14
Research paper I Оригинални научни рад
DOI 10.7251/STP2215142B
ISSN 2566-4484

Borislava Blagojević, Univeristy of Niš, borislava.blagojevic@gaf.ni.ac.rs
Žana Topalović, University of Banja Luka, zana.topalovic@aggf.unibl.org
Petar Praštalo, University of Banja Luka, petar.prastalo@aggf.unibl.org

COMPARATIVE ANALYSIS OF AN UNGAUGED BASIN MODELLING RESULTS BY THREE CONCEPTUAL HYDROLOGICAL MODELS

Abstract

The hydrometeorological data availability is the main issue for hydrological modeling, especially pronounced in ungauged basins. The research presented in the paper attempts at overcoming the data availability issue by applying three different hydrological models, and observing the most acceptable basin response from an ungauged basin. The calibration and validation of models is performed on flow duration curves from nearby gauged catchments, and the agreement of simulated and 'observed' flows is compared visually and quantitively for characteristic flows. An annual distribution of monthly to mean flow ratio is also observed. The best performing model is HBV light, although the studied annual flow ratio and the ratio pattern cannot be achieved by any of the applied models in the periods of calibration and validation.

Keywords: Flow duration curve, ungauged basin, HEC-HMS, HBV light, GRJ4.

UPOREDNA ANALIZA REZULTATA MODELIRANJA NEIZUČENOG SLIVA POMOĆU TRI KONCEPTUALNA HIDOLOŠKA MODELA

Сажетак

Расположивост хидрометеролошких податакa је један од главних проблема у хидролошком моделирању, нарочито на хидролошки неизученим сливовима. Истраживање представљено у овом чланку има за циљ да превазиђе проблем расположивости података употребом три различита хидролошка модела и уочавањем најприхватљивијег одговора неизученог слива. Калибрација и валидација модела је извршена коришћењем кривих трајања протока формираних из података околних изучених сливова. Слагање симулираних и постојећих кривих трајања је оцијењено визуелним прегледом и квантитативно за карактеристичне протоке са криве трајања. Унутаргодишња расподјела односа мјесечних и средњих протока је такође анализирана. ХБВ лигхт модел даје најбоље резултате иако однос мјесечних и средњих годишњих протока као и њихова унутаргодишња расподјела није добро репродукована ни са једним моделом у периодима калибрације и валидације модела.

Кључне ријечи: криве трајања протока, неизучен слив, HEC-HMS, HBV light, GRJ4.

1. INTRODUCTION

Hydrological modeling as a scientific discipline is introduced in the 1960s. Hydrological models provide insight to the temporal and spatial variability of water resources essential for a variety of water-related fields including effective management of these resources, and preventing risk disasters. Transformation of precipitation into runoff is a complex natural process per se, therefore demanding for hydrological modeling. Simulating runoff and/or assessing flows has always been a key task in hydrology, especially in the hydrologically ungauged basins where statistical methods cannot be applied due to the absence of flow observation data [1]. Besides the lack of runoff data in the desired period or absence of these data at all, another modelling issue is insufficient quality of the runoff data that can be present in the gauged catchments. Such a situation increases already existing uncertainty of modelling both in the model calibration and validation periods. One of the questions regarding calibration (and validation) strategy is: What should be the main object of calibration?

Costa et al. [2] performed the parameter calibration of the large basin model consisting of several smaller catchments, having flow duration curves (FDCs) as the main object of calibration. The research goal was production of the ranked flows through a set of parameters, regardless of runoff serial structure. Through the evolution of rainfall and evaporation over the simulation period, this structure is retrieved indirectly. This approach reduces regionalization to the FDC parameters.

By using the HBV runoff model that only requires daily temperature, precipitation and monthly potential evaporation as input, Pool et al. [3] investigated the choice of a sampling strategy for individual runoff measurements when taken at strategic points in time during one year. They have found that FDCs were generally better simulated when strategies captured low and mean flows.

The approach Westenberg et al. [4] used for regionalization of FDCs accounted for runoff and input-output data uncertainties in FDC and rainfall-runoff model regionalization, while Westenberg et al. [5] developed a new calibration method using FDCs. The method addresses issues found in calibration with traditional performance measures such as the Nash-Sutcliffe model efficiency.

The research goal in this paper is to find out which model structure can be considered an appropriate hypothesis of the mean daily flows in an ungauged catchment through calibrating a hydrological model, as recommended in [5]. The object of calibration is FDC, while indirect validation also includes reproducing an annual distribution of monthly to mean flow ratio.

The motivation for the research is a demand for a water reservoir operation management plan in an ungauged basin in a poor data environment, emphasized by the data gap typical in Bosnia and Herzegovina for the period 1991-2000 and later.

2. METHODOLOGY

2.1. HYDROLOGICAL SIMULATION MODELS

Three hydrological models for continuous hydrological simulations were used in this research: HEC-HMS, HBV light and GR4J.

The HEC-HMS model is primarily intended for modeling runoff from isolated rainfall episodes such as design storms, but also allows for continuous hydrological simulations [6]. It consists of several components intended for modeling effective precipitation, direct and base runoff and runoff transformation. In this research, two variants of HEC-HMS model were considered: model A, with snow in its structure in addition to the input data on precipitation, temperature and evapotranspiration. Model B has no snow in its structure, therefore it uses precipitation and evapotranspiration as the input data. A total of 8 parameters were used when calibrating the model.

The HBV light model is based on the water balance equation [7]:

$$P - E - Q = \frac{d}{dt}(SP + SM + UZ + LZ + lakes) \qquad (1)$$

where P – precipitation [mm], E - evapotranspiration [mm], Q – runoff [mm/day], SP – snow pack [-], SM – soil moisture [mm], UZ – upper groundwater zone [mm], LZ – lover groundwater zone [mm], lakes – lake volume [-].

The model simulates daily discharge using daily rainfall, temperature and potential evaporation as input. A total of 19 parameters were used when calibrating the model [8], [9].

The GR4J model is a water balance hydrological model with four parameters developed by Perrin et al. [10]. It is an empirical model but its structure is similar to the conceptual models. It takes into account the humidity and contains two reservoirs (production and routing). Unit hydrographs are also associated with the hydrological behavior of the basin.

Figure 1 shows the structure of the hydrological models used.

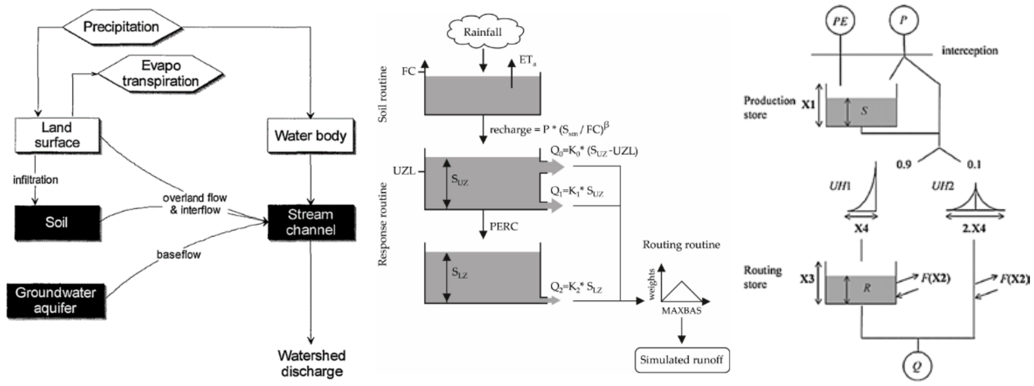

Figure 1. *Structure of hydrological model: HEC-HMS (left) [7], HBV light (center) [9], GR4J (right) [10]*

2.2. THE STUDIED CATCHMENT AND INPUT DATA

The Drenova Reservoir was established by the construction of the Drenova concrete dam on the river Vijaka, the largest left tributary of the Ukrina river, a direct right tributary of the Sava River. The research treated the catchment area up to the location of the Drenova dam, with a basin area of 68 km^2. The elevation range of the catchment is from 161 m above sea level (masl) at the dam location and 594 masl at the highest catchment point. The hydrographic river network comprises of four small rivers: Vijaka, Topolova, Lišnja and Drenovica with their tributaries [11].

The main river is the Vijaka river, 14 km long with an average slope of 1.25%. The catchment is considered hydrologically ungauged basin, regardless of the short period of flow and precipitation observations in the vicinity, due to unreliable hydrological data for the Vijaka river [12].

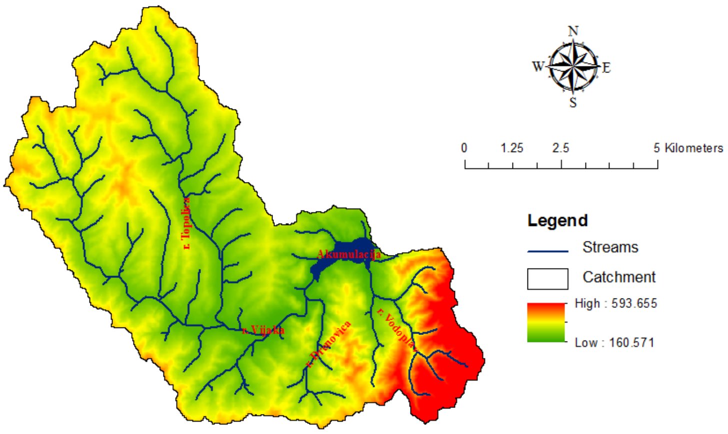

Figure 2. *Digital elevation model (DEM) and river network of the studied Drenova catchment [11]*

Data on daily precipitation and air temperatures from the meteorological station (MS) Banja Luka were used as input data for hydrological modeling of the Drenova dam basin, according to the spatial analysis results where MS Banja Luka, MS Doboj and MS Slavonski Brod were considered [11].

In the HEC-HMS and HBV light models, a monthly evapotranspiration is assessed by the Thornthwaite method, while in the GR4J model, daily evapotranspiration input data is determined by the Hamon method.

The time step for all hydrological models is one day.

2.3. CALIBRATION OF MODEL PARAMETERS

The choice of strategy for calibration of model parameters and validation of simulation results is complex when it comes to gauged basins. Usually split-sample test (SST) [13] is used to determine period for calibration on which model is trained and period of validation (different from calibration period) on which model will be tested in means of capability to simulate runoff outside of the training period. Nowadays, calibration is performed using some of the many automatic optimization algorithms which exclude subjectivity incorporated in the process of manual calibration and recommended use of more than one calibration criteria [14], [15].

For ungauged basins, a special model calibration and verification strategies are used. The basic strategy, also applied here, is the division of the available observed data period into periods for model calibration and verification, and using a dimensionless flow duration curve (FDC) instead of flows. A FDC formulated in this way, links the ratio of the characteristic flows of a given duration to the mean annual flow.

To obtain the dimensionless FDCs at the Drenova ungauged basin in the calibration and verification periods (Figure 3), FDCs from the eight hydrological stations (HS) are averaged. The obtained two dimensionless FDCs are considered the reference FDCs for the Drenova ungauged catchment. In the HS selection process, the main criterion is hydrometeorological data availability, while other criteria are data completeness, the catchment area and the distance (as crow flies) from the Drenova catchment, as shown in Table 1. In Figure 4, the map of selected HS and MS is presented.

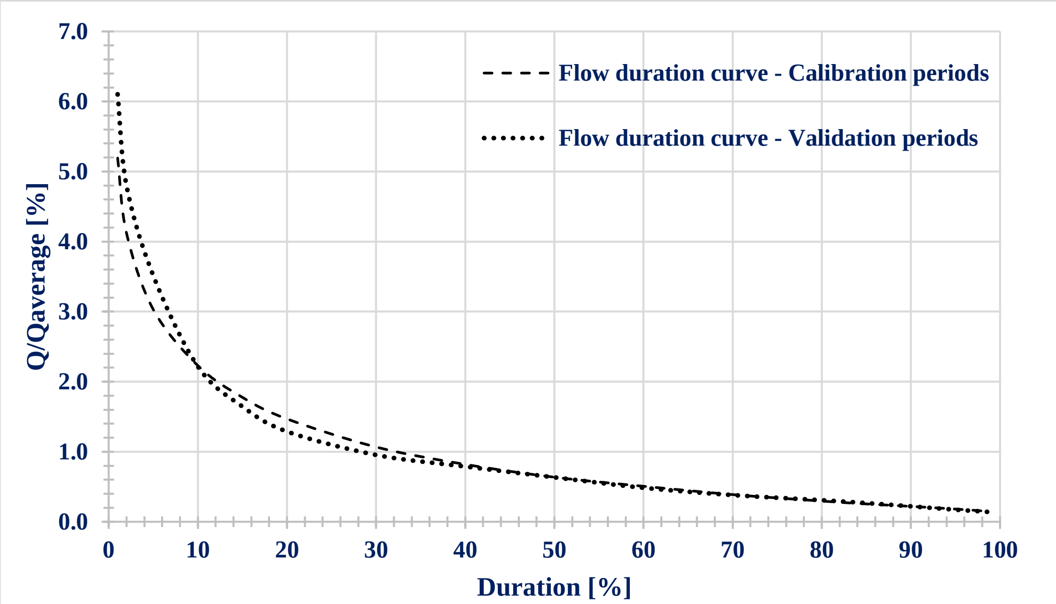

Figure 3. *The reference dimensionless averaged FDC in the model calibration and validation periods [11], [16]*

Table 1. The set of HS used for calibration and validation of the Drenova basin model [16]

No.	HS	River	Area [km^2]	Available data records	Distance from Drenova [km]
1	Hrustovo	Sanica	348	1966-1990; 2006-2008	74
2	Rmanj Manastir	Unac	1010	1961-1990; 2007-2008	125
3	Blažuj	Zujevina	155	1966-1990; 2006-2008	118
4	Dobrinje	Bosna	2677	1961-1990	93
5	Kalošević	Usora	633	1961-1990; 2006-2009	27
6	Karanovac	Spreča	1828	1961-1990; 2006-2008	52
7	Merdani	Lašva	950	1961-1990; 2006-2008	80
8	Modrac	Spreča	1176	1961-1990; 2006	77

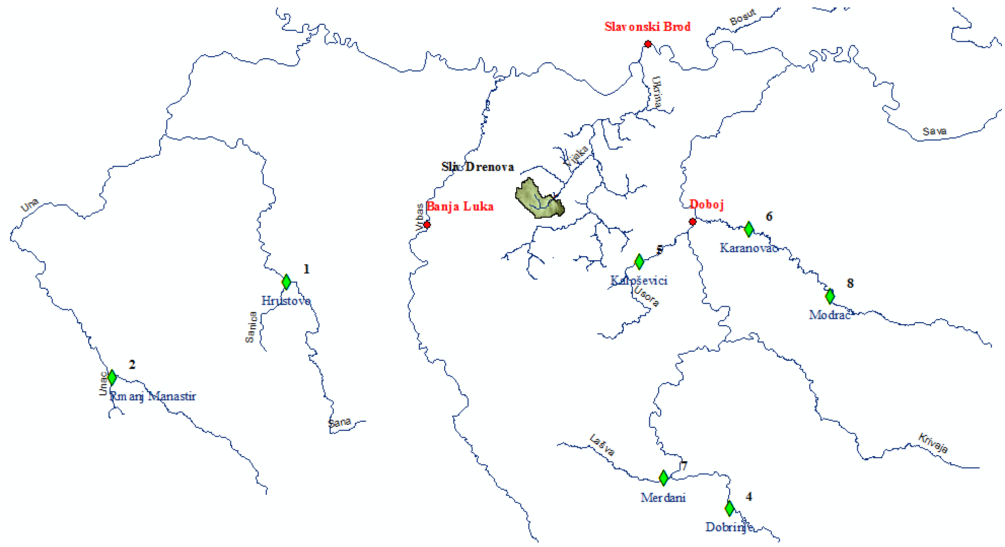

Figure 4. *Location of the Drenova catchment, meteorological stations (red circles), and hydrological stations (green diamonds) used for calibration and validation [16]*

3. RESULTS AND DISCUSSION

3.1. FLOW SIMULATION BY THE THREE MODELS

The daily flows simulated by the three studied models is shown in Figure 5 for one year. In this year, HBV light model exhibits the highest flow responses to precipitation, GR4J the lowest, while HEC-HMS model A with snow, results in higher flows than model B without snow.

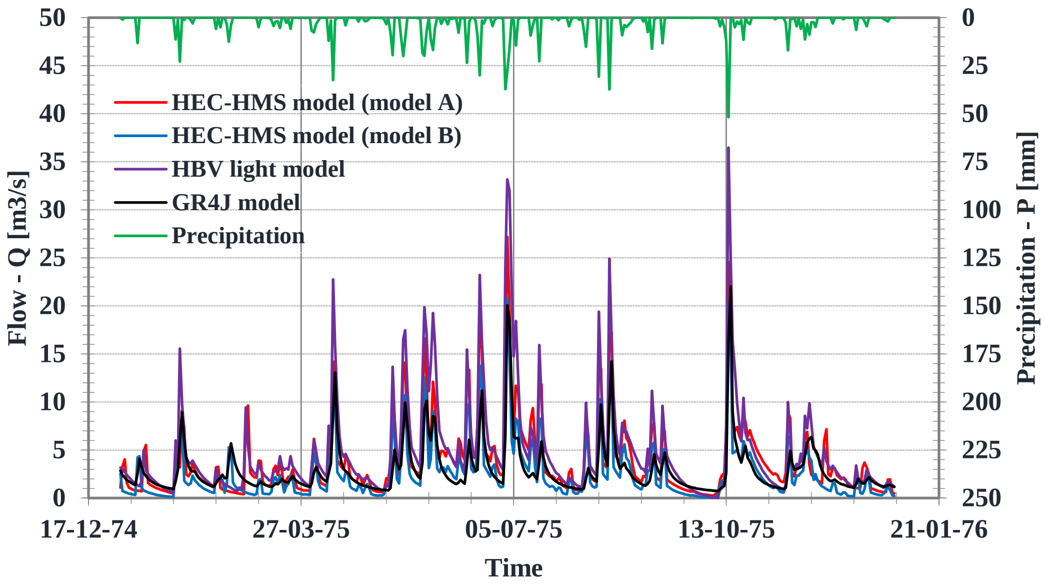

Figure 5. *Simulation results for the year 1975 in the calibration period*

3.2. FLOW DURATION CURVES IN CALIBRATION AND VALIDATION PERIODS

The reference dimensionless FDCs used for calibration (Figure 6) and validation (Figure 7) are shown with the achieved FDCs generated from the modelling results. These two sets of FDCs behave differently in the calibration and validation periods, i.e. their shifts compared to the reference FDC are more pronounced in the flood to mean flow range durations (<30%) in the validation compared to calibration periods. In the mean to low flow durations (>50%), the gap between FDCs is similar in these two periods.

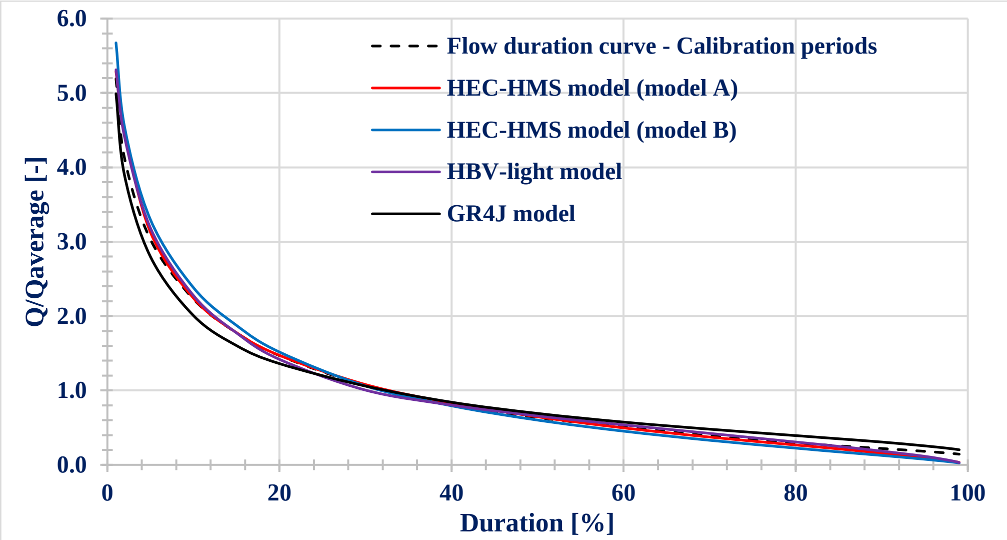

Figure 6. *The reference FDC and FDCs generated from flow modelling results in the calibration periods*

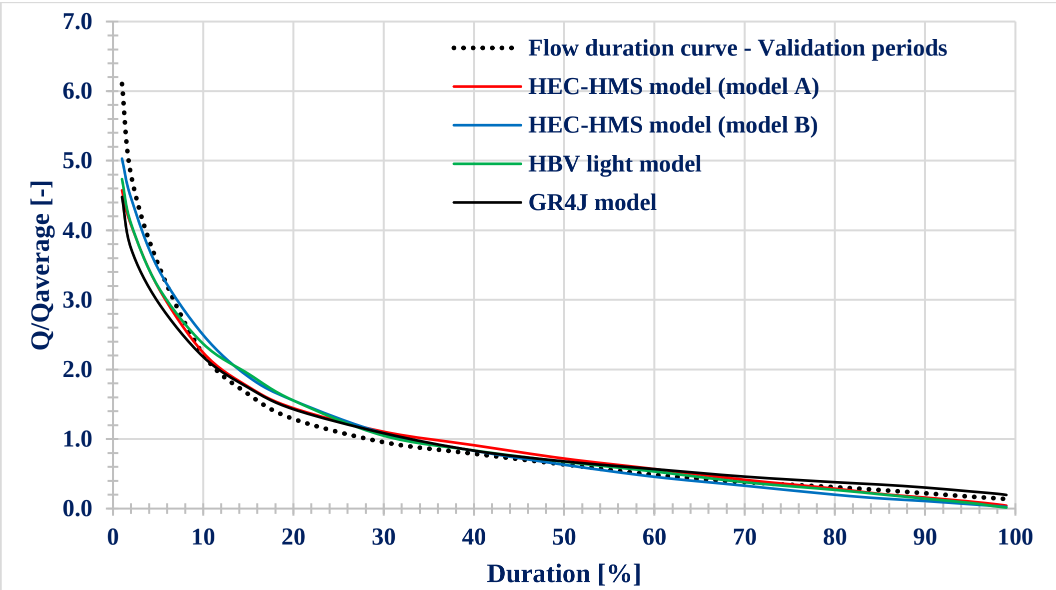

Figure 7. *Observed and simulation FDC and FDC for validation periods*

The fit between the reference FDC and the simulated FDC was determined for six characteristic durations: 1, 5, 30, 50, 70 and 95%. The absolute errors per model and duration are shown in Table 2.

In the model calibration period:

– HEC-HMS model (model A) is the best fit for durations of 1%, 5%, 50% and 70%, while HBV light is the second best;
– HEC-HMS model (model B) and GR4J are best fit for the duration of 30%;
– HBV light model is best fit for the duration of 95% where GRJ4 is the second best.

In the model validation period:

– HEC-HMS model (model B) is the best fit for durations of 1%, 5% and 50%, while HBV light is the second best for all durations but 30% and 70%, where it is the best performing model.
– HEC-HMS model (model A) is the best fit for duration 95%.

Overall, HBV light is the best performing model, ranked first in the validation, and second in the calibration period.

Table 2. Absolute error of the dimensionless FDCs for characteristic durations

Periods	Duration	HEC-HMS model (model A)	HEC-HMS model (model B)	HBV light model	GR4J model
Calibration (1961-1990)	1%	0.096	0.482	0.120	0.202
	5%	0.099	0.267	0.155	0.231
	30%	0.012	0.007	0.062	0.008
	50%	0.010	0.035	0.022	0.055
	70%	0.015	0.058	0.035	0.091
	95%	0.086	0.106	0.067	0.074
Validation (2005-2008)	1%	1.529	1.073	1.368	1.624
	5%	0.333	0.065	0.324	0.548
	30%	0.151	0.128	0.093	0.130
	50%	0.085	0.005	0.039	0.044
	70%	0.033	0.053	0.002	0.078
	95%	0.071	0.109	0.091	0.075

3.3. ANNUAL FLOW DISTRIBUTION

The ability of models to replicate flow dynamics is assessed in this research via the annual flow distribution. Again, the ratio of monthly to mean annual flow is considered, but for calendar months. This merely visual comparison of annual flow patterns is done for the set of diagrams constructed for the HS used for generating the Drenova ungauged basin reference FDC, and HSs on the direct river Sava tributaries in BiH. The source of the latter background diagram is the analysis of water balance of Republika Srpska [12].

3.3.1. Annual flow distribution in calibration period

The annual distribution of runoff is similar in the HS shown in Figure 8, when it comes to the periods of high and low flow, except for the river Spreča and the river Unac, where the wettest month is February. The results of the simulation in the HEC-HMS package for model A and model B, indicate that the model is not able to reproduce the annual distribution of runoff both in the terms of dynamics and flow variability [16]. The same stands for the HBV light and the GR4J model in the calibration period, although HBV light model shows better variation in runoff between the high and low water periods, compared to the other models.

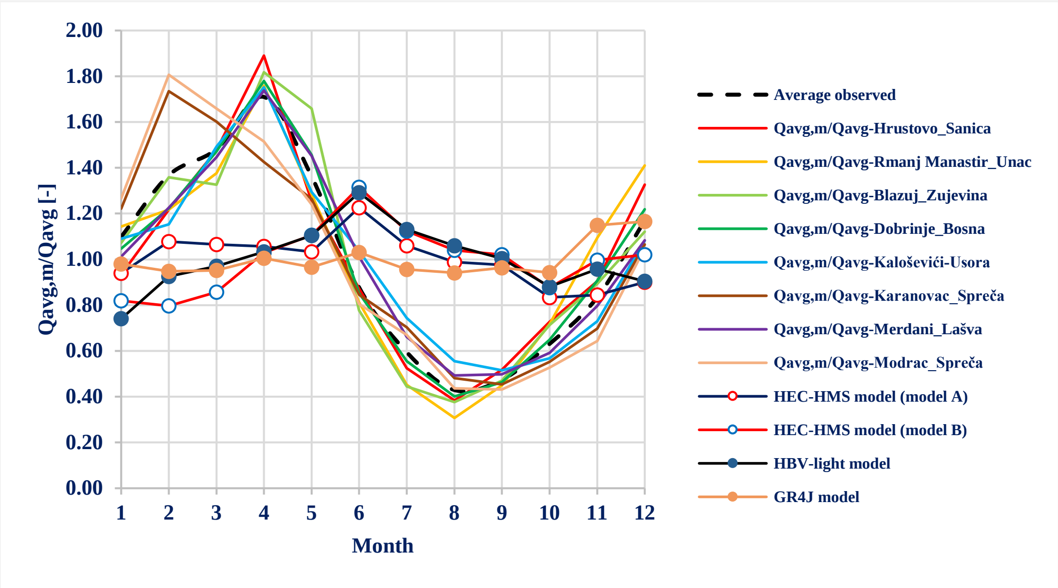

Figure 8. *Calibration period: Annual flow variability at HS used for model calibration and variability achieved by modelling the ungauged catchment of the Drenova*

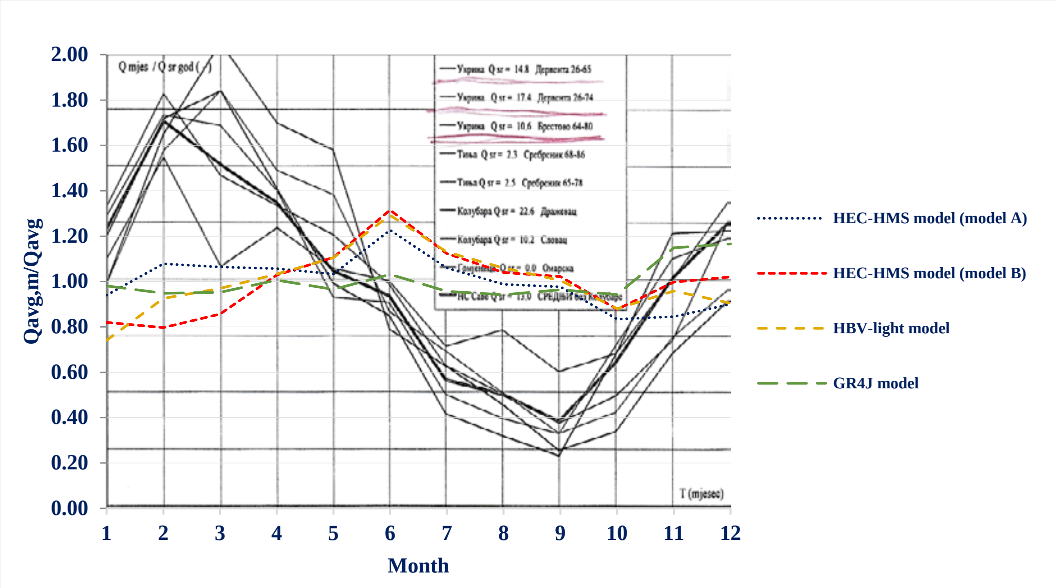

Figure 9. *Calibration period: Annual flow variability for the direct tributaries to the river Sava [12] and variability achieved by modelling the ungauged catchment of the Drenova*

A more pronounced differences are found in the comparison with the immediate Sava River tributaries in Figure 9 for the calibration period. The diagram shows the dimensionless annual flow distribution in the river basins of the rivers Ukrina, Tinja and Gomjenica, and the HS in the Kolubara river in Serbia. The applied models were not able to produce flows that would lead to a realistic annual distribution both in the period of flood and low flows and the variability of flows. GR4J model performs worst in both comparisons shown in Figure 8 and Figure 9.

3.3.2. Annual flow distribution in validation period

The dimensionless annual flow distribution diagram achieved by the three investigated models in the river Drenova catchment is plotted on the corresponding diagrams shown in Figure 10 and Figure 11. The validation period of three years (2006-2008) used for validation of FDCs is short for reliable insight to annual flow distribution. Therefore, the diagrams are used to observe if models are able to produce any variability in annual flow distribution, and match periods of high and low flows.

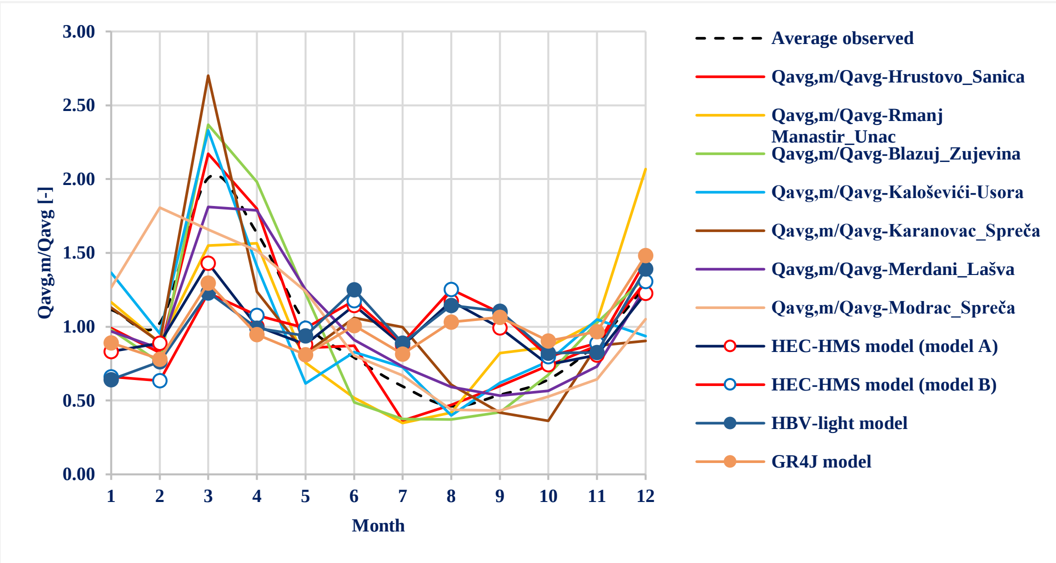

Figure 10. *Validation period: Annual flow variability at HS used for model calibration and variability achieved by modelling the ungauged catchment of the Drenova in the same period*

The obtained variability of monthly flows is better in the validation period in all models compared to the calibration period. All of them exhibit primary maximum in March, that corresponds to general behavior of HSs shown in Figure 10. The months of June, August and September in the river

Drenova catchment show higher flows than expected in the validation period by all models. A similar situation is in comparison to the direct tributaries to the river Sava, shown in Figure 11: The most noticeable mismatch appears in the low flow period August-September where modelled flows point out to the secondary flow maximum. Such a case is most pronounced for the GRJ4 model according to timing.

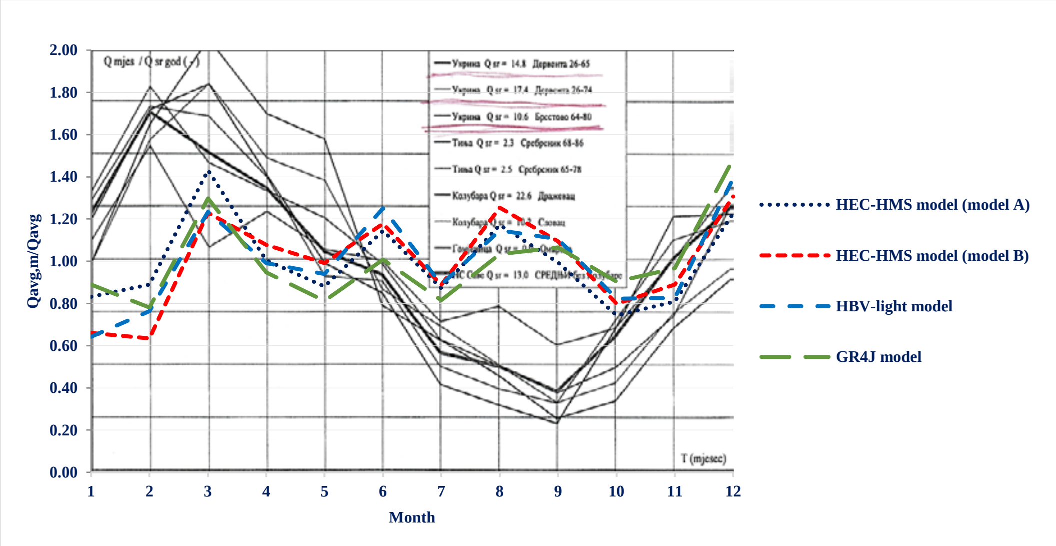

Figure 11. *Annual flow variability for the direct tributaries to the river Sava [12] and variability achieved by modelling the ungauged catchment of the Drenova in the validation period*

3.3.3. Annual flow distribution in the climatic data availability period

The best performing model according to the dimensionless FDC replicability, HBV light, is used here in posterior analysis to test the model adequacy for daily simulations in longer period. While flow gauge records at HSs were available for two separate periods with the data gap between the years 1991 and 2005 (Table 1), daily precipitation and air temperature data from the MS Banja Luka were available without gaps. A monthly evapotranspiration required for input data in HBV light model is assessed by the Thornthwaite method.

The red line in Figure 12 shows annual flow variability obtained by processing daily flow simulation results of the HBV light model in the period 1961-2008. Both flow variability and line shape resemble the pattern shown at the locations in closest proximity to the Drenova river catchment.

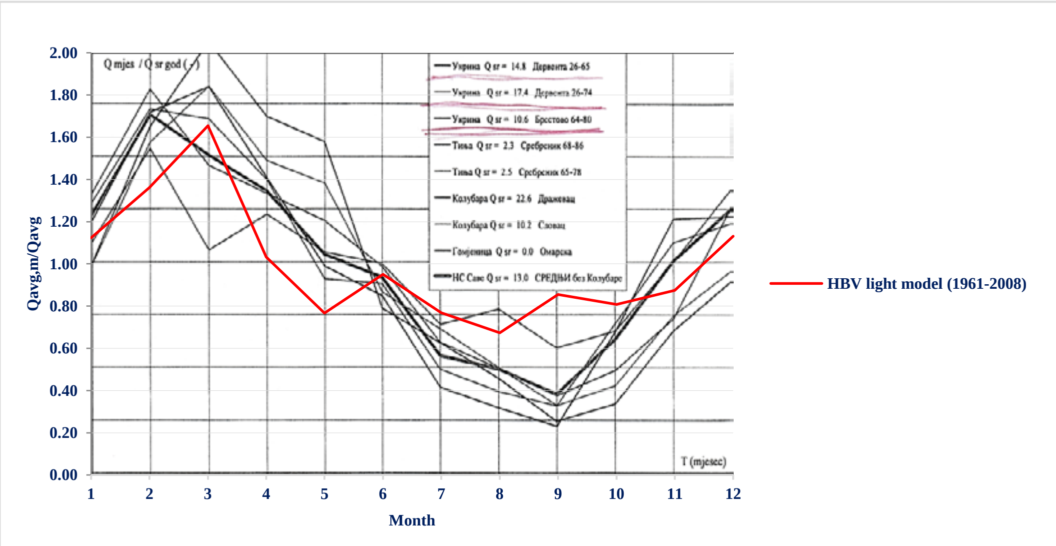

Figure 12. *Annual flow variability for the direct tributaries to the river Sava [12] and variability achieved by modelling the ungauged catchment of the Drenova in the period 1961-2008*

The thick black line denoting averaged annual flow distribution in the direct right tributaries to the river Sava in BiH only (in the river basins of the Ukrina, Tinja and Gomjenica river) shows the situation prior to the year 1980 in different sampling periods, ranging from 14 to 50 years. It is not known if there were record gaps and in general, there is a question regarding the quality of runoff data in previous period. It is also not possible to differentiate lines by colour between catchment locations in the original diagram [12] for more detailed analysis. Nevertheless, the results achieved by the HBV light model daily flow simulations for this long period are generally acceptable in all annual periods but for the month of May where it seem underestimated, and in the low flow period (August and September), potentially overestimated.

4. CONCLUSION

The paper investigates the potential for calibrating and verifying three hydrological models for simulation of daily flows using dimensionless FDCs. The prevailing calibration and verification periods are uneven: 30 years (1961-1990) for calibration and 3 years (2006-2008) for the verification period. Among the hydrological models, HEC-HMS models with snow (model A) and without snow (model B) have 8 parameters each, HBV light model 19 parameters and the GR4J model 4 parameters. Both HBV light and GR4J model are applied without snow in their structure.

Based on the flow simulation results by the three models for the studied Drenova ungauged basin, the following may be concluded:

1. According to the fit of six characteristic duration flows of the FDCs, the HEC-HMS model A with snow and HBV light perform better in the calibration period, while in the validation period, HBV light as well as HEC-HMS model B without snow perform well.
2. In the calibration and validation periods, annual flow pattern is not matched by any of the models both in the terms of dynamics and flow range. However, simulations by the HBV light model in the longer period (1961-2008) show significantly improved annual flow pattern when calibrated model is run on the fully available sets of climatic data.
3. The best performing model overall is the HBV light, the model with the most parameters, while the worst performing is GRJ, with the least parameters. The GRJ model has shown poor results in the similar input data environment [17].
4. When modelling ungauged catchments, it is recommended that at least two different models are used for better perception of simulation results. The HEC-HMS model A with snow is also worth further consideration according to the results of this research.
5. Models calibrated by the FDCs should undergo additional testing of the simulation results. One of possible means of the result verification shown in this research is by the achieved annual flow pattern, while some authors focus on reproducing the observed flow frequency distribution rather than the exact hydrograph [5].
6. Using the three present models with different calibration strategies/objects (e.g. using other flow characteristics beside FDC) might produce different results in the terms of model adequacy for ungauged catchments.

The recommendation for future research is to spatially extend the set of HSs for generating FDCs to the locations in broader region, and include HSs that would have a longer or at least even period for calibration and validation of the models. The catchment similarity should also be checked beyond homogeneity presumption based on proximity and catchment area range.

Regarding the HBV light model, further improvement of the catchment representation should be considered by increasing the number of elevation zones and subcatchments. The HEC-HMS model A with snow should also be considered in the future research. The structure of these two models seems the most appropriate in the studied case.

LITERATURE

[1] A. Petroselli, A. Mulaomerović-Šeta, and Ž. Lozančić, “Usporedba metodologija za određivanje velikih voda na odabranim slivovima u Bosni i Hercegovini,” vol. 71. pp. 729–738, 2019.

[2] V. Costa, W. Fernandes, and M. Naghettini, “Regional models of flow-duration curves of perennial and intermittent streams and their use for calibrating the parameters of a rainfall-runoff model”. *Hydrological Processes*, 59 (2), 262–277, 2014.

[3] S. Pool, D. Viviroli, and J. Seibert, “Prediction of hydrographs and flow-duration curves in almost ungauged catchments: Which runoff measurements are most informative for model calibration? ” *Journal of Hydrology*, 554, 613–622, 2017.

[4] I.K. Westerberg, L. Gong, K. Beven, J. Seibert, A. Semedo, C.-Y. Xu, and S. Halldin, "Regional water-balance modelling using flow-duration curves with observational uncertainties". *Hydrology and Earth System Sciences*, 18 (1), 2993–3013, 2014.

[5] Westerberg, I.K., Guerrero, J.L., Younger, P.M., Beven, K., Seibert, J., Halldin, S., Freer, J.E., and Xu, C.-Y., 2011. "Calibration of hydrological models using flow-duration curves". *Hydrology and Earth System Sciences,* 15 (7), 2205–2227, 2011.

[6] A. Todorović and J. Plavšić, "Mogućnost primene modela HEC-HMS za kontinualne hidrološke simulacije," *Vodoprivreda*, vol. 46, no. 1–6, pp. 117–128, 2014.

[7] J. Seibert, "HBV light," *HBV Light version 2 User's Man.*, no. November, 2005.

[8] J. Seibert and M. J. P. Vis, "Teaching hydrological modeling with a user-friendly catchment-runoff-model software package," *Hydrol. Earth Syst. Sci.*, vol. 16, no. 9, pp. 3315–3325, 2012, doi: 10.5194/hess-16-3315-2012.

[9] A. Foehn *et al.*, "RS MINERVE - User Manual," *v2.15. Ed. CREALP*, no. April, p. 124, 2020.

[10] C. M. Munajat, I. K. Hadihardaja and D. Harlan, "The improvement of GR4J model parameter to estimate unit hydrograph". International Seminar on Advanced of Water Resources Management in a Global Challenge. Kupang – East Nusa Tenggara – Indonesia, November, 2019.

[11] P. Praštalo, B. Blagojević, and Ž. Topalović, "Flow duration curves as a tool for calibration and verification of the HBV-light model in ungauged catchment," pp. 88–99, 2008.

[12] Zavod za vodoprivredu (ZZV) (2011) *Analiza bilansa voda u Republici Srpskoj, Hidrološka studija*, Zavod za vodoprivredu d.o.o., Bijeljina

[13] V. Klemeš, "Operational testing of hydrological simulation models," *Hydrol. Sci. J.*, vol. 31, no. 1, pp. 13–24, 1986, doi: 10.1080/02626668609491024.

[14] H. V. Gupta, S. Sorooshian, and P. O. Yapo, "Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information," *Water Resour. Res.*, vol. 34, no. 4, pp. 751–763, 1998, doi: 10.1029/97WR03495.

[15] P. O. Yapo, H. V. Gupta, and S. Sorooshian, "Multi-objective global optimization for hydrologic models," *J. Hydrol.*, vol. 204, pp. 83–97, 1998, doi: 10.1016/S0022-1694(97)00107-8.

[16] P. Praštalo, Ž. Topalović and B. Blagojević, "Kalibracija i verifikacija HEC-HMS modela neizučenog sliva pomoću krivih trajanja proka, Nauka i praksa, vol 20. pp. 20–27, 2017.

[17] P. Praštalo, Ž. Topalović and B. Blagojević, "Geomorfološki jedinični hidrogram kao alat u hidrološkom modelu za određivanje velikih voda na hidrološki neizučenim slivovima". Zbornik radova 19. Naučnog savetovanja Srpskog društva za hidraulička istraživanja (SDHI) i Srpskog društva za hidrologiju (SDH). Beograd, 18-19. oktobar 2021., Urednici: Jaćimović, N., Plavšić, J. Izdavač: Univerzitet u Beogradu - Građevinski fakultet, Beograd, 2021, ISBN 978-86-7518-219-1, p. 200-211, 2021