50
Research paper
Doi 10.61892/STP202601074J
ISSN 2566-4484

STEPGRAD
СТЕПГРАД

Nenad Jaćimović, University of Belgrade - Faculty of Civil Engineering, njacimovic@grf.bg.ac.rs
Miloš Stanić, University of Belgrade - Faculty of Civil Engineering, mstanic@grf.bg.ac.rs

APPLICATION OF PHYSICALLY BASED HYDROLOGIC MODELLING FOR WATER RESOURCES MANAGEMENT IN THE KARST BASINS

Abstract:

Runoff modelling in karst areas represents a specific challenge, due to inherent complexity and uncertainty of underground flow paths. Utilization of physical relationships to describe the individual components of the runoff requires a much more detailed understanding of the conditions in the basin. However, the application of such models, with an acceptable level of complexity, can provide a reliable model that can be used for predictive purposes, even when some structural changes are expected in the basin, as in the case of the construction of objects that influence water balance (hydropower plants, dams, reservoirs, etc.). Example of application of developed physically based, semi-distributed hydrological model at the Trebišnjica river basin is presented in this paper.

Keywords: Karst, Water management, Hydrological modelling

ПРИМЕНА ФИЗИЧКИ ЗАСНОВАНОГ ХИДРОЛОШКОГ МОДЕЛА ЗА УПРАВЉАЊЕ ВОДНИМ РЕСУРСИМА У КАРСТУ

Сажетак:

Моделовање отицања у карстним подручјима представља посебан изазов због природне комплексности и неизвесности у вези са подземним токовима. Примена физички заснованих релација за опис појединачних компоненти отицања захтева знатно детаљније разумевање услова на сливу. Међутим, примена таквих модела, уз прихватљив ниво сложености, може обезбедити поуздан модел који се може користити у предиктивне сврхе, чак и када се очекују одређене структурне промене у сливу, као у случају изградње објеката који утичу на водни биланс (хидроелектране, бране, акумулације и сл.). У овом раду приказан је пример примене развијеног физички заснованог, полудистрибутивног хидролошког модела на сливу реке Требишњице.

Кључне ријечи:Карст, Управљање водним ресурсима, Хидролошко моделирање

1. INTRODUCTION

Hydrological models are systems of mathematical formulations that connect independently variable parameters of a hydrological system, thereby simulating hydrological processes of interest. This enables, among other things, the prediction of the behavior of the system under modified, planned or projected conditions in relation to the existing state of the system. In general, hydrological models mathematically describe the transformation of precipitation (as an input) into runoff (surface or subsurface), and the new state of the hydrological system (as an output).

Due to the complexity and uncertainty of underground flow paths, runoff modeling in the karst basins is a challenge [1], [2]. Generally, two approaches for mathematical modeling of precipitation transformation into the runoff are possible. The first one is a 'black box' model with statistical relations between the individual water balance processes, based on recorded time series. It has been shown that application of modern techniques for calibration of involved parameters provide possibilities to simulate hydraulic quantities in complex karst systems very well [1]. However, any structural change in the water resources management system, which influences the water balance or dynamics of the system, practically requires a completely new such model.

Alternative approach is utilization of physically based relationships to describe the individual components of the runoff processes. This approach requires a much more detailed understanding of the conditions in the basin and implies a significant number of model parameters that are subject to calibration. However, the application of such models, with an acceptable level of complexity and with quality-implemented calibration, can provide a reliable model that can be used for predictive purposes, even when some structural changes are expected in the basin, as in the case of the construction of objects that are changing water balance in individual parts of the basin (hydropower plants, reservoirs, derivations, etc.).

This paper presents implementation of the distributed physically based hydrologic model 3dNet-HET (University of Belgrade , Faculty of Civil Engineering) as a tool for analysis of effects of the planned structural change of the current water management system of the Dabarsko and Fatnicko polje, in the karst area of eastern Herzegovina (Bosnia and Herzegovina). Namely, the focus in this paper is potential effects of tunnel Dabar-Fatnica capacity increase, with the aim to decrease flooding in Dabarsko polje and to lower extreme water levels in polje in order to obtain more energy production of future HPP Dabar. The model was fully developed at the University of Belgrade - Faculty of Civil Engineering and has been utilized for hydrological analyses in the Trebisnjica river basin for many years. The model was extended through the years and now involves the entire area of the Trebisnjica and Zalomka river basins. Model description, modeling details and calibration results can be found in Jacimovic, et al. (2019) [3], [4]. For this study, it is important to mention that the model is calibrated for three periods. The first period considers natural conditions, i.e. without tunnels in operation (before 1986. year), with the Dabar-Fatnica tunnel in operation (1986-2006), and both tunnels in operation. As illustration, model calibration in terms of water level duration curve in Fatnicko polje is shown in Figure 1.

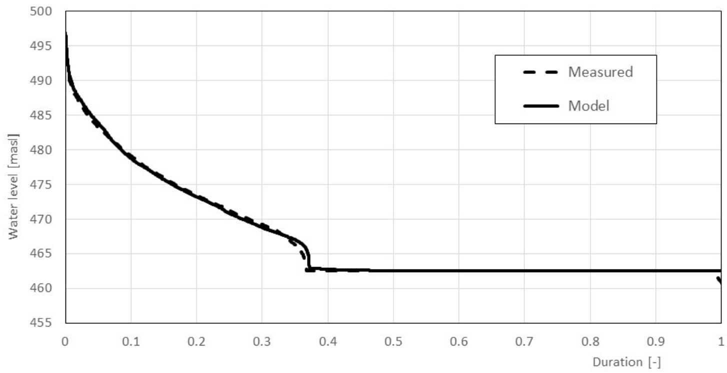

Figure 1. *3DNet-HET model comparison with measured water levels in Fatnicko polje (1963-1990) (created by author).*

2. TREBIŠNJICA RIVER BASIN AND HYDROPOWER SYSTEM

Hydropower system Trebišnjica (HST) is a complex multipurpose water management system in the wider area of the Trebišnjica river basin. The system is primarily intended for hydropower production, irrigation and flood protection. The realization of HS Trebišnjica takes place in stages, and upon completion of construction, the system would include six reservoirs, seven hydro power plants and would enable the irrigation of around 240 km^2 of arable land and the protection of karst fields from flooding.

In the first stage of the development of the HST, the following key facilities were built: reservoir "Bileća" with a volume of about 1300 million m^3, HPP "Dubrovnik 1" with an installed capacity of 210 MW (commissioned in 1965), HPP "Trebinje 1" with installed capacity of 180 MW (commissioned in 1968), RHE "Capljina" with installed capacity of 420 MW (commissioned in 1979), and HPP "Trebinje 2" with installed capacity of 8 MW (commissioned in 1981). The Bileća reservoir enabled, in addition to hydropower production, flood protection of Trebinjsko and Popovo polje. This, generally southern, part of the system is also called the „Donji horizonti" (Lower Horizons) (Figure 2).

The second stage of system development refers to the collection and use of water from the northern part of the system, i.e. „Gornji horizonti" (Upper Horizons). In this stage, the construction of several reservoirs is planned, which would redistribute the runoff over time and at the same time additional flood protection. Spatial redistribution and access to water would be made possible by the construction of a tunnel between the karst fields (Nevesinjsko, Dabarsko and Fatnicko polje) and canals through these fields, as well as a canal through Bilećko polje. Until now, the Dabar-Fatnica tunnel and the Fatnica-Bileća tunnel have been built, which enabled the drainage of the Dabar and Fatnica fields. In addition, completion of tunnel Nevesinjsko polje – Dabarsko polje and HPP Dabar is expected in next few years. The total installed power of all built and planned hydroelectric power plants of the HST is almost 1100 MW. with a total annual production of about 4000 GWh. About 23% of the total power and about 30% of the total energy production is expected to obtain from facilities belonging to "Gornji horizonti".

The area of the HST is mountainous (with mountains up to 1500 m.a.s.l.), while between the mountains there are extensive karst surfaces and karst fields, which play a significant role in the very specific regime of groundwater and surface water. The fields are mostly closed, elongated, with distinctly developed karst forms, and they gradually descend in height from the northeast to the southwest. In the northern part of the area, among the most significant fields are Gatačko, Nevesinjsko, Slato, Lukavačko, Cerničko, Dabarsko, Fatničko and Bilećko polje. In the southern part of the area, the largest is Popovo polje, which is followed by Trebinjsko polje and Mokro polje, with Ljubinjsko polje and Ljubomirsko polje also belonging to the Trebišnjica basin. Together with karst aquifers, springs, sinkholes and estavelles, these fields form a unique hydrogeological and hydrological system of subbasins and karst aquifers with over 125 registered springs (Milanović, 2023).

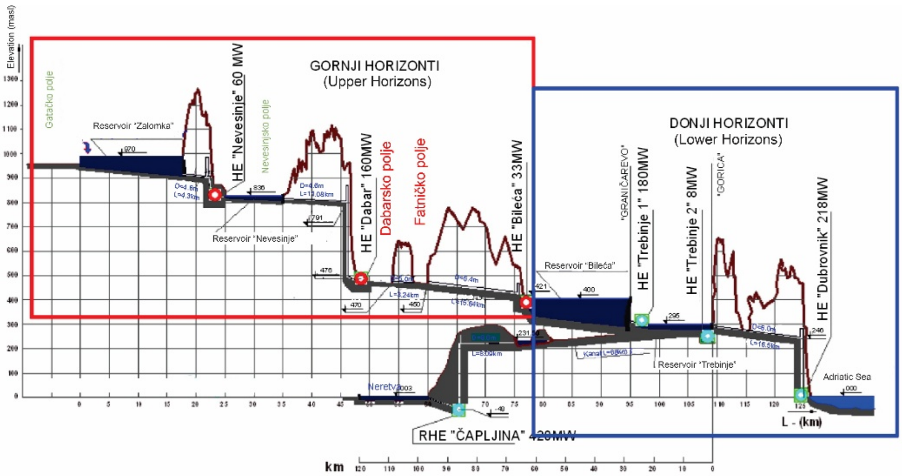

Figure 2. *Schematic representation of the Hydropower system Trebisnjica (created by author).*

The whole area is characterized by significant precipitation (on annual average about 1500-1700 mm), which mostly occurs in the autumn and winter period (October - April). During that period, there are frequent and/or long-term floods in the fields, primarily since the fields are characterized by underlaying layers of impermeable rock mass under a thin layer of soil, while the surrounding terrain is characterized by exceptional water permeability that allows subsurface runoff to the fields. Hydraulic schematization of the Dabarsko and Fatnicko polje model is shown in Figure 3.

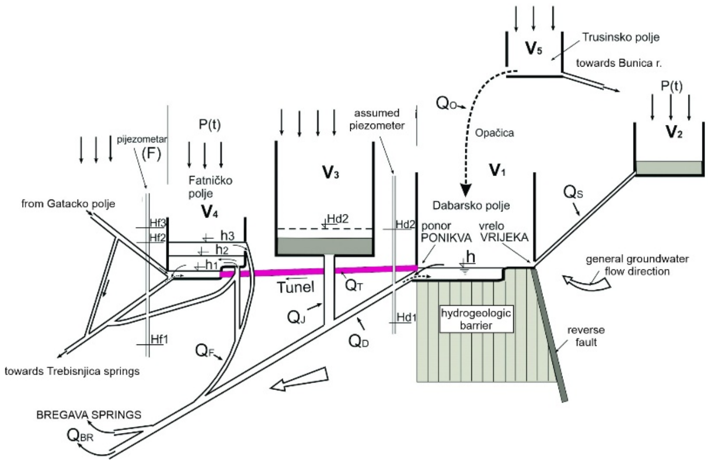

Figure 3. *Hydraulic schematization of the Dabarsko and Fatnicko polje hydrological model (created by author).*

3. FLOODS IN DABARSKO POLJE

Total catchment area of the Dabarsko polje is approximately 178 km^2 (Figure 4, 5). In natural conditions it represents an indirect catchment area of the Bregava river springs. In natural conditions water from this catchment first appears in Dabarsko Polje, flows through polje, and then sinks and flows as underground flow to Bregava Spring zone. Dabarsko polje intersects the underground water paths, and water appears in springs located along north-east edge of the Polje. Water flows across the Polje and sinks into ponors situated on the south-west edge. The most important and the only permanent is the Vrijeka Spring, with discharges approximately 100-150 l/s in dry periods (with absolute minimum of 43 l/s) up to 25 m^3/s in flood periods. Water flows as Vrijeka River, 2.5 km long, to the Ponikva sinkhole, where it sinks and appears on the Bitunja Spring. Beside the Ponikva sinkhole water from Dabarsko polje discharges through the ponor Kutske Jame, sink area Stupići and Ljelješnica estavelle. It has been established, by tracer test, the water from Dabarsko Polje discharges at Bregava Springs. Possibility for direct connection between Dabarsko polje and Hutovo Blato can't be excluded. However, if exist this connection is negligible and without influence on general water regime.

Hystorical data on flooding of Dabarsko and Fatnicko polje is analyzed in the Study of water routing from Dabarsko polje, Fatnicko polje and HE Dabar discharge into the Bileca reservoir (2020, Energoprojekt hidroinženjering, UB-Faculty of Civlil Engineering) [6], [7]. Dabarsko and Fatnicko polje are regularly flooded every year with periods of flood that can last for several months. According to data from HS Ponikva, Dabarsko polje was flooded for the longest time in 1951 and 1970, year for 158 days each. However, Figure 5 shows that the total annual number of days with floods on HS Ponikva decreases with time. Figure 6 compares the average number of days with floods on HS Ponikva by month and on an annual basis for the two periods:1963-1985 and 2007-2018. The former period relates to natural conditions, i.e., from the period without tunnels Dabar-Fatnica and Fatnica-Bileca. The letter period is period with both tunnels in function.

The average annual number of days with floods has decreased from about 93 to about 38, and that the greatest decrease in the number of flood days is in the part of the year from November to January. While in the earlier period the highest number of flood days was in December (18 days on average), in the recent period the most flood days are in February (11.4 days on average).

On the other hand, if one observes the maximum level elevations in Dabarsko polje (Table 1), it can be seen that the extreme floods that occurred in the earlier period can also occur in the recent period (e.g., elevation 483.31 m.a.s.l. from December 2010 compared to 484.70 m.a.s.l. from 1965). On average, the maximum elevations in the recent period are lower than in the earlier period, but this conclusion should be taken carefully, because a relatively short recent period was considered. This is also indicated by the fact that extreme floods have occurred in the recent period and in months when they did not occur before (e.g. over 482 m.a.s.l. in January 2010 and January 2011, as well as an elevation of 482.43 in April 2013).

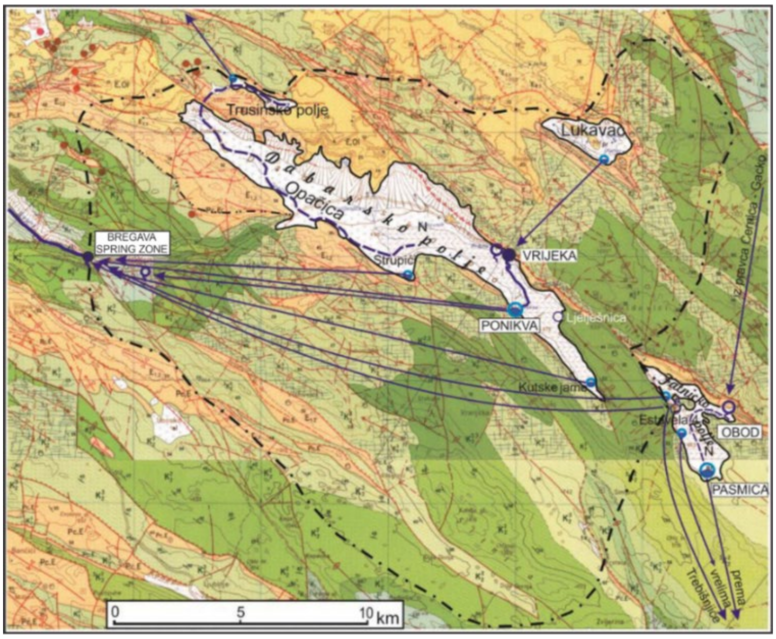

Figure 4. *Map of the the Bregava river basin with significant sinks, spring zones, estavelle and confirmed hydraulic links [4].*

4. HYDROLOGIC ANALYSIS

The 3dNet-HET model is utilized for analysis of the impact of the Dabar-Fatnica tunnel capacity on the water regimes of Dabarsko and Fatnicko polje with HPP Dabar in operation. For the analysis, a series of data on precipitation in the basin from the period 1961-2014. year. In other words, the analysis formally did not directly include the available hydrological and meteorological data that were collected in the later period, from 2015 onwards. However, the recent data on flow measurements (available since 2017. year) through the tunnels Dabar-Fatnica and Fatnica-Bileca reservoir were directly used to use more reliable flow curves in the existing conditions in the model, but also indirectly, because the model was calibrated in previous studies with hydrological data until 2018. year.

Figure 5. *Panoramic view of the Dabarsko polje*

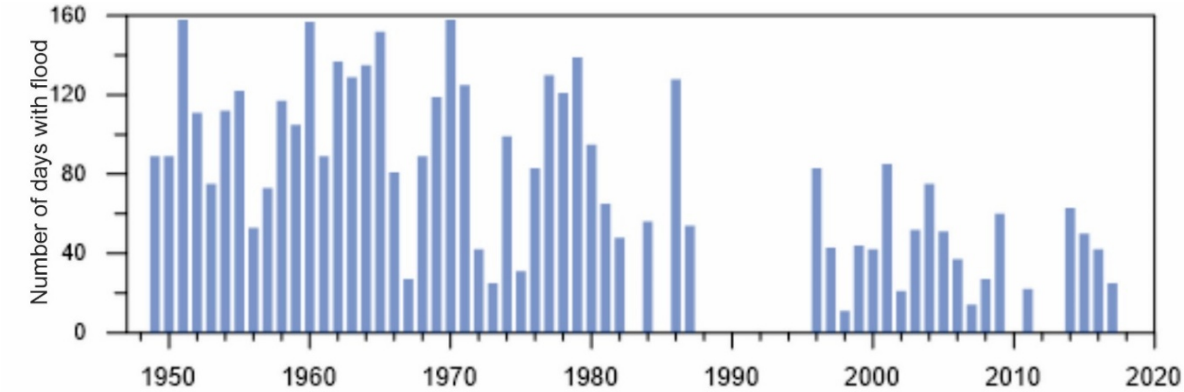

Figure 6. *Number of days in a year with floods in Dabarsko polje at HS Ponikva (in the period 1988-1995 the station did not work; without complete data for 2010, 2012, 2013 and 2018) (created by author).*

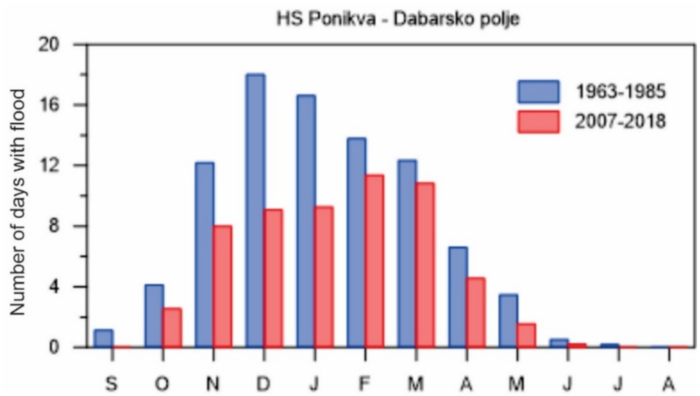

Figure 7. Number of days with floods by month in Dabarsko polje on HS Ponikva for two periods (created by author).

Figure 8. *Entrance of the tunnel Dabarsko – Fatnicko polje (photography by author).*

Table 1. Basic statistical indicators of the maximum flood levels at HS Ponikva in Dabarsko polje, by month and year.

	Jan.	Feb.	Mar.	Apr.	Maj	June	July	Aug. .	Sept.	Oct.	Nov.	Dec.	Max. Ann.
	1963-1985												
Aver.	477.49	476.73	475.77	475.14	475.12	473.99	474.03	--	473.66	474.76	476.34	477.62	479.58
Min	473.49	472.93	472.97	473.35	472.71	473.33	474.03	--	472.92	472.75	473.02	472.74	475.50
Max	484.70	482.05	481.31	481.35	479.95	474.37	474.03	--	475.00	479.95	482.07	484.04	484.70
st. dev.	3.28	3.22	2.49	2.07	2.46	0.57		--	0.71	2.25	2.94	2.47	2.70
	2007-2018												
Aver.	477.86	475.19	475.75	477.32	474.34	472.89	--	--	--	474.15	474.25	475.77	476.82
Min	473.04	473.08	472.86	472.70	473.43	472.89	--	--	--	473.41	472.94	473.82	474.04
Max	482.64	478.60	481.66	482.43	475.24	472.89	--	--	--	475.69	478.59	483.31	483.31
st. dev.	3.45	2.06	3.08	4.88	1.04		--	--	--	0.83	1.54	3.11	2.94

The main input for applied 3Dnet-HET model are precipitation data and air temperatures, while model calibration required relevant hydrological data and data from groundwater gauging stations. This analysis and above-mentioned studies were based on the hydological data from the gauging stations at the Trebisnjica and Zalomka river catchments:

- Traditional rain gauging stations: 52 stations
- Automatic weather stations: 8 stations
- Traditional river gauging stations: 7 stations
- Automatic river gauging stations: 19 stations
- Automatic measurements of groundwater level: 13 piezometers
- Automatic measurements of flow rate in tunnels (Dabar-Fatnica (DF) tunel and Fatnica – Bileca reservoir (FB) tunnel)

The availability of data from these stations (Figure 9) is varied and can be broadly divided into two periods: 1) the period until 1990, where daily data is available from traditional river and rain gauging stations, and 2) the period from 2007, when the automation process began at gauging stations collecting hourly hydrological data. Extremely valuable data on hourly flow rates in the tunnels are available from 2017 (with gaps).

The influence of four rating curves for Dabar-Fatnica tunnel, depending on the status of tunnel lining and eventual expansion, as shown in Figure 10. It should be noted that backwater effects are implemented in the model, and therefore, the actual flow through the tunnel is also function of the water level in the Fatnicko polje. Obviously, the water regime of the Dabarsko polje strongly depends on water regime of the Fatnicko polje, which in turn, depends on natural inflow and outflow of the field, as well as the rating curve of the Fatnica-Bileca tunnel and its open/close status (water management of the HST system). In this analysis, the Fatnica-Bileca tunnel is considered opened all the time, with the maximum capacity of 115 m^3/s.

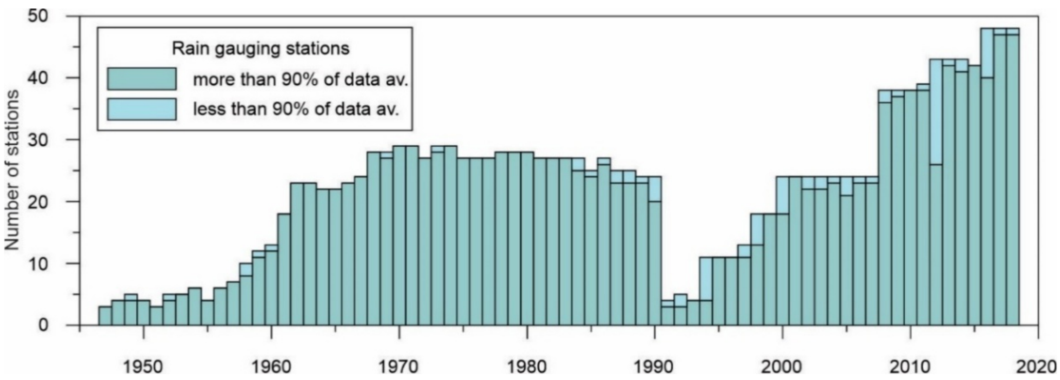

Figure 9. *Availability of daily precipitation data from traditional rain gauging stations (number of stations with data per year) (created by author).*

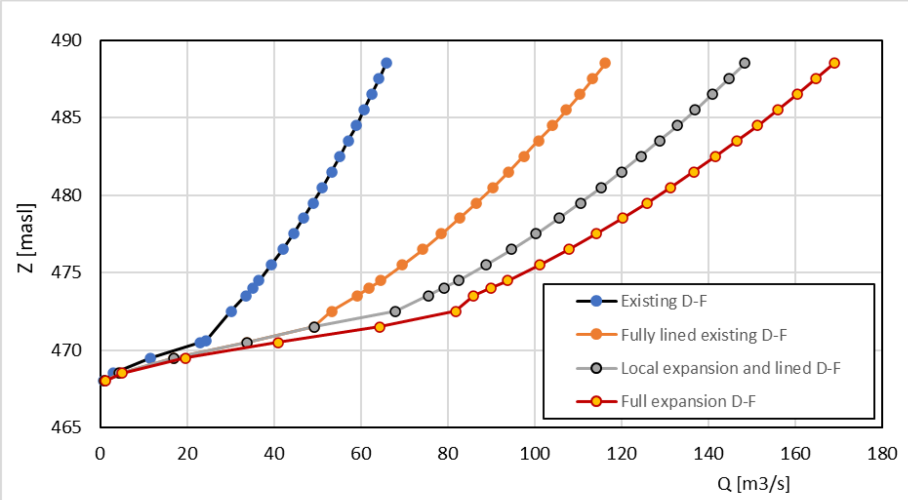

Figure 10. *Considered Dabar-Fatnica tunnel rating curves for 4 schemes (created by author).*

The operation of HPP Dabar represents the "interior" boundary for analysis of Dabarsko polje water regimes, and it certainly will have significant impact on it. The installed capacity of 55 m^3/s is an order of magnitude higher than natural annual average inflow to Dabarsko polje. The HPP Dabar operation will depend on natural inflow to Poscenje reservoir, as well as water management strategy of the entire HS Trebisnjica. For the purpose of this analysis, the following, relatively simple operation rule is adopted: 1) for water levels higher than 836,0 m.a.s.l. in the Poscenje reservoir, the HPP operates at full capacity (55 m^3/s), 2) for water levels between 830,0 m.a.s.l and 836,0 m.a.s.l in the Poscenje reservoir, the HPP flow is equal to Poscenje reservoir natural inflow, and 3) for water levels below 830,0 m.a.s.l in the Poscenje reservoir, the HPP Dabar operation stops.

The simulation results in a form of flood duration curves in Dabarsko and Fatnicko polje are shown in Tables 2 and 3, respectively. According to presented results it can be concluded as follows:

- Increase of Dabar – Fatnica tunnel capacity has limited effects on flooding of Dabarsko polje. In general, increase of tunnel capacity results in slightly decrease of flood duration in Dabarsko polje and increase in Fatnicko polje. However, peak flood levels remain similar.
- The most significant effects are found between Scenario 1 (existing conditions) and Scenario 2 (full lining of the tunnel), with significant decrease of annual days with floods above 478 m.a.s.l. in average, and with maximum flood level decreased for 1 meter in Dabarsko polje. Further increase of tunnel capacity showed relatively small effects, practically negligible.
- Above conclusions are a consequence of the fact that the water level (flood) in Fatnicko polje is the main factor influencing the flood regime of the Dabarsko polje (with the tunnel in operation).

5. CONCLUSIONS

The application of physically based distributed hydrological models is possible in the karst basins. Moreover, it is prerequisite for prediction of water regimes in the case of catchment structural changes. However, the strong condition is existence of observations data, which includes precipitation, discharges, and especially the water levels in the karst aquifers. It is reasonable to conclude that such models provide more reliable forecasts of the discharges in altered (planned) conditions in the basin, compared to the frequently used statistical models.

The paper presented an study case of tunnel capacity influence on water regimes of Dabarsko and Fatnicko polje, where the hydrologic modelling of the whole basin is required. The modelling revealed that tunnel discharge capacity has limited influence on water regimes, due to dependence of water levels between karst fields and the fact that flooding in both fields frequently occurs simultaneously.

In addition, flood management and related tunnel Fatnica – Bileca reservoir operation strategy may have significant influence on flood regimes in Fatnicko and Dabarsko polje with HPP Dabar in operation. Therefore, HPP Dabar operation should always be considered as a part of the complex water management of the hydrosystem Trebisnjica.

Table 2. Flood duration curves in Dabarsko polje for 4 considered Scenarios (HPP Dabar in operation)

p [%]	Z [masl]	p [%]	Z [masl]	p [%]	Z [masl]	p [%]	Z [masl]
-	486.07	-	485.12	-	484.90	-	484.12
1	480.03	1	478.67	1	478.33	1	476.40
2	479.25	2	477.74	2	477.27	2	474.85
5	477.45	5	475.73	5	475.24	5	472.14
10	475.83	10	473.98	10	473.52	10	469.14
20	473.67	20	472.35	20	472.35	20	463.23
30	472.35	30	472.35	30	472.35	30	462.69
40	472.35	40	472.26	40	472.25	40	462.53
50	472.24	50	472.14	50	472.14	50	462.51
60	472.12	60	472.06	60	472.06	60	462.51
70	472.03	70	472.01	70	472.01	70	462.51
80	471.97	80	471.96	80	471.96	80	462.51
90	471.92	90	471.92	90	471.92	90	462.50
95	471.88	95	471.88	95	471.88	95	462.50

Table 3. Flood duration curves in Fatnicko polje for 4 considered Scenarios (HPP Dabar in operation)

p [%]	Z [masl]	p [%]	Z [masl]	p [%]	Z [masl]	p [%]	Z [masl]
-	482.75	-	484.02	-	484.12	-	484.16
1	474.70	1	475.95	1	476.40	1	476.60
2	472.85	2	474.34	2	474.85	2	475.09
5	469.95	5	471.61	5	472.14	5	472.41
10	465.67	10	468.61	10	469.14	10	469.37
20	463.31	20	463.24	20	463.23	20	463.24
30	462.87	30	462.69	30	462.69	30	462.69
40	462.60	40	462.54	40	462.53	40	462.53
50	462.51	50	462.51	50	462.51	50	462.51
60	462.51	60	462.51	60	462.51	60	462.51
70	462.51	70	462.51	70	462.51	70	462.51
80	462.51	80	462.51	80	462.51	80	462.51
90	462.50	90	462.50	90	462.50	90	462.50
95	462.50	95	462.50	95	462.50	95	462.50

LITERATURE

[1] C. Makropoulos, D. Koutsoyiannis, M. Stanić, S. Djordjević, D. Prodanović, T. Dašić, S. Prohaska, Č. Maksimović, and H. Wheater, “A multi-model approach to the simulation of large-scale karst flows,” *J. Hydrol.*, vol. 348, pp. 412–424, 2008.

[2] A. Kovacs and M. Sauter, “Modeling karst hydrodynamics,” in *Methods in Karst Hydrogeology*, N. Goldscheider and D. Drew, Eds. London, U.K.: Taylor & Francis Group, 2007, vol. 26, pp. 201–222.

[3] N. Jacimović, T. Dašić, M. Stanić, P. Milanović, and B. Đorđević, “Distributed hydrological-hydraulic modeling of the karst polje water balance,” *Environ. Earth Sci.*, vol. 78, no. 15, 2019, Art. no. 8495, doi: 10.1007/s12665-019-8495-6.

[4] N. Jaćimović, T. Dašić, M. Stanić, B. Djordjević, P. Milanović, N. Sudar, and S. Savić, “Distributed hydrologic model for runoff simulation in karst basin,” *Vodoprivreda*, vol. 47, no. 273–275, pp. 29–40, 2015.

[5] P. Milanović, *Karst of East Herzegovina and Dubrovnik Littoral*. Cham, Switzerland: Springer, 2023.

[6] Energoprojekt Hidroinženjering and Univ. Belgrade–Fac. Civ. Eng., Study of water routing from Dabarsko polje, Fatnicko polje and HE Dabar discharge into the Bileca reservoir. Belgrade, Serbia, 2020.

[7] Inst. Water Manage. Bijeljina and Univ. Belgrade–Fac. Civ. Eng., Flood Hazard and Flood Risk Maps Project in Bosnia and Herzegovina – Annex for the Trebisnjica River Basin District in the Republika Srpska. Bijeljina, Bosnia and Herzegovina, 2020.