HYDROLOGICAL MODEL OF THE TOPLICA WATERSHED IN ADDRESSING NEW CHALN LENGES IN FLOOD RISK ASSESSMENT

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ABSTRACT

Torrential floods are hydrological natural hazards by nature of their occurrence, but with a high scale of severe damages to the facilities and infrastructure and a high number of casualties in human populated environment, they can become a natural disaster. In addition, they cause more or less significant environmental changes, such as geomorphological damages to river banks and river channels. In enhancing the existing capabilities of flash flood risk management for meso- and small-scale basins, building a hydrological model for a specific watershed is of great significance. In this paper, a hydrological model is created using the Shetran hydrological software for the upper part of the Toplica River basin located on the eastern slopes of Mount Kopaonik in Southern Serbia. The watershed model is based on extreme rainfall events and involves a large dataset of natural characteristics (relief, geological terrain, soil, vegetation and microclimate) and land use factor in the calculation of torrential flood occurrence. Shetran is used to enable the transformation of rainfall in the runoff with the aim of getting simulated flood hydrographs that correspond with the registered hydrographs as much as possible. Model-sensitive parameters are determined and subsequently calibrated and validated. The average coefficient of determination for the watershed model of the Toplica River/ profile Magovo when registered and modelled hourly discharges are compared reaches 0.87, showing a good precision so that it can be useful in torrential flood forecasting.

Keywords: Runoff modelling, Maximal discharges, Torrential floods, Toplica River

INTRODUCTION

The initiation of torrential processes is related to a wide range of watershed conditions [1], [2], [3], [4]. Watershed hydrology research is supposed to include all spatially variable natural characteristics (microclimate, topography, geology, soil, vegetation) and anthropogenic factors (for example, land use) [5], [6]. In urbanized landscapes, surface runoff is dominant due to a decrease of permeable surfaces and low infiltration rate. In rural regions, forest covered areas have a positive role, but agriculture is an influential modifier of soil and vegetation characteristics creating erosion- and runoff-friendly conditions in watersheds.

Engineering risk assessment relies on the risk modelling approach with the aim of reaching the best risk assessment and optimal decision-making support [7]. In torrent hydrology, it is essential to understand the philosophy of relationships and interactions between watershed characteristics and watershed processes. Mathematical modelling of watersheds provides a simulation of hydrological processes and their relations, taking into account the physical-geographical specificity of watershed characteristics, finally enabling runoff prediction. Hydrological simulations are a valuable instrument for determining the threshold of torrential flood occurrence and the rate of watershed reaction to an extreme rainfall event. The aim of this paper is to create a hydrological model of a watershed located in a mountainous region of Serbia in order to provide hydrological simulations of extreme maximal discharges, i.e. torrential flood waves. The main focus is on the transformation of rainfall in the runoff to get simulated flood hydrographs that correspond to the registered hydrographs to the greatest possible extent.

CHARACTERISTICS OF THE MODELLED WATERSHED

The Toplica River is a left tributary of the Južna Morava River and its river basin covers an area of 2,180 km2. Given that hydrological modelling of small areas is more accurate and relevant than in the case of larger areas, the study area covers the upper part of the Toplica River basin up to the Magovo profile (hereinafter also: watershed Toplica/Magovo) (A=173.46 km2). The watershed Toplica/Magovo spreads in the west/southwest direction to the east and is located in a rural region on the eastern slopes of the Kopaonik Mountain in Southern Serbia. The upper part of the study area (sub-watersheds of Duboka and Zaplanjska reka) belongs to the National Park of Kopaonik, so this territory is under a strict protection regime.

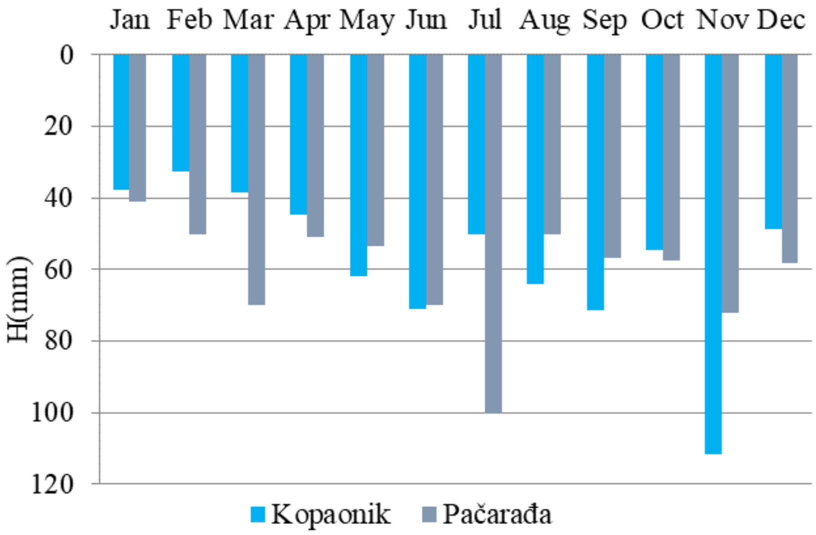

Figure 1. Absolute maximal daily precipitation per month for the 1968-2012 period on main meteorological gauge Kopaonik and period the 1976-2012 period with interruptions in measurement on gauge Pačarađa (Source: Republic Hydrometeorological Service of Serbia)

Precipitation and discharge extremes are always at issue when talking about torrential floods. The most-rainy months in the upper part of the Toplica River basin are June, May and July according to the recorded data on the main meteorological gauge Kopaonik and precipitation gauge Pačarađa, while the absolute maximal daily precipitations are recorded in July, then November, June and March on gauge Pačarađa and in November, September and June on gauge Kopaonik (Figure. 1). Since the theoretical trigger rainfall quantity for the occurrence of a torrential flood event is more than 30mm/day, all of these recorded absolute maximal daily precipitations could have resulted in a genesis of a torrential flood wave in the watershed. As an example, absolute maximal daily precipitation on the gauge Pačarađa was recorded in July (H=100.2 mm) after an extreme rainfall event which caused the occurrence of a flood with an absolute maximal discharge (Qmax = 192 m3s-1) on 17th July 1986. In addition to torrential flood events in warmer part of the year as a consequence of spring/summer extreme rainfall events, the precipitation during colder periods of the year is mostly in the form of snow since the study area is situated in a mountainous region (the highest point of the watershed is at an altitude of 2017 m a.s.l – Pančić's peak) and they can trigger a torrential flood event when melting, especially when coinciding with a rainfall episode.

Hydrological analysis of the watershed in terms of the time of concentration, lag time and time of regression is given in Table 1. The value of concentration time on the profile Magovo in the Toplica watershed, using equations after Ristić [8], is calculated in the range from 6.3h to 6.8h and the average Tc is 6.46h. The average lag time calculated according to the equations [9] in Table 1 is 4.56 h, while the average time of regression is 11.3 h.

Table 1. Time of concentration, lag time and time of regression for the watershed Toplica/Magovo

Time of concentration - T_c	h	Lag time–T_l	h
$0{,}502 \cdot A^{0{,}506}$	6.8	$0.751\ (\frac{L \cdot Lc}{\sqrt{Smr}})^{0.336}$	4.7
$0{,}316 \cdot L^{0{,}933}$	6.6	$1.399\ (\frac{L \cdot Lc}{\sqrt{Smr \cdot Smt}})^{0.315}$	4.5
$0.819\ (\frac{L \cdot Lc}{\sqrt{Iu}})^{0.376}$	6.3	$0{,}693 \cdot Tc$	4.5
$0{,}47 \cdot L^{0{,}826} \cdot S_{mr}^{-0{,}127}$	6.3	Time of regression - T_r	h
$0{,}609 \cdot L^{0{,}898} \cdot S_{mr}^{-0{,}17}$	6.4	$1.145 \cdot A^{0{,}446}$	11.4
$0{,}56 \cdot L^{0{,}846} \cdot S_{mr}^{-0{,}084} \cdot S_{mt}^{-0{,}08}$	6.4	$L^{0{,}743}$	11.2

(A– Watershed area in km2; L- watershed length along the main channel, from the point on a watershed boundary to the profile/outlet, Lc– distance from the profile, measured along the main channel to the point in the river bed closest to the centroid of watershed, Smr– mean slope of the riverbed; Smt - mean slope of terrain)

Average maximal annual discharge of the Toplica River on the profile Magovo is 29.3 m3s-1, while average minimal annual discharge is 0.28 m3s-1 (average annual discharge is 1.61 m3s-1). The ratio between the absolute maximal discharge which occurred in 1986 and the absolute minimal discharge which occurred in 2012 is 1:1.714, indicating the torrential hydrological regime of the Toplica River/Magovo. From the maximal discharge data series, four events (Table 2) were suitable - due to data requirements, to be taken into the modelling process.

The BFI program was used to analyze these torrential flood waves in order to split the base flow and direct runoff. As in Table 1, the share of the base flow is the lowest in the total runoff volume of the greatest flood wave in July 1986, so BFI is the lowest and specific maximal discharge is the highest. The intensity of rainfall precipitation was the highest in the downpour episode in July 1986, while the duration of all four rainfall events was almost equal (6-8 hours). The peak surface flow was reached at midnight on 16/17th July, 1986, 2 hours after the direct flow started.

Table 2. Some characteristics of the distinguished flood waves of theToplica River/Magovo profile

Flood event	T_r(h)	I_r	W_d (10^6m^3)	Q_{dmax} ($m^3 \cdot s^{-1}$)	W_b (10^6m^3)	Q_{bmax} ($m^3 \cdot s^{-1}$)	W_t (10^6m^3)	BFI (Wb/Wt)	Q_{max} ($m^3 \cdot s^{-1}$)	q_{maxsp} ($m^3s^{-1}km^{-2}$)
13.-14.08.1983	8	1.19	1.98	3.908	6.67	1.300	8.65	0.771	4.90	0.028
17.-20.06.1986	5+2	2.23	6.91	12.079	15.25	3.800	22.16	0.688	13.9	0.079
16.-18.07.1986	7	13.96	89.03	187.182	59.52	17.760	148.55	0.401	192.00	1.106
03.-06.08.2010	6	4.03	9.10	14.513	13.29	3.590	22.39	0.594	16.1	0.093

In the watershed of the upper Toplica River up to the profile Magovo, the greatest area is under flysch sediments according to the digitalized geological map of Kuršumlija and Novi Pazar whose scale is 1:100000 issued by the Geological Service of Serbia. With regard to the soil cover (Figure. 2), dominant soils are Eutric Leptosol and Dystrict Lepotosol (87.3%) and Cambisol (10.2%), according to the digital soil map from 1979 (source: Institute of Soil Science, Belgrade). Land use is defined by CORINE Land Cover 2006 (Fig. 3) and it is presented by deciduous forest (60.2%), arable land (19.9%) and shrub (12%) (in interpretation of the CLC database for the Shetran modeling purposes). Due to socio-economic trends in the upper part of the Toplica River basin, such as depopulation and migrations, the local forest areas have increased after 2000 [10]. According to the geomorphological map of Kuršumlija and Novi Pazar [11], there are thirteen fans in the watershed of Toplica/Magovo, as evidence of historical torrential floods with the transport of a huge amount of sediment and accumulation of it at the mouth of the tributaries. According to the Inventory of torrential floods in Serbia [12], there are 19 recorded torrential flood events in the Toplica River basin at the time lapse of 99 years. It is supposed that this number is much higher, but not recorded due to a lack of data.

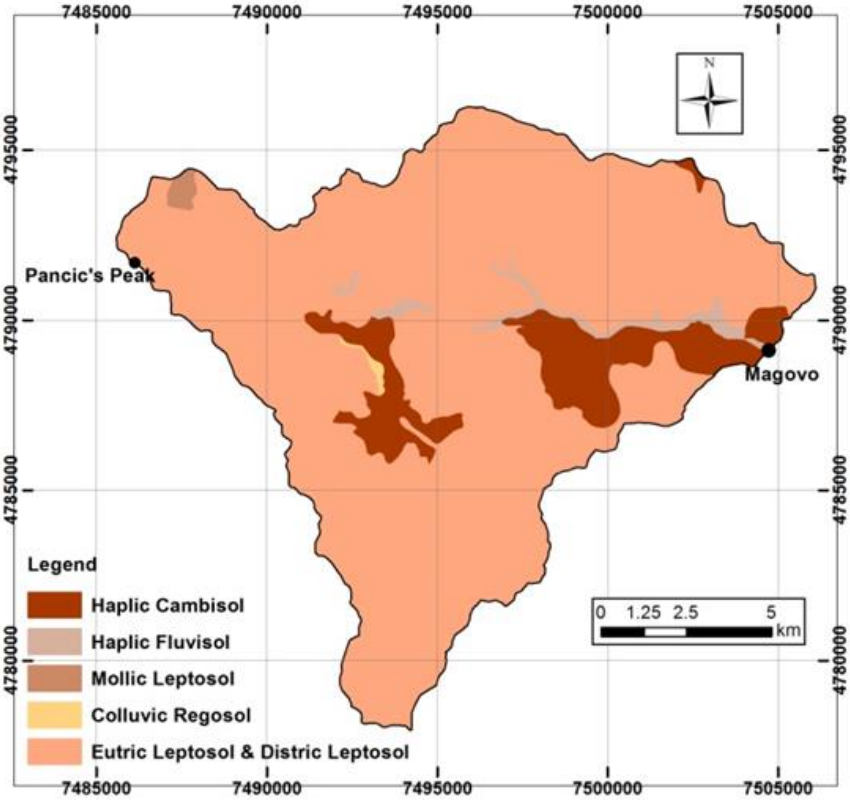

Figure 2. Soil map of study area

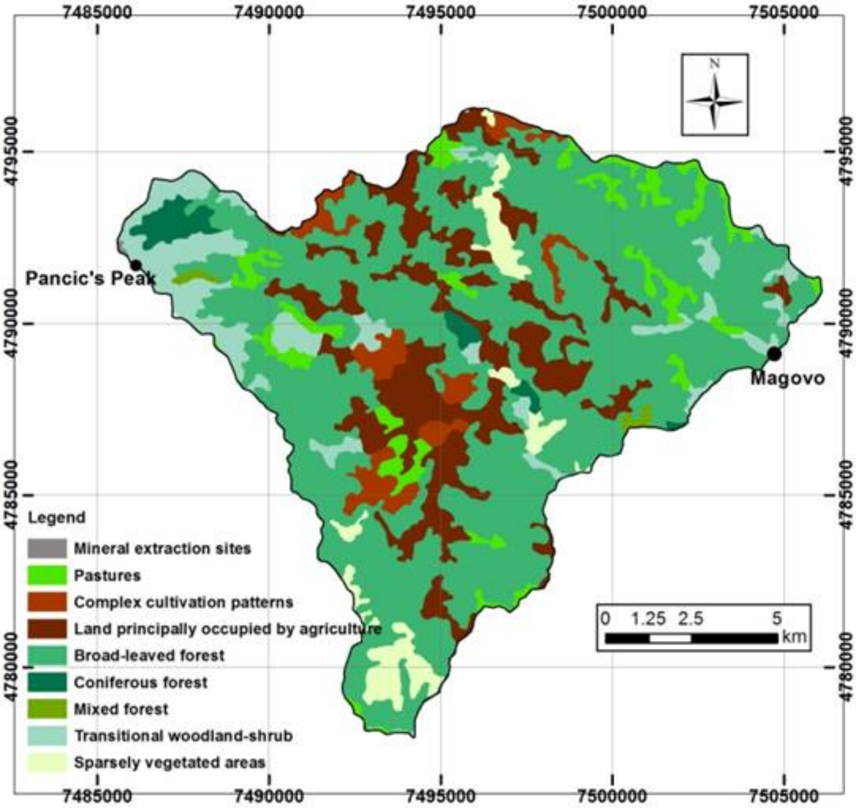

Figure 3. Land cover of study area

SHETRAN AS A SOFTWARE FOR HYDROLOGICAL MODELLING

SHETRAN (written in Fortran) is designed as a modelling system for watersheds using the physics-based governing partial differential equations (such as Rutter storage model, Penman–Monteith equation, Richards equation, Boussinesq equation, Saint Venant equations) working on a three-dimensional grid level. It is a rainfall-runoff model on a slope-channel scale, calculating processes of infiltration, evapotranspiration, overland flow, basic flow and flow through the river network. Input data are rainfall data altogether with the watershed data and output data are modelled discharges.

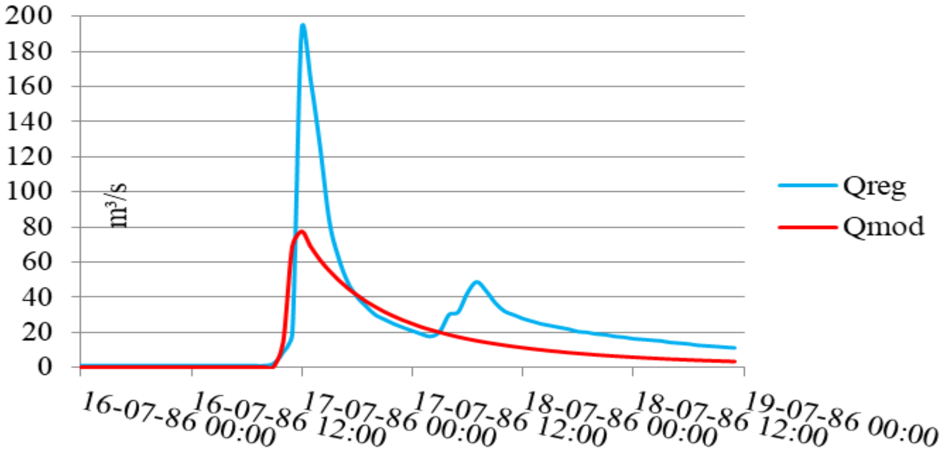

Figure 4. Initial modelled hydrograph for the flood event in July 1986 created by running the Shetran GUI aplication

In terms of the spatial discretization of watershed, there are three types of elements – grid, channel and bank, which are linked so that computations at the watershed level at defined time step and through the whole simulation period are enabled. For each simulation and calculation, the three flow modules are mutually inter-dependent and automatically included by Shetran: variably saturated zone (VSS), evapotranspiration/interception (ET), overland/channel (OC).

After processing and preparing the data on topography (using SRTM 90m digital elevation model), geology, soil, vegetation and land use for the watershed of the Toplica River/Magovo in ArcGIS, the starting point of using this software for hydrological modelling is to run Shetran graphical user interface - GUI application on the base of the digital elevation model and watershed mask, with dominant land use, i.e. vegetation type, dominant soil type, hydrological and meteorological hourly data for the flood wave event. Typical heavy downpour event (H∑4h=76.5mm) and related absolute maximal discharge in July 1986 (Qmax=192 m3s-1) is taken for sensitivity analysis and calibration, and maximal discharge events (which belong to the medium discharges) in June 1986, August 1983 and August 2010 are used for the validation of the watershed model. The result of this initial simulation is a primary modelled hydrograph with the shape non-fitting to the registered hydrograph and the maximal ordinate which was much lower than recorded one (Figure. 4). In this first step, two main outputs for the development of the watershed model were derived: the river network which is integrated in the watershed grid matrix and the input files, to feed them in the phase of calibration. The size of grid cells is 500x500m and the dominant geological, soil, vegetation and land use property of one grid is attributed to the whole grid. The grid matrix (Figure. 5) includes 698 grid cells, while the number of rows and columns for computations are 40 and 43.

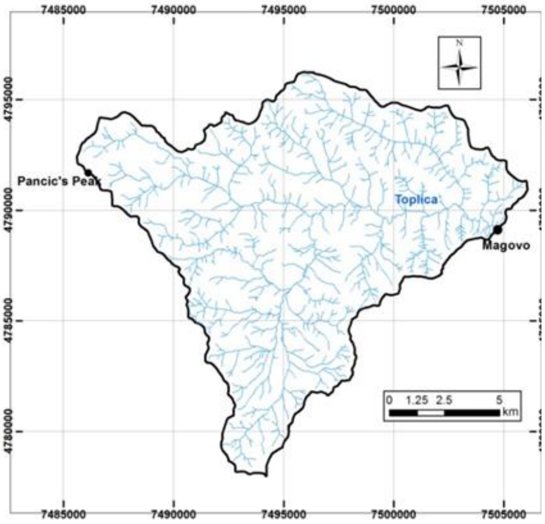

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Figure 5. Study area and its grid definition

ESTABLISHMENT OF THE TOPLICA/MAGOVO WATERSHED MODEL

For further development of the watershed Toplica/Magovo model, the input files were supposed to be fed with the specific parameters listed in Table 3 and their field research and literature values (according to Rawls 1982; Breuer et al. 2003; Dunn and Mackay 1995; Shuttleworth 1993; Gregory 1988).

Table 3. Needed data for watershed model

River network	Strickler roughness coefficient for river network
Geology	Rock depth, saturated water content, residual water content, saturated conductivity, specific storage, van-Genuchten n and a parameters for each rock type
Soil	Soil depth, saturated water content, residual water content, saturated conductivity, specific storage, van-Genuchten n and a parameters, for each soil type and textural classes
Vegetation	Canopy storage capacity, plant area index, canopy leaf area index, root depth, root density function, drainage k and b parameters, evapotranspiration parameters for each vegetation type
Land use	Strickler roughness coefficient for each type of land use

From the listed parameters, there are parameters which greatly influence the runoff output, so these are taken for the model sensitivity and calibration. According to the previous research [6], [13], [14], the characteristics of runoff hydrographs, i.e. slope of growth and recession branches and peak of hydrograph are very sensitive to the values of the vertical saturated hydraulic conductivity of the subsurface soil (Ks), horizontal saturated hydraulic conductivity in the saturated zone (Kr), the Strickler's coefficients for overland flow for different types of land use (inverse of Manning's roughness coefficient) (So) and the Strickler's coefficients for river network (Sr).

The influence of each parameter on simulated discharge will be well perceived when changing the values of only one parameter. Model sensitivity for the watershed Toplica/Magovo is examined with the upper and lower values of highly influential parameters (Table 4) and their impact on maximal ordinate, as given in Table 5 which shows that the greatest variation of simulated maximal discharges is caused by the input of the upper and the lower values of hydraulic conductivity for soils, then hydraulic conductivity for rocks, while upper and lower values of the Strickler's coefficients for overland flow and river network cause a lower variation of simulated maximal discharge. By using the upper value of the Strickler's coefficients for overland flow Somax, simulation gives the peak discharge closest to the registered one, it is decreased by only 0.57%. With examining the impact of Ksmax, the simulated peak discharge shows the least match, it is reduced by 26.84% in comparison with the recorded peak discharge. Model calibration is the next phase, in which the point is optimisation of the model parameter values, by performing a large number of simulations with different combinations of parameter values in defined intervals, in order to get a set of model parameters which will be used further in the validation process. In the calibration process, the main focus is on getting the simulated flood hydrographs corresponding to the registered hydrographs as much as possible.

Table 4. Intervals of parameter values for sensitivity analysis

Parameter	min	max	Unit
K_r	0.0126	5	md^{-1}
K_s	$2.74*10^{-6}$	10	md^{-1}
S_o	4	60	$m^{1/3}s^{-1}$
S_r	20	40	$m^{1/3}s^{-1}$

Table 5. Impact of parameters' values on maximal discharge on 17th July 1986(Qmax=192 m3s-1)

Parameter	min	max	ΔQ
Q_{Ks}	219.55	140.48	79.07
Q_{Kr}	231.95	183.83	48.12
Q_{So}	170.84	190.91	20.07
Q_{Sr}	178.65	196.72	18.07

The calibrated values of parameters for the watershed of Toplica River up the profile Magovo are as follows: Hydraulic conductivity coefficient for different soils are 0.051 md-1 for clay loam, 0.159 for loam, 0.0153 for clay, 0.099 for sandy clay loam, 0.0327 for silt loam, while hydraulic conductivity coefficient for rocks is calibrated to 0.74 md-1; Strickler roughness coefficient for the river network is 35 m1/3s-1, while Strickler roughness coefficient for overland flow is in the range of 4 m1/3s-1 for forests, 9 for arable land, 10 for grassland, 12 for schrub to 50 m1/3s-1 for bare lands.

RESULTS

When performing the simulation with calibrated parameters for the watershed model (Figure. 6), the coefficient of determination (R2) of the recorded and simulated hourly discharges for the extreme and historical flood event of the Toplica River/Magovo in July 1986 is 0.85 and multiple R is 0.92. Modelled peak discharge is slightly higher than recorded, Qmaxmod=192.32 m3s-1. When applying the calibrated watershed model on three other runoff events in the validation phase (Figure 7-9), also a high determination coefficient of the modelled and recorded discharges appears: R2=0.92 and correlation coefficient, multiple R=0.96 in the case of validation event in August 1983; R2=0.89 and correlation coefficient, multiple R=0.94 in the case of validation event in June 1986; R2=0.83 and correlation coefficient, multiple R=0.91 in the case of validation event in August 2010

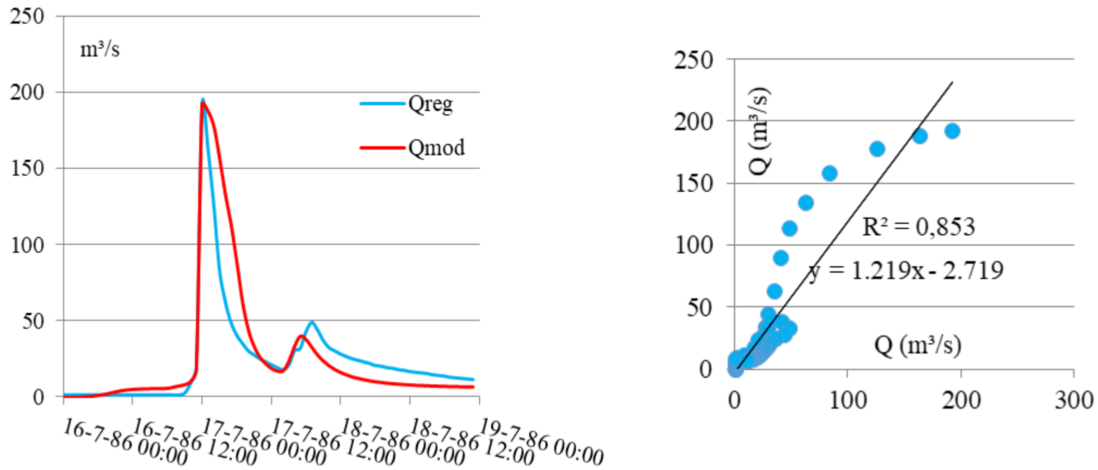

Figure 6. Simulated and recorded hydrograph for maximal discharge in July 1986 (a) and its coefficient of determination (b)

In all four simulation events, the probability of error according to the F test is lower than 0.05. When observing visually the simulated and modelled hydrograph of all four events, the best matching is in the case of the hydrographs in August 1983 and June 1986. In the case of maximal discharge in July 1986, there is a visible mismatch between the modelled and recorded regression branch of the hydrograph as well as at the secondary peak. As presented in the Figures 8 and 9, the modelled growth branches start earlier than recorded ones.

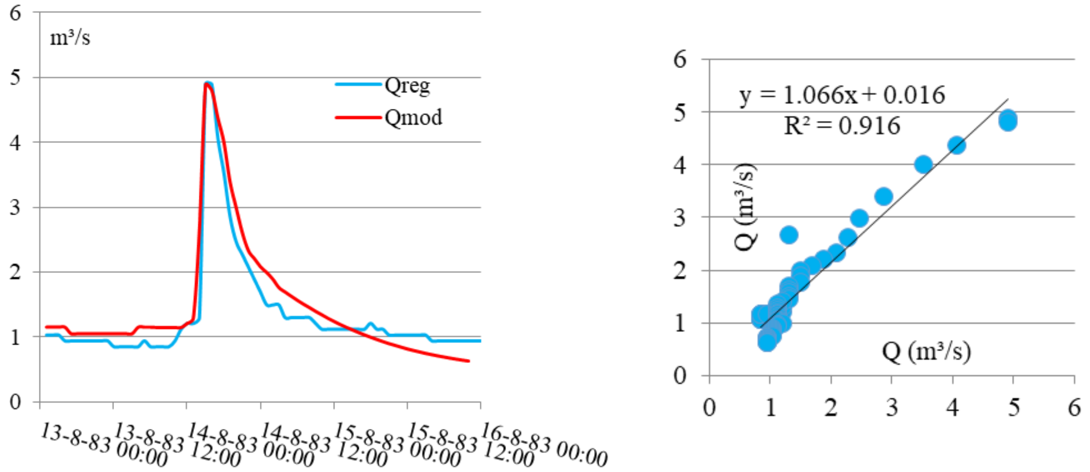

Figure 7. Simulated and recorded hydrograph for maximal discharge in August 1983 (a) and its coefficient of determination (b)

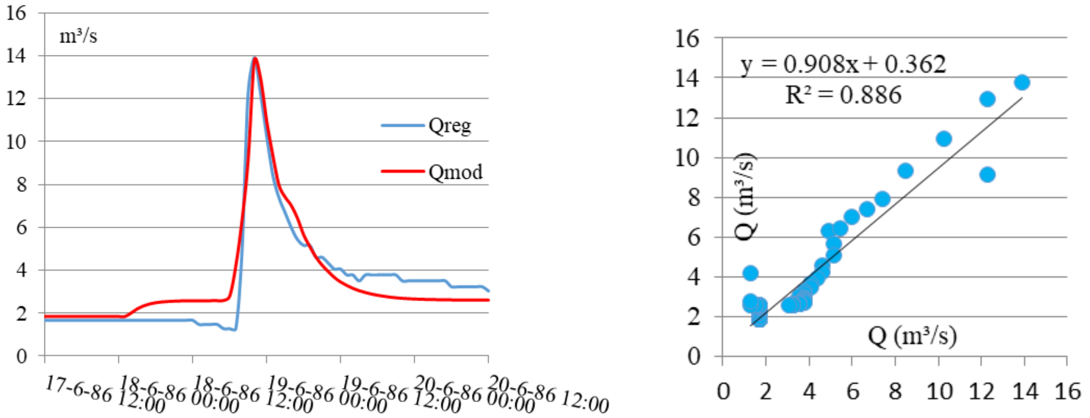

Figure 8. Simulated and recorded hydrograph for maximal discharge in June 1986 (a) and its coefficient of determination (b)

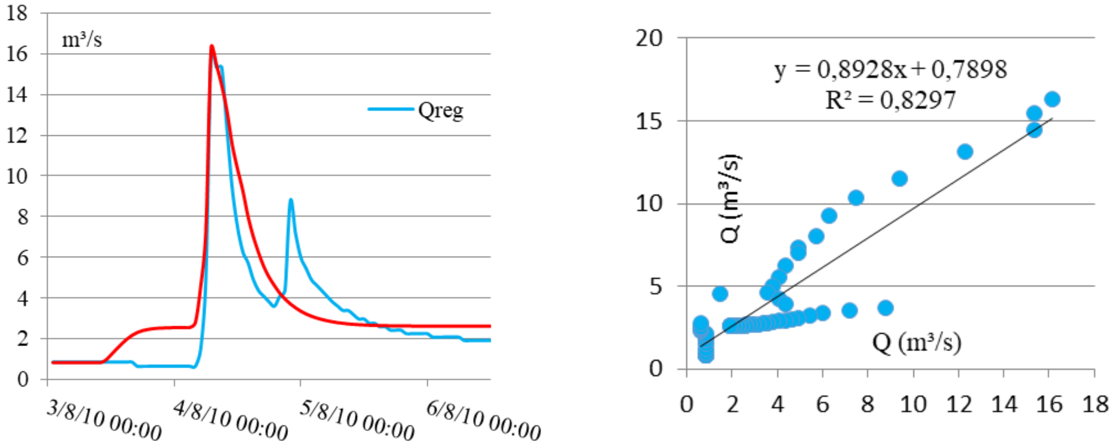

Figure 9. Simulated and recorded hydrograph for maximal discharge in August 2010 (a) and its coefficient of determination (b)

Finally, the average coefficient of determination for the watershed model of the Toplica/Magovo is 0.87, which is satisfactory in practice of hydrological simulations. By way of comparison, the model developed for the Topčiderska River basin [6], which is hydrologically better studied and gauged and it is situated in peri-urban area (macro region of Serbian capital, Belgrade), the average coefficient of determination for simulated flood events is 0.9. Also, in other studies [13], [15], a high agreement between the modelled and the recorded hydrographs in hydrological simulations is reached.

CONCLUSION

The hydrological modelling system Shetran is used in this paper to develop the watershed model of the Toplica River on the Magovo profile by calibration in the case of the historical torrential flood event in July 1986 and verification in the case of three other torrential flood events in August 1983, June 1986 and August 2010, but starting with the model sensitivity in which the impact of influential parameters on modelled discharge is analyzed. Although the setting up a model for new watershed is difficult and time consuming, once developed hydrological model with comprehensive dataset of characteristics for one watershed can be helpful in the forecast of torrential flood events contributing to the natural hazard warning (when forecasted extreme rainfall data are available).

However, it is not possible to define risk zones in the riverine area using modelling system Shetran. The advantage of this software in terms of reliability of output data is the possibility to compare modelled with registered discharges. This research is focused on torrential flood events in hydrological terms and further research could get even more significance if this model is developed for sediment transport withal, so that it will be able to predict both torrential processes – fluvial and erosion processes. Moreover, there are studies of the effects of land use changes and climate change [16], as well as of pollutant transport [17], [18] using the modelling system Shetran, so these results should be a reminder in decision making.

There are many approaches in dealing with the flood risk phenomenon as the most frequent natural hazard whose severity and harmfulness increases from decade to decade [19]. Integrated flood risk management should inevitably comprise hydrological modelling as a valuable tool in flood risk assessment [20] [21] [22], which can finally also contribute to soil and water resources management. According to the Law on disaster risk reduction and emergency situations management of the Republic of Serbia (2018), it is compulsory for local authorities to create natural hazards risk assessment and plan of natural hazard risk reduction. In this progress towards risk reduction, local communities should collaborate since collaboration on the watershed/river basin level is necessary.

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