New Integrated Hydrologic Approach for the Assessment of Rivers Environmental Flows Into the Urmia Lake

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Research Article

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DOI: https://doi.org/10.21203/rs.3.rs-783211/v1

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New integrated hydrologic approach for the assessment of rivers environmental flows into the Urmia Lake

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Graphical Abstract

Abstract

In the conducted researches recently the greatest focus has been on the environmental water supplement of rivers individually and independently. However, in closed basins leading to lakes and wetlands, a comprehensive and integrated view of all rivers in the basin is required simultaneously. This has affected Lake Urmia, which is the second largest saltwater lake in the world. This lake has been in danger of drying up in recent years as a result of not allocating the
required environmental flow due to the increase in water resources consumption in the agricultural sector and climate change. In this study, a method derived from the flow duration curve (FDC) shifting method is presented in addition to the possibility of providing the environmental flow of rivers leading to the lake that can make the least amount of change in the hydrological characteristics of rivers to provide the volume of required water by the ecosystem of lakes or downstream wetlands. This method is based on daily data of hydrometric stations and, unlike the conventional method, which presents the results on a monthly basis, it can calculate the amount of environmental requirement of rivers in real-time according to the upstream inlet of the river. This method has been used in the Urmia Lake basin and according to the results, it can provide the environmental requirement of lake by allocating 70.5% of the annual flow of rivers and save the lake and the ecosystem of the region from the current critical conditions.

Key words: Ecohydrological approach - environmental water- FDCshifting- instream flow -Lake restoration-RVA- Urmia Lake

1- Introduction

With the increasing population and the human need for water, intense competition between ecosystems and water resources development projects especially in rivers has been emerged. Many aquatic ecosystems are declining and disappearing due to human intervention in the overuse of water resources and climate change. Environmental flow (e-flow) allocation is an important factor in maintaining ecosystems, flora and fauna species. Given the importance of this type of flow and to converge concepts used in these studies in Brisbane declaration the quantity, time and quality of water flow required for the sustainability of river ecosystems and estuaries were known as e-flow. This definition emphasizes maintenance the regime of natural river flows.
In recent decades, more than 200 methods for estimating e-flows have been proposed. Most of them are based on hydrological time series due to their ease of use. In the meantime, some of the proposed methods such as Tennant have a simple basis. The others such as holistic methods have studied the general dimensions of the ecosystem and social conditions of the region. Complexity of estimating e-flows in these methods has increased due to the raise in the number of parameters and the use of multi-objective optimization algorithms. To increase the efficiency and compatibility of hydrological methods with the ecosystem of each region, an echohydrological method (combination of ecological and hydrological methods) is used. Selecting the adequate ecosystem conservation criteria in allocating e-flows is one of the most important challenges in estimating the appropriate e-flow for a basin in ecohydrological methods.

To determine the class of hydrological environmental management and e-flow allocation, hydraulic methods have been used in some studies. Other studies emphasize on methods based on water quality and the importance of spatial changes of qualitative and hydrological parameters on the performance of e-flow in the restoration of river ecosystems are considered. However, in some studies, the water supply adequacy of downstream wetlands has been mentioned as an ecological criterion for e-flow allocation.

According to global studies, a decade after the first declaration, the supply of aquatic ecosystems required water has received more attention. Considering the needs of these ecosystems such as lakes and wetlands and water level parameter in the second statement were added to the original definition to comprehend the definition of e-flow. Due to this explanation, previous methods should be reviewed in order to provide downstream ecosystems water and the comprehensive method should be introduced. In some studies only the water need of rivers leading to the wetland has been estimated. In other studies water requirement of wetlands and lakes
The consideration and determination of the e-flow of rivers has reached a certain level. Despite all presented studies, each river, wetland, or lake has been considered independently. If the rivers are in an Endorheic basin, the ecosystem of the area under their coverage must be rehabilitated and collectively assess the environmental needs of the lake ecosystem. To study this type of rivers' e-flow, besides the fact that each river must be studied separately, it is necessary for all rivers to restore the downstream lake or wetland using an integrated method.

Ecosystems in different basins of Iran are not in a good condition due to excessive use of water resources. This issue in some water basins, such as Urmia Lake, is tangible. Increased water withdrawals from agriculture, households, and industry, on the one hand, and climate change, on the other, have led to excessive declines in water levels. As a result, less than 10% of the lake remained under optimal conditions. The sharp decline in lake water levels has been associated with reduced tourism activity and damage to agriculture in the region. This issue has had a detrimental effect on urban and rural infrastructure and the livelihood of families in this area. As the lake water volume decreased, its salinity increased. Therefore, extinction threatens the dominant species of lake and causes major problems in the food chain of this ecosystem. According to the Urmia Lake Restoration Program (ULRP), there are ongoing government efforts to improve the condition of the lake. Precipitations in recent years and through measurements taken, the lake has reached a relative stabilization even though it is far ecological level. In this research, an integrated ecohydrological method was utilized to estimate the e-flow requirement (EFR) of rivers leading to the lake and maintain the Environmental Water Requirement (EWR) of the lake. This study was carried out on the basis of Urmia Lake and its supplying rivers. The environmental conditions of rivers and lakes were independently examined.
based on previous studies and a suitable integrated method for allocating the required e-flow for each river leading to the lake was presented.

2- Material and methods

2-1- Specifications of the study area

Urmia Lake, Iran’s largest inland lake, is a national park and also one of the Iran’s largest Ramsar sites (Ramsar 1971). The lake is formed in a natural depression within the catchment area in the northwest of Iran. The lake basin covers an area of 52,000 km$^2$ and the lake’s area is about 5,700 km$^2$ and its maximum length and width are 140 and 50 km, respectively. The lake catchment is a closed inland basin in which all rainwater runoff flows to the central saline lake and the only way out is evaporation from the surface of the lake. It is the largest saltwater lake in Iran and the second largest saltwater lake in the world.

Figure1: An overview of Urmia Lake Basin, the rivers and selected Gauging stations

| No | River Name  | Station  | From | Up to |
|----|-------------|----------|------|-------|
| 1  | Zola        | Nazarabad| 1972 | 2015  |
|    |             | chahreh Olya | 1972 | 2015  |
| 2  | Nazlu       | Tapik    | 1950 | 2015  |
| 3  | Rozeh       | Kallior  | 1976 |       |
| 4  | Shahar      | Band Urmia| 1949 | 2015  |
| 5  | Barandooz   | Dizaj    | 1956 | 2015  |
|    |             | Ghasemli | 1973 | 2015  |
| 6  | Gadar       | Naghadeh| 1965 | 2015  |
| 7  | Mahabad     | Bitas    | 1964 | 2015  |
|    |             | Kutar    | 1972 | 2015  |
| 8  | Simineh     | Dasband  | 1950 | 2015  |
| 9  | Zarrineh    | Anian    | 1974 | 2015  |
|    |             | Senteh   | 1987 | 2015  |
|    |             | Safakhaneh| 1973 | 2015  |
|    |             | Panbedan | 1974 | 2015  |
| 10 | Aji         | Venyar   | 1949 | 2015  |
The current surface flow system to Urmia Lake consists of 10 main rivers with permanent flow potential, which are: 1- Zola 2- Nazlu 3- Rozeh 4- Shahrchaj 5- Baranduz 6- Gadar 7- Mahabad 8- Simineh 9- Zarrineh 10- Aji. In terms of water supply potential of Urmia Lake, Zarrineh, Simineh, Aji and Nazlu rivers with a flow allocation of 41%, 11%, 10% and 6% have a key role respectively.

### 2-2- Appropriate criteria for allocating the EWR of the Urmia Lake

Due to the high salinity of the Urmia Lake, only a small number of invertebrates make up living organisms of this huge water body. Saltwater shrimp or Artemia is a type of aquatic crustacean which can be found in saltwater lakes or coastal lagoons around the world. Artemia can tolerate salinity less than 10 g/l up to 340 g/l and adapt to environmental conditions. Artemia Urmiana, the most well-known species of the Urmia Lake, is considered as the main food of migratory birds that spend part of their wintering period on the lake and surrounding wetlands. The presence of Artemia Urmiana in the Urmia Lake was first reported by Gunter in 1899 and many researchers have confirmed the existence of this bisexual creature in the Urmia Lake 50-54.

One of key factors in estimating the EWR of the Urmia Lake is to create an appropriate environmental condition for the dominant species of the lake. Abbaspour and Nazari Doost 39 identified the Urmia Lake EWR by considering the living conditions of Artemia as the dominant species of the lake. In this study, Artemia Urmiana was selected as a biological indicator, NaCl and elevation above mean sea level (AMSL) as indicators of water quality and quantity. The combination of these three indicators forms the ecological basis of the Urmia Lake. Therefore, consider salinity equal to 240 g/l as the tolerable limit of the biological index. Using long-term statistics in the Urmia Lake and the relationship between quantitative and qualitative water indicators, the water level of 1274.1m (AMSL) as the ecological level of the lake was chosen so
that the balance of these three indicators remained within the allowable range. The study indicated that the calculated environmental water demand of the Urmia Lake was equal to 3084 Mm³ per year provided by main rivers entering the lake. Therefore, the proposed new method should be able to deliver this volume of water to the lake and feed the river's EFR at the same time.

2-3- Ordinary method of FDC Shifting in estimating e-flow

Since the early 1990s, various methods based on the hydrological indices have been developed to determinism of e-flow, by taking into account the flow variability and adaptation to the ecological conditions of rivers. One of the diagrams used in the study of the hydrological characteristics is the flow duration curve (FDC), which is used to assess the fluctuations and variability of water flow from an environmental point of view. Given the importance of the presence of flood currents in the restoration of river and wetland ecosystems, the FDC is one of the most practical methods to show the full range of river discharge characteristics from water shortage to flood events. This diagram also demonstrates the relationship between the amount and frequency of flow which can be prepared for daily, annual and monthly time intervals. One method in which FDC is used to estimate river flow is the FDC shifting method. This method was introduced by Smakhtin and Anputhas to evaluate the e-flow in the river system. The method called "flow duration curve shifting (FDCS)" which provides a hydrological regime to protect the river in the desired ecological conditions.

In the previous researches, most of the rivers in the Urmia Lake basin have been compatible with FDCS and due to the lack of biological data of these rivers, it is always one of the top priorities among the methods of estimating e-flow in rivers leading to the Urmia Lake. Due to its simplicity and flexible structure in performing flow volume calculations, this method also provides the possibility of managing the flows volume across the river. Therefore, in the new method...
presented in this research, the basis of this method was used to estimate the e-flow of rivers. As the characteristics of calculation steps between the old and the new methods are the same, so a common description of the steps is provided below.

This method consists of four main steps:

1. Assessment of the existing hydrological conditions (preparation of the FDC for natural river flow regime).
2. Select the appropriate environmental management class.
3. acquire the environmental FDC
4. Generate e-flow time series

The first step is to prepare the FDC in the desired river range using monthly flow data. In this method, FDC for natural river flow regime by using 17 fixed percentage points of occurrence probabilities (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99/99, 99/99) are prepared, in which $P_1 = 99.99\%$ and $P_{17} = 0.01\%$ represent the highest and lowest probability of occurrence, respectively. These points ensure that the entire flow range is adequately covered, as well as making it easy to continue with the next steps.

This method, which uses mean monthly flow (MMF) data, uses six environmental management classes (EMC) A to F. Based on the natural river FDC obtained using the MMF, the FDC of e-flow requirement (FDC-EFR) for each class in terms of EMC is determined. The higher EMC will need more water to maintain the ecosystem. These classes are determined based on empirical relationships between the flow and ecological status of rivers, which currently have no specific criteria for figuring out these limits. The selection of the appropriate class is based individually on expert judgment of the river ecosystem condition.
Once the natural FDC is obtained, the next step is to calculate the FDC-EFR for each EMC using lateral shifts of FDC to the left along the probabilistic axis. For EMC-A rivers, one lateral shift to the left is used and for EMC-B, EMC-C and EMC-D rivers, two, three and four lateral shifts are used respectively. It should be noted that, although the flow variation is lost for each shift, the overall hydrological pattern of the flow will be maintained.

In this study, global e-flow calculation (GEFC) software \(^{62}\) has been used to calculate e-flow by FDCS method. The required input data to this software is long-term data (at least 20 years) MMF.

According to the research conducted in the rivers of the Urmia Lake basin, the minimum EMC for 10 main rivers of the lake has been considered is EMC-C, so in this study, the EMC-C has been considered and all calculations for classes A, B, C were performed.

### 2-4- New method

The main purpose of presenting a new method is to combine the EWR of wetlands or lakes and the hydrological method of FDCS, which can be used to calculate the e-flow of rivers and meet the needs of lakes or wetlands in downstream. This method is based on the FDCS, with the difference that the proposed method includes three fundamental changes compared to the original one.

1. Use monthly FDC (FDC for each month separately) instead of annual FDC
2. Use daily flow data instead of MMF
3. Consider the downstream EWR in the amount of lateral shift in the FDCS method.

The use of this method’s structure leads to a dynamic process that is based on the selected EMC of the river, the amount of natural flow and the date of occurrence and can calculate the
amount of e-flow of the river on each day of the year.

River hydrology varies greatly depending on the type of basin, the climate of the area and the relationship between the basin and the river. Each of them exhibits different behavior during the months of the year, so the proposed methods should provide sufficient comprehensiveness in estimating e-flow by considering different flow characteristics. Due to the type and timing of precipitation in the Urmia Lake Basin, the rivers are full of water in the period from March to June and spend much less flow during the rest of the year. For example, Figure 2 shows the distribution of the Nazlu River flows west of the Urmia Lake throughout the year. According to this graph, 74% of the annual flow crosses the river during the four months from March to June, and also the highest and lowest river discharges are related to May with 29% and Sep and Aug with 2% of the annual flow, respectively.

Figure 2-Historical hydrograph at the Tapik Station, Nazlu River. a) Daily and mean monthly distribution of flows; b) Magnified hydrograph for a typical year, 1993

According to the flow distribution throughout the year, the annual FDC which is an average
FDCs of each month of the year, and the flow of a river during the months of the year which has significant changes, it can inferred that in the high-water months (e.g. May) the monthly FDC chart is higher than the annual and in the low-water months (e.g. Sep) this chart is lower than the annual FDC. With this description, the use of monthly FDCs provides more details of changes in the hydrological parameters of the flow and can be a better indicator of the hydrological index of river flows.

In the conventional FDCS method, the FDC is obtained using the MMF data of each station. This causes misunderstanding in the average river flow curve obtained during the month, the minimum and maximum and the effect of flow fluctuations in the Estimation of e-flows (Figure 2).

In the new method, all FDC diagrams were obtained using daily data. Both Annual (EFR-Ann) and Monthly (EFR-Mon) methods separately utilized to compare the calculation of the e-flow and to choose the best method. 1- The annual FDC is a probabilistic chart for the whole year and 2- The Monthly FDC includes 12 probability curves for each year. Due to the use of FDC in e-flow calculations, an attempt has been made to perform all calculations from this diagram. Therefore, the concepts related to flow volume can be integrated with the FDCS method. Some of the concepts used for this purpose are as follows.

In the FDCS method, the FDC is defined based on 17 probabilistic percentage points. To calculate the mean annual flow (MAF) volume, the theorem of the mean value for a definite integral is used in the FDC diagram. Accordingly, since FDC is continuous between the first and seventeenth probability points, the mean flow ($F_m$) is obtained from Eq. (1).
\[ F_m = \frac{1}{P_1 - P_{17}} \int_{P_1}^{P_{17}} F(p) \, dp \]  

Given that the FDC consists of 17 probability points and the probability function \( F(P) \) is not available for this curve as a mathematical equation. Obtaining this equation for each flow curve increases the computational cost. Therefore, numerical integration methods can be used. For this purpose, the trapezoidal numerical solution method has been used. By applying the trapezoidal method in solving Eq. (1), Eq. (2) is obtained, which is used to calculate the mean flow of the FDC curve.

\[ F_m = \frac{1}{P_1 - P_{17}} \sum_{i=1}^{17} \frac{(F_i + F_{i+1})}{2} \ast [P_i - P_{i+1}] \]  

To calculate the annual flow (AF) volume by using monthly and annual FDC, Eq.(3) can be used for the AF volume in the EFR-Ann method and Eq.(4) and Eq.(5) for the monthly and AF volume in the EFR-Mon method can be used, respectively.

\[ V_{AF\text{-}EFR-Ann} = \frac{365 \ast 24 \ast 3600}{P_1 - P_{17}} \sum_{i=1}^{17} \frac{(F_i + F_{i+1})}{2} \ast [P_i - P_{i+1}] \]  

\[ V_{Monthly} = \frac{D_k \ast 24 \ast 3600}{P_1 - P_{17}} \sum_{i=1}^{17} \frac{(F_i + F_{i+1})}{2} \ast [P_i - P_{i+1}] \]  

\[ V_{AF\text{-}EFR-Mon} = \sum_{k=1}^{12} \left[ V_{Monthly} \right]_k \]  

\( D_k \) = Number of days of the kth month

\( n \) = Number of input rivers to lake

\( P_i \) = 17 point of FDC probability that \( P_i=99.99\% \), \( P_{17}=0.01\% \)
The e-flow required by wetlands and lakes must have two basic characteristics: 1- The volume of EWR to maintain the ecological level of them, which must be determined and provided by studies of their ecosystems. 2- Fluctuations must be maintained in water levels in the lake due to hydrological conditions under the basins of the lake supplying rivers. Considering that maintaining the hydrological conditions of the river is one of the major goals of the FDCS method in estimating the e-flow of the river. On the other hand, the rehabilitation of wetlands or lakes downstream of rivers requires a certain amount of water and the new method must be applied to combine these two goals. Regarding this, without considering the uses and taking into account the normal flow conditions of the rivers in the basin, the AF volume that these rivers can transfer to the lake ($V_{L_{Mon}}$ or $V_{L_{Ann}}$), is calculated.

$$V_{L_{Ann}} = \sum_{j=1}^{n} [V_{AF_{Annual}}]_{j}$$  \hspace{1cm} (6)

$$V_{L_{Mon}} = \sum_{j=1}^{n} [V_{AF_{Monthly}}]_{j}$$  \hspace{1cm} (7)

At this stage, the ratio of the EWR of the lake or wetland to the average annual volume of the basin should be determined.

$$b = \frac{V_{EWR}}{V_{L_{Ann}} \text{ or } V_{L_{Mon}}}$$  \hspace{1cm} (8)

In the conventional FDCS method, which is determined using GEFC software (It is then called the GEFC method), depending on the type of river EMC, the allocation curve is obtained with one or more shifts of the FDC. Each EMC includes a certain ratio of the MAF volume of the river and changing the flow EMC makes it possible to change the flow volume. It is not possible
to supply a specific and predetermined downstream water volume of the river. Therefore, in the new methods, to provide a certain volume of water in the shifting of FDC, a new method must be used to calculate the amount of FDC shift. First, a new definition of the EMC was developed for the new methods. In this definition, instead of using a specific shift of the FDC, the range between the two classes was defined as an EMC. For example, the region between the curve of EMC-A and the natural flow and the region between the EMC-A and EMC-B curves are defined as the EMC-A and EMC-B areas, respectively. These regions can be defined for all EMCs as shown in Figure 3.

![Comparison of the EFR allocated for each of the environmental management classes (EMC) from this new approach (on the left) with the conventional FDCS methods (on the right)](image)

Based on new definition of the range of EMC, the FDC curve can be shifted as much as needed according to the volume of downstream EWR. The EWR can be defined as annual percentage river flow respecting the shift of EMCS or a percentage between two specific classes. If the required flow volume is between two specific classes, the Eq. (9) can be used to shift the FDC. In fact, with the new definition, any required probable shift can be applied to the
FDC diagram to reach a certain volume. In this case, new probable points are determined using Eq. (9) and in the next step, the FDC shift similar to the FDCS method is performed.

\[ P_{i_{new}} = P_i + a \times (P_{i-1} - P_i) \quad i = t, \ldots, 16 \]  

\( a = \) coefficient of shift which defined between 0 and 1

The concept of numerical integration and equations 9 and 3 were used to calculate the annual volume of different EMCs for each river and equations 10 and 12 were obtained for the new annual and monthly methods, respectively.

\[
V_{AF\ class_t\ Ann} = \frac{1}{P_1 - [P_{t+1} + a \times (P_{t+1} - P_t)]} \times \left[ F_1 \times \left[ P_1 - [P_{t+1} + a \times (P_t - P_{t+1})] \right] + \right.
\sum_{i=t+1}^{16} \frac{(F_{i-t} + F_{i-t+1})}{2} \times \left[ P_i - P_{i+1} + a \times (P_{i-1} - 2P_i + P_{i+1}) \right] \left. \right] \times 365 \times 24 \times 3600
\]

\[
V_{class_t\ Mon} = \frac{D_k \times 24 \times 3600}{P_1 - [P_{t+1} + a \times (P_{t+1} - P_t)]} \times \left[ F_1 \times \left[ P_1 - [P_{t+1} + a \times (P_t - P_{t+1})] \right] + \right.
\sum_{i=t+1}^{16} \frac{(F_{i-t} + F_{i-t+1})}{2} \times \left[ P_i - P_{i+1} + a \times (P_{i-1} - 2P_i + P_{i+1}) \right] \left. \right]
\]

\[
V_{AF\ class_t\ Mon} = \sum_{K=1}^{12} \left[ V_{class_t\ Mon} \right]_K
\]

In Equations 10 and 12, \( t \) is the number of shifts performed on the FDC diagram numbered 1-6 for the areas of EMC A, B, C, D, E, F, respectively. To find the exact value of “\( a \)” in these equations, the scope of the EMC must be determined based on the volume required by downstream.

Therefore, assuming \( a = 0 \) in these equations, the annual flow volume at the boundary of each class
is obtained for both the EFR-Mon (Eq. 10) and EFR-Ann (Eq. 12) methods. The nearest calculated annual volume is selected as the appropriate EMC which is smaller than the volume of downstream. And the corresponding t-class is used to solve the equations which represents the range of the selected EMC.

At this stage, the value of ‘a’ obtained from the FDC shift diagram will be equal to the required volume of downstream. For this purpose Equation 13 for the EFR-Ann method and Equation 14 for the EFR-Mon method are obtained from Equations 10 and 12.

\[ b \times V_{AF_{Annual}} = V_{AF\ class\ Ann} \]  
\[ b \times V_{AF_{Monthly}} = V_{AF\ class\ Mon} \]

By solving equations 13 and 14, the obtained value of “a” represents the annual and monthly methods, and the obtained shifted FDC stands for the required annual volume downstream.

Once the appropriate FDC is determined, it is used to calculate the daily environmental flow needs of the river using spatial interpolation algorithm \(^{63}\), which is also used in the FDCS method. For this purpose, first the probability of river flow occurrence from the annual or monthly FDCs (according to the selected method) is determined and then using the e-flow curve, the required river flow in the specified probability of occurrence is obtained.

Finally, the RVA method is used to compare the methods and select the best one based on the least hydrological change compared to the natural flow of the river. The range of variability approach (RVA) \(^{64,65}\) is a complex method based on the use of e-flow to achieve the goals of river ecosystem management. This method is based on the importance of the hydrological features impact of the river on the life, biodiversity of native aquatic species and the natural ecosystem of
the river. Its purpose is to provide complete statistical characteristics of the flow regime.

In the RVA method, indicators of hydrologic alteration (IHA) parameters related to natural river flow are considered as a basis and the changes in the IHA parameters of different EMCs are evaluated based on it. Richter et al. suggested that the distribution of annual values of the IHA parameters to maintain river environmental conditions must be kept as close as possible to natural flow condition parameters. In several studies, this method was used to investigate the changes in the hydrological parameters of a river over time.

In the RVA method, the total data related to the natural flow of the river for each IHA parameter are classified into three categories. In this study, this classification is based on Default software and the 17% distance from the median is introduced as the boundary of the classes. By this definition, three classes of the same size are created, in which the middle category is between 34 and 67, and the lower and higher of this range are called the lowest and the highest category, respectively.

The RVA method using the current change factor obtained from Equation 15 can quantify the change amount in the values of the 33 IHA parameters compared to the natural flow conditions.

\[
HA = \left( \frac{O_f - E_f}{E_f} \right)
\]

(15)

In Equation 15 \(O_f\) is the number of flows occurring within a certain category of the IHA parameter under changed flow conditions and \(E_f\) is the number of flows occurring in the same category specified by the parameter under natural flow conditions. In this case, for each IHA parameter, three Hydrologic Alteration Factor (HA) is obtained, which can be examined for river flows in these three categories separately. In the analysis of parameters the positive HA means that
the number of occurrences of the phenomenon compared to the natural conditions of the river flow in a certain IHA category has increased. Negative values mean a decrease in the number of occurrences of the same phenomenon. To compare the number of changes in the IHA parameters, the HA factor of RVA method and IHA software V7.1 was used to allocate e-flows in different methods. Based on the methodology presented in this research, a step-by-step diagram for determination of rivers environmental flows in the Urmia Lake Basin is shown in Figure 4.

Figure 4- Step-by-step flowchart for determination of rivers environmental flows in the Urmia Lake Basin
3- Results and Discussion

Initially, the MMF for each available statistical month was obtained by daily data from stations located upstream of the Urmia Lake basin rivers (Figure 1). Using MMF values and GEFC software, FDC curve for natural flow and various EMCs were obtained. In the next step, to perform the calculations in the EFR-Ann method, FDC of a natural flow and different EMCs during the year were plotted by using daily data. In the last step for the EFR-Mon method, the daily data of each month of the year were examined and the FDC of natural flow and EMCs were plotted for each month separately.

To calculate the e-flow of the rivers entering the lake, at first the mean total surface water potential supplied by 10 river basins was calculated using equations 6 and 7. Then, considering the volume of EWR of the lake by the amount of 3084 Mm$^3$ and using Eq. 8, the coefficient $b$ is obtained equal to 0.705.

To select the appropriate class for e-flow allocation using equations 3 and 4, the MAF volume for natural conditions and EMCs were calculated for all three methods. The percentage of annual flow allocation was calculated using each method which is demonstrated in Table 1.

Table 1- Comparison of estimated EFR from conventional method of GEFC with two new Annual (EFR ANN) and Monthly (EFR MON) methods as percent of mean annual flow (MAF) of the Urmia Lake Basin

| River name | Station | GEFC (%MAF) | EFR ANN (%MAF) | EFR MON (%MAF) |
|------------|---------|-------------|----------------|----------------|
|            |         | Class A     | Class B | Class C | Class A | Class B | Class C | Class A | Class B | Class C |
| Zola       | Chahrigh olya | 71.5 | 54.4 | 42.8 | 68.5 | 50.1 | 37.8 | 77.6 | 62.1 | 50.0 |
|            | Nazar Abad | 75.9 | 61.9 | 52.1 | 70.9 | 55.4 | 44.1 | 74.8 | 60.0 | 48.6 |
| River     | Station | Flow Ratio |
|-----------|---------|------------|
| Nazlu     | Tapik   | 64.8       |
|           |         | 42.7       |
|           |         | 28.9       |
|           |         | 63.0       |
|           |         | 40.9       |
|           |         | 27.4       |
|           |         | 78.9       |
|           |         | 63.3       |
|           |         | 50.9       |
| Rozeh     | Kalhor  | 67.0       |
|           |         | 47.0       |
|           |         | 33.5       |
|           |         | 63.0       |
|           |         | 43.5       |
|           |         | 30.5       |
|           |         | 70.1       |
|           |         | 53.6       |
|           |         | 41.6       |
| Shaharchay| Band    | 63.7       |
|           |         | 40.9       |
|           |         | 26.7       |
|           |         | 61.5       |
|           |         | 38.1       |
|           |         | 23.7       |
|           |         | 76.4       |
|           |         | 59.7       |
|           |         | 46.4       |
| Barandooz | Dizaj   | 70.3       |
|           |         | 50.2       |
|           |         | 36.4       |
|           |         | 67.2       |
|           |         | 46.4       |
|           |         | 32.4       |
|           |         | 77.2       |
|           |         | 60.9       |
|           |         | 47.6       |
|           | Ghasemlu| 48.7       |
|           |         | 31.7       |
|           |         | 24.6       |
|           |         | 48.9       |
|           |         | 29.5       |
|           |         | 19.3       |
|           |         | 54.7       |
|           |         | 36.6       |
|           |         | 26.7       |
| Gadar     | Naghadeh| 65.1       |
|           |         | 41.9       |
|           |         | 27.0       |
|           |         | 60.9       |
|           |         | 37.0       |
|           |         | 22.2       |
|           |         | 77.7       |
|           |         | 61.0       |
|           |         | 47.4       |
| Mahabad   | Bitas   | 59.8       |
|           |         | 37.0       |
|           |         | 23.3       |
|           |         | 53.9       |
|           |         | 29.6       |
|           |         | 15.9       |
|           |         | 69.1       |
|           |         | 50.5       |
|           |         | 37.4       |
|           | Kutar   | 63.0       |
|           |         | 38.8       |
|           |         | 23.3       |
|           |         | 56.2       |
|           |         | 32.1       |
|           |         | 18.1       |
|           |         | 71.4       |
|           |         | 53.4       |
|           |         | 40.4       |
| Simineh   | Dashband| 57.6       |
|           |         | 34.3       |
|           |         | 20.2       |
|           |         | 51.2       |
|           |         | 27.4       |
|           |         | 14.5       |
|           |         | 67.8       |
|           |         | 48.5       |
|           |         | 35.3       |
| Zarrineh  | Anian   | 59.0       |
|           |         | 34.7       |
|           |         | 19.6       |
|           |         | 54.0       |
|           |         | 28.7       |
|           |         | 14.6       |
|           |         | 71.2       |
|           |         | 52.6       |
|           |         | 39.3       |
|           | Panbedan| 58.0       |
|           |         | 34.5       |
|           |         | 20.2       |
|           |         | 53.5       |
|           |         | 29.9       |
|           |         | 16.7       |
|           |         | 70.2       |
|           |         | 52.0       |
|           |         | 39.4       |
|           | Safakhaneh| 56.9   |
|           |         | 33.2       |
|           |         | 19.7       |
|           |         | 55.3       |
|           |         | 31.3       |
|           |         | 17.9       |
|           |         | 72.8       |
|           |         | 54.7       |
|           |         | 41.2       |
|           | Senteh  | 59.2       |
|           |         | 34.3       |
|           |         | 19.3       |
|           |         | 54.5       |
|           |         | 29.5       |
|           |         | 15.6       |
|           |         | 71.2       |
|           |         | 52.9       |
|           |         | 39.9       |
| Aji       | Venyar  | 58.7       |
|           |         | 35.1       |
|           |         | 21.0       |
|           |         | 55.3       |
|           |         | 31.1       |
|           |         | 17.3       |
|           |         | 70.2       |
|           |         | 51.2       |
|           |         | 37.4       |

| Total Lake Input | 61.1 | 38.2 | 24.0 | 57.1 | 33.6 | 19.9 | 72.5 | 54.7 | 41.6 |

According to Table 1, the ratio of allocated e-flow to the total river flow, in the same classes for different rivers is not necessarily the same. The nature of the river and its FDC shape can be different so that in the EFR-Mon method the maximum and the minimum percentage of flow is related to Tapik and Ghasemlou stations. Also, by comparing the flow ratio values of an EMC in each of the three proposed methods, it can be concluded that in all rivers the allocation percentage of the conventional GEFC method in terms of annual allocation volume is between the EFR-Ann and EFR-Mon methods. According to the coefficient $b = 0.705$, to meet the EWR of the
Urmia Lake, in each of the 10 main rivers of the basin, 70.5% of their AF volume is released to meet the EWR of the lake. Table 1 shows that none of the rivers in any of the EMCs have exact amount of 70.5% of the annual flow. To achieve this, it is necessary to use the facilities of the newly proposed methods. Therefore, by solving equations 13 and 14, the appropriate value of coefficient “a” in the EFR-Ann and EFR-Mon methods is calculated. To solve Equations 13 and 14, first it is necessary to obtain the factor t in Equations 10 and 11, which represent the range of the selected EMC. For this purpose, Table 1 is used and the EMC is selected for each river according to Table 2 in which 70.5% of the flow is located. Then the corresponding t-factor is obtained.

Table 2- Selection of EMCs and corresponding t-values for two new Annual (EFR ANN) and Monthly (EFR MON) methods based on providing 70.5% of the annual flow of each of the rivers as the EWR

| River name | Station | EFR ANN | EFR MON |
|------------|---------|---------|---------|
|            |         | Class   | t        | Class | t |
| Zola       | Chahrigh olya | A       | 1       | B     | 2 |
|            | Nazar Abad       | B       | 2       | B     | 2 |
| Nazlu      | Tapik            | A       | 1       | B     | 2 |
| Rozeh      | Kalhor           | A       | 1       | A     | 1 |
| Shaharchay | Band             | A       | 1       | B     | 2 |
| Barandooz  | Dizaj            | A       | 1       | B     | 2 |
|            | Ghasemlu         | A       | 1       | A     | 1 |
| Gadar      | Naghadeh         | A       | 1       | B     | 2 |
Urmia Lake has 10 main rivers, which due to the similarity of the results in the study of rivers leading to the lake, only the Nazlu River was discussed and the results presented.

Using the t-values obtained from Table 2, for each of the rivers, Equations 13 and 14 are solved and a new shifted FDC diagram is obtained for passing 70.5% of the annual river flow for both of new methods. The FDC for estimating the EFR-ADJ-Ann and EFR-ADJ-Mon environmental needs are demonstrated according to the lake EWR in comparison with EMCs A, B and C in Figure 5 and Figure 6 respectively.
Figure 5- Comparison of annual FDCs for different EMCs with the shifted FDC based on adjusted EFR of the lake at the Tapik Station, Nazlu River
Figure 6- Comparison of monthly FDCs for different EMCs with the shifted FDC based on adjusted EFR of the lake at the Tapik Station, Nazlu River

Due to the difference in probability of occurrence of a specific flow during different months
of the year, a simple FDC cannot be used as a flow characteristic of the river during the whole year. For example, according to Figure 6, a flow of 10 CMS at the Tapik station on the upstream of Nazlu River in July is considered to be a high flow with a 20% probability, while in May, when the river has the highest MMF of the year, it is considered to be a low flow with a 95% probability of occurrence. However, in the EFR-Ann method, regardless of the month of occurrence, the probability of flow of 10 CMS is 31% and the allocation of e-flow is based on the probability of flow occurrence. Therefore it can be concluded that by using the monthly method, the nature of river hydrological change can be used to allocate e-flow in different months of the year. To prove this, Figure 7 shows the ratio of e-flow allocation volume relative to the natural flow conditions in July and May at the Tapik Station on the Nazlu River for the EMC-A of annual method and the EMC-B of the monthly method. Calculations indicate that both of these EMCs provide 63% of the annual river flow volume as downstream EWR during the year.

![Figure 7](image_url)

**Figure 7**- Percentage of monthly environmental flow allocation relative to the natural flow capacity with comparison of EMC-A of the Annual Method with EMC-B of the Monthly Method at the Tapik Station, Nazlu River. (a): September; (b): May
According to Figure 7, when monthly FDC is higher than the annual, the allocated flow volume to the downstream of the river in EFR-Mon method in high flow months will be more than the EFR-Ann method. During the statistical period of Tapik Station for May, the EFR-Mon method allocates an average of 14% more flow volume to downstream of the river compared to the EFR-Ann method. Also, by examining the data of this station, it was found that in low flow months, when the monthly FDC is lower than the annual, the EFR-Mon method allocates smaller amounts of flow than the annual to downstream. Therefore in Sep, the EFR-Mon method compared to the EFR-Ann method allocates 21% less amount of water to the downstream. According to the analysis performed, this difference between the EFR-Ann and EFR-Mon methods increases with the decrease of the percentage of the flow volume allocated to the downstream annually compared to the natural flow regime.

To supply the volume of EWR of the Urmia Lake from the Tapik Station of Nazlu River, according to Figure 5 by annual method (EFR-Adj-Ann) the shifted FDC is located in the EMC-A region while in monthly method (EFR-Adj-Mon) according to Figure 6, the shifted FDC is located in the EMC-B region. To determine the average volume of the allocated flow using the EFR-Mon method in different months of the year, the volume of each EMCs and the class-ADJ are calculated using Equation 11 and presented in Table 3.

**Table 3-** Monthly distribution of EFR values as percent of mean annual flow (MAF) using the new Monthly method (EFR MON) in different conventional EMCs and the Adjusted class of river management at the Tapik Station, Nazlu River

| Month | EFR MON (%MAF) |
|-------|----------------|
|       | Class A | Class B | Class C | ADJ  |

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|       |       |       |       |
|-------|-------|-------|-------|
| January | 86.3  | 74.3  | 63.5  | 79.9  |
| February | 86.2  | 74.4  | 64.0  | 79.8  |
| March   | 79.1  | 64.3  | 52.9  | 71.1  |
| April   | 79.4  | 64.4  | 52.3  | 71.3  |
| May     | 80.8  | 65.9  | 53.7  | 72.7  |
| June    | 75.7  | 57.6  | 43.7  | 65.9  |
| July    | 71.0  | 51.3  | 37.2  | 60.4  |
| August  | 72.3  | 52.8  | 38.3  | 61.7  |
| September | 73.5 | 54.9  | 40.5  | 63.4  |
| October | 71.3  | 54.6  | 41.9  | 62.0  |
| November | 79.9 | 65.0  | 52.8  | 71.8  |
| December | 83.7  | 70.6  | 59.3  | 76.6  |
| Total   | 78.9  | 63.3  | 50.9  | 70.5  |

The RVA method was used to better evaluate the number of changes and also to compare the new methods presented with the conventional FDCS method (GEFC), and the diagram of hydrological alteration is in Figure 8.
Figure 8- Hydrological alteration (HA) values using RVA method for EFR allocations in two A
and C EMCs with three approaches (GEFC, Annual and Monthly) at the Tapik Station, Nazlu River

Figure 8 shows the HA of parameters for the two new methods EFR-Ann and EFR-Mon and the conventional method (GEFC) for Class A and C to examine the trend and magnitude of these changes. According to this diagram, the HA parameters of the GEFC method are much higher than the new methods presented. Using absolute averaging (regardless of the negative or positive values of the changes) HA for GEFC in EMC-A in the range High, Middle and Low RVA categories are 0.6, 0.38 and 0.85, respectively. However, the absolute average value of HA for the mentioned categories is 0.35, 0.18 and 0.51 in the EFR-Ann method and 0.27, 0.11 and 0.36 in the EFR-Mon method. Also, by examining the diagram in Figure 8, selecting a lower EMC increases the HA in hydrological parameters and the EFR-Mon method provides better results. To prove this point, using the absolute averaging of HA for GEFC method in EMC-C, the RVA categories were examined in the high, middle and low ranges, which are 0.683, 0.587 and 1.195, respectively. However, the absolute average value of HA for the mentioned categories in the EFR-Ann method is 0.69, 0.52 and 1.12 and in the EFR-Mon method is 0.54, 0.20 and 0.69. According to the presented results, it was found that both new methods provide better results compared to the GEFC method and bring less HA to the river ecosystem. However, to compare the results of two EFR-Ann and EFR-Mon methods of supplying the EWR of the lake, a diagram of HA was used for the class-ADJ in both new Methods, which supplies the Urmia Lake. In the class-ADJ, the FDC was shifted in such a way that both methods transfer 70.45% of the MAF volume to the lake and the results of this study can be seen in Figure 9.
According to Figure 9, the absolute mean HA values for the High, Middle and Low RVA classification intervals for the EFR-Ann method in the class-ADJ, which are 0.28, 0.13 and 0.4, respectively. However, the absolute average of HA for the class-ADJ in the EFR-Mon method is 0.27, 0.11 and 0.36. Also, the standard deviation (SD) of the absolute HA values of both methods was calculated for three RVA classes, and the SD value for the High, Middle and Low classes in the EFR-Ann method was 0.22, 0.13 and 0.30, respectively, and in the EFR-Mon method was 0.20, 0.10 and 0.24, respectively. According to the Figure 9 and the calculated SD, HA has a more uniform trend for the monthly method than the annual method in different parameters.

After calculating the EFR of the inflow rivers to the Urmia Lake for both new methods, the total volume of water allocated to the 10 main inflow rivers to the lake from 2010 to 2015 is
examined for each method and presented in Figure 10.

Figure 10- Comparison of environmental flow allocation from two new annual and monthly methods with the conventional GEFC method and with natural river flow capacity and water entering from 10 main rivers to the lake in 2010-2015

Figure 10, shows that in all six years, the GEFC method in EMC-C has the lowest volume of allocated water concerning the EWR of the lake (3084Mm³) and on average 26% of the annual volume of natural river flow equivalent to 670Mm³ of water is delivered to the lake each year. Also, the average volume of water allocated to the Urmia Lake in the EFR-Ann method class-ADJ with 71% and the EFR-Mon method class-ADJ with 74% of the natural flow of the river will be equivalent to 1852Mm³ and 1938Mm³, respectively. In the period from 2010 to 2015, the average natural flow volume of rivers was equal to 2618 Mm³, equivalent to 60% of the long-term average natural flow volume of these rivers.

According to Figure 10, the flow allocated to the Urmia Lake in these six years is much higher than the volume calculated through the GEFC-Class C method, but by the 1361Mm³
allocation of water to the Urmia Lake only 44% of EWR of the lake has been supplied. However, if the EWR of the Urmia Lake be considered by Equation 8, the water volume equal to or more than 70.5% of the natural flow of the river as e-flow should be allocated to the lake. So, the volume of water that can be allocated to the Urmia Lake must be more than 1844Mm$^3$ which is equal to 60% of the lake EWR, that both EFR-ADJ-Ann and EFR-ADJ-Mon methods can supply this amount of water.

4- Conclusion

This new method is designed to bridge the hydrological method of FDCS, which provides the required e-flow of the river and the EWR supply for wetlands and lakes downstream of the rivers. By using the proposed method, river flow can provide the EWR in which it makes the least changes to the natural flow regime. In this research, two new methods, EFR-Ann and EFR-Mon, have been introduced. Both methods can create a connection between the lake and the river. Based on the results the EFR-Mon method due to considering the hydrological conditions of the flow during different months of the year makes the least HA (based on studies using RVA method). So, it is the most appropriate in estimating the e-flow of rivers leading to wetlands and lakes by considering the EWR for these aquatic ecosystems compared to the EFR-Ann method. One of the most important advantages of the two new methods compared with conventional method that can be calculated through GEFC software is the use of daily data and performing e-flow calculations in real-time. This new method can calculate the EFR value on each day of the year according to the upstream inflow and allocate it to the downstream. However, using the conventional FDCS method, due to the use of average monthly data, it is not possible to check the adequacy of the allocated e-flow before obtaining the average monthly flow at the end of each month. Based on
the studies using RVA method in this research, the monthly method is the most appropriate method in estimating the environmental flow of rivers compared to the annual method due to consider the hydrological conditions of the flow during different months of the year and make the least hydrological change. In addition, both new methods with the allocation of 70.5% of the annual flow volume of the basin rivers in the long run will be able to allocate EWR Urmia Lake and rehabilitate it. The use of the new method has reduced the impact of expertise biases and thus increased the reliability of this method by creating a suitable quantitative criterion to determine the shifting amount of the FDC and allocate the appropriate flow volume to provide EWR of downstream lakes and wetlands.

5- Acknowledgment

This article was extracted from the PhD thesis prepared by Ali Mobadersani. The authors acknowledge the department of water science and engineering, Faculty of agriculture, university of Tabriz.

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