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Research paper

HYDROLOGICAL AND HYDRAULIC MODELING OF RIVER CRNA FOR EVALUATING RIVER BASIN RESTORATION MEASURES

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Abstract

The degradation of the rivers and river basins caused by natural and/or anthropogenic factors can be prevented or significantly reduced by taking restoration measures. To define the restoration measures, it is necessary to perform a hydrological analysis of the river basin as well as a hydraulic analysis of the watercourse in the river basin. In this research, the hydrological-hydraulic analysis is carried out for the river Crna, for a characteristic section from the estuary of the river Crna in the river Vardar to the bridge on the E75 highway, at the Stobi archaeological site. This section is of great importance for the Republic of Macedonia because apart from the archaeological site of Stobi, which is a national institution in the field of culture, there are also the railway bridge on the "Skopje-Thessaloniki" railway and the bridges on the regional road R1102 and the highway E75, which are buildings of the first category. During the hydrological analysis, different methods are used, due to insufficient and discontinuous data. To determine the basic hydrological parameters, measured annual maximum flows (from 1961 to 1996) are used, and by using the databases of modern GIS, the physical-geographical characteristics of the river basin, height representation, geological, hydrogeological and pedological characteristics as well as land use are determined. By applying the HEC-RAS software package, a one-dimensional hydraulic model was created for the simulation of unsteady flow in the riverbed. With the hydraulic modeling, the hydraulic consequences are defined (flood surfaces, active erosion zones and sediment filling zones), and the most critical points are determined. The obtained results of the hydraulic analysis are analyzed, and measures are proposed in order to reduce the consequences of a flood wave.

Key words: *river basin restoration, hydrology, hydraulics, modeling.*

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1. INTRODUCTION

River basin restoration is an increasingly common approach utilized to reverse past degradation of river basins and to mitigate the anticipated damage from future development and resource-extraction activities. With new efforts to evaluate river basin restoration projects that use channel reconfiguration as a methodology growing exponentially over the last several decades, there has been little evidence for measurable ecological improvement or achieving the legally mandated goals of improving the structure and function of streams and rivers [1]. The complexity of restoration as a task, by which a degraded ecosystem is returned to its original state, requires a good hydrological-hydraulic analysis to be performed in order to determine the most appropriate restoration measures. In order to prevent errors in determining restoration measures, it is necessary to perform an assessment and monitoring of a specific ecosystem. However, the effects of river restoration on hydraulic and hydrological processes are complex and are often difficult to determine because of the long-term monitoring required before and after restoration works. For an effective river base restoration, detailed pre-restoration and post-restoration hydrological data is required to provide important insights into the hydrological effects of river basin restoration [2]. Due to different models obtaining different results on the same problem, incomplete or absent data, and climatic/social/cultural changes, the designers and managers of such projects frequently face high levels of uncertainty [3]. With the increase of flood risks all over the world, the approach to river flood management is beginning to make way for a paradigm shift towards 'living with water'. The ecological co-benefits of this shift, where rivers are given the space they need to migrate on the landscape, have so far been undervalued [4]. Methods like embankment removal or returning the channel to its natural, pre-engineered dimension for floodplain rehabilitation, can be a valuable part of the flood management strategy of a river. Both measures lead to increased inundation of the floodplain, which can be positive for ecological restoration [5]. River restoration as part of a river basin restoration is an appropriate solution for rivers which are degraded, yet have the potential to return to natural condition. Proposition of a new strategic plan for river restoration based on quantitative analysis rather than only qualitative assessment gives better results [6]. Hydrologic and hydraulic modeling allow to satisfy all regulatory requirements and ensure that natural, agricultural, and social resources are not damaged by flooding induced by modifications to the river system [7].

The objective of this study is to analyze and determine the problems and to define the most appropriate restoration measures for the river basin and also river restoration of the river Crna in the area around the archeological site Stobi.

The analysis will show the importance of a good hydrological and hydraulic modelling is the base for choosing and implementing the best solutions for river basin restoration and river restoration.

1.1. Case Study: River Crna

The degradation of the watershed of the river Crna is causing the river to overflow from its river bed even in the case of small quantities of rainfall and historically, the biggest problems of river Crna occur at the archaeological site of Stobi, the railway bridge on the "Skopje-Thessaloniki" railway and the bridge on the regional road R1102.

The aim of this research is to identify the problems and define the most appropriate restoration measures for the river basin.

The analysis was done with an appropriate hydrological analysis of the river basin and a hydraulic model for the propagation of the flood wave to determine the flooded areas and identify the critical zones for which restoration measures are recommended.

1.1.1. Study Area

River Crna is the biggest right tributary to the river Vardar and its river basin extends across two countries: in the southwestern part of the Republic of Macedonia and in the northern part of the Republic of Greece.

The study area is located from the mouth of the river Crna to the bridge on the E75 highway, at the archaeological site of Stobi. On this section there is also the railway bridge on the "Skopje-Thessaloniki" railway line, which connects Europe with the port of Thessaloniki.

The area of the river basin of river Crna is 5861.19 km^2 and has a developed and rich hydrographic network, consisting of 20 tributaries longer than 10 km with a total length of 461 km. Due to the favorable hydropower conditions in the river's Crna river basin, around 35 reservoirs have been built. The geological composition of the region is composed of three tectonic zones, with Paleozoic and Triassic formations in the upper and western parts, Precambrian rocks in the middle part and mix of shists, granites, flysch, tuffs, limestones, dolomites and marbles in the lower part of the river basin.

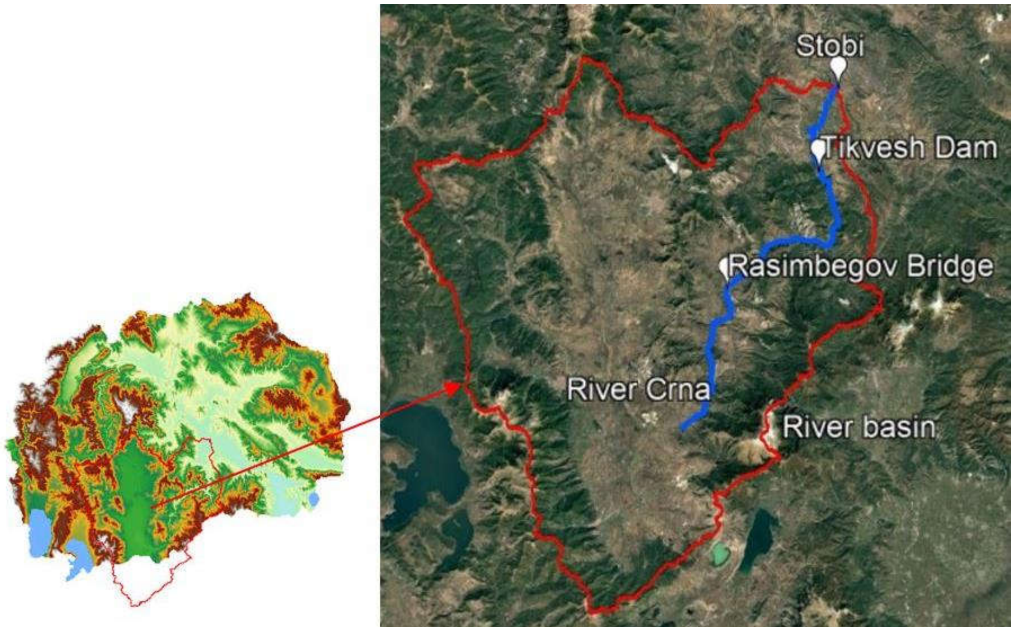

Figure 1. Study Area (source: Google Earth)

1.1.2. Data sources

In the river basin of river Crna there are two measuring stations for measuring flow. One is the measuring station Vozarci near the the archaeological site of Stobi, downstream of the Tikvesh Dam and the other is Rasimbegov bridge, upward of the Tikvesh Dam. The measuring station Vozarci is seriously damaged and it is not in use, and because of that the flows that are used in this research are from the measuring station at Rasimbegov Bridge. The data about the flows are annual maximum flows that were monitored and measured continuously for the period from 1961 to 1996, Figure 2, (source: Hydrometeorological Service-HMS).

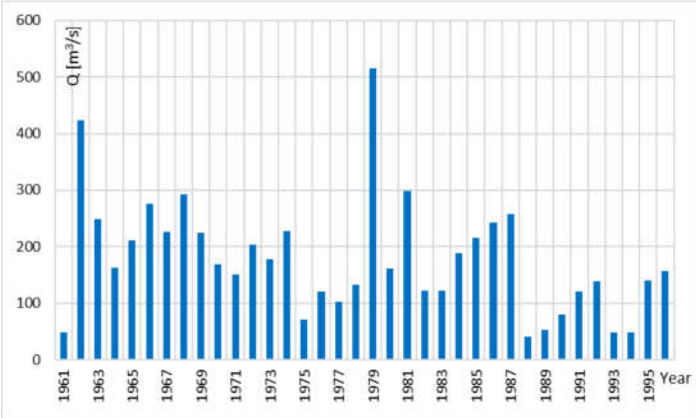

Figure 2. Maximum annual flow (Rasimbegov Bridge 1961 – 1996)

Digital terrain model of Macedonia in raster format with a resolution of 5x5 m was used as a terrain model, and information about the land use in this research was obtained by applying the data from the CORINE Land Cover database from 2018 [8]. The information for the soil textures of the land was obtained from the Pedological Map of Macedonia 2015 and the geological structure of the subject area from the Geological Map of Macedonia (according Arsovski 1997).

2. METHODOLOGY

2.1. Hydrological modeling

Hydrological modeling of the river basin of river Crna up to the mouth in river Vardar was done to determine the maximum flood waters in the analyzed section around the Stobi archaeological site. The delineation of the river basins is done with the help of GIS software ArcMap, module ArcSwat [9] and the physical-geographical characteristics of each sub-basin were calculated, Table 1. Detailed maps have been created in order to showcase the basic geological characteristics (Figure 3a), pedological [10], climatological and meteorological characteristics, as well as land use according to the CORINE Land Cover databases (Figure 3b).

Due to insufficient and discontinuous information for measured flow, combination of methods is used to determine the maximum flood waters in the subject area [11,12,13]. The calculations of the maximum flood waters for the river basin of river Crna were done in three steps, Figure 4.

The first step is up to Rasimbegov Bridge where the measured data from the measuring station is used and with the help of statistical analysis the maximum flood waters in that point were determined.

From the Rasimbegov Bridge to the Tikvesh Dam, for determination of the maximum flood waters a method of regional analyses is used. This method is based on the principle of hydrological analogy, i.e. comparing the ungauged basin with an analogous studied basin. Due to the existence of the dam and its influence on the water runoff, an analysis of the transformation of the flood wave through dam with a return period of 100 years was done. The input and output hydrograph of the Tikvesh Dam for the scenario where the flood wave reaches the spillway height and all the evacuation spillways are in use is shown on Figure 5 (Qd – input flow, Qi – output flow and Qpr – overflow over spillway). Input data for the transformation of the flood wave through the Tikvesh Dam are the available accumulation space, the type of spillway, as well as the law of discharge of the accumulation, depending on downstream conditions.

The last step is from the Tikvesh Dam up to the mouth in the river Vardar. To determine the maximum flood waters at the mouth, surface water runoff was calculated for this section and added to the maximum water output from the Tikvesh Dam.

Table 1. Basic geometric characteristics of the river sub-basins

	F [KM^2]	O [M]	S_S [%]	Z_{MAX} [MASL]	Z_{MIN} [MASL]
Rasimbegov Bridge	4515.04	505.69	23.38	2598.00	357.00
Tikvesh Dam	5346.08	586.22	25.66	2598.00	210.00
Mouth in Vardar	5861.19	595.29	25.98	2598.00	117.00

F – area of river basin, O – perimeter of river basin, S_s – average slope of river basin, Z_{max} – maximum elevation in the river basin, Z_{min} – minimum elevation in the river basin.

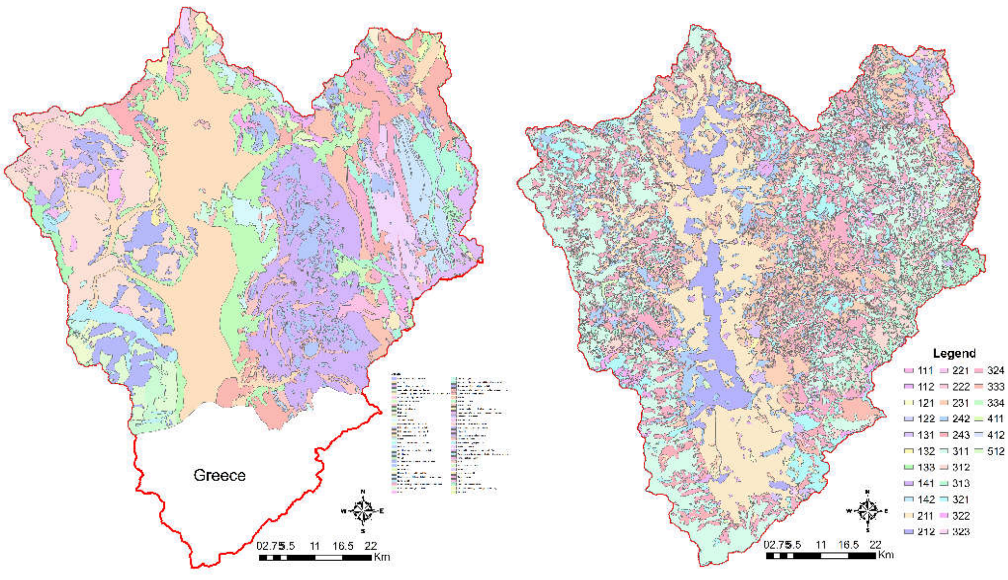

Figure 3. a – Geological map, b – CORINE Land Cover map

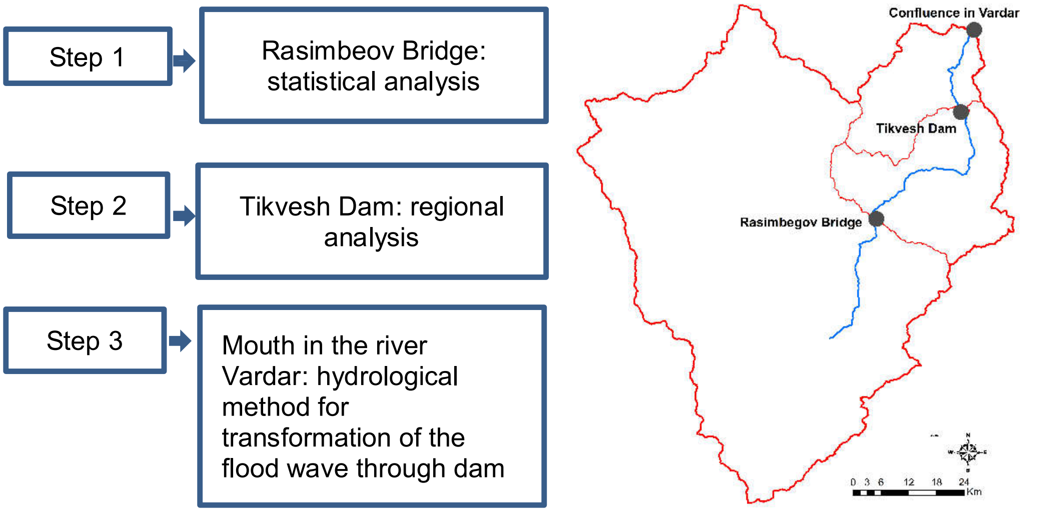

Figure 4. Algorithm for calculations of the maximum flood waters for the river basin of river Crna

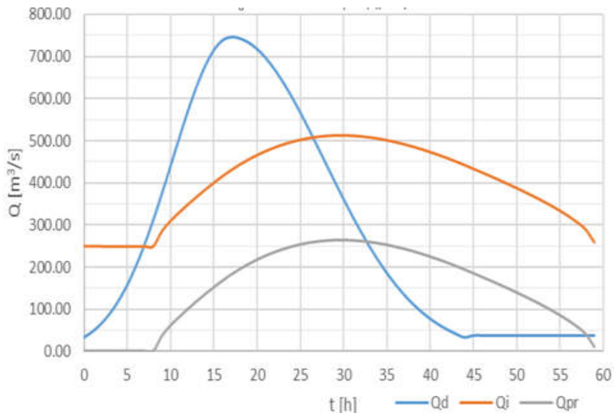

Figure 5. Input and output hydrograph at Tikvesh Dam

2.2. Hydraulic modeling

The hydraulic analysis were done for the riverbed of river Crna within the subject area from Bridge 3 (at the mouth in river Vardar) to Bridge 1 (at the bridge of E75 highway), with the software package HEC-RAS, made and developed by The Center for Hydraulic Engineering (HEC) of the US Army Corps of Engineers (USACE) [14]. For the purposes of this research, hydraulic analysis of the subject area were performed using a 1D model [15].

2.2.1. Input data

The hydraulic model for the analyzed section starts at the mouth of river Crna in the river Vardar and ends at the bridge of E75 higway with a total lenght of 813.45 meters, Figure 6. Geometrical data for the riverbed of river Crna was obtained from the 29 measured cross sections of the river Crna.

Figure 6. Analyzed section

Along the section there are modelled three bridges in the hydraulic model and was analyzes their influence. The characteristics of the bridges are given in Table 2.

Table 2. Characteristics of modeled bridges

Bridge	Type	Stationing data [km]	Number of bridge openings	Bridge top constr. [m.asl]	Bridge bottom constr. [m.asl]
B1 (at E75 higway)	Concrete	0+770.00	4	152.00	149.80
B2 (at regional road)	Steel	0+116.00	1	136.70	136.20
B3 (at mouth in river Vardar)	Concrete	0+080.00	3	137.40	136.00

2.2.2. Boundary conditions

Boundary conditions are defined at the downstream and upstream cross sections of the analyzed section as slope of the river bed, S_0 = 0.004 m/m for downstream and S_0 = 0.057 m/m for upstream, with the assumption that the flow in these profiles is stationary and uniform and with the given slope the normal depth in these boundary sections is defined.

The riverbed in the analyzed section is characterized by changes in the cross sections and the longitudinal profile, is overgrown with lush vegetation, big trees and erosion is apparent along the whole section. Given this state, the Manning's roughness coefficient for the river in the hydraulic model are 0.045 for the riverbed and 0.1 for the inundations.

Hydraulic analysis using the 1D model consists of simulating a flood wave propagation through the riverbed. The adopted maximum high water is $Q_{100years}$ = 585.99 m^3/s.

3. RESULTS

Hydrological modeling of the river basin of the river Crna was done to determine the hydrological characteristics needed for the calculations of the maximum flood waters in each sub-basin and the adopted maximum flood waters for the subject area used in the hydraulic modeling, Table 3.

Table 3. Results from the hydrological analysis

Sub-basin	$Q_{100years}$ [m^3/s]
Up to Rasimbegov Bridge	630.80
Rasimbegov Bridge to Tikvesh Dam	746.90
Mouth in river Vardar	**585.99**

With the hydraulic modeling of the river Crna a total number of 29 cross sections and the influence of the river on the bridges have been analyzed. The results of the hydraulic model of the water flow and flooded areas at the analyzed section are shown in the map of flooded areas for the analyzed return period of 100 years, Figure 7, the longitudinal profile of the riverbed, Figure 8, the influence of the river on the bridges, Figure 9 and the hydraulic parameters in Table 4 (Q – max. high water, Z_{min} – channel elevation, Z_{max} – max. water elevation, H – water depth, V – velocity, A -area , B –top width , Fr – Froude's number, τ – sheer stress).

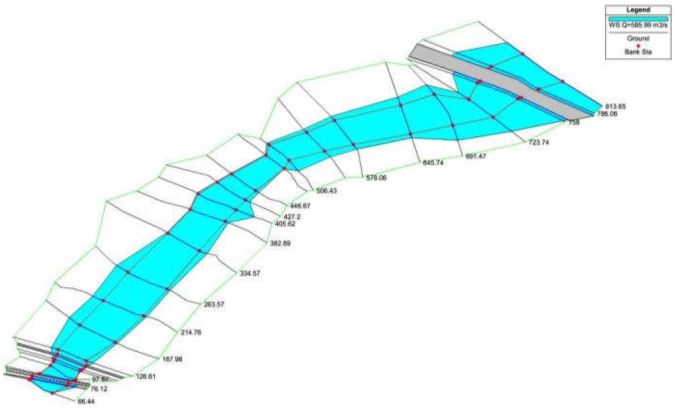

Figure 7. Map of flooded areas

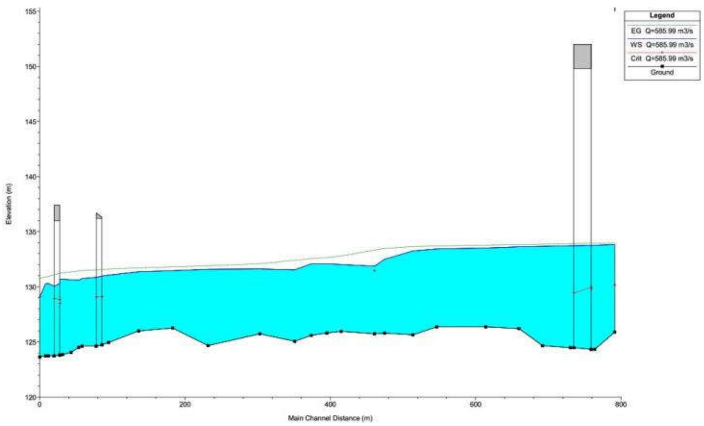

Figure 8. Longitudinal profile

Table 4. Hydraulic parameters

Prof.	Station	Q	Z_{min}	Z_{max}	H	V	A	B	Fr	τ
	(km)	(m^3/s)	(m)	(m)	(m)	(m/s)	(m^2)	(m)		(N/m^2)
1	0+813,65	585,99	125,90	133,83	7,93	1,76	416,73	139,34	0,24	20,42
2	0+786,06	585,99	124,33	133,78	9,45	1,93	393,09	128,91	0,25	20,49
3	0+782,00	585,99	124,33	133,77	9,44	1,93	392,61	128,89	0,25	20,52
	0+770,00	**Bridge 1 (at E75 highway)**								
4	0+758,00	585,99	124,48	133,73	9,25	1,94	358,65	123,17	0,24	18,67
5	0+723,74	585,99	124,66	133,67	9,01	1,94	328,27	92,36	0,24	22,25
6	0+691,47	585,99	126,21	133,63	7,42	2,02	315,78	87,78	0,27	29,52
7	0+645,74	585,99	126,37	133,52	7,15	2,28	269,64	64,00	0,31	45,58
8	0+578,06	585,99	126,37	133,43	7,06	2,30	260,90	56,82	0,30	46,38
9	0+545,52	585,99	125,64	133,25	7,61	2,79	225,04	50,85	0,36	66,11
10	0+506,43	585,99	125,80	132,49	6,69	4,41	139,53	47,90	0,65	150,93
11	0+492,54	585,99	125,74	131,87	6,13	5,34	109,80	29,01	0,86	361,09
12	0+446,67	585,99	125,95	132,02	6,07	3,89	151,62	41,45	0,61	167,56
13	0+427,20	585,99	125,81	132,08	6,27	3,37	176,61	46,88	0,52	123,36
14	0+405,62	585,99	125,59	132,09	6,50	3,03	198,46	70,80	0,48	79,27
15	0+382,89	585,99	125,06	131,55	6,49	4,12	143,26	44,98	0,71	210,13
16	0+334,57	585,99	125,74	131,62	5,88	3,05	198,80	53,19	0,46	94,92
17	0+263,57	585,99	124,67	131,60	6,93	2,46	257,76	67,93	0,36	56,52
18	0+214,76	585,99	126,26	131,46	5,20	2,63	234,73	64,68	0,40	67,86
19	0+167,98	585,99	126,00	131,37	5,37	2,65	238,32	63,64	0,39	65,18
20	0+126,61	585,99	124,95	131,06	6,11	3,32	198,10	49,73	0,47	100,60
21	0+119,88	585,99	124,73	130,98	6,25	3,44	176,09	43,28	0,50	120,84
	0+116,00	**Bridge 2 (at regional road P1102)**								
22	0+111,94	585,99	124,62	130,75	6,13	3,74	158,83	37,59	0,55	153,16
23	0+108,42	585.99	124,51	130,61	6,10	4,00	147,03	33,38	0,59	184,12
24	0+097,87	585.99	124,06	130,64	6,58	3,73	157,23	33,44	0,55	172,48
25	0+086,21	585,99	123,85	130,70	6,85	3,31	176,81	36,60	0,48	134,96
26	0+084,06	585.99	123,81	130,70	6,89	3,27	179,16	39,26	0,48	130,50
	0+080,00	**Bridge 3 (at mouth in river Vardar)**								
27	0+076,12	585,99	123,74	130,30	6,56	3,51	168,37	43,09	0,53	137,76
28	0+074,47	585.99	123,74	130,28	6,54	3,53	167,45	42,73	0,54	139,99
29	0+066,44	585.99	123,64	129,07	5,43	5,73	102,23	31,35	1,01	456,92

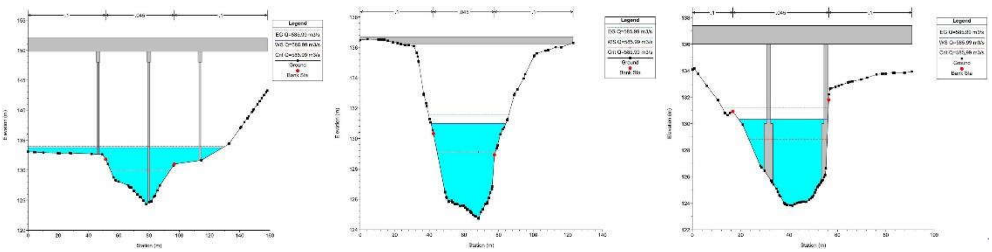

Figure 9. Influence of river Crna on bridges (a – Bridge 1, b – Bridge 2, c – Bridge 3)

4. DISCUSSION

Relevant and accurate data are required for quality hydrological analyses. Continuous and sufficiently long hydrological series of measured data play a major role in the quality of hydrological analysis. The insufficient number of measuring stations along the river Crna imposes the use of multiple methods for determining the maximum flood waters, which is the basis for further hydraulic analysis. The outlet flow from Tikvesh Dam indicates the importance of the Dam for reducing high water levels downstream.

In this hydrological analysis, different methods of maximum flood waters calculations were used for different profiles. Any transfer of flow from one profile to another and the use of different methods is a basis for error in calculating the maximum flood waters, but in the absence of measured flow data for the appropriate location, with a certain degree of reserve, they can be used for the necessary analyses.

By analyzing the results of the hydraulic calculations, it can be concluded that there is a significant flooding at almost the whole analyzed section. Only part where there are no flooding areas are before the mouth in the river Vardar, mainly because the cross sections of the river Crna are expanding. The depth of the river and flooded zones ranges from 5 m to up to 9.5 m, the velocities in the river reach values of up to 5.73 m/s, and the sheer stress is greater than 456 N/m^2 resulting in the erosion in the river bed.

Bridge 1 is safely operating with a height of 15 meters above water level. Because the riverbed is natural, there is flooding around the bridge. The middle pillar of the bridge is located in the middle of the riverbed and is prone to erosion, so it is necessary to regulate the riverbed.

Bridge 2 is operating safely with a height of 4 meter above water level, but due to the narrow cross section at the bridge, the water has high velocity and sheer stress which results with occurrence of erosive processes. It is recommended that the riverbed be regulated to protect the bridge.

At the bridge on the Skopje-Thessaloniki railway, a deepening of the bottom, i.e. the presence of erosion, is observed, while one opening of the bridge is filled with material.

The bridges with its pillars are hydraulically unfavorable and increase flow resistance, which causes slowdown of the flow upstream of the bridges The flow regime is subcritical in the whole section and Froude numbers are below the critical value, $Fr < 1$.

The riverbed has a significantly reduced capacity and in the event of $Q_{100years}$ = 585.99 m3/s most of the section will be flooded.

River regulation can be carried out with technical measures first in the river basin, and then in the riverbed and banks. Measures that can be taken in the river basin are:

- Afforestation of the river basin enables retention of runoff, increasing of the runoff time, and significant reduction of flood waters.
- Control of the erosive areas of the river basin with technical-meliorative measures primarily intended for the reduction of surface runoff, reduction of erosion processes, creation of conditions and opportunities for biological works.
- Clearing the natural riverbed of dense low and tall-stemmed vegetation and its further maintanance.
- Operational plan for reservoir management.

In addition to measures in the river basin, for complete protection from the consequences of high water levels on the river Crna, it is necessary to foresee protective measures in the riverbed and on the banks. The most critical slopes that are subject to collapse need to be protected. Protection of the archarological site of Stobi from flooding can be done by building a parapet reinforced concrete wall, which will be founded on a layer of improved material.

5. CONCLUSION

With the help of the hydrological modeling the hydrological characteristics of the river basin of the river Crna were calculated and with the combination of statistical, regional and flood wave propagation analysis, the maximum flood waters at the profile of the mouth into the river Vardar was determined. The lack of sufficient measuring stations and the unavailability of continuous and high-quality input data (measured flows) imposes the use of multiple methods for determining the relevant flow, thereby complicating the analysis itself.

The hydraulic modeling of the river Crna at the analyzed section around the Stobi archaeological site, from the mouth in river Vardar to the bridge at the E75 highway was done in order to determine the effects of the river Crna on the bridges and determine the flooded areas. The results obtained from this research enable further research in this area with the aim of timely detection and prevention of hydraulic consequences. With the help of the results obtained from the analysis, a map of critical zones of flood areas can be created that will serve for the analysis of flood zones as well as preparation for prevention and management in the event of a large flood wave and also for the application and analysis of proposed restoration measures to prevent current and future hydraulic consequences.

In order to determine the best river basin restoration measures for the whole river basin of river Crna, a more thorough and bigger hydraulic analysis should be done for the whole basin and a more complex 2D model should be developed. Also, detailed pre-restoration data is required to prove the effects of the restoration.

REFERENCES

[1] Bernhardt S. Emily, Palmer A. Margaret: **River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation,** Ecological Applications, Vol. 21, No. 6, 1926-1931, 2011, DOI: 10.2307/41416628

[2] H. M. Clilverd, et.al.,: **Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics**. *River Research and Applications*, Vol. 32, No. 9, 1927-1948, 2016, **https://doi.org/10.1002/rra.3036**.

[3] Darby Stephen, Sear David: **River Restoration: Managing the Uncertainty in Restoring Physical Habitat,** *WILEY Online Library,* 2008

[4] McCabe, C.L., Matthaei, C.D., Tonkin, J.D: **The ecological benefits of more room for rivers**, *Nat Water 3*, 260–270, 2025, https://doi.org/10.1038/s44221-025-00403-0

[5] Acreman M. C., Riddington R., Booker D. J.: **Hydrological impacts of floodplain restoration: a case study of the River Cherwell, UK,** *HESS*, Vol. 7, 75-85, 2003, https://doi.org/10.5194/hess-7-75-2003

[6] Sersawy El Hossam, Barbary El Zeinab: **Hydraulic Evaluation of River Restoration Using Numerical Modelling Approach**, *IJSRSET*, Vol. 1, No. 12, 607-617, 2016,

[7] Misganaw, et.al: **Hydrological and Hydraulica Modeling of the Cache River for Evaluating Alternative Restoration Measures**, *Cache River Symposium,* 2015

[8] Copernicus Land Monitoring Service (CLMS) & European Environmental Agency (EEA), (2012): Corine Land Cover

[9] Tiffany Schanatre, MGEO (2014): ESRI ArcMap 10.1 Manual For Hydrography & Survey Use. www.Geo-Tiff.com

[10] Mitrićeski J.: **Interpreter of the pedological/soil map of the Republic of Macedonia**, *FAO (Food and Agriculture Organization of the United Nations, FAO), 2015*

[11] Popovska C., Stavrić V., Sekovski D.: **Hydrology and Hydraulic Structures in Environmental Engineering**, Faculty of Civil Engineering, University Ss Cyril and Methodius, Skopje, Macedonia. ISBN978-608-4510-07-9, 2011

[12] Popovska C., Gjeshovska V.: **Hydrology - theory with solved problems**, *Faculty of Civil Engineering, University of St. Cyril and Methodius*, Skopje, 2012

[13] Gjeshovska V., Taseski G., Ilioski B.: **Intensive rainfall in Republic of N. Macedonia**, *Faculty of Civil Engineering, University Ss Cyril and Methodius*, Skopje, Macedonia, 2024

[14] US Army Corps of Engineers, Hydrologic Engineering Center, (February 2016): Hydraulic Reference Manual Version 5.0

[15] Popovska C.: **Hydraulics**, *Faculty of Civil Engineering, University of St. Cyril and Methodius*, Skopje, Macedonia, 2012