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Modification of Tennant and Wetted Perimeter Methods in Simindasht Basin, Tehran Province

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ABSTRACT: Environmental Flow Requirement (EFR) is defined as the flow that is necessary to ensure the existence of habitats in water resources systems. EFR is defined in rivers as flow index commonly. Tennant method is the most popular hydrological method in rivers and based on the historic flow data. The most common method of hydraulic rating method is the wetted perimeter method. Habitat simulation techniques attempt to assess environmental flow requirements on the basis of detailed analyses of the suitability of instream physical habitat. Investigation of the relationship between simple approaches and physical habitat simulation approach and presentation of new recommendations based on the hydraulic and hydrological data can be very useful in estimation of environmental flow in planning phase of river projects. Main objective of present research are modification of Tennant and wetted perimeter methods and providing more reliable recommendations in Simindasht basin in Tehran province which Rainbow Trout is dominant species. Based on the results, in April to September 60% of mean annual flow (MAF) and in October to March 120% of MAF can provide sustainable habitats approximately. Also common wetted perimeter method estimates EFR more than real instream flow need of target species. This method will assess the suitable value for environmental flow on 86% of the maximum wetted perimeter approximately. But based on Physical habitat analysis mean suitable environmental flow will be assess in 63% of the maximum wetted perimeter. Hence modification of wetted perimeter based on physical habitat analysis can reduce instream flow need significantly.

Keywords: Environmental Flow, Habitat Simulation, Rainbow Trout, Tennant, Wetted Perimeter.

INTRODUCTION

River systems are used by mankind as sources of industry, irrigation and etc. water quantity in a stream is affected by natural factors such as precipitation and geology, as well effects of humans' activities including construction of dams and weirs and implementation of

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different water abstraction projects. Environmental flow requirement (EFR) is defined as the flow that is necessary to ensure the existence of habitats in water resources systems. Hydrological methods are almost the most straight-forward approach in rivers. These types of methods are also known as desktop methods that rely on annual, monthly or daily flow discharge data of the river (Godinho et al., 2014; Wang et al., 2013). There are two main limitations for hydrological approach. First, ecological values and considerations are not discussed. Secondly, these methods have little defense capability in interactions of water allocation, but because of having some advantages such as simplicity, it is applied in many countries (Martinez et al., 2017; Godinho et al., 2014. The Tennant method (Liu et al., 2016) is the most popular hydrological method which in different management conditions a percentage of annual flow is assessed as EFR. The threshold of flow announced by Tennant have been used with other judgments, in the region of Atlantic in Canada 25% of the mean annual flow is determined as minimum environmental flow (Caissie and El-Jabi, 1995). predictions fromthe Tennant methodis not as reliable as those from the FDC shifting technique (Karimi et al., 2012).

Another applicable approach in assessment of instream flow needs is hydraulic rating method. This approach also does not focus on ecological condition of river and environmental flow is determined by using a relationship between discharge and one of the hydraulic properties of the stream. The most common method of hydraulic approach is the wetted perimeter method. This method works based on the relationship between river flow and wetted perimeter in riffle habitat cross sections (Karakoyun et al., 2016). A flow that covers a reasonable proportion of the bed area of riffles with flowing water should be adequate as a minimum flow for riffle, pool and run macro invertebrates (Gippel and Stewardson, 1998). In some cases sediment transport modeling is essential. Mike21would be the suitable model in precise sediment transport modeling (Ardani and Soltanpour, 2015).

Habitat simulation techniques try to estimate instream flow needs in compliance with the suitability of physical habitat condition in different flows using integrated hydrological, hydraulic and biological response data. Conspicuously, river flow is simulated using data on flow depth, channel slope, cross section shape, etc. collected at multiple cross sections within a study reach. The results will be in used as habitat-discharge curves to prognosticate acceptable flow as water demand of sustainable river ecosystem.

Also there is some models such as CE-QUAL-RIV1 (Nourmohammadi Dehbalaei et al., 2016) which can estimates EFR based on water quality purposes. Different researches are carried out in EFR assessment in rivers (Kennard et al., 2010: Zhang et al., 2012: Bradford et al., 2011). Mann (2006) concluded that the Tennant's original dataset was most applicable in low gradient streams <1%, but not representative of high gradient streams in the west (>1 %). Stalnaker and Arnette (1976) reported that the breakpoint for some U.S. streams happened at river flows corresponding to approximately 80% of the maximum available wetted perimeter. The Oregon Department of Fish and Wildlife recommended that at least 50% of maximum wetted perimeter be provided at riffles (Stalnaker and Arnette, 1976).

Since the development of physical habitat simulation in the 1980s, physical habitat techniques have been considered a momentous tool for river ecosystem management (Bockelmann et al., 2004). Aquatic habitat simulation models have been used for fish in water resource management, particularly in North America. The Physical Habitat Simulation (PHABSIM) is considered to be the first of these fish habitat models and is now being applied worldwide. This method defines the change in physical habitat availability for key target species given a change in river flow. (Ahmadi-Nedushan et al., 2008). Assessment of habitat conditions is a complicated issue and for this reason assessment of EFR by this method is not popular in many countries in planning phase of river projects (Shokoohi and Amini, 2014).

Rainbow trout in Simindasht basin is dominant species. Rainbow trout would be distinguishable based on appearance, depending on where they are found and their life stage. Maximum size also alters in accordance with population and habitat, for example maximum size in lake and river would be different totally. According to observation of Abdoli and Naderi (2009) in southern basin of the Caspian Sea mean length and weight of this species are 150mm and 75gr, respectively. In many areas, the mature age of rainbow trout is 1 year. Spawning time of rainbow trout is March and April. Adult and juvenile rainbow trout are basically opportunistic feeders and consume a broad range of invertebrates and other aquatics as food source. The fry of lake-resident spawners may immigrate into the lake immediately, or when there is adequate stream flow, they may spend up to three years in the stream to eschew lake predators (Coad, 2013).

Main contribution of this study is modification of Tennant and wetted perimeter method in Simindasht basin in Tehran province and use of more reliable flow indices for these applied and suitable methods. Development and modification of simple and common methods in environmental flow assessment can be very useful for assessment of EFR and reduction of expenses in projects.

MATERIALS AND METHODS

In the present research, Delichai stream in Tehran province in Iran was selected as a case study. In this stream rainbow trout was a dominant species. Delichai stream is in upstream of great Hablerood river which is like drainage channel of Tar and Havir lakes and joins to Hablerood in Simindasht basin. Hablerood flows toward south direction and would be as main water resource for agricultural activities in Garmsar region. The area watershed of this stream is approximately 340 km^2. Mean altitude of region of this stream is 2182 m and total length of stream was 37 km (Keshtkar et al., 2013). The previous studies have been affirmed that currently qualitative factors of the stream are not in a critical condition. Due to the morphological and hydraulic conditions self purification of the river is possible. Special topographic condition and dearth of wide industrial activities in vicinity of this river has been effective on relatively outstanding habitat qualities. It should be noted that the scope of this research was instream flow needs assessment of a stream under natural condition so this stream was an appropriate option. Detailed statistical mean monthly flow data of the study stream are displayed in Table 1.

In hydrological approach, according to Tennant's recommendations (these recommendations are shown in Table 2) and recommendation in Atlantic region EFR was estimated.

The most common method of hydraulic approach is the wetted perimeter method. In this method, there is a direct relationship between wetted perimeter and habitat conditions of the river at riffle habitats. By plotting of wetted perimeter and discharge relationship and deriving the point that has the most curvature in the curve as the index point, the minimum environmental flow can be determined. Schematic view of this method is shown in Figure 1. Estimation of break point by observation method will not produce proper result and there are two methods to estimate breakpoint. In the first method the first derivative of discharge-wetted perimeter equation equals to 1, but according to scenarios in river ecosystem management other values can also be applied instead of 1. In the second method according to the relationship of maximum curvature of the discharge-wetted perimeter, the discharge equivalent to the maximum curvature of the function is computed and is applied as the minimum instream flow need. (Gippel et al., 1998)

In the present research 1-D physical habitat simulation is implemented in order to simulation of physical habitat for Rainbow trout. Physical habitat simulation describes the effect of flow alterations for three main physical factors and transmute them into a curve for prognostication of the microhabitat area for aquatic organisms. Unequivocally, direct output from these types of models is Weighted Usable Area (WUA). WUA is computed within the reach at a specific discharge from:

$$WUA = \sum_{i=1}^{n} A_i \times C_i \quad (1)$$

where A_i: is the surface area of cell i and C_i: is the combined suitability of cell i (i.e., composite of depth, velocity and channel index individual suitability). Common method in estimation of C is multiplying depth, velocity and substrate suitability for development of combine habitat suitability in each habitat cell.

Table 1. Monthly flow data in study stream (cms)

Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
2.813	2.209	0.893	0.36	0.182	0.265	0.574	1.157	1.137	0.938	1.063	1.728	1.11

Table 2. Tennant's recommendations (Liu et al., 2016)

Description	%MAF (Oct. to Mar.)	%MAF (Apr. to Sep.)
Maximum	200	200
Optimum	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	<10	<10

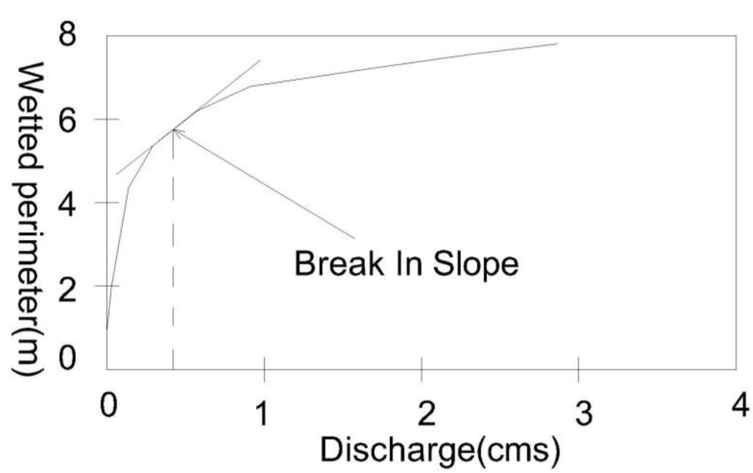

Fig. 1. Schematic view of wetted perimeter method (Gippel et al., 1998)

To perform present study, hydrological, hydraulic and habitat simulation approaches were assessed in a mountainous stream. In this regard the Tennant method in minimum condition (10% of MAF), the average optimal condition (80% of MAF) and maximum (200% of MAF) were examined. We also compute 25% of mean annual flow recommended for Atlantic.

One dimensional hydraulic modeling for development of hydraulic and habitat simulation approaches, was carried out by HEC-RAS version 4.0 model. This model is one-dimensional hydraulic model and it has been developed by US army corps of engineers and released in 2008. HEC-RAS is chosen based upon its widespread use and reliability. The stream schematic and cross section data were engendered in geographic information system software and then used as input in HEC-RAS for hydraulic simulation. Due to the shape of cross sections and other conditions of the stream, one-dimensional model provided proper responses.

For hydraulic approach after hydraulic simulation of the stream, riffle cross sections which had more critical condition were selected (8 cross sections) and discharge-wetted perimeter curve was plotted for these cross sections and finally with curve fitting the discharge-wetted perimeter function was extracted and according to the methods described in previous section minimum instream flow need was determined.

In physical habitat simulation modeling, physical habitats of rainbow trout were assessed and Weighted Usable Area (WUA) against discharge relationships are engendered for disparate life stages of Rainbow trout. These habitat-discharge relationships were used to assess minimum of EFR.

Different percent of mean annual flow (MAF) recommended from the Tennant method and also minimum, maximum and 40% of maximum of mean monthly flow of the study stream, according to the statistical flow data of the stream presented in Table 1 were used for habitat simulation approach. These flows are displayed in Table 3.

RESULTS AND DISCUSSION

Estimation of E-flow using hydrological method is displayed in Table 4.

Based on precise analysis, flow- wetted perimeter equation can be stated as follows:

$$P = 3.71Ln(Q) + 13.64 \tag{2}$$

in which P: is wetted parameter in meter and Q: is flow in cms. Eqs. (3) and (4) show the minimum instream flow need using the maximum slope and curvature methods in hydraulic rating method, respectively.

$$\frac{dP}{dQ} = \frac{3.71}{Q} = 1 \Rightarrow Q = 3.71 \text{ cms} \tag{3}$$

$$\kappa = \frac{\left|\frac{-3.71}{Q^2}\right|}{\left[1+(\frac{3.71}{Q})^2\right]^{1.5}} \Rightarrow \tag{4}$$

$$\frac{d\kappa}{dQ} = 0 \Rightarrow Q = 2.63 \text{ cms}$$

Results indicate that the method of maximum slope estimates EFR 33 times greater than corresponding value in Tenant method. According to the statistical data of monthly discharge, it can be observed that the maximum mean monthly flow was 2.813 cms (see Table 1). The maximum curvature method assesses the EFR only 6% lower than the maximum mean monthly flow of the stream. The maximum slope method also estimates the minimum environmental flow 24% more than the maximum mean monthly flow. So these two methods are not applicable for estimation of EFR in performance, because even the natural flow regime in river is not sufficient for the minimum environmental requirements. Based on the results of hydraulic approach, natural regime in stream is not sufficient for maintenance of sustainability of ecological conditions and water cannot be used for various purposes. According to the statistical data of the stream flow, the mean flow discharge is zero in few month and indicates that the stream regime is arid and semi-arid, It should be noted that due to the climate of Iran many of the streams have the same climatic condition and we can observe similar flow regimes in other arid and semi-arid countries.

The Tennant method predicted minimum of EFR 0.11 cms. Considering the mean monthly flow in the stream, this amount is less than the mean monthly flow in the driest month. The mean monthly flow in the driest month of the year is 0.182 cms that is approximately 65% more than the minimum annual flow predicted from Tennant method. Due to this high difference application of Tennant method is ambiguous too.

Based on the Tennant method the average optimum flow is 0.88 cms. Analysis showed that, 0.88 cms in eight months of the year is less than the mean monthly flow. Based on the Atlantic method EFR is 0.27 cms and only in two month of the year the mean monthly flow is less than 0.27 cms. The Tennant maximum flow in the study stream is 2.22 cms and the same as hydraulic method this index is not applicable too. According to the results given from studied approaches, it is unequivocal that the estimated amount from hydraulic approach cannot be supplied. Based on the physical habitat simulation, weighted Usable Area against discharge relationships for different life stages of Rainbow trout for total length of the study stream is displayed in Figure 2.

Table 3. Applied flows in habitat simulation method

10% MAF	**40% MAF**	**60% MAF**	**80% MAF**	**100% MAF**	**200% MAF**	**Min (MMF)**	**Max (MMF)**	**40%Max (MMF)**
0.11	0.44	0.66	0.88	1.11	2.22	0.182	2.813	1.125

Table 4. EFR estimation in hydrological approach

Criteria	**Estimation Method**	**Estimated Value (cms)**
minimum flow Tennant	10% of MAF	0.11
average optimum flow Tennant	80% of MAF	0.88
maximum flow Tennant	200% of MAF	2.22
Minimum flow in Atlantic	25% of MAF	0.27

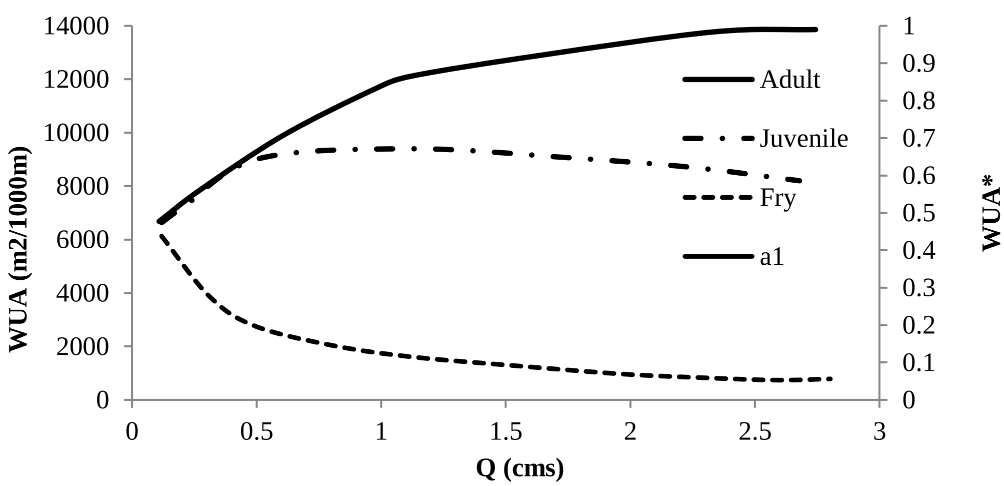

Fig. 1. Habitat-flow relations in different life stages of target species

This graph shows that WUA for fry Rainbow trout peaks at low flows and decreases with higher flows whereas for adult Rainbow trout habitat availability increases with increasing the flow. Therefore adult Rainbow trout can tolerate higher velocities relative to the fry Rainbow trout.

It can be seen from the WUA-discharge relations that the maximum mean monthly flow of the stream that is 2.813 cms and is about 253% of MAF, has the most WUA value for adult Rainbow Trout, but for fry Rainbow Trout the most available habitat (WUA) occurs at 10% of MAF that is equal to 0.11 cms. Also the most available habitat for juvenile Rainbow trout occurs at the flow range of MAF and 80% of MAF. Differences between maximum and minimum of WUA among all life stages of rainbow trout show that we will need accurate analysis of habitat suitability in different life stages of Rainbow trout.

According to habitat analysis, when flow is 0.56 cms, WUA is maximum. In other words, minimum of EFR in this life stage is 0.56 cms but in fry and adult life stage suitability condition is more complicated. We can have logarithmic curve fitting in these two life stages for relationship between flow discharge and WUA. Equation (5) and (6) are shown these relations for adult and fry life stage respectively.

$$WUA^{*}_{Adult} = 0.18\ln(Q) + 0.82 \quad (5)$$

$$WUA^{*}_{Fry} = -0.12\ln(Q) + 0.14 \quad (6)$$

Maximum curvature in these two curves for adult and fry occur in Q = 1.3 cms and Q = 0.7 cms respectively. We can consider maximum curvature point as a critical point. In adult life stage after critical point, changes in WUA are limited. In other words, increasing in flow discharge cannot improve habitat suitability dramatically. In fry life stage after critical point, WUA decreases significantly. An appropriate method in assessment of minimum of EFR to allocate a fixed amount for environmental flow in rainbow trout habitats can be average of 0.56, 1.3 and 0.7 cms. This value is 0.85 cms. Another method is allocation of two value of EFR in stream. According to Abdoli and Naderi (2009) the mature age of rainbow trout is 1 year in Iran, so we can allocate two values for EFR in two periods. In first period in range of spawning time and six month later (i.e. April to September) EFR can consider 0.7 cms and in range of October to March EFR will be 1.3 cms. Time limits provide is exactly the time limits provided by Tennant. In fixed method the value of EFR for rainbow trout habitats is equal to 77% or 80% MAF approximately. So average of optimum range of Tennant method is appropriate to provide sustainable habitats. In second method (i.e. allocation of two amount for EFR in two periods), in first period (i.e. April to September) 60% of MAF and in second period (i.e. October to March) 120% of MAF can provide sustainable habitats approximately.

In the next step, we can investigate hydraulic approach and results of physical habitat simulations. WP (Wetted Perimeter) in 0.7, 0.85 and 1.3 cms will be 12.3,13 and 14.6 m and based on these values we can modify hydraulic approach in Rainbow trout habitats. In fixed method the value of WP in appropriate EFR for rainbow trout habitats was 13 m. According to this amount, we can modify maximum slope and maximum curvature methods. These modifications are shown in Eqs. (7) and (8).

$$\frac{3.71}{0.85} \approx 4.3 \Rightarrow \left(\frac{dP}{dQ}\right)_{FA} = 4.3 \quad (7)$$

$$\kappa(0.85) = 0.55 \times \kappa_{MAX} \Rightarrow \kappa_{FA} = 0.55\ \kappa_{MAX} \quad (8)$$

In two period method the value of WP in appropriate EFR for rainbow trout habitats were 12.3 and 14.6 m. According to these amounts, we can modify maximum slope and maximum curvature methods. These modifications are shown in Eqs. (9-12).

$$\kappa(0.7) = 0.46 \times \kappa_{MAX} \Rightarrow \kappa_{FP} = 0.46\ \kappa_{MAX} \tag{9}$$

$$\frac{3.71}{0.7} = 5.3 \Rightarrow \left(\frac{dP}{dQ}\right)_{FP} = 5.3 \tag{10}$$

$$\kappa(1.3) = 0.76 \times \kappa_{MAX} \Rightarrow \kappa_{SP} = 0.76\ \kappa_{MAX} \tag{11}$$

$$\frac{3.71}{1.3} = 2.85 \Rightarrow \left(\frac{dP}{dQ}\right)_{SP} = 2.85 \tag{12}$$

in which, *P*: is wetted perimeter in meter, *Q*: is the discharge of stream in cms, κ: is the curvature of the function in each point and κ_{max}: is the maximum curvature of the function. FA index represents using the fixed method, FP and SP represent the first period and second period in evaluating environmental flow for two different periods.

By comparing the natural regime of the Delichai stream and results of habitat simulation it can be interpreted that the mean flow of the stream in spring is 1.76 cms and suitability of the stream is not critical for the target species. In summer due to the severe reduction of flow in the stream the mean flow is 0.269 cms and habitat condition of the stream suffer some tensions for juvenile and adult life stages but fry has the most suitable habitat condition, of course it should be considered that due to the severe reduction of the discharge total habitat area reduced a lot but yet these available habitats are in the most suitable condition for fry. Considering the reduction of suitable habitats for juvenile and adult life stages river restoration and rehabilitation projects can create the most suitable condition in this season. In the autumn that lies in the second study period the mean flow of the stream is 0.95 cms which is greater than 0.85 cms, thus in the fixed method there is not any problem in providing the environmental flow of the stream practically, of course the differences between the mean flow and the defined environmental flow is very little, and the allocated environmental flow is 89% of the mean flow of the stream. But the mean flow of the stream is approximately 27% less than the environmental flow defined from the second method and restoration and rehabilitation projects can create suitable habitat conditions. The mean flow of the stream in winter is 1.24 cms which has a little difference with evaluated value from habitat simulation method (1.3 cms). According to the Eq. (6) it can be seen that the wetted perimeter in fixed method is approximately 75% of the maximum wetted perimeter (considering the maximum monthly discharge as the average maximum discharge in the stream). In fact, it can be mentioned that the flow equivalent to the 75% of the maximum wetted perimeter can be considered as the minimum environmental flow in rainbow trout habitats. Also according to the second method if the year is divided to two six month periods, in the first six month period (April to September) the discharge equivalent to the 70% of the maximum wetted perimeter can be considered as the suitable environmental flow for stream habitats of rainbow trout. In the second six month period the discharge equivalent to the 84% of the maximum wetted perimeter will be a suitable environmental flow. The results from the equivalence of habitat simulation method and hydraulic method represent important antithesis. According to the hydraulic approach the environmental flow evaluated from the maximum slope and maximum curvature is 3.71 cms and 2.63 cms, respectively. The maximum slope method is completely rejected for environmental flow assessment because the evaluated discharge is even greater than the maximum mean monthly flow and practically this condition cannot happen in the stream except in extreme floods. The second method also will create the wetted perimeter approximately equivalent to the maximum wetted perimeter in the present research. Thus it can be concluded that while the wetted perimeter method is not modified according to Eqs. (7-12), it will predict unreal values for environmental flow that cannot happen in arid and semi-arid climatic conditions, that will not be defensible in water allocation discussions too. Totally it can be said that the Tennant method for environmental flow assessment in rainbow trout habitats is reasonable while the mean optimum flow (80% of the mean annual flow) is considered as the minimum environmental flow. Because of the high variety in the study stream regime and due to the severe reduction of the flow in some month of the year, selection of the 80% of the mean annual flow as the environmental flow is considered a suitable and reliable selection in many streams. According to the long term statistical data (20 year) of the stream, if the maximum wetted perimeter is considered equivalent to the wetted perimeter at maximum discharge (7.1 cms), maximum wetted perimeter will be 20.92 m. In this situation the suitable environmental flow in fixed method will be created in 63% of the maximum wetted perimeter. Also in the second method, it will be provided in 59% and 70% of the maximum wetted perimeter for the first and second period of time, respectively. Maximum slope and maximum curvature methods will estimate the suitable value for environmental flow of the stream in 89% and 83% of the maximum wetted perimeter, respectively. Evaluated flow for rainbow trout habitats with different methods is illustrated in Figure 3. Some parts of the present research that are related to the regime of the stream can be applicable only in mountainous streams of the semi-arid regions with the same regime but the other part that estimate the EFR in rainbow trout habitats without considering the regime of the stream are applicable in each stream that is the habitat of this species.

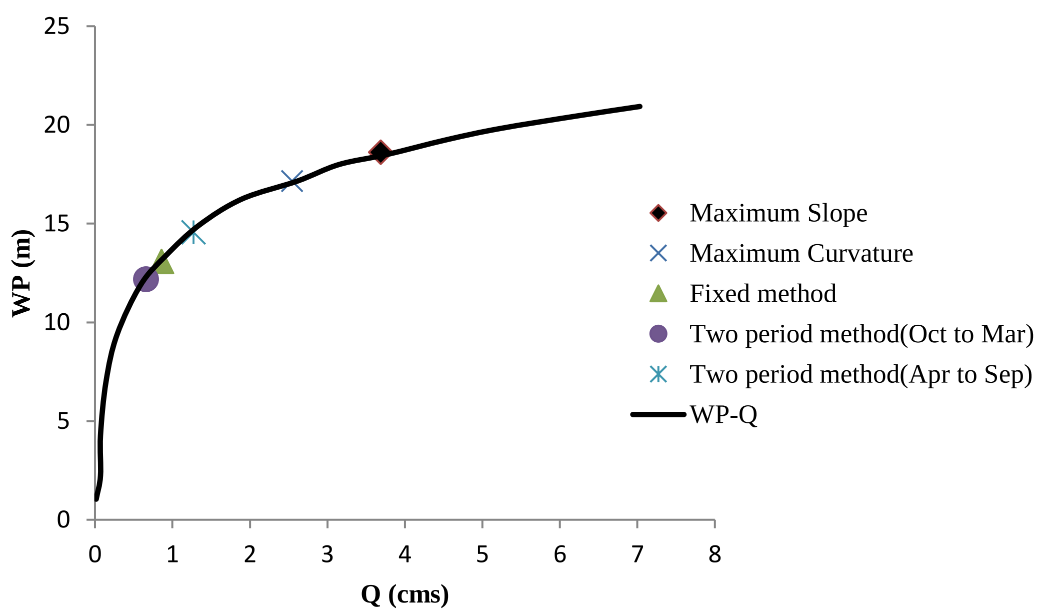

Fig. 3. View of different methods in WP-Q curve

CONCLUSIONS

Investigation of relationship between simple approaches and physical habitat simulation approach and presentation of new recommendations based on the hydraulic and hydrological data can be very useful in estimation of environmental flow in planning phase of river projects. Main objective of present research is presentation of these recommendations in rainbow trout habitats as one of the most major species in river habitats. Delichai-Simindasht stream in Tehran province in Iran was selected as a case study. In this stream rainbow trout was a dominant species. In hydrological approach, according to Tennant's recommendations and recommendation in Atlantic region EFR was estimated. In hydraulic approach, the selected method was the wetted perimeter. In this method, there is a direct relationship between wetted perimeter and habitat conditions of the river at riffle habitats. By plotting of wetted perimeter and discharge relationship and deriving the point that has the most curvature in the curve as the index point, the minimum environmental flow can be determined. In physical habitat simulation modeling, physical habitats of rainbow trout were assessed and Weighted Usable Area (WUA) against discharge relationships are generated for different life stages of Rainbow trout. These habitat-discharge relationships were used to assess minimum of EFR. Based on the results, fixed amount for environmental flow in rainbow trout habitats can be 80% of MAF, so average of optimum range of Tennant method is appropriate to provide sustainable habitats. In second method (i.e. allocation of two amount for EFR in two period), in first period (i.e. April to September) 60% of MAF and in second period (i.e. October to March) 120% of MAF can provide sustainable habitats approximately. Also hydraulic approach was modified in two methods of estimation and two methods of EFR point recognition. These modifications are provided in Eqs. (7-12). If the maximum wetted perimeter is considered equivalent to the wetted perimeter at maximum daily discharge, in this case the maximum slope and maximum curvature methods will assess the suitable value for environmental flow of the stream in 89% and 83% of the maximum wetted perimeter, respectively but suitable environmental flow in fixed method will be created in 63% of the maximum wetted perimeter. Also in the second method, it will be provided in 59% and 70% of the maximum wetted perimeter for the first and second period of time, respectively. Developed indices in this study cannot be used as assured modification in other river basins. But in similar streams which Rainbow trout is dominant species, results may be useable with ecological considerations. Development of regional environmental flow indices for other main fish species such as Brown trout in future researches can reduce expenses of environmental flow expenses considerably.

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