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Disaster Risk Reduction Based on a GIS Case Study of the Čađavica River Watershed

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ABSTRACT

Background and Purpose: Although natural hazards cannot be prevented, a better understanding of the processes and scientific methodologies for their prediction can help mitigate their impact. Torrential floods, as one of the consequential forms of the existing erosion processes in synergy with extremely high precipitation, are the most frequent natural hazard at the regional level, which was confirmed by the catastrophic events in May 2014 when huge territories of Serbia, Bosnia and Herzegovina and Croatia were flood-struck. The basic input data for the design of protective structures in torrential beds and watershed slopes are the values of the maximal discharge, area sediment yields, and sediment transport. The calculation of these values requires a careful approach in accordance with the characteristics of torrential watersheds, such as the steepness of slopes and beds in torrential watersheds, intensive erosion processes, favorable conditions for fast runoff formation and the transport of huge quantities of sediment.

Materials and Methods: The calculations of maximal discharges, area sediment yields, and sediment transport in the experimental watershed of the Čađavica River were based on using two different spatial resolutions of digital elevations models (DEMs) – 20 m resolution DEM, with land use determined from aerial photo images, and the 90 m resolution DEM, with land use determined on the basis of the CORINE database. The computation of maximal discharges was performed by applying a method that combined synthetic unit hydrograph (maximum ordinate of unit runoff q_{max}) and Soil Conservation Service methodologies (deriving effective rainfall Pe from total precipitation Pb). The computation was performed for AMC III (Antecedent Moisture Conditions III – high content of water in the soil and significantly reduced infiltration capacity). The computations of maximal discharges were done taking into account the regional analysis of lag time, internal daily distribution of precipitation and classification of soil hydrologic groups (for CN – runoff curve number determination). Area sediment yields and the intensity of erosion processes were estimated on the basis of the "Erosion Potential Method".

Results and Conclusions: The selected methodology was performed using different input data related to the DEM resolution. The results were illustrated using cartographic and numerical data. Information on relief conditions is a vital parameter for calculating the elements of the environmental conditions through the elements of maximal discharge, area sediment yields and sediment transport. The higher precision of input data of DEM provides a more precise spatial identification and a quantitative estimation of the endangered sites.

Keywords: torrential floods, erosion, DEM resolution, land use, maximal discharge, area sediment yield, sediment transport

INTRODUCTION

Natural catastrophes lead to the loss of human lives and inflict huge material damage [1], leaving strong environmental and social impacts [2-4]. Torrential (flash) floods are the most common hazard in Serbia, having caused a loss of more than 130 human lives and material damage exceeding 10 billion euros in both urban and rural areas [5] in the period from 1950 to 2014 [6]. This was confirmed when huge parts of Serbia, Bosnia and Herzegovina and Croatia were struck by torrential floods in May 2014.

The torrential (flash) flood represents a sudden appearance of maximal discharge in a torrent bed with a high concentration of sediment. The torrential watershed is a hydrographic entity which involves the bed of the mainstream and its tributaries, and the gravitating surfaces with erosion processes of a certain intensity. The attribute "torrential" refers to any watershed with a sudden appearance of maximal discharge with a high concentration of sediment, regardless of the size and category of the stream [7]. Climate, specific relief characteristics, distinctions of the soil and vegetation cover and social and economic conditions cause the occurrence of torrential floods as one of the consequences of the existing erosion processes.

It is very important to raise public awareness of the threats of flooding and promote a wise use of watersheds [8], combining environmental protection and flood management as factors of similar importance [9]. Destructive erosion processes [10-12] and torrential floods cannot be prevented. However, a better understanding of the processes and scientific methodologies for their prediction can help mitigate their impact [13]. In most cases, torrential floods are caused by natural incidents (such as climatic and morpho-hydrographic particularities of watersheds), but the human factor contributes significantly to the effects of disasters (the mismanagement of forest and agricultural surfaces, uncontrolled urbanization and the absence of erosion control and flood protection structures). Inadequate dimensions of protective structures are commonly the initial cause of their damage or destruction, which significantly increases the intensity of torrential floods. Therefore, hydraulic and hydrological computations should be based on reliable input data (precipitation, land use, hydrographic characteristics and runoff curve number).

Representative examples are the torrential floods in Western Serbia, particularly in the Municipality of Krupanj, covering a territory of 342 km². Local watersheds received a three-day rainfall ranging from 180 to 420 mm, while the absolute daily maximal precipitation amounted to 218 mm. A few settlements were struck by floods on local torrents on May 15th 2014, causing the deaths of two people, almost 900 hectares of flooded arable land or damage by landslides, 333 flooded buildings (of which 40 severely damaged or destroyed), 120 km of destroyed or damaged roads, 14 destroyed and 8 damaged bridges, 5 km of destroyed river regulations and 300 evacuated inhabitants. In addition, 269 landslides were activated during the propagation of heavy precipitation and flood waves. The estimated material damage amounted to over 30 million €. A total of four protected surfaces with areas ranging from 0.03 to 6.73 ha were endangered (three monuments of nature and one nature reserve).

The values of the maximal discharge, area sediment yields and sediment transport, are the basic input data for the design and dimensioning of ETCS (Erosion and Torrent Control Structures) such as check-dams, overflows, regulations, contour ditches and channels, silt-filtering stripes and wattle works. In May 2014, during the torrential floods, numerous river regulations, check-dams, cascades, and culverts did not have a sufficient capacity for maximal discharge and sediment, which caused their obturation, damaging and destruction. A GIS-based flood reconstruction was carried out, with a recalculation of maximal discharges (using data on the maximal daily precipitation in May 2014), area sediment yields and sediment transport. The corrected results of the calculations will be used as the basic input data for ETCS dimensioning, both for the reconstructed structures and the new ones.

This paper presents the results of calculations of the maximal discharge, area sediment yields and sediment transport in the experimental watershed of the Čađavica River, using GIS processing of two digital elevation models (DEMs) with different spatial resolution.

STUDY AREA

The experimental watershed of the Čađavica River is located in Western Serbia, in the Municipality of Krupanj, with the outlet profile in the center of the city (Figure 1). The watershed is built from schists and sandstones, with layers of phyllite and argillaceous schist [14]. The dominant soil is Dystric Cambisol with a light mechanical composition, medium porosity and good aeration [15]. The soil profile is shallow, with good infiltration and poor retention capacity, due to the high percentage of sand.

METHODOLOGY

Spatial analysis was carried out by processing of the DEM of 20 m (hereinafter referred to as DEM_{20}) and 90 m (hereinafter referred to as DEM_{90}) resolutions using software ArcMap 10.3 and its extension 3D Analyst. In addition, analyses concerning watershed and stream network delineation were performed using ArcHydro Tools in Arc Map. DEM_{20} was generated using scanned topographic maps (scale 1:25000) and vectorized isolines as primary spatial elements for the triangulated irregular network (TIN) database creation and later conversion to a 20 m raster resolution. DEM_{90} was derived from Shuttle Radar Topography Mission (SRTM). The land use analysis for DEM_{20} was performed using 2014 orthophoto with a 1 m resolution. The land use analysis for DEM_{90} resolution was performed using the CORINE database [16]. The determination of hydrographic characteristics was performed with the ArcHydro® model [17], which is often used for creating hydrological information systems on the basis of geospatial and temporal information about water resources [18]. ArcHydro® was developed as an extension of ArcGIS software, which is suitable for the delineation of watershed boundaries [17]. DEM is a necessary input data for spatial analysis and could be generated using different techniques such as photogrammetry [19, 20], interferometry [21], laser scanning [22] and topographic surveys [23].

The factors dominating the formation of torrential floods were analyzed, such as natural characteristics (hydrographic characteristics, soil and geological conditions) and human impact (land use structure, the relation between surfaces with low and high water infiltration-retention capacity). Land use analysis was based on the field investigations, orthophoto, the CORINE (COoRdination of INformation on the Environment) database, topographic, geological and soil maps. Land use

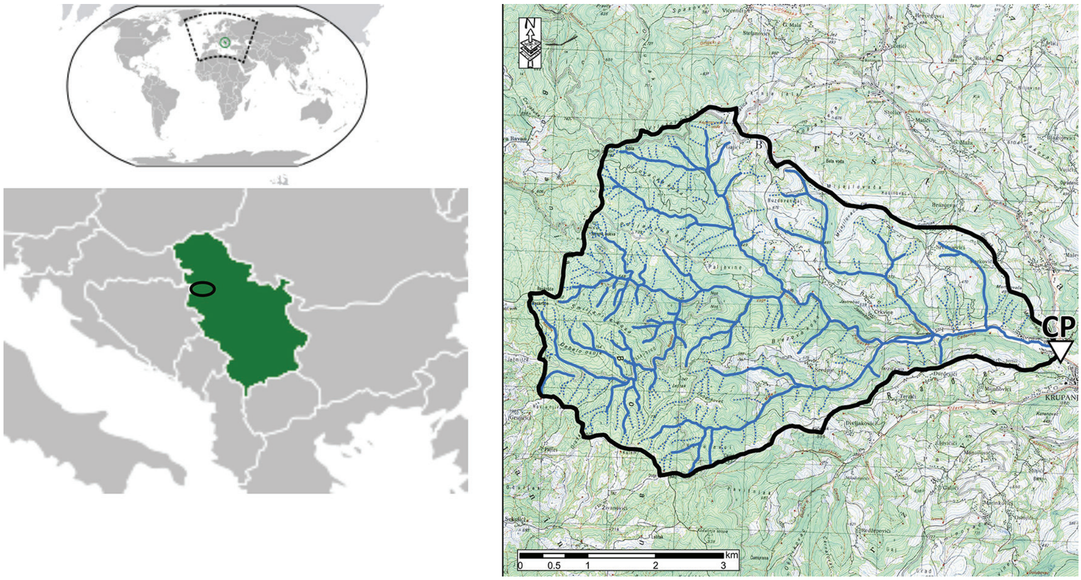

FIGURE 1. Location of the experimental watershed of the Čađavica River.

classification was based of the CORINE methodology [16]. Area sediment yields and the intensity of erosion processes were calculated using the "Erosion Potential Method" (EPM). This method was created, developed and calibrated at the Faculty of Forestry of the University of Belgrade and at The Jaroslav Černi Institute for the Development of Water Resources in Belgrade [24, 25]. The method is still in use in all countries that originate from former Yugoslavia. The application of this method is based on the calculation of the basic parameters: the coefficient of erosion Z, sediment yields and sediment transport:

$$W_a = T \cdot H_{year} \cdot \pi \cdot \sqrt{Z^3} \cdot A \;\; (\mathrm{m^3})$$

T - temperature coefficient,

$$T = \sqrt{\frac{t_{mean}}{10} + 0.1}$$

t_{mean} - average yearly temperature of air (°C)
H_{year} - average yearly precipitation [mm]
π - 3.14159
Z - coefficient of erosion
A - magnitude [km^2]

$$W_{asp} = \frac{W_a}{A} \;\; (\mathrm{m^3 \cdot km^{-2} \cdot year^{-1}})$$

$$W_{abls} = W_{at} \cdot \delta \;\; (\mathrm{m^3})$$

R_u - sediment delivery ratio,

$$R_u = \frac{(P \cdot A_{md})^{0.5}}{0.25 \cdot (L + 10)}$$

P - perimeter of the watershed (km)
L - the length of the watershed (km)
A_{md} - medium altitude difference of the watershed (km)

$$W_{atsp} = \frac{W_{at}}{A} \; (\mathrm{m^3 \cdot km^{-2} \cdot year^{-1}})$$

$$W_{abls} = W_{at} \cdot \delta \;\; (\mathrm{m^3 \cdot year^{-1}})$$

δ - content of bed load sediment

$$\delta = \frac{z \cdot (\rho_1 - 1)}{\pi \cdot \rho_2}$$

ρ_1 - mean volume mass of bed load sediment (t·m^{-3})
ρ_2 - mean volume mass of suspended sediment (t·m^{-3})

$$W_{ass} = W_{at} - W_{abls} \; (\mathrm{m^3 \cdot year^{-1}})$$

The method is based on the analytical processing of data on factors affecting erosion. The erosion spatial phenomenon appears on the map according to the classification based on the analytically calculated erosion coefficient (Z), which does not depend on climate, but on soil characteristics, vegetation cover, relief and visible representation of erosion. The coefficient of erosion (Z) is obtained from the following expression [24]:

$$Z = Y \cdot X \cdot a \cdot (\phi + \sqrt{I_m})$$

Y - coefficient of soil resistance to erosion
X·a - the land use coefficient,
ϕ - coefficient of the observed erosion process (takes into consideration clearly visible erosion processes),
I_m - mean slope of terrain

The computations of maximal discharges (for control profile CP, Figure 1) were performed using a method combining the synthetic unit hydrograph (maximum ordinate of unit runoff q_{max}) and Soil Conservation Service

[26] methodologies (deriving effective rainfall Pe from total precipitation Pb). This combined method is the most frequently used procedure for the computation of maximal discharges in unstudied watersheds in Serbia. The computations were performed for AMC III (Antecedent Moisture Conditions III- high content of water in the soil and significantly reduced infiltration capacity). Synthetic triangular unit hydrographs were transformed to synthetic (computed) curvilinear hydrographs using the SCS basic dimensionless hydrograph [27]. The computations of maximal discharges were performed using the regional analysis of lag time [28], the internal daily distribution of precipitation [29] and the classification of soil hydrologic groups for CN-runoff curve number determination [30].

RESULTS

The main hydrographic characteristics of the experimental watershed are presented in Table 1.

Land Use

Land use was determined using DEM_{20} and DEM_{90} with a structure presented in Table 2 and Figure 2.

Erosion and Sediment Transport

The result of the area sediment yields and sediment transport calculations based on using different DEMs resolutions (DEM_{20}, DEM_{90}) are presented in Table 3, as well as the representative values of the coefficient of erosion Z.

W_a – annual yields of erosive material; W_{asp} – specific annual yields of erosive material; W_{at} – annual transport of sediment through the hydrographic network; W_{atsp} – specific annual transport of sediment through the hydrographic network; W_{abls} – annual amount of bed load sediment; W_{ass} – annual amount of suspended sediment.

The spatial distribution of the erosion coefficient Z is presented in Figure 3 (DEM_{20}; DEM_{90}), while the structure of erosion categories is presented in Table 4.

TABLE 1. Main hydrographic characteristics of the Čađavica River watershed.

Parameter	Mark	Unit	DEM_{20}	DEM_{90}
Magnitude	A	km²	24.10	24.23
Perimeter	P	km	29.92	27.90
Peak point	Pp	m a.s.l.	863.967	869.46
Confluence point	Cp	m a.s.l.	290	288.54
Mean altitude	Am	m a.s.l.	586.32	594.16
Length of the main stream	L	km	10.97	9.84
The distance from the centroid of the watershed to the outlet profile	Lc	km	5.47	5.11
Absolute slope of the river bed	Sa	%	5.23	5.90
Mean slope of the river bed	Sm	%	3.78	4.31
Mean slope of the terrain	Smt	%	33.24	21.14
Density of hydrographic network	D	$km \cdot km^{-2}$	4.64	4.62

TABLE 2. Land use in the Čađavica River watershed.

Land use	DEM_{20}		DEM_{90}	
	km²	%	km²	%
Land principally occupied by agriculture, with significant areas of natural vegetation	2.30	9.53	2.71	11.19
Degraded area	0.01	0.04	/	/
Degraded forests	0.04	0.19	/	/
Complex cultivation patterns	1.50	6.22	1.28	5.30
Broadleaved forest	19.49	80.87	19.82	81.80
Pastures	0.44	1.81	0.28	1.16
Discontinuous urban fabric	0.32	1.35	0.13	0.55
Total	**24.10**	**100.00**	**24.23**	**100.00**

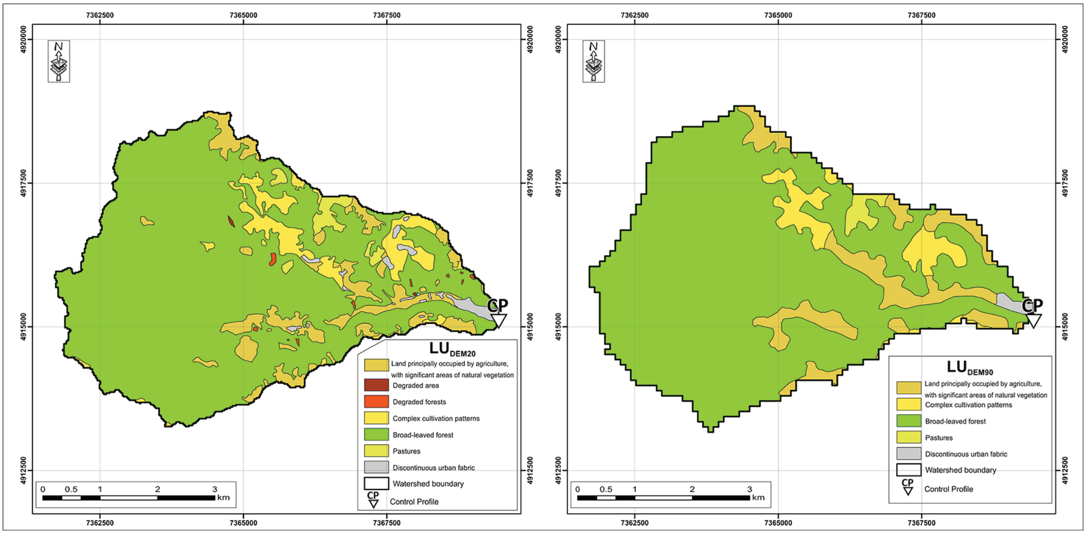

FIGURE 2. Land use (DEM_{20} and DEM_{90})

TABLE 3. Characteristic outputs of computations of sediment yields and transport.

Parameter	DEM_{20}	DEM_{90}
W_a (m^3)	12367.51	9005.05
W_{asp} ($m^3 \cdot km^{-2} \cdot year^{-1}$)	513.17	371.65
W_{at} (m^3)	7049.48	5312.98
W_{atsp} ($m^3 \cdot km^{-2} \cdot year^{-1}$)	292.51	219.27
W_{abls} ($m^3 \cdot year^{-1}$)	695.78	422.91
W_{ass} ($m^3 \cdot year^{-1}$)	6353.7	4890.07
Z	0.31	0.25

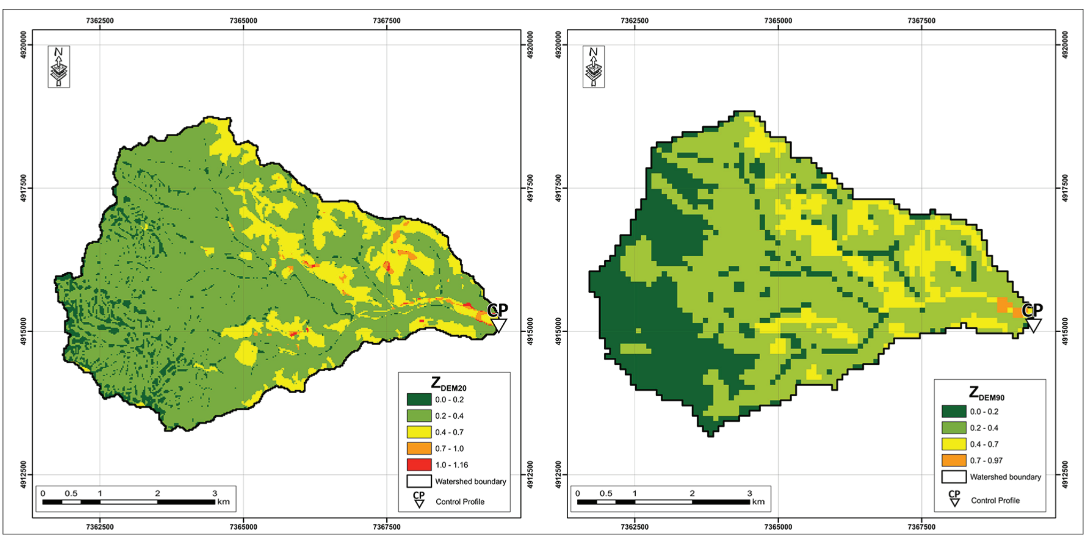

FIGURE 3. Spatial distribution of erosion coefficient Z (DEM_{20} and DEM_{90})

TABLE 4. Structure of erosion categories.

Category	Erosion process intensity	DEM$_{20}$		DEM$_{90}$	
		km^2	%	km^2	%
V	Very weak erosion	1.81	7.50	7.55	31.16
IV	Weak erosion	18.00	74.67	13.17	54.36
III	Medium erosion	4.05	16.79	3.42	14.11
II	Intensive erosion	0.21	0.86	0.09	0.37
I	Excessive erosion	0.04	0.17	/	/
Total		**24.1**	**100.00**	**24.23**	**100.00**

Hydrological Conditions

Maximal discharges ($Q_{max1\%}$) were computed using a combined method based on designed precipitation $Pbr_{24h(1\%)}$=113.8 mm. The hydrographs of maximal discharges ($Q_{maxDEM20\_1\%}$; $Q_{maxDEM90\_1\%}$) are presented in Figure 4. Some characteristic outputs of hydrologic computations are presented in Table 5 (unit runoff q_{max}; CN – runoff curve number; Pbr – total precipitation; Pe – effective rain).

TABLE 5. Structure of erosion categories.

Parameter	DEM$_{20}$	DEM$_{90}$
q_{max} ($m^3 \cdot s^{-1} \cdot mm^{-1}$)	1.617	1.672
$Q_{max1\%}$ ($m^3 \cdot s^{-1}$)	75.06	63.84
$CN_{sr}III$	84	79
$P_{br(24h1\%)}$ (mm)	113.8	113.8
P_e (mm)	46.41	39.07

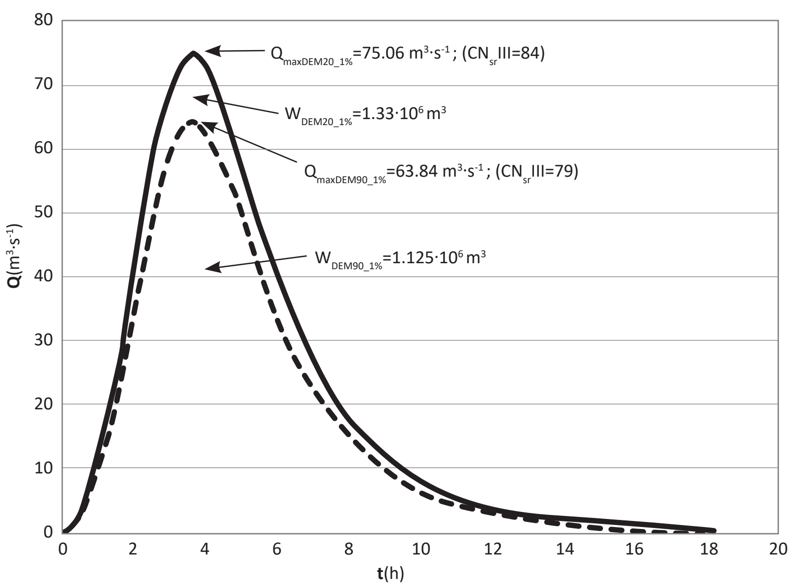

FIGURE 4. Hydrographs of maximal discharge for AMC III (Antecedent Moisture Conditions III - high content of water in the soil and significantly reduced infiltration capacity).

DISCUSSION

Destructive erosion processes and torrential floods endanger the life security of the population and material goods, while they also have environmental and social impacts. Current climate fluctuations (precipitation, air temperature extremes, droughts) associated with anthropogenic impacts (urbanization, forest fires, land degradation) provoke intensive erosion processes and a frequent occurrence of torrential floods.

The experimental watershed of the Čađavica River was analyzed using GIS processing of two DEMs with different spatial resolution (20 m (DEM_{20}) and 90 m (DEM_{90}) resolution), which produced differences in hydrographic characteristics, land use, and the runoff curve number. It also affected the values of maximal discharges, area sediment yields, and sediment transport. Among the hydrographic characteristics, the most expressive one is the difference in Smt (mean slope of terrain): $S_{mtDEM20}$=33.24% and $S_{mtDEM90}$=21.14%. Unlike DEM_{90}, DEM_{20} m recognized some specific land uses such as degraded areas and degraded forests.

The actual state of erosion processes is marked with the representative Z values of Z_{DEM20}=0.31 (dominant weak erosion - deep processes) and Z_{DEM90}=0.25 (dominant weak erosion - mixed surface and deep processes). Consequently, the annual yields of the erosive material amount to W_{aDEM20}=12367.5 m^3 and W_{aDEM90}=9005.1 m^3, with a specific annual transport of sediment through the hydrographic network of $W_{atspDEM20}$=292.5 $m^3 \cdot km^{-2} \cdot year^{-1}$ and $W_{atspDEM90}$=219.3 $m^3 \cdot km^{-2} \cdot year^{-1}$. DEM_{20} registered excessive erosion and larger surfaces under medium and strong erosion than DEM_{90}.

The runoff curve number values CN_{DEM20}=84 and CN_{DEM90}=79 have an impact on the computed maximal discharges $Q_{maxDEM20\_1\%}$=75.06 $m^3 \cdot s^{-1}$ and $Q_{maxDEM90\_1\%}$=63.84 $m^3 \cdot s^{-1}$. In addition to that, the volume of the computed hydrograph of direct runoff $W_{DEM90\_1\%}$=$1.125 \cdot 10^6$ m^3 is significantly reduced in comparison to the volume of direct runoff $W_{DEM20\_1\%}$=$1.33 \cdot 10^6$ m^3.

A decrease in the DEM resolution (DEM_{90} in comparison to DEM_{20}) leads to a loss of detailed topographic characteristics such as mean altitude, slope steepness and area [31, 32].

Field work was carried out to determine the accuracy of the spatial analysis using different DEMs resolutions (DEM_{20} and DEM_{90}), especially for land use and the erosion map. DEM_{20} m recognized degraded areas and degraded forests, as well as surfaces under excessive erosion processes, which was not possible when DEM_{90} was used. The higher accuracy of DEM_{20} enabled a more precise identification of the zones which were the sources of erosive material production and generation of surface runoff. Consequently, the results of the computations of area sediment yields and transport and maximal discharge on the basis of DEM_{20} were significantly higher. Since they are the basic input data for the dimensioning of ETCS in the torrent bed and on watershed slopes, these higher results caused the design of structures with larger dimensions and higher construction costs, but also an elevated level of security. In addition, DEM_{20} recognized small protected areas (0.03-6.73 ha), which were almost “invisible” when DEM_{90} was used.

CONCLUSION

The values of the maximal discharge, area sediment yields, and sediment transport are the basic input data for the design and dimensioning of protective structures in torrential beds and on watershed slopes. GIS applications and their tools offer an effective spatial analysis of the watershed with a precise determination of hydrographic characteristics, land use, land use changes and runoff curve number, as parameters of great importance for the final values of the maximal discharge, area sediment yields, and sediment transport. This requires a careful approach in accordance with some specific conditions at torrential watersheds, including the steepness of slopes of the terrain and the torrent bed, intensive erosion processes, favorable conditions for fast surface runoff formation and transport of huge quantities of sediment. The usage of nonrepresentative input data produces inadequate results of computations and poor subsequent dimensioning of protective structures. As a result, the insufficient capacity for maximal discharge and sediment leads to obturation, damage, and destruction of these structures. The higher accuracy of DEM enables a more precise identification of the “source” zones of erosive material production and generation of surface runoff. That was confirmed by this investigation, where the usage of DEM_{20} resolution produced a more “realistic” picture of the experimental watershed than the usage of DEM_{90}. The results of computations of area sediment yields and transport and maximal discharge on the basis of DEM_{20} m are significantly higher, which affects the dimensions of ETCS in the torrent bed and on watershed slopes, the costs of their construction and the achieved level of security. In addition to other measures, the reduction of flood risk is based on the construction of effective and well-dimensioned structures, with a capacity that is sufficient for maximal discharge and sediment. An adequate GIS approach can help in the precise evaluation of the factors affecting the generation of destructive erosion processes and torrential floods in order to provide effective erosion control and torrential flood protection in endangered watersheds.

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