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Evaluation of environmental flow requirements using eco-hydrologic–hydraulic methods in perennial rivers

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ABSTRACT

The assessment of environmental flows in rivers is of vital importance for preserving riverine ecosystem processes. This paper addresses the evaluation of environmental flow requirements in three reaches along a typical perennial river (the Zab transboundary river, in north-west Iran), using different hydraulic, hydrological and ecological methods. The main objective of this study came from the construction of three dams and inter-basin transfer of water from the Zab River to the Urmia Lake. Eight hydrological methods (i.e. Tennant, Tessman, flow duration curve analysis, range of variability approach, Smakhtin, flow duration curve shifting, desktop reserve and 7Q2&10 (7-day low flow with a 2- and 10-year return period)); two hydraulic methods (slope value and maximum curvature); and two habitat simulation methods (hydraulic–ecologic, and Q Equation based on water quality indices) were used. Ecological needs of the riverine key species (mainly *Barbus capito* fish), river geometries, natural flow regime and the environmental status of river management were the main indices for determining the minimum flow requirements. The results indicate that the order of 35%, 17% and 18% of the mean annual flow are to be maintained for the upper, middle and downstream river reaches, respectively. The allocated monthly flow rates in the three Dams steering program are not sufficient to preserve the Zab River life.

Key words | eco-hydrologic–hydraulic methods, environmental flows, water resources, Zab River

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INTRODUCTION

The protection of the aquatic environment is a high priority for water resource managers throughout the world. Many countries, developing ones in particular, face a number of water-related challenges, including an increasing demand for water on the one hand, and the need to allocate a share of water to maintain the functioning of freshwater-dependent ecosystems in a river basin on the other. This share is often referred to as 'environmental flows' (EFs), 'environmental water requirements' (EWRs) and 'environmental demand' (Smakhtin *et al.* 2006). There is now broad acceptance that it is in society's best interests to consider rivers as legitimate 'users' of fresh water (Arthington *et al.* 2006). However, the recognition that rivers and adjacent wetlands need adequate water of good quality to sustain ecological processes and associated goods and services is not new. Methods designed to quantify minimum 'in-stream flows' to sustain fish appeared in the USA in the late 1940s. With increasing concern about the impact of dams and flow regulation on river biota, the scientific field of EF prospered to produce more than 200 methods that can be grouped into four categories: hydrological rules, hydraulic rating methods, habitat simulation methods, and holistic methodologies (Tharme 2003).

The vast majority of EWR methodologies available globally have focused almost exclusively on riverine systems (Jiang *et al.* 2006). Among these methods, the best known is the Tennant hydrological method, developed in the USA, which identifies various levels of minimum flows based on specified proportions of the mean flow (Tennant 1976). More recently, the range of variability approach (RVA) is an advanced hydrological procedure which evaluates flow regimes based on a correlation of 33 flow statistics for the regulated and natural flow regime (Richter *et al.* 1998). A new framework named as ecological limits of hydrologic alteration (ELOHA) was recently presented (Poff *et al.* 2010). This framework is a combination of some existing hydrologic measures and environmental flow requirement (EFR) methods that are currently being used to different degrees and that can help to maintain widespread regional flow management. One of the

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most popular models in the hydraulic–habitat models group is instream flow incremental methodology (IFIM) (Tharme 2003). The physical habitat simulation model (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. (Shokoohi & Hong 2011). The influence of water quality was incorporated in the EWR assessment (Tchobanoglous *et al.* 2003).

Various methods have been acquired over the last decades. These methods are not necessarily based on similar hypotheses, databases or approaches, and do not follow an identical river management target. Most of them have been developed independently with no further modification over time. In the literature, there is no general agreement on which method should well be adapted to any specific river environment. The newly developed methods are not yet justified as the more appropriate ones. Therefore, the predetermination of a best fitted method does not seem to be an appropriate approach. The main aim of the present study was to provide a framework to determine EFRs of a typical perennial river in different reaches. For this, the Zab River was selected. Twelve different hydrological–hydraulic–ecological methods were tested in three reaches of the river. The comparison of the selected methods is correlated with the evaluation of conformity of the methods based on eco-hydrologic–hydraulic circumstances in the Zab River.

MATERIALS AND METHODS

Study area

The Zab River is a major transboundary and shared river between Iran and Iraq. This river flows from the Zagros mountain range, passes the city of Piranshahr and Sardasht in north-west Iran, then crosses the borderline of Iran–Iraq to flow into the Dukan dam in Iraq, and finally joins the Tigris River, near Baghdad. The river reaches under study are located in West Azerbaijan, west of Iran. In this segment, the Zab River basin covers an area of about 2,662 km^2 (36°06′–36°55′ N, 44°51′–5°42′ E). The environmental assessment of the Zab river is particularly important because of the construction of three dams and the plan for inter-basin transfer of water from the river to the Urmia Lake. Urmia Lake is an internationally registered ecosystem which is currently suffering from dramatic shrinkage, and its restoration is partly dependent on the inflow from the Zab River.

Three river reaches were selected along 160 km of the Zab River from upstream to downstream, where three existing gauging stations (Derabkay, Grejal and Pol-Sardasht) represent the flow regime at these three sites. These three reaches are the sites of the three recently constructed dams: Silveh Dam (2007) at upstream (corresponding to Derabkay reach), Kani-Sib Dam (2008) in the middle of the river (corresponding to Grejal reach), and Sardasht Dam (2008) located downstream (corresponding to Pol-Sardasht reach). An overview of the study area is presented in Figure 1. General information of these three river reaches and corresponding hydrometry stations are shown in Table 1.

Hydrologic methods

Smakhtin & Anputhas (2006) developed the flow duration curve shifting (FDC Shifting) hydrological method. According to this procedure, six environmental management classes (EMCs) are used (Shaeri Karimi *et al.* 2014). The EMCs are similar to those described in the South African Department of Water affairs and Forestry (DWAF 1997). Table 2 presents a description for a typical environmental management class, Class B. In this study, a global environmental flow calculator (GEFC) was used to analyze the data and to estimate EFRs (GEFC software).

The Tennant method (Tennant 1976) was partially modified to adapt to Iran's hydrological regime, and is recommended to use nation wide. For this reason, the prediction from the Tennant method was tested and compared with that from other methods. In this approach, the acceptable environmental level is 30% of mean annual runoff (MAR) for April to September, and 10% of MAR for March to October. With the derivation of these seasonal variations by the Tennant method, Tessman (1980) uses the combination of mean monthly flow (MMF) and mean annual flow (MAF) to determine minimum monthly flow as EWR.

According to the flow duration curve analysis (FDCA) procedure, the Q95 and Q90 flows (the flows that are equalled or exceeded 95% and 90% of the time) are most often used as low flow indices. The low-flow index is interpreted as the 7-day low flow with a 2- and 10-year return period (7Q2&10), using daily discharge data from the river reach under study (Pyrce 2004). Smakhtin *et al.* (2004) further referred to low-flow requirement (LFR) and high-flow requirement (HFR) in a procedure known as the Smakhtin method. LFR is believed to approximate to the minimum requirement of water of the fish and other aquatic species throughout the year. HFR is important for river channel maintenance, as a stimulus for processes such as migration and spawning, for wetland flooding and establishment of riparian vegetation. The sum of LFR and HFR forms the total EWR (Smakhtin *et al.* 2004).

Figure 1 | A landscape of the Zab River in the study area.

Table 1 | The information of the three selected river reaches in the Zab River

River reach (gauging station)	Distance from upstream (km)	Length of the reach (m)	Elevation (m)	Statistical period	Mean annual runoff (MCM)	Average flow (CMS)
Derabkay	30	250	1,425	1974–2012	210.2	6.6
Grejal	105	260	1,100	1974–2012	1,271.9	43.7
Pol-Sardasht	140	280	1,000	1974–2012	1,388.5	44.4

MCM = million cubic metres; CMS = cubic metres per second.

Table 2 | Characteristics of selected class of EMCs in FDC shifting method

EMC	Most likely ecological condition	Management perspective
B (slightly modified)	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed

The desktop reserve model (DRM) is a hydrology-based, planning-type EFR methodology developed in South Africa by Hughes & Hannart (2003). The parameters of DRM have been determined empirically for South African rivers, and DRM parameter values must be modified for other conditions. In computing the results, the model assumes that the primary dry-season months are June to August and the primary wet season months are January to March, as occurs over much of South Africa. This assumption cannot be altered within the model (Shaeri Karimi *et al*. 2012). In the case of the Zab river basin's climatology, April to June and September to November represent the wet and dry seasons, respectively. To reflect these key months, the input data were shifted by 3 months (i.e. January became April and so forth) and the results were then readjusted.

The RVA method was developed by Richter *et al*. (1998) as a complex approach for setting streamflow-based river ecosystem management targets. The proposed approach derives from aquatic ecology theory concerning the critical role of hydrological variability, and associated characteristics of timing, frequency, duration and rates of change, in sustaining aquatic ecosystems. In this paper the Indicators of Hydrologic Alteration (IHA) Version 7 software was used to evaluate EWRs in the RVA method.

Hydraulic methods

The main hypothesis for developing hydraulic methods is to provide sufficient depth and velocity for aquatic life. 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 hydraulic methods used to compute the EFR of a river (Shokoohi & Hong 2011). The critical minimum discharge is supposed to correspond to the point where there is a break in the shape of the curve (usually a logarithmic or power function). Below this discharge, the wetted perimeter declines rapidly (Gippel & Stewardson 1998). There are two well-known approaches: the slope value and the maximum curvature. For the slope value approach, the critical point is a point that gives the slope of the curve equal to 1. A second systematic method of selecting the breakpoint in the curve is to define the point of maximum curvature, as described by Gippel & Stewardson (1998). The hydraulic geometry of the river flows was calculated using the HEC-RAS (Hydrologic Engineering Centers River Analysis System) model in each of the three river reaches.

Ecological methods

All ecological-based models such as IFIM are semi-empirical in nature, and reliable adaption of the model depends on the similarity in the river system and the detailed ecological data on domestic riverine habitats. The PHABSIM model is a well-known tool that can be used to assess and help to improve river habitats (Moir *et al.* 2005). The IFIM PHABSIM system is a collection of computer programs that combines open channel hydraulics and behavioral response of fishes to hydraulic characteristics. Figure 3 illustrates several key features representing both the conceptual and practical processes for modeling instream habitat in PHABSIM (Waddle 2001).

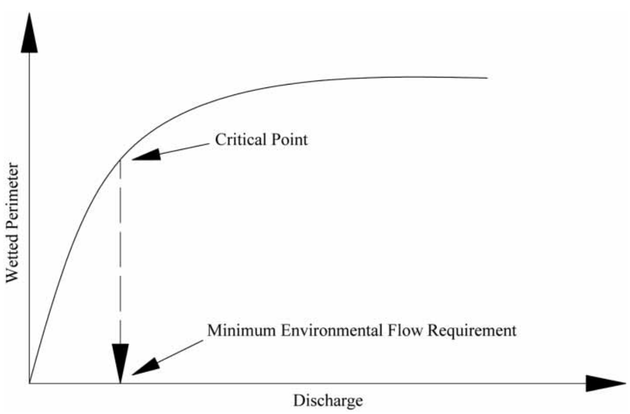

Figure 2 | Relationship between discharge and wetted perimeter (Ahmadipour & Yasi 2014).

Among different aquatic species in the Zab River ecosystem, the so-called *Barbus capito* fish (Cyprinidae family) was selected to represent the bio-indicator species for habitat modeling in PHABSIM. Two important periods (April–June) and (July–March) were considered for spawning and adulthood of the key fish, respectively (Abdoli 1999; Naderi & Abdoli 2004). Table 3 indicates both the critical period of spawning and the hydraulic requirements (water depth and velocity) of the *Barbus capito* fish.

To determine the influence of water quality parameters in determining EFs, the Q equation (Equation (1)) was used for assessing the efficiency of this procedure in EWRs assessment (Tchobanoglous *et al.* 2003). Different water quality parameters were considered using this equation such as total dissolved solids, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand (COD) and pH.

$$(Q_1 + Q_c).C_o = (Q_2.C_2) + (Q_1.C_1) \qquad (1)$$

where, Q_1 and Q_2 are the initial and secondary discharges; C_1 and C_2 are corresponding concentration of each of the quality parameters; and C_o is the desired concentration value of the parameter. The water chemical statistics of the Zab River were investigated in the three gauging stations. Among different parameters, COD was selected as representative of water quality, and the USEPA standard (given in Stone (n.d.)) was used as the reference for acceptable values of COD.

The step-by-step methodology for the determination of environmental flows from different eco-hydro approaches in this study is presented in Figure 4.

RESULTS AND DISCUSSION

The main aim of the present study is to highlight the potential use of different methods, and the importance of choosing the most appropriate method, given the nature of the river and the data available. The results of calculating environmental flows from different echo-hydrologic–hydraulic methods at three reaches of the Zab River are

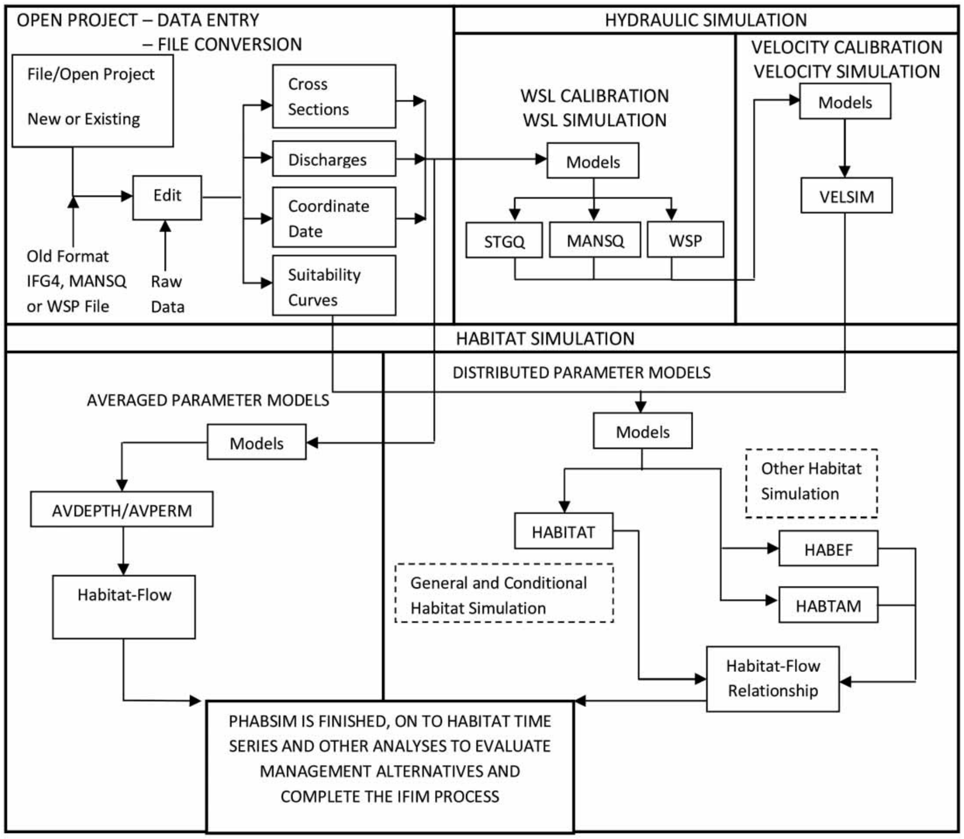

Figure 3 | PHABSIM for Windows flowchart (Waddle 2001).

Table 3 | Hydraulic requirements for the domestic targeted species in the Zab River

Key species	Spawning period	Optimum depth in spawning period (m)	Optimum depth in non-spawning period (m)	Optimum velocity in spawning period (m/s)
Barbus capito	April–June	1.0	0.7	1.2

presented in Table 4, and compared with that reported for the three dams located at the same reaches.

The Tennant method proposes different percentages of MAF as EFRs. Based on the national standard, 10% MAF in dry-season (October–March) and 30% MAF in wet-season (April–September) are considered as EFs. These two seasons do not have conformity with the hydrological condition of the river. Therefore, it was modified to 10% MAF for August–February as dry-season, and 30% MAF for March–July as wet-season. The results for monthly distribution of flows from the 'modified Tennant method' are presented in Table 4.

In the FDCA method, the environmental requirements were assessed by FDCs of three gauging stations. The values of Q90 and Q95 were considered as EFRs, as shown in Table 4. The 7-day flow with 2- and 10-year return periods were used as common low-flow indices in determining EFRs. Daily discharge data and minimum 7-day moving average for each of the years in the period of 1990–2012 were used to calculate 7Q2&10 (SMADA software). The 2-year and 10-year return period flows were selected for EFRs based on choosing the distribution of log Pearson type III for Derabkay, normal for Grejal and three-parameter log-normal for Pol-Sardasht. The DRM calculates the EFR by considering ecological characteristics of the study area in different ecological management categories. The evaluated EFRs by DRM method (ver. 2) in different management classes are presented in Table 5. In the study area of the Zab River, the ecological class B (i.e. partly modified condition of the river) was selected as EMC.

Calculation of the environmental flows with the FDC shifting method was made using GEFC software (ver. 1). The MMFs of the period of 1974–2012 were introduced to

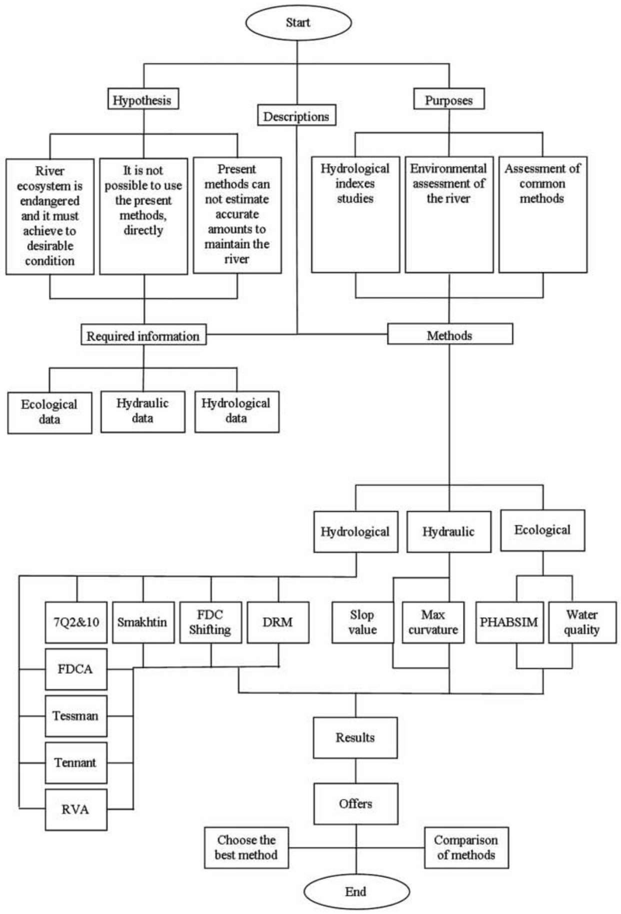

Figure 4 | Step-by-step flowchart for determination of environmental flows in this study (Ahmadipour & Yasi 2014).

this model. The EWRs in each of the three river reaches were investigated based on different ecological classes (class A to class F), and are presented in Table 6. The ecological management class B (i.e. ecologically important rivers despite water resources development) was chosen based on the field study of ecological values of the river, and current water resources development projects. Figure 5 shows typical derivation of the environmental FDCs for different EMCs in the Pol-Sardasht river reach.

The IHA model (ver. 7) was used to calculate EFs by the RVA method. In this model, the effects of each of the three dam reservoirs on regulating the river flows can be investigated. The results showed that the values of MMFs after construction are significantly less than that before the dam operations. The predicted environmental flows from the RVA method at three reaches of the Zab River are presented in Table 4.

The evaluation of EFRs from the two hydraulic approaches (i.e. slope value and maximum curvature methods) is derived based on the relationship between discharge (Q) and wetted perimeter (P) in each of the three river reaches. The hydraulic geometry of the river flows was calculated using the HEC-RAS model, and based on a river survey in 2010. Manning's n-values in the Derabkay, Grejal and Pol-Sardasht reaches were determined to be 0.04, 0.075 and 0.065, respectively. According to the recommendation made by Gippel & Stewardson (1998) and Shokoohi & Hong (2011), the logarithmic relationship was considered, and the best-fitted P–Q equation is presented in Table 7 for each of the three reaches for both slope value and maximum curvature algorithms. The results indicate that the EF values from the maximum curvature approach are more realistic, as those predicted from the slope method are more than the potential MMFs in several months.

Basic ecologic data and hydraulic geometries of the three river reaches are necessary to evaluate the EFRs by the habitat simulation model PHABSIM. In the Zab River ecosystem, the *Barbus capito* fish was selected as the bio-indicator species, for which the required information is provided in Table 3. Accordingly, the variable habitat suitability (WUA) curves were developed by the PHABSIM model for two different periods of spawning and adulthood of the targeted fish. Figure 6 represents the WUA diagram for Pol-Sardasht reach. Spawning condition was considered to present EWRs for the spawning period (April–June), which is critical for the fish life. Adulthood requirement of the fish was considered for the other months (i.e. July–March). As indicated in Table 4, the results from the PHABSIM model do not conform with the potentially available flows in the upper reach Derabkay, but gives reasonable flows through the two other reaches.

The influence of water quality in determining EFs was investigated in the three reaches using the Q equation (Equation (1)). Targeting values of COD were set to adapt to the national standard of surface water quality in Iran and for the key fish (*Barbus capito*). The results are indicated in Table 4.

The overall results of estimating the mean annual environmental flows from different eco–hydraulic–hydrologic methods are summarized in Table 4, and compared with corresponding values reported in the three dams' documents. The minimum flow depth and velocity requirements for the targeted riverine species (*Barbus capito*), the limits of water quality indices, the natural potential of flow regime and the environmental status of river management were considered to offer sustainable monthly environmental flows in these three reaches.

In the Zab upper reach (Derabkay khaneh), the results from the FDC shifting method gives more realistic feature

Table 4 | Estimation of EWRs from different methods and from the dam reports, Zab River

Method		Derabkay		Grejal		Pol-Sardasht	
		EWR (CMS)	MAF%	EWR (CMS)	MAF%	EWR (CMS)	MAF%
FDC shifting	Class A	4.5	68	33.0	75	32.8	74
	Class B	2.3	35	20.2	46	22.1	50
	Class C	1.5	23	16.1	37	16.2	36
	Class D	1.0	15	11.9	27	11.3	25
	Class E	0.7	11	9.0	20	8.1	18
	Class F	0.6	10	7.1	16	6.0	13
DRM	Class A	3.2	48	25.1	57	25.2	57
	Class A/B	2.7	41	20.6	47	20.6	46
	Class B	2.2	33	16.4	37	16.4	37
	Class B/C	1.8	27	12.5	29	13.6	31
	Class C	1.4	21	10.5	24	10.6	24
	Class C/D	1.2	18	8.6	20	8.8	20
	Class D	0.9	13	6.7	15	6.8	15
Modified Tennant	March–July	2.0	30	13.1	30	13.4	30
	August–February	0.7	10	4.4	10	4.4	10
Tessman		3.3	50	20.8	47	23.8	54
Smakhtin		2.7	41	19.1	44	20.8	47
Low-flow index	7Q10	0.3	4.5	4.9	11	4.7	10
	7Q2	0.7	11	7.1	16	7.8	17
FDCA	Q50	6.2	94	37.0	84	36.4	82
	Q70	4.4	67	31.2	71	34.4	77
	Q75	4.3	65	27.1	62	28.0	63
	Q80	3.8	57	23.9	54	25.7	58
	Q85	3.2	48	21.7	50	23.8	54
	Q90	2.5	38	19.1	44	20.8	47
	Q95	2.3	35	16.5	38	19.5	44
RVA	Low RVA	4.4	67	26.8	61	31.1	70
Wetted Perimeter	Slope value	2.9	44	4.5	10	10.4	23
	Max curvature	2.0	30	3.2	7	7.4	16
PHABSIM	April–June	12.0	–	13.9	31	14.2	32
	July–March	3.6	54	5.5	12	5.7	13
Water quality		0.9	13	36.9	84	18.0	40
Constructed-dam reports		2.0	30	9.0	20	4.6	10

Table 5 | Estimation of EFRs as percent of MAF for different EMCs in DRM method, Zab River

River reach	MAF (CMS)	Long-term EFR (percent of MAF) at different EMCs						
		Class A	Class A/B	Class B	Class B/C	Class C	Class C/D	Class D
Derabkay	6.6	48	40	33	27	22	18	14
Grejal	43.8	57	47	37	31	24	20	15
Pol-Sardasht	44.4	56	46	37	30	24	19	15

of the ecological and hydrological conditions. The mean annual flow (MAF) is to be 2.3 m^3/s (equivalent to 35% of MAF) in order to preserve the river in the environmental class B (i.e. the condition of ecological importance of the river despite water resources development and/or basin modification). In the main branch of the Zab River, the

Table 6 | Estimation of EFRs as percent of MAF for different EMCs in FDC shifting method, Zab River

		Long-term EFR (percent of MAF) at different EMCs					
River reach	**MAF (CMS)**	**Class A**	**Class B**	**Class C**	**Class D**	**Class E**	**Class F**
Derabkay	6.6	65	38	23	15	11	9
Grejal	43.8	73	52	37	27	21	16
Pol-Sardasht	44.4	73	52	36	25	18	13

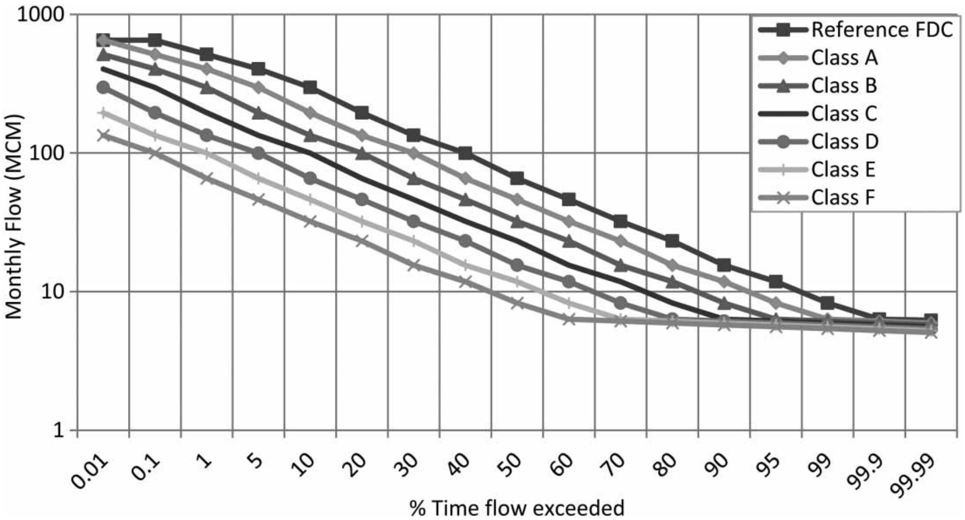

Figure 5 | Environmental FDCs for different EMCs (classes A–F), Pol-Sardasht river reach.

Table 7 | Estimation of EFRs from hydraulic-wetted perimeter method at three river reaches

	Logarithmic fitting		EFR (CMS)	
River reach	**Equation**	**R^2 (%)**	**Slope value**	**Maximum curvature**
Derabkay	$P = 2.29\ln(Q) + 9.2$	98	2.9	2.0
Grejal	$P = 4.52\ln(Q) + 11.6$	96	4.5	3.2
Pol-Sardasht	$P = 10.44\ln(Q) + 7.8$	96	10.4	7.4

results from the hydraulic–ecologic method of PHABSIM are superior considering ecological needs of the habitat representative species (*Barbus capito*), river geometry and flow regime of the two reaches (i.e. Grezhal and Pol-Sardasht). Accordingly, the mean annual environmental flow is to be 7.6 m^3/s (i. e. 17% of MAF) in the middle reach Grezhal, and 7.7 m^3/s (i.e. 18% of MAF) in the downstream reach of Pol-Sardasht.

The potential monthly flow rates are proposed in Table 8, as the suitable threshold for EFRs in these three river reaches. The period of August–October is critical for the river ecosystem, as monthly flows of 5.7 m^3/s are required to flow down the Pol-Sardasht reach in order to preserve the river life. The results indicate that the allocated monthly flow rates in the three dams' steering program are not sufficient to preserve the Zab River life.

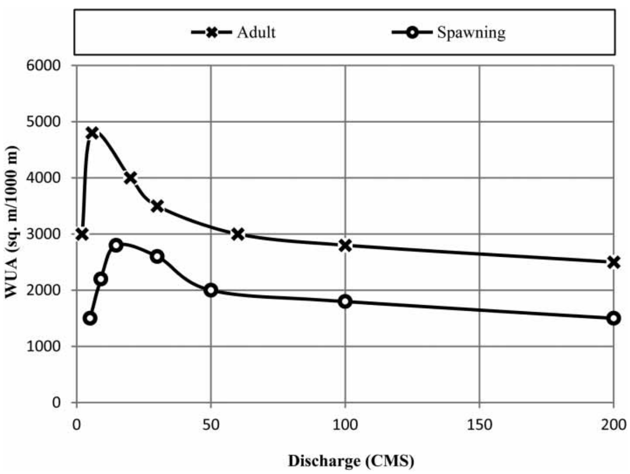

Figure 6 | WUA curves estimated from PHABSIM model, Pol-Sardasht reach, Zab River.

Table 8 | Mean monthly flows and evaluated environmental flows (CMS), Zab River

Reach	EFR	October	November	December	January	February	March	April	May	June	July	August	September	Mean
Upstream (Derabkay)	MMF	0.8	1.6	1.6	1.5	1.3	2.3	7.7	22.1	25.5	10.5	3.0	1.2	6.6
	EFR*	0.4	0.8	0.8	0.7	0.6	1.0	2.3	8.1	8.1	3.6	1.1	0.5	2.3
	EFR**	0.2	0.2	0.3	0.2	0.2	0.3	0.9	7.1	8.9	3.8	1.3	0.7	2.0
Middle (Grejal)	MMF	8.0	17.9	20.7	22.5	25.7	50.3	95.0	113.6	74.1	32.5	12.9	7.7	43.7
	EFR*	5.5	5.5	5.5	5.5	5.5	5.5	13.9	13.9	13.9	5.5	5.5	5.5	7.6
	EFR**	0.9	1.8	1.8	2.6	2.7	5.1	10.8	37.6	26.2	11.5	4.6	2.6	9.0
Downstream (Pol-Sardasht)	MMF	8.1	19.2	1.3	26.0	30.2	63.1	155.8	122.5	81.4	34.8	13.4	7.5	44.4
	EFR*	5.7	5.7	5.7	5.7	5.7	5.7	14.2	14.2	14.2	5.7	5.7	5.7	7.8
	EFR**	3.0	3.0	3.0	3.0	3.0	6.0	10.0	10.0	6.0	3.0	3.0	3.0	4.6

MMF = mean monthly flow (CMS); EFR* = recommended environmental flow in the study (CMS); EFR** = reported environmental flow in the dam reports (CMS).

CONCLUSION

Development of water resources projects are accompanied by several environmental impacts, among them, the changes in the natural flow regime and the reduction of downstream water flow. In this study, the ecological requirements of the Zab transboundary River (in north-west Iran) was investigated in three different reaches along the 160 km length of the river (i.e. upper reach of Derabkay khaneh, middle reach of Grezhal, downstream reach of Pol-Sardasht). The construction of three dams on these three reaches (i.e. Silveh, Kani-Sib and Sardasht dams), the inter-basin transfer of water from the Zab River for restoration of the internationally recognized Urmia Lake, and the preservation of the Zab cross-boundary river were the main concerns in this study.

Eight hydrological, two hydraulic and two habitat simulation methods were used to determine the environmental flows in the Zab River. The mean annual environmental flows predicted from different methods are presented in Table 4. The minimum flow depth and velocity requirements for the targeted species (*Barbus capito* fish), the limits of water quality indices (COD), the potential of natural flow reproduction and the environmental status of river management were considered to offer sustainable monthly environmental flows in these three reaches. The potential monthly flow rates are proposed in Table 8, as a suitable threshold for EFRs in these three river reaches.

It is considered that there is no unique and universal method to adapt to different rivers and/or different reaches in a river. In the Zab upper reach, the FDC shifting method adapts well with the eco-hydrological features of the river, while the eco-hydraulic method of PHABSIM is superior for the conditions of the middle and downstream reaches. The environmental MAF is higher at the upper reach (equivalent to 35% of MAF), due to lower base flows, and falls between 17 and 18% of MAF at downstream reaches. The period of August–October is critical for the river ecosystem. The results indicate that the allocated monthly flow rates in the three dams' operational programs have to be increased to provide sufficient support for the Zab River life.

Similar studies and experiments in the region denote that an order of 20–40% of MAF is to be considered for the EFRs of a river system, and for preserving the river ecological values within the class B–C. The larger portion goes to smaller rivers and/or rivers with lower base flows, and also to rivers with environmental and/or recreational importance. It is noted that minimum flow requirements are to be allocated in critical months of the year or during the drought period of the river basin. Water leasing from agricultural users is an option or a necessary action whenever long-term environmental damages to the river ecosystem must be avoided.

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