

A Spatial Interpolation Approach for Environmental Flow Assessment in Bulgarian-Greek Rhodope Mountain Range

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Abstract. Nowadays, the environmental flow (e-flow) is globally recognized as an essential component of the sustainable water resources management. Therefore, defining flow requirements is an important step forward, especially in transboundary regions where different water management practices exist. This study aims to test a spatial interpolation approach for estimating the e-flow in the Bulgarian-Greek Rhodope Mountain Range, incorporating hydrological methods, GIS techniques and expert judgment. It was found that the minimum flow required to maintain rivers and riverine ecosystems in the region with a probability of exceeding 90% of the time ranges from 0.027 to 6.11 m³/s, which represents from 1.92 to 32.98 percentages of the mean annual flow. The base flow variability index varies from 2 (low) to 20 (extremely high). Based on the Tennant method and low-flow duration indices, the rivers were regionalized into 5 ecological management classes that identify the quality of ecosystems and their conservation status.

Keywords: Environmental flow; Rhodope; GIS; river ecosystem.

1 Introduction

The concept of environmental flow (e-flow) is nowadays recognized as an essential step towards sustainable management of the natural resources, the need of which is constantly increasing for the demand to ensure the human livelihoods in the context of global climate change and growing exigency. This concept, widespread in the last 3 decades, defines e-flow as the flow regime (i.e. quantity, quality, and timing of water flow) required to sustain freshwater and riverine ecosystems (Clausen and Biggs, 2000; EC-Guidance No 31, 2015; Acreman, 2016; Karakoyun et al., 2018; Palmer and Ruhi, 2019).

One of the main reasons for increasing the use of water is to generate electricity via hydroelectric power plants (HPPs) (Karakoyun et al., 2018). As a consequence of the abundant water reserves of the Rhodope Mountain, a significant part of Bulgaria's hydropower plants is located here, whereat many of the largest country's dams have been constructed during the 50s and 60s of the 20th century. The construction of small

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hydroelectric plants (SHP) is also a strategic goal for Greece, which can reduce the electricity imports and contribute to balance of payments (Myronidis et al., 2008). Even supporting the economic development of the countries, the HPPs cause damage to biological diversity in rivers and their ecosystems, changing the basic components of the river flow (i.e. volume and timing), as well as the natural interrelation between the river and its flood areas (Karakoyun et al., 2018). Degradation of watershed ecosystems can also affect soil erosion, since the healthy vegetation is one of the best protections against erosion. Myronidis et al., (2010) address the issue of land degradation caused by excessive erosion in the Mediterranean region, pointing out the need of sustainable plan to mitigate the negative impact on natural ecosystems.

In the past, many of these environmental problems have not been taken into account in the watershed management and the construction of HPPs, which in turn requires a scientific approach to ensure the future sustainable development of the Bulgarian-Greek transboundary region. Recently, the rapid development of information technology has significantly increased the technical capacity to assess the variability of flow regimes in both temporal and spatial perspective, and hence the variability in ecosystem processes, using a broad range of spatial scales, resolutions and data availability (Tharme, 2003; Smakhtin et al., 2006).

This study aims to test a spatial interpolation approach to reveal the spatiotemporal variability in the flow regime in the Bulgarian-Greek Rhodope Mountain Range, integrating Geographic Information Systems (GIS) and the most commonly used hydrological indices that might predict the magnitude, frequency and timing of flow events to further define environmental flow requirements.

2 Methods

2.1 Study area and data

The entire territory of The Rhodope Mountain Range was considered in this study, extending on an approximately 23 500 km² between longitudes 23°40'E and 26°40'E and between latitudes 40°50'N and 42°15'N in Bulgarian-Greek transboundary region (Figure 1). Both the humid continental climate of the North and the Mediterranean climate of the South influence the local climate of the region. The average annual temperature varies from 5 to 10-13 °C whilst average annual precipitation ranges between 600-1100 mm (Yordanova et al., 2002). The relief differs from low-mountainous in the south-east to high-mountainous in the west (0–2191 m) with mean elevation 630 m.

The Rhodope Mountain Range is famous for the highest species diversity in the Balkans and rivers play a significant role in their conservation (Tsiftsis and Tsiripidis, 2012). According to the Bulgarian Ministry of Environment and Water and the Greek Ministry of Reconstruction, Environment and Energy the region includes 36 Natura 2000 protected sites (17 in Bulgaria and 19 in Greece) with a total area of 11 000 km². The flow inventory data, employed in a previous study (Myronidis and Ivanova, 2020), contain monthly records for maximum, minimum and mean discharges in m³/s for

time period of at least 10 years of measurements (between 1936 and 1995) for 22 pristine watersheds with mean annual discharge from 0.19 to 27.7 m³/s.

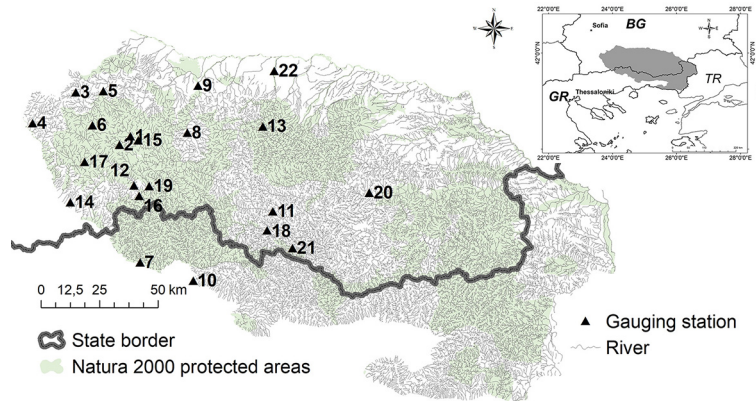


Fig. 1. Location map of the Bulgarian-Greek Rhodope Mountain Range.

2.2 Environmental flow assessment methodology

A large number of methods have been used for environmental flow assessment, varying from simple statistics to complex models. Generally, they have been categorized in Hydrological, Hydraulic Rating, Habitat Simulation and Holistic methods (Gopal, 2013; Karakoyun et al., 2018). In this study simple methodology was compiled in order to assess environmental flow and classify flow regime for water management and habitat maintenance. The methodology includes following steps:

1. Selecting hydrological indices that adequately characterize flow regime;
2. Statistical analysis of the hydrological data to arrive at index values;
3. Spatial interpolation of the index values to characterize the spatial variability of flow regime;
4. Compiling a classification of the flow regime to predetermine the state of riverine ecosystems, based on sustainable flow requirements, in terms of Ecological Management Classes (EMC) proposed by the South African DWAF (1997).

The hydrological methods, selected and applied in a historical record, are the most widely used method of Tennant (1976), based on percentages of mean annual discharge, and Flow Duration Curve (FDC) method, which is a cumulative frequency curve representing the percentage of time during which the flow rate is equal or exceeds particular value (Gopal, 2013). Several low-flow indices were obtained from FDCs in a monthly step in order to determine e-flow, including Q₅₀, Q₉₀ and Q₉₅ (daily flows exceeding 50%, 90% and 95% of the time) expressed in both m³/s and % of mean annual flow (MAF). In addition, Low Exceedance Flow Index – LEFI (Q₉₀/Q₅₀) (Pyrce, 2004; Clausen and Biggs, 2000) and Baseflow Variability Index – BVI (Q₅₀/Q₉₀) (Nelms et al., 1997; Pyrce, 2004) were calculated.

Spatial interpolation was applied to all indices to determine flow regime requirements in their spatial and temporal variability, enforcing “Topo to Raster” tools in the ArcGIS software, which represents an interpolation technique based on the ANUDEM program, specially designed to create a surface closer to natural drainage surface (Hutchinson et al., 2011). The procedure uses interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity.

Finally, a holistic approach based on calculated indices was applied to classify rivers according to certain requirements for maintaining the whole riverine ecosystem in its ecological integrity.

3 Results

3.1 Instream flow regime based on the Tennant method

Since the development of Tennant's hydrological methodologies (Tennant, 1976) involves the collection of field habitat, hydraulic and biological data, this method differs from many others and is considered one of the most suitable for e-flow assessment (Tharme, 2003; Pyrcie, 2004). The methodology consists of linking certain percentages of mean annual flow (MAF) to eight categories of river condition on a seasonal basis to sustain fish, wildlife, recreation, and related environmental resources. To apply this method, the mean monthly flow was obtained for all gauging stations in the Rhodope Mountain Range, averaging the mean monthly discharge data for all observed years. Then, the percentage of the MAF was calculated month by month (Table 1).

Table 1. Mean monthly flow, calculated as a percentage of MAF.

| Gauge N: | % of MAD (October-March) | | | | | | % of MAD (April-September) | | | | | |
|----------|--------------------------|----|-----|-----|-----|-----|----------------------------|-----|-----|-----|------|----|
| | X | XI | XII | I | II | III | IV | V | VI | VII | VIII | IX |
| 1 | 52 | 62 | 64 | 56 | 48 | 65 | 159 | 252 | 197 | 117 | 71 | 54 |
| 2 | 43 | 75 | 97 | 81 | 73 | 88 | 173 | 238 | 148 | 89 | 49 | 42 |
| 3 | 42 | 66 | 76 | 110 | 87 | 164 | 199 | 162 | 137 | 79 | 44 | 37 |
| 4 | 63 | 64 | 80 | 100 | 143 | 208 | 203 | 116 | 101 | 66 | 37 | 40 |
| 5 | 50 | 63 | 83 | 105 | 115 | 169 | 189 | 154 | 119 | 66 | 45 | 43 |
| 6 | 41 | 67 | 75 | 83 | 72 | 101 | 218 | 221 | 141 | 90 | 49 | 39 |
| 7 | 51 | 82 | 119 | 94 | 120 | 139 | 183 | 171 | 131 | 50 | 33 | 30 |
| 8 | 33 | 69 | 108 | 117 | 108 | 135 | 185 | 175 | 120 | 65 | 47 | 42 |
| 9 | 36 | 87 | 100 | 62 | 105 | 148 | 235 | 192 | 97 | 72 | 35 | 31 |
| 10 | 46 | 93 | 120 | 89 | 205 | 183 | 243 | 198 | 162 | 66 | 28 | 27 |
| 11 | 39 | 80 | 139 | 139 | 122 | 146 | 168 | 153 | 104 | 56 | 28 | 30 |
| 12 | 30 | 78 | 97 | 139 | 123 | 158 | 185 | 159 | 112 | 65 | 30 | 25 |
| 13 | 42 | 59 | 98 | 164 | 114 | 143 | 174 | 188 | 129 | 68 | 39 | 32 |
| 14 | 33 | 89 | 112 | 144 | 133 | 158 | 165 | 120 | 75 | 36 | 73 | 33 |
| 15 | 46 | 63 | 71 | 74 | 67 | 99 | 244 | 243 | 125 | 81 | 44 | 38 |
| 16 | 24 | 81 | 138 | 144 | 121 | 150 | 187 | 139 | 107 | 70 | 22 | 19 |
| 17 | 25 | 55 | 106 | 150 | 141 | 135 | 234 | 172 | 98 | 49 | 18 | 16 |
| 18 | 33 | 99 | 183 | 194 | 166 | 146 | 140 | 107 | 74 | 31 | 13 | 17 |
| 19 | 23 | 80 | 104 | 125 | 95 | 152 | 226 | 169 | 116 | 75 | 18 | 16 |
| 20 | 30 | 79 | 170 | 165 | 206 | 145 | 122 | 101 | 79 | 39 | 18 | 21 |
| 21 | 30 | 85 | 185 | 263 | 239 | 142 | 82 | 66 | 45 | 37 | 8 | 9 |
| 22 | 25 | 32 | 71 | 78 | 111 | 176 | 270 | 189 | 111 | 68 | 28 | 40 |

Once obtained, these percentages were interpolated via ArcGIS software to reveal the spatial and temporal variability of in-stream flow regimens with respect to different aquatic and riverine habitat conditions. Following the Tennant's environmental flow recommendations, we assumed the threshold of 10% of the MAF as the lowest limit corresponding to "severe degradation" of a riverine ecosystem. The category up to 10% (max to 30%) of MAF (Apr.–Sept.) was assumed to be "poor". The other categories are "fair", "good", "excellent", "outstanding", "optimum" and "flushing", joined to ranges of 10%–20% (Oct.–Mar.) – 30%–40% (Apr.–Sept.); 20%–30% (Oct.–Mar.) – 40%–50% (Apr.–Sept.); 30%–40% (Oct.–Mar.) – 50%–60% (Apr.–Sept.); 40%–100% (Oct.–Mar.) – 60%–100% (Apr.–Sept.); 100%–200% and over 200%, respectively.

As can be seen from Figure 2 and 3, the river flow maintains an ecological optimum over the year, ranging from good to flushing, except for the period August–September, during which the ecological status of rivers dramatically degrades to poor, leading to damage of the river and riverside habitats.

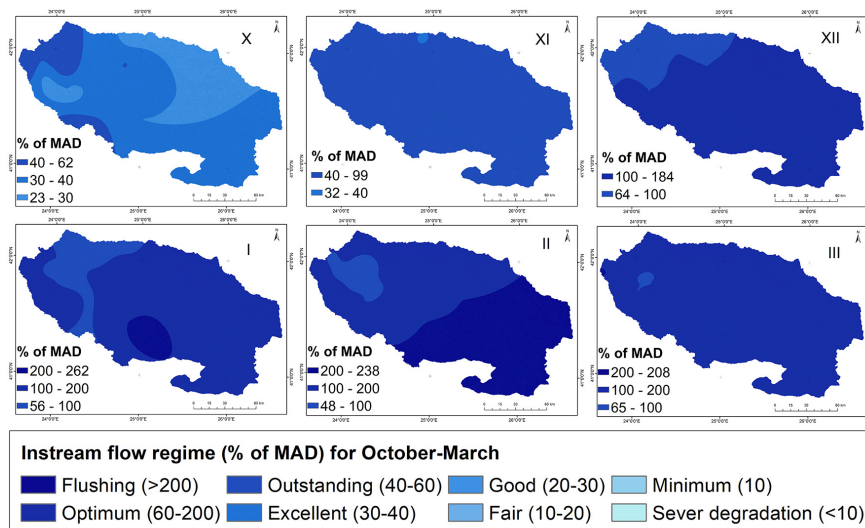


Fig. 2. Instream flow regime in the Bulgarian-Greek Rhodope Mountain Range for the period October–March based on the Tennant (1976) method.

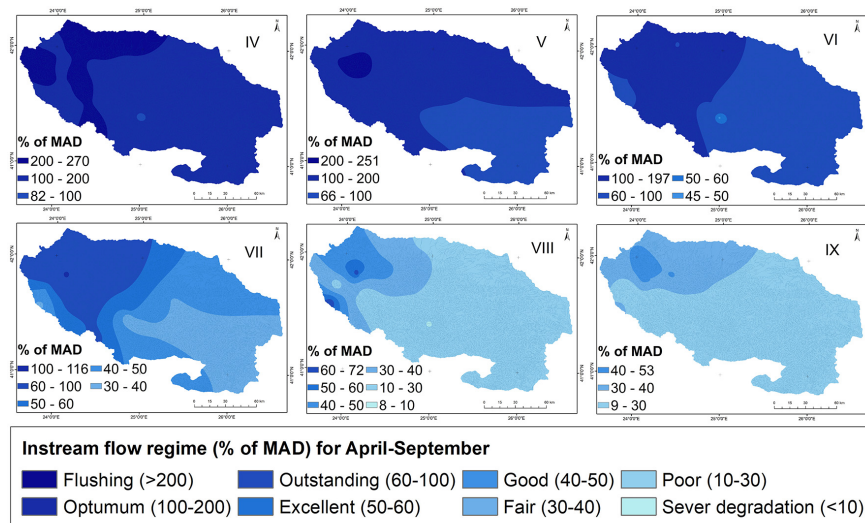


Fig. 3. Instream flow regime in the Bulgarian-Greek Rhodope Mountain Range for the period April–September based on the Tennant (1976) method.

3.2 Classification of natural flow regimes for e-flow estimation

The FDC combined with other methods, as Vogel and Fennessey (1995) indicated, has been used in many hydrologic studies including flood control, water quality

management and aquatic habitats maintenance, due to its easy application and expression of wealth hydrologic information (Dakova et al., 2000; Smakhtin and Anputhas, 2006; Smakhtin et al., 2006; Shaeri Karimi et al., 2012; Efstratiadis et al., 2014; Ridolfi et al., 2020).

In an attempt to find a more comprehensive approach to determine environmental flow requirements for the Rhodope Mountain transboundary area, FDCs were prepared for all gauging stations based on long-term data (from 10 to 28 years), which is sufficient to assess the availability of water in the study area. Focusing on duration of low flow events, several indices, obtained from FDCs, were used for the purpose of this study, which are most often employed in the government and academic literature regarding environmental flow assessment (Table 2).

Table 2. Low-flow duration indices calculated from FDCs.

| Gauge N: | MAF | Q50 | Q90 | Q95 | | LEFI | | BVI | EMC | BV class |
|----------|-------|-------|-------------------|-------|-------------------|-------|-----------|-----------|-----|----------------|
| | | | m ³ /s | % | m ³ /s | % | (Q90/Q50) | (Q50/Q90) | | |
| 1 | 0,94 | 0,65 | 0,31 | 32,98 | 0,26 | 27,66 | 0,48 | 2,10 | A | Low |
| 2 | 0,37 | 0,27 | 0,12 | 32,43 | 0,11 | 29,73 | 0,44 | 2,25 | A | Low |
| 3 | 0,69 | 0,52 | 0,19 | 27,54 | 0,17 | 24,64 | 0,37 | 2,74 | A | Low |
| 4 | 0,70 | 0,45 | 0,18 | 25,71 | 0,14 | 20,00 | 0,40 | 2,50 | A | Low |
| 5 | 2,63 | 1,79 | 0,65 | 24,71 | 0,5 | 19,01 | 0,36 | 2,75 | A | Low |
| 6 | 0,35 | 0,24 | 0,086 | 24,57 | 0,068 | 19,43 | 0,36 | 2,79 | A | Low |
| 7 | 25,85 | 20,1 | 6,11 | 23,64 | 3,61 | 13,97 | 0,30 | 3,29 | B | Moderate |
| 8 | 17,48 | 13,4 | 4,06 | 23,23 | 3,45 | 19,74 | 0,30 | 3,30 | B | Moderate |
| 9 | 21,82 | 15,1 | 4,73 | 21,68 | 3,83 | 17,55 | 0,31 | 3,19 | B | Moderate |
| 10 | 21,68 | 19,14 | 4,58 | 21,13 | 2,70 | 12,45 | 0,24 | 4,18 | B | High |
| 11 | 4,74 | 3,55 | 1 | 21,10 | 0,76 | 16,03 | 0,28 | 3,55 | B | Moderate |
| 12 | 3,52 | 2,4 | 0,64 | 18,18 | 0,3 | 8,52 | 0,27 | 3,75 | B | Moderate |
| 13 | 5,88 | 4,46 | 1,03 | 17,52 | 0,85 | 14,46 | 0,23 | 4,33 | C | High |
| 14 | 0,19 | 0,077 | 0,027 | 14,21 | 0,024 | 12,63 | 0,35 | 2,85 | C | Low |
| 15 | 0,39 | 0,23 | 0,05 | 12,82 | 0,038 | 9,74 | 0,22 | 4,60 | C | High |
| 16 | 2,90 | 2,09 | 0,32 | 11,03 | 0,25 | 8,62 | 0,15 | 6,53 | D | Very high |
| 17 | 0,89 | 0,54 | 0,081 | 9,10 | 0,059 | 6,63 | 0,15 | 6,67 | D | Very high |
| 18 | 2,55 | 1,73 | 0,23 | 9,02 | 0,16 | 6,27 | 0,13 | 7,52 | D | Very high |
| 19 | 1,71 | 1,14 | 0,15 | 8,77 | 0,071 | 4,15 | 0,13 | 7,60 | D | Very high |
| 20 | 27,68 | 19,8 | 1,91 | 6,90 | 1,47 | 5,31 | 0,10 | 10,37 | D | Extremely high |
| 21 | 0,42 | 0,17 | 0,027 | 6,43 | 0,02 | 4,76 | 0,16 | 6,30 | D | Very high |
| 22 | 5,74 | 2,22 | 0,11 | 1,92 | 0,06 | 1,05 | 0,05 | 20,18 | E | Extremely high |

Average flow magnitude (Q50), Q90 and Q95 exceedance flows overall years, expressed as well in percentages of the MAF, were obtained directly from the FDCs. Low exceedance flows index (LEFI) was calculated dividing mean magnitude of flows exceeded 90% of the time (Q90) by Q50 (Clausen and Biggs, 1997, 2000), while Base flow variability index (BVI) was obtained dividing Q50 by Q90 (Nelms et al., 1997; Pyrcce, 2004). Those indices combined with expert opinion were utilized to define ecological management classes (EMC), which express the state of the riverine ecosystems, based on the e-flow regimes, following the procedure proposed by Smakhtin and Anputhas (2006) and some of the steps proposed by South African Water Research Commission (King et al. 2008). The relationship between the low-flow indices and the biological conditions of the benthic biota (e.g. elements such as biomass, total number of species, etc.) was also taken into account (Clausen and Biggs,

1997). The five EMCs were predetermined (see Table 3) assuming that higher EMC requires more water as a percentage of MAF with low baseflow variability for ecosystem maintenance and conservation.

Table 3. Ecological management classes (EMC) assigned to the Bulgarian-Greek Rhodope Mountain Range.

| EMC | Description of water, habitat and ecosystem quality |
|-----|---|
| A | <i>Negligible modifications from natural conditions:</i> Rivers with minor changes in in-stream and riparian habitats. Negligible risk to intolerant biota. |
| B | <i>Slight modifications from natural conditions:</i> Ecologically important rivers with largely intact biodiversity and habitats. Slight risk to intolerant biota. |
| C | <i>Moderate modifications from natural conditions:</i> The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Moderate risk to intolerant biota. |
| D | <i>High degree of modifications from natural conditions:</i> Large changes in natural habitats, biota and basic ecosystem functions have occurred. Habitat diversity and availability have declined. High risk of loss of intolerant biota. |
| E | <i>Critical degree of modifications from natural conditions:</i> Modifications have reached a critical level and ecosystems have been completely modified with almost total loss of natural habitats and biota. |

Q90 exceedance flow, expressed in percentages of MAF, was selected in order to pre-define the spatial extend of the EMCs. The values for Q90, which vary from 32.8% to 1.9% of MAF, were interpolated in the ArcGIS software and were classified into five classes, corresponding to A, B, C, D and E of the EMC, respectively (Figure 4a). The same procedure was applied to BVI, identifying five baseflow variability classes (Figure 4b).

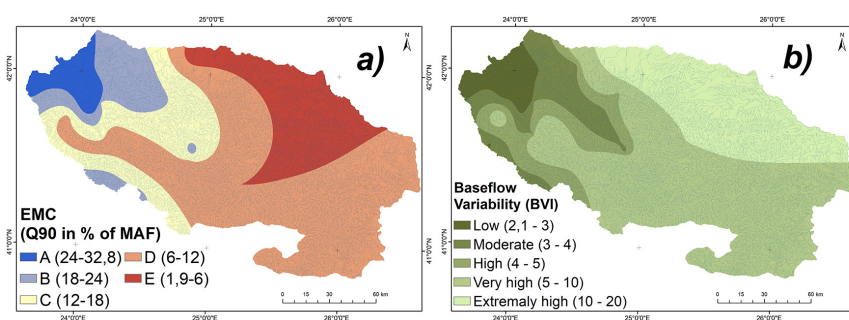


Fig. 4. Environmental flow classification in the Bulgarian-Greek Rhodope Mountain Range: a) ecological management classes (EMC); b) baseflow variability classes.

Looking at the continuity of the FDCs distribution (Figure 5: a, b), the five classes can be clustered into two groups of rivers: (1) rivers of high quality habitats (classes A

and B) with negligible to slight risk of degradation (15% of the total area) and (2) rivers of low quality habitats (classes C, D and E) with moderate to high risk of degradation. The second group differs significantly in the stability of the flow regime, expressed through greater flow variability over time.

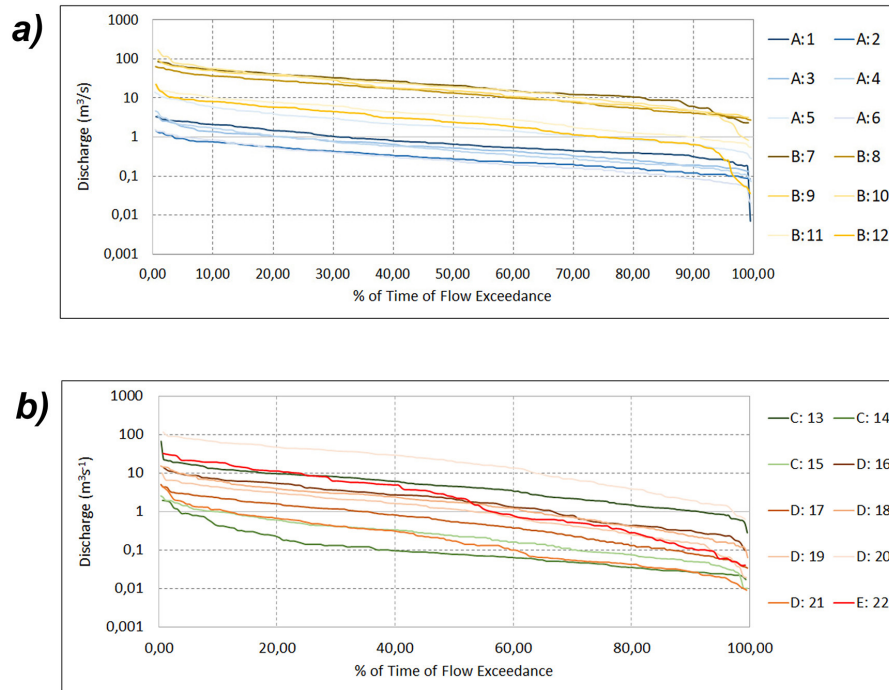


Fig. 5. Flow duration curves (FDCs) of the rivers in the Bulgarian-Greek Rhodope Mountain Range: a) rivers of EMC “A” and “B”; b) rivers of EMC “C”, “D” and “E”.

4 Conclusions

This study is the first attempt for a comprehensive environmental flow assessment in Bulgaria, where other ecological information (e.g. biological parameters) is still scarce. The Bulgarian-Greek Rhodope Mountain Range was chosen for this purpose, which is the most important transboundary area for both countries. A simple procedure combining hydrological methods, a holistic approach and geoinformation techniques was applied, emphasizing the spatiotemporal variability of the flow regime.

The results indicate that to maintain the rudimentary functions of the rivers in the Rhodope Mountain Range requires an average daily flow in the range of 0.027 to 6.11 m³/s with a probability to exceed 90% of the time, which varies from 1.92 to 32.98% of the MAF. On the other hand, the base flow variability index changes between 2 (low) and 20 (extremely high). High resolution gridded surfaces were generated by

spatial interpolation of the obtained data. Based on the calculated indices and applying expert judgment of the flow regime, the rivers were regionalized into 5 EMCs according to their potential to maintain the whole riverine ecosystem.

Finally, a disadvantage of this study is that it relies solely on hydrological data. We therefore recommend building a more holistic methodology, involving biological surveys and socio-economic information, which can better define the environmental flow requirements in the transboundary region.

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