and will put great stress on the aquatics which are living in a hypersaline lake. Three approaches are usually applied to determine the environmental flow in rivers, including hydrological methods, wetted perimeter methods and habitat-based methods. However, habitat-based methods due to the high costs of extensive ecological field studies might not be practically useable in many cases. In contrast, hydrological methods and hydraulic rating methods such as the wetted perimeter method are likely to be useful in most cases with reasonable cost. However, the wetted perimeter method considering the base flow, which is an applicable method to assess the environmental flow, is not able to consider environmental indices at downstream habitats of the hypersaline lake connected to the river.

A point should be discussed regarding adding water quality parameters to the environmental flow model of the rivers. In similar cases to our case, the freshwater ecosystem of the rivers and the saltwater ecosystem of the lake are connected. However, the ecosystem of fresh water is ecologically different in terms of species and definition of ecological suitability. Therefore, even if there is a method that takes into account the quality parameters of the rivers, the ecological indicator of fresh water in the river is investigated, while it is needed to add the ecological indices of the saltwater ecosystem. As a result, using conventional methods of environmental flow assessment in rivers is not appropriate for those rivers drained to saltwater ecosystems. We proposed a method in which different scenarios of environmental flow regimes could be analyzed considering ecological indices of saltwater ecosystems. However, we only analyzed one scenario of environmental flow assessment in the case study in which the wetted perimeter considering the base flow was applied to assess the environmental flow regime in the rivers.

Another issue should be noted regarding the environmental water requirements of a hypersaline lake. A predefined ecological level in a lake is usually applied to assess the environmental water requirements. However, assessing the ecological level does not necessarily guarantee the environmental requirements in a hypersaline lake. Some recent studies highlighted the need for changing directions in the environmental assessment of these types of water bodies (Sima *et al.* 2021). The present study highlighted the importance of salinity simulation to assess ecological water demand in hypersaline lakes. In fact, in the ecological level determining, the lake's historical data is generally taken into consideration which means that the water quality is not considered by water quality models such as hydrodynamic ones. We presented an integrated system for environmental flow analysis, in which an environmental flow scenario is defined in the rivers. Then, this environmental flow scenario is analyzed using the hydrodynamic model. The outputs are helpful for changing scenarios of defining environmental flow regimes in rivers. Providing such a method has several important advantages. First, experts are able to analyze many potential scenarios of environmental flow in rivers in other words, different methods can be applied and the best one could be selected based on the results of the hydrodynamic model. In this study, the wetted permitter method considering the base flow was used. However, the results showed that this method is not suitable for the Urmia Lake. Therefore, one of the future research needs is to analyze a wide range of environmental flow methods in the Urmia Lake basin.

One of the important advantages of our method is to use SWAT for simulating the natural flow of the river. The results indicated the acceptable performance of this model to simulate several catchments. Hence, outputs confirmed that it should be prioritized for hydrological simulations needed in environmental flow analysis. Rare studies have used SWAT to assess the environmental flow. Hence, this study broadened the application of SWAT for ecological flow modelling in hypersaline lakes. One of the advantages is the low computational complexity (required computational time and memory) of this model which means that engineers who like to apply less complex models are able to use this model practically. Therefore, it is recommended to apply this model in future projects. In the present study, *Artemia* was selected as the target species in the Urmia Lake which was considered for defining salinity threshold. As presented, the salinity threshold was defined as 270 g/L which indicates an excessive increase in salinity due to farming development at upstream basins can threaten biological activities remarkably. Therefore, the lake inflow should provide the ecological requirements of the target species. Using other species in other case studies is recommendable based on initial ecological surveys. It is needed to clarify why 270 g/L was selected as the threshold of salinity in the study area. Some previous works have studied the population of the species in the lake during recent decades considering changing water quality parameters (e.g., Sima *et al.* 2021). Based on the long-term observations, expert opinions and hydrodynamic simulations of the natural flow regime in this study, the population of the selected target species in the annual natural flow regime is considerable, which means that equivalent average annual salinity concentration (spatially and temporally average) can be selected as the average threshold of habitat suitability for assessing environmental water requirements in the lake. Based on this, we selected 270 g/L as the average threshold of salinity concentration for environmental flow analysis of the lake.

Computational complexity in the application of hydrodynamic methods should be discussed as well. One of the important problems of using these models is high computational complexity (required computational time and memory), which is a serious disadvantage to hydrodynamic models such as TUFLOW FV. Significant computing time is required for simulation by these models which means that powerful computers must be applied for effective use of this model. The computational mesh has a great impact on the complexity of the calculations which implies that using the optimal mesh size is essential. As a description of this issue, using a very fine mesh will lead to an increase in the computational complexity, while the accuracy improves as well. On the other hand, using coarser cells reduces the complexity, while the accuracy decreases as well. Therefore, it seems that trial and error are very necessary for determining the size of the computational cells. Moreover, having more boundary conditions can enhance the accuracy of the model. The high computational complexity of the hydrodynamic models is one of the reasons why engineers are not willing to apply these models. Thus, optimizing the computational cell size is essential in practical applications. Increasing both the size of the lake and the time of the simulation period can have a significant effect on increasing the computational complexity, which should be considered in computational costs. Several research needs could be investigated in future. We used the wetted perimeter method considering the base flow to assess the environmental flow based on the outputs of regional studies. However, habitat-based methods should be investigated as well. Moreover, similar studies should be carried out in freshwater lakes. Water quality parameters as well as ecologic indicators can be different in the freshwater lake compared with saltwater lakes. Climate change is another essential research need which should be linked with the proposed model for assessing future environmental challenges. Climate change can alter the precipitation as well as the temperature, which means that potential impacts on the habitats should come to the picture. Therefore, using a hydrodynamic model combined with climate change models can be a useful step for further assessments in the hypersaline lakes.

CONCLUSIONS

This study developed a novel method of environmental flow analysis in hypersaline lakes in which the outputs of the hydraulic rating method considering the base flow as a known method for environmental flow assessment in rivers are analyzed using linked SWAT- TUFLOW FV. SWAT was applied to simulate the natural inflow of the lake's ecosystem in the simulated period. Moreover, TUFLOW FV was used to simulate the salinity distribution of the lake in the same simulated period. Based on the results of the models and monthly analysis of the environmental flow, both models are reliable for simulations. Furthermore, outputs indicated that using the hydraulic rating method considering the base flow in rivers is not able to provide environmental requirements in the lake's ecosystem of the case study. Hence, it is needed to renew the environmental flow studies in rivers and test different scenarios by the proposed method. The lack of using a framework of environmental analysis like the proposed one causes environmental degradation and will put great stress on the aquatics living in a hypersaline lake.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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