doi.org/10.62683/SINARG2025.071

Research paper

MODELING, MAPPING AND ANALYSIS OF URBAN FLOODS - CASE STUDY: SKOPJE 2016

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Abstract

An increasing trend of urban floods in Macedonia from past several years causes major damages on the infrastructure, agriculture and human life. Uncontrolled urbanization, inadequate exploitation and management of forest and agricultural land in combination with climate change increase the possibility of more frequent and more intense floods, especially flash floods in urban areas. The subject of this research is the devastating flood that affected the region of Skopje in August 2016, the analysis and determination of the formation process of the flood wave, the modeling and mapping of the flooded zones. A detailed hydrological analysis of the region was developed to determine the reasons for the large peak of the flood wave and a 2D hydraulic model was prepared for the simulation of the propagation of the flood wave and mapping of the flood zones. A digital terrain model (DTM) by applying the GIS tools ARC Map and QGIS was prepared and the physical-geographic characteristics of the watershed were determined. For the needs of the hydrological analysis, information about the land use, pedological, geological and climate characteristics were obtained and substrates were developed. For the generation of surface runoff hydrographs, hydrological models with the application of the WINTR 55 software program were created. By applying the HEC-RAS software package, a two-dimensional (2D) hydraulic model was created and flooding zones in the Skopje region have been defined. Calibration and verification of the model was done with aerial photogrammetry of the flood after 72 hours from the beginning of the flood. The results are presented on maps of maximum depths, maximum velocities and maximum shear stresses in the flood zone.

Key words: *Urban floods, intensive rainfall, GIS, hydrological and hydraulical modeling, flood mapping.*

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1. INTRODUCTION

In the past decades, thousands of lives have been lost, directly or indirectly, by flooding. Every year floods cause enormous damage all over the world. Floods are among the most recurring and devastating natural hazards, impacting human lives and causing severe economic damage throughout the world. It is understood that flood risks will not subside in the future, and with the onset of climate change, flood intensity and frequency will threaten many regions of the world [1]. The study with high developing urbanization is potential about flood. In addition, the urban area that has bigger potential effect is not always has the bigger flood vulnerable in extreme climate condition. The system can effectively show urban flooding vulnerability [2]. Heavy convective rainfall often results in flooding in urban areas. Urbanization results into conversion of agricultural land, natural vegetation and wetlands to built-up environments and construction on natural drainages as well increase in the population of those living in flood vulnerable areas such as flood plains and river beds [3]. There is a direct relationship between urbanization and hydrological characteristics; decreased infiltration, increase in runoff, increase in frequency and flood height [4]. Small streams in urban areas can also rise quickly after heavy rain due to higher generated runoff and less concentration time [5]. Changes in the urban area and in storm intensity produce higher flows that exceed the capacity of small culverts under roads designed for non-urbanized areas. Although such structures can be adequate when designed, their capacity may turn out to be inadequate and thereby cause overflows onto the roads creating new water paths and flood the built-up areas. In developing countries, inadequate maintenance of the drainage channels, and debris and solid waste disposed into such drainage systems may accentuate the situation [6]. Those reviewed studies show that the study of flood vulnerability has to pay attention in urban area.

The objective of this study is to analyze and determine the formation process of the flood wave that affected the region of Skopje in August 2016.

The analysis will show that the dominant factors for the formation of the flood wave can be located in the extreme intense rainfall, but the influence of urbanization as well as the inadequate drainage system: culverts and channels and their maintenance/non-maintenance is huge.

1.1. Case Study: Skopje 2016

In August 2016, a flood occurred in the region of Skopje, which caused huge material damages. The estimated value of the total damage is 35.7 million euros, and unfortunately 21 victims [7]. The causes of this catastrophic flood according to different experts are different [8].

The aim of this research is to locate the possible reasons for this situation through the simulation of the flood wave caused by the intense rainfall, measured on the day of the flood [9].

The analysis was done with an appropriate hydrological analysis of the wider region where the flood was observed and a hydraulic model for the propagation of the flood wave downstream.

1.1.1. Study Area

The study area is located in the southwest part of the City of Skopje. It is located in the lower part of the mountain Skopska Crna Gora, in the area of the villages Stajkovci and Smilkovci. The mountain is characterized with rivers descending from high points and carrying eroded materials. Additionally, the geological composition of the region is complicated as there are new sediments in the west, Mesozoic layers in the middle and old Paleozoic layers in the east. The villages Stajkovci and Smilkovci are lowland villages, with 99% agricultural land and close to the City of Skopje which contributes for the villages to be highly populated.

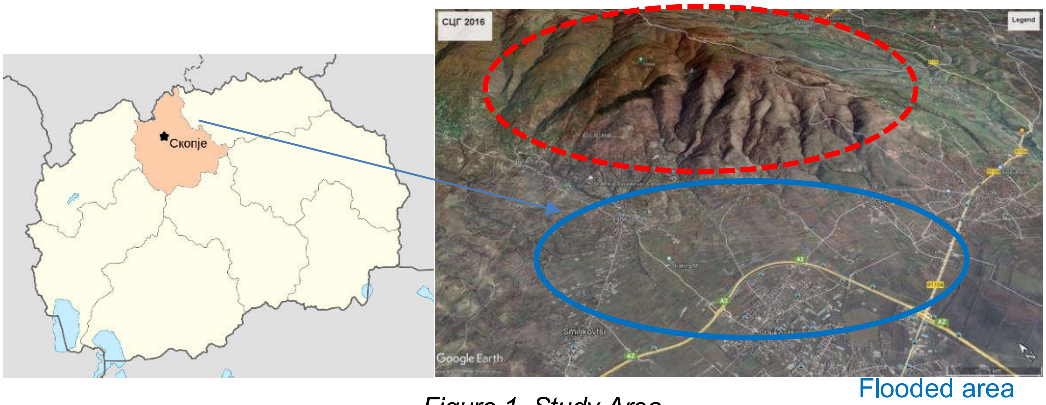

Figure 1. Study Area

1.1.2. Data sources

In this research the data used is measured rainfall for a period of 24 hours in the Skopje region on the day of the flood [8] [10]. The rainfall that is registered is for the period from 17:00 to 22:30 on 06.08.2016, in several automatic measuring stations: Zajcev Rid, Gazi Baba and Karposh and information about the total rainfall according to the pluviograph located at Zajcev Rid, Figure 2. The information shows that the rainfall has an extreme spatial distribution. In further analyses, data from the station in Gazi Baba is used, as the closest one to the flooded area, Figure 3.

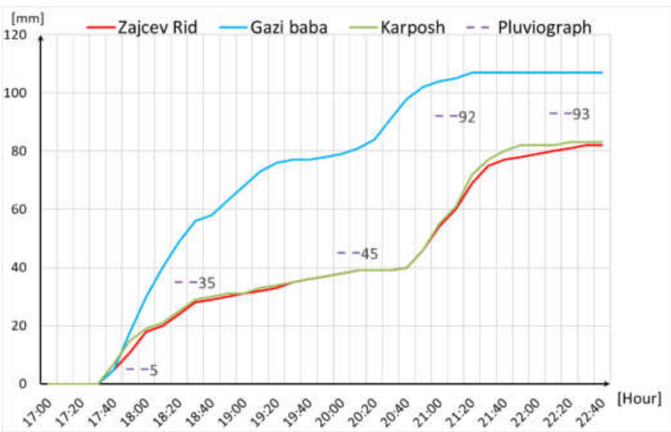

Figure 2. Rainfall hyetograph

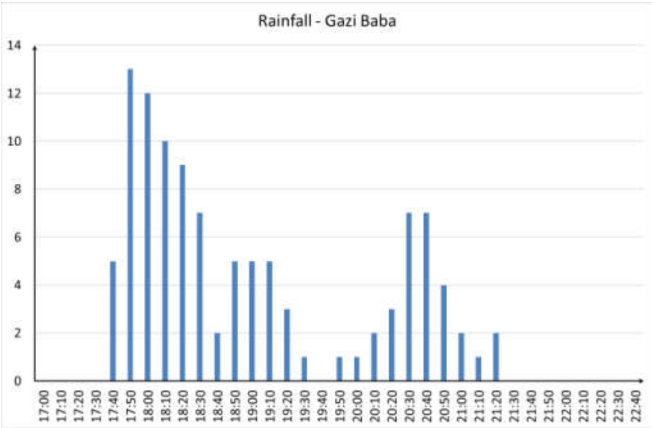

Figure 3. Rainfall hyetograph in measuring station Gazi Baba – histogram display

Digital terrain model of Macedonia in raster format with a resolution of 5x5m was used as a terrain model [11], and information about the land use in this research was obtained by applying the data from the CORINE Land Cover database from 2018 [12]. The information for the soil textures of the land was obtained from the Pedological Map of Macedonia [13] and the geological structure of the subject area from the Geological Map of Macedonia.

2. METHODOLOGY

2.1. Hydrological modelling

The hydrological modelling was done with the use of the software WinTR55. The delineation of the river basins and the defining of their physical-geographical characteristics is done with the help of GIS tools. The raster data is processed through the GIS software ArcMap [14], and with the help of the module ArcSwat the delineation of the 6 river basins was performed, Figure 4. With the analyzes carried by the module ArcSwat, in addition to the creation of individual DTM, the physical-geographical characteristics of each sub-basin were calculated, Table 1. Detailed maps have been created in order to showcase the basic pedological and geological characteristics (Figure 5a, 5b), climatological and meteorological characteristics, as well as land use according to the CORINE Land Cover databases (Figure 5c). Input data for the model for the transformation of rainfall into surface runoff are rainfall hyetograph and spatial distribution of CN. The runoff curve number (CN) is an empirical parameter for predicting direct runoff or infiltration from rainfall excess, known as a "SCS runoff curve number" [15]. A hydrological simulation of the runoff of six watercourses within the subject area was made, namely: Rashtanska river, Bulacanska (Creshnevska) river, Vinicka river, Stracinski watercress, Stracinski torrent and Brnjarska river. The results of the simulations refer to the output profile of the analyzed basins for 7 scenarios with return periods of 2, 5, 10, 25, 50, 100 and 1000 years, Table 2. A typical runoff hydrograph from the model is shown on Figure 6.

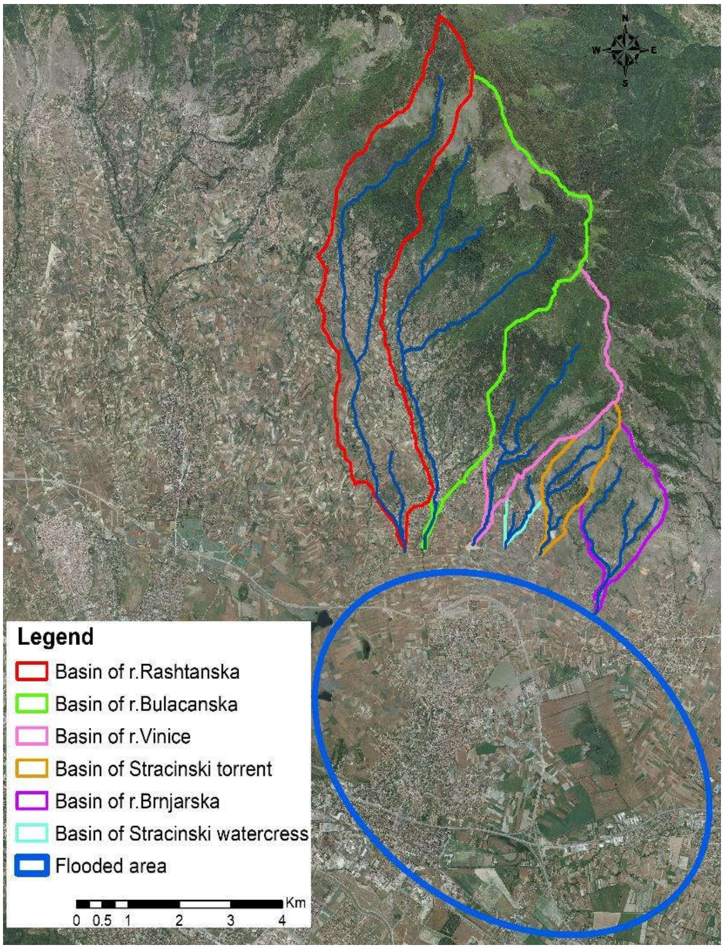

Figure 4. River basins gravitating towards the flooded area

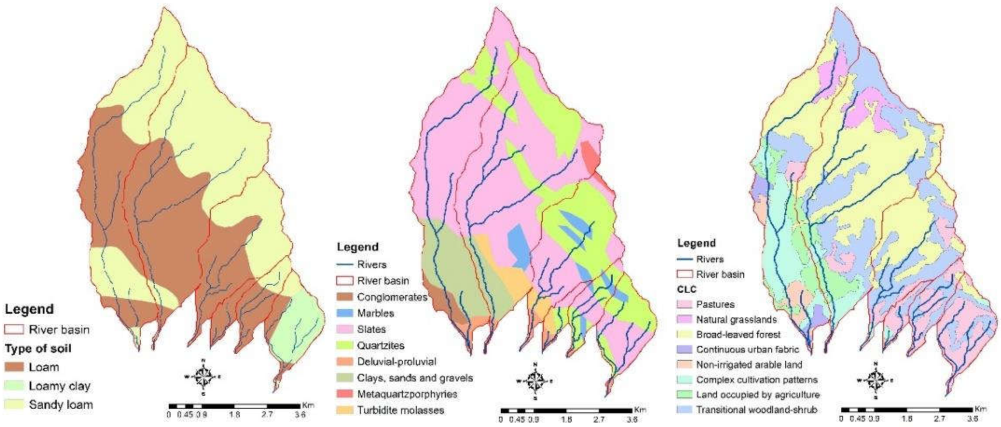

Figure 5. a – Pedological map, b – Geological map, c – CORINE Land Cover map

Table 1. Basic geometric characteristics of the river basins

	F [KM^2]	O [M]	S_S [%]	Z_{MAX} [MASL]	Z_{MIN} [MASL]
Rashtanska river	10.97	19514.66	27.53	1627	288
Bulacanska (Creshevska) river	15.45	22056.14	37.47	1575	287
Vinichka river	6.17	13628.14	38.96	1316	306
Stracinski watercress	0.82	4536.47	29.58	851	310
Stracinski torrent	1.63	8964.44	36.85	1070	331
Brnjarska river	2.77	10047.46	37.03	1016	274

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

Table 2. Results from the hydrological analysis

Watercourse	T – period [years] / Q – maximum high waters [m^3/s]						
	2	5	10	25	50	100	1000
Rashtanska river	10.47	21.01	29.11	37.42	49.81	62.89	113.39
Bulacanska river	11.61	25.31	36.06	47.32	63.15	77.73	144.90
Vinichka river	7.38	13.69	19.09	25.64	35.06	42.92	72.65
Stracinski watercress	1.21	2.25	3.15	4.08	5.39	6.46	10.47
Stracinski torrent	2.24	4.11	5.83	7.64	10.19	12.30	20.21
Brnjarska river	4.45	8.36	11.51	14.74	19.25	22.94	36.57

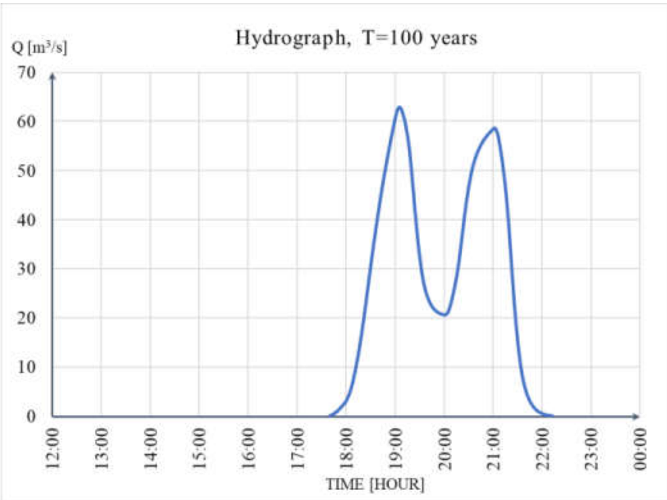

Figure 6. Runoff hydrograph

2.2. Flood Modelling

In the hydraulic analysis for the watercourses within the subject area of Skopska Crna Gora, the software package HEC-RAS was used, made and developed by The Center for Hydraulic Engineering (HEC) of the US Army Corps of Engineers (USACE) [16]. HEC-RAS enables hydraulic analyzes to be performed using one-dimensional, two-dimensional and combined 1D/2D models for the simulation and analysis of runoff in river systems, as well as unconcentrated surface runoff. Additionally, the software package features sediment transport modules. For the purposes of this research, hydraulic analyzes of the subject area were performed using a 2D model.

The boundaries of the computational grid are defined by an iterative procedure, with successive simulations determining the maximum range of flooded areas in the subject area and based on those simulations the limits of the computational grid are determined.

The flooded areas are modeled with cells with lower density in order to achieve rational durations of the simulations, while in more sensitive zones of the subject area, the grid is more detailed in order to improve the precision of the simulations.

The grid is structured by over 50 000 square cells with maximum dimensions of 30x30m in zone of wide flat flooded areas, while in the zone of the river bed with dimensions of 2x2m (i.e. 1x1 in zones of culverts, bridges, and the ring road itself). The grid cells along the length of the river bed, around the ring road and local roads are correctly oriented with the local landforms by applying break lines, Figure 7a. Based on the land use map the CN is defined in the ranges from 73 to 86, Figure 7b and the roughness coefficient, Figure 7c. The Manning's roughness coefficient varies in the range of 0.013 to 0.1 depending on the land cover, where the lowest is for urban zones and the highest for forest.

Boundary conditions are defined as input and output boundary condition (upstream and downstream) for selected scenario for the occurrence of a flood wave with a return period of 100 years. The upstram (input) boundary condition is defined by importing the runoff hydrographs of all the analyzed watercourses, where the main condition for flow distribution through the inlet profiles is the slope of the energy grade line in the zone of the boundary condition. For the downstream (output) boundary condition of the two-dimensional grid, a normal depth in the output profile zone is defined.

For the simulation, the calculations are done using the diffusion wave equations [17]. The adopted duration of the simulation for the analyzed scenario is 72h, while the calculation interval Δt has a variable value and it is controlled by the condition that the Courants number C ranged from 1 to 3.

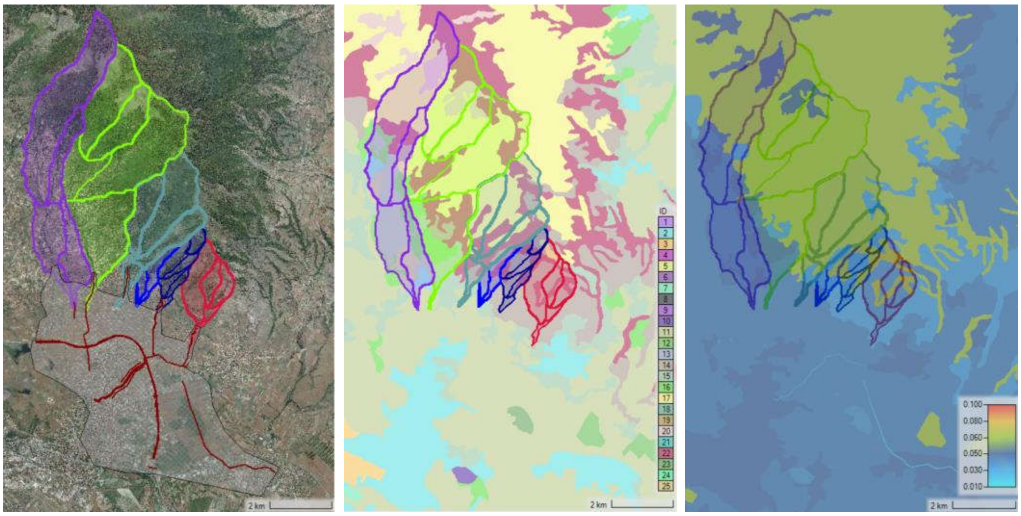

Figure 7. a – 2D computational grid, b – CN, c – roughness coefficient

2.3. Validation Method

For the validation of the model, a comparative technique was used to define the parameters in the model that affect the final results, i.e. the comparison of the calculated and measured parameters. The process of verification of the obtained results is a comparative analysis of flooded areas obtained after 72h according the hydraulic model and flooded areas obtained with aerial photogrammetric images taken two days after the flood.

3. RESULTS

As relevant results of the hydraulic simulation of the water flow at the subject area are separated envelope maps of the maximum values of depths, velocities and shear stresses of the water flow for an analyzed return period of 100 years, Figure 8, 9 and 10.

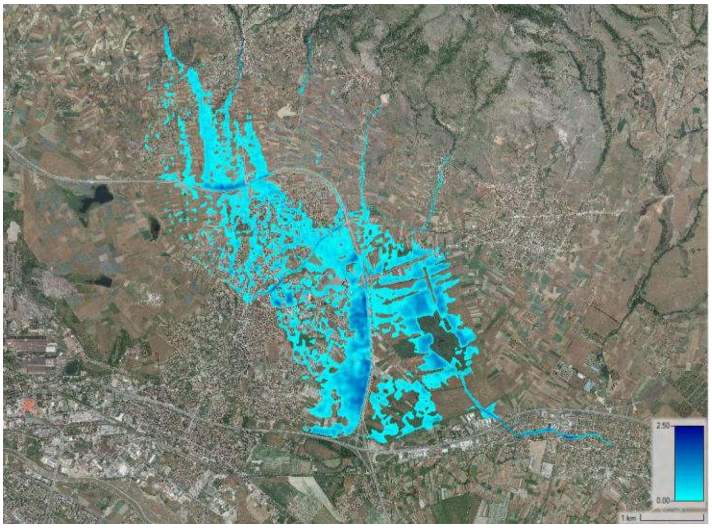

Figure 8. Map of maximum water depths

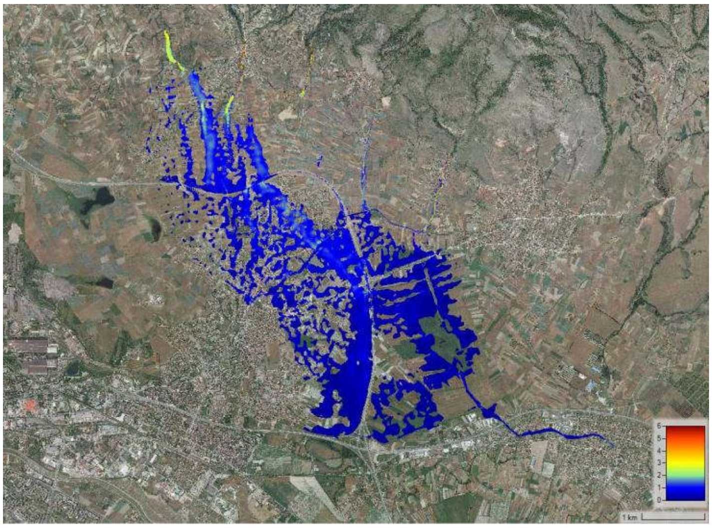

Figure 9. Map of maximum flow velocities

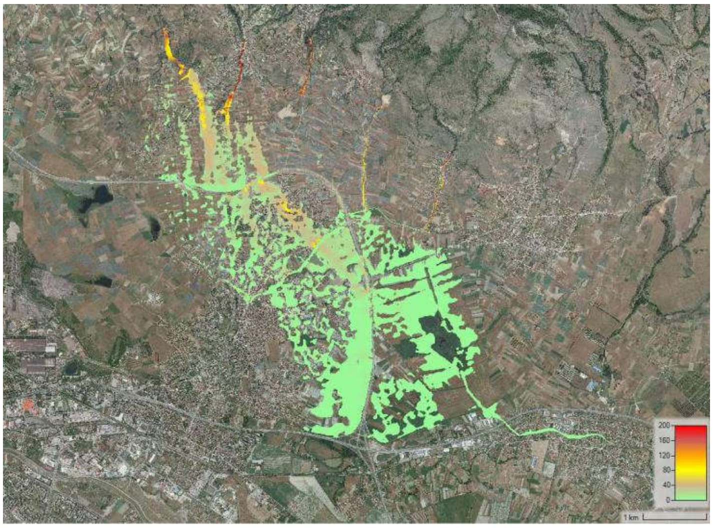

Figure 10. Map of maximum shear stress

Table 3. Monitoring of flood wave and flooded areas

Time period	Flooded area	
	[m^2]	[km^2]
06.08.2016 19:20	1,434,375.00	1.43
06.08.2016 19:50	2,273,425.00	2.27
06.08.2016 20:50	3,370,850.00	3.37
06.08.2016 21:10	3,872,175.00	3.87
06.08.2016 21:40	**4,054,675.00**	**4.05**
06.08.2016 22:40	3,778,995.00	3.78
07.08.2016 17:40	3,030,975.00	3.03
08.08.2016 17:40	2,400,275.00	2.40
09.08.2016 17:40	2,164,875.00	2.16

4. DISCUSSION

By analyzing the results, it can be concluded that there is a significant flooding of part of the urban surface and the arable land in all the settlements, with the biggest flooding being in the area of Stajkovci and Smilkovci. The overflow from the riverbed threatens densely populated residential buildings in populated areas as well as a significant area of arable agricultural land above the ring road of the City of Skopje. The most critical zones occur in close vicinity of the stretch Smilkovci-Stajkovci as well as in the southeastern region of the village Stajkovci. The depth of the dissipated flows from the overflow ranges from a few centimeters to 30 cm, while in the zones around the ring road, channels and rivers, depths of up to 2.5m were reported. The velocities in the zones where the overflow is concentrated reach values of up to 2.5 m/s, causing significant damage to exposed surfaces, objects and unfortunately also human casualties. Along the riverbeds, where most of the flow is concentrated, velocities reach values of over 6 m/s. On most of the flooded areas, the shear stress is greater than 30 N/m^2, which result in the erosion of the agricultural areas. The maximum shear stress occurs in the zones of the concentrated flows, where they reach up to 200 N/m^2 in individual watercourses due to large longitudinal slopes

The propagation of the flood wave is monitored by analysis of the flooded area, Table 3. The first major impact of flood wave appears at 19:40 immediately after the first peak of the hydrograph. It floods agricultural areas in the attar of Smilkovci and breaks through the ring road of the City of Skopje. Thirty minutes after the arrival of the peak of the flood wave (19:50), the flooded surface increase intensively, covering a residential area in settlement of Stajkovci. In the central area of Stajkovci transits a drainage channel that receives the surface runoff water and transport it to the recipient. At this moment, it reaches its maximum capacity and accepts part of the surface runoff waters, while part of it overflows through it and floods a part of Stajkovci towards the eastern part of the Skopje ring road.

Ninety minutes after the arrival of the first wave of the flood wave (20:50), the flooded area in the urban area in Stajkovci is increasing. The box culvert on the eastern part of the ring road reaches its maximum capacity and creates a slowdown. At this moment the embankment from the eastern part of the ring road acts as a dam and limits the flood wave from spreading in the urban part of Stajkovci.

At 21:10 the flood wave reaches its second peak, resulting in increase of the flooded areas around the northern and eastern part of the ring road. Thirty minutes after the second peak of the flood wave (21:40) the flooded areas along the eastern part of the ring road increase.

Immediately after the end of the rainfall around 22:40, the propagation of the flood wave due to the short time of concentration of the surface runoff ends, and in that moment the draining process begins.

Comparative analysis of the flooded areas obtained after 72h according to the hydraulic model and aerial photogrammetric images taken two days after the flood, Figure 11, shows that the flooded areas from the hydraulic model coincide with the polygons made from the aerial photogrammetric images. The shapes of the areas differ due to the geometric characteristics from the digital terrain model, as well as the time period of the photogrammetric recordings.

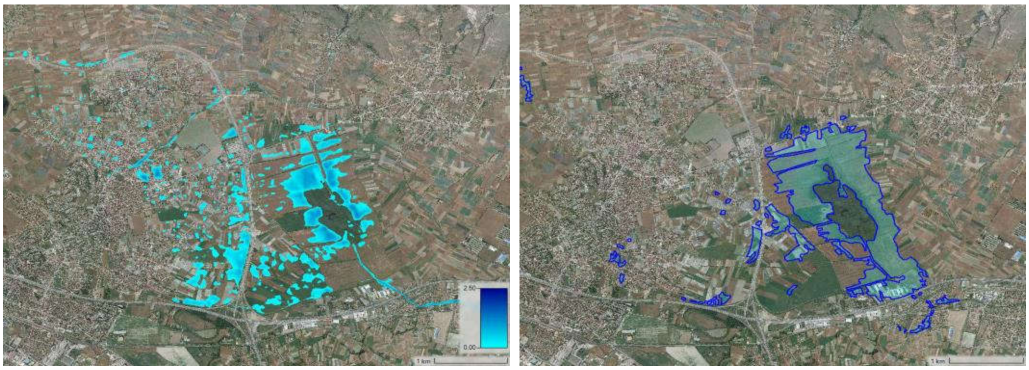

Figure 11. Map of flooded areas from the hydraulic model – t = 72 h (09.08.2016 17:40), left and Map of flooded areas from aerial photogrammetric imaging, right (Source: Agency for real estate cadastre)

5. CONCLUSION

The reasons for the flood in Skopje from 06.08.2016 are primarily the high intensity rainfall for a period of nearly 4 hours [18]. According to the official data of the Hydrometeorological service, about 93 mm of rainfall fell per square meter, that is 107 mm for a time period of 24 hours [8]. According to the analysis of the rainfall, the rain that fell during 24 hours corresponds to the rainfall with return period of T=100 years [19], [20]. Additional reasons for the flood include the bareness of the southern slopes of Skopska Crna Gora which are characterized by small, torrential catchment areas, which conditions the sudden accumulation and rapid surface runoff of water from the higher areas to the lower areas in the river basins. If the afforestation was greater or the vegetation cover was greater, a significant part of the rain would have been absorbed in the vegetation and into the soil, which unfortunately has been completely washed away due to the bareness. An extremely important role as the cause of floods is the catastrophic condition of the drainage systems and facilities for the safely implementation of flood waters. Abandoned channels, full of debris, blocked riverbeds from wildly constructed structures, roads without sufficient number of culverts, low bridges with low capacity [21]. All of this cause accumulation of water and create large flood areas.

This research encourages as massive as possible use of hydrological and hydraulic modeling, and emphasizes their importance in early detection of the critical zones of the flooding and contribute in preventing the effects of flooding.

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