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Assessment of Environmental Water Requirement Allocation in Anthropogenic Rivers with a Hydropower Dam Using Hydrologically Based Methods—Case Study

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Abstract: Anthropogenic activities such as damming have caused an alteration in the natural flow regime in many rivers around the world. In this study, the role of constructing a hydroelectric dam on the natural flow regime of the Kor River, Iran, is investigated. Nine different methods, which fall into the category of hydrological methods, were used to determine the environmental water requirement (EWR) of the Kor River. In addition, two indices are introduced to evaluate the environmental flow allocation in anthropogenic rivers. The results show that although the supply of environmental flow in some months is in relatively acceptable conditions on average, there is a deficiency in the allocation of EWR in the range of 1.92–30.2% in the spawning period of the dominant fish species. The proposed indicators can provide a general picture of the status of environmental flow allocation in rivers where little ecological data is available and the hydrological regime has changed due to human activities, particularly in rivers with hydropower plants. Moreover, after the construction of the dam, no major floods have occurred in the river, which has led to the loss of the morpho-ecological balance in the river and disruption of the natural state of habitats. Therefore, the negative impact of dam construction on the environmental conditions of the river should be considered in the active management of the dam outlets.

Keywords: environmental flow; hydroelectric dams; natural rivers; hydrological impacts; ecosystem resilience

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1. Introduction

Human interference in the ecosystem has intensified in recent years. In most parts of the world, the construction of dams and over-exploitation of water resources, such as river water diversion for agricultural, urban, and industrial purposes, have affected the main variables of river water [1]. In many cases, these interferences can have a negative impact on the hydrological and ecological services provided by ecosystems, making them vulnerable to humans and other organisms dependent on these services [2–4].

The construction of dams leads to drastic changes in the natural flow regime of rivers [5] and negative effects on the ecological status of the river catchment, especially in dry seasons [6,7]. The change in the hydrological regime affects a number of other processes taking place in the downstream part of the river channel, including the transformation of its geomorphological features, which is, for example, evident in the study of the impact of the Włocławek Reservoir on the hydrological regime of the lower Vistula, Poland [8]. One cannot forget about created reservoirs that serve multiple purposes on one side but at the same time are subject to various environmental concerns such as sediment deposition [9], cyanobacteria blooms [10], and greenhouse gas emissions [11]. Among different types of dams, hydropower dams have a considerable impact on the release in the river [12,13]. Renöfält et al. [14] noted that in some anthropogenic rivers with hydropower dams, water is released from dams only in cases where the flow exceeds the installed capacity of power plants or in cases where power is shut down. In addition, to meet the peak energy demands, reservoirs store water during the wet seasons with high and low floods to be released during the dry seasons (Figure 1). As turbine valves often open intermittently in this type of dam, disrupting the natural flow of water can have a major impact on the river flow, ecosystem, and the environment [15,16]. In some cases, dam construction does not change the annual runoff trend, but due to runoff control in winter and increased base flows in summer for irrigation, the average daily flow shows less change [17].

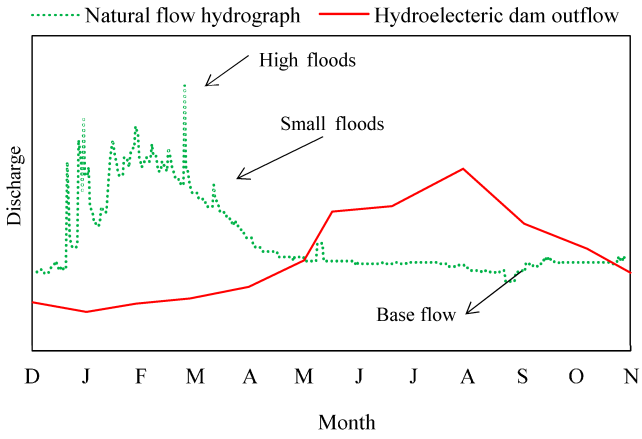

Figure 1. Schematic of hydrological regime of a natural and an anthropogenic river with a hydropower dam.

Although the construction of the dam at first glance seems to disrupt the environmental conditions of the river, active dam management and enforcement measures, such as the planned opening of the dam outlets, increase the reliability of providing the downstream minimum environmental flow. Under such conditions, a complete flow regime that includes base flows and flood flows can be provided, ensuring that sufficient water remains in the river throughout the year, especially during dry periods [18–20].

It is necessary to define the hydrological and ecological requirements of the river in the form of an environmental flow requirement and to consider them in water allocation interactions to prevent the long-term negative effects of these projects on river ecosystems [21,22]. Environmental flow is the water regime, with the appropriate quantity and quality, provided to a river, wetland or coastal area to protect ecosystems and their benefits when there are competing uses and regulated flows [23].

Depending on the scale of the study site, the available data, the time available for evaluation, and the technical and financial capacities, various methods can be used to determine the environmental flow requirements [24]. So far, more than 200 methods have been proposed to determine the environmental water needs of rivers, which can be divided into five distinct categories, namely hydrological, habitat simulation, hydraulic rating, holistic, and combined methods [25]. The most widely used category of environmental flow determination in the world is hydrological methods, which rely mainly on historical river flow statistics. Environmental flow in these methods is determined from the flow duration curve at different time scales (annual, seasonal or monthly) or as a percentage of the average annual river discharge. Older methods in this group only determine the minimum Environmental Water Requirement (EWR) of the river, while more recent methods take into account several flow characteristics such as flood flow discharge, minimum flow (base flow), small floods, and large floods (Figure 1). The Tennant method [26] and the Range of Variability Approach (RVA) [27] are among the most common methods in this category that have been widely used in several rivers [28–33].

Newer methods emphasize the preservation of variable hydrological indices because changes in these indices have the greatest impact on the river ecosystem [34]. These methods include the desktop reserve model (DRM) and the flow duration curve shifting

(FDC-Shifting) methods. Although numerous environmental characteristics such as temperature, water quality, and turbidity have been shown to affect river health [35], the common assumption of these methods is that the flow regime is the main driving force except in polluted rivers [27]. Thus, methods called hydrological methods, which are mainly based on hydrological data and involve less engineering judgment, have retained their validity, and researchers have used many of these methods to estimate environmental flow in a river [36–41]. In some cases, these methods have even been introduced as the most efficient ones in determining environmental flow because they offer cost-effective, time-saving solutions requiring low computational facility [42–45]. However, the appropriate hydrological regime should be considered in the calculations to provide the quantitative and qualitative threshold required by the dominant ecological species, taking into account their temporal and spatial variations [46–51]. While different criteria of flow hydrological regime have been proposed by researchers to determine the minimum EWR, it is not yet fully clear which of these methods is superior to the other.

Although much research has been done to estimate the EWR in different ways, so far the adequacy of the allocated flow in rivers to meet the minimum EWR is not guaranteed, especially in anthropogenic rivers such as rivers subject to the construction of dams. In many countries, the allocation of environmental flow is a common practice, but still there are countries where environmental flow allocation is rarely applied. For example, several wetlands and rivers in Iran are drying up due to the lack of proper allocation of environmental flow as a result of the construction of dams and their lack of active management. Among the water bodies suffering from the incomplete environmental flow allocation, sixty wetlands in Iran, e.g., the Bakhtegan, Hor-al-Azim, Gavkhoni, Urmia, Zayandehrud, and Parishan wetlands, are in critical condition. Talukdar and Pal [52] stated that because of the construction of dams and other water diversion structures in the Punarbhaba River in the Barind tract of India and Bangladesh, the area of wetlands in the period 1978–2015 in the region was reduced up to 34%. On the other hand, the area of wetlands in China increased by about 0.4% between 2000 and 2015, and the active management of dams has played an important role in this increase [53].

Despite extensive research, the positive or negative role of dams in ecosystem changes has not yet been fully elucidated. Although decision-makers' focus on the environment and ecosystem has increased in recent years, social and economic constraints in many countries have made water allocation largely based on economic priorities, not environmental demands [54]. This means that in many of these countries there are two major challenges in this regard: releasing the flow for economic gains, such as generating electricity and agricultural products, and meeting the ecological needs of the river by allocating the required amount of environmental flow at the right time. In some cases, including the present case study, although pressure from NGOs and public opinion has led decision-makers to release environmental flows, it must be ensured that these releases are done in the right quantity and at the relevant time. The main objectives of the current study are: (i) comparison of the differences in environmental water requirement using nine hydrology-based EWR determination methods applied to a study site; (ii) investigating the effect of the construction of Mollasadra Dam on changes in the flow parameters of the Kor River by the Range of Variability Approach; and (iii) evaluating the adequacy of the allocated flow in the river to meet the EWR after the dam construction. We do realize that the analysis of water quality is necessary to derive definite conclusions, but it goes beyond the scope of this research. In addition, it should be noted that utilizing nine different methods for the determination of the EWR was to present a general picture of the EWR in the studied region. Unfortunately, the selection of the most suitable methods is beyond the scope of this study as it requires a very extensive field investigation as well as laboratory observations on the river geometry and the characteristics of the biota of the river that can provide a foundation for future studies exploring this key point. This methodological study refers to a particular river but exemplifies the problems discussed in many corners of the globe. A recent heated debate on the impact of the Włocławek dam itself and on the planned barrage on the Vistula river (one of the last large European rivers with many stretches preserved in close to natural morphological conditions) downstream from Włocławek is an example worth a mention in this context [8,55].

2. Materials and Methods

2.1. Study Area Description

The Kor River, with an approximate length of 280 km and a catchment area of 9700 km^2, is the largest river in the Fars province, located in southern Iran, and one of the main sources of water supply in the agricultural, industrial, and urban sectors of the province. This river branches off from the Zagros highlands and flows to the southeast. The catchment of this river with 9700 km^2 area is located between the eastern longitude of 51°45′ and 54°03′ and the northern latitude of 29°22′ and 31°15′. The river is formed by the confluence of the Tang-e-Boraq River from the northeast and the Shorshirin River from the west. It is joined by several drains and tributaries of the Maein and Sivand and eventually flows into the Bakhtegan Wetland. On the Kor River, two storage dams named Mollasadra and Dorodzan have been built with heights of 72 and 58 m and reservoir volumes of 440 and 993 MCM, respectively (Figure 2a). The Mollasadra Dam is a multipurpose dam with the aim of controlling the floods of the Kor River, providing water for agricultural, drinking, and industry sectors as well as electricity generation. The Mollasadra Dam hydroelectric power plant with a capacity of 100 MW plays an important role in supplying electricity to the region. The hydrological regime of the Kor River upstream of the Dorodzan Dam after the operation of the Mollasadra Dam (since 2008) is largely affected by the regulatory flow released from the Mollasadra dam [56].

The average annual rainfall in the Kor River basin is 443 mm. Some previous studies show that while there is a decreasing and increasing trend before and after 2004, respectively, in the precipitation of the Kor River basin in the studied period, these trends are not statistically significant [57,58]. However, statistical analysis shows a decreasing trend in the Kor River flow confirming the intensive human activities and land-use changes in the catchment [58]. Variations of the average rainfall in the studied region during 1965–2019 is plotted in Figure 2b.

2.2. Data Description

For hydrological calculations, the daily flow data of the Chamriz hydrometric station located at an eastern longitude of 52°08′ and a northern latitude of 30°27′ on the Kor River, between the two storage dams, during the years 1965–2019 have been used. The area of the catchment upstream of the Chamriz hydrometric station is 3390 km^2. The climate of the river catchment in the study reach is in the cool sub-humid zone based on Emberger classification [59]. The average minimum, average and average maximum temperatures in Chamriz station are 6.4, 14.7 and 23 °C [60]. The river has a gravel bed in the study reach. On the riverside terraces, cereal cultivation, which basically includes rice (paddy), is common. The natural vegetation of the basin consists mainly of dense forests of Zagros. Capoeta is the most important aquatic animal species in the Kor River [61].

2.3. Methods of Data Analysis

Nine hydrological methods, including traditional and modified Tennant, Tessman, flow duration indices, Smakhtin, low-flow indices, FDC shifting method, Desktop Reserve Model (DRM), and the Range of Variability Approach (RVA) were used to determine the EWR. In the Tennant method, a percentage of the Mean Annual Flow (MAF) was used to determine the quality of aquatic habitat. Tennant concluded from 58 cross-sections of 11 rivers in the highlands of the United States that the minimum flow for short-term survival of fish is 10% MAF. If 30% MAF is considered, the stream will be able to maintain relatively good survival conditions, and if 60% MAF is considered, the desired habitat conditions will be met [26].

(**a**)

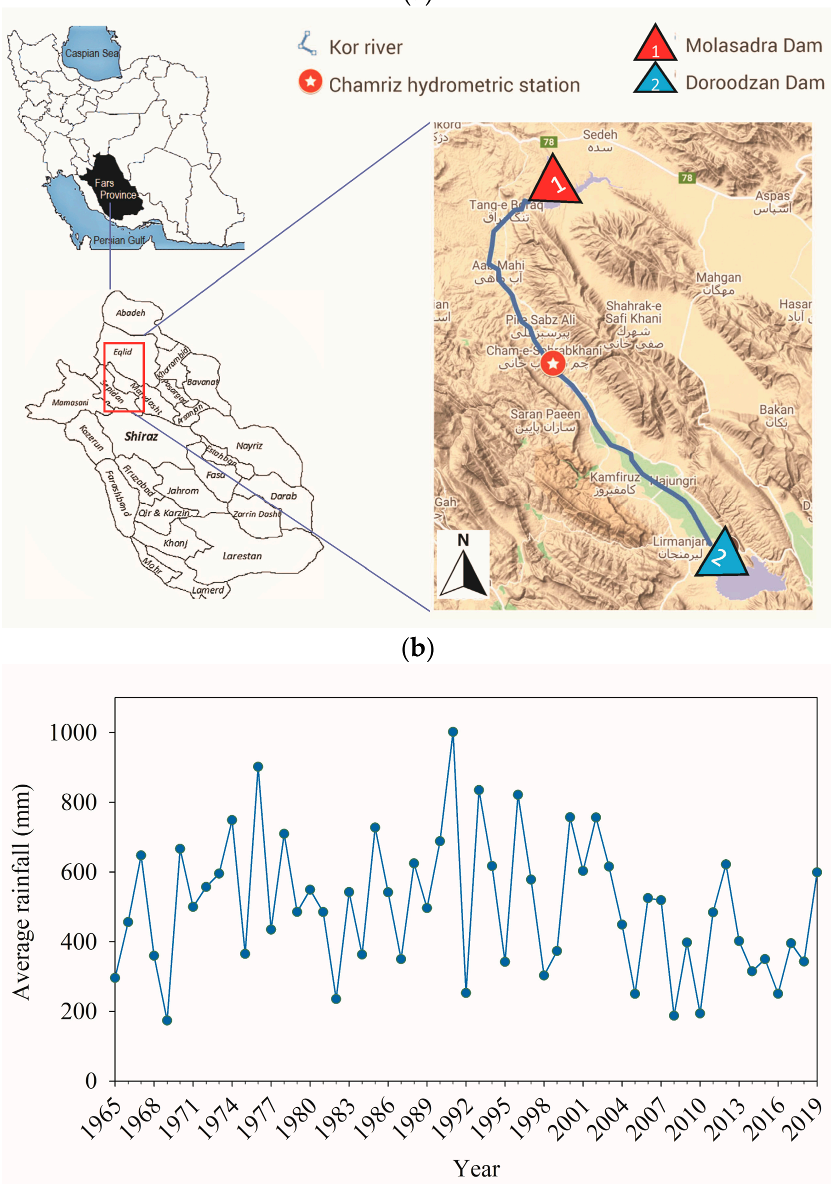

Figure 2. (**a**) Location of the study area, upstream reach of the Kor River. (**b**) Temporal variations of the average yearly rainfall.

Tessman in 1980, using the Tennant method, combined MAF and Mean Monthly Flow (MMF) to determine the minimum EWR. Using Flow Duration Curves (FDC), different low-flow indices are obtained. Q_{70}, Q_{95}, and Q_{99} flows, corresponding to 70th, 95th, and 95th percentile on the flow duration curve, respectively, are commonly used as low-flow indices. The MMF (or Q_{50}) is another indicator of the flow duration [62]. Among different low-flow indices, Pyrce [62] introduced $7Q_2$ and $7Q_{10}$, corresponding to the 7-day low-flow value with a 2-year and 10-year return period, respectively, as the most widely used indicators.

The Smakhtin method uses a combination of (LFR: environmental Low-Flow Requirement) and (HFR: environmental High-Flow Requirement) to determine the EWR. HFR is reflected in floods and their impact on the morphology of the river and the plants surrounding the river, and LFR is the minimum water required for fish and other aquatic organisms. In the Smakhtin method, the LFR should be considered equal to Q_{90} to maintain relatively good conditions in the river. Q_{90} is a flow that 90% of the time of the year, the river flow is higher than that amount. In addition, HFR is determined according to the environmental management objectives and the river flow regime.

The flow duration curve shifting method (FDC-shifting) was introduced to assess the EWR in rivers [63]. The four main steps in this method are as follows: simulating reference hydrological conditions, defining environmental management classes, establishing environmental FDCs from reference conditions, and simulating continuous monthly time series of environmental flows. The environmental management classes vary from class A for natural rivers to class F for critically modified river conditions. In this method, the most important issue is the proper use of lateral shifts of the original reference FDC, in each environmental management class. More details about this method can be found in [63,64].

The Desktop Reserve Model (DRM) was first developed by Hughes and Hannart (2003) to assess the environmental flow requirements of South African rivers. This method can calculate the EWR in situations where a rapid assessment is required and available data are limited. This method defines four classes of environmental management. These four classes include class A for natural and undisturbed rivers, class B for modified but mostly natural rivers, class C for relatively modified rivers, and class D for highly modified rivers with high damage to the natural habitat and basic function of the ecosystem [65]. In this classification, hybrid classifications such as A/B and B/C are also used to increase the range of environmental flows. Flow requirements in the DRM model are calculated based on these classifications.

Range of Variability Approach (RVA) has been developed as one of the most complex and desirable hydrological methods [27]. In this method, the main purpose is to provide a series of statistical features and ecological aspects of the hydrological regime of the river by highlighting the important role of hydrological changes in the protection of ecosystems. The RVA method requires at least 20 years of flow statistics. This method uses a conventional range of variability based on ±1 times the standard deviation from the mean or 25% or 75% quarters. It is then recommended that water resources development projects be managed in such a way that the distribution of the annual values of the Indicator of Hydrological Alteration (IHA) parameters is as close as possible to the distribution of the parameters under natural conditions. If most of the hydrological time series after development are within the normal range of parameters, it is clear that the effects of development plans on the river ecology are small and the river is still in relatively normal condition. A summary of different methods used in the present study along with their advantages and disadvantages is provided in Table 1.

To more accurately investigate the impact of the construction of Mollasadra Dam on the flow conditions in the Kor River, adequacy in the EWR supply, i.e., *AEWR*, is calculated using Equation (1). *AEWR* reflects the difference between the mean monthly flow of the river and EWR during a specific month.

$$AEWR\ (\%) = \left(1 - \frac{\text{EWR}}{\text{MMF}}\right) \times 100 \quad (1)$$

In addition, to determine the most critical months of the year in terms of minimum EWR allocation, deficit percentage in EWR, *DEWR*, is calculated using Equation (2) by dividing the number of methods with a deficit in EWR in a specific month (N_d) by the total number of methods examined (N_m), i.e.,

$$DEWR\ (\%) = \frac{N_d}{N_m} \times 100 \quad (2)$$

Table 1. A review of some of hydrological methods for the Environmental Water Requirement (EWR) determination.

Method	Description	Advantages	Disadvantages	Sources
Tennant and Modified Tennant	-Also known as the Montana Method -Based on testing on 11 rivers -EWR values are recommended based on percentages of MAF	-Simple -Low-cost -Fast -Requires low data -No field works -Adaptability to wet and dry seasons in each region	-Considers only the physical suitability of the habitat -Highly dependent on degree of professional judgement -Not applicable to high gradient rivers (>1% slope) -Not suitable for rivers with varying flow regime -the percentages need to be re-calculated for each region	[26,46,66–68]
Tessman	-Considers flow variations on a monthly basis	-Easy to implement -Applicable for rivers with varying hydrological regimes -No field work	-Low accuracy in low-flow periods -Highly dependent on degree of professional judgement	[69,70]
Smakhtin	-Uses a combination of HFR as flood events and LFR as minimum water requirements for fish and other aquatic organisms as a percentage of MAF.	-Easy to implement -Low-cost -No field works	-Highly dependent on degree of professional judgement	[70,71]
Flow duration indices	-Express the percent of time definite flows will be corresponded or exceeded over different time scales -Shows the full range of river flows from low flows to floods as well as the relationship between flow magnitude and frequency.	-Fast -Easy to implement -Inexpensive -Better fits to different geographical regions -Daily, weekly, or monthly discharge data can be used -Provide stable hydrologic conditions that would therefore be beneficial to aquatic habitat	-Low reliability especially during low flows -Highly dependent on degree of professional judgement -Harmful effects on stream biota by application of high flows	[68,71,72]
Low-flow indices	-Based on more than 50% exceedance obtained from FDC for daily discharge data -Involves a statistical low-flow frequency analysis of the minimum mean daily flow during a given period of 7 days within a 2- or 10-year return period	-Simple -Low cost -Habitat preservation during low-flow seasons -Maintaining water quality under the effect of wastewater	-Low reliability -Not recommended for the variable flow regimes	[62,70,72,73]
FDC shifting	-Uses monthly flow data -Includes four subsequent steps -An environmental management class should be defined based on ecological conditions and management perspective	-Better fits to different geographical regions -Desktop method -Can be implemented using a free software package	-Highly dependent on degree of professional judgement	[64]
DRM	-Defines four classes of environmental management -Assumes that EWR increases with increasing base flow contribution and decreases with increasing flow variability.	-Based on monthly flow data which are more readily available or accessible in developing countries.	-Highly dependent on degree of professional judgement -Parameter values must be modified for each region	[64,74]
RVA	-Based on the time series of natural daily flows in a given area, thirty-two hydrological parameters, which reflect different aspects of flow variability including magnitude, duration, frequency and timing are estimated. -Calculates EWR as a range between the 25th and 75th monthly flow percentile using non-parametric analyses or as a range of mean monthly flow using parametric analyses	-Can be implemented as a desktop tool. -Gauged or modelled daily flows can be used	-The number of parameters used is too large	[74–77]

3. Results

The results of the Tennant method for the Chamriz hydrometric station for different ecological conditions of the Kor River are presented in Table 2. Based on national legislation [78] and suggested by other researchers for similar rivers in Iran [64], fair or degrading class was selected in the present study for the Kor River for comparison purpose with the results of other methods, corresponding to 30% of MAF for April to September and 10% MAF for October to March according to Tennant method. The selection of the six-month period in the Tennant method is based on the division of the year into two low-flow and high-flow periods, but according to the results presented in Table 2, two periods of low flow (October to March) and high flow (April to September) specified in the Tennant method do not match with the hydrological conditions of the Kor River. In other words, the temporal distribution of rainfall at the Chamriz hydrometric station is such that rainfall occurs mainly in winter and early spring. Therefore, considering the long-time mean monthly rainfall, the months with average rainfall lower than the mean monthly rainfall, i.e., June to January, have been considered as the low-flow period. In addition, the months with average rainfall higher than the mean monthly rainfall, i.e., February to May, have been considered as the high-flow period. After this redistribution of the low-flow and high-flow months, 10% and 30% of MAR were considered the environmental flow for each period, respectively. The results are presented in Table 3 under the heading of modified Tennant. With this regionalization, which is more in line with the hydrological situation of the study area, the months of February and March, which were considered in the traditional Tennant method in the low-flow period shift to the high-flow period in the modified Tennant method. In addition, the months of June–September, assigned to the high-flow period in the traditional Tennant method move to the low-flow period in the modified Tennant method. There is no change in the situation of other months in the traditional and modified Tennant method.

Table 2. Determination of the EWR of the Kor River according to the Tennant method.

Description of Flows	Recommended EWR (% of MAF)		Recommended EWR (m^3/s)	
	October–March	April–September	October–March	April–September
Flushing or maximum	200	200	52.62	52.62
Optimum range	60–100	60–100	15.79–26.31	15.79–26.31
Outstanding	40	60	10.52	15.79
Excellent	30	50	7.89	13.16
Good	20	40	5.26	10.52
Fair or degrading	10	30	2.63	7.89
Poor or minimum	10	10	2.63	2.63
Severe degradation	<10	<10	<2.63	<2.63

Table 3. Monthly distribution of EWR of the Kor River by different methods (m^3/s).

Month	MMF	MAF	Tenant		Tessman	FDC Shifting	DRM	Flow Duration Indices			RVA
			Traditional	Modified				Q_{50}	Q_{90}	Q_{95}	
October	10.13	26.31	2.63	2.63	10.13	5.00	5.34	8.95	6.31	6.07	8.10
November	12.96	26.31	2.63	2.63	10.53	6.30	5.75	11.01	6.68	6.28	7.55
December	24.32	26.31	2.63	2.63	10.53	11.00	6.42	16.15	10.78	10.38	10.19
January	33.63	26.31	2.63	2.63	13.45	13.90	7.60	20.06	12.48	11.95	14.15
February	42.07	26.31	2.63	7.89	16.83	15.70	8.38	33.82	15.51	13.83	15.36
March	56.76	26.31	2.63	7.89	22.71	19.50	9.97	45.48	20.5	18.20	22.50
April	57.02	26.31	7.89	7.89	22.81	19.50	11.88	46.95	24.66	22.61	31.64
May	30.43	26.31	7.89	7.89	12.17	12.20	9.50	24.71	12.02	10.85	31.94
June	15.81	26.31	7.89	2.63	10.53	8.00	8.14	12.92	6.50	5.91	15.05
July	12.03	26.31	7.89	2.63	10.53	6.30	4.30	10.28	6.40	6.04	10.71
August	10.60	26.31	7.89	2.63	10.53	5.40	4.11	9.22	6.17	5.89	9.24
September	9.98	26.31	7.89	2.63	9.98	5.00	3.81	8.64	5.67	5.40	8.66

The average environmental flow proposed by the Tessman method is 13.4 m^3/s, corresponding to 51% of the MAF. According to the Tessman method, in the July to October period, the entire river flow should be allocated to the environmental sector. Since this period coincides with the harvesting of crops from agricultural lands around the river in the study reach and flow is not diverted from the river [79], there is no problem in the supply of environmental water. For June, the calculated EWR was 10.5 m^3/s, which corresponds to 67% of MMF. The minimum environmental flows calculated by the Tessman method are inconsistent in terms of management and agricultural use for the months of June and July, which coincide with the growing season of crops in the region. According to a study on the water resources and demands in the study area, 8.84 m^3/s water is diverted on average in June by the local farmers [79], approximately 56% of the MMF. Therefore, if this method is used to allocate the environmental flow, other beneficiaries of the river flow such as the farmers face some water shortage for their products, leading to serious social challenges due to the dependence of the farmers' livelihood on the river water.

In addition, the results of the EWR calculations by the Smaktin method are presented in Table 4. According to this method, the minimum EWR of the Kor River is 15.1 m^3/s, corresponding to 57% of MAF. It should be noted that as Q_{90} > 0.3 MAF then the high-flow requirement (HFR) is considered 0 according to [63] and then EWR = LFR where LFR is the low-flow requirement. In addition, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, and Q_{95} flow duration indices are presented in Table 5. Moreover, monthly variations of Q_{50}, Q_{90}, and Q_{95} flows derived from the flow continuity curves for October to September are given in Table 3.

Table 4. EWR of the Kor River in Chamriz station by Smakhtin method (m^3/s).

MAF	10% MAF	20% MAF	30% MAF	LFR	HFR	EWR
26.31	2.63	5.26	7.89	15.13	0	15.13

Table 5. Flow duration indices of the Kor River.

Indices	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
Flow (m^3/s)	18.41	17.51	16.66	15.87	15.13	14.42

To calculate the EWR by the FDC shifting method, the data of the Kor River in the Chamriz station were used. Figure 3 shows the shifted flow duration curves for the 6 environmental management classes A to F. A summary of the annual EWR calculations for the six management classes is shown in Table 6. In this figure, classes A to F represent the state of natural, slightly modified, moderately modified, largely modified, seriously modified, and critically modified, respectively. According to the conditions of the Kor River, including the need of the locals to the river water for socio-economic development, and construction of dams, water diversion projects, habitat changes, and water quality reduction [80,81], class C corresponding to moderately modified, can be considered for this river. According to [63], most likely ecological conditions for the environmental management class C are as follow: the habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact; some sensitive species are lost and/or reduced in extent; alien species present. For this class, the river experiences multiple disturbances (e.g., dams, diversions, habitat modification, and reduced water quality) associated with the need for socio-economic development. Based on Table 6, the EWR of the Kor River in Chamriz station by the FDC shifting method equals 9.6 m^3/s, i.e., 36.4% of MAF. In addition, the EWR for different months by the FDC shifting method in class C is given in Table 2.

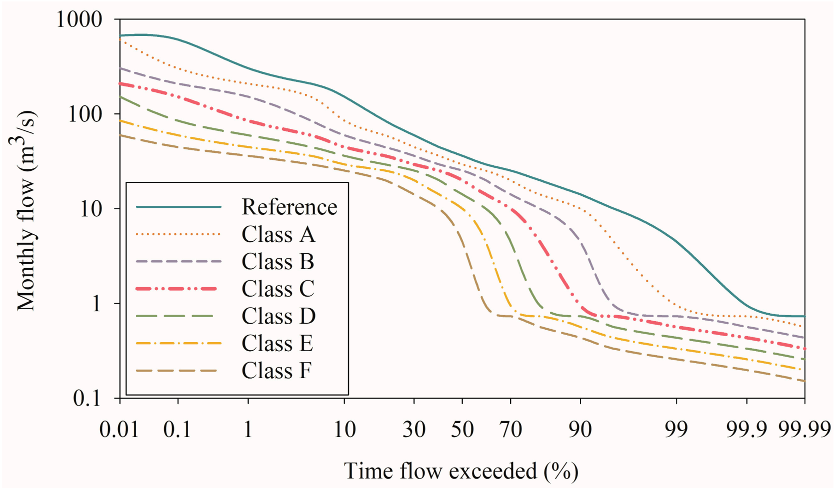

Figure 3. Flow duration curves for different environmental management classes using the flow duration curve (FDC) shifting method, the Kor River.

Table 6. Estimation of Long-term EWR for different environmental management classes using the FDC shifting method, Kor River.

Environmental Management Class	Class A	Class B	Class C	Class D	Class E	Class F
EWR (% of MAF)	69.7	49.9	36.4	27.2	20.4	15.0
EWR (m^3/s)	18.3	13.1	9.6	7.2	5.4	3.9

To calculate the EWR using the Low Flow Indices method, minimum 7-day flows with a return period of 2 and 10 years ($7Q_2$ and $7Q_{10}$) should be determined using daily flows. $7Q_2$ and $7Q_{10}$ values can be calculated using different statistical distributions as summarized in Tables 7 and 8. These results show that the daily flow data of the Chamriz hydrometric station is well adapted to the Pearson type III distribution with the minimum error among the 5 probability distributions studied. In addition, the minimum EWR according to $7Q_2$ and $7Q_{10}$ indices was calculated to be 7.2 and 10.7 m^3/s, respectively. However, the use of $7Q_{10}$ may significantly underestimate the EWR and its application can have detrimental biological effects [72]. Although there are concerns about the appropriateness of the EWR determined using the $7Q_{10}$ flow, both the $7Q_{10}$ and $7Q_2$ indices have been used as two widely used indices to determine the low flows in the EWR calculations. Although this method may be compatible with rivers with a significant base flow in the regions with humid climates, the use of this indicator for environmental purposes in dry and semi-dry climates, such as the study area, is not very certain [64]. Therefore, it is recommended that this method is used along with other indicators.

Table 7. Error of different statistical distributions in Low Flow Indices method.

Probability Distribution	Error (%)
Normal	0.59
Log-normal	0.80
Pearson type III	0.51
Log-Pearson type III	1.21
Gumbel	0.65

Table 8. Minimum annual 7-day flow with 2 and 10 years return period for the Kor River.

$7Q_2$		**$7Q_{10}$**	
Flow (m^3/s)	Percent of MAF (%)	Flow (m^3/s)	Percent of MAF (%)
7.2	27.3	10.7	40.6

The EWR was calculated using the Desktop Reserve Model (ver.2) software. The results of this method for different ecological categories for the studied hydrometric station are presented in Table 9. In this study, class C (relatively modified rivers) is considered the ecological status of the Kor River. This management class considers about 20% to 30% of the average flow rate as EWR, in which case the basic function of the river ecosystem is still intact and most species are preserved. Ecological class C also corresponds well to the flow potential in different months and is acceptable in terms of domestic water, agricultural uses, and management purposes in the region. The monthly distribution of the EWR taking into account ecological class C in the Kor River is given in Table 3.

Table 9. Estimation of EWR for different environmental management classes using the desktop reserve model (DRM) method, Kor River.

Environmental Management Class	**A**	**A/B**	**B**	**B/C**	**C**	**C/D**	**D**
EWR (% of MAF)	64.40	51.90	40.80	33.20	25.50	20.80	16.20
EWR (m^3/s)	16.94	13.65	10.73	8.73	6.71	5.47	4.26

As mentioned before, IHA software [82] was used to calculate the EWR by the RVA method. The data input to the software was divided into two periods: 1965–2007 before the construction of Mollasadra Dam and 2008–2019 after the construction of the dam. The results of this method are presented in Figures 4 and 5 and Table 10. According to Figure 4, it can be seen that after the construction of Mollasadra Dam, the average monthly flow throughout the year has decreased. The maximum and minimum decrease in the monthly flow is observed in March and July, respectively. The difference between the surface under the two curves in Figure 4 indicates an increase in water consumption upstream. Before the dam was built, much of the flow passed through the river in winter in the form of floods and was out of the reach of farmers. After dam construction, winter floods are stored in the reservoir and released over time, thus giving the opportunity for upstream beneficiaries to use the released water during the spring and summer months. In addition, variations of the monthly flow before and after the construction of the Mollasadra Dam are shown in Figure 5 for July, which has the least change in the average monthly flow after the construction of the dam according to Figure 4. It can be seen that while the median flow line has not changed considerably, the 75th and 25th percentile lines have experienced a significant reduction after the construction of the dam. The impact of the dam on the river flow is more significant in other months. In addition, minimum, maximum, and average monthly values of the Kor River flow before and after the construction of the Mollasadra Dam are calculated in Table 10 using the RVA method. While the average and minimum monthly flows have decreased for all months after the construction of the dam, except in July for the minimum monthly flow, the maximum monthly flow has increased in October, November, December, and August. The increase in high flows during the dry season of the Kor River is of high importance for environmental purposes. For example, these high flows can prevent riparian vegetation from encroaching into the main channel, restore normal water quality conditions after long low flows, and flush away waste products and contaminants [82,83]. Because of the importance of the Kor River for the downstream ecosystem and the conflict of interest among different users (agriculture, industry, domestic, and ecosystem sections) along the river, the lower boundary of the RVA has been chosen for the minimum EWR for the Kor River.

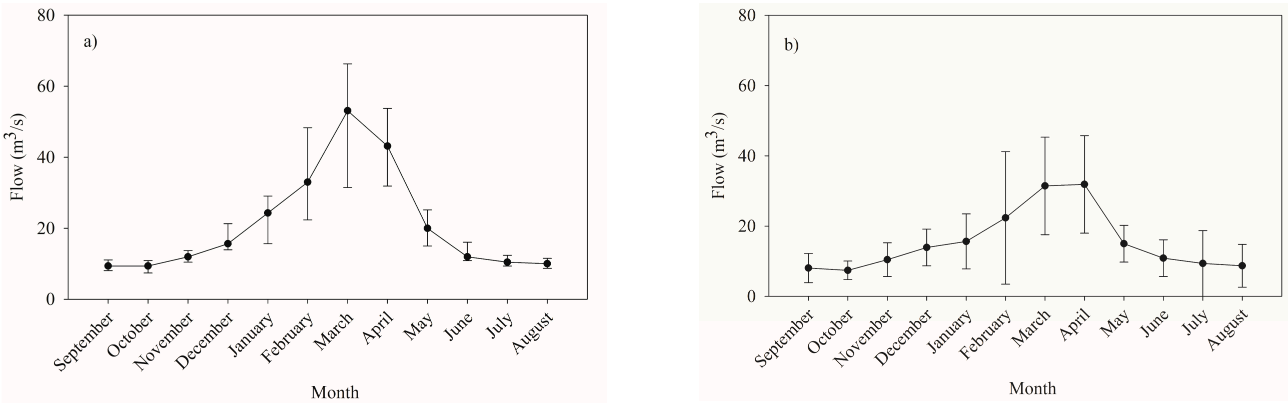

Figure 4. Changes in the average monthly flow of the Kor River at Chamriz station due to the construction of the Mollasadra Dam. (**a**) pre-impact period (1965–2007) and (**b**) post-impact period (2008–2019).

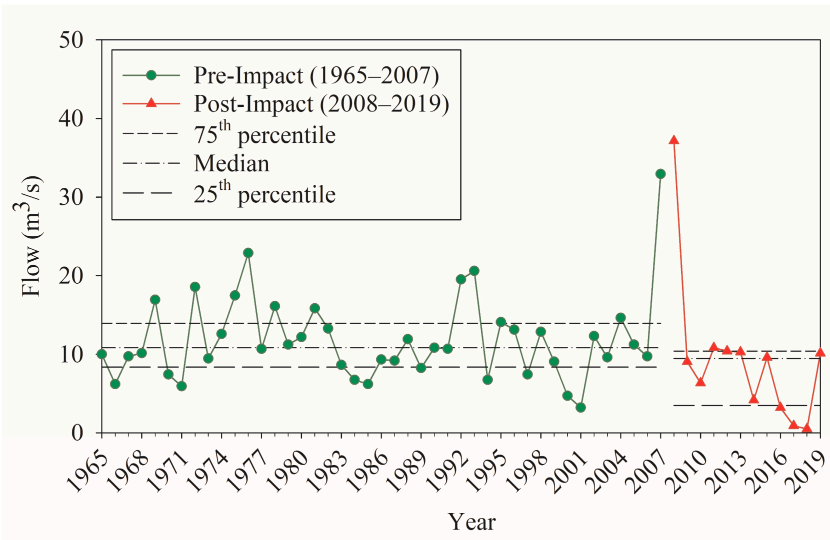

Figure 5. Variation of the Kor River flow in July before and after the construction of Mollasadra Dam.

Table 10. Monthly flows of the Kor River using the Range of Variability Approach (RVA) method (m^3/s).

Month	Before Dam Construction			After Dam Construction			RVA Boundaries	
	Ave.	Min.	Max.	Ave.	Min.	Max.	Lower	Upper
October	9.38	5.25	22.40	4.49	0.77	24.05	8.10	11.12
November	9.30	4.90	22.40	3.02	1.64	23.90	7.55	10.72
December	11.44	6.20	29.60	4.87	3.29	36.60	10.19	13.58
January	16.00	6.90	71.00	5.42	2.66	20.50	14.15	21.19
February	24.00	7.52	83.00	7.79	3.47	40.70	15.36	29.28
March	33.10	12.75	113.70	18.95	4.08	57.10	22.50	48.56
April	53.20	130	134.00	13.6	3.07	35.00	31.64	66.40
May	42.90	8.38	108.00	13.95	3.39	43.40	31.94	53.72
June	19.70	2.25	77.60	5.28	2.92	27.30	15.05	25.22
July	11.92	3.40	43.50	5.22	1.00	14.35	10.71	16.02
August	10.66	3.10	33.10	9.24	0.61	37.50	9.236	12.64
September	9.88	3.40	22.70	6.38	0.11	10.70	8.66	11.39

In Table 11, adequacy in the EWR supply, i.e., *AEWR*, is calculated using Equation (1). It can be seen that the results of both traditional and modified Tennant, $7Q_2$, and DRM indicate that the flow situation in the Kor River is environmentally suitable after the construction of the Mollasadra Dam, i.e., the mean monthly flow after the dam construction is higher than the calculated EWR. However, the results of Tessman, Smakhtin, flow duration indices, $7Q_{10}$, FDC shifting, and RVA methods show that there are some levels of deficiency in the minimum EWR, i.e., negative values of *AEWR*. In addition, the average of *AEWR* values for each method is calculated and shown in the last row of Table 11. It can be found that the modified Tennant and Q_{50} flow duration indices methods with the average *AEWR* values of 63.6% and −60.9% have the most and least compatibility with the hydrological conditions of the Kor River in terms of EWR allocation. The average of *AEWR* values determined by different methods for each month is also calculated in the last column of Table 11. It can be seen that April, May, June, and September with negative values of average *AEWR* are the worst cases among all months in term of EWR allocation. In addition, the calculated values of *DEWR* for different months are shown in Table 11.

Table 11. *AEWR* percentage for the Kor River after the construction of the Mollasadra dam.

Month	Tenant		Tessman	FDC Shifting	DRM	Flow Duration Indices			RVA	*DEWR*	Average
	Trad.	Modi.				Q_{50}	Q_{90}	Q_{95}			
October	61.21	61.21	−49.41	26.03	21.24	−32.01	6.93	10.47	−19.47	33.33	9.58
November	71.29	71.29	−14.96	31.43	37.23	−20.20	27.07	31.44	17.58	33.33	28.02
December	72.40	72.40	−10.49	−15.52	32.63	−69.46	−13.12	−8.92	−6.93	66.67	5.89
January	78.91	78.91	−7.86	−11.57	39.05	−60.87	−0.08	4.17	−13.47	55.56	11.91
February	87.97	63.92	23.05	28.26	61.68	−54.64	29.08	36.76	29.77	22.22	33.98
March	89.37	68.10	8.17	21.20	59.68	−83.91	17.10	26.41	9.02	22.22	23.90
April	63.04	63.04	−6.84	8.63	44.36	−119.91	−15.50	−5.90	−48.20	55.56	−1.92
May	39.35	39.35	6.46	6.13	26.98	−89.93	7.61	16.60	−145.50	22.22	−10.33
June	−19.18	60.27	−59.06	−20.92	−22.96	−95.17	1.81	10.73	−127.34	66.67	−30.20
July	6.29	68.76	−25.06	24.99	48.93	−22.09	23.99	28.27	−27.20	33.33	14.10
August	−10.20	63.27	−47.07	24.58	42.60	−28.77	13.83	17.74	−28.99	44.44	5.22
September	−40.64	53.12	−77.90	11.05	32.09	−54.01	−1.07	3.74	−54.37	55.56	−14.22
Average	41.65	63.64	−21.75	11.19	35.29	−60.91	8.14	14.29	−34.59		

4. Discussion

To study the impact of the construction of Mollasadra Dam on the Kor River flow more closely, the changes in the daily flow rate during the period 1965–2019 are depicted in Figure 6. It can be seen that although several major floods occurred during the studied period before the construction of Mollasadra Dam, no major floods can be observed after the construction of the dam. Severe floods are important in many ways, such as improving the biological and physical structure of rivers and floodplains, balancing the population of organisms, and creating important habitats such as oxbow lakes and floodplain wetlands. Therefore, the construction of the dam has significantly reduced the peak flow of floods in many months and potentially endangers the quality as well as the quantity of habitats [84,85]. Decreased peak flood discharge due to dam construction has been observed in some other studies [17,52,86–89].

The reduction of river runoff due to controlled flow has led to severe water stress to the Tashk and Bakhtegan wetlands, which are located downstream of the Kor River. The heavy dependence of the Bakhtegan wetland on the incoming runoff and the reduction of runoff due to the construction of the dam and water diversion for irrigation of upstream agricultural lands has caused the area of this wetland to be greatly reduced in recent years [90,91]. On the other hand, forecasts indicate that because of climate change, the trend of precipitation changes, and consequently runoff in the catchment area of the studied river will decrease in the future [92]. Therefore, the pressure on the river ecosystem and its downstream wetlands will increase in the near future, which indicates the increasing importance of active management of outflow from the dam reservoir. The decrease in the water area of the Bakhtegan wetland, despite the increase in rainfall in a short period between 2006–2009, shows that the role of reducing the river due to the construction of the dam and also increasing the water diversion for agricultural use has played a greater role in this process compared to climate change [93].

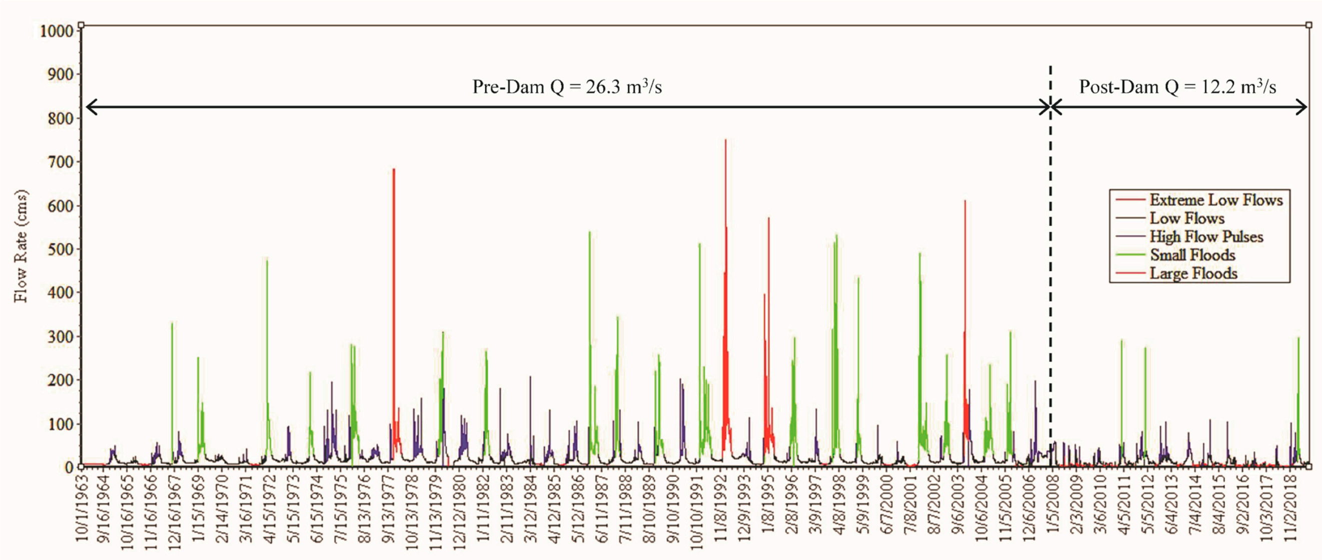

Figure 6. IHA environmental flow components of the Kor River showing the effect of Mollasadra Dam construction in 2008 on the river flow.

Another role of dams in changing the downstream regime is to change the probability of different currents occurring that influence the fluvial processes and result in a variety of environmental and species responses [94,95]. For example, the changes in exceedance probability for different flows before and after the construction of Mollasadra Dam in March and July, with the most and least influence in the average monthly flow after construction of the Mollasadra Dam, respectively, are shown in Figure 7. The area between the two curves indicates the pure volume of water that is no longer available to meet the river ecological requirements due to flow regulation by dam outlets. As can be seen, in March, which coincides with the winter rainy season in the region, the probability of various floods after the construction of Mollasadra Dam has significantly decreased compared to before the construction of the dam that is called eco-deficit [96,97]. This is due to the upstream flood storage and controlled release of flow from the dam outlets. On the other hand, in July, although for flows larger than 20 m^3/s, a similar trend is observed as in March, for flows less than 20 m^3/s, exceedance probability for a certain flow after the construction of the dam has increased compared to pre-impact conditions that are called eco-surplus. However, a significant eco-deficit is also observed in July. Both eco-deficit and eco-surplus are harmful to the ecosystem and can lead to the loss of its ecological diversity [98]. Since Mollasadra Dam is mainly a hydropower dam, and July coincides with the peak of electricity consumption, frequent, rapid, and short-term outflows in response to fluctuations in hourly adjusted electricity markets, which is referred to in the literature as hydropeaking [15,99], could be the reason for this change.

A summary of the ecological flow results obtained from the different methods for the Kor River at Chamriz hydrometric station is presented in Table 12. The Tennant method proposes environmental flow based on different percentages of the average annual flow. These percentages are 30% of MAF for high-flow months and 10% of MAF for low-flow months under the fair or degrading conditions of the river. Therefore, the EWR for the Kor River was calculated to be 7.89 m^3/s between January to May and 2.63 m^3/s between June to December. The Tessman method proposes the minimum EWR in different months by comparing the monthly flow with the annual flow. Therefore, the average EWR of the Kor River was calculated as 13.39 m^3/s corresponding to 51% of MAF. The EWR in the Smakhtin method was obtained as a combination of the minimum and the maximum EWR.

Accordingly, the EWR of the Kor River is 15.13 m^3/s, equal to 57% of MAF. In the flow duration curve analysis method, various indicators have been used to estimate the EWR. According to this method, the range of low flows for the Kor River at the Chamriz station is between 14.42 to 18.41 m^3/s, corresponding to 55% to 70% of MAF.

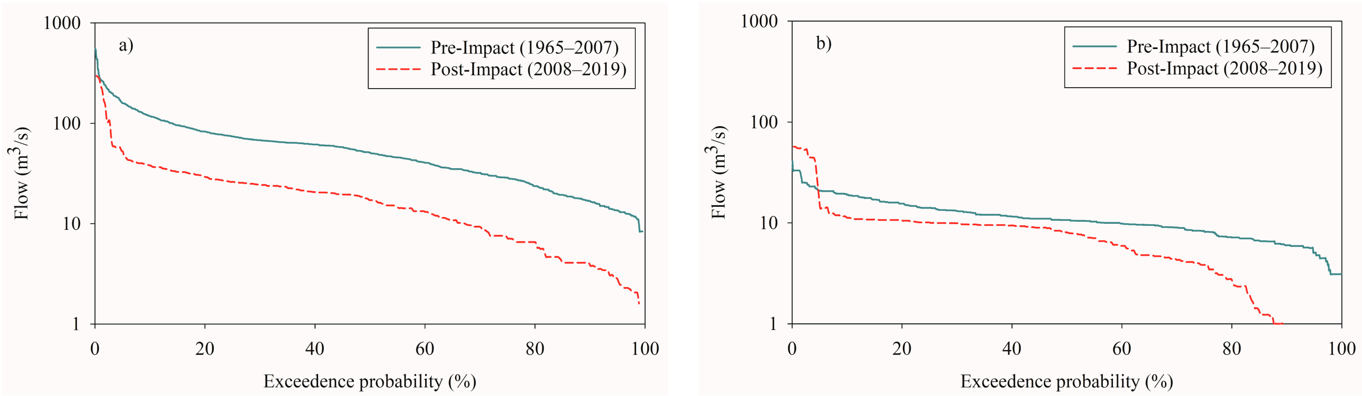

Figure 7. Variations of the exceedance probability against flow rate for (**a**) March and (**b**) July.

Table 12. Comparison of different methods of determination of the EWR for the Kor River.

Method	Description	EWR	EWR
		(% of MAF)	(m^3/s)
Tennant	October–March	10	2.63
	April–September	30	7.89
Tennant Modified	February–May	30	7.89
	June–January	10	2.63
Tessman		51	13.39
Smakhtin		58	15.13
Flow duration indices	Q_{70}	70	18.41
	Q_{75}	67	17.51
	Q_{80}	63	16.66
	Q_{85}	60	15.87
	Q_{90}	58	15.13
	Q_{95}	55	14.42
Low-flow indices	$7Q_{10}$	40.6	10.65
	$7Q_2$	27.3	7.17
FDC shifting	Class C	36.4	9.60
DRM	Class C	25.5	7.10
RVA	Low RVA limit	59	15.42

According to the results, two indicators $7Q_{10}$ and $7Q_2$ are 10.65 and 7.17 m^3/s, respectively; $7Q_{10}$ represents a high percentage of MAF and its use is not recommended. In the FDC shifting method, management class C was chosen as the desired class because, in this class, the basic functions of the ecosystem are still intact. According to this method, the ecological flow for the Kor River is 10.36 m^3/s, equal to 40% of MAF. The DRM method is based on the fact that under natural conditions, different components of the flow regime play different roles in the ecological performance of a river. Therefore, it is necessary to maintain the differences between wet and dry seasons. According to this method, different components of the flow are combined to provide an ecologically acceptable flow regime. The need for environmental flow in this method is a combination of low-flow and high-flow requirements. According to this method, the EWR of the Kor River for environment management class C is 6.65 m^3/s equal to 25% MAF. In the RVA method, 33 hydrological parameters were calculated using IHA software based on daily flow data. The results of this method show that the EWR for the Kor River is 15.42 m^3/s equal to 59% MAF. Of all the methods used in the present study, FDC shifting, DRM and RVA methods could be more preferable to other methods due to the variability of the flow, considering different ecological classes, and trying to maintain this variability in their proposed environmental flows. FDC shifting and RVA methods suggest 40% and 59% of MAF as environmental flow, respectively.

As can be seen in Table 12, although the environmental flow supply seems to be more or less satisfactory in February, March, and May, 66.7% of the methods confirm the inadequacy of allocated flow in December and June. In addition, 55.6% of the methods show some levels of deficiency in January, April, and September. In other months, *DEWR* values between 22.2% and 44.4% can be observed. Therefore, all of the methods used in the present study indicate some level of insufficient supply of environmental flow. This deficiency in supplying the EWR cause a disconnection of the mainstream of the river and its surrounding floodplains, as a result of which many aquatic habitats have lost their usage, and less food is transferred from the floodplains downstream [100]. In addition, changes in flow regime due to dam construction can lead to changes in oxygen levels, temperature, suspended solids, the drift of organisms, and cycling of organic matter [52,101].

As the dominant fish species in the Kor river is Capoeta [61] and this fish spawns between April and June [102], more attention should be paid to meeting the minimum EWR of the Kor River in this period to maintain habitat suitability for the indicator fish species. While the focus of the present study was on the hydrological variations due to the construction of the Molasadra Dam, it should be noted that another regulating dam is under construction on the Kor River. Hence, the evaluation of the effect of any new anthropogenic activity on the flow regime, water quality, and water temperature, not discussed in the present paper, is of great importance to the Kor River ecosystem sustainability.

5. Conclusions

The health and biodiversity of freshwater ecosystems, such as rivers, respond negatively to flow alteration. Therefore, to maintain the service of the river ecosystem, certain amounts of flow at certain times must be maintained in the river. This specific flow, called the minimum environmental water requirement (EWR), is affected by human activities, including the construction of dams. In this research, the environmental flow in a river in two different periods, before and after the construction of a dam, has been investigated. Nine different methods including traditional and modified Tennant, Tessman, Flow duration indices, Smakhtin, low-flow indices, FDC shifting, desktop storage model (DRM), and range of variability approach (RVA), which fall into the category of hydrological methods, were used to determine the EWR. Environmental flow values in different months were calculated by the above methods. Summarizing, our findings show that although the methods of traditional and modified Tennant, $7Q_2$, and DRM indicate the suitability of the flow situation in the Kor River in terms of providing minimum EWR, the results of Tessman, Smakhtin, flow duration indices, $7Q_{10}$, FDC shifting, and RVA methods show that there are some levels of deficiency in the minimum EWR for the minimum performance of the river ecosystem. In addition, by exploring the allocated flow in the river in different months, it was observed that although the supply of environmental flow in February, March, and November is in relatively acceptable conditions on average, there is a deficiency in the alloca7tion of EWR in the range of 1.92–30.2% in April, May, June, and September. This period of deficiency in EWR is of critical importance because it is concurrent with the spawning of the dominant fish species in the Kor River. In addition, an insufficient supply of EWR leads to a disconnection between the main channel of the river and its surrounding floodplains, disrupting the performance of many habitats. We demonstrated that the *DEWR* and *AEWR* indicators can provide a general picture of the status of environmental flow allocation in rivers with a hydrological regime that has changed due to human activities. For the Kor River, the results show that the river is currently suffering from both quantity- and timing-induced EWR problems. Since the Kor River flows into the Bakhtegan Wetland, as one of the protected areas of Ramsar Convention, at the downstream end, and the wetland is not in good condition now due to the reduction of inflow, it can be concluded that anthropogenic activities such as the construction of the Mollasadra Dam have led to disruption of the natural conditions of the ecosystem and this issue should be considered by the beneficiaries in the dam control curve. Finally, the proposed indicators can be used to assess the status of environmental flow allocation in other areas where little ecological data is available, particularly in case of rivers with hydropower plants. In this study, only the variations of the Kor River flow data due to the construction of the Molasadra Dam are included in the analysis. However, the possible effects of the meteorological parameters such as precipitation and air temperature could be considered in future studies.

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