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RESEARCH ARTICLE - HYDROLOGY

Comparative assessment of environmental flow using hydrological methods of low flow indexes, Smakhtin, Tennant and flow duration curve

Saman Karimi[1] · Meysam Salarijazi[2] · Khalil Ghorbani[2] · Mohammad Heydari[3]

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Abstract

There are different methods in hydrological approach for estimating the environmental flow and a comparative assessment is necessary. The low flow indexes (7Q2 and 7Q10), Smakhtin, Tennent and flow duration curve were used to estimate the environmental flow of Zohreh River in the southwest of Iran. The Smakhtin, 7Q2, 7Q10 and Tennant methods resulted in the estimation of constant values of 27.2, 12.7, 5.9 and (8 and 24) cms, so that, on average 52.8, 26.9 and 12.3, 36.7 percent of the monthly flow is allocated to the environmental flow. The monthly environmental flow pattern for these methods does not fit well with the monthly flow pattern, and thus it can be concluded that the Smakhtin, 7Q2, 7Q10 and Tennant methods cannot be used in the initial form. The application of the flow duration curve leads to an environmental flow assessment in the range of 6.8–38 cms in different months, whose time pattern completely matched with the monthly flow pattern. In this method, on average, 30.8% (range 18–48%) of the monthly flow allocated to the environmental flow, which is reasonable and acceptable amounts. Investigating the results of this study shows that the time pattern of the results should be analyzed in comparison with the observational flow pattern to estimate the environmental flow with a hydrological approach. The results also suggest that the methods that provide a constant amount of environmental flow in different months of the year should be interpreted cautiously along with other methods.

Keywords Zohreh river · Hydrological methods · Environmental flows · Flow duration curves · Low flow indexes · Tennant · Smakhtin

Introduction

In recent years, different studies show changes in various hydrological components such as groundwater (Ansarifar et al. 2019), precipitation (Moazed et al. 2012), water quality (Salarijazi and Ghorbani 2019) and river flow (Ghorbani et al. 2019; Bahrami et al. 2019) which could lead to significant impacts on the environmental systems of the river (Noori et al. 2013). The protection of the vital river system is one of the main goals of river management and engineering in sustainable water resources development (Othman et al. 2014). Flows which have good maintenance conditions of a set of aquatic habitats and provide ecosystem processes, are called as "environmental flows", "environmental water requirements", "environmental flow requirements", and the process of calculating these flows "are also called " environmental flow assessment " (Poff 2017; Bardina et al. 2016). The assessment of the intensity of the environmental flow is one of the important factors to organize or reservoir dam

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✉ Meysam Salarijazi
meysam.salarijazi@gmail.com; meysam.salarijazi@gau.ac.ir

Saman Karimi
saman_karimi2@yahoo.com

Khalil Ghorbani
ghorbani.khalil@yahoo.com

Mohammad Heydari
m3heydariii@yahoo.com

1 Water Resources Engineering, Lamei Gorgani Institute of Higher Education, Gorgan, Iran

2 Department of Water Engineering, Water and Soil Engineering Faculty, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

3 Water Resources Engineering, Kuala Lumpur, Malaysia

construction plan on the rivers (Chen and Aldon 2017). Studies show that water withdrawals and water demand from rivers (for example, irrigation, hydropower and drinking water) are increasing (Zhuo et al. 2016). The environmental studies have specific and high complexity such as the goals and magnitude of the project, the availability of data and the required resources to protect (Davies et al. 2014). Different studies performed in the field of global environmental flow estimation that have examined this issue with different approaches.

(Richter et al. 1996) described the 32 hydrological parameters that their changes have the most role in the ecosystem. The 32 parameters divided into five groups of hydrological characteristics including the magnitude of monthly water conditions, the magnitude and duration of annual extreme water conditions, the time of annual extreme water conditions, frequency and duration of high and low pulses and rate and frequency of water condition changes. These changes are used to assess the relationship between flow regime change and ecosystem response to it. Poff et al. (1997) introduced the natural flow variability as the main driving component for the sustainability and health of the river ecosystem, and they stated that in the regulated river, if the lower release water to downstream is closer to the natural flow of the river, the river biota is in a better position. Tharme (2003) classified the methods for estimating environmental flow in five distinct approaches including hydrological methods, hydraulic gradation method, simulation habitat, comprehensive approaches and the combined method. Different studies have been done in different parts of the world related to the environmental flow estimation in the rivers. In another study, the Tennant method was used to estimate the environmental flow in the waterways which had a great slope. Mann (2006) was conducted this study on 151 cross-sections of 70 rivers in the west of the United States and concluded that the Tennant method is more applicable in the rivers with the slope (less than 1%). It was also found that in rivers with slopes of more than 1%, the Tennant method should be used more cautiously, and be restricted to the planning stages of instream flow recommendations. The Tennant method should apply in the river's instream protection programs, not in the rehabilitation and recovery programs. Smakhtin and Anpottas (2006) used the flow duration curves (FDC) method to investigate the environmental flow intensity of 13 rivers in India. This method uses monthly flow statistics to ensure that the natural environmental flow changes are stabilized in the time series and provides the required amounts of the environmental flow for managing different environmental classes. In a study on the rivers in Ontario, Canada, Watt (2007) used three methods of Tennant, Tessman and a combination of Q50 and Q90 monthly to determine the minimum environmental flow. He concluded that the two methods of Tennant and Tessman are not compatible with the Ontario River status and applying these methods will be suitable if further studies and corrections are done for the Ontario River. In a study on Brahmani and Baitarani Rivers in India, which carried out by hydrological methods of the estimation environmental flow, the flow duration curves provide better results for maintaining the river in typical droughts (Jha et al. 2008). By conducting a study on 11 rivers in different parts of the world by using the hydrological methods of the Tennant, flow duration curves, and the Smackchint and Tessman methods, Pastor et al. (2014) concluded that average annual flow of 37% is needed to maintain the ecosystem. Accordingly, the maximum water required for a low flow period is a flow of 46–71% of average low flows, and in the high flow period, the average flow 17–45% is the average high flow, which is acceptable amounts. In a study on the Maritime River in Canada, Caissie et al. (2015) evaluated the environmental flow by hydrological method of low flow indexes application and concluded that by applying this method for the return periods of 10 and 2 years, the environmental flow estimated to be 3.6 and 8.2% of the annual average flow. The comparison of Tessman, flow duration curve, and Tennant methods on Ochotnica, Wielki, and Rogoznik rivers showed the Tessman method has better outcomes for these three rivers than the other two methods. It estimated the environmental flow considering environmental criteria in accordance with the European commission's guidelines (Wałęga and Młynski 2015). In a study on Nepal's hydroelectric project, which was at the planning stage, Rijal and Alfredsen (2015) used the Tennant method for this study and concluded that the amount of environmental flow has had the lowest amount of discharge in December, January and February, and it is not justifiable. Ates and Dogan (2016) in a study on the Göksu River in the eastern Mediterranean that used the Tennant method to estimate the environmental flow that was not consistent with the environmental conditions of the area, but the modified Tennant method used to improve the results. The Tessman, Tennant and building block methodology (BBM) used to estimate the environmental flow of Mula dam site in India. The results showed that the amounts provided by Tennant method and BBM were not enough suitable for the characteristics of the river's normal Regime, but the Tessman method- in this study—resulted in providing the logical amounts of the environmental flow in different months (Balsane and Bansod 2016). Various methods developed to estimate the environmental flow that hydrological methods, due to the lack of need for large amounts of data, require far less time than other methods in the early studies of environmental flow estimations. Considering the variety of different hydrological methods in estimating environmental flow, which can lead to different estimates of environmental flow, a comparative study of these methods seems necessary.

The first objective of this study is environmental flow estimation using Tennant, Smakhtin, flow duration curve and low flow indexes (7Q2, 7Q10) methods as hydrological approach considering the recorded data of the Zohreh River (Dehmolla hydrometric station) in the southwest of Iran. The second objective is the analysis of the results of different methods and the comparison with the observed pattern of recorded river flow data.

Materials and methods

The Zohreh watershed is located in the southwest of Iran with geographic coordinates of 28° 66′–30° 56′ N latitude and 49° 16′–52° 18′ E longitude. The area of this basin is 15660 square kilometers, and the average height of the basin is 1060 m above sea level. Zohreh River, located in this basin, is one of the most important rivers of Persian Gulf basin collected the waters of the large areas of Ardakan, Noorabad, Fars, the southern area of Do-Gonbadan, Behbahan and the Hendijan district of Mahshahr and then will end to the Persian Gulf. In this study, the recorded river flow data of Dehmolla hydrometric station located at the bottom of the watershed is used. The position of the Zohreh basin is presented in Fig. 1.

Hydrological methods of environmental flow estimation

Tennant method

In 1976, Tennant provided a method for estimating the environmental flow needed for fish, known as the Montana method or, more commonly, Tennant method. In this method, only the mean annual flow amount of the river used to estimate the river environmental flow. In its reviews, Tennant examined 58 cross-sections of 11 rivers in Montana, Nebraska and Wyoming, and according to this and by considering time situation throughout the year (in two 6-month periods), the values of environmental flow were proposed based on different ecological conditions as shown in Table 1.

Table 1 Estimation of environmental flow based on Tennant method

Description of flows	Recommended base flow regimes (percent of mean annual runoff)	
	October–March	April–September
Flushing or maximum	200	200
Optimum range	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	< 10	< 10

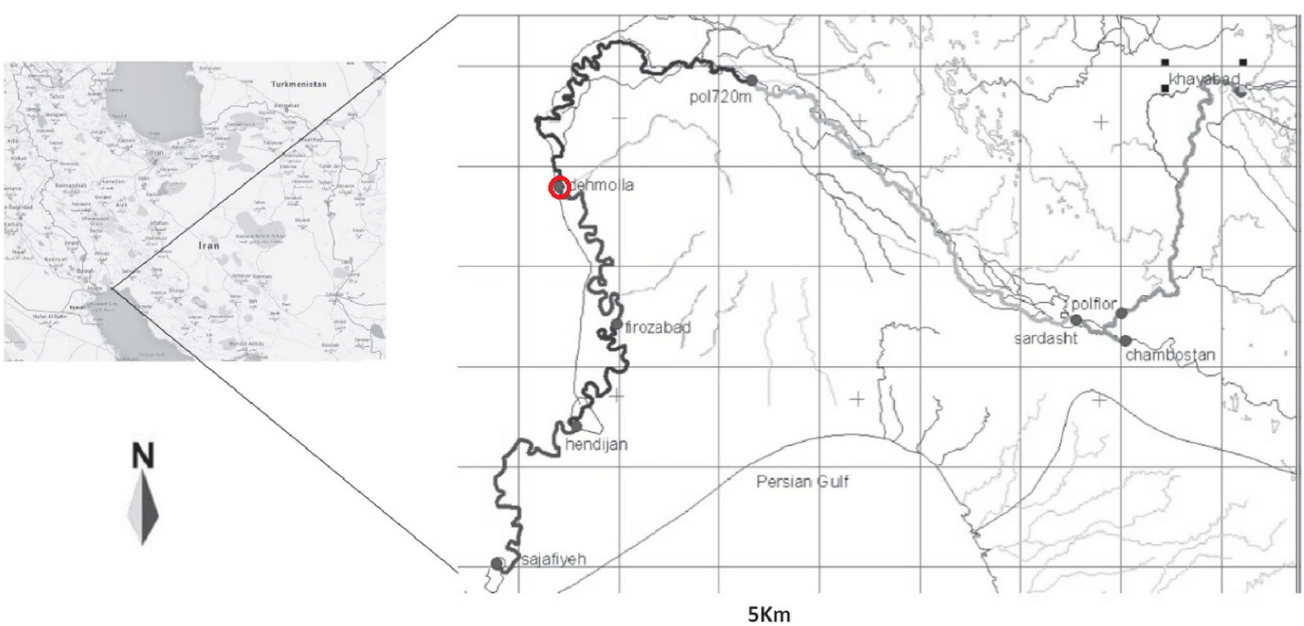

Fig. 1 Map of the catchment area of the Zohreh River and Dehmolla station

An examination of this table shows that the estimation of the environmental flow in Tennant method is easily feasible and because of the ease of using this method, Tennant Method is widely used in environmental flow estimation. Specifically, given that this method leads to the selection of two specific flow values for two six-month periods per year, so the application of this method should be considered as an initial estimation with comparing to other methods.

Flow duration curve method

Flow duration curves can provide valuable information on the pattern of river flow changes, and therefore can be a suitable method in estimating the environmental flow (Zhang 2017). Due to the nature of the flow duration curves in the estimation of the environmental flow, its application commonly considered by researchers (Verma et al. 2017). Flow duration curve is one of the best ways to display a full range of river discharges of low flow events to flood events. Flow duration curve is the relationship between the river flow intensity and the percentage of times when the certain flow (during the statistical period) is equal or increased, or, in other words, the relationship between the amount and frequency of flow (Smakhtin 2001). Regarding the application of the flow duration curves, various indicators used for the minimum environmental river flow ranging from Q50 to Q95 (McClain and Anderson 2015; Elhatip and Hinis 2015; Ghanbarpour et al. 2013). These indicators are presented for specific purposes, for example, Q50 indicator is used for maintaining aquatic biota (Ghanbarpour 2013), and Q95 indicator of minimum flow is used for river protection (Shenton et al. 2011; Acreman et al. 2008; Piniewski et al. 2014). To calculate flow duration curves, the following procedures performed:

The flow duration curves plotted by sorting the statistical flow data into descending order. In other words, the largest number rated one. Then, these flows are plotted against the probability value. The probability of occurrence of each discharge obtained from the Weibull equation.

Low flow indexes

Low flow indexes are based on the occurrence of low flows over a given time period during the data period recorded in different years, and their probability level is considered. One of the most widely used low flow indicators defined and used based on the 7-day period (Richter et al. 2012; Pastor et al. 2014). The minimum 7-day flow indicates the lowest amount of flow in a continuous 7-day period, which observed under different natural conditions in the river during each year. 7Q2 and 7Q10 indicators are the most usable indicators of low flow indicators, which indicate the minimum amount of river flow for 7 consecutive days in the return periods of 2 and 10 years (Verma et al. 2015; Trudel et al. 2017). One of the most important uses of the 7Q10 indicator related to the river water quality's standards for pollution control. However, the applications of this flow have been expanded in other cases, including in the context of environmental flow estimation (Wurbs 2017; Pyrce 2004). Among low flow indicators, Pyrce (2004) introduces two minimum 7-day flows with a return period of 10 and 2 years (7Q2 and 7Q10) as the most commonly used indicators for estimating the environmental flow. In most flow studies, the low flow indicator 7Q10 has been used more than the low flow 2Q7 indicator. The most common applications of low flow indicators are environmental flow estimates in the following areas (Brooks et al. 2006; Jensen et al. 2002):

1. To protect/regulate water quality from wastewater discharges or waste load allocations (to prevent adverse biological/ecological impacts on the receiving water).
2. Minimum quantity of streamflow necessary to protect habitat during a drought situation.
3. Total maximum daily load to assess aquatic life protection.

Smakhtin method

Smakhtin et al. (2004) used a new method for 128 catchment areas in different parts of the world to assess the status of exploitation of the world's rivers with the consideration of environmental water requirements. In this method, the environmental water requirement (EWR) considered as the combination of the environmental low flow requirement (LFR) and environmental high flow requirement (HFR) (Smakhtin et al. 2004). The Environmental low- flow requirement is the minimum amount of water needed for fish and other aquatic organisms per year, and the environmental high-flow requirement is shown in floods and its impact on the shape of the river and the plants around the river (Smakhtin et al. 2004). In this method, to make the river condition "fairly good", it is suggested that the environmental low flow requirement in that river should be equal to Q90 (Q90 is the flow that is 90 percent of the year; the river discharge is greater than that amount). If the river has a fluctuating flow such that the Q90 is less than 10% of the annual average flow, the environmental high flow requirement considered equal to a 20% annual average. In the rivers where the Q90 is between 10 and 20% and 20%–30% of the annual average flow, the amount of environmental high flow requirement considered equal to 15% and 7% average annual yield, respectively. In rivers, which have a steady flow, if the Q90 exceeds 30% average annual yield, the environmental high flow requirement considered equal to zero (Table 2).

Table 2 Estimating environmental high flow requirement (HFR) by Smakhtin method

Explanation	Environmental low flow requirement (LFR) (Q_{90})	Environmental high flow requirement (HFR)
In basins with a variable regime, the flow is mainly created by the flood in the water season	10% MAR > Q_{90}	HFR = 20%MAR
	20% MAR > Q_{90} > 10%MAR	HFR = 15%MAR
	30% MAR > Q_{90} > 20%MAR	HFR = 7%MAR
In basins with a constant regime-where the flow is constant throughout the year and low flow requirements are considered as the main component	30%MAR < Q_{90}	HFR = 0

Results and discussion

Estimation of environmental flows has great importance in management and planning of water resources allocation, and different methods have been introduced in this regard. Hydrological methods of Tennant, flow duration curve, Smakhtin and low water flow indexes used in this research. Given that the estimation of the environmental flow in the river is carried out and analyzed by considering the mean annual flow and mean monthly flow, the annual and monthly mean of flow amounts are presented in Table 6.

Different percentage of mean annual flow is suggested as an environmental flow in Tennant method. These percentages are subject to the desired ecological conditions as well as the time over the year (two six-month periods). In most studies, fair or degrading conditions used to allocate the minimum logical values for the environmental flow. According to these conditions, 10% of the mean annual flow during the period from October to March and 30% of the mean annual flow in the period from April to September is considered as the environmental flow, which is based on the discharge of 8 and 24 cms has been determined as the environmental flow in the periods from October to March and April to September, respectively. Considering the ratio of environmental flow per month to the mean monthly flow of that month, appropriate information on the time pattern of the assigned values of the environmental flow can be obtained. These ratios are presented in Table 6 for the Tennant method. A review of these values suggests that this ratio is in the range of 7.4%–100% in different months of the year. Accordingly, in the months of August and September, almost all the mean monthly flow should be allocated to the environmental flow, and in the month of July, a large part of the mean monthly flow is allocated to the environmental flow, which this allocation will not be possible in practice. On the other hand, in the overflowing season during the year, the amount of environmental flow allocated to it is a very small amount of mean monthly flow, which does not seem logical.

In the method of flow duration curve, different flow duration indexes (range between Q50 and Q95) investigated. The results show that Q50, Q80, Q90 and Q95 indexes lead to environmental flow discharge estimation in the range of 19–140, 10–60, 7–38 and 4–30 cms for different months of the year, respectively. Considering the ratio of the estimated environmental flow to the monthly mean flow per month, it is determined that this ratio in the Q50, Q80, Q90 and Q95 indexes is in the range of 68–94, 28–58, 18–48 and 15–30%, respectively, with a mean of 86.1, 44.8, 30.8 and 23.6%, respectively. Taking into account the declared values for various indexes and according to experts, the Q90 index selected because, on the one hand, the estimated values by this method are largely allocable, and on the other hand, it seems that these values can properly provide ecological needs. The application of the Q95 index has led to an environmental flow estimation of 18–27 percent of the monthly flow in the watery period (February-April) and 29–48% in the low water period (August–October).

Hyfran and Easyfit used to calculate low water flow indexes. In this method, the minimum seven-day flow rate for the return periods of 2 and 10 years was investigated. Table 3 shows the results of the return periods of 2 and 10 years. For a return period of 10 years, the discharge flow rate is equal to 5.9 cms (equivalent to 7% of mean annual flow) and for the discharge of the return period of 2 years, the discharge flow rate is equal to 12.7 cms (equivalent to 16% of mean annual flow rate). Examining these values shows that the estimated value for the 7Q10 index is very small, far lower than the estimated values by other methods. The estimated value for the 7Q2 index is more than twice the value estimated by the 7Q10 index and appears to be relatively reasonable and usable according to the determined value. The ratio of the environmental flow rate estimated using the 7Q10 and 7Q2 indexes to the monthly mean flow rates presented in Table 6. The analysis of this ratio for the 7Q10 index in different months shows that its value ranges from 3 to 28% is changeable in different months(on average 12.3%), and during the

Table 3 The minimum flow of 7-Day with a return period of 10 years and 2 years

7Q2		7Q10		The hydrometric station under study
%MAR	(cms) Q	%MAR	(cms) Q	
16	12.7	7	5.9	DehMolla

Table 4 Computational components for high environmental flow (cms in Smakhtin method)

HFR	30%MAR	20%MAR	10%MAR	MAR	Q_{90}	Station
5.6	24	16	8	80	21.6	DehMolla

Table 5 Environmental water requirement of the studied time period by Smakhtin method (cms)

Station	Mean annually rate (MAR)	low flow requirement (LFR = Q90)	high flow requirement (HFR)	Environmental water requirement (EWR)
DehMolla	80	21.6	5.6	27.2

Table 6 Estimation of environmental flow with different methods

7Q10		7Q2		Smakhtin		FDC(Q90)		Tennant		Discharge	
%	Q	%	Q	%	Q	%	Q	%	Q	MMF	Month
26	5.9	56	12.7	100	27.2	48	10.8	35.7	8	22.4	October
13	5.9	30	12.7	64	27.2	34	14.5	18.8	8	42.5	November
7	5.9	16	12.7	35	27.2	36.6	28.3	10.4	8	77.2	December
5	5.9	10	12.7	22	27.2	29	35.5	6.6	8	120.6	January
4	5.9	9	12.7	19	27.2	27	38	5.7	8	140.2	February
3	5.9	7	12.7	16	27.2	18	31.5	4.7	8	167.5	March
3	5.9	8	12.7	16	27.2	19	30.9	14.8	24	162	April
6	5.9	13	12.7	28	27.2	29	28.3	25.1	24	95.6	May
10	5.9	22	12.7	47	27.2	31	18.3	41.5	24	57.8	June
19	5.9	40	12.7	87	27.2	37	11.6	77.2	24	31.1	July
24	5.9	52	12.7	100	27.2	29	7.1	99.6	24	24.1	August
28	5.9	60	12.7	100	27.2	32	6.8	100	24	21	September
12.3	5.9	26.9	12.7	52.8	27.2	30.8	21.8	36.7	16	80	Mean

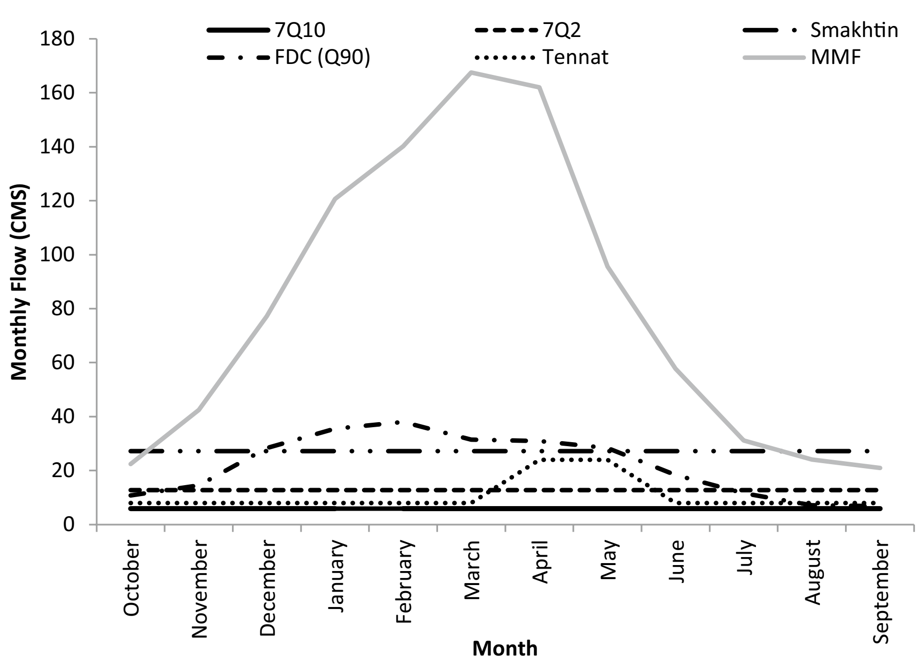

Fig. 2 The monthly distribution of the environmental flow

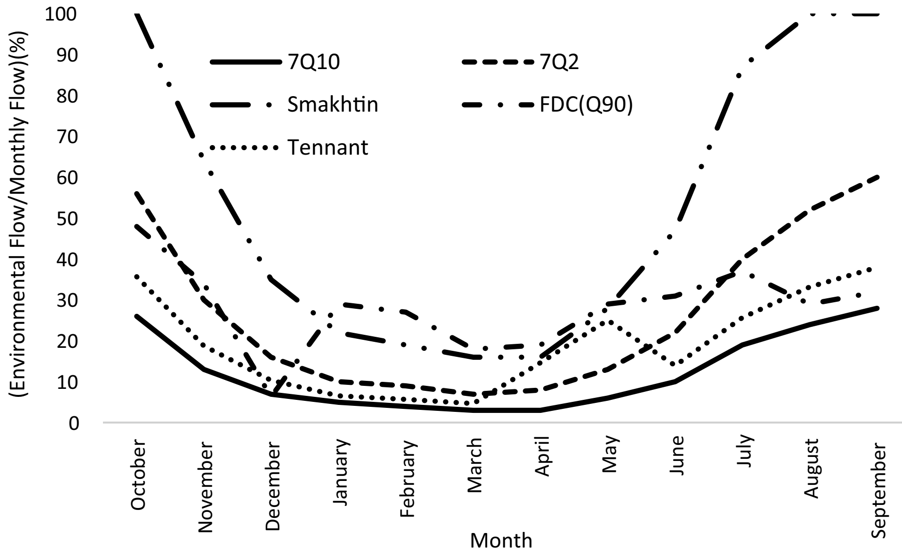

Fig. 3 The monthly ratio of environmental flow to monthly mean flow (in percent)

period from August to October, it contains more than 20% of the mean monthly flow. The ratio of estimated environmental flow by 7Q2 index to mean monthly flow varied range of 7–60 percent (on average 26.9%) in different months. This ratio was more than 50% from August to October, and it means a significant part of the mean monthly flow devoted to environmental flow in the dry season.

As stated, the Smakhtin method uses two environmental low flow requirement components and environmental high- flow requirement to estimate the environmental flow. With the use of Smakhtin method in this study, the environmental low flow requirement rate is equal to 21.6 cms and the environmental high- flow requirement is equal to 5.6 cms (Table 4). Thus, in the Smakhtin method, the environmental flow rate is estimated to be 27.2 cms (Table 5). Given that the mean annual flow rate is 80.8 cms, it is clear that the amount equivalent to 34% of the mean annual flow per month during the year is allocated to the environmental requirement based on the Smakhtin method. The ratio of environmental flow estimated by Smakhtin method to monthly mean flow in different months of the year is presented in Table 6. The minimum amount of this ratio is 16% in March and April, which have the highest monthly mean flow throughout the year. During the period from August to October, 100% of the monthly mean flow in the Smakhtin method allocated to the environmental flow, which is unacceptable. In addition, in June, July and November, this ratio is 47, 87 and 64%, which is not possible to allocate this amount of water to the environmental flow in practice due to the agricultural conditions and exploitation of the river. The monthly distribution of the environmental flow and the monthly ratio of environmental flow to monthly mean flow (in percent) presented in Figs. 2 and 3, respectively.

Conclusion

There are different methods to estimate the river environmental flow, and these methods fall into different categories in terms of complexity and time required for the survey. Hydrological methods are one of the easiest methods for estimating the river environmental flow, which, on the one hand, are simpler than other methods and require more limited data, and, on the other hand, the time required for the estimations carried out by these methods is not high and, therefore, can be used in early and fast evaluations. Due to the expressed characteristics, the hydrological methods of environmental flow estimates are widely used in developing countries. Hydrological methods are varied in the estimation of the environmental flow and are largely based on the analysis of historical recorded river flow data. The application of various hydrological methods must be performed with enough care to lead to acceptable solutions, since various hydrological methods of estimating the environmental flow may lead to different and sometimes unbalanced solutions. In this study, to compare the hydrological methods of environmental flow estimation, Tennant, Smakhtin, flow duration curve (Q90) and low flow indexes 7Q2 and 7Q10 used to estimate the environmental flow of Zohreh River in the southwest of Iran.

The results of the application of the Tennant method lead to the estimation of two monthly flows for two six-month periods (April–September and October–November). The comparison with the observational flow pattern shows, on the one hand, monthly mean river flow allocated to environmental flow for two months of a year and, on the other hand, the pattern of allocated environmental flow is not consistent with the observational pattern. Therefore, the application of this method in this study leads to an unreliable answer. The use of the Smakhtin method leads to the provision of a fixed amount assigned to the environmental flow throughout the year, which cannot be specifically consistent with the pattern of river flow changes throughout the year. In addition, the application of the Smakhtin method in three months, all, and in the other several months, allocates a large part of the monthly mean flow to the environmental flow, so it is clear that this method also leads to unacceptable solutions. The results obtained from the application of low flow indexes 7Q2 and 7Q10 lead to a constant value for the environmental flow throughout the year so that the flow allocated by the 7Q2 index is almost twice the flow allocated by the 7Q10 index. Although unlike Smakhtin method, the results of these two indicators do not result in the allocation of the entire monthly mean flow to the environmental flow in some months of the year, but like the Smakhtin method, cannot be in line with the pattern of the observational river flow, and this confines the use of them. Moreover, the estimated values for the environmental flow in this method also confirmed the results of the Caissie et al. (2015) study, which pointed to a significant underestimation of the 7Q10 low flow index, as compared to other methods. In any case, it should be noted that low water flow indexes have been developed for water quality issues and its application that has been taken into consideration by researchers in the environmental flow estimation should be cautious, and this index should be used in addition to other methods. The results of the application of the flow duration curve (Q90) method indicate the allocation of acceptable values to the environmental flow so that in any of the months of the year, the ratio of environmental flow to the monthly mean flow does not have unreasonable and inapplicable amounts. Also, by examining the in-year pattern of the environmental flow allocated by the flow duration curve (Q90) method and the monthly mean flow pattern, it is found that there is an appropriate fit between these two patterns. In other words, in this method, the allocated flow of environmental requirement follows the river mean flow changes in dry and wet periods, and therefore, it can be expected that the results of this method are reliable. According to the results of this research, although the use of hydrological methods is unavoidable in many practical cases, it is better to use several hydrological methods to estimate the environmental flow simultaneously and select the suitable method(s) for the study area based on the interpretation of the results.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Acreman M, Dunbar M, Hannaford J, Mountford O, Wood P, Holmes N, King J (2008) Developing environmental standards for abstractions from UK rivers to implement the EU Water Framework Directive/Développement de standards environnementaux sur les prélèvements d'eau en rivière au Royaume Uni pour la mise en œuvre de la directive cadre sur l'eau de l'Union Européenne. Hydrol Sci J 53(6):1105–1120

Ansarifar MM, Salarijazi M, Ghorbani K, Kaboli AR (2019) Simulation of groundwater level in a coastal aquifer. Marine Georesource Geotechnol 38(3):257–265

Ates H, Dogan S, Berktay A (2016) The effect of river type hydroelectric power plants on aquatic ecosystems: the case study of Göksu River-Eastern Mediterranean. Eur J Eng Nat Sci 1(1):39

Bahrami E, Mohammadrezapour O, Salarijazi M, Jou PH (2019) Effect of base flow and rainfall excess separation on runoff hydrograph estimation using gamma model (case study: Jong catchment). KSCE J Civ Eng 23(3):1420–1426

Balsane VK, Bansod RD (2016) Evaluation of hydrological criteria of environmental flow. Int J Trop Agric 34(6):1821–1827

Bardina M, Honey-Rosés J, Munné A (2016) Implementation strategies and a cost/benefit comparison for compliance with an environmental flow regime in a Mediterranean river affected by hydropower. Water Policy 18(1):197–216

Brooks BW, Riley TM, Taylor RD (2006) Water quality of effluent-dominated ecosystems: ecotoxicological, hydrological, and management considerations. Hydrobiologia 556(1):365–379

Caissie J, Caissie D, El-Jabi N (2015) Hydrologically based environmental flow methods applied to rivers in the Maritime Provinces (Canada). River Res Appl 31(6):651–662

Chen W, Olden JD (2017) Designing flows to resolve human and environmental water needs in a dam-regulated river. Nat Commun 8(1):2158

Davies PM, Naiman RJ, Warfe DM, Pettit NE, Arthington AH, Bunn SE (2014) Flow–ecology relationships: closing the loop on effective environmental flows. Mar Freshw Res 65(2):133–141

Elhatip H, Hinis MA (2015) Statistical approaches for estimating the environmental flows in a river basin: case study from the Euphrates River catchment, Eastern Anatolian part of Turkey. Environ Earth Sci 73(8):4633–4646

Ghanbarpour MR, Zolfaghari S, Geiss C, Darvari Z (2013) Investigation of river flow alterations using environmental flow assessment and hydrologic indices: Tajan River Watershed Iran. Int J River Basin Manag 11(3):311–321

Ghorbani K, Salarijazi M, Abdolhosseini M, Eslamian S, Ahmadianfar I (2019) Evaluation of Clark IUH in rainfall-runoff modelling (case study: Amameh Basin). Int J Hydrol Sci Technol 9(2):137–153

Jensen P, Lee KL, Su YC, Glick R, Magin D (2002) Wet weather and the application of appropriate criteria for contact recreation. Proc Water Environ Fed 2002(8):1210–1222

Jha R, Sharma KD, Singh VP (2008) Critical appraisal of methods for the assessment of environmental flows and their application in two river systems of India. KSCE J Civ Eng 12(3):213–219

King JM, Tharme RE, Brown CA (1999) Definition and implementation of instream flows Thematic Report for the World Commission on Dams. Southern Waters Ecological Research and Consulting, Cape Town, SA, p 63

Mann, J. L. (2006). Instream flow methodologies: an evaluation of the Tennant method for higher gradient streams in the national forest system lands in the western US Master of Science thesis. Colorado State University, Fort Collins

McClain ME, Anderson EP (2015) The gap between best practice and actual practice in the allocation of environmental flows in integrated water resources management. In: Setegn S, Donoso M (eds) Sustainability of integrated water resources management. Springer, Cham, pp 103–120. https://doi.org/10.1007/978-3-319-12194-9_7

Moazed H, Salarijazi M, Moradzadeh M, Soleymani S (2012) Changes in rainfall characteristics in Southwestern Iran. Afr J Agric Res 7(18):2835–2843

Noori M, Zarghami M, Sharifi MB, Heydari M (2013) Utilization of LARS-WG model for modelling of meteorological parameters in Golestan Province of Iran. J River Eng 1. https://europub.co.uk/articles/32947

Othman F, Heydari M, Sadeghian MS, Rashidi M, Shahiri Parsa M (2014) The necessity of systematic and integrated approach in water resources problems and evaluation methods, a review. Adv Environ Biol 8(19):307–315

Pastor AV, Ludwig F, Biemans H, Hoff H, Kabat P (2014) Accounting for environmental flow requirements in global water assessments. Hydrol Earth Syst Sci 18(12):5041–5059

Piniewski M, Laizé CL, Acreman MC, Okruszko T, Schneider C (2014) Effect of climate change on environmental flow indicators in the Narew Basin. Poland J Environ Qual 43(1):155–167

Poff NL (2018) Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. Freshw Biol 63(8):1011–1021. https://doi.org/10.1111/fwb.13038

Poff LeRoy N, David Allan J, Mark Bain B, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime. BioScience 47(11):769–784

Pyrce, R. (2004). Hydrological low flow indices and their uses. Watershed Science Centre,(WSC)Report, (04–2004).

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrological alteration within ecosystems. Conserv Biol 10:1163–1174

Richter BD, Davis MM, Apse C, Konrad C (2012) A presumptive standard for environmental flow protection. River Res Appl 28(8):1312–1321

Rijal NH, Alfredsen K (2015) Environmental flows in Nepal-an evaluation of current practices and an analysis of the upper Trishuli-I hydroelectric project. Hydro Nepal: J Water Energy Environ 17:8–17

Salarijazi M, Ghorbani K (2019) Improvement of the simple regression model for river' EC estimation. Arab J Geosci 12(7):235

Shenton W, Hart BT, Chan T (2011) Bayesian network models for environmental flow decision-making: 1. Latrobe River Australia. River Res Appl 27(3):283–296

Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol 240(3):147–186

Smakhtin VY (2006) An assessment of environmental flow requirements of Indian river basins, vol 107. IWMI. https://www.tandfonline.com/doi/abs/10.1080/02508060408691785

Smakhtin V, Revenga C, Doll P (2004) A pilot global assessment of environmental water requirements and scarcity. Water Int 29(3):307–317

Tennant DL (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1:6–10

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res Appl 19(5–6):397–441

Trudel M, Doucet-Généreux PL, Leconte R (2017) Assessing river low-flow uncertainties related to hydrological model calibration and structure under climate change conditions. Climate 5(1):19

Verma RK, Murthy S, Tiwary RK (2015) Assessment of environmental flows for various sub-watersheds of Damodar river basin using different hydrological methods. J Waste Resour 5(182):2

Verma RK, Murthy S, Verma S, Mishra SK (2017) Design flow duration curves for environmental flows estimation in Damodar River Basin. India Appl Water Sci 7(3):1283–1293

Wałęga A, Młyński D, Kokoszka R, Miernik W (2015) Possibilities of applying hydrological methods for determining environmental flows in select catchments of the upper Dunajec basin. Methodology (BBM) 29:32

Watt SP (2007) A methodology for environmental protection of ontario watercourses with respect to the permit to take water program, Master Thesis. Queen's University, Canada, p 124

Wurbs RA (2017) Incorporation of environmental flows in water allocation in Texas. Water Int 42(1):18–33

Zhang Z (2017) The index gage method to develop a flow duration curve from short-term streamflow records. J Hydrol 553:119–129

Zhuo L, Mekonnen MM, Hoekstra AY, Wada Y (2016) Inter-and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River basin (1961–2009). Adv Water Resour 87:29–41