Iskustva u korištenju regionalnih analiza za ocenu kvantila velikih voda na teritoriji BiH

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Experience in using regional analyzes to assess large water quintiles in B&H

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Kvantili velikih voda predstavljaju računske vrednosti od kojih se biraju merodavne veličine za mnoge namene u vodoprivredi i hidrotehnici. Ocena ovih kvantila je izazov i za izučene i za neizučene slivove. U radu će se prikazati iskustva u korišćenju različitih pristupa oceni kvantila za neizučene slivove metodama regionalne analize. Slivovi na kojima će se ilustrovati rezultati pripadaju slivu reke Save i deo su nedavno sprovedenih istraživanja i projekata za reku Unu, Vrbas, Bosnu i neposredne pritoke reke Save: Ukrinu, Tinju i Brku. Osim što je ovim pristupima zajedničko korišćenje regresione analize, najčešće između specifičnog oticaja i površine sliva, svaki pristup ima svoju specifičnost u pogledu izbora grupe stanica za preslikavanje karakteristika velikih voda.

Ključne riječi

Kvantil poplava, MIKE 11 – parametri NAM modela, regionalna analiza, nemjerljivi bazen, odabir donatorske stanice

Flood-related characteristics, most often flood quantile estimates, represent a set of assessed values from which a design flood is selected for many purposes in water management and hydraulic engineering. Estimating these characteristics/quantiles is a challenge for both gauged and ungauged basins. The paper presents experiences in using different approaches to flood related characteristics estimation for ungauged basins in Bosnia and Herzegovina by regional analysis methods. The basins where the results are illustrated belong to the Sava River Basin in Bosnia and Herzegovina, and are part of the recently conducted research and projects for the whole territory, and a specific large river basins of the Sana River, the Bosna River, the immediate right tributaries of the Sava River: the Ukrina, the Tinja and the Brka River. Each presented regionalization approach has its own specifics that varies from the common approach where specific/normalized runoff from gauged sites is transferred to ungauged sites within the same river basin by the regression model using catchment area as the only catchment attribute.

Key words

Flood quantile, MIKE 11 – NAM model parameters, regional analysis, ungauged basin, donor station selection

The problem of floods is a common problem of developed and underdeveloped countries of the world. In the period from 1998 to 2017, floods took the first place among natural disasters according to the frequency (43.4 %) and damage caused (45 % - $2 billion) [1]. Like many countries around the world, Bosnia and Herzegovina has improved its flood risk management in order to prevent or at least mitigate the damage.

In that sense, some of the measures included the adoption of the legal acts i.e. bylaws which provided the basis for development of the flood hazard and flood risk maps in accordance with EU Floods Directive (e.g. [2], [3]), building/maintaining flood protection structures (e.g. [39]) and installing/improving flood forecasting and early warning systems (e.g. [40]).

The base for flood estimation required for most of the flood risk management measures is gauged flow data, burdened by uncertainty due to short or interrupted gauging period, flow rating curve extrapolation, and lack of instantaneous flow records [4]. For both gauged and ungauged basins, statistical analysis is required for a flood quantile estimation. It can be performed on the annual maxima series (AMS) or the partial duration series (PDS). Issues that are most often present in statistical modelling of floods include presence of low outliers in data sets and their impact on the right end of the distribution [5], and mixed population.

The flood quantiles are most often estimated from the AMS in Bosnia and Herzegovina [17]. Maximum annual flows are generally more variable compared to average monthly or annual flows and therefore require long gauging period for the estimation of reliable statistics [6], which is why minimum series lengths are set. In Germany, an AMS length of at least T / 2 is required to estimate the quantile of the T-year return period [7], while in the former Yugoslavia it was mostly T / 5 to T / 3 [8].

To provide reliable estimates of floods in the conditions of short and unreliable datasets, hydrologists use alternative sources of information. The goal is to more reliably determine the statistical parameters, flood quantiles, and/or other flood-related characteristics. For this purpose, several information expansion techniques are commonly used: temporal [9], causal, and spatial [10, 11]. The presentation of the recent spatial information transfer application in Bosnia and Herzegovina is the focus of this paper.

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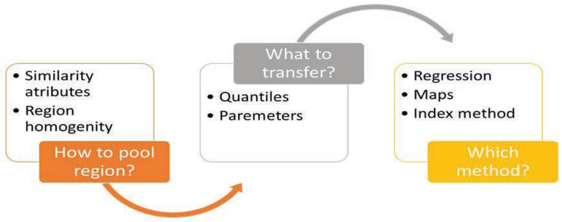
1. Regional analysis methodology issues

Spatial information transfer includes spatial regionalization methods in estimating flood parameters or flood quantiles. It is most often used when the gauging database is modest or the data is completely missing (ungauged site). Spatial transfer can be achieved through envelope curves, specific (normalized) flow diagrams, maps of statistical parameters (mostly higher order moments), or statistical regionalization procedures. Statistical regionalization involves determining the relationship between the flood parameters/ quantiles and morphological and/or meteorological parameters of the basin. This approach raises several questions (Figure 1):

- Which similarity parameter(s) and which method(s) to use for defining the region?
- How to examine the homogeneity of the region?
- What information to transfer from the region to the desired station and in what way?

The diversity of approaches to each of the issues has resulted in a large number of regionalization methods. Various methods for pooling groups have been proposed in the literature [10], but in practice there is no generally accepted procedure [11].

In the beginnings of statistical regionalization, regions were pooled in a subjective way. Areas within administrative, catchment and other borders, covering continuous geographical regions, were often considered homogeneous [12], under the assumption that changes in climate, morphology, geology, etc. are gradual in space.



Slika 1. A common issues in regional analyses

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2. Practice in Bosnia and Herzegovina

In Bosnia and Herzegovina, statistical regionalization is used almost exclusively for the assessment of flood quantiles in ungauged basins [17], whereby grouping of basins is done according to the proximity - location in the larger basin, pooling continuous regions.

The regression is often used as a transfer model within a region:

$$Q_{max,T} = a_T \cdot A^{b_T}$$

where:

$Q_{max,\,T}$ - the flood quantile (m^3/s) of the T-year return period,
a_T and b_T - the regression coefficients (for the return period T) obtained most often by the least square method.

A more often used regression form is:

$$q_{max,T} = a_T \cdot A^{b_T - 1}$$

where

$q_{max,\,T}$ - the specific/normalized flood quantile $q_{max,\,T} = Q_{max,\,T}/A$ ($m^3/s/km^2$) of the T-year return period.

On the territory of Bosnia and Herzegovina, the most used regional model is (2) (e.g. [28]), although its predictive characteristics are weak. In the basins of Austria, it has been shown that model (1) for estimating 100-year flood quantiles can produce significant differences (up to the third order) [29], while possible reasons are measurement errors, dry and wet periods in series and unrepresentative time frame, non-stationarity due to land use change.

3. Regionalization examples from Bosnia and Herzegovina

The recent examples of regional analysis on the territory of Bosnia and Herzegovina shown in this section are selected to illustrate any analysis part or step different from the common approach.

3.1. Small catchments in the Sana River basin

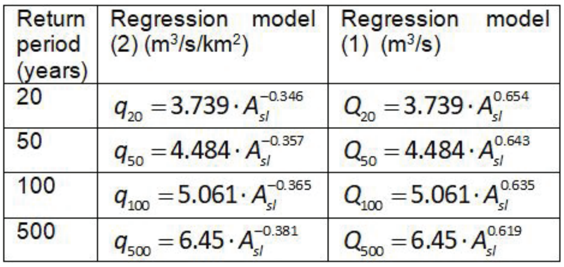
Three flood-related characteristics are analysed in the Sana and the Una River Basin as a part of flood protection project in the area of the Prijedor city [39]. The project focus is two flood defence channels and ungauged basin of the Bubnjarica stream. The Flood defence channels are of peripheral and drainage type, one protecting area on the left bank of the Sana River, the other located on the defending side of the levee (draining the area captured by levee and the main roads). These areas are typical plains that collect and drain precipitation generated runoff without interaction with the streams or rivers i.e. pluvial flood is treated here. The corresponding catchment areas are 3.87 km2 and 2.96km2 for the channels, and 1.71km2 for the Bubnjarica stream.

Three different sets of flood attributes are regionally analysed:

1. Flood quantiles estimated from the gauged data at hydrological stations available on the Una and the Sana River;
2. Cumulative distribution function (CDF) parameters obtained in the statistical analysis of flood flows of the Una and Sana Rivers;
3. Runoff coefficients from the rational method.

3.1.1. Flood quantiles vs. catchment area

The base regional analysis relies on the flood quantiles estimated from the AMS by the three-parameter Generalized Extreme Value (GEV) CDF. Gauged flows were available for 13 stations on the Una and Sana River, with gauging period in the range of 29-56 years. Regional regression model (2) is used. Results of the regional analysis are given in Table 1. The coefficient of determination R2 is between 0.91 for return period of 20, 50 and 100 years and 0.88 for return period of 500 years.



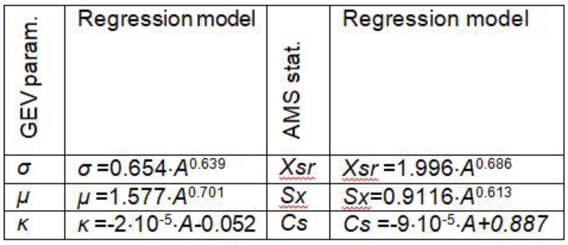
Return period (years)	Regression model (2) (m³/s/km²)	Regression model (1) (m³/s)
20	$q_{20} = 3.739 \cdot A_{sl}^{-0.346}$	$Q_{20} = 3.739 \cdot A_{sl}^{0.654}$
50	$q_{50} = 4.484 \cdot A_{sl}^{-0.357}$	$Q_{50} = 4.484 \cdot A_{sl}^{0.643}$
100	$q_{100} = 5.061 \cdot A_{sl}^{-0.365}$	$Q_{100} = 5.061 \cdot A_{sl}^{0.635}$
500	$q_{500} = 6.45 \cdot A_{sl}^{-0.381}$	$Q_{500} = 6.45 \cdot A_{sl}^{0.619}$

Table 1. Regression models between specific runoff and runoff and catchment area obtained from statistical analysis of AMS using GEV CDF

3.1.2. CDF parameters vs. catchment area

The second regression model is established between catchment area and three GEV parameters, namely parameter of scale - σ, location - μ, and shape - κ. The last one is poorly correlated with catchment area while for first two coefficient of determination R^2 is higher than 0.9.

The same procedure is conducted to obtain regression models between catchment area and AMS statistical parameters namely mean value, standard deviation and skew. The last one, mainly used to determine GEV shape parameter κ, is poorly correlated to catchment area, while mean value and standard deviation are correlated with R^2 of 0.98 and 0.93, respectively. Obtained regression models are given in Table 2.



GEV param.	Regression model	AMS stat.	Regression model
σ	$\sigma = 0.654 \cdot A^{0.639}$	Xsr	$Xsr = 1.996 \cdot A^{0.686}$
μ	$\mu = 1.577 \cdot A^{0.701}$	Sx	$Sx = 0.9116 \cdot A^{0.613}$
κ	$\kappa = -2 \cdot 10^{-5} \cdot A - 0.052$	Cs	$Cs = -9 \cdot 10^{-5} \cdot A + 0.887$

Table 2. Regression models between catchment area, GEV parameters and AMS statistics obtained from flood frequency analysis

3.1.3. Runoff coefficient regression models

The third regression analysis is conducted on the runoff coefficients.

Using flood quantiles obtained by the statistical analysis and known precipitation intensity-duration-frequency (IDF) curves at the nearby Prijedor meteorological station, runoff coefficients are calculated using well known rational method:

$$Q_{max,T} = \eta \cdot i_T \cdot A$$

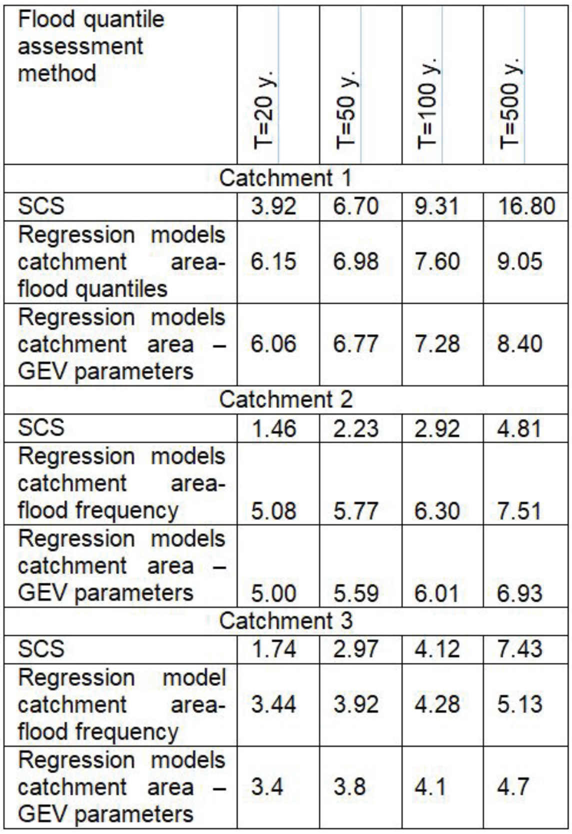
where:

$Q_{max,T}$ - the peak flow (m3/s) of the T-year return period,
η - runoff coefficient,
i_T - storm intensity (for the return period T),
A - catchment area.

Regression models are established between calculated runoff coefficients and three catchment characteristic: catchment area, longest flow path and average slope. The highest R^2 was found to be 0.18, i.e. no significant correlations were found. Therefore this analysis is rejected for flood quantile estimation.

3.1.4. Results

An additional flood quantile assessment is performed for the studied catchments by the rainfall-runoff modelling (the synthetic unit hydrograph method combined with the SCS-CN for assessing effective precipitation) [39]. The results of this analysis (denoted SCS) and those obtained from the regression models given in Table 1 and Table 2 are shown in Table 3.



Flood quantile assessment method	T=20 y.	T=50 y.	T=100 y.	T=500 y.
Catchment 1				
SCS	3.92	6.70	9.31	16.80
Regression models catchment area-flood quantiles	6.15	6.98	7.60	9.05
Regression models catchment area – GEV parameters	6.06	6.77	7.28	8.40
Catchment 2				
SCS	1.46	2.23	2.92	4.81
Regression models catchment area-flood frequency	5.08	5.77	6.30	7.51
Regression models catchment area – GEV parameters	5.00	5.59	6.01	6.93
Catchment 3				
SCS	1.74	2.97	4.12	7.43
Regression model catchment area-flood frequency	3.44	3.92	4.28	5.13
Regression models catchment area – GEV parameters	3.4	3.8	4.1	4.7

Table 3. Flood quantiles (m3/s) estimated from different analysis for the three studied small catchments

3.2. The direct right tributaries of the Sava River

The MIKE 11 – NAM model [38] for the basins of the Ukrina River, the Tinja River, the Brka River and the Bosna River is calibrated according to the regionally assessed model parameters. The model is set up for hydrological-hydraulic modelling within the frame of the Flood Forecasting and Early Warning System (FFEWS) [40].

The real-time FFEWS comprises the four river basins, out of which three are ungauged: the Ukrina (1500 km^2), the Tinja (950 km^2), and the Brka (233.2 km^2). The fourth is the gauged Bosna River Basin, all being the direct right tributaries of the Sava River (Figure 2). The optimized MIKE 11 – NAM model parameters at all subcatchments of the Bosna River Basin are used to establish the regression models between calibrated parameters and some physical and morphological basin characteristics. The combined hydrological-hydraulic modelling in the Ukrina, the Tinja and the Brka (UTB) river basins is done according to the subdivision of the basins in 14, 5 and 8 subcatchments respectively (Figure 3, Figure 4, Figure 5).

The proxy data (observed water levels) collected on sites during the flood in the year 2010 are used to verify the results of combined simulation of hydrologic and hydraulic models, where the MIKE 11 – NAM model parameters for the UTB Basins are estimated from the established regional regression models in the Bosna River Basin.

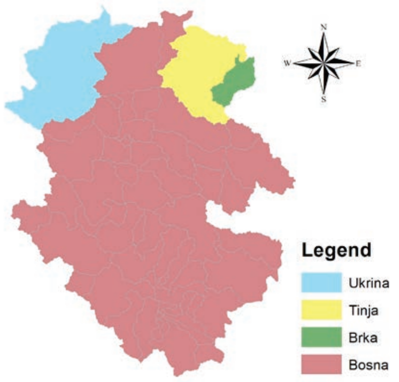


Figure 2. The FFEWS project area

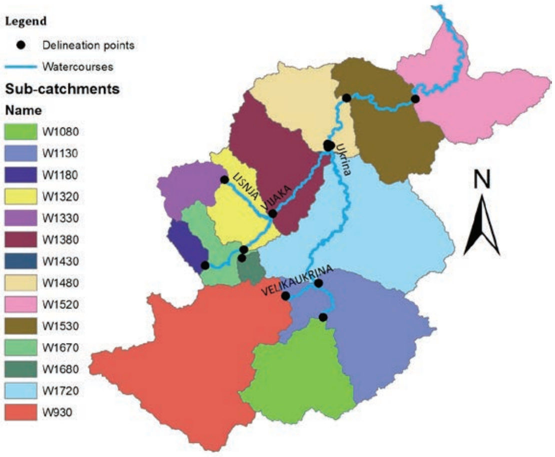


Figure 3. The subcatchment delineation scheme in the Ukrina River Basin

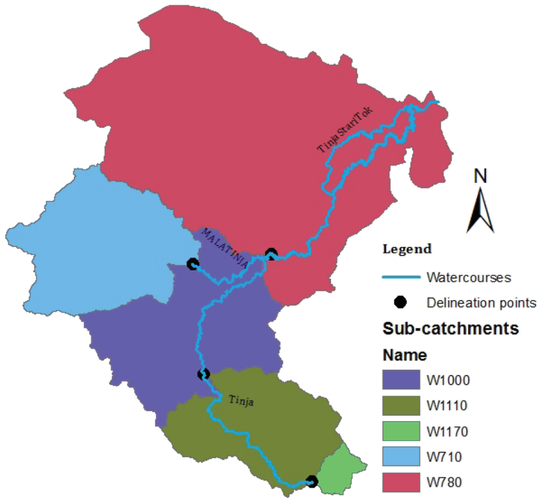


Figure 4. The subcatchment delineation scheme in the Tinja River Basin

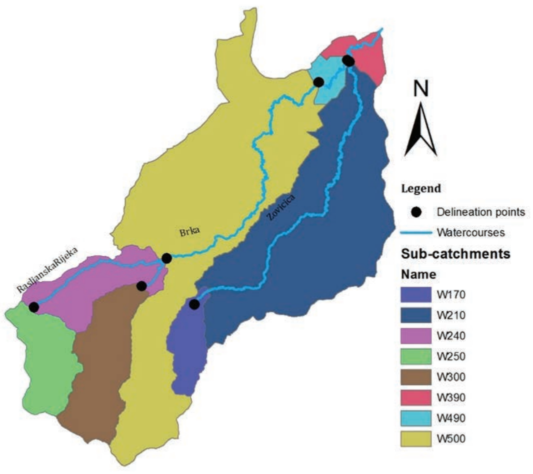


Figure 5. The subcatchment delineation scheme in the Brika River Basin

3.2.1. Regional analyses of the MIKE 11 – NAM model parameters and catchment attributes

A common starting approach regarding hydrological region pooling group composition is applied here: The catchment similarity base is spatial proximity that emerges from the assumption that rainfall-runoff relationship varies smoothly in place or is uniform in the specific (predefined) region. According to Merz and Blöschl [10], spatial proximity yields much better prediction results in ungauged basins than with any other catchment characteristic, while best results are obtained by combining spatial proximity approach and catchment attributes. Therefore, several catchment attributes are chosen for regionalization of the optimized MIKE 11 – NAM model parameters in the Bosna River basin subcatchments: (a) catchment area, (b) average catchment slope, (c) drainage network length, (d) density of drainage network (drainage network length divided by basin area), (e) forest coverage, (f) mean index of drainage density (GIS tool line density, density of linear feature in the neighbourhood of each output raster cell [41]), (g) catchment shape length, (h) catchment shape (the difference between min and max basin elevation divided by the catchment area) and (i) percent of basin area under hypsometric curve between two elevations (for example 450-500 m.a.s.l.).

The regressions are based on these catchment attribute sets and optimized parameter sets for the Bosna River subcatchments. Prior to that, pool of sub-catchments is grouped by their similarity according to each attribute. After hydrological model parameter determination, a preliminary flow simulation results are checked upon normalized regional flow duration curves (presented as ratio to mean flow) in the Bosna River Basin.

The final flow modelling results are verified using available proxy at-site data: 1) additional spatial data available at predefined areas under potential significant flood risk (APSFR), and 2) maximum inundation zones along the UTB rivers based on the 2010 flood. The latter is used for model recalibration.

Regarding catchment area, no significant correlations with the set of MIKE 11 – NAM model parameters were found. For the average catchment slope, a significant correlation is found only with CK1,2 parameter (timing constant for overland flow) including only 10 relatively low-land catchments with slopes between 6-15%. From this pool of catchments, the ones with very small areas are removed. With such a catchment area range, significantly better results are achieved. The correlation coefficient is 0.76, while regression model is two-degree polynomial, as shown in Figure 6. Somewhat weaker correlation is found between catchment drainage length and CQOF (overland flow coefficient) parameter, R^2=0.66. However, this parameter is highly correlated with the drainage density, as shown in Figure 7.

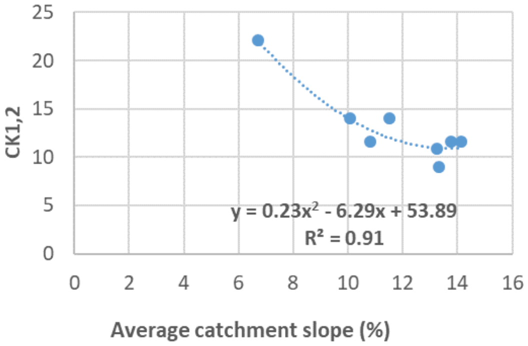


Figure 6. Regression models for average catchment slope and CK1,2 parameter

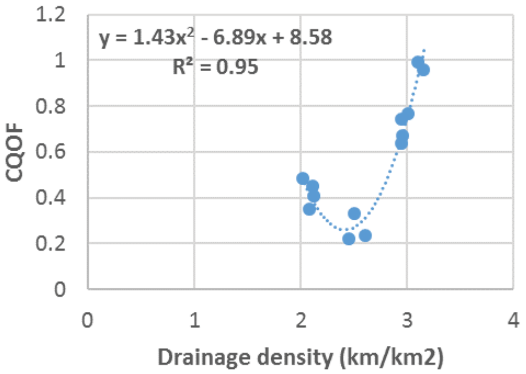


Figure 7. Regression model for drainage density and CQOF parameter

According to the percentage of forest coverage on catchments, 12 catchments were found similar to the ungauged catchments. Expectedly, parameters related to the surface storage and root zone are correlated with this characteristic. Correlations are shown in Figure 8 and Figure 9.

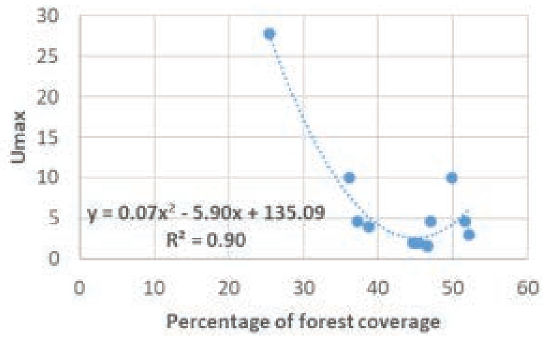


Figure 8. Regression model for forest coverage percentage

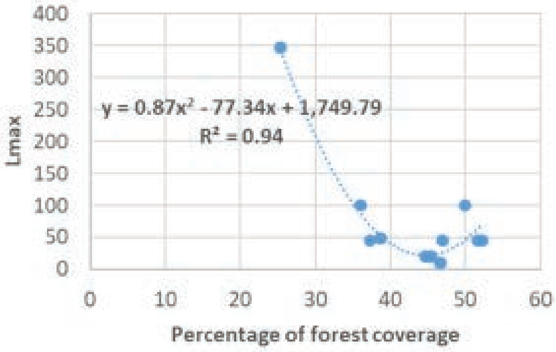


Figure 9. Regression model for root zone model parameter

The parameter of threshold for overland flow TOF is correlated with the drainage density index, as shown in Figure 10.

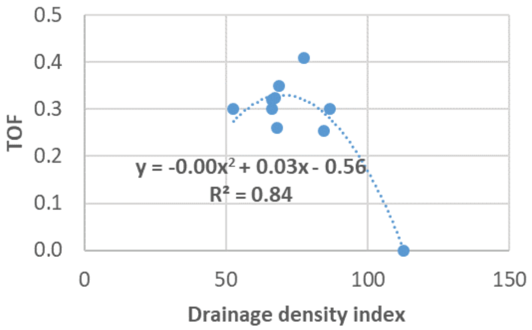


Figure 10. Regression model for drainage density index and TOF model parameter

3.2.2. Regional analyses significance in the UTB flow simulation

The complete regional analysis process was successful, because all sensitive MIKE 11 – NAM model parameters are connected (with known strength) to some of the catchment characteristic. The insensitive parameters are not, which was both expected and acceptable, due to their negligible influence on the model efficiency.

Although regional regression models provide for assessment of the MIKE 11 – NAM model parameters by using a specific catchment characteristics, there are situations where regional models give irrational parameter values (e.g. CQOF larger than 1, or L_{max} larger than recommended 300). Then, values are kept at the maximum /minimum of the recommended parameter range.

The final verification of hydrological modelling through hydrodynamic models has shown some of the parameters in subcatchments needed refinement in order to increase runoffs to meet water levels achieved during the 2010 flood. The most influential model parameters on runoff increase are CQOF and CK1,2, as well as L_{max} to some extent. Therefore, these parameters are fine-tuned for all subcatchments in the UTB basins until simulated water levels came close to the extent in the APFSR. This means that regional analysis i.e. the established regression models have led to the underestimation of floods in larger basins of the Tinja and the Ukrina River, while in the Brka River Basin, runoffs required only slight increase.

3.3. The Bosna River basin

3.3.1. An index flood method application

One of the earliest atypical regional analysis in the Bosna River Basin is published by Husno [31]. Flood quantiles are estimated by the regional analysis of average ratios between flood quantiles and mean flood data (AMS), versus flood recurrence intervals (return periods). The obtained regression models can then be used to calculate flood quantiles at ungauged sites within the same hydrologically-homogenous region.

The research results are based on the gauged data from the 19 hydrological stations in the Bosna River Basin with AMS ranging from 17 to 54 years, where the region homogeneity is checked by the test conducted on the 10-year flood characteristics. The CDF is Gumbel. Within the two-phased process, two regressions are established: 1) Mean flood vs. catchment area (Figure 11), and 2) Flood quantile to mean flood data (AMS) ratio vs. flood return period (Figure 12).

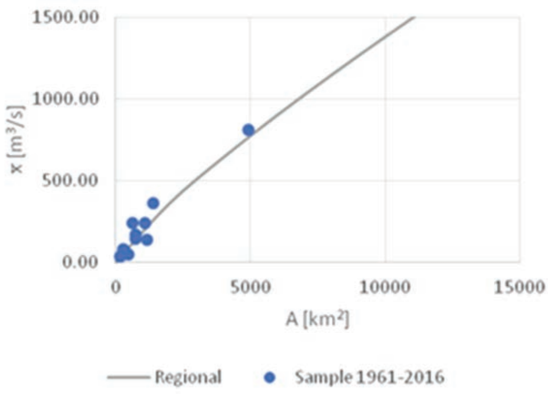


Figure 11. The original regression model (grey line) [31] with blue dots representing data based on the sample from the 1961-2016 period

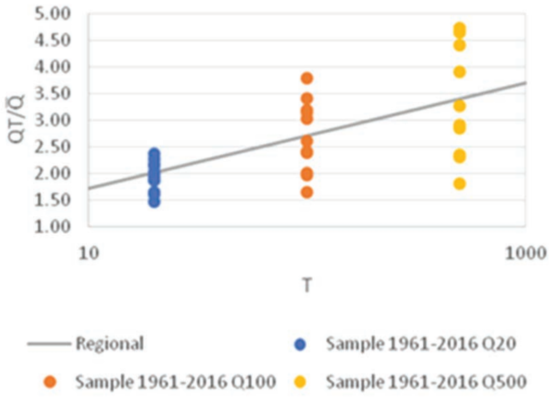


Figure 12. The original regional model (grey line) [31] with dots representing flood quantiles based on the sample from the 1961-2016 period

The index-floods shown in Figure 12 by blue, orange and yellow dots represent flood quantiles (T= 20, 100 and 500 years) estimated by regional analysis explained in the section 3.4 at eight hydrological stations matching those used in the original research [31]. The mean flood mapped on the Figure 11 is from the same stations/samples. The dispersion of the dots in both Figure 11 and Figure 12 point out the need for reassessing established regional relations.

3.3.2. A comprehensive regional study

The most recent comprehensive regional research of the Bosna river basin [17] starts from the assumption that continuous geographical area is usually not homogeneous in hydrological terms [15], and consequently rejects subjective regionalization (all catchments in the larger basin) due to its arbitrary character [16]. The study shows that the regions composed of catchments within the same basic basin are significantly heterogeneous [17]. The research phases are illustrated in Figure 13.

After pooling the region, as a prerequisite for regional analysis, homogeneity is examined. A large number of parametric and nonparametric tests have been proposed in the literature to examine whether the values of statistical parameters, quantiles or empirical functions are the same, or whether the differences between them are small enough to be attributed to sampling errors. Parametric tests examine the variability of the parameters (Cs, Cv, of a certain order of L-moment) or a dimensionless quantile within a region [18, 19, 20, 21, 22, 23, 24] and compare it with variability expected within homogeneous regions. The assessment of the parameters/quantiles variability of homogeneous region is most often examined using Monte Carlo simulation. On the other hand, nonparametric tests are based on a comparison of local and regional empirical distribution functions, obtaining critical values of test statistics using bootstrap simulations.

Regionalization methods are performed under the assumption of homogeneous regions, but often in practice, this step is neglected. It is assumed that the catchments in the proximity, belonging to the same basic basin are a priori homogeneous.

Due to the findings that physically close areas do not imply similarity in hydrological terms, the cluster methods and region of influence (ROI) are most used in hydrology [25, 26, 27, 28]. Regionalization in the Sava River Basin, part of which belongs to Bosnia and Herzegovina and part to Serbia is shown in [29, 30], while ROI and a combined ROI and cluster approach are used here [17].

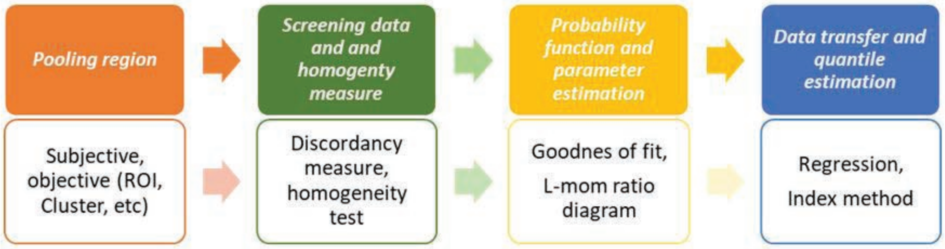


Figure 13. Regional analyses phases conducted in the comprehensive research [17]

To improve the flood quantile and/or CDF parameter estimates, additional variables/ attributes have been introduced, most often precipitation of a certain duration. However, a recommendation about variable types and their correlation with dependent variables still cannot be made.

Based on the AMS analysis by multiple linear regression for the first three conventional and L-moments in 366 Austrian basins, it was concluded that the model with three variables in most cases shows a significant correlation with flood characteristics, but also results in a substantial estimation errors [30]. The result is explained by the fact that flood frequencies are variable within regions. The paper also shows that the average annual precipitation as a significant variable stands out only in 8 basins, showing a negative correlation with the mean flood, while the basin area is significant in 2 basins only. Such a result is in contrast to the most studies where the average annual precipitation, along with the catchment area, represent best performing independent variables in regressions [31], [32]. [33].

In general, regression forms, regardless of their complexity, cannot adequately model quantiles of larger return periods or conventional or L-moments of higher order.

In an attempt to improve flood quantile estimation in Bosnia and Herzegovina by regional analyses [17], the Bosna River Basin data is expanded by the data from stations in Serbia from the Danube River Basin. The hydrological regions were pooled by the subjective and objective approach to catchment similarity, using a set of attributes:

- Subjective
    - all available stations comprise one region – label 1REG, and
    - all stations from the Bosna river basin comprise one region - label BASIN.
- Objective, based on:

- morphology (catchment area, mean altitude and average basin slope – label MORFO)
- annual maxima date (via Direction statistics- XY, relative frequency - RF, season-SEASON)
- combined morphology and annual maxima date (mean altitude and directional statistics- label H_XY)

The regions were pooled applying two common methods: ROI and CLUSTER, and two newly proposed procedures by Mulaomerović-Šeta [17] (labelled as CL_POD and R_C).

A variety of flood quantile estimation by the statistical analyses is performed considering:

- data gauging period (standard normal WMO period 1961-1990, and all gauged data until the year 2016),
- CDF (GEV with parameters estimated by the L-moment method, and LPT3 with expected moment algorithm (EMA) – B17C [42], [43].

The index-flood method is used for flood quantile transfer. The 100-year flood quantiles are shown in Figure 14.

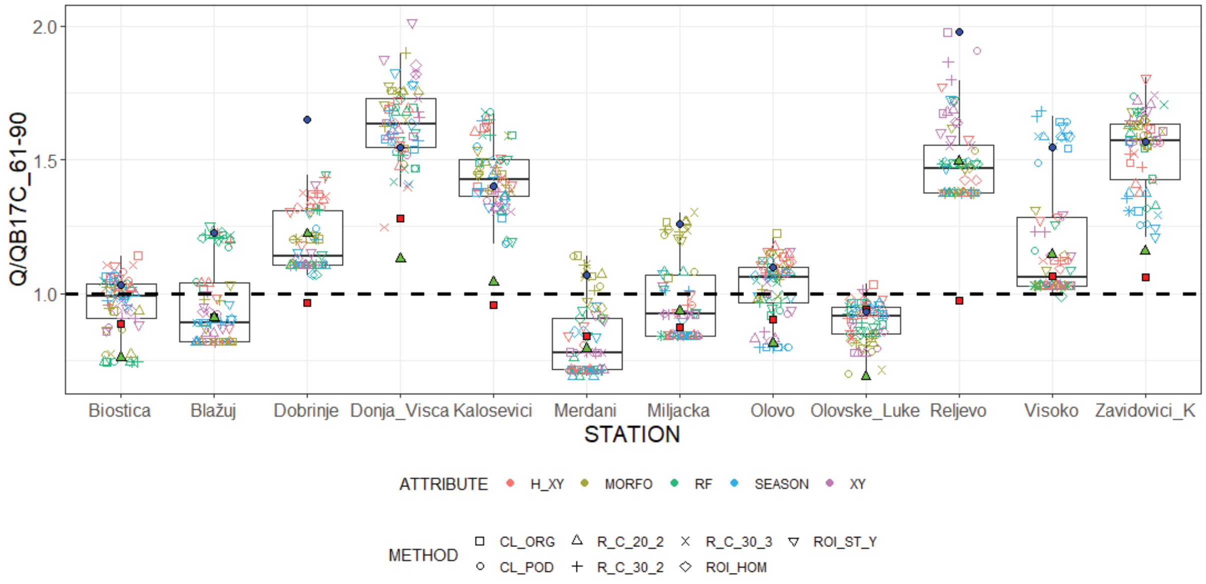


Figure 14. The 100-year flood quantile ratio of regionally estimated to statistically estimated quantiles by the B17C procedure (period 1961-1990) at stations in the Bosna River Basin

All markers without fill in Figure 14 show 100-year flood quantile ratio where objective approach to catchment similarity is applied (METHOD), while marker colour points out to the attribute used in region pooling (ATTRIBUTE). Three markers with fill show 100-year flood quantile ratio obtained by subjective approach: 1REG (blue dots) and BASIN (green triangles), as well as alternative 100-year flood quantile estimated by the statistical modelling - B17C (red squares) from the whole gauging period.

As point is closer to the dashed line y = 1, the closer is the value to the QB17C_61_90 quantile at station. Among subjective methods, 1REG overestimates quantiles at all stations but one (Olovske Luke), while BASIN is mostly between +/- 0.25 around 1, except at the Reljevo station where the ratio is 1.5. Blažuj and Donja Višća are the only stations where B17C quantile estimated from the longer period is close to 1.25, compared to the prevailing range of +/- 0.15 around 1 at other stations.

The applied regionalization methods in general give balanced 100-flood quantiles at six stations: Bioštica, Blažuj, Merdani, Miljacka, Olovo and Olovske Luke, while for the remining six stations, they tend to overestimate flood quantiles. The regionalization methods or attributes that systematically over or underestimate flood quantiles cannot be singled out from the results shown in Figure 14. The stations where the flood quantile overestimation is present: Donja Višća, Reljevo and Zavodovići_K, comprise carstic formations in their basins, which is not the case in the Kaloševići station, also overestimated by the regional analyses methods.

3.4. The Sava River basin in Bosnia and Herzegovina

Understanding the importance of karst in the rainfall-runoff process in the basins of Bosnia and Herzegovina, a subjective regionalization of catchments is performed in the Flood hazard and flood risk mapping project [44], where a robust division of the territory in three belts of Dinaric Alps or Dinarides is used [45] (Figure 15).

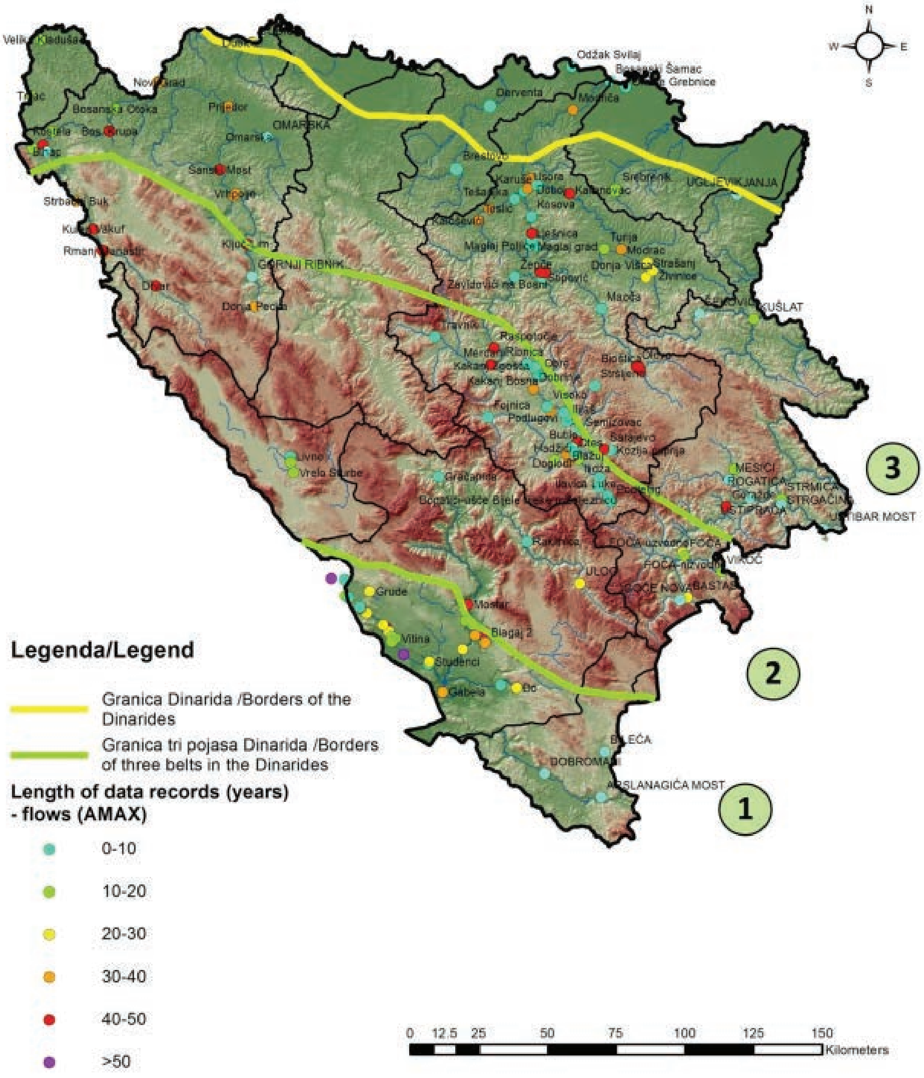


Figure 15. Three belts of Dinarides and location of hydrologic stations with gauging data record lengths

The station marker colors in Figure 15 show the available data record length in the period 1961-2016 at each hydrologic station. The stations considered for regional analysis are selected according to both physical/morphological and statistical requirements: 1) up to 2500 km2 of catchment area, due to difference in flood-generating processes in larger and smaller catchments, 2) more than 20 years in data record, and 3) homogeneous AMS proven by statistical tests.

The classification of catchments in three belts of Dinarides is done according to its prevailing area (>50%) in the belt. A number of stations that met the requirements set for regional analysis in belts 2 and 3 of the Dinarides is satisfactory, while in belt 1 it is not, due to the requirements of the intended regression analysis with two-parameter model. Therefore, further regionalization is done for the Belts 2 and 3. Four CDFs are considered for flood quantile estimation at each station: two-parameter Log-normal, Gumbel, Pearson 3 and Log-Pearson 3 (LPT3). The CDF adopted at each station is the best fit to empirical function. The prevailing CDF is LPT3.

The estimated flood quantiles at the Belt 2 and Belt 3 stations are transformed to specific/normalized runoff and two regression models type (2) are defined, as shown in Table 4 and Figure 16 and Figure 17. Region homogeneity is not tested.

Return period T (years)	Region/ Belt 2		Region/ Belt 3	
	$q_{max,T}$ regression model (2)	R^2	$q_{max,T}$ regression model (2)	R^2
20	$3.9952\ A^{-0.356}$	0.76	$4.3705\ A^{-0.349}$	0.38
100	$7.2716\ A^{-0.406}$	0.76	$6.5257A^{-0.361}$	0.36
500	$6.8608\ A^{-0.364}$	0.52	$13.244\ A^{-0.435}$	0.41

Table 4. Regression models for estimating specific flood runoff via catchment area, defined for the Belt 2 and Belt 3 of the Dinarides

Better regionalization results are achieved in the Belt 2 compared to the Belt 3, according to the coefficient of determination (Table 4). However, the corresponding 100-year flood quantile estimates in the Vrbas River Basin catchments [45], shown in Figure 16 and Figure 17, exhibit better agreement in the Belt 3 compared to the Belt 2 where they are definitely smaller.

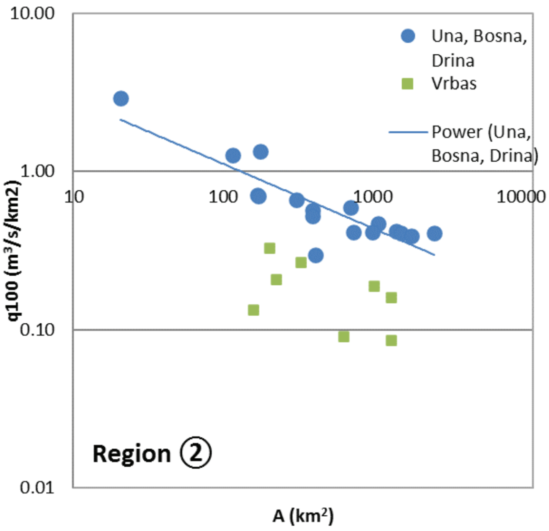


Figure 16. 100-year normalized flood quantile regression model in the three belts of Dinarides – Region 2

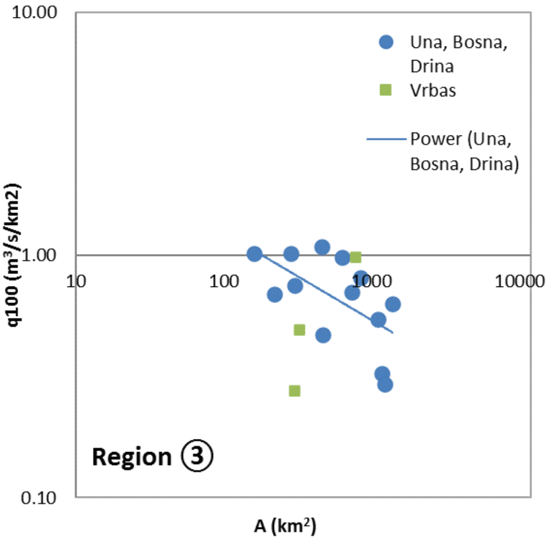


Figure 17. 100-year normalized flood quantile regression model in the three belts of Dinarides – Region 3

The hydrodynamic flow modelling conducted for the flood hazard mapping [43], yielded better results with flood quantiles assessed from the presented regionalization results when applied to ungauged locations at the river reaches, compared to other flood quantile estimates obtained by the alternative regionalization (large basin by large basin) and rainfall-runoff modelling performed within the project [43].

4. Conclusion

Seven different regional analysis examples for the territory of Bosnia and Herzegovina are shown in the paper, where the spatial information expansion technique is used as an option for more reliable determination of the AMS statistical parameters, CDF parameters, flood quantiles, and simulation model parameters.

In the examples where flood quantiles are used, a different CDFs are considered: the GEV in two examples, LPT3 as a second choice, and a mix according to the best fit to empirical function.

The prevailing region pooling method in the examples is subjective, run by affiliation of catchments to a larger basin, or forced by the karst content. Among objective region pooling methods, three different methods are shown in one example, ROI, Cluster and a newly proposed combined method of the two. There is one example where region homogeneity is tested prior to flood information transfer. Two examples use index-flood method for the information transfer, while the rest use regression.

The following is concluded:

1. There are catchment attributes not suitable for regional analysis (e.g. runoff coefficient);
2. Regional analysis may be an excellent source of support when estimating simulation model parameters. However, results obtained by the models with regionally assessed parameters need to be verified:
3. Hydrological homogeneity of the region has to be tested;
4. Regional models developed in the past have to be updated and checked for performance;
5. Besides catchment area, there is a variety of attributes that should be considered in any new regional analysis. Some of them should reflect karst content of the catchment.

The recent regionalization examples from the territory of Bosnia and Herzegovina show that new research findings and newly developed methods are successfully implemented in regional hydrology in the Country.

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