HYDROLOGICAL MODELING OF A RIVER BASIN: CASE STUDY ON THE BASIN OF RIVER CRN KAMEN

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Hydrological analysis of rivers and their basins is a basic task that is set in hydrology. When there is a lack of data on measured values of the surface runoff in a river basin, the so-called procedure of hydrologic modeling of the river basin is used. Hydrological modeling is applied in order to determine the surface runoff based on the meteorological parameters of the river basin (precipitation, air temperature) and the basic geometrical characteristics of the watershed (area of the river basin, length of the river, land use cover, etc.).

The subject of this paper is a hydrological analysis of the river Crn Kamen up to the outlet where the construction of a stone dam with central clay core is planned for the formation of the “Lukovo Pole” reservoir, using hydrological modeling of the river basin. The aim of the research in this paper is to study all of the parameters that affect the surface water in the river basin. For this purpose, a hydrological analysis of the river basin of the river Crn Kamen was made. The definition of the physical characteristics of the watershed was performed using the GIS platform, based on a Digital Terrain Model (DTM) and an appropriate model for hydrological modeling of the river basin (SWAT). A detailed map showing the land use of the river basin was also created (CORINE). Using the HEC-HMS software, a hydrological model of the river basin of Crn Kamen was developed in order to define the surface waters of the river Crn Kamen. The hydrological sequences of flow in the river were analyzed using the available measured data: historical sequences of characteristic flows (minimum, maximum and average monthly) from the hydrological station Lukovo Pole for the period 1974-2009.

A statistical analysis of data (array of 36 elements, formed from the maximum annual flows in the period from 1974 to 2009), was performed using the HEC-SSP software package. The maximum high waters with a given recurrence period of the analyzed basin were determined, using theoretical distribution functions.

Keywords: hydrological analysis, maximum high water, HEC-HMS, HEC-SSP

1. INTRODUCTION

The procedure of hydrological modeling (in some literature the terms mathematical modeling or simulation can be also found) refers to the establishment of a relationship between the real system (hydrological basin) and its mathematical (or physical) model. Simulation refers to the relationship between the model and the computer.

When modeling a river basin, all the techniques and procedures used can be divided into two basic groups:

- models that serve to assess the basin's characteristics, forecast and data generation, that is, models that operate the input-output relationship, in our case (precipitation-surface runoff);
- models dealing with water management systems for multi-purpose use of water, with the aim of finding an optimal solution based on physical characteristics, but at the same time respecting economic, social, environmental and political requirements.

The hydrological model is often associated with the term hydrological system. A hydrological system [Clark,1973] is defined as a set of physical, chemical and/or biological processes that influence input variables and transform them into output variables. The hydrological model represents simplified representation of the hydrological system and can be a physical model for a certain prototype and a mathematical model for representing the system through a set of equations.

In the development process of each model, it is constantly changing and upgrading. It begins as a rough empirical model, and with further study it is refined and changes its components with more plausible and sophisticated theoretical foundations.

The flow of surface water that falls in the form of precipitation in a basin can be non-stationary, uneven and three-dimensional. The basis of the hydrodynamic flow model is the physical laws of flow. The most accurate model would be obtained if equations were applied at the elementary volume level, observing the principle of conservation of mass (equation of continuity) and the principle of conservation of momentum (dynamic equation). Since the process is three-dimensional, non-stationary and spatially non-uniform, initial and boundary conditions must be defined at the boundary of the elemental mass, which would mean that such a model can function with spatially distributed parameters. It is about the numerical solution of the spatial (3D) models of flows under the influence of precipitation, which is not yet possible. If this model could be solved, a large number of input parameters, measured at the elementary volume level, are required, which make the model complicated and irrational. For these reasons, simpler (2D) models are considered, and for practical examples, linear (1D) flow models.

A thorough knowledge and understanding of the hydrological processes in the basin are of crucial importance for successful planning and management of water resources. To understand these processes, hydrological modeling has been widely applied in the last few decades. The models represent the processes in the river basin in a simplified way.

Thus, Ilias A. et al. (2006), presented a simulation of flood events from a single storm in the Ali Effendi basin, a sub-basin of the Pinios river basin, [1]. Flood risk assessment in this area is very important because the region suffers from frequent and dangerous floods, causing damage and operational problems to downstream multipurpose reservoirs and agricultural and residential areas. The simulation is performed using the NAM model, a core component of the DHI MIKE 11 package. The resulting mathematical model can be tuned to simulate a single storm. The model was applied in two phases (calibration and verification phase), giving good results.

Ibrahim-Bathis K., Ahmed S. A. (2016) applied the HEC-HMS 3.5 hydrological model to simulate precipitation-runoff in the Dodahala basin, [2]. The area is prone to drought and therefore, the failure of agriculture and/or other economic activities in this region can be minimized by conserving and rationally managing the available water. The simulated results of the Dodahala basin have been verified by the neighboring measured Huvinahole basin, with which they have similar characteristics. For run calibration and validation, a series of daily rainfall from October 20, 2009 to October 30, 2009, measured at the Hubinahol weather station, was used. The simulated result of this study can be useful for ungauged basins and water-scarce regions, and runoff estimation is mandatory for water resource maintenance.

Shimelis A.W. etc. (2017) conducted a study to assess the performance of the VHM and NAM models, by simulating precipitation-runoff in a small agricultural catchment area located southwest of the upper Blue Nile basin, [3]. Precipitation and evaporation were used as input to the models. The models are then calibrated for the period from January 1, 1990 to December 31, 2000. It is concluded that both models show good results in simulating the dominant hydrological processes.

Santillan J. R. et al. (2013), used the HEC-HMS model, to simulate the precipitation-runoff process, in order to assess the flood risk of the Marikina River located in Luzon Island, Philippines, [4]. This paper describes the model development as well as the calibration and validation of the flood model by comparing modeled and measured flow data. Based on the results, it is shown that the HEC-HMS model has more than satisfactory performance in simulating rainfall events. Therefore, this model can be used for forecasting and flood hazard assessment using hypothetical rainfall scenarios that could occur in the near future.

Fattah W. H., Yuce M. I. (2015), in order to determine the relationship between precipitation and runoff, performed a hydrological analysis of the Murat River Basin, the largest tributary of the Euphrates River, Turkey [5]. The hydrological characteristics of the wbasin were determined using the standard digital elevation model (DEM) and geographic information systems (GIS). Annual average runoff was obtained from seven streamflow measuring stations, while annual total precipitation data were obtained from nineteen precipitation measuring stations located near the basin.

Gjeshovska V. and Ivanoski D. (2016) performed a hydrological analysis of the upper basin of the Vardar river, [6]. The Ministry of Agriculture, Forestry and Water Management recently carried out the preparation of technical documentation for the regulation of rivers. The main objectives of the project are: to assess the overall condition of the flooded section of the riverbed, to assess the change in the hydrological regime and to propose protection measures. In order to achieve these goals, within the framework of the above technical documentation, the hydrological analysis was performed. The characteristics of the basin are defined by DTM (Digital Terrain Model). The study presents some of the output results of this analysis, as well as the results of the calibration of the hydraulic modeling of the flow in the natural river bed.

Rocha P. C., Santos A. A. (2018), performed a hydrological analysis of the Aguapei and Peix river basins, Brazil [7]. The purpose of this analysis is to give an account of the hydrological regime of the considered rivers.

The hydrological analysis for the basin of the river Crn Kamen done with the help of appropriate software packages (SWAT, HEC HMS, HEC SSP) provides the opportunity for a quick, precise and accurate definition of the necessary parameters for an appropriate hydrological analysis of a river basin [8].

2. HYDROLOGICAL MODELING OF THE BASIN OF R.CRN KAMEN

2.1 STUDY AREA

The river Crn Kamen is located in the northwest part of the Republic of N.Macedonia on the border of the Shara's and Korab's mountains massifs and is part of the basin of the river Radika. From its source to the confluence in Lake Debar, Radika river flows under different names. Thus, from the upper part to the confluence of Ajina River, it is known under the name r.Crn Kamen, from the confluence of Ajina River to the confluence of river Mavrovska, under the name r.Nichpurska, and from the confluence of the river Mavrovska to the confluence in the lake Debar flows under the name Radika. In its upper part, the construction of a rock dam with a central clay core is planned for the purpose of forming the reservoir "Lukovo Pole".

The reservoir Lukovo Pole is planned to be built in order to increase the capacity of the hydro system on the upper reaches of river Radika. The main purpose of the reservoir is to retain the water from the upper course of the river Crn Kamen, as well as the flow from the mountain Korab and their controlled use in the hydro system. By retaining and regulating these waters, floods will be avoided, and energy can be produced.

2.2 DATA SOURCES

The determination of the physical-geographical characteristics of the river basin of the river Crn Kamen was made on the basis of digital layers DTM (Digital Terrain Model) and DEM (Digital Elevation Model). The physical-geographic

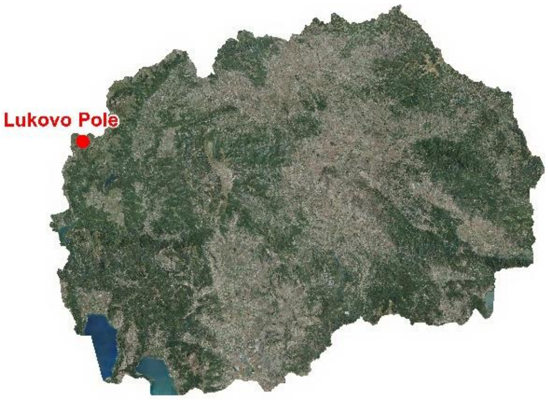

Figure 1. Location of the planned dam Lukovo Pole

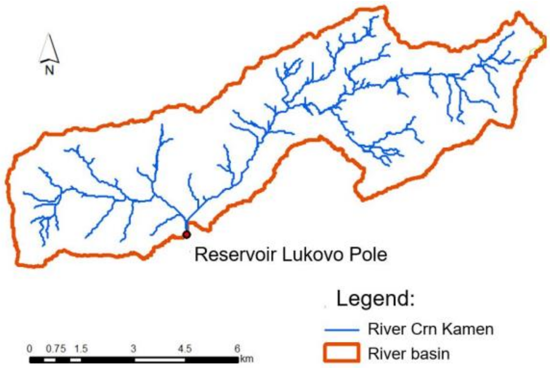

Figure 2. River basin of r.Crn Kamen at outlet Lukovo Pole

characteristics of the river basin of Crn Kamen are defined using a GIS software package. Information from the CORINE Layer Classification database from 2018 was used to define the land use. Precipitation has been analyzed through data on measured precipitation in the meteorological stations Lazaropole and Popova Shapka, in the period 1961-1990. Surface water has been analyzed with data on daily flow for the period 1974-2009, at the outlet of Lukovo Pole. In the HEC-HMS simulation daily data for the year 1975 is used.

2.3 METODOLOGY

The hydrological modeling of the river basin of r.Crn Kamen was made using the HEC-HMS software package. With the GIS processing (Spatial Analyst) and application of the SWAT module, the river basin of the r.Crn Kamen and its sub-basins is determined. The terrain data is transformed into a spatial database in an appropriate format (ArcGIS Shapefile), whis is used for input into the HEC-HMS model. Statistical analysis and application of probability distribution functions was done by using the HEC-SSP software package. Statistical Software Package - HEC-SSP was developed by the US Army Corps of Engineers as part of the research and development program of the Hydrological Engineering Center (Hydrologic Engineering Center-HEC).

2.4 HYDROLOGICAL ANALYSIS

2.4.1 Physical-geographic characteristics of the river basin of r.Crn Kamen

The river basin of the r.Crn Kamen and the physical-geographic characteristics of the river basin are defined based on the DEM, and with the application of SWAT, Figure 1. The geometric characteristics of the river basin are shown in Table 1 (A-area of the river basin in km^2, H_{max}-maximum elevation of the river basin in m asl., H_{min}-minimum elevation of the river basin in m asl., H_{avg}-average elevation of the river basin in m asl., L_t-length of the river in km, St-slope of the river in %, L_s-length of the river basin in km and S_s-slope of the river basin in %).

Table 1. Geometric characteristics of the river basin of river Crn Kamen from the source to the outlet at Lukovo Pole

A [km^2]	H_{min} [masl]	H_{max} [masl]	H_{avg} [masl]	L_t [km]	S_t [%]	L_s [km]	S_s [%]
52,8	1518	2519	1896,5	16,7	3,9	15,4	29

2.4.2 Land use

Within the boundaries of the basin of the river Crn Kamen, there are several classes of land use, characteristic for a given region, which were obtained by applying the CORINE Layer Classification, Figure 3. Land use classes in the river basin with their representation expressed in [km^2] are shown in Table 2.

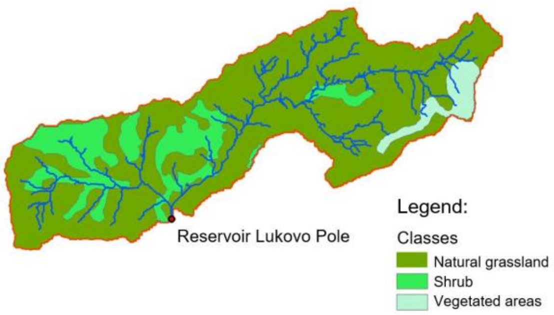

Figure 3. Land use classes in the river basin

Table 2. Land use classes according to the CORINE classification

No.	Code	Classes	Area [km^2]	CN
1	321	Natural grassland	39,5	79
2	324	Shrub	9,6	66
3	333	Vegetated areas	3,7	68

2.4.3 Hydrological characteristics

Within the basin of the river Crn Kamen as part of the hydrological network of R.N.Macedonia, data on daily flows for analysis are available for the time period from 1974 to 2009. With these data, a hydrological series of 36 years has been defined, which is sufficient for further statistical analyses.

Average monthly flows for the period from 1974 to 2009 measured on the Lukovo Pole profile are shown in Figure 4. The maximum and minimum average flows are shown graphically in Figure 5. The maximum average monthly flows are observed in the spring months, while the lowest average monthly flows are observed in the winter months. The highest amount of flow was recorded in 1974 in May, and the lowest was in February in 1981.

For the simulation in HEC-HMS daily data for one year was used, for the year 1975. The daily flows in the river Crn Kamen for the year 1975 are shown graphically in Figure 6.

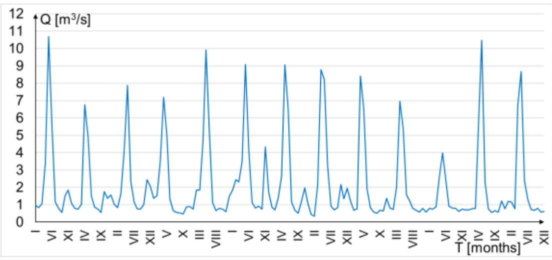

Figure 4. Hydrograph of average monthly flow for the river Crn Kamen for the period 1974-2009

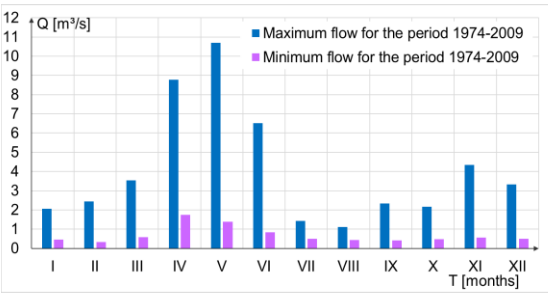

Figure 5. Maximum and minimum monthly flow for the period 1974-2009

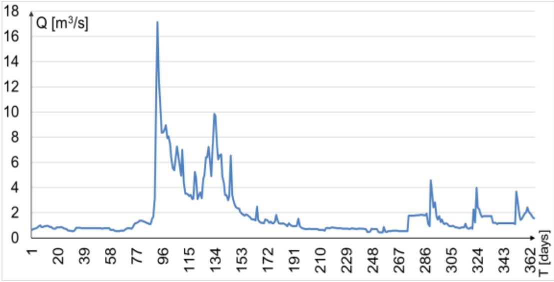

Figure 6. Hydrograph of daily flow in the r.Crn Kamen at the outlet of the dam Lukovo Pole in 1975

2.4.4 Climatic meteorological characteristics

Climatic characteristics of the basin are obtained from data recorded by the meteorological stations "Lazaropole" and "Popova Shapka" in the period 1981 - 2010 for air temperature and precipitation. In the area where the basin of the river Crn Kamen is located, climatic conditions prevail, which are characterized by mild and moderate winters and warm summer periods with pleasant evening temperatures. The climate is moderate-continental, and in certain areas it changes to Mediterranean. In Mavrovo National Park there is a continental climate with moderate influences of the Mediterranean currents along the valleys of Crn Drim and Radika, a colder mountain climate in the area of the Mavrovo Lake and its immediate surroundings, and an alpine climate in the highest mountain areas.

The average annual temperature measured in Lazaropole is about 7.3˚C, in Popova Shapka 4.9˚C. The average monthly temperature in the winter months was negative, in January it was -1.6˚C in Lazaropole and -4.6˚C in Popova Shapka. The highest average temperature was recorded in July with 16.9˚C in Lazaropole and 14.2˚C in Popova Shapka and August with 16.5˚C, ie 14.2˚C, respectively. The average annual temperature variation is about 18.8˚C.

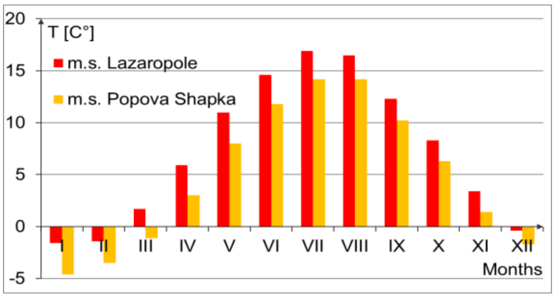

Figure 7. Average monthly air temperatures (m.s. Lukovo Pole and Popova Shapka, 1981-2010)

The average annual amount of precipitation for the period from 1961 to 1990 measured at the

Lazaropole meteorological station is 1059.09 mm. The highest average amount of precipitation was measured in November and was 145.60 mm, and the lowest average amount of precipitation was recorded in July with 48.86 mm and August with 50.43 mm.

The average annual amount of precipitation for the period from 1961 to 1990 measured at the Popova Shapka meteorological station is about 901.36 mm. The highest average amount of precipitation was measured in November and was 104.16 mm, and the lowest average amount of precipitation was recorded in February with 53.39 mm and August with 59.06 mm.

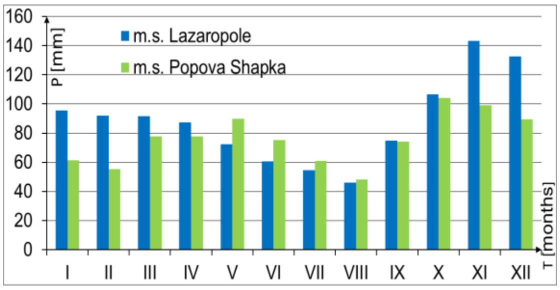

Figure 8. Average monthly precipitation (m.s. Lazaropole and Popova Shapka, 1961-1990)

2.5 HYDROLOGIC MODEL HEC-HMS

The river basin model is created based on a digital spatial model of the terrain. With the help of GIS processing (Spatial Analyst) it is determined the basin area of the river C. Kamen and its sub-basins. The terrain data is transformed into a spatial database in an appropriate format (ArcGIS Shapefile), which is used for input into the HEC-HMS model in the Background Maps section.

The base map added to the river basin model is a shapefile., obtained by processing the river basin in the Arcmap software package. The basin of the river Crn Kamen, up to the profile

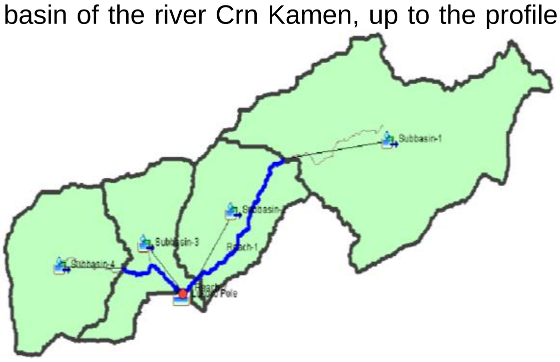

Figure 9. The basin with its sub-basins and their interconnections

of the planned Lukovo Pole dam, is divided into four sub-basins with different surfaces. Figure 9 shows the river basin of the river Crn Kamen with the subbasins Subbasin-1, Subbasin-2, Subbasin-3 and Subbasin-4, their interconnections (Reaches), as well as the outlet profile of the basin , marked with Lukovo Pole.

Input parameters in the model are as follows:

- the CN number for each of the sub-basins, defined according to Corine;
- concentration time Ts, calculated according to SCS: $T_c = (0.868 \cdot Lt^2/St)0.385$;
- precipitation, daily precipitation for 1975.

Table 3 Calculation of the number of concentration Ts for each of the sub-basins

	CN	Lt [km]	St [‰]	Tc [h]	Tc [min]
Sub-basin 1	77.51	7.69	46.1	1.042	62.535
Sub-basin 2	75.27	2.07	55.1	0.354	21.254
Sub-basin 3	75.69	4.88	27.9	0.891	53.457
Sub-basin 4	73.67	2.29	30.9	0.478	28.703

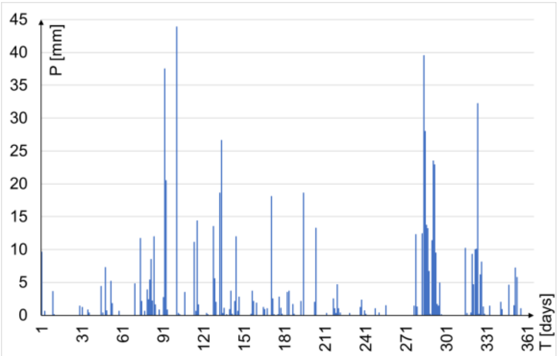

Figure 10. Daily measured precipitation for 1975, m.s. Lazaropole

During the hydrological modelling of the river basin of Crn Kamen, the SCS Unit Hydrograph Transform Method is used as a transformation method, or method for transforming precipitation into runoff according to SCS recommendations, which is parametric method and is based on the relationship between input (precipitation) and output (flow). The simulation was made for a time period of one year (start 12/31/1974, 00:00, end 12/31/1974). The daily runoff hydrograph calculated with HEC-HMS is shown in Figure 11, and the results for all the elements of the hydrological model in Table 4.

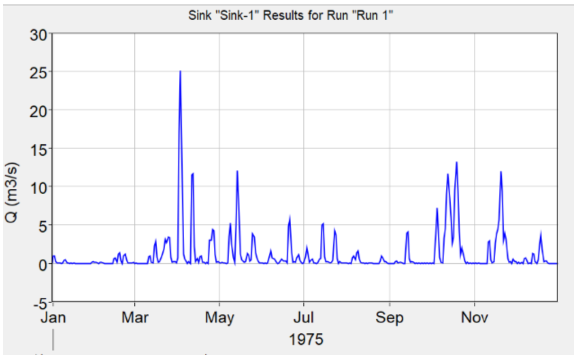

Figure 11. Hydrograph of daily flows in the r.Crn Kamen in 1975, obtained in HEC-HMS

Table 4. Summary table of results in HEC-HMS

Hydrological element	A [km^2]	Qmax [m^3/s]	T	V [mm]
Reach 1	25.23	7.7	03/04/75	666.93
Reach 11	51.63	14.6	03/04/75	668.68
Reach 2	33.98	10.1	03/04/75	669.56
Reach 3	10.20	3.5	11/04/75	668.95
Outlet 1	51.63	14.6	03/04/75	668.69
Sub-basin 1	25.23	8.9	11/04/75	659.14
Sub-basin 2	8.75	3.1	11/04/75	653.61
Sub-basin 3	7.46	2.6	11/04/75	654.66
Sub-basin 4	10.20	3.5	11/04/75	649.55

2.5.1 Calibration of the model

The adaptability of the simulated results with the measured values can be seen from the similarity between the runoff hydrographs, Fig.12. However, the quality and validity of the model can be assessed through the correlation coefficients: Nash Sutcliffe Efficiency (NSE) or Nash-Sutcliffe Efficiency, (0-1), and Root Mean Squared Error Ratio (RMSE) (<1).

In this case, it can be seen that RMSE has a value of 1.2, greater than 1, and Nash-Sutcliffe is -0.385, less than 0, which means that the model cannot be accepted as valid. Therefore, it is necessary to perform calibration and validation of the model, by changing certain input parameters, in order to obtain valid output results close to the measured values.

Calibration includes optimization of CN number values and control of correlation coefficients. With the following values for CN (83,586 for sub-basin 1, 79,458 for sub-basin 2, 79,161 for sub-basin 3 and 55,239 for sub-basin 4) RMSE after calibration has a value of 0.9, less than 1, and Nash-Sutcliffe is 0.195, within 0, Fig. 13. With these values, the model can be accepted as valid and used in further analyses.

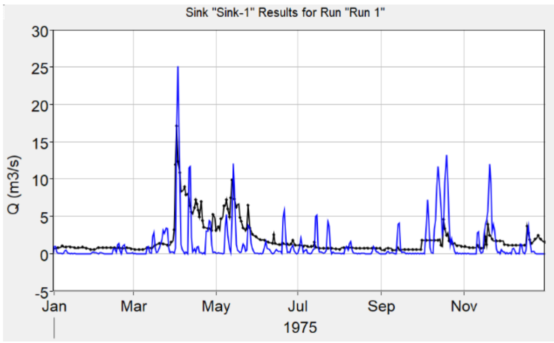

Figure 12. Runoff hydrograph of measured and simulated data

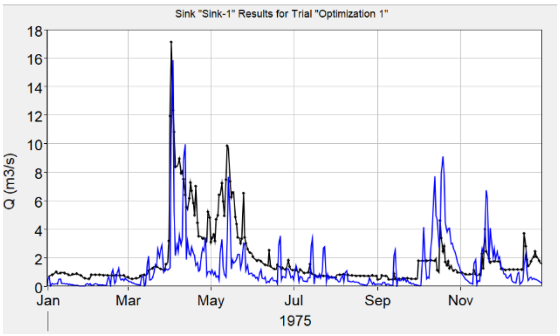

Figure 13. Runoff hydrograph of measured and simulated data after calibration

3 DEFINING HIGH WATERS

Statistical methods were used to determine the high waters of the river Crn Kamen up to the Lukovo Pole dam profile, that is, the maximum flows with a certain recurring period were determined by methods based on historical data of registered high waters. The analysis used the series of maximum registered annual flows of the river Crn Kamen to the Lukovo Pole dam profile for the period 1974-2009, Figure 14.

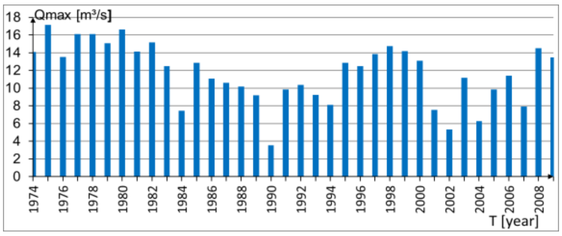

Figure 14. Maximum recorded annual flows of the river Crn Kamen

Determination of the statistical parameters of the sequence of maximum registered annual flows of the river Crn Kamen to the profile of the Lukovo Pole dam for the period 1974-2009, as well as the application of probability distribution functions was done using the HEC-SSP software package. Statistical Software Package - HEC-SSP was developed by the US

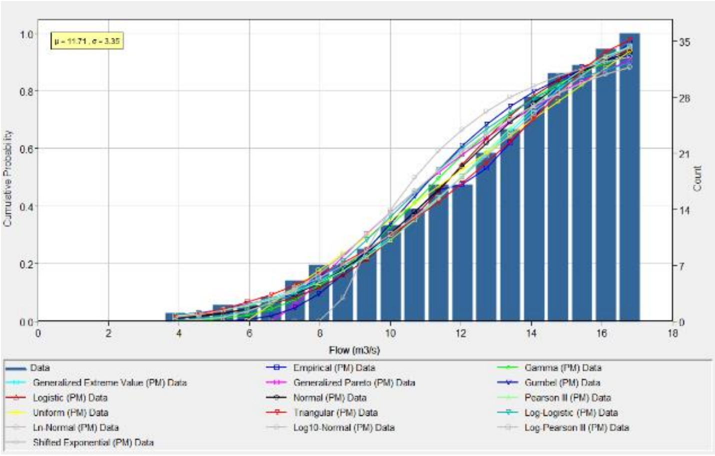

Figure 15. Theoretical distributions considered in HEC-SSP

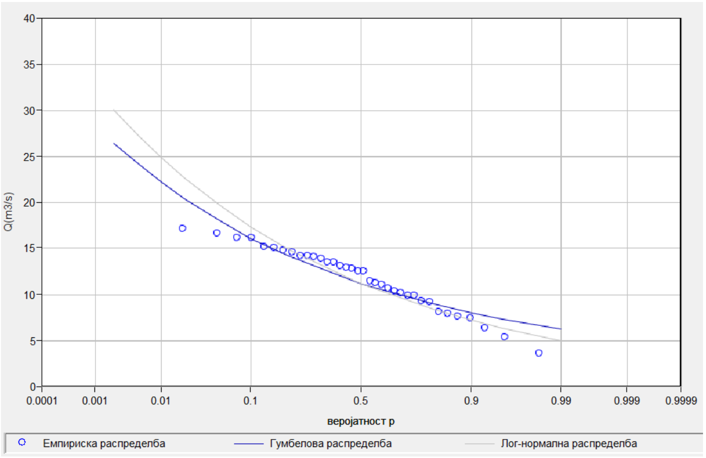

Figure 16. Most adequate distributions chosen

Army Corps of Engineers as part of the research and development program of the Hydrologic Engineering Center (HEC).

Table 5. Statistical parameters of the series of maximum annual flows in a period of 36 years calculated in HEC-SSP

Summary Statistics

Statistic	Original Data	Processed Data
Min	3.562	3.562
Max	17.123	17.123
Median	12.482	12.482
Mode	3.562	3.562
Sample Size	36	36
Mean	11.711	11.711
St Dev	3.346	3.346
Skew	-0.497	-0.497

In total 15 theoretical distributions were considered, Figure no. 15, and the adaptability was evaluated according to the Kolmogorov-Smirnov and Chi-Square tests. The following distributions are presented as the most adequate (Test statistics - Standard Product Moment): Gumbel's and Log-normal distribution, Figure 16. The Log-normal distribution was chosen for the analysis of the high flows in a specific recurrence period. According to this analysis, the determined values for the flows with different recurrence periods are shown in Table 6.

Table 6. Flows with defined recurrence periods according to Log-normal and Gumbel's distributions in HEC-SSP

p [%]	Log-normal	Gumbel's
	Q [m^3/s]	Q [m^3/s]
0.2	31.5	27.3
0.5	28	24.6
1	25.4	22.6
5	19.8	18
20	14.9	14.1
50	11.1	11.2
80	8.3	9
90	7.1	8
95	6.3	7.3
99	4.9	6

4. RESULTS ANALYSIS

The analysis of the results obtained by simulation of the hydrological model for the river basin of Crn Kamen, Figure 17, show that the maximum flow obtained from the simulated flow data is Q=14.6 m^3/s, which appears on 04/03/1975. The total runoff volume obtained from simulated data is V=668.69 mm.

If the measured data is analyzed, the maximum flow is Q=17.1 m^3/s and appears on April 2, 1975. Total runoff volume obtained from measured flow data, V=1153.17 mm.

The difference between simulated and measured data is also confirmed by model validation, Figure 17, where it can be seen that RMSE=1.2, and Nash-Sutcliffe is -0.385. After calibration of the model, these values are within the limits of acceptance, Figure 18, RMSE=0.9, and Nash-Sutcliffe is 0.195, and the validity of the model can be confirmed. With the calibration of the model, the maximum flow obtained from the simulated data is Q=15.8 m^3/s on 04/03/1975.

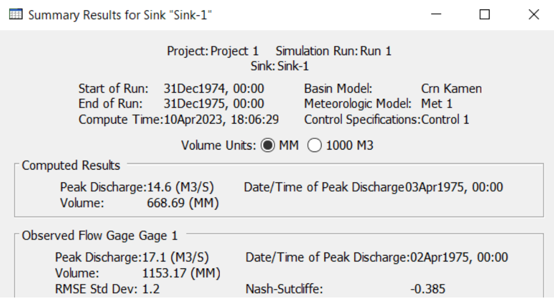

Figure 17. Results of measured and simulated data

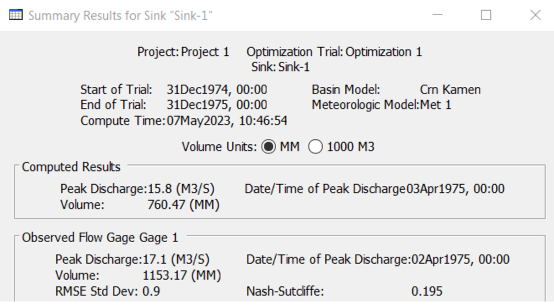

Figure 18. Results of measured and simulated data after model calibration

The definition of high waters of river Crn Kamen made with the HEC SSP software package, according to a larger number of theoretical distributions, shows that the Log-Normal distribution best adapts to the empirical distribution and it is recommended for use in further analyses.

5. CONCLUSION

From the analyzes made in this paper, it can be concluded that the hydrological modeling of a river basin with the help of appropriate software packages (SWAT, HEC HMS, HEC HSS, etc.) provides the opportunity for a quick, precise and accurate definition of the necessary parameters for an appropriate hydrological analysis of a river basin. In this particular case, for the river Crn Kamen, the average height above sea level of the river basin is 1896.5 m, the area of the river basin is A=70.6 km^2, of which 52.80 km^2 fall on the river basin area up to the profile of the future Lukovo Pole dam.

Most of the river basin, with an area of 39.5 km^2, is covered with natural grassland, and a part with shrub and vegetated areas, with an area of 9.6 km^2 and 3.7 km^2 respectively.

Determination of the hydrological sequences of flows in the river was made using the available measured data: historical sequences of characteristic flows (minimum, maximum and average monthly) from the Lukovo Pole hydrological station for the period 1974-2009.

The hydrological modeling of the river basin of Crn Kamen was done using the HEC-HMS software package. The model was made in order to define surface runoff based on measured precipitation data, that is, the transformation of precipitation into surface runoff was made. Precipitation data were used from Lazaropole station. Statistical analysis of hydrological data was done with the HEC-SSP software package.

The measured data for daily flows of the river Crn Kamen at the profile where the construction of the dam is foreseen for the period from 1974 to 2009 were used to define the high waters for different recurrence periods. The high waters of the river Crn Kamen with different recurrence periods have been analyzed by applying several theoretical distributions. The Log-Normal distribution best fits the empirical distribution and is recommended for use in further analyses.

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