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Hydrological based environmental flow assessment methods (Case study: Gharasou River, Ardabil)

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ABSTRACT

Water flow management is one of the most important parts of river engineering. Non-uniformity distribution of rainfall and various flow demand with unreasonable flow management will be caused destroyed of river ecosystem. Then, it is very serious to determine ecosystem flow requirement. In this paper, four hydrological based environmental flow assessment methods have been used to calculate environmental flow in Gharasou River, Ardabil, Iran as following: Flow duration curve indices method, Range of variability approach, Tessman method, and Global environmental flow calculator. In the first method, Q90 and Q95 for different return periods were calculated. Their magnitude were determined as 1-day, 3-day, 7-day and 30 day. Accordingthe second method, hydraulic alteration indices often had low and medium range. In order to maintain river at an acceptable ecological condition, July based flow was selected as environmental flow, i.e. 15 m^3s^{-1}. Using Tessman method, minimum and maximum values of monthly environmental flow was estimated 1.8 and 13.72 m^3s^{-1}, respectively. Based on the last method, seven scenarios were studied. Of all scenarios, scenario C indicates moderate situation of ecological habitat of river. according to calculations, the amount of the C scenario was determined as 6 m^3s^{-1}.

Key words : *Environmental flow, Hydrological methods, Gharasou River, Ardabil.*

Introduction

Alteration to the natural flow regimes of rivers and streams is considered a major threat to the health of waterways, aquatic flora and fauna communities and the maintenance of essential instream ecosystem processes (SAC, 1992). The construction of dams and subsequent downstream changes to both flow and sediment regime is one of the most profound anthropogenic impacts upon river ecology. Changes to the hydrologic regime include a decrease in flow volume, decrease in the magnitude, frequency and duration of flood discharges, a reduction and/or attenuation in seasonality of flows and change in the variability and predictability of flows (Poff *et al.*, 1997; Rose, 1999). Goals of inflow management extend from preservation of the extant aquatic system to its enhancement, and occasionally include restoration of the ecosystem that existed prior to human impacts. Such management goals require a means of determining the requisite environmental flows, based upon stream hydrology and the responses of aquatic organisms to their hydrological environment. Worldwide, an imposing literature has developed addressing various aspects of the technical problem of establishing a cause-and-effect connection of specific classes of organisms to specific characteristics of the hydrology of a stream (Arthington *et al.*, 2006; Tharme, 2003; Whiting, 2002; Petts, 1996).

The methods of environmental flow assessment are categorized in four groups which hydrological (desktop estimates) group is one of them. This method is the most simple environmental flow

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methodologies which have been used globally. They are often referred to as desktop models and rely primarily on the use of hydrological data, usually in the form of historical flow records, for making EFRs. The results are often presented as a minimum required flow to maintain the ecological status at some acceptable level. There are numerous methodologies in hydrological group as: Rapid Reserve Determination, Flow Duration Curves percentiles (FDCs), Range of Variability approach (RVA), VHI, BWE, Ecotype-based Modified Tennant Method (Tharme, 2003).

One of the common hydrological method is Flow Duration Curve (FDC) which is a convenient way of presenting hydrological frequency characteristics of a river flow.It is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded, or in other words-the relationship between magnitude and frequency of stream flow discharges.

FDCs are widely used in hydrological practice. Vogel and Fennessey (1994) refer to several early studies related to the theory and application of FDC (Vogel and Fennessey, 1994). Searcy (1959) was possibly the first to summarize a number of FDC applications including the analysis of catchment geology on low flow, hydropower and stream water quality studies (Searcy, 1959). Male and Ogawa (1984) advocated the use of FDCs in the evaluation of the trade-offs among various characteristics involved in determination of the capacity of waste-water treatment plants including flow, flow duration, water quality requirements and costs (Male and Ogawa, 1984). Alaouze (1989, 1991) developed the procedures based on FDC, for estimation of optimal release schedule from reservoirs, where each release has a unique reliability (Alaouze, 1989 and 1991). Estes and Osborn (1986) and Gordon *et al.*, (1992) illustrated the use of FDC for the assessment of river habitats in estimation of instream flow requirements (Alaouze, 1991). Hughes *et al.*, (1997) developed an operating rule model which is based on FDCs and is designed to convert the original tabulated values of estimated ecological instream flow requirements for each calendar month into a time series of daily reservoir releases (Estes and Osborn, 1986). A review of numerous possible applications of FDCs in engineering practice, water resources management and water quality management is given by Vogel and Fennessey (Vogel and Fennessey, 1995).

Range of Variability Approach (RVA) has been developed by Rutcher *et al.*, (1996, 1997, 1998) to establish flow based river management targets. This method is based on the concept of natural hydrologic variability. The RVA includes thirty-two hydrological parameters which called indicators of hydrologic alteration (IHAs). These parameters are employed to assess anthropologic flow alteration in terms of magnitude, timing, frequency, duration, and rate of changes (Shiau and Wu, 2004).

Global Environmental Flow Calculator (GEFC) is a software package for desktop assessment of Environmental Flows (EFs) incorporating an in-built global database of simulated flow time series. It is widely known that the ecological integrity of river ecosystems depends on their natural dynamic character, maintaining natural flow patterns in rivers is normally impossible due to 274 water resources development and catchment land-use changes. Considering this, environmental flows do not necessarily require restoring the natural, pristine flow patterns but, instead, are intended to produce a broader set of values and benefits from rivers than from management focused strictly on water supply, energy, recreation, or flood control. Environmental flows should therefore be seen as a compromise between river basin development and maintenance of river ecology and considered as means of maintaining an ecosystem in, or upgrading it to, a desired future state through selection of environmental management class and a complementary strategy (Smakhtin and Eriyagama, 2008).

According to the lockage of related information, four above mentioned hydrological methods were used to evaluate environmental flow in Gharasou River, Ardabil, Iran (Fig. 1).

Materials and Methods

Flow Duration Curve indices method

Flow duration curve is a graphical presentation of river discharge from low flows to flood events. On the other hand, it shows the relationship between magnitude and frequency of flow discharges. Various indices may be extracted from FDC. The flows within the range of 70-99% time exceedence are usually most widely used as design low flows. Design low flow range of FDC is in the 70% to 99% range or the value of probability of exceedance corresponding to the Q70 to Q99 range. According to Table 1,

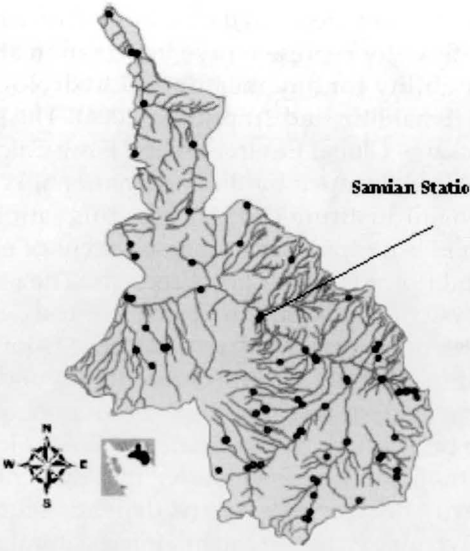

Fig. 1. Gharasou catchment and Samian hydrometric station

Q95 and Q90 flow indices have been used globally by researchers for various cases. In this method, FDC is developed for various return periods using the characteristics of distribution of probability plots of stream, calculated by the Weibull plotting formula, at suitable time intervals from 0 to 100 percent on the time axis.

The following steps are considered for this approach:

1. After construction of an FDC for each year, read values of daily discharge at every 5% probability of exceedance.
2. Make separate Table for each year discharge versus probability of exceedance.
3. Rank discharge values in ascending order and read from each flow duration curve of a given N year term.
4. Calculate the plotting position with the following Weibull plotting formula, select the type probability paper to be used, and plot the data on the probability paper:

$$P=\frac{m}{N+1}\times 100$$

Where P is the probability of all events less than or equal to a given discharge value, m is the rank of the event, and N is the number of events in the record.

5. Visually fit a straight line through the estimated values.
6. Using a straight line equation, get the discharge value down from the best fit line for the chosen probability value for various return periods (1

Table 1. Application of Q90 and Q95 flow indices to assess environmental flow

Index	Application	Researchers
Q95	Commonly used low flow index or indicator of extreme low flow conditions	Riggs *et al.*, (1980), Brilly *et al.*, (1997), Smakhtin (2001), Wallace and Cox (2002), Tharme (2003)
	Minimum flow to protect the river	Petts (1996)
	Minimum monthly condition for point discharges	Michigan Department of Environmental Quality (2002)
	Licensing of surface water extractions and effluent discharge limits assessment	Higgs and Petts (1988), Smakhtin and Toulouse (1998)
	Biological index for mean monthly flow	Dakova *et al.* (2000)
	Used to maintain the natural monthly seasonal variation used to optimize environmental flow rules	Stewardson and Gippel (2003)
Q90	Commonly used low flow index	Smakhtin *et al.* (1995), Smakhtin (2001)
	Monthly value provides stable and average flow conditions	Caissie and El-Jabi (1995)
	Monthly value gives minimum flow for aquatic habitat	Yulanti and Burn (1998)
	Used to examine discharge-duration patterns of small streams	Ogunkoya (1989)
	Threshold for warning water managers of critical stream flow levels	Rivera-Ramirez *et al.* (2002)
	Describes limiting stream flow conditions, and is used as a conservative estimator of mean base flow	Wallace and Cox (2002)

year, 2 year, 5 year, 10 year, 20 year, 50 year and 100 year).

7. Repeat steps 3 to 6 at suitable time intervals from 0 to 100 percent of the time axis (in the present case it is taken at every 5%).
8. Plot probability daily discharge values read at suitable intervals and draw a smooth FDC of return period of 1 year, 2 year, 5 year, 10 year, 20 year, and 50 year.

Range of Variability Approach (RVA)

RVA is Indicators of Hydrologic Alteration (IHA) method to assess hydrologic regime alteration. The objective is to restore or maintain the natural hydrologic regime of a river for settingechological management targets. The hydrologic alteration index (H.A.I. in percentage) is calculated by:

$$H.A.I = \frac{N_{Observed} - N_{Expected}}{N_{Expected}} \quad .. (1)$$

Where $N_{Observed}$ and $N_{Expected}$ are the number of years in which the corresponding observed and expected values of the hydrologic parameter fall within the targeted range, respectively. H.A.I. is equal to zero when the observed frequency of post-impact annual values falling within the RVA target range equals the expected frequency. Hydrologic Alteration Index (H.A.I.) is classified as: High (H), if H.A.I be greater than 67%, Medium (M), if H.A.I. belongs to 34-66%; and Low (L), if H.A.I. be less than 33%.

Tessman Method

Tessman adapted Tennant's seasonal flow recommendations based on mean monthly flows (MMF) as well as MAF. The specific monthly Tessman recommendations are as: if MMF <40% of MAF, then Minimum Monthly Flow equals the MMF; for MMF > 40% MAF and 40% MMF < 40% MAF, then Minimum Monthly Flow equals 40% MAF; and if 40% MMF >40% MAF, then Minimum Monthly Flow equals 40% MMF. Tessman also recommends a two-week period of 200% MAF during the month of highest runoff for flushing.

Global Environmental Flow Calculator (GEFC)

GEFC is a desktop method to assess environmental flow. In desktop approaches as a basic means of computing environmental flow requirements, monthly observed or modeled time-series data are assessed together with corresponding flow duration curves (FDC) provided that the monthly data would carry sufficiently representative information about flow variability for any meaningful hydrological analysis (Smakhtin and Anputhas, 2006). The software package, Global Environmental Flow Calculator (GEFC), developed by the International Water Management Institute (IWMI) uses this rationale and provides a rapid desktop assessment of environmental flows from monthly records. The objective ecosystem conditions are described in six environmental management classes ranging from unmodified to critically modified conditions, and the management class best suited for the river in question is to be selected in environmental flow calculations. Although it is widely known that the ecological integrity of river ecosystems depends on their natural dynamic character, maintaining natural flow patterns in rivers is normally impossible due to water resources development and catchment land-use changes (Smakhtin and Eriyagama, 2008). Considering this, environmental flows do not necessarily require restoring the natural, pristine flow patterns but, instead, are intended to produce a broader set of values and benefits from rivers than from management focused strictly on water supply, energy, recreation, or flood control. Environmental flows should therefore be seenas a compromise between river basin development and maintenance of river ecology and considered as means of maintaining an ecosystem in, or upgrading it to, a desired future state through selection ofenvironmental management class and a complementary strategy (Smakhtin and Anputhas, 2006; Smakhtin and Eriyagama, 2008).

Results and Discussion

Daily flow discharges were used to develop flow duration curve and to generate flow requirements in Samianstation. Figs. 2 to 5 shows the results of FDC indices method. Using Weibul plotting formula, no results were obtained for flow index Q95 for 30-day and flow indices Q90 and Q95 for 90-day. In these figures, linear trendline has had acceptable correlation coefficient. As it clear, good agreement has been occurred in low return periods u to 5 years. On the other words, these relations can estimate environmental flow in mean situation of river. According to fitting curve equation, the magnitude of the low flow indices for different return periods are presented in Table 2.

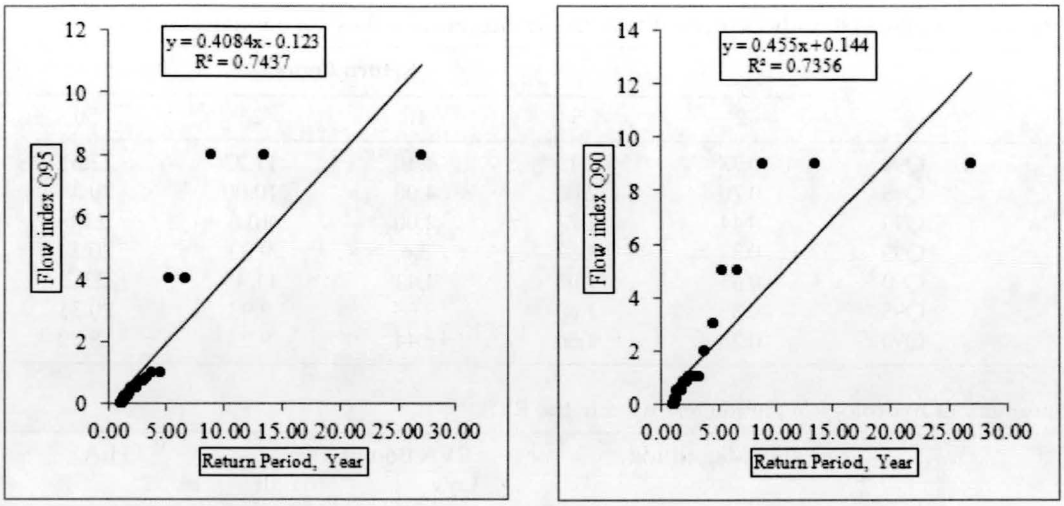

Fig. 2. Return period vs. flow indices Q95 and Q90 for daily discharge

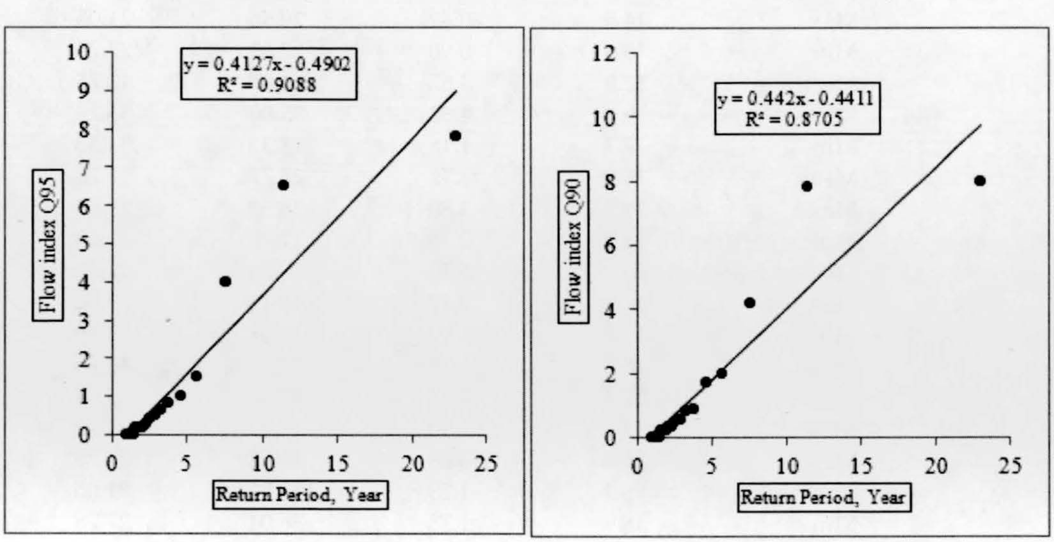

Fig. 3. Return period vs. flow indices Q95 and Q90 for 3-day discharge

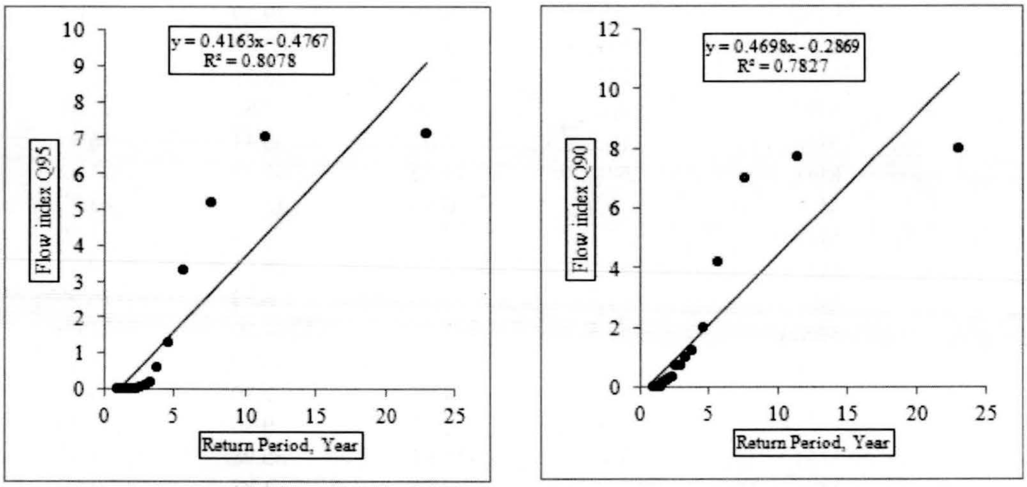

Fig. 4. Return period vs. flow indices Q95 and Q90 for 7-day discharge

Table 2. The results of the FDC indices method to assess environmental flow for Samian station

		Return Period					
		2	5	10	25	50	100
1-day	Q90	0.77	2.13	4.40	11.23	22.61	45.35
	Q95	0.70	2.00	4.00	10.00	20.30	40.70
3-day	Q90	0.44	1.77	4.00	10.6	21.6	43.75
	Q95	0.33	1.57	3.6	9.83	20.14	40.8
7-day	Q90	0.65	2.00	4.41	11.45	23.2	46.7
	Q95	0.35	1.60	3.68	9.93	20.34	41.15
30-day	Q90	0.35	1.50	3.44	9.23	18.90	38.15

Table 3. Summery of hydrological parameters used in the RVA

Month	Monthly Magnitude		RVA Boundaries		I.H.A.	Class
			Low	High		
October	Mean	7.0	0.10	13.88	27.78	L
	Max	14.5	-0.42	29.56	21.05	L
	Min	3.4	-0.90	7.63	27.78	L
November	Mean	12.9	3.87	21.87	43.75	M
	Max	19.8	4.62	35.00	35.29	M
	Min	7.2	1.16	13.31	53.33	M
December	Mean	16.3	3.75	28.77	27.78	L
	Max	21.2	3.80	38.52	21.05	L
	Min	12.2	2.58	21.77	21.05	L
January	Mean	16.0	5.32	26.73	27.78	L
	Max	21.8	3.20	40.43	9.52	L
	Min	11.8	4.00	19.64	43.75	M
February	Mean	18.8	4.28	33.32	43.75	M
	Max	27.1	7.11	47.06	35.29	M
	Min	13.5	2.90	24.03	64.29	M
March	Mean	34.3	-0.86	69.53	21.05	L
	Max	56.2	-1.23	113.57	21.05	L
	Min	18.9	1.73	36.04	27.78	L
April	Mean	45.0	6.55	83.39	35.29	M
	Max	89.3	-1.28	179.95	21.05	L
	Min	23.0	-3.42	49.39	91.67	H
May	Mean	38.0	8.55	67.36	27.78	L
	Max	77.3	28.44	126.23	43.75	M
	Min	16.1	-1.28	33.50	21.05	L
June	Mean	18.2	3.07	33.41	76.92	H
	Max	54.4	19.12	89.64	91.67	H
	Min	5.9	-0.98	12.76	43.75	M
July	Mean	3.1	-0.30	6.44	21.05	L
	Max	12.9	-2.71	28.61	9.52	L
	Min	1.1	-1.33	3.53	15.00	L
August	Mean	1.8	-1.01	4.70	21.05	L
	Max	4.7	-3.66	13.09	15.00	L
	Min	0.9	-1.07	2.89	15.00	L
September	Mean	4.2	-1.43	9.90	21.05	L
	Max	18.2	-19.61	55.98	9.52	L
	Min	0.7	-0.51	1.83	21.05	L

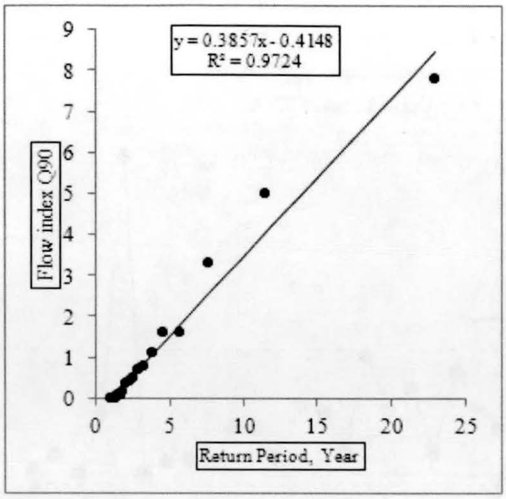

Fig. 5. Return period vs. flow index Q90 for 30-day discharge

The RVA method has been applied for monthly flow discharge analysis. The magnitude of mean, maximum and minimum of flow discharge and IHA index for each month was calculated. According to IHA, each month variation was classified which the results are presented in Table 3.

In the absence of supporting ecological information, ±1standard deviation (SD) from the mean values of the parameters was used as the environmental flow targets for each of the parameters. As it clear, minimum and maximum magnitudes of IHA index belong to July and June, respectively. Figures 6 and 7 show the alteration of monthly discharges for June and July. Then, the amount of environmental flow should be determined according to the minimum of the RVA; on the other word July is base for environmental flow assessment. It is convenient to select the minimum value of the monthly discharge of July for the other months, i.e.,15 $m^3.s^{-1}$.

Table 4 illustrates the Tessman method to assess environmental flow. Minimum and maximum values of monthly environmental flow are equal to 1.8 and 13.72 $m^3.s^{-1}$, respectively.

Figure 8-A to 8-F show the monthly magnitude of environmental flow according to 7 scenarios. These scenarios are presented at the following:

- Scenario A: pristine condition or minor modification of in-stream and riparian habitat
- Scenario B: largely intact biodiversity and habitats despite water resources development and/or basin modification
- Scenario C: the habitats and dynamics and biota have disturbed, but basic eco system functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.
- Scenario D: large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail.
- Scenario E: habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.
- Scenario F: modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible.

The amount of Mean Annual Runoff (MAR) is

Table 4. Estimation of environmental flow using Tessman method

Month	Mean discharge ($m^3.s^{-1}$)	Mean Annual flow($m^3.s^{-1}$)	Environmental Flow Requirement($m^3.s^{-1}$)
October	7.0	17.9	1.8
November	12.9		7.16
December	16.3		7.16
January	16.0		7.16
February	18.8		7.52
March	34.3		13.72
April	45.0		18
May	38.0		15.2
June	18.2		7.28
July	3.1		1.8
August	1.8		1.8
September	4.2		1.8

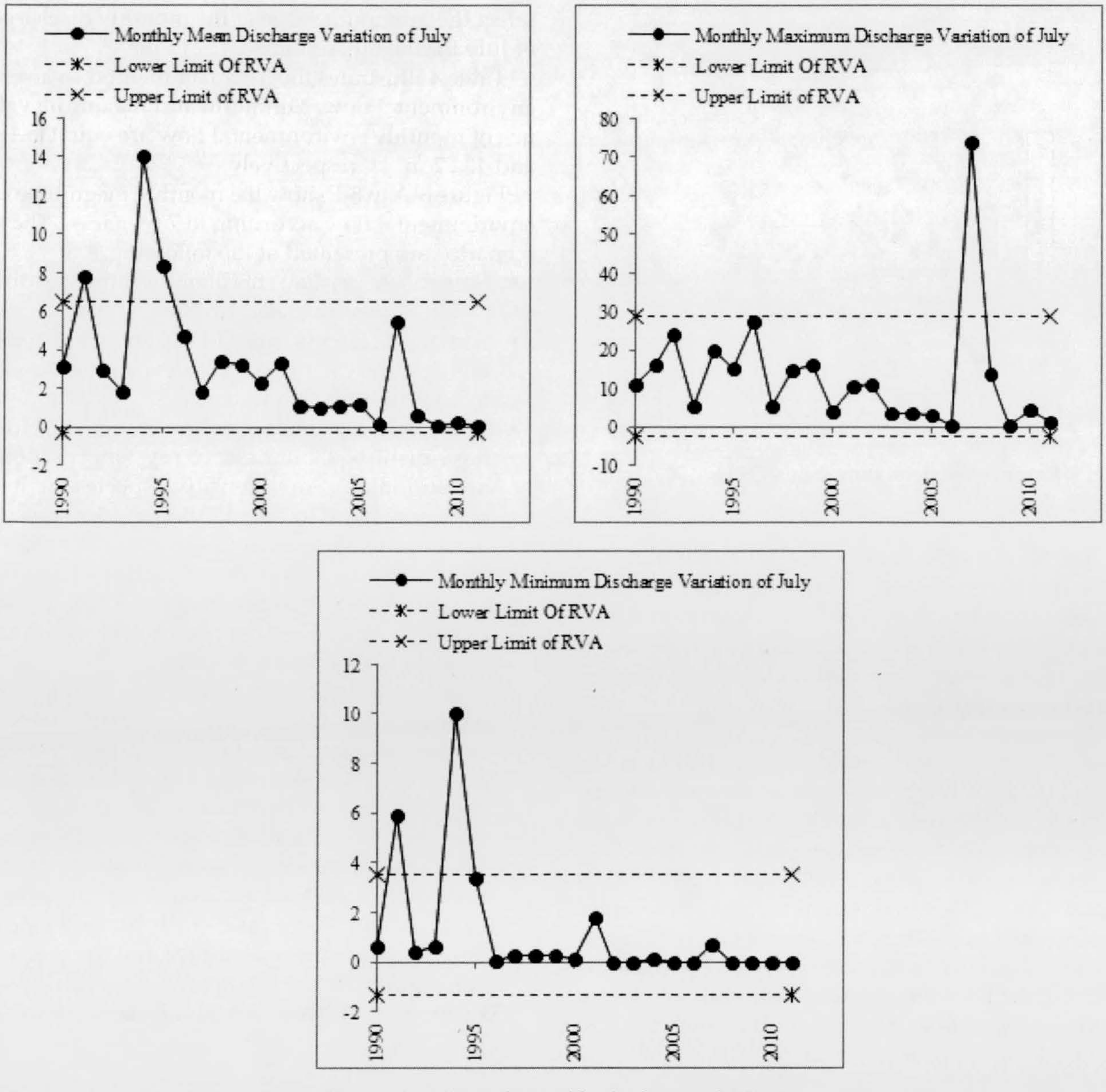

Fig. 6. Alteration of monthly discharges for June

equal to 558.9 (MCM). Fig. 8-A is correspond to scenario A. This scenario is names as Natural regime. According to calculations, 74% of MAR is determined for scenario A, i.e.413.586(MCM). On the other words, the mean value for each month is equal to 13.3 ($m^3.s^{-1}$).

Scenario B, which is named as Slightly Modified, is presented in Fig.8-B. For this scenario, 49.6% of MAR is dedicated, i.e, 277.2144(MCM). The mean value for each month for scenario B is equal to 8.91($m^3.s^{-1}$).

Moderately Modified Regime which is presented in Fig.8-C is graphical presentation of scenario C. The percent of MAR for this scenario is 33.5%, i.e. 187.23(MCM). The average magnitude for each month of each month is 6 ($m^3.s^{-1}$).

The forth scenario is called Largely Modified. It is presented in Fig. 8-D. The calculations determine 23% of MAR for it, i.e. 128.547(MCM). Then, the mean value for each month of scenario D is 4.13($m^3.s^{-1}$).

According to scenario E, habitat diversity and

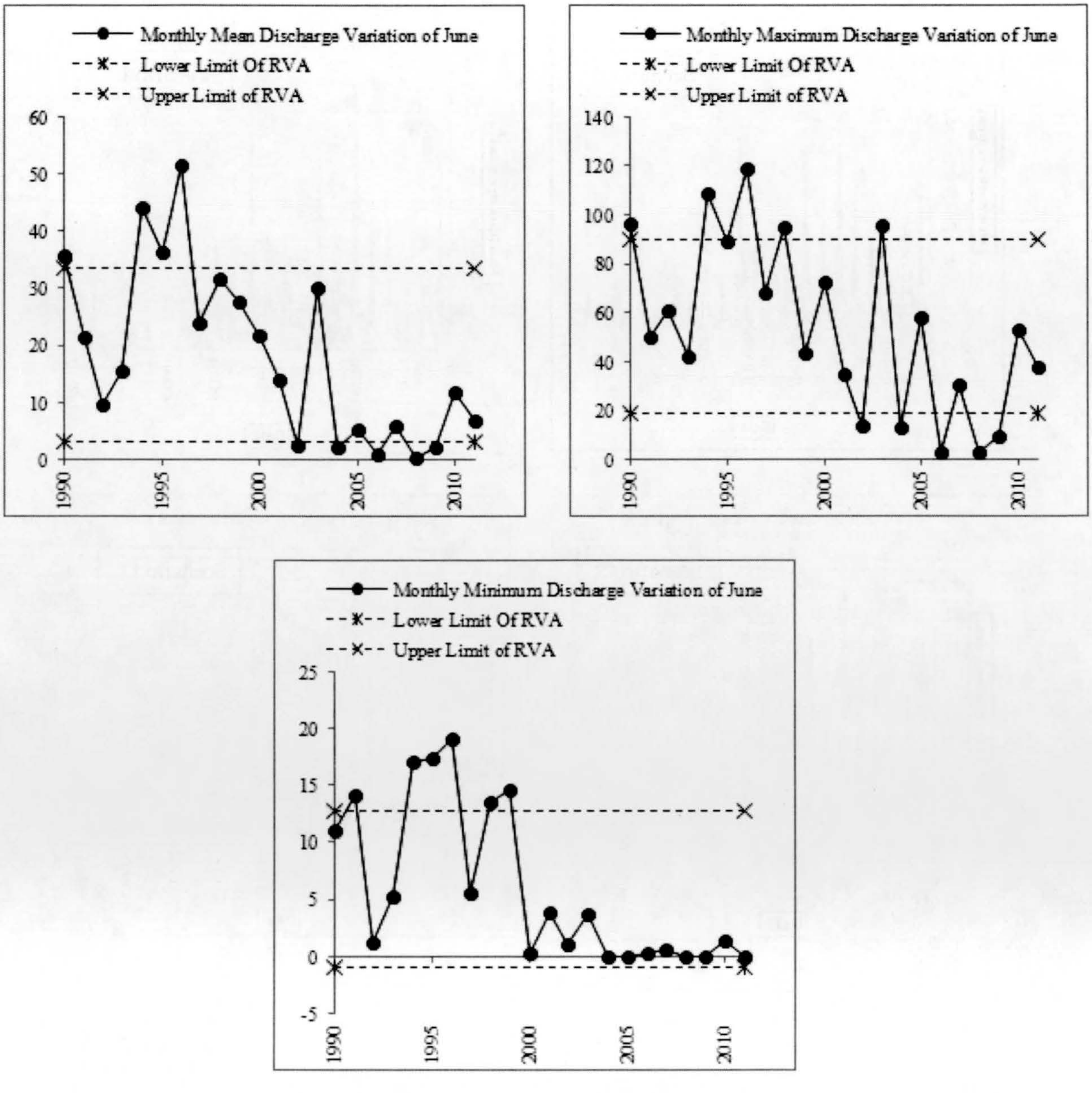

Fig. 7. Alteration of monthly discharges for July

availability have declined. A strikingly lower than expected richness.Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem. Amount of 15% of MAR is selected as mean monthly environmental flow for this scenario; i.e., 2.65 m^3s^{-1}.

In the last scenario, modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitats and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible. In this scenario, the percent of MAR is 10.4%, or on the other words mean monthly environmental flow is 1.84 m^3s^{-1}.According to these seven scenarios, flow duration curve is plotted in Fig. 9.

Conclusion

In this paper, four hydrological based methods have

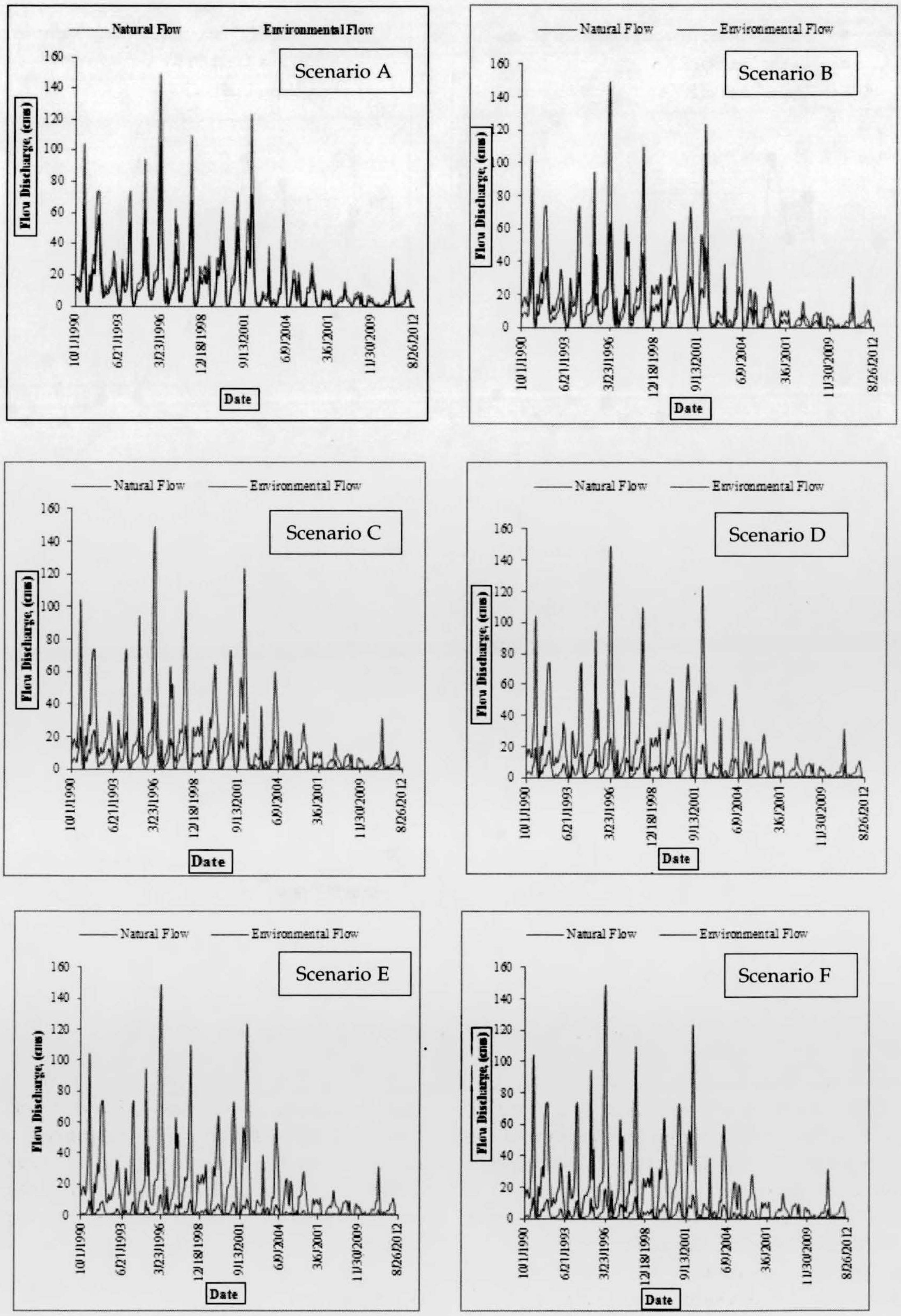

Fig. 8. Monthly environmental flow magnitude according to seven scenarios

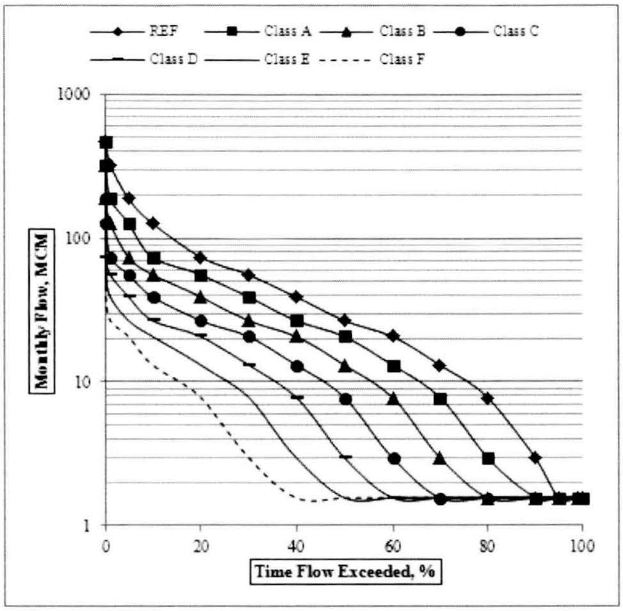

Fig. 9. Flow duration curve corresponding to environmental management classes

been applied to calculate environmental flow in Gharasu River, Samian station, Ardabil, Iran as following: Flow duration curve indices method, Range of variability approach, Tessman method, and Global environmental flow calculator. Q90 and Q95 with different return periods are two indices which are used widely to evaluate environmental flow. Based on this indices, different values of environmental flow was calculated. The RVA method is based on 32 variables which describe river flow conditions. These parameters were extracted and finally, July's based flow was selected as amount of environmental flow for other months. The amount of environmental flow was determined as 15 m^3s^{-1}. The third method was Tessman.This method which is based on mean monthly flows, proposed monthly environmental flow as a percent of mean annual flow. According to this method minimum and maximum monthly of environmental lfow were calculated as 1.8 to 18 m^3s^{-1}. The last approach which was used here, was Global Environmental Flow Calculator which is based on seven flow management scenarios. Each scenario is a percent of annual mean flow. In this paper, scenario C was selected because it is describe moderate situation of river ecosystem. Amount of environmental flow in this scenario was calculated as 2.65 m^3s^{-1}.

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