# Using hydrologic and hydraulically derived geometric parameters of perennial rivers to determine minimum water requirements of ecological habitats (case study: Mazandaran Sea Basin—Iran)

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## Abstract:

This paper studies one of the most important problems of dry countries that are confronted with water deficit and the competition of rivals to allocate water. Some common methods have been investigated for computing the minimum water requirement to save a river's biological activity. After a discussion of the currently used method in Iran (the Tenant Method), the application of some other methods, which are known as Hydraulic and Hydrological Methods, is illustrated. The case study is a river in the northern part of Iran and this research addresses the critical situation of this river in near future regarding the planned anthropogenic alteration and its consequences. It has been shown that the application of environmental water allocation methods that have no background in a region could be misleading. The first proposed method is the Texas Method, in which flexibility in water allocation helps to develop an integrated river management paradigm in the study area. The second preferred method is a Hydraulic Method, by which the implementation of morphological parameters or flow geometrical properties could sustain physical habitat within an acceptable range in terms of depth, width, velocity, and bed shear stress. In the case study, the Maximum Curvature Method was superior to the Slope Method. The investigation revealed that using a widely recommended slope of 1 for the discharge-wetted perimeter function can lead to an overestimated and unacceptable discharge. The Tenant Method in respect to minimum environmental flow requirement yielded the weakest result, and it has been illustrated that its application might impose irrecoverable shock to the ecosystem. The Flow Duration Curve Method (the $Q_{95}$ Method), in spite of its subjectivity, showed more compatibility with the river's condition in comparison with the Tenant Method. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS    ecological water requirement; environment; river; Texas Method; Maximum Curvature Method; Slope Method; Tenant Method; Flow Duration Curve Method; $Q_{95}$

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## INTRODUCTION

Existence of a long-term drought, degradation of the aquifers in terms of quality and quantity, the rapid rate of population growth, and low irrigation efficiency in Iran caused a rush towards over committing the surface water resources across the country, especially in the study area of this research. The use of water for agricultural, industrial, and civilian purposes has caused many rivers to become depleted to the point of endangerment, particularly with the decreasing rainfall in recent years.

While Earth Summit in Rio de Janeiro in 1992 declared ecosystem conservation as a public duty and recognized an ecosystem's water rights alongside the rights of mankind (Acrerman and Dunbar, 2004), these rights are still not respected fully in Iran. Like South Africa and Tanzania, there are some laws in Iran that consider the allocation of environmental water after meeting mankind's requirements, but the existing situation of the rivers shows that there are at least some deficiencies in the application of this rule.

In recent decades, the most important problem in this regard in Iran is the absence of an explicit policy towards defining the minimum environmental water requirement for rivers, particularly in water withdrawing projects. All efforts to set up rules have focussed mainly on structures like large dams, which ban the flow of water, while for diversion works there is no clear instruction. The accustomed policy in Iran was to release a constant discharge or in the best circumstances leave a discharge with a monthly variation, which could differ per region based on the judgment of specialists. In recent years, the Tenant Method, which is known as the Montana Method in Iran, has been officially recommended to assess the environmental water requirements in Iran. As will be described subsequently, this method was developed for special purposes and allocates environmental water requirements seasonally. For the case study, a river (the Safarood River), which has not experienced effective anthropogenic alteration and has adequate and reliable

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data for analysis, was selected. There are some plans including constructing a diversion dam and a pump station in two different parts of the Safarood River in future. The focus of this research is on the critical situation of this river in near future regarding the endangered habitat of the river and also the other rivers across Iran and perhaps in all of the countries that use arbitrary procedures to allocate water for ecological requirements. In this regard, the present (natural) state of the Safarood River was analyzed and its future state was demonstrated by employing some water allocation policies (discussed later), which do not need extensive ecological data. The results of the present research showed that the Tenant Method is not suitable for environmental water allocation in the study area.

To find a more reliable and compatible method for the study area, different methods that do not need abiotic and biotic detailed data have been investigated. Those methods can be categorized into the two major groups of Hydrological and Hydraulic Methods. While the Hydrological Methods use historical records to evaluate the required flow/flows, the Hydraulic Methods base their judgment for maintaining aquatic creatures' lives on deriving uniform flow parameters, as a consequence of past climatic and hydrologic conditions, which influence the quality of river habitats directly. In the subsequent parts of the paper, after introducing the methods' background, the detailed results of their application are presented, and finally the methods are ranked according to their compatibility with the study river and in terms of minimum environmental water.

## BACKGROUND

Investigation of most of the regulated rivers around the world and recognition of their environmental degradation has led to the development of the environmental flow assessment methods whereby the required flow for sustaining the ecosystem of rivers is determined (Tharme, 2003).

The main problem in determining the environmental flow requirement is making a decision about the allowable extent of modifications in the river's natural regime. In this respect, more than 207 different methods have been developed in 44 countries within six different parts of the world (Tharme, 2003). The simplest definition of instream flow is the water flowing in a river (Anonymous, 2005). According to Instream Flow Council (USA), instream flow can be defined as follows (IFC, 2004):

> The objective of an instream flow prescription should be to mimic the natural flow regime as closely as possible. Flow regimes must also address instream and out-of-stream needs and integrate biotic and abiotic processes. For these reasons, inter- and intra-annual instream flow prescriptions are needed to preserve the ecological health of a river.
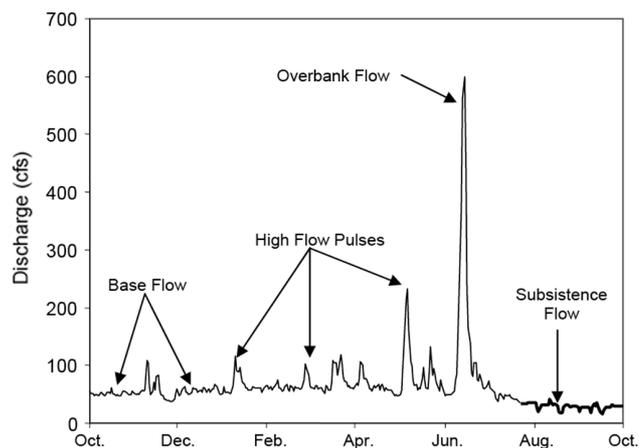


Figure 1. Four levels of the flow in a perennial river (Anonymous, 2005)

The flow regime in IFC definition can be called the hydrologic attribute of a river and involves four levels of flow (Anonymous, 2005): subsistence flow for drought period; base flow as normal flow for sustaining the river's biota and abiotic condition in healthy condition; high flow, which remains in the river channel, washes the sediment from bed, and enhances the quality of the river after a long time running of the base flow; and finally overbank flow, which connects the main river with its flood plains and is very important from geomorphologic points of view. A combination of these stages has been illustrated in Figure 1.

There are some new efforts to show the importance of saving the full hydrologic regime of rivers after alteration. Botter *et al.* (2010), emphasizing on saving the natural regime of rivers, could simulate the past natural hydrograph of some altered rivers in a catchment in Italy, and in comparison with the current state of which illustrated the effects of anthropogenic alteration on the hydrologic regime of those rivers.

The target of different methods that have been developed to sustain rivers' ecosystems is to sustain one or more parts of the flow regime that could be used to categorize them. In an attempt to do this, Acreman and Dunbar (2004) grouped all of the existing methods into four classes: Look-up tables, Desk top analysis, Functional analysis, and Hydraulic Habitat Modelling. The Look-up table methods, which are also called historical or Hydrological Methods, are generally based on available hydrological data (long-term data of daily, monthly, and annual discharge). Sometimes these methods are also called Tabular Methods (Petts, 1996). The main purpose of all of the methods in this category is to determine the subsistence flow for ecological systems. At least 15 methods can be recognized in this group (Smakhtin, 2001; Marchand, 2003), and most of them are developed for a special region (King *et al.*, 1999). The most important and common methods in this group are the Tenant Method (Tenant, 1976), the Flow Duration Curve Analysis (FDCA), and the 7Q10 Method (Smakhtin *et al.*, 2006; Ames, 2006; Anonymous, 2009c).

The Desk top methods are based essentially on the available data. This group involves two types of methods: (1) the methods which are based merely on hydrological data. The Range of Variability (RVA; Richter *et al.*, 1997) belongs to this group. (2) The methods which use both hydrological and ecological data. The Lotic Invertebrate Index for Flow Evaluation (LIFE; Dunbar *et al.*, 2004) is an example of this method.

The Functional analysis refers to the methods which intend to establish a direct relationship between the hydrological aspect and the ecological system of a river. The South African Building Block Methodology (BBM; King *et al.*, 1999, 2008) and the Flow Event Method (FEV; Stewardson and Gippel, 2003) can be placed in this group. These types of methods are scenario based and because of searching for a direct relationship between hydrology and ecology have to use a panel of experts that are not always available (Acreman and Dunbar, 2004).

Hydraulic Habitat Modeling has been developed to cover this problem (Tharme, 2003). In this kind of model, the physical habitat is used as an intermediate step between hydrology and ecology. The most influential physical parameter that has been used so far is the wetted perimeter of an indicated cross section that will be described in the subsequent section. It is possible to use the physical habitat simulation separately to find the minimum environmental requirement. In this situation, one can add a further category to the above-mentioned group of environmental flow simulation methods. This method can be called the Hydraulic Method or the Habitat Retention Method (Jowett, 1997; Gippel and Stewardson, 1998; Tharme, 2003). However, the Hydraulic Habitat Models try to simulate rivers with hydraulic variables such as depth, average velocity, and bed shear stress. In these models the hydraulic variables are combined with other data, including habitat of living creatures, raising period, and important information about existing species in the region to predict an optimum amount of discharge (Jowett, 1997). One the most popular models in this group, which is used in many of the developed countries in the northern hemisphere, is the Instream Flow Incremental Methodology (IFIM) (Tharme, 2003). The PHysical HABitat SIMulation System (PHABSIM) is a basic part of the IFIM, and its main idea is that the living environment in rivers reacts with the hydraulic medium and its variations (Jowett, 1997; Zappia and Hayes, 1998; King *et al.*, 1999). There are some reports on its shortcomings regarding lack of required information to transfer the model results to the other sites (Hudson *et al.*, 2003).

In some references, another combined methodology called the Holistic Method has been introduced. These models require comprehensive data about river flow such as its quantity, duration and frequency, flow hydraulic variables, and living creatures including people who live beside the ecosystem (Marchand, 2003). In this regard one can say that all of the environment flow allocation models are implicitly holistic. The BBM is one of the best known models of this category.

Table I. Suggested discharges in Tenant Method (all the discharges are a percent of average annual discharge) (Tenant, 1976)

| Description of flows | Recommended base flow regimes | |
| | October–March | April–September |
| --- | --- | --- |
| Flushing or maximum | 200% | |
| Optimum range | 60–100% | |
| Outstanding | 40% | 60% |
| Excellent | 30% | 50% |
| Good | 20% | 40% |
| Fair or degrading | 10% | 30% |
| Poor or minimum | 10% | 10% |
| Severe degradation | 0–10% | |

## MATERIALS AND METHODS

### Tenant method

As previously mentioned, this method was developed for 11 rivers in the states of Montana, Wyoming, and Nebraska in the US to determine appropriate discharge for saving fish-passing on the streams' beds. In this regional method, according to the observed data, a flow equal to 30% of average annual discharge is necessary to maintain proper width, depth, and velocity of the stream (Tenant, 1976). All the discharge limitations, as mentioned in Table I, are seasonally variable.

There are some doubts about using this method in other rivers. Tenant did not mention the necessary criteria to derive the critical discharges, so morphological resemblance is the key for its transferability to other rivers. Another important point in using the Tenant Method is the fact that this method does not consider daily, monthly, and annual discharge variation directly. This issue has been noted in another way in the other studies, as Smakhtin *et al.* (2006) believe that the criteria in Table I are subjective and heuristic. Primarily, these criteria reduce a fixed value from all of the flows regardless of low or high flow conditions, which could pose severe losses to the river environment during low flow periods (Smakhtin *et al.*, 2006).

### Texas Method

The Lyons Method, which is called the Texas Method as well, is currently used in Texas for water permitting. This method has been developed by Barry W. Lyons at the Texas Parks and Wildlife Department (TPWD) on the basis of the hydraulic approach that uses the wetted perimeter of rivers as the representative of physical habitat. In this method the spring and summer instream flow is considered more important than that of the remaining part of the year. In this respect, 40% of the median monthly flow is allocated as the instream flow from October to February. This figure from March to September is equal to 60%. There is some investigation in the state of Texas that shows for 60% level, about 80% of substrate was wetted and after 40% level, the wetted substrate began to drop off significantly (Anonymous, 2005).

*Flow duration curve analysis*

The fundamental of this simple Look-up table method is using the flow duration curve of a river on the basis of long term average daily flow. This method has been used in many countries, including New Zealand, UK, Bulgaria, Taiwan, and Australia. In most of the cases, $Q_{95}$ or $Q_{96}$ criteria have been used so far as a measure for the minimum environmental flow. As a hydrological definition, $Q_{95}$ or $Q_{96}$ is equal to a discharge of a river that in 95 or 96% of a water year is exceeded (Jowett, 1997; Tharme, 2003; Acreman and Dunbar, 2004).

*Wetted Perimeter Method*

The Wetted Perimeter Method, owing to its simple and exact definition of critical point in a discharge-wetted perimeter curve (Figure 2) is more applicable than the other methods used to compute the environmental flow requirement of a river.

In this method it is supposed that there is a direct relationship between wetted perimeter and usable aquatic environment (Gippel and Stewardson, 1998; Suxia *et al.*, 2006). As can be seen in Figure 1, there is a sharp reduction in the wetted perimeter for discharges less than the critical point; after this point, variation of discharge has a minor effect on wetted perimeter. Accordingly, one can describe this character of flow hydraulics as an ecological phenomenon; hence, if the critical discharge could be maintained in a river, one could say the ecological environment would remain safe and alive (Suxia *et al.*, 2006). In the US and Australia, the critical point of the wetted perimeter-discharge curve has been used to determine the optimum and minimum flow that is required for fish breeding. In comparison with Tenant's works in Wyoming and Montana, it has been reported that for discharges equal to 10% of average annual discharge, 50% of maximum wetted perimeter is usable, and for a discharge equal to 30% of average annual discharge, about 100% of the maximum wetted perimeter is usable (Tenant, 1976). According to these criteria, researchers on Arkansas' rivers revealed that the critical point corresponds to 50% of annual average discharge (Gippel and Stewardson, 1998). These facts show the inherent dynamics of the environment flow requirement computation and the unreliability of the Tenant Method.
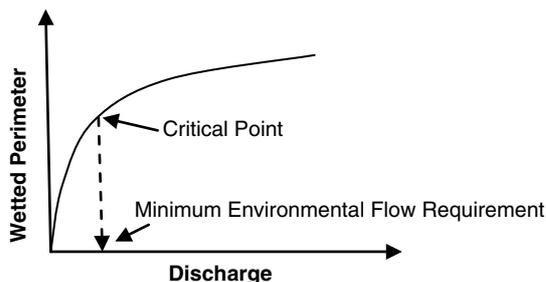


Figure 2. Demonstration of relationship between discharge and wetted perimeter (critical point and minimum environmental requirement)

For emphasis on the ecological meaning of the critical point in the wetted perimeter–discharge curve, it is enough to consider the situation of a river bed in discharges less than the critical point. In this state with insufficient usable wetted perimeter, the sands, gravels, and cobbles stay out of the water's surface and lose their appropriateness for invertebrates. In addition, plant cover of rivers' sidewalls, as an important source of food, could not be used by some types of fishes anymore. Insufficient depth in ditches and passages for big fishes could be added to these problems (Jowett, 1997; Gordon *et al.*, 2004).

There are numerous experiments with the hydraulic approach towards solving the problem of environmental flow requirement, and while the definition of the point is so clear, the mathematical definition of this point is controversial. The simplest way to find this critical point is the by-eye method and using personal judgment (Annear and Conder, 1984). Gippel and Stewardson (1998) proposed mathematical formulation to find the critical point. There are two well-known methods: the Slope Method and the Maximum Curvature Method. In the Slope Method with a differentiated discharge-wetted perimeter curve, one can find an equation and hence the slope of the curve for each points. According to the proposed method by Gippel and Stewardson, in addition to many others, for the Slope Method critical point is a point that gives the slope of the curve equal to 1:

$$\frac{\mathrm{d}y}{\mathrm{d}x} = 1 \qquad (1)$$

The above criteria are not fixed and can be adjusted according to the sensitivity of living creatures. For more sensitive species, it is possible to choose a milder slope (Gippel and Stewardson, 1998). However, the final decision to determine the critical point in this regard is a subjective one.

The curvature of a smooth curve is defined as the curvature of its osculating circle at each point, while the osculating circle of a curve at a given point is the circle that has the same tangent at that point (as well as the same curvature). The curvature of a circle is reciprocal of its radius, so one can find the curvature of a plane curve with the help of its osculating circle. In a mathematical sense, the curvature of a plane curve at a point is a measure of how sensitive its tangent line is to moving the point to other nearby points. According to these definitions, when there is no deflection, as in the case of a line, the curvature will be 0, and the curvature of a circle of radius $R$ should be large if $R$ is small and small if $R$ is large. Thus, one can find the maximum curvature of a curve by investigating on the radius of its osculating circles. This phenomenon has been used in the Maximum Curvature method. If a curve could be defined as $y = f(x)$, its curvature is (Weisstei, 2003; WolframMathWorld, 2011):

$$k = \frac{(\mathrm{d}^2 y / \mathrm{d}x^2)}{[1 + (\mathrm{d}y/\mathrm{d}x)^2]^{3/2}} \qquad (2)$$

Equation (2) will be maximized only at one point, which is the critical point. On this basis, it is necessary to compute wetted perimeter for a designated cross section at different discharges via uniform flow equations. Then one of the two equations (1) or (2) is used to find the critical point, namely, minimum environmental flow requirement.

*Case study*

The case study is the Safarood River, which is located in the southern part of the Caspian Sea and is near to Ramsar city in the northern part of Iran. The dominant climate of the region is Semi-Mediterranean. The total length of this river is 20 km, while its average slope is about 13% in mountainous area and about two percent in plain. The overall area of the catchment at its closure is about 137 km$^2$ while its average elevation is about 1425 m a.s.l (with a maximum elevation of 3546 m a.s.l and a minimum elevation of 0 m a.s.l.). The hydrologic regime of the Safarood River is snowy-rainfall, mostly rainfall, and its biggest floods occur mostly in spring due to rainfall (Anonymous, 2009a).

*Geometric data.* Figure 3 shows the TIN map of the Safarood catchment, and Figure 4 shows its longitudinal
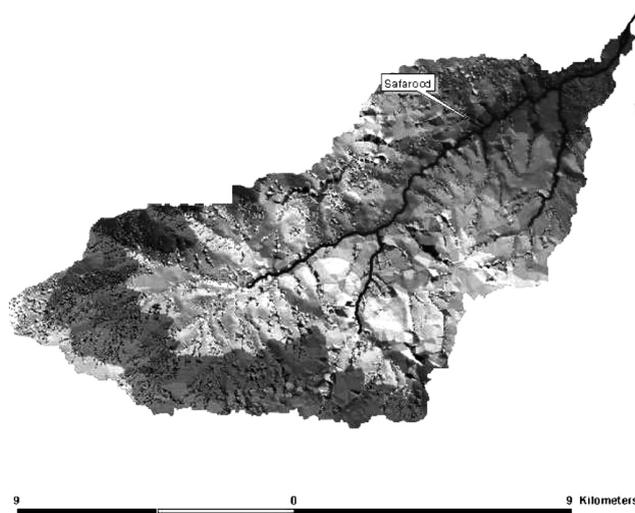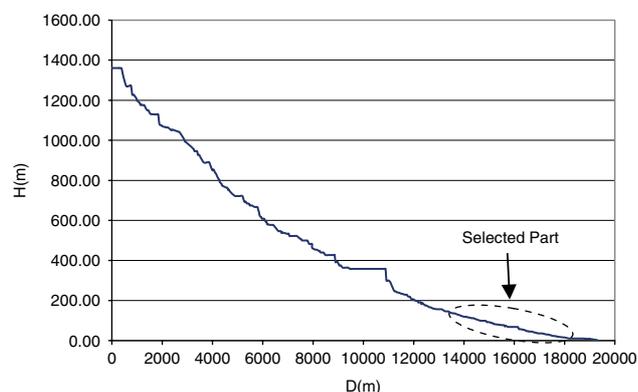


Figure 3. TIN map of Safarood Watershed



Figure 4. Longitudinal profile of Safarood River

profile derived from 1 : 25 000 topographical digital maps. The former figure shows the area chosen for study.

For deriving the relationship between discharge and wetted perimeter about 5 to 6 kilometers of the river upstream of its mouth were considered, and an indicator cross section as an average section of the whole area was determined. For the purpose of friction coefficient calibration, cross sections, which are located in the aforementioned area and near to the river gauge station, were derived as illustrated in Figure 5.

*Hydrological data.* Since 1953, there is good and reliable gauge data on the Safarood River at a point where it comes to the plain area of its catchment (36°54′N, 50°37′E). There are two sources of recorded data at the gauge station. The first series of the data has been recorded for the sediment rating of the Safarood, and the second source includes recorded floods in two different periods. The data for the higher levels show a linear relationship between the stage and discharge, but for the low stages this relationship is approximately exponential. Figure 6 shows the regression line and its 95% confidence boundaries, and Equation (3) represents a statistically reliable stage-discharge equation for the Safarood gauge station.

$$Q = (0.2879 + 0.0267H)^2 \quad R = 0.97 \quad (3)$$

The Safarood River is a perennial river and has its highest flow in the spring and autumn seasons. Its seasonal flow distribution is shown in Figure 7, and its flow duration curve, accompanied with the time series of average daily discharge, is illustrated in Figure 8.

To discover the hydrological behavior of the Safarood River, statistics of its monthly discharge, as well as its wet and dry period frequency, were derived in Tables II and III. Results are based on the available data from 1958 to 2006.

Frequency analysis of 38 annual maximum flood data compilations proved the lognormal distribution as the best fit. Accordingly, the 2 and 5 year annual flood in this river are equal to 22.8 and 50.5 m$^3$/s, respectively. The result of the flood data analysis has been illustrated in Table IV.

*Environmental data.* Aquatic creatures in the Safarood River are classified in different categories including phytoplankton, zooplankton, benthic, and nektons (fishes). On the basis of the existing reports of The Fishery Office of Iran and The Department of Environment and Fishery Research of Mazandaran Province, fish of this region are classified into two major classes: indigenous and diadromous. Indigenous fish of the rivers in the region are mostly River Carps and Roaches, which are spread in the rivers up to 500–600 m in height relative to the Caspian Sea's surface elevation. The majority of diadromous species belong to two classes of Sea Carp and Salmon that migrate to spawn from the Caspian Sea to the available rivers in the region including the Safarood River
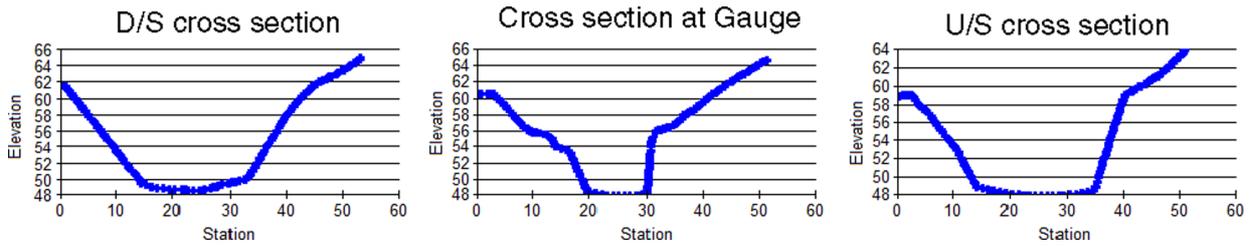
Figure 5. Cross section of Safarood at gauge station, downstream and upstream of the gauge (distances and elevations are in meter)
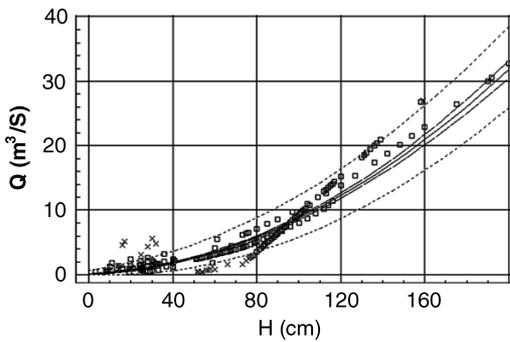


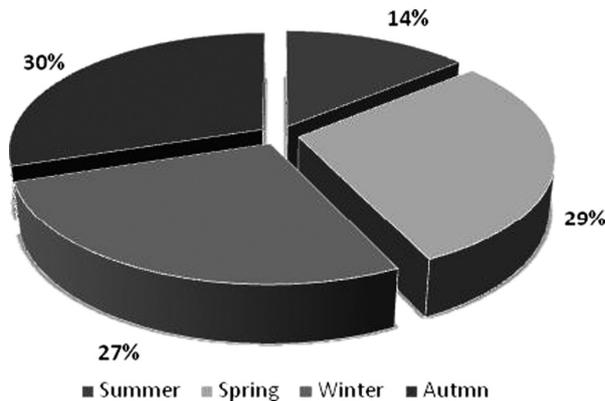Figure 6. Regression line of discharge-stage data at Safarood gauge station



Figure 7. The seasonal distribution of Safarood River flow as a percent of total annual flow

sea have been indicated as the main reasons (Anonymous, 2009b).

## RESULTS

All of the described methods, except the Texas Method, introduce minimum environmental flow. By the Flow Duration Curve (the $Q_{95}$ Method), the minimum required flow is equal to 0·9 $m^3$/s, while applications of the Tenant Method for the minimum acceptable situation of the river (Table I) yield this flow as 0·2 $m^3$/s. In the Texas Method, the environmental flow can vary seasonally and monthly. Unlike the Tenant Method, where the environmental flow is a percentage of average annual flow, the admitted flow is dependent on the median of the monthly flow in the Texas Method. These results are shown in Table VI.

Finding a reliable relationship between discharge and wetted perimeter requires a reliable estimation of the roughness coefficient (in this case, the Manning coefficient). The Manning coefficient for the study area has been found through a calibration process. The Discharge-elevation equation (3) for each elevation gives a discharge, and afterwards, it is possible to find geometric properties of the section with respect to the assumed elevation. Solving the Manning equation for its coefficient yields values that vary with depth. This process for the Safarood River gave a reasonable range for the Manning coefficient as $0·07 \leq n \leq 0·09$. To finalize the process and confirm the results, a pictorial method, which compares the Safarood River study area with the standard pictures (Anonymous, 2009d), was applied. Finally, a unique number of 0·078 for low to mean discharges of the wet period was accepted.

during spring and autumn. Available reports show a sharp decrease in Roach migration in recent years, and water scarcity and lost hydrological connectivity of rivers to the
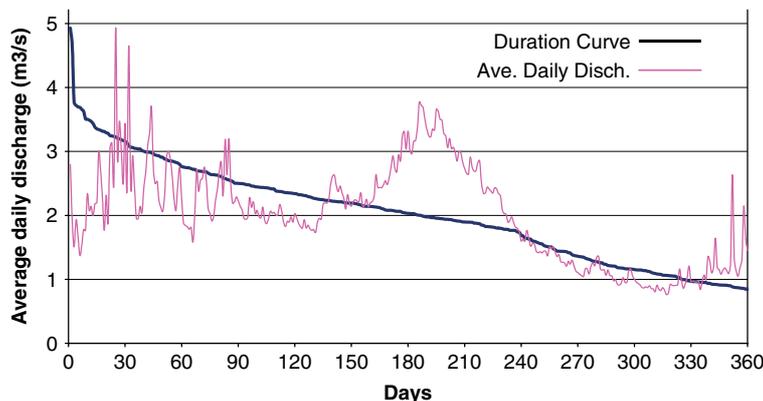


Figure 8. Flow duration curve and mean daily discharge of Safarood River

Table II. Statistics of monthly and annual discharge (m³/s) of Safarood River

| | Oct | Nov | Dec | Jan | Feb | March | April | May | June | July | Aug | Sep | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 2·49 | 2·39 | 2·17 | 1·93 | 2·07 | 2·6 | 3·45 | 2·32 | 1·33 | 1·13 | 0·94 | 1·44 | 2·01 |
| SD | 1·53 | 1·41 | 1·22 | 0·95 | 1·07 | 1·12 | 1·75 | 1·18 | 0·55 | 0·65 | 0·47 | 0·88 | 0·64 |
| CV (%) | 0·61 | 0·59 | 0·56 | 0·49 | 0·52 | 0·43 | 0·51 | 0·51 | 0·41 | 0·58 | 0·5 | 0·62 | 0·32 |
| Skew | 0·52 | 0·94 | 0·63 | 2·23 | 2·61 | 0·7 | 1·21 | 1·03 | 0·98 | 2·59 | 2·32 | 1·16 | 0·48 |
| Max | 5·46 | 5·39 | 4·82 | 5·82 | 6·78 | 5·18 | 8·93 | 6·1 | 2·59 | 3·87 | 2·83 | 3·64 | 3·46 |
| Min | 0·49 | 0·43 | 0·51 | 0·77 | 0·88 | 0·91 | 1·02 | 0·9 | 0·5 | 0·45 | 0·31 | 0·26 | 0·94 |

Table III. Frequency of discharges of Safarood River in wet and dry period

| | | | Dry period | | | | Mean | | | Wet period | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tr (year) | 100 | 50 | 25 | 20 | 10 | 5 | | 5 | 10 | 20 | 25 | 50 | 100 |
| Q (m³/s) | 0·86 | 0·93 | 1·02 | 1·06 | 1·2 | 1·42 | 2 | 2·5 | 2·88 | 3·24 | 3·35 | 3·69 | 4·03 |

Table IV. The probable floods of Safarood River

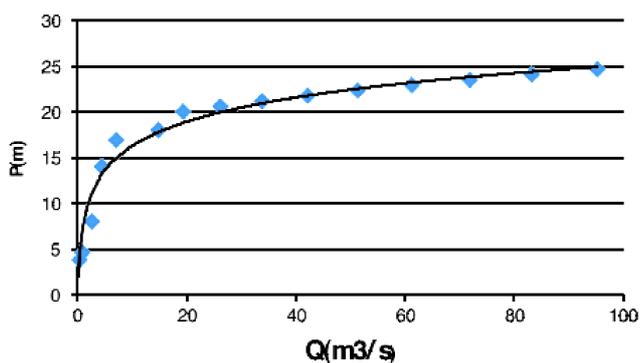| Return period (year) | 2 | 5 | 10 | 25 | 50 | 100 |
|---|---|---|---|---|---|---|
| Q (m³/s) | 22.81 | 50.45 | 76.39 | 118.91 | 158.27 | 204.68 |



Figure 9. Illustration of wetted perimeter and discharge relationship

The downstream cross section in Figure 5 was used to derive the relationship between wetted perimeter (*P*) and discharge (*Q*), which is demonstrated in Equation (4) and Figure 9:

$$P = 3.834 \mathrm{Ln}(Q) + 7.4776 \quad R^2 = 0.97 \quad (4)$$

Equation (4) is very similar to that of Gippel and Stewardson (1998), although they obtained a logarithmic equation with a fixed constant of 1 for rectangular sections, whereas our results showed that it could be a variable for trapezoidal sections. Equations (5) and (6) are the equations needed for deriving a critical point according to the Slope Method and Maximum Curvature Method, respectively.

$$\frac{dP}{dQ} = \frac{3.834}{Q} \quad (5)$$

$$|k| = \frac{\left| \dfrac{-3.834}{Q^2} \right|}{\left[ 1 + \left( \dfrac{3.834}{Q} \right)^2 \right]^{\frac{3}{2}}} \quad (6)$$

Setting Equation (5) equal to 1 gives 3·8 m³/s as the minimum environmental discharge, and solving Equation (6) for all the discharges for finding its maximum value gives the minimum environmental discharge as 1·25 m³/s. Environmental discharge by the Montana Method is not a unique value and depends on the accepted criteria as mentioned in Table V.

To compare the different methods with each other in terms of the minimum environmental flow, Table VI has been prepared, where the results of the $Q_{95}$, the Texas Method, the Minimum Curvature Method, and the Tenant Method were illustrated.

According to Table VI regarding the annual flow volume, the Maximum Curvature Method yields the highest value, while the Tenant Method suggests the lowest to sustain the Safarood River environment. The results of the $Q_{95}$ and the Texas Method are close to each other. This can be seen well in Figure 10.

One of the most important consequences of applying a discharge to a river is its influence on the geometric parameters of the river section and the hydraulic parameters of the flow that represent its physical habitat. Table VII illustrates these parameters derived for the Safarood River via the mentioned methods. Figure 11 shows the channel wetted perimeter for each case as a percentage of this parameter in the average annual flow.

Table V. Results of hydraulic and Tenant Method

| Hydraulic Method | | Hydrological Method | | | |
|---|---|---|---|---|---|
| Min. discharge (m³/s) | Min. discharge (m³/s) | Tenant | | | |
| | | 10% | 30% | 60% | 100% |
| Max. curvature 1·25 | Slope 3·83 | 0·2 | 0·6 | 1·2 | 2·01 |

Table VI. Comparing the results of different methods for minimum environmental flow

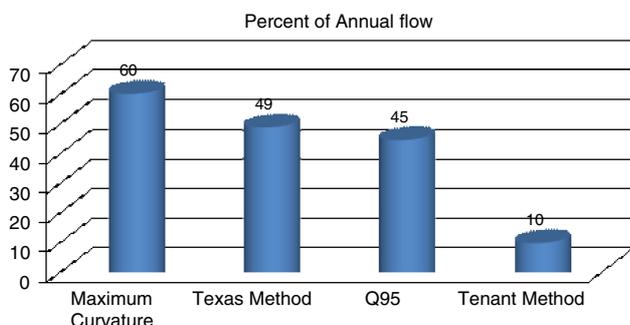| | Oct | Nov | Dec | Jan | Feb | March | April | May | June | July | Aug | Sep | Annual Vol(Mm3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| River monthly $Q$ (m³/s) | 2.5 | 2.4 | 2.2 | 1.9 | 2.1 | 2.6 | 3.5 | 2.3 | 1.3 | 1.1 | 0.9 | 1.4 | 63·6 |
| Maximum curvature | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.1 | 0.9 | 1.3 | 38·3 |
| Texas Method | 1.0 | 1.0 | 0.9 | 0.8 | 0.8 | 1.0 | 2.1 | 1.4 | 0.8 | 0.7 | 0.6 | 0.9 | 31·1 |
| $Q_{95}$ Method | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 28·4 |
| Tenant (min) | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 6·3 |



Figure 10. The results of different method as a percentage of annual flow volume

Table VII. Comparison of the effects of various methods on the physical habitat

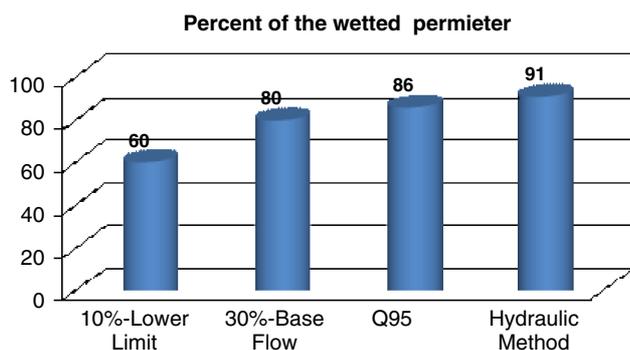| | 10%-Lower limit | 30%-Base flow | Hydraulic Method | Normal |
|---|---|---|---|---|
| $Q$ (m³/s) | 0·2 | 0·6 | 1·25 | 2 |
| $V$ (m/s) | 0·18 | 0·25 | 0·34 | 0·4 |
| Width (m) | 21·1 | 27·99 | 31·83 | 34·9 |
| Depth (cm) | 6 | 11 | 16 | 20 |
| Wetted perimeter (%) | 60 | 80 | 91 | 100 |



Figure 11. Wetted perimeter of the channel for different methods as a percentage of average flow condition

## CONCLUSION

The principal reason for this research is the existence of an ambiguity in the environmental water allocation policy in Iran. Present research investigates minimum environmental flow requirements of rivers. In this respect, with the help of a case study in the northern part of Iran, we tested the applicability of some hydraulic and hydrological models and showed that without considering the actual situation of a river, application of any of these methods to determine the environmental flow requirements may lead to a wrong conclusion and cause serious problems for a riverine ecosystem. Obtained results from this research reveal that application of the Tenant Method in many of the rivers may have doubtful efficacy, although it is the officially recommended method.

In this research, it has been demonstrated that Hydraulic Methods are more sophisticated than the Tenant Method, which is the most widely used Hydrological Method in Iran. In the case study, the Tenant Method resulted in a minimum environmental discharge equal to 0·2 m³/s, vis-à-vis 1·2 and 3·8 m³/s from the Maximum Curvature and Slope Method, respectively. Statistical investigation of the Safarood River (Tables II and III) showed that the long term average discharge of this river was about 2 m³/s, and the discharge of the river in the wet period with a return period of 50 years was equal to the value that the Slope Method gave as minimum flow requirement. The minimum flow requirement of a river could not exceed the long term average of a river, so on this basis, the results from the Slope Method regarding $dP/dQ = 1$ could not be accepted. For the Slope Method if one uses $dP/dQ = 3$, results will be close to that of the Maximum Curvature Method. Conversely, it is obvious that the proposed minimum discharge via the Tenant Method (Table III) is less than the discharge of the river in the dry period with a return period of 100 years. With keeping minimum environmental discharge, a river can survive for a limited period. Therefore, recommending release of a discharge less than a critical discharge, which will be observed every 100 years on the average, is misleading.

One of the most important problems in environmental water allocation, particularly during the season of migration, is to sustain biotic habitat. In the study area, fish migration occurs in the spring and autumn, so maintaining width, depth, and velocity in the river in March through June is of major importance. In this regard, the Tenant Method yielded the weakest result, and the Maximum Curvature Method with the maximum amount of water allocation (Table VI and Figure 10) was the closest method to the natural state. But if one considers the monthly flow distribution (Table VI), it could be recognized that the Texas Method gave the results as good as the Maximum Curvature Method, particularly in the critical months. From a practical point of view, the Texas Method is closer to real conditions; while the Maximum

Curvature Method allocates 81% of the spring and summer volume to the river, the Texas Method allocates 60% to the river.

The required bottom shear stress to move sediments from the bed for all of the methods is much more than critical shear stress. In this regard, the Maximum Curvature Method has the least amount of problems. While the variation of shear stress in the Texas Method is enough to change the form of the bed, the shear stress exerted by the most probable flood with a probability of 50% (Table IV) is equal to 70·4 N/m$^2$, which can refresh bed material for invertebrates.

One of the considerable results of this research is the superiority of the Maximum Curvature Method to the Slope Method. It has been proved that, in spite of the other research (Gippel and Stewardson, 1998), the minimum discharge of the river given by the Slope Method is higher than that of the Maximum Curvature Method.

According to the obtained results, the best method for determining the minimum environmental flow for the study area is the Texas Method. It seems that using the Hydraulic Method as the basic component of Physical Habitat Models set the river on the safety side but may cause conflict between the users. The results of the $Q_{95}$ are close to that of the Texas Method in critical months, while it could not show enough flexibility in an integrated river management paradigm.

Providing a pool around the mouth of the river and digging a pilot channel before the pool, towards the upstream of the river, may be helpful in the end of spring and during the summer for providing adequate depth in the river to sustain life.

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