WATER BALANCE ANALYSIS OF THE KARST POLJE BY DYSTRIBUTED HYDROLOGICAL MODELING

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Abstract: The paper presents results of the physically based, distributed hydrologic model for simulation of runoff in karst areas. The 3Dnet-HET model is developed for simulation of river Trebišnjica catchment, however, in this study it is applied for simulation of a long-term time series (50 years hydrological input) of the Dabarsko polje catchment, as well as the river Bregava catchment. The model is firstly calibrated based on recorded water levels in the Dabarsko polje and flow discharges at the Bregava spring. Obtained model is utilized to analyze the Dabarsko polje water balance and possible effects of the planned hydropower plant "Dabar". Results indicate a high flow variation and that water management of the whole Trebišnjica system will require an integrated real-time management.

Key words: distributed hydrological modeling, karst catchment, Dabarsko polje

Introduction

The Trebišnjica River catchment area in Eastern Herzegovina is one of the most complex karst areas in the Balkan region. It is characterized by complex karst landforms and drainage systems including karst poljes, ponors, springs, estavelles, developed underground connections, as well as underground bifurcation zones. Detailed description of the area is presented in Milanović (2006). In order to prevent flooding of karst poljes and to keep water in the reservoirs being used for different purposes the complex water resources system was planned. Its construction has begun the 1960s and still last. Realization of the part so-called "The Upper Horizons" require the analysis and prediction of flow regime in physically changed conditions. That is reason why development of hydrological a mathematical model for this area was required.

The basic task of hydrological models is to describe the hydrological processes by connecting relevant parameters by application of numerical modeling techniques and to enable predictions of system properties in different conditions. In general, the hydrological model describes the transformation of precipitation (as inputs) into the runoff and the new conditions of the system (as output).

Due to the complexity and uncertainty of underground flow paths, runoff modeling in the karst basins is a challenge (Makropoulos et al, 2008, Kovacs et al, 2005). Generally, two approaches for mathematical modeling of precipitation transformation into the runoff are possible. 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 (Makropoulos et al, 2008).

Another approach is utilization of physically based relationships to describe the individual components of the runoff processes. This approach clearly 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 a case study of Dabarsko polje, a karst polje in Bosnia and Herzegovina, where a distributed, physically based model 3DNet-HET (Faculty of Civil Engineering, University of Belgrade) was utilized for simulation of the discharges in the basins of the Trebišnjica River and the river Bregava in eastern Herzegovina. A 50 years hydrological input was applied to the model in order to obtain detailed insight of the water balance of the DP in the context of the future water management strategies at the basin.

Brief model description

The 3Dnet-HET hydrological model belongs to a group of physically based distributed models (Jaćimović et al, 2015). The term "distributed" means hydrological model which is spatially decomposed into a number of smaller sub-basins. Surface and subsurface runoff from these sub-basins reach the control profiles of the hydrographic network - hydroprofiles (HP) or karst aquifers (KA).

The adopted hydrological model is entirely based on physical laws describing the transformation of precipitation into surface and groundwater recharge. Spatial decomposition of the model implies the division of the catchment area into elements of arbitrary shape, each element being described by a certain number of characteristic values (coefficient of vertical filtration, porosity, characteristic humidity, etc.). Calculations are functionally divided into two parts, where the output from the first part represents the input to the second part. The first part simulates the vertical movement of water and the formation of the underground and surface runoff.

Calculation of the vertical water balance in the hydrological mathematical models for very karstified catchments is especially significant. Input data for the calculation of the vertical balance are precipitation and potential evapotranspiration, given in the form of flux on the surface, as well as the characteristic air temperatures (T_{max}, T_{min} and T_{aver}). If data from multiple meteorological stations are entered in the model, spatial interpolation and height correction of precipitation and temperature are applied, so each sub-catchment has its unique 'own' input meteorological data (Fig. 1).

The vertical balance is calculated for each sub-catchment (CATCH) and the components of the surface runoff (Q_{surf}), percolation into deeper layers (W_{perc}) and change in the amount of water in a sub-basin (SW) are determined. The surface runoff is transformed into a flow at the specific crossection of the hydrographic net, through the linear direct-runoff tank (LR_d). The percolation (W_{perc}) is transformed through a system of reservoirs simulating a base flow. Total percolation from CATCH flows into the nonlinear resevoir (NLR_b). One output (Q_b^{slow}) simulates slow-base flow and goes/discharges directly into the coresponding karst aquifer (KI), and another goes into the linear reservir (LR_b) where it is additionaly transformed simulating fast-base flow and goes also into the coresponding karst aquifer (KI). More detailed mathematical description of this process

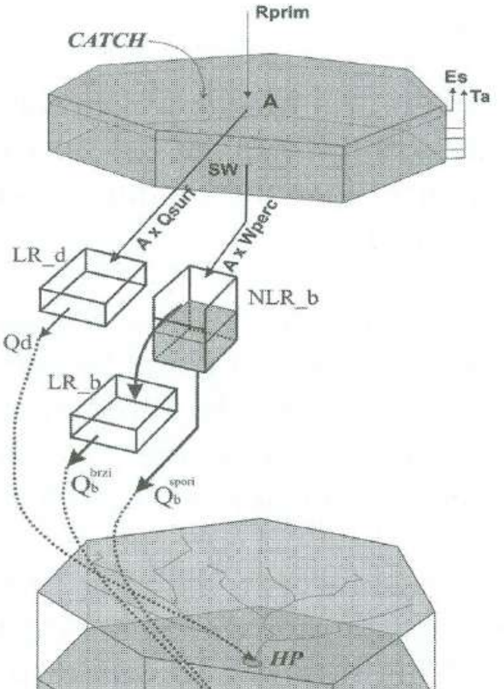

Fig 1. Components of vertical water balance

is presented in other papers and reports (Jaćimović et al, 2015, Water Management Institute Bijeljina, 2015).

The horizontal water balance calculation is based on the assumed hydraulic links by which the nodes of the system are connected. The nodes of the system represent the karst poljes, reservoirs and the karst aquifers, while hydraulic links connect, for example, the karst polje and the karst aquifers through the sinking zones. This is achieved by using the general hydraulic expression:

$$Q = C_1\sqrt{2g(\Pi - Z_1)} + C_2\sqrt{2g(\Pi - Z'_1)} \qquad (1)$$

where: Π is the water level, Z_1 - the level at the control section and Z'_1 - characteristic level at which there is a change in the flow conditions.

It is important to note that the coefficients in the preceding equation have a physical meaning. For example, under pressure conditions, the coefficients C_1 and C_2 can be expressed as:

$$C_1=C_{q1}\,A_1 \qquad (2)$$

$$C_2=C_{q2}\,A_2 \qquad (3)$$

where A is the hydraulically representative surface of the cross-section of the conductor, C_q so-called. the flow coefficient, which depends on the hydraulic resistance along the conductors between the locations where the Π and the Z_1 are defined.

It should be noted that the piezometer level in equation (1) can represent the state of the level of groundwater at an arbitrary place of the karst reservoir. The change of the location implies correction of the C_1 and C_2 coefficients, since the location of the piezometer level depends on the hydraulic losses along the conductor, and therefore the flow coefficients.

The equation (1) assumes the possible influence of the level in the downstream reservoir to the capacity of the sink, in the case of a pressurized flow. This way it is possible to simulate the estavelle. Namely, when the downstream level exceeds the level in the polje, there is a change in the direction of flow. Naturally, in this case it is the pressurized flow, where it is assumed that the hydraulic resistance along the flow is the same in both directions. In other words, the same pressure coefficients apply, regardless of the direction of flow.

The horizontal water balance is completed by iterative numerical solution of the balance equation for each node in the system.

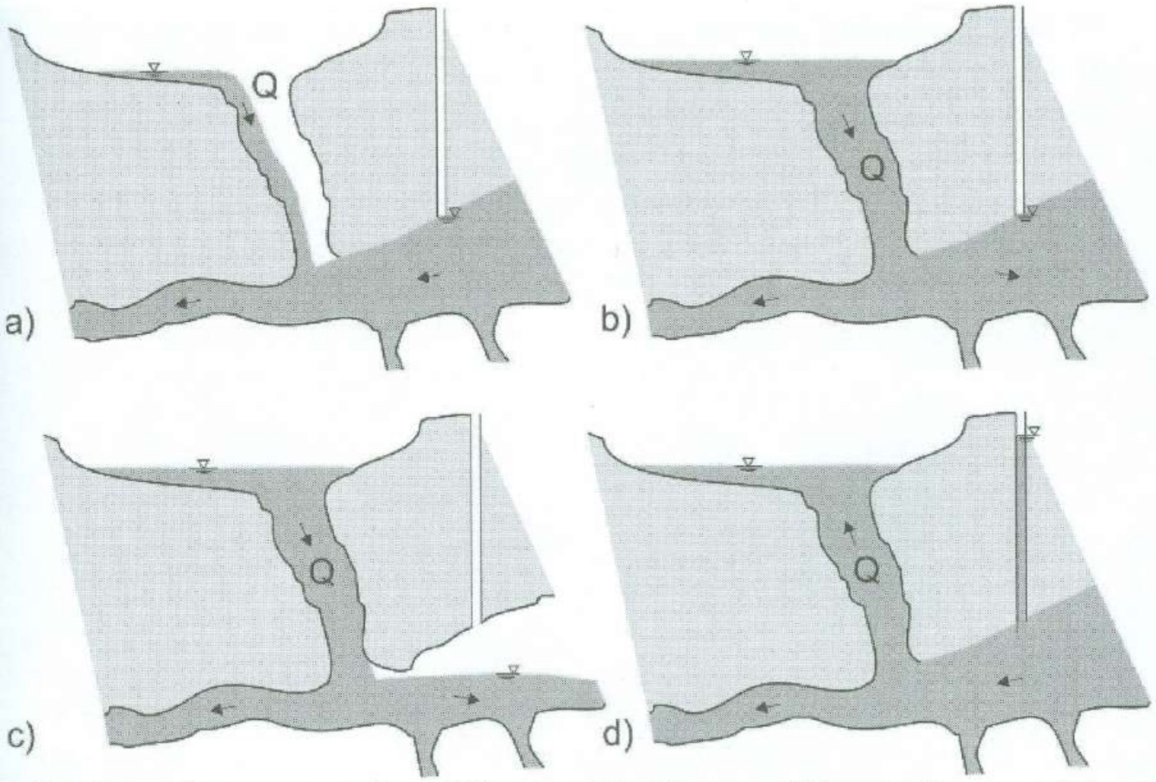

Fig. 2. Schematic representation of the simulated flow conditions in the case of the sink: a) overflow-weir flow, b) pressurized flow under the influence of the downstream level, c) pressurized flow without influence of the downstream level, d) – opposite flow direction

Dabarsko polje and the Bregava river basin

Study area is highly karstified catchment area of Bregava River spring zone in Eastern Herzegovina (Fig. 1). It includes parts of the mountain massifs of Hrgud and Sitnica and the Dabarsko Polje with sub-catchments of the Trusinsko and Lukavačko Polje. The spring zone of the river Bregava includes the area between the permanent Spring Bitunja at 130 m a.s.l. and the periodical springs of Mali Suhavići and Veliki Suhavići at 195 m a.s.l. Figure 1 shows a simplified hydrogeological map of the catchment area of Bregava spring zone. The flows are measured at the gauging station Do, a few kilometers downstream from the spring zone. Basic characteristics of the flow of the Bregava River: $Q_{min} \approx 0.40$ m^3/s; $Q_{max} = 59$ m^3/s; $Q_{sr} = 17.5$ m^3/s. In the drought year 2003, the minimal flow was measured $Q_{min} = 380$ l/s. In that period flow of 43 l/s sink into the Ponikva Ponor in the Dabarsko Polje (August 13, 2003).

Total catchment area is estimated at approximately 396 km^2. It can be divided into two parts: direct and indirect catchment areas. Direct catchment area includes parts of the mountain massifs of Hrgud and Sitnica. Its area is estimeted at approximately 218 km^2. Water from this area flows directly toward the Bregava Spring zone as underground water flow.

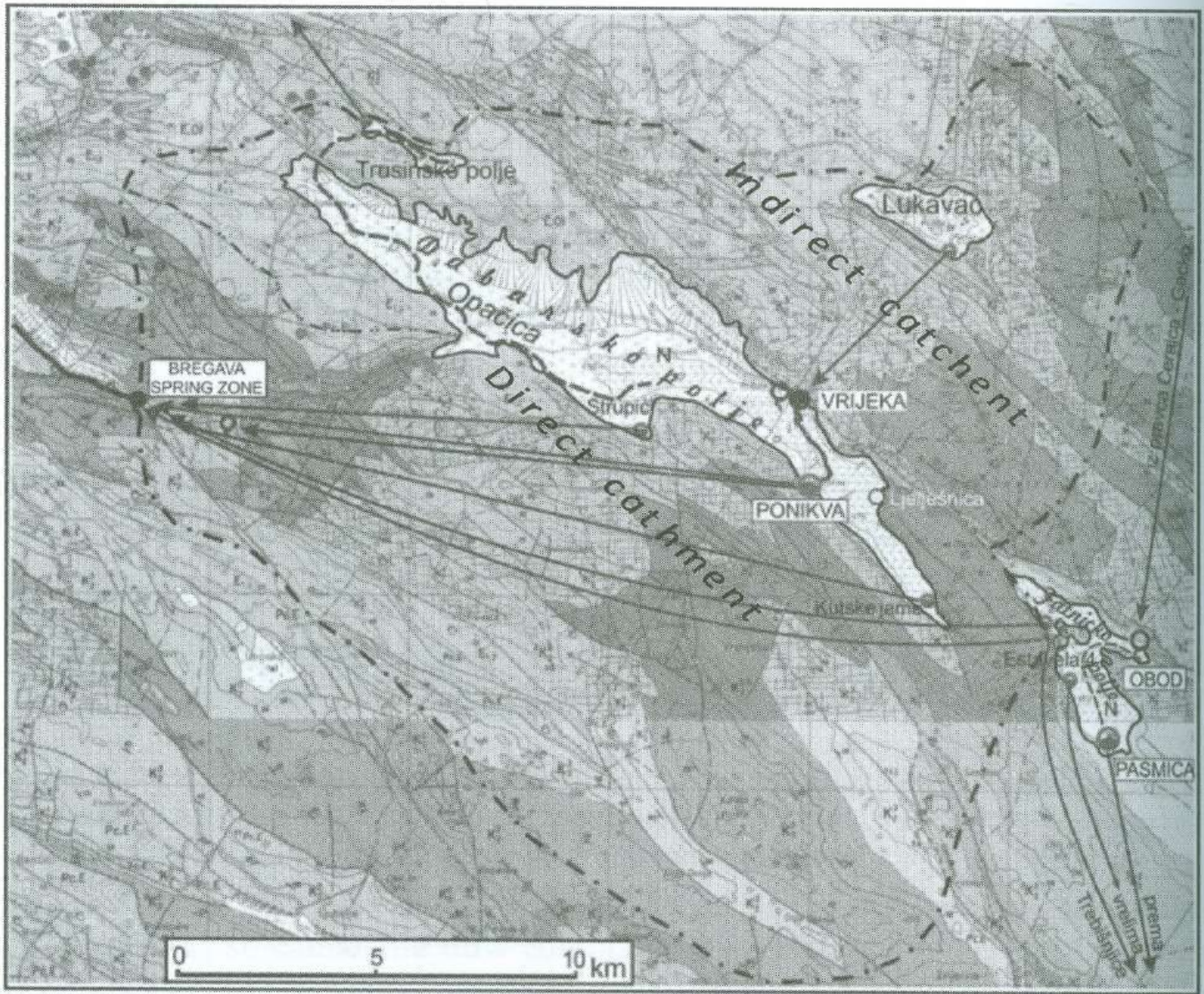

Fig. 3. Map of the the Bregava river basin with significant sinks, spring zones, estavelle and confirmed hydraulic links (Jaćimović et al, 2015)

Indirect catchment area is catchment area of Dabarsko Polje, with estimated area of approximately 178 km^2. Water from this catchment first appears in Dabarsko Polje, flows through polje, and then sinks and flows as underground flow to Bregava Spring zone. The watersheds of the catchment area include two bifurcation zones: Trusinsko and Fatničko polje. While the bifurcation zone of the Trusinsko Polje has limited/small significance for the water balance of the Dabarsko Polje, the bifurcation zone of the Fatničko polje in some hydrological conditions can be significant for water balance of the Bregava springs. Fatničko Polje is a part of Trebišnjica River catchment area. But, in flood periods when water level in Fatničko Polje is higher than 671 m a.s.l, bifurcation zone activates and a part of water flows toward the Bregava Springs.

The Dabarsko Polje (Fig. 1) was formed along the regional reverse fault with slope of 60º to 70º in the direction of north-east. The northern edge of the polje consists of limestones and sediments of Promina Formation, and the southern edge is formed of karstified limestone Cretaceous age. There is a deep hydrogeological barrier of impervious Tertiary sediments beneath the Dabarsko Polje (with depths between 200 and 400 m). It 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 form 100-150 l/s in dry periods (with absolute minimum of 43 l/s) to 25 m^3/s in flood periods. Water flows as Vrijeka River, 2.5 km long, to the Ponor Ponikve, where it sinks and appears on the Bitunja Spring. Beside the Ponor Ponikva water from Dabarsko Polje discharges through the ponor Kutske Jame, ponor zone 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.

Model application

The 3Dnet-HET model was firstly calibrated for a period of nine years, 1.1.1972. - 31.12.1980. During this period, the hydraulic tunnel between the Dabarsko and Fatničko poljes, as well as the tunnel between the Fatničko Polje and the Bileća reservoir did not exist, i.e. this represents the natural state of the catchment.

Considering the global water balance in the analyzed part of the basin, the obtained runoff coefficient was 0.88, that is, only about 12% of water is lost to evapotranspiration processes.

For the evaluation of the quality of the model, i.e. the agreement of the simulated values obtained by the hydrological modeling, the linear correlation coefficient and the Nash-Sutcliffe coefficient were used. Two data sets were compared with the observed values: the river Bregava discharges, and the water levels in the Dabarsko Polje.

The obtained values of the correlation coefficient for the simulated period of nine years amount to 0.87 for the flows in the river Bregava and 0.81 for the levels in the Dabarsko Polje. At the same time, the value of the Nash-Sutcliffe coefficient is 0.74, which indicates a very good agreement between the results of the model and the observed values. Another indicator of model performances is difference of the total volume of water flowing on the gauging station. By comparing the mean values of measured and simulated flows of Bregava River for the analyzed period, the difference was less than 1.7% ($Q_{measured}$= 18.36 m^3/s, Q_{model}= 18.64 m^3/s).

The comparison of the flow duration curves at the river Bregava obtained on the base of measured and simulated data are shown in Figure 4. Curves are calculated for the same period (1972 – 1980), and there is a very good agreement between them, which indicates that all physical processes are adequately simulated in the model. The water level curve in Dabarsko Polje also shows very good agreement with the duration curve of the observed values.

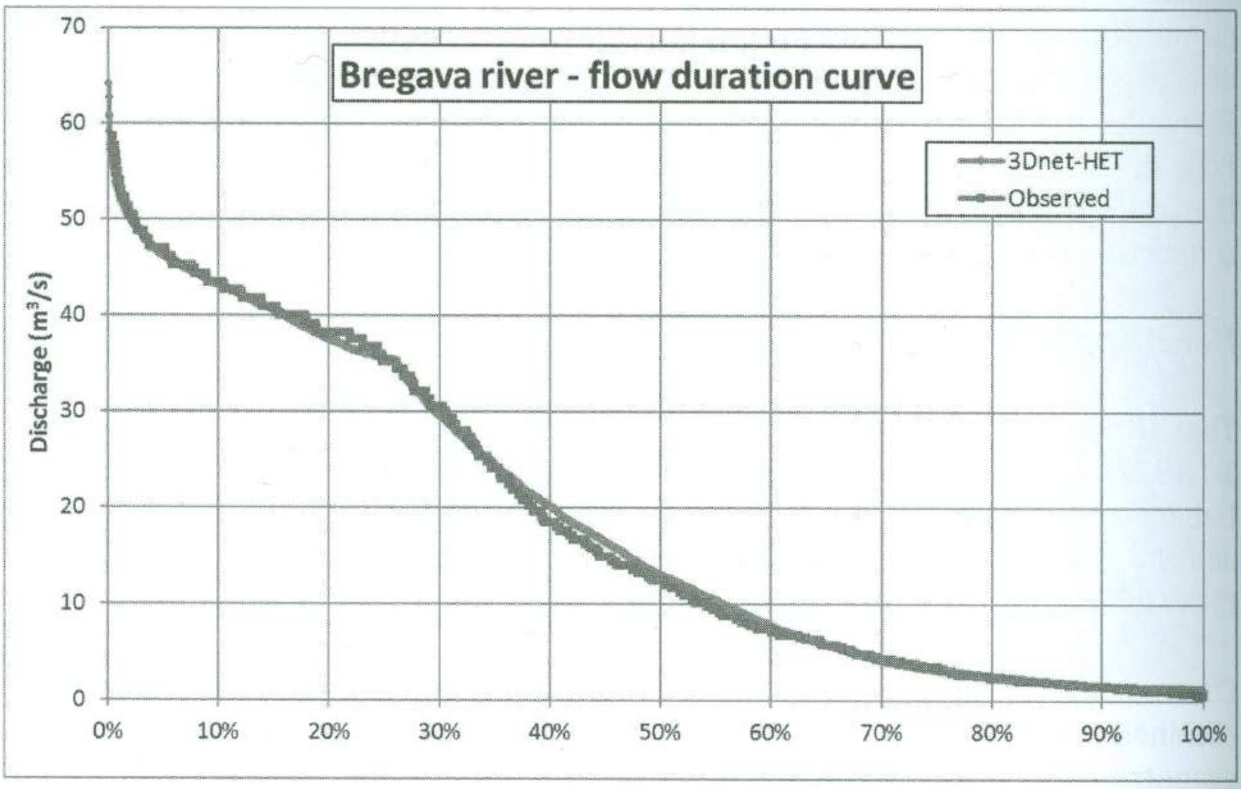

Fig. 4. Flow duration curve comparison of modeled and observed data sets for the period 1972. - 1980. year

Obtained model is utilized for simulation of the 50 years hydrologic period (1961-2014) for natural conditions. Figure 5 reveals the subcatchment partition in the total discharge of the Dabarsko Polje. Namely, the direct runoff to Dabarsko Polje is very similar to the discharge of the spring Vrijeka. This is important result in regard of considered possibility to transfer the water toward the Trebišnjica river basin. This will be a challenging task in the future, since the most of runoff occur during the short period of time, as shown in Figure 5.

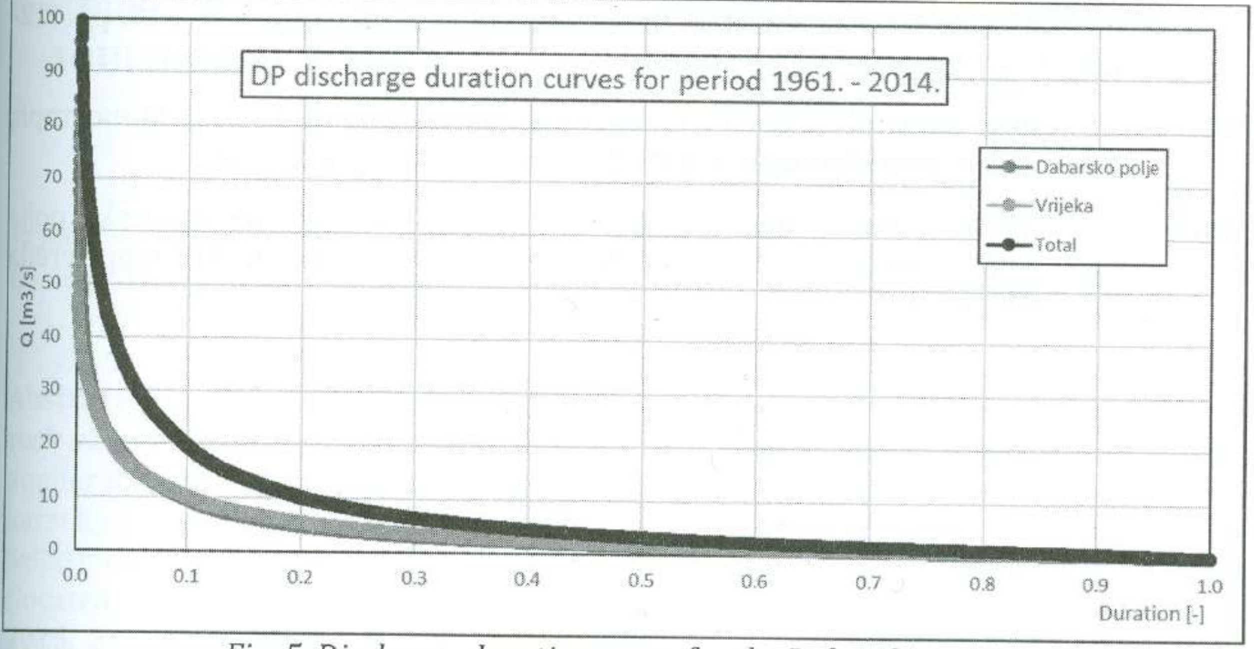

Fig. 5. Discharge duration curve for the Dabarsko polje. Contributionof the spring Vrijeka versus direct runoff.

Conclusions

The application of distributed hydrological models, based on the physical laws of precipitation transformation, is possible even for the karst basins. The precondition for this is the existence of quality observations data, which includes precipitation, discharges, and especially the water levels in the karst aquifers. We believe that such models provide more reliable forecasts of the discharges in altered (planned) conditions in the basin, compared to the frequently used statistical models. In this study, application of developed hydrological model 3Dnet-HET provided better insight into the components of water balance of the Dabarsko polje karst polje. This may be of great importance considering the goals of the water management system "Gornji horizonti", which is in the construction phase.

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