

THE HYDROLOGICAL AND ENVIRONMENTAL ASPECT OF LOW FLOW ASSESSMENT IN UNGAUGED BASINS – A CASE STUDY IN THE JUŽNA MORAVA RIVER BASIN

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Abstract. *Eighteen low flow indicators are considered in the research of sixteen hydrological stations in the Južna Morava river basin. The indicators are estimated by statistical analysis and grouped as hydrological and environmental indicators. A cross-correlation between all indicators is assessed. Environmental flows at hydrologic stations are obtained by the GEP method. The environmental low flow indicators are transferred to two small ungauged basins by regression with physiographic characteristics. The adjustment of environmental flows at ungauged basins is performed according to locations of the donor stations in the hydrogeological regions of the studied area.*

Key words: *low flow indicators, statistical analysis, regional analysis, ungauged basin, environmental flow, GEP method*

1. INTRODUCTION

Many applications in water resources planning and management include low-flow conditions. The main topic related to low flows is water availability, defined by quantity, quality, and location over time [1] i.e. the dynamics of water availability at the location of interest. The World Meteorological Organization, WMO [2] provides a broad list of the low-flow regimes of a river, and for each one, the analysis technique, data requirements, and some common applications. The techniques for estimating and predicting low river flows are shown for both gauged and ungauged basins. In this way, quantity and location component of the low river flow is explicitly covered, while the water quality component

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is linked to water quantity in an implicit way – there are commonly used flow variables like 95% duration daily flow (Q95 or Q95%), used to simulate downstream water quality distributions. This is a typical example of the design flow in use until the 1980s as a maintenance flow – the water resources management related flow such as the minimum guaranteed release flow for a reservoir.

A growing concern worldwide over the relationship between water and the environment, has brought the concept of environmental flow, meant for the protection of biological and social systems supported by rivers [3]. In the 1980s, the USA Environmental Protection Agency (EPA) has started differentiating the design flow methods to the ones determined by the hydrologically-based and biologically-based methods [4]. The former is independent of biological considerations, while the latter includes the actual frequency of biological exposure to continuous concentration of a pollutant, and maximum concentration in water. These criteria are used to protect aquatic life from chronic and acute harmful effects respectively. The rationale for both hydrological and biological methods is different, although both rely upon statistical analysis of gauged flows, and final results of both analyses have to be compared for the final decision on design flow. While these methods are based on gauged flows only, there are more complex methods for assessing environmental flow that incorporate water quality monitoring and data sampling over several years. Although there are many examples of successful application of such models, including MABIS model applied in the region [5], it has been observed that similar results might be obtained by simpler and less data demanding methods [6].

Tharme [7] has proposed the following classification of environmental flow assessment models: 1) Hydrological index methods, 2) Hydraulic rating methods, 3) Habitat simulation methodologies, 4) Holistic methodologies. One third of all methods belongs to the Hydrological methods category relying upon gauged flow data, therefore also called Historical Flow methods [8]. As mentioned for the EPA's recommendation [4], the flows assessed by hydrological methods have to be compared to the needs of the river ecosystem for final decision upon design flow. This requirement is well communicated in the Three-Level Framework [9], where Comprehensive hydrologic desktop models are at the Level 1, followed by the second level Expert Panel Assessment, and ending by Level 3: Examining Tradeoffs and Predicting Results of Operational Changes.

The methodology for environmental flow assessment in Serbia is not yet decided and put in power [10]. Traditionally, the following hydrologic low flow indicators have been used for the purpose: a percentage of mean annual flow (10%-15%), and 95% exceedance probability of either minimum averaged 30-day daily flow or minimum monthly flow. Đorđević and Dašić [6] have proposed the GEP method that utilizes listed traditional variables for a cold/winter season (October-March), while in warm/summer season (April-September), higher values are used: 15% and 25% of mean annual flow, and 80% exceedance probability of either minimum averaged 30-day daily flow or minimum monthly flow. The alternative for using minimum monthly flow instead of minimum averaged 30-day daily flow is recommended due to local (country) gauged hydrologic data situation, being aware of the fact, a minimum monthly flow is somewhat larger than minimum averaged 30-day daily flow.

Although rarely used, there are examples of presenting 95% (also, 90%, 80% and 50%) exceedance probability of minimum annual flow as hydrologic low flow indicators [11], [12].

The aim of this research is to assess the range of low flow variables used for environmental flow assessment, and examine its transferability to ungauged basins in the Južna Morava river basin.

The motivation for the research is concern raised due to expected impact of two greenhouse gas emission scenarios on changes in climatological and hydrological parameters in Serbia [13], adverse for both water management and environmental systems. Low flow reduction is of particular concern in the upper and middle basin parts of the Južna Morava river, the most vulnerable to potential change being the tributaries of the first and second order to the main river [10].

Two small ungauged basins are studied in this research, one of the first and one of the second order tributary to the Južna Morava river. Low flow assessment relies on background analysis on hydrogeological conditions in Hydrological studies of the Tulovska river [14] and Vujanovačka river [15]. In the low flow periods, especially in the small and medium size river catchments, the main factor influencing flow magnitude is geologic/hydrogeologic composition [16]. Gauged flow data are collected from hydrological stations with drainage basins characterized by similar hydrogeological factors, situated in the upper and middle basin parts of the Južna Morava river. In the low flow regional analysis, these are donor stations used to transfer information on low flow indicators from gauged to ungauged basins.

2. METHODOLOGY

2.1. Study area and collected data

2.1.1. Location

The study area comprises drainage basins of 16 hydrological stations (HS) shown in Fig. 1 in the Južna Morava river basin, with perimeter highlighted in yellow. The two ungauged locations are indicated by blue squares, HS by red triangles. Majority of the study area belongs to the region III, one of five hydrogeological regions defined in the South of the Danube and Sava rivers, as shown in Nikić [16].

2.1.2. Data for low flow analysis

The relevant data for low analysis in this research is time series of daily mean flow values at selected HS, in the period up to the year 2020 (Table 1). The data is published in the Hydrological Yearbooks of the Republic Hydrometeorological Service of Serbia [17]. The physiographic data for the two ungauged basins is taken from the design projects [14], [15], and catchment area for gauged basins – HS, from the Hydrological Yearbooks [17].

An initial daily flow data check has shown that gauging period at selected HS ranges from 56 to 73 years. In the gauging period, years without any data and years with incomplete data are found (Table 1).

2.1.3. Daily flow data examination

In the data examination process, two main issues are addressed: 1) deriving the datasets for statistical analysis from the daily flow time series with gaps, and 2) examining suitability of datasets for statistical analysis.

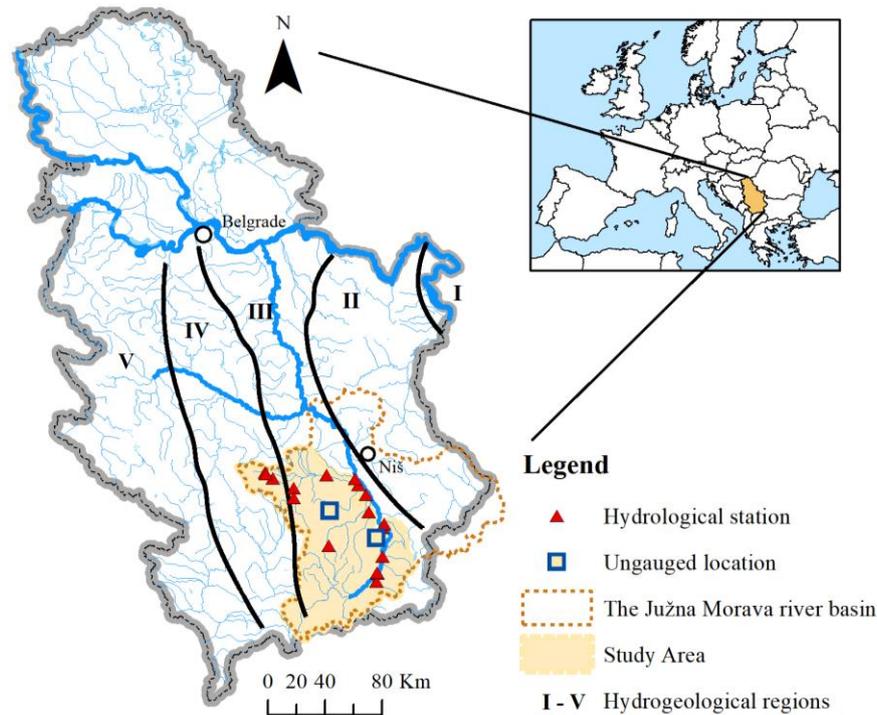


Fig. 1 Study area location in Serbia with hydrogeological regions from [16]

The following datasets are composed for low-flow investigation:

1. 30-day flow minima (Q_{30dMin}),
2. Annual flow minima (Q_{AnnMin}),
3. Mean monthly flow minima (Q_{MonMin}),
4. Mean annual flow (Q_{AnnAvg}).

In the case the data are missing for the whole year, that year is rejected when composing any dataset. For the years with incomplete data it has been observed which part of the year is with the data gap. If the gap is located in the period July-October, the typical low flow period, that year is not included when composing any dataset. Appearance of data gaps in the period January-June and November-December is ignored for deriving 30-day minima, mean monthly minima and annual minima datasets, but not for the dataset comprising annual average flows. When ignoring missing daily data, characteristic flows are obtained from the remaining daily data in that year. The basic data processing period is a calendar year.

Suitability of the datasets for statistical analysis is examined at 5% significance level by the tests intended to detect:

1. Inhomogeneity: t/z test, F-test, Leven's test, Mann-Whitney test;
2. Trend: Mann-Kendal test, Spearman's rank test, linear trend presence test, significance test for the slope of linear regression;
3. Outliers: Grubbs and Beck test.

Table 1 The initial daily flow data check results

No. [#]	Hydrologic station (HS)	River	HS code	Start gauge [year]	Years with		
					complete data [no.]	no data [no.]	incompl. data [no.]
1	Vranj. Banja	Banjska	47526	1964	56	0	1
2	Vranj. Priboj	J. Morava	47528	1948	68	5	0
3	Vlad. Han	J. Morava	47530	1949	67	4	1
4	Tupalovce	Kozarska	47539	1961	58	0	2
5	Grdelica	J. Morava	47540	1948	73	0	0
6	Sij. banja	Jablanica	47720	1965	52	4	0
7	Magovo	Toplica	47820	1958	46	16	1
8	Merćez	Lukovska	47825	1953	49	16	3
9	Donja Selova	Toplica	47830	1952	66	0	3
10	Pepeljevac	Toplica	47850	1951	70	0	0
11	Prokuplje	Toplica	47880	1951	64	4	2
12	Doljevac	Toplica	47890	1954	67	0	0
13	Pukovac	Pusta	47548	1950	67	4	0
14	Leskovac	Veternica	47665	1948	71	2	0
15	Pečenjevce	Jablanica	47740	1950	70	0	1
16	Visoka	Kosanica	47855	1960	55	2	4

When inhomogeneity or a trend is detected in the dataset, the oldest data is step by step deleted from the record and tested, until the truncated dataset becomes homogeneous and without a trend, meaning the datasets comprise the most recent data. All of the truncated datasets still have more than the minimum of 30 gauged years (the initial representativeness condition).

Outlier treatment approach applied is: High outliers are removed from the datasets, while the low ones are left in it.

Zero flows in the datasets are noted for further consideration in the statistical analysis.

The main findings and decisions in the data examination process are given in Table 2.

2.2. Low flow assessment

Two groups of low flow indicators are used in the research, one related to mean annual flow, the other to low flow quantiles assessed by statistical analysis.

Statistical analysis of low flows is performed on the Q_{30dMin} , Q_{AnnMin} and Q_{MonMin} samples. Among several theoretical distributions considered [18], as illustrated in Fig. 2 for the Q_{30dMin} dataset at HS Visoka, the prevailing best fit to empirical distribution (Weibull's plotting position) is Log Pearson III (LP3) distribution, according to a several criteria applied (statistical properties of sample, probability plots, Kolmogorov-Smirnov test, Cramer von Mises test, RMSE).

In the datasets with zero flows, conditional probability is applied [19]:

$$H(x) = q + (1 - q) \cdot F(x). \quad (1)$$

Here,

$H(x)$ – probability distribution function of variable x ,

$F(x)$ – probability distribution function for $x > 0$ only,

q – probability of $x=0$, calculated from $q=m/N$ i.e. ratio of number of zero flows (m) and sample size (N).

It should be noted that all quantiles cannot be estimated from the samples with zero flows. Therefore, at some HS, the highest exceedance probability quantiles could be absent regardless of their importance in low flow analysis. In practice, it should be checked when the condition $F(x) > 0$ is met [20]. From equation (1) it is obtained that the smallest flows (the highest exceedance probability quantiles) that can be estimated correspond to the probability $H(x) = q$.

Table 2 The data examination review

No.	Hydrologic station (HS)	Sample start	Sample size of Ann Avg dataset	Data gap duration	Ignored data gap in year	Sample size of AnnMin, 30dMin and MonMin dataset
[#]		[year]	[no.]	[year (days)]	[year]	[no.]
1	Vranj. Banja ¹	1977*	43	2016 (99), 2016 (9)	-	43
2	Vranj. Priboj	1948	68	-	-	68
3	Vlad. Han	1949	67	2018 (47)	2018	68
4	Tupalovce	1977*	42	1993 (26), 2015 (92)	1993, 2015	44
5	Grdelica	1948	73	-	-	73
6	Sij. banja	1982*	36	-	-	36
7	Magovo	1958	46	2006 (165)	2006	47
8	Merčez	1953	49	2006 (165), 2008 (158), 2015 (42)	2006, 2015	51
9	Donja Selova	1977*	41	1990 (92), 2018 (28), 2019 (56)	2018, 2019	43
10	Pepeljevac	1984*	37	-	-	37
11	Prokuplje	1951	64	2019 (82), 2020 (112)	-	64
12	Doljevac	1954	67	-	-	67
13	Pukovac ⁰	1961*	57	-	-	57
14	Leskovac ⁰	1955*	50	-	-	50
15	Pečenjevce ⁰	1982*	34	1990 (59)	1990	35
16	Visoka ⁰	1980*	35	1992 (31), 2015 (30), 2019 (35), 2019 (42), 2020 (30), 2020 (27)	1992, 2015	37

* - truncated dataset; 1 – high outlier detected in any dataset; 0 – zero flow(s) in any dataset

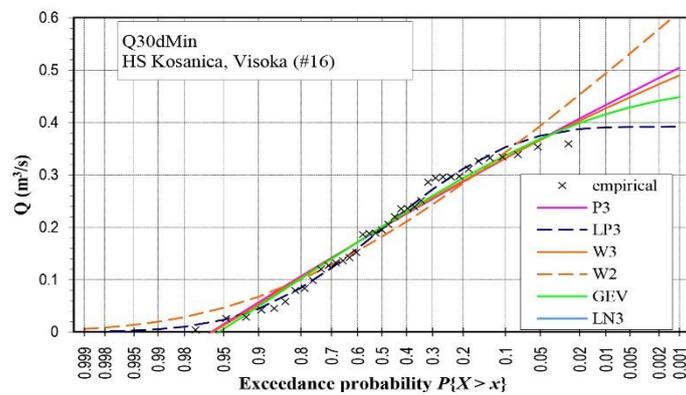


Fig. 2 Probability plot of the Q_{30dMin} sample at HS Visoka (no. 16)

2.3. Environmental flow assessment

Environmental flow is assessed by the GEP method [6], based on the comparison of 30-day minima (Q_{30dMin}) quantile to the lower and the upper threshold – a percentage of mean annual flow (Q_{AnnAvg}), depending on the season. The assessment procedure is given in the form of logical test – IF (logical test, value if true, value if false).

Winter flow:

$$Q_{Env} = IF(Q_{30dMin}, 80\% < 0.1 \cdot Q_{AnnAvg}, 0.1 \cdot Q_{AnnAvg}, (IF(Q_{30dMin}, 80\% > 0.15 \cdot Q_{AnnAvg}, 0.15 \cdot Q_{AnnAvg}, Q_{30dMin}, 80\%))) \quad (2)$$

Summer flow:

$$Q_{Env} = IF(Q_{30dMin}, 95\% < 0.15 \cdot Q_{AnnAvg}, 0.15 \cdot Q_{AnnAvg}, (IF(Q_{30dMin}, 95\% > 0.25 \cdot Q_{AnnAvg}, 0.25 \cdot Q_{AnnAvg}, Q_{30dMin}, 95\%))) \quad (3)$$

2.4. Regional analyses

The models based on regional analysis are selected for transfer of low flow indicators from donor stations – sixteen HS, to two ungauged basins. In general, the transfer is eligible within a hydrological homogeneous region. In this research, it is assumed that the homogeneity condition is met by the prevailing location of the donor catchments in the hydrogeological region III (Fig. 1) for the selected low flow model. In the case of the mean annual flow assessment model, homogeneity is confirmed in the original research [21]. In addition, a cross-correlation matrix is generated using all of the low flow indicators assessed for donor stations and the catchment area.

2.4.1. Low flow

In the hydrogeological homogeneous region, the following relations may be established according to Vladimirov's method [22]:

$$Q_{30dMin}, 80\% = f_1(A), \quad (4)$$

$$Q_{30dMin}, 95\% = f_2(Q_{30dMin}, 80\%) \quad (5)$$

where:

A – catchment area (km^2),

$Q_{30dMin}, 80\%$ – 30-day minimum flow of 80 % exceedance probability (m^3/s),

$Q_{30dMin}, 95\%$ – 30-day minimum flow of 95 % exceedance probability (m^3/s).

The procedure of Vladimirov's incorporates the following steps:

- Selection of donor stations (HS) to use the data for the regression model;
- Low flow statistical analysis for selected HS to obtain required flow quantiles;
- Development of linear regression models (4) and (5), where both independent and dependent variables are logarithmic transformations of original data.

2.4.2. Mean flow

On the sample of 184 catchments, Živković [21] has established a set of region-specific regression models for mean annual runoff estimation based on precipitation data in the period 1951-1980 and runoff in the period 1961-1990. The regional regression

equations are variable-specific and region-specific. The form of the established equation that uses physiographic characteristic – mean catchment altitude, is used here.

According to the regression equation for the region 8 – 'Južno Moravski' [21]:

$$\ln q = 1.47 + 0.001 \cdot X_{sr}, \quad (6)$$

where:

q - specific runoff -mean annual runoff per unit catchment area (l/s/km²)

X_{sr} - mean catchment altitude (masl - m above sea level).

Applied to the Tulovska river, ungauged basin I, equation (6) yields $q = 6.68$ l/s/km², i.e. mean annual flow $Q = 0.139$ m³/s [14]. In the ungauged basin II of the Vujanovačka river, $q = 6.578$ l/s/km², and $Q = 0.244$ m³/s [15].

2.5. Low flow indicators

A total of eighteen low flow indicators is considered in the research for each HS (Table 4). One set of indicators is merely hydrological, the other related to environmental flow. Fifteen indicators are low flow quantiles (50%, 70%, 80%, 90% and 95% exceedance probability) estimated by statistical analysis of three datasets: Q_{30dMin} , Q_{AnnMin} and Q_{MonMin} . Three indicators are calculated based on Q_{AnnAvg} assessment (10%, 15% and 25% of it).

The left pane in Fig. 3 shows the selection scheme of low flow indicators for environmental flow according to the two key criteria by the EPA [4]. $Q_{1dMin,90\%}$ and $Q_{7dMin,90\%}$ are hydrological indicators that have to be compared to the needs of the river ecosystem expressed through 'B' (biological) flows for the final decision upon design flow. Focusing on hydrological indicators in the research, $Q_{1dMin,90\%}$ is selected as a representative variable among lower extremes in the low flow indicators set. $Q_{1dMin,90\%}$ is interpreted as $Q_{AnnMin,90\%}$ quantile here, because the difference has not been found during the data examination process in the gauged flows between mean daily flow in the day of annual minima occurrence and an instant annual minima flow.

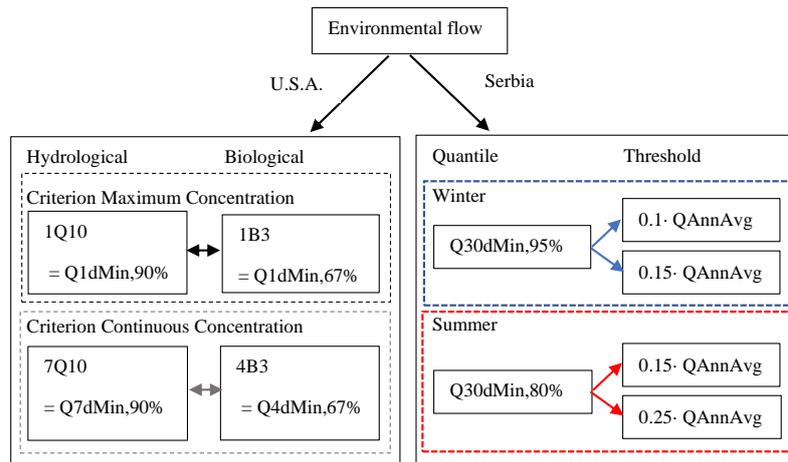


Fig. 3 The low flow indicators used in environmental flow assessment according to EPA (U.S.A.) and GEP (Serbia) methodology.

In the right pane of Fig. 3, the scheme for environmental flow selection according to the GEP method is presented, as explained in the section 2.3. The low flow indicators shown in the boxes are referred to as environmental flow related indicators, with addition of $Q_{AnnMin,90\%}$ quantile used in the EPA procedure.

Table 4 Low flow indicators considered in the research. Environmental flow related indicators are highlighted in blue.

No.	1	2	3	4	5
Ind.	$Q_{MonMin,50\%}$	$Q_{MonMin,70\%}$	$Q_{MonMin,80\%}$	$Q_{MonMin,90\%}$	$Q_{MonMin,95\%}$
No.	6	7	8	9	10
Ind.	$Q_{AnnMin,50\%}$	$Q_{AnnMin,70\%}$	$Q_{AnnMin,80\%}$	$Q_{AnnMin,90\%}$	$Q_{AnnMin,95\%}$
No.	11	12	13	14	15
Ind.	$Q_{30dMin,50\%}$	$Q_{30dMin,70\%}$	$Q_{30dMin,80\%}$	$Q_{30dMin,90\%}$	$Q_{30dMin,95\%}$
No.	16	17	18		
Ind.	$0.10 \cdot Q_{AnnAvg}$	$0.15 \cdot Q_{AnnAvg}$	$0.25 \cdot Q_{AnnAvg}$		

3. RESULTS AND DISCUSSION

3.1. Low flow indicator range

A general review of all eighteen low flow indicators at studied HS is shown in Fig. 4 and Fig. 5 by the box plots. The actual values of flows or statistics are not important, but the spread of flows/specific flows and its relative standing to the adjacent group of HSs. The box plots are arranged according to the catchment area in the ascending order.

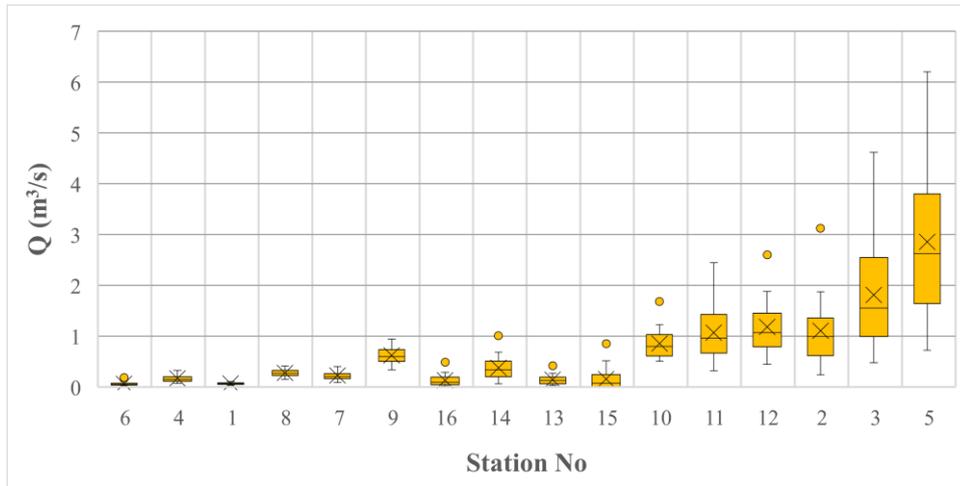


Fig. 4 The range of low flow indicators (flows) at HS ordered by ascending catchment area

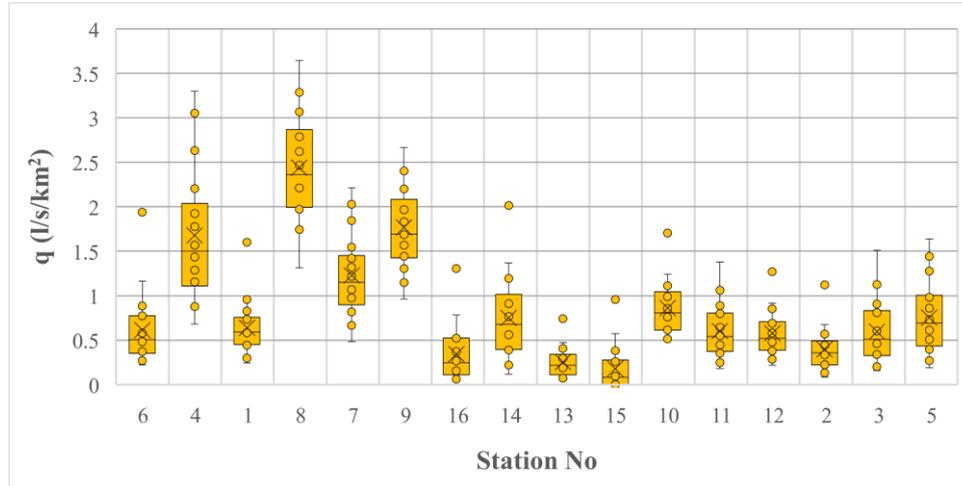


Fig. 5 The range of low flow indicators shown as specific runoff at HS by catchment area in ascending order

Both gradual rise of the box positions in Fig. 4 and gradual fall in Fig. 5 is expected. The HSs that behave differently in both Fig. 4 and Fig. 5 (the central part) are no. 16, 14, 13 and 15. These are the HS with zero flows in the Q_{AnnMin} datasets, while HS no. 15 also has zero flows in the Q_{MonMin} and Q_{30dMin} datasets. Due to a large number of zero flows at that station, some low flow quantiles ($Q_{MonMin,95\%}$; $Q_{AnnMin,90\%}$; $Q_{AnnMin,95\%}$ and $Q_{30dMin,95\%}$) could have not been assessed. Instead, the flow of $0.0001 \text{ m}^3/\text{s}$ is used for the calculation sake.

Among the HSs with small catchment area ($95\text{-}180 \text{ km}^2$), stations no. 6, 4, 1 and 7 seem too low with both flows and specific flows. They are on the left side in Fig. 4 and Fig. 5. Station no. 6 is upstream from the no. 14 with zero flows, being poor in water. Stations no. 4 and 1 are on the first order right tributaries to the Južna Morava river. It is interesting that in Živković's research findings [21], stations no. 1, 2, 3 and 4 belong to the same region for the mean annual runoff assessment. HS no. 7 is one of the stations protruding to the hydrogeological region IV in Fig. 1. However, stations no. 8 and 9 also do, but have higher flows. A different behavior of the station no. 7 from the whole set of HSs considered is also highlighted by the fact that it is the only station where LPT3 distribution could have not been used for quantile assessment but LN3 for the Q_{AnnMin} dataset.

3.2. Low flow indicator and catchment area correlation

Correlation between seventeen variables is examined, fifteen variables are low flow indicators 1-15 in Table 4, sixteenth is Q_{AnnAvg} , and seventeenth, catchment area (A). Fig. 6 shows output - a scatter plot of matrices, with bivariate scatter plots below the diagonal, histograms on the diagonal, and the Pearson correlation coefficient above the diagonal. Correlation ellipses are also shown. Robust fitting is done using LOWESS (locally estimated scatterplot smoothing) regression. The flow values are converted to l/s and log transformed - these values are reported as well as log transformed values of the catchment area.

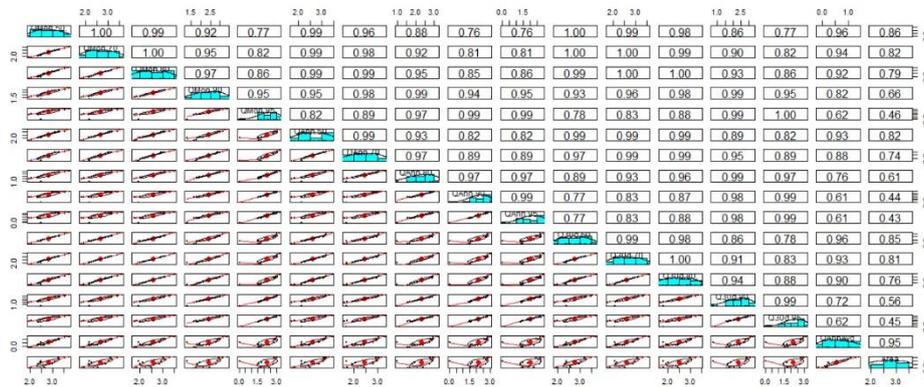


Fig. 6 Correlation among low flow indicators and catchment area

Correlation among the variables used in the GEP method, EPA method, and catchment area is shown in Fig. 7. The strongest correlation is exhibited between $Q_{MonMin,80\%}$ and $Q_{30dMin,80\%}$, $Q_{MonMin,95\%}$ and $Q_{30dMin,95\%}$ providing for assessment of Q_{30dMin} when instead of daily, monthly flows are available. Then, $Q_{AnnMin,90\%}$ and $Q_{30dMin,95\%}$ are also strongly correlated, and most importantly, Q_{AnnAvg} and catchment area, allowing assessment of the thresholds in the GEP method in ungauged basins.

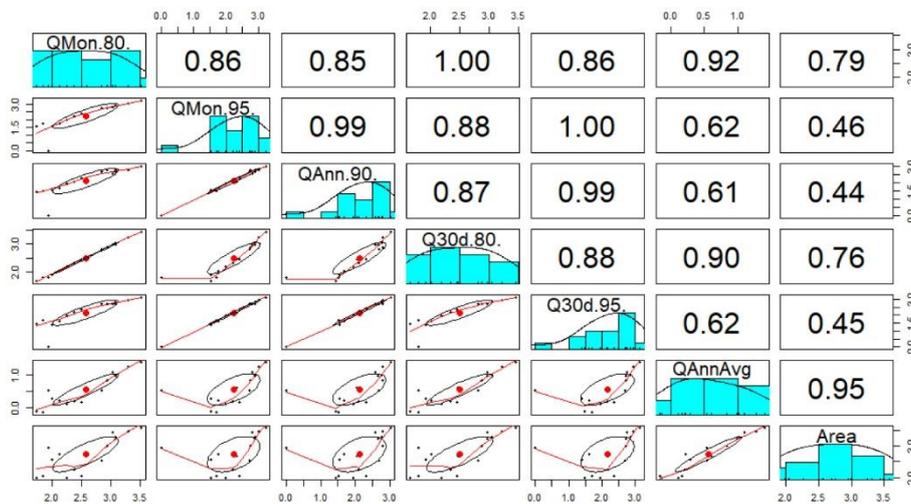


Fig. 7 Correlation among the environmental flow related indicators and catchment area – an excerpt from the 17 x 17 matrix shown in Fig 6.

3.3. Environmental flow at HS

The low flow indicators that are constitutive elements in the environmental flow assessment by the GEP method in the winter and summer period are shown in Fig. 8 and Fig. 9 respectively. The environmental flows are presented by the squares, while the EPA

methodology variable, the same for both winter and summer period - $Q_{AnnMin,90\%}$, is also shown in Fig. 8 and Fig. 9. The same variable types are connected by lines for better perception of their order throughout HS, represented by catchment area. The actual values of all low flow indicators from the group related to environmental flows are shown in Table 3. The values adopted for environmental flow Q_{Env} are highlighted in blue for the winter period, and in red for summer.

In all stations but no. 8 and no. 9, the environmental flow according to the GEP method equals the lower threshold, meaning the corresponding low flow quantile is below it. In the majority of the HS, $Q_{AnnMin,90\%}$ is the lowest flow, followed by the Q_{30dMin} and Q_{MonMin} quantiles, exhibiting strong correlation among each other as shown in Fig. 7. The correlation of $Q_{AnnMin,90\%}$ is stronger to the 95% than 80% quantile.

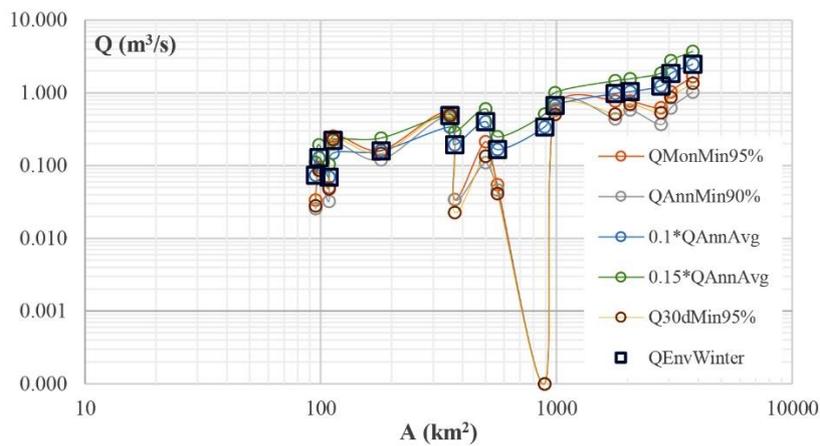


Fig. 8 Winter environmental flow and associated low flow indicators

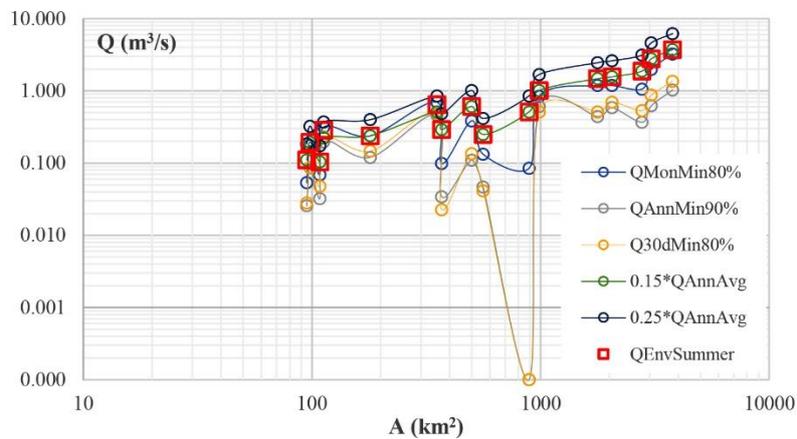


Fig. 9 Summer environmental flow and associated low flow indicators

At HS no. 15, there are 7, 4 and 3 zero-flows in the Q_{AnnMin} , Q_{30dMin} and Q_{MonMin} datasets respectively, presenting the case when quantiles cannot be estimated from the samples with zero flows due to the unmet condition $F(x) > 0$ as explained in 2.2.

In the stations no. 8 and no. 9, Q_{Env} is higher than the lower threshold both in the winter and summer period. These are the stations from the hydrogeological region IV (Fig. 1), and higher flows found in these stations is discussed in 3.1.

Table 3 Environmental flow assessed by the GEP method at HS ordered by catchment area

No	HS	A	$Q_{30dMin80\%}$	$Q_{30dMin95\%}$	$0.1 * Q_{AnnAvg}$	$0.15 * Q_{AnnAvg}$	$0.25 * Q_{AnnAvg}$	QEnv	
								Winter	Summer
[#]		[km ²]	[m ³ /s]						
6	S. Banja	95	0.046	0.028	0.074	0.110	0.184	0.074	0.110
4	Tupal.	98.1	0.154	0.087	0.129	0.194	0.324	0.129	0.194
1	V. Banja	108	0.063	0.048	0.069	0.104	0.173	0.069	0.104
8	Merčez	113	0.287	0.230	0.148	0.222	0.370	0.222	0.287
7	Magovo	180	0.219	0.147	0.159	0.239	0.399	0.159	0.239
9	D.Selova	353	0.646	0.487	0.339	0.509	0.848	0.487	0.646
16	Visoka	370	0.083	0.023	0.193	0.290	0.483	0.193	0.290
14	Leskovac	500	0.294	0.135	0.403	0.604	1.007	0.403	0.604
13	Pukovac	561	0.105	0.041	0.166	0.249	0.415	0.166	0.249
15	Pečenj.	891	0.063	0.000	0.341	0.511	0.852	0.341	0.511
10	Pepelj.	986	0.747	0.508	0.672	1.008	1.680	0.672	1.008
11	Prokup.	1774	0.926	0.509	0.979	1.469	2.448	0.979	1.469
12	Doljevac	2052	1.099	0.698	1.041	1.561	2.602	1.041	1.561
2	V. Priboj	2775	0.927	0.534	1.248	1.872	3.119	1.248	1.872
3	V. Han	3052	1.651	0.869	1.848	2.771	4.619	1.848	2.771
5	Grdelica	3782	2.765	1.355	2.480	3.721	6.201	2.480	3.721

3.4. Low flow indicators transfer to ungauged basins

The regression models employed for the transfer of environmental flow related low flow indicators by the method of Vladimirov’s are shown in Fig. 10 and Fig. 11. Station no. 15 is excluded from the modelling due to the zero-flow issue in the dataset Q_{30dMin} . The points representing stations (empirical points) are labelled according to the station number, while ungauged locations are labelled I and II (I - the Tulovska river, II - the Vujanovačka river).

In Fig.10, stations no. 8 and no. 9 are on the upper side of the regression line, between the upper confidence limit and prediction limit, while stations no.13 and no.16 lie in the lower belt between the lower confidence limit and the prediction limit. In Fig. 11, stations no. 1, 7, 8 and 9, are upper, only no. 16 is lower.

In the case when regression model is applied on the Q_{AnnAvg} and A variables, a different behavior of stations is exhibited in Fig. 12. Here, stations no. 4, 8 and 9 are in the upper belt, while no. 16 and 15 are in the lower belt, and station no. 13 is almost out of the prediction interval lower limit.

While stations no. 13, 15 and 16 are expectedly in the lower belts, stations no. 8 and 9 in the upper (Fig. 10 – Fig. 12), stations no. 1 and 7 (Fig. 11) and no. 4 (Fig. 12) point out to a different behavior during low-flow and mean-flow regime compared to other stations in the study area.

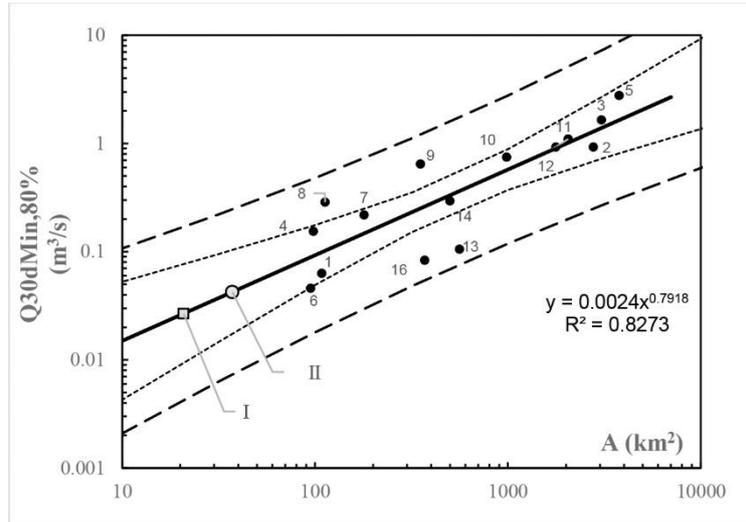


Fig. 10 Regression line according to eq. (4), 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

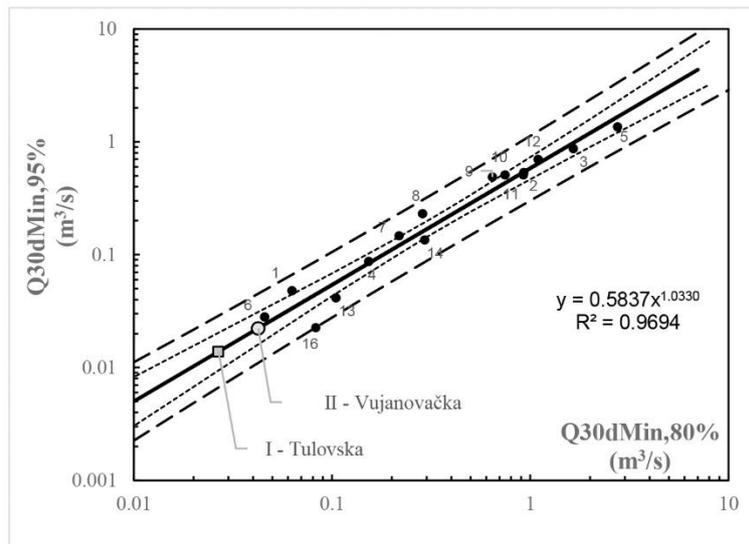


Fig. 11 Regression line according to eq. (5), 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

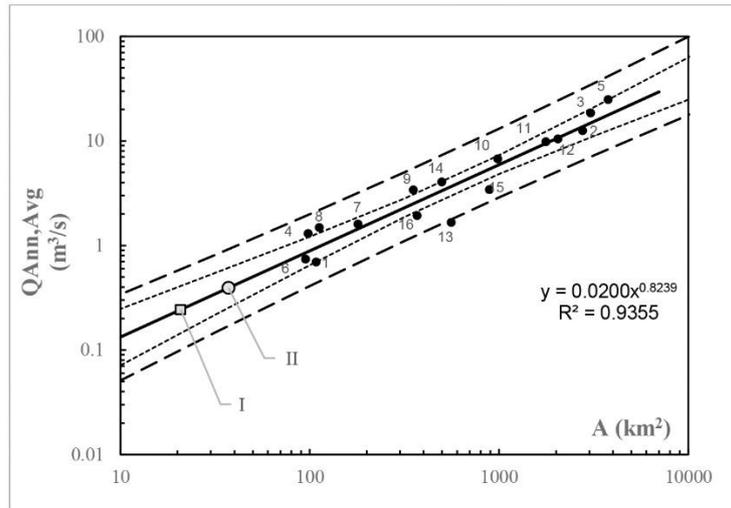


Fig. 12 Run 1: Regression line for $Q_{AnnAvg} = f(A)$ in the studied region, 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

3.5. Environmental flows assessed in ungauged basins

Based on the $Q_{30dMin} 80\%$ and $Q_{30dMin} 95\%$ low flow quantiles assessed by the Vladimirov method at both ungauged basins, Q_{AnnAvg} from both regression with catchment area (Fig. 12), and from the regional equation (6), environmental flow is determined by the GEP method (Table 3).

The difference in environmental flows obtained using the Q_{AnnAvg} values from the regression equation in Fig. 12 for the study area is -40% for the winter flow and -30% for the summer flow, compared to the ones assessed from the regional equation using mean catchment altitude as predictor variable [21].

Table 3 Environmental flows in two studied ungauged basins, run 1

Location	A [km ²]	Q _{30dMin} 80% [m ³ /s]	Q _{30dMin} 95% [m ³ /s]	Q _{AnnAvg} [21] [m ³ /s]	Q _{AnnAvg} regression, r. 1 [m ³ /s]	Q _{Env} - [21]		Q _{Env} - regr.1	
						Winter [m ³ /s]	Summer [m ³ /s]	Winter [m ³ /s]	Summer [m ³ /s]
I	20.8	0.026	0.014	0.139	0.244	0.014	0.027	0.024	0.037
II	37.2	0.042	0.022	0.244	0.394	0.024	0.042	0.039	0.059

Due to the significant differences between the assessed environmental flows, and previous research results related to mean flow of the Tulovska river - ungauged location I [23], a new regression model of Q_{AnnAvg} and catchment area is estimated (Fig. 13).

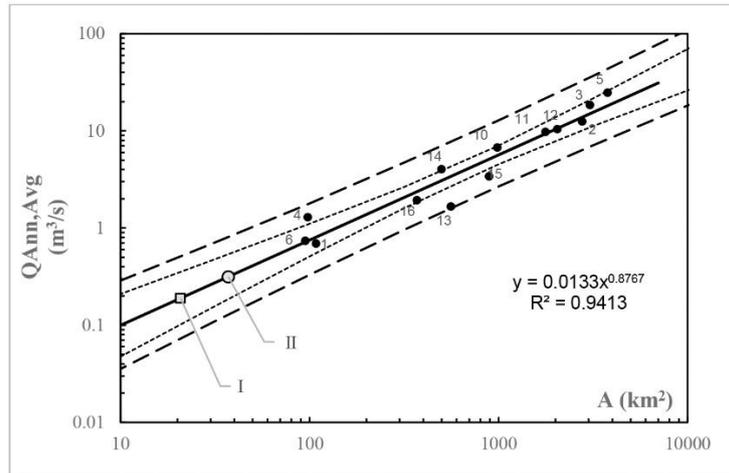


Fig. 13 Run 2: Regression line for $Q_{AnnAvg} = f(A)$ in the studied region without stations no.7, 8 and 9; 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

Stations no. 7, 8 and 9 are not considered in this model (run 2), as the stations from the hydrogeological zone IV, exhibiting different behavior in many investigated low flow aspects so far.

The difference in environmental flows obtained using the Q_{AnnAvg} values from the regression equation in Fig. 13 for the study area dropped to -25 % for the winter flow and -8 % for the summer flow, compared to the ones assessed by the equation (6), as shown in Table 4.

Table 4 Environmental flows in two studied ungauged basins, run 2

Location					QEnv - [21]	QEnv – regr.2			
	A	Q30dMin80%	Q30dMin95%	QAnnAvg [21]	QAnnAvg regression, r. 2	Winter	Summer	Winter	Summer
	[km ²]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]
I	20.8	0.026	0.014	0.139	0.190	0.014	0.027	0.019	0.029
II	37.2	0.042	0.022	0.244	0.316	0.024	0.042	0.032	0.047

4. CONCLUSION

A set of low flow indicators comprising eighteen hydrologically based variables is assessed by statistical analysis of four datasets. Sixteen investigated hydrologic stations belong to the upper and middle part of the Južna Morava river basin. Environmental flow

is assessed at each station by the GAP method - the hydrological index method. In the regional analysis procedure, regression models are applied for the transfer of low flow indicators to two small catchment area ungauged locations, where the environmental flows are also assessed.

The following is concluded:

1. Too many zero flows in the dataset may preclude quantile estimation. A practical approach is applied here – a flow of 0.0001 m³/s is assigned for such a quantile in the cases an absence of value would prevent a larger scale estimation like cross-correlation. Otherwise, stations having such quantiles are deleted from the set of donor stations, like in the method of Vladimirov's. For any further more detailed research, other options of zero-flow treatment should be considered, like in drought studies [24].
2. An examination of the low flow variables range prior to analyses is informative. Here, it was shown that some stations stand out from the others, therefore rising awareness about potential issues in the assessed environmental flows at ungauged basins.
3. Any hydrogeological information is helpful in low flow research. Even a macro-scale hydrogeological regionalization used here [16] has improved the final assessment of environmental flows by signaling on the need to eliminate stations located in the other region from the set of donor stations.
4. It is possible to switch between low flow indicators in the absence of daily flow data. A cross-correlation matrix of the low flow indicators and catchment area shows there is a strong correlation between some of the considered variables.
5. In the studied region of the Južna Morava river basin, the GEP method for environmental flow assessment may be based on the mean annual flow only. The environmental flows (winter and summer ones) assessed for the stations in the hydrogeological region III, correspond to the lower threshold values, a portion of the mean annual flow.
6. It appears that not only minimum monthly flow quantile can be used as an alternative to 30-day minimum flow quantile in the GEP method, but the minimum annual 90% quantile as well.
7. Knowing mean flow in ungauged basin is important for low flow regime. The regional equations for mean annual flow assessment developed by Živković [21] are recommended.

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REFERENCES

1. Đorđević, B. 1990. Vodoprivredni sistemi, Naučna knjiga, Beograd.
2. WMO. 2009. Manual on Low-flow Estimation and Prediction. Operational Hydrology Report No.50. World Meteorological Organization (WMO). WMO-No. 1029.
3. Bunn, S. E., and Arthington, A. H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492-507.
4. EPA. 1986. Technical Guidance Manual for Performing Wasteload Allocation. Book IV: Design Conditions, Chapter 1.
5. Knežević, B. & Đorđević, B. 2012. Metoda 'MABIS' kao podrška odlučivanju pri izboru ekološki prihvatljivih protoka. *Određivanje potrebnih protoka nizvodno od brana i rečnih vodozahvata*, *Vodoprivreda*, 44 (2012) 255-257 p. 25-41, Beograd, 2012

6. Đorđević, B. & Dašić, T. 2011. Određivanje potrebnih protoka nizvodno od brana i rečnih vodozahvata, Vodoprivreda, 252-254, (4-6/2011), Beograd, 2011.
7. 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: 397-441.
8. Gopal, B. 2013. Methodologies for the assessment of environmental flows. Environmental Flows an Introduction for Water Resources Managers (New Delhi: National Institute of Ecology) pp 129-82
9. The Nature Conservancy. 2018. Environmental Flows Methods and Tools. <https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/Pages/environmental-flows-metho.aspx> Visited on 29.11.2021.
10. Đorđević, B., Dašić, T., Plavšić, J. 2020. Uticaj klimatskih promena na vodoprivredu Srbije i mere koje treba preduzimati u cilju zaštite od negativnih uticaja, Vodoprivreda, Vol. 52 No. 303-305, pp. 39-68 Beograd, 2020.
11. Prohaska, S., Simić, Z., Orlić, A., Ristić, V. 2004. Osnovne hidrografske-hidrološke karakteristike sliva Drine i hidrometeorološki podaci, Vodoprivreda, Vol. 36 No. 207-208, pp. 21-38 Beograd, 2004.
12. Institut za vodoprivredu Jaroslav Černi (IJČ). 2015. Strategija upravljanja vodama na teritoriji Republike Srbije. Vlada Republike Srbije i Ministarstvo Poljoprivrede i životne sredine. Beograd.
13. Đurđević, V., A. Vuković, M. Vujadinović Mandić (2018): Izveštaju o osmotrenim promenama klime u Srbiji i projekcijama buduće klime na osnovu različitih scenarija budućih emisija, Treća nacionalna komunikacija o klimatskim promenama, Beograd
14. Radivojević, D., Blagojević, B., Mihailović, V., Blagojević, J. 2019. Hidrološka studija - Hidrološke podloge za potrebe izrade rasteretnog kanala Tulovske reke. Institut za građevinarstvo i arhitekturu Građevinsko-arhitektonskog fakulteta Univerziteta u Nišu.
15. Radivojević, D., Blagojević, B., Mihailović, V. 2020. Hidrološka studija Vujanovačke reke do profila lokacije propusta na ukrštanju kp.br.7956 i kp.br.7941 i kp.br.7944 KO Brestovac, Bojnik, Consult biro, Niš.
16. Nikić, Z. 2003. Hidrogeološka analiza formiranja i regionalizacija malih voda, Zadužbina Andrejević, 2003, ISBN: 86-7244-341-1
17. Republic hydrometeorological Service of Serbia .-. Hidrološki godišnjaci http://www.hidmet.gov.rs/ciril/hidrologija/povrsinske_godisnjaci.php
18. Kroll C.N. & Vogel R. M., 2002: Probability distribution of Low Streamflow Series in the United States. Journal of Hydrologic Engineering, ASCE 7(2), pp. 137-146.
19. Jennings M.E. i Benson M.A., 1969: Frequency Curves for Annual Flood Series with Some Zero Events or Incomplete Data. Water Resources Research, Vol. 5, No. 1, pp. 276-289.
20. Bulu A., 1998: Statistical Tehniques in Low Flow Hydrology. Proc. Low Flows Expert Meeting, Belgrade, Yugoslavia, FRIEND UNESCO IHP-V Project.
21. Živković N. 2009. Prosečni godišnji i sezonski oticaji reka u Srbiji, Naučna monografija. Univerzitet u Beogradu Geografski fakultet, Beograd, p. 1-175
22. Vladimirov A.M. 1976. Сток рек в маловодний период года. - Л.: Гидрометеиздат, Ленинград. 295 p
23. Blagojević, J., Blagojević, B., Mihailović, V., Radivojević, D. 2020. Prediction of mean runoff in a small ungauged basin using raster climatological data. Bulletin of the Serbian Geographical Society. Vol 100, No 2 (2020), p. 45-66.
24. Cavus, Y. & Aksoy, H. 2019. Critical drought severity/intensity-duration-frequency curves based on precipitation deficit Journal of Hydrology 584 (2020) 124312.

HIDROLOŠKI I EKOLOŠKI ASPEKT PRORAČUNA MALIH VODA U NEIZUČENIM SLIVOVIMA – STUDIJA SLUČAJA U SLIVU JUŽNE MORAVE

U radu je razmatrano osamnaest pokazatelja malih voda u šesnaest profila hidroloških stanica u slivu Južne Morave. Pokazatelji su ocenjeni statističkom analizom i grupisani u hidrološke i ekološke pokazatelje. Sračunata je korelacija između svih pokazatelja. Ekološki protoci u profilima hidroloških stanica dobijeni su metodom GEP. Pokazatelji malih voda su prebačeni na dva neizučena profila korišćenjem regresije sa geo-morfološkim karakteristikama sliva. Podešavanje vrednosti ekološkog protoka u neizučenim profilima urađeno je na bazi pripadnosti slivova donora hidrogeološkim regionima u izučavanoj oblasti.

Ključne reči: *pokazatelji malih voda, statistička analiza, regionalna analiza, neizučeni sliv, ekološki protok, GEP metoda*