Implementation of flow duration curves for evaluating the environmental flow

LAGOGIANNIS S.[1,*], BOURNAS A.[1], HATZIGIANNAKIS E.[2] and BALTAS E.[1]

[1] Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, 5 Iroon Polytechniou, 157 80, Athens, Greece;
[2]Soil and Water Resources Institute, ELGO-DEMETER (ex NAGREF), Sindos 57400, Greece

*corresponding author:
e-mail: sergioslagogiannis@gmail.com

Abstract In this research work, the implementation of Flow Duration Curves (FDC) was assessed, as a mean of estimating the environmental flow (e-flow) in rivers segments in Greece. The FDC of fifteen river basins varying in size and geomorphological characteristics and covering a wide area of mainland Greece, were derived by using high quality monthly discharge measurements of two years period. The e-flows were first calculated by applying the current Greek regulation method, which makes use of measurements of only the summer and September months, and by relating the e-flow as a percentage of the Mean Annual Flow (MAF). The e-flows were then plotted upon the FDC and compared with specific quartiles. The results show that the e-flows calculated by both the Greek regulation methodology and the 10% of MAF are a very good approximation of the 90% quantile of the FDC (Q_{90}) while the 30% MAF falls very close to the 70% quantile (Q_{70}). Therefore this study suggests that the Q_{90} could be used insted of the Greek regulation method, as it produces quite similar but safer (higher) discharge values. It was also indicated, that a strong correlation of 10% MAF to Q_{90} and 30%MAF to Q_{70} exists.

Keywords: Flow duration curves, environmental flow, ecological flow, basic flow, Q_{90}

1. Introduction

As increasing human water demands compete with varying water allocation needs and ecosystem reservation, water resources management is confronted with serious challenges (Arthington et al., 2018). Growing human population, degradation of ecosystems and uncertainty from climate change effects are noted as major impacts on the hydrologic cycle (Ward et al., 2019; Curtis, 2020). In recent decades there has been a considerable shift of interest in management of water resources, towards the provision of e-flows as a mean of protecting, preserving and restoring riverine ecosystems (Petts, 2009; Poff, 2018). This trend has also significantly affected the water science and engineering community and led to the application of numerous hydrologic tools, in order to address the issue. Hydrological methods have proved to be, the most commonly used techniques for environmental flow assessment (EFA). In Greece a legislative framework for the definition of ecological supply has been established since 2008, as the country complied with the requirements of EU Directive 2000/60, on the sustainable management of water resources. The Greek regulation is a hydrological method, which is based on calculating discharge as a percentage of certain months flow. However, the quite often absence of hydrometric data and the limited amount of case specific work on assessing e-flows in Greek rivers, has hindered the quantitative evaluation of the Greek regulation for EFA. As a consequence, the validity of the Greek regulation method is not yet fully assessed.

For this evaluation, the FDC and resulting well established low-flow indices were used. An FDC is a cumulative frequency curve over the whole range of discharges recorded over a specific time period (Searcy, 1959). It illustrates the percent of time a certain discharge was equaled or exceeded over a certain time period. FDCs are a simple and powerful tool widely used in hydrological practice. They have a long application history over water management problems and are often used in hydrologic or other environmental issues (Viola et al., 2011). Many low-flow indices can be estimated from the "low-flow" section of the FDC and more specifically from the 70-99% range. The indices Q_{70}, Q_{90} and Q_{95} indicating the discharge exceeded 70%, 90% and 95% of the time, are commonly used as design low-flows from different countries (Tharme, 2003).

In addition, the Tennant (1976) method was also implemented on the available field data measurements and evaluated, on the premise that it is the most widely used hydrological method and that it has a very similar to the Greek regulation way of EFA. The Tennant method is quite simple, as it assumes that maintaining a percentage of the mean annual flow of the river is enough to avoid degradation of the river ecosystem and was developed from an empirical base of many small US streams. The 10% and 30% MAF were estimated and examined for the purpose of this study.

This study aimed at evaluating the validity of these EFA methods, namely the Greek regulation and the 10% and 30% MAF, for Greek rivers. This study examined the relationship between these hydrologic EFA methods (Greek regulation, 10% MAF, 30% MAF) to established low-flow indices. At first, this comparison enabled the evaluation of the Greek regulation method and secondly specified the applicability of the Tennant method in Greek rivers.

2. Study Area & Data Used

This research study was based on the analysis of primary (raw) field data, spanning over a two-year period from April of 2018 until December of 2019, of gauging sites covering the most part of mainland Greece. For each month a unique value was recorded over stage and discharge, totaling 21 measurements per site. In the absence of more measurements, these unique values were treated as indicative mean values for each month. Audit of the datasets excluded all gauging sites with heavily regulated flow regimes, sites with frequent cross-section alterations, sites with insufficient number of measurements and sites in transboundary rivers that do not originate from Greece. Finally, 15 sites were selected (Figure 1), with a high number of good quality measurements and significant geomorphological variation.

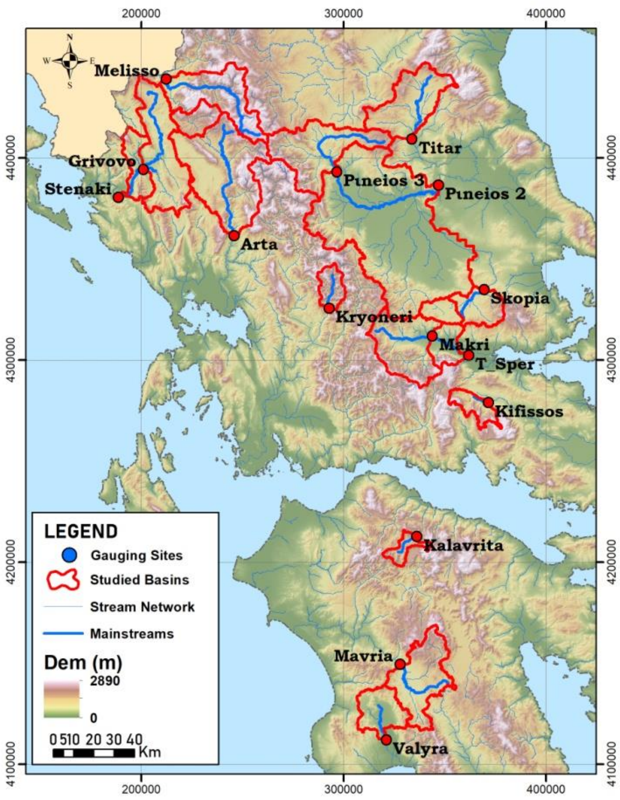

Figure 1. Geographical location of gauging sites and their subbasins.

The selected sites were distributed over a wide range of mainland Greece, occupying six different River Basin Districts (RBD). Four of them Arta, Stenaki, Gribovo and Melisso are located in the RBD of Epirus, in the north-western part of Greece. Three of them Kalavrita, Mavria and Valyra are located, in the southern part of Greece, the first in Northern Peloponnese RBD and the latter two in the Western Peloponnese RBD. Another cluster of 4 sites Pineios_2, Pineios_3, Titar and Skopia is located in the RBD of Thessaly. The remaining four sites fall within the prefecture of Sterea Ellada; Makri, T_Sper and Kifissos in the Eastern Sterea Ellada RBD and Kryoneri in Western Sterea Ellada RBD. All gauging sites included in the Thessaly and Sterea Ellada RDBs, occupy locations in central Greece. The subbasins defined for each gauging site varied greatly in their geomorphological characteristics: catchment areas, river length, mean elevation and geology.

3. Methodological Framework

The Greek regulation, is a hydrological method of EFA and defines three different processes for calculating discharge: a) 30% of the average supply of the summer months June - July – August, b) 50% of the average supply for the month of September and c) 0.03 m^3/s at least, in each case. These three values are to be compared and the biggest value should be regarded as the recommended e-flow, according to Greek regulations.

The Tennant method uses historical hydrological data to estimate ecological supply and is based on the concept of relating percentages of MAF with different ecological conditions of the river. The average discharge was calculated for each of the two years of records. Then the mean of the two was assumed as the mean annual flow for each site. From this value, the designated percentages of 10% and 30% were acquired.

The process of creating the FDCs requires that recorded discharges are gathered and sorted in a decreasing order of magnitude and subsequently a rank value is assigned to each discharge, starting with 1 for the largest value. FDC can be developed for different time resolutions and the choice is a matter solely depending on the streamflow data available and the time scale of interest, in each case. In this study, the available monthly values were treated as indicative mean values for each month and defined the time resolution of the FDCs that were developed. The exceedance probability was finally calculated for each value of discharge.

The correlation coefficient, *r*, and Root Mean Square Error (RMSE) were used to examine the relationship of each of the three different implemented EFA methods to the FDC low-flow indices. The correlation coefficient is measured on a scale from -1 to +1, with values closer to ±1 indicating high correlation and values closer to 0 indicating absence of correlation. Higher *r* values between the discharge estimated from an EFA method and one of the low-flow indices would indicate a better approximation of that index.

RMSE was also used as a goodness-of-fit measure. It would provide a measure of the error of the estimation for each of the EFA methods implemented in this study. RMSE has the same units as the dependent variable, with values closer to 0 indicating a smaller error and therefore a better approximation.

4. Results & Discussion

Discharge values according to the three EFA methods (Greek regulations, 10% MAF, 30% MAF) were calculated and then projected to the low-flow section of the FDCs to investigate their relationship with established low-flow indices of the FDCs. It was found that both the Greek regulation and the 10% MAF were, as average values, a very good approximation to the Q_{90} index, with the Greek regulation method showing a strongest correlation with the Q_{90}. Furthermore, it was found that, when the estimated discharge based on the Greek regulation method was compared to the Q_{90} values, they produced a RMSE of only 1.75 m^3/s, while the respective error for the 10% MAF discharge values was 3.21 m^3/s, which was almost the double. In addition, the discharge values from the Q_{90} index and the Greek regulation method showed a higher correlation, r, of as high as 0.88, while that of the 10% MAF to the Q_{90} index being 0.63.

Concerning the discharge values calculated based on the Greek regulation method, for all sites, the corresponding range was found to be between the 60.5% and the <95% exceedance probability of the FDCs, as seen in Table 1. Their estimated average FDC percentile value was 88.2%, a very good approximation of the Q_{90}. Likewise, the discharge values calculated with the 10% MAF method, were also within the same range but with a slightly lower average value of FDC percentile, at 86.7%, a producing also a good approximation of the Q_{90} index. However, this observation concerns the average of the discharge values of all sites for each method. Instead, when each site was examined separately, the discharge values according to the Greek regulations, varied to some certain extent, with some values producing higher values (Figure 2a), others equaling the Q_{90} discharge (Figure 2b, 3c) and others producing lower values (Figure 2d). It was found that in 7 out of 15 sites, the suggested discharge values had an equal or higher value than the 95% exceedance probability. As a consequence, the estimated e-flow with that method would be lower than the expected discharge value based on the Q_{90} thus using a lesser environmentally friendly value. For that reason, it is suggested that the Q_{90} is a safer, more environmentally friendly, alternative, since it would produce similar, i.e. values of the same range, but safer, i.e. higher, discharge values. The above finding was also observed in the 10% MAF method, in which in 5 out of 15 sites, the suggested discharge values had an equal or higher value than the 95% exceedance probability, as well.

Finally, the examination of the 30% MAF indicated that this method lies in a different value range from the other two EFA methods. It seems that in this case, there were strong indicators that the results were better linked to the Q_{70} index of the FDCs. Concerning the discharge values estimated for the 30% MAF method, their exceedance probability ranges between 41.1% and over 95% when plotted in the FDCs. This wide range, makes it difficult to identify a relationship with any of the low-flow indices examined. The average value for the 30% MAF estimated discharges was 69.6%, which directly links this method to the Q_{70} index. However, the wide range of exceedance probability percentages, adds a certain degree of uncertainty on the validity of this correlation. The 30% MAF had a high correlation, r equal to 0.88, with the Q_{70} proposing a strong link between the two.

Table 1. Estimated e-flows per site, according to the three different EFA methods and their corresponding percentiles in the FDC.

Site Name	Greek Regulations		10% MAF		30% MAF	
	Discharge (m^3/s)	FDC percentile	Discharge (m^3/s)	FDC percentile	Discharge (m^3/s)	FDC percentile
Arta	7.22	87.4%	3.32	<95%	9.96	81.0%
Gribovo	4.77	<95%	2.19	<95%	6.57	<95.0%
Kalavrita	0.16	76.6%	0.12	87.5%	0.37	64.7%
Kifissos	0.18	<95%	0.25	92.4%	0.76	61.1%
Kryoneri	0.78	95.0%	0.70	95%	2.09	69.7%
Makri	0.35	<95%	0.35	89.4%	1.04	63.6%
Mavria	0.20	91.4%	0.41	75.8%	1.23	49.3%
Melisso	4.69	<95%	2.29	<95%	6.87	<95.0%
Pineios_2	3.41	82.5%	3.77	82.2%	11.31	54.1%
Pineios_3	0.57	60.5%	0.58	60.5%	1.74	57.8%
Skopia	0.10	87.4%	0.13	86.2%	0.39	41.1%
Stenaki	5.90	<95%	2.41	<95%	7.23	<95.0%
T_Sper	1.60	<95%	1.09	<95%	3.26	87.3%
Titar	0.13	81.3%	0.05	84.5%	0.15	78.9%
Valyra	0.22	90.9%	0.32	72.7%	0.97	50.5%

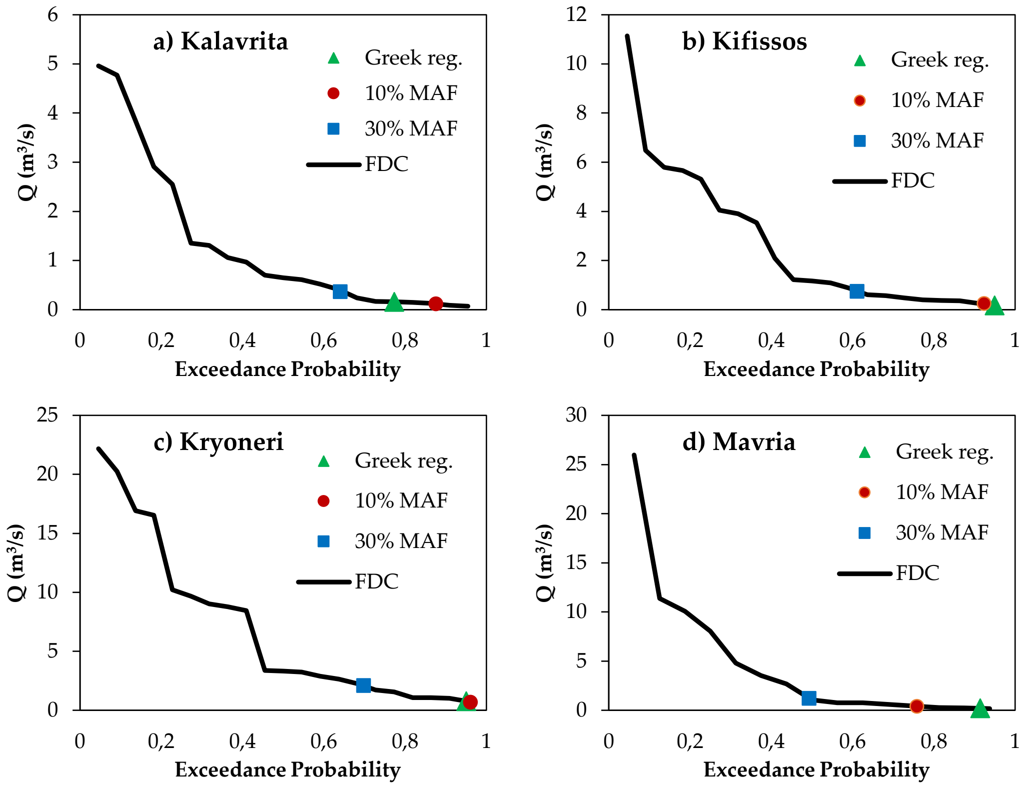

Figure 2. The corresponding exceedance probability, on the FDC, for discharge values estimated with the three different EFA methods and their distribution over the low-flow part (70-99%) of the curve.

5. Conclusions

In this study, three different hydrological EFA methods were examined and evaluated with regard to well established low-flow indices of the FDC, namely the Q_{70}, Q_{90} and Q_{95}. At first, the validity of the Greek regulation method was examined in that procedure. The same process was also applied for the 10% and 30% MAF, the most widely used hydrological methods for EFA. It was shown that both the Greek regulation and the 10% MAF were producing discharge values in the same value range and that they were both satisfactorily approximating the Q_{90} index, as average values per method. Yet, between the two, the Greek regulation had the better performance as well as a stronger correlation with the Q_{90}. Concerning the 30% MAF method, the analysis showed a strong link of this method to the Q_{70} index. However, it was found that in many cases the proposed discharge values by the examined methods can range a lot, to the point of even reaching values that correspond to 95% or higher exceedance probabilities. To account for this limitation, this paper suggests to make use of the Q_{90} index as it would produce similar but safer (equal to 90% by default) discharge values. It was therefore proposed, that the Q_{90} could be also used as a good and safe estimation for e-flows in Greek rivers and that Q_{70} could be used as an indicator of the 30% MAF.

6. References

Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A. C., Kendy, E., McClain, M. E., Poff, N. L., Richter, B. D., & Ward, S. (2018), The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). *Frontiers in Environmental Science*, **6**, 45

Curtis, S. (2020), Hydroclimatic Variability at Local, Regional and Global Scales. *Water*, **12(5)**, 1490

Petts, G. E. (2009), Instream Flow Science for Sustainable River Management. JAWRA *Journal of the American Water Resources Association*, **45(5)**, 1071–1086.

Poff, N. L. (2018), Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. *Freshwater Biology*, **63(8)**, 1011–1021

Searcy, J. (1959), Flow-Duration Curves. Manual of Hydrology: Part 2. Low-Flow Techniques. U.S. Geol. Surv. Water Supply Pap.1542-A

Tennant DL (1976), Instream fow regimes for fsh, wildlife, recreation and related environmental resources. In: Orsborn JF, Allman CH (eds) Instream fow needs. American Fisheries Society, Bethesda, pp 359–373

Tharme, R. E. (2003), A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, **19(5–6)**, 397–441

Ward, S., Borden, D. S., Kabo-Bah, A., Fatawu, A. N., & Mwinkom, X. F. (2019). Water resources data, models and decisions: International expert opinion on knowledge management for an uncertain but resilient future. *Journal of Hydroinformatics*, **21(1)**, 32-44.