GIS used for determination of the maximum discharge in very small basins (under 2 km^2)

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Abstract. The purpose of this article is to predict the maximum discharge caused by runoff on hillslopes from very small rural basins. It is known that runoff generated by torrential rainfall in very small rural basins is difficult to predict but very important to know because of the damage it causes in isolated households or even villages. This work uses a methodology of determining the surface runoff hydrograph when the storm characteristics are known. The methodology was automated in a Geographic Information System model that can be used in any study if the user can provide the necessary parameters. The model, built by implementing some well known hydrologic methods in GIS, consists of four components that address the following requirements: the runoff depth in mm, the runoff coefficient, the travel/concentration time and the discharge. The discharge calculation is carried out by applying the rational method in each cell of the watershed to determine the specific discharge for that cell. If data from the meteorological predictions is used as an input, the model can be used as a tool included in a warning system as a method to anticipate flash flood.

Keywords: Flash-Flood, Hydrograph, Very Small Basins, GIS, Hydrology, Rural Areas.

1. Introduction

In mountainous areas, like the Apuseni Mountains, some extreme flash flood events occurred in the last years, even in zones where this kind of disasters had not been recorded before.

Flash floods are sudden floods occurring with little lead time - there is a surprise element and the time available for communication is very limited. These floods are generally at a small local scale - whereas the media, which are usually key to warning message dissemination, operate at increasingly large scales; and they are rare and generally of short duration - so much emergency activity takes place after the physical event is over. Earlier recognition of the storms likely to develop into catastrophic flash floods would aid in the preparedness, warning and rescue operations [12] .

In most cases, these events occure on ungauged catchments in rural areas. This is the reason why indirect models are the only tools that can be used to offer information on the discharge generated by flash floods. Previous contributions in indirectly determining the hydrograph generated by torrential rainfall can be found in scientific literature [16, 17, 18, 19, 20].

A previous work presented the methodology to calculate the flash flood for basins with a surface of over 20 km^2 in the temperate continental area. This article examines the same methodology for other areas, in very small basins with the surface of less than 2 km^2. At this scale, the runoff is not always permanent and the application presumes certain limitations that will be presented.

A 50 km^2 basin already has concentrated flow, but these very small basins are not characterized with this type of flow.

The methodology that we applied is a computer model built in a Geographical Information System to be able to work with large, spatially distributed data sets.

GIS technologies are the most efficient way to work with geographic data. A GIS is essentially a database with capacity to store geographic and alphanumeric information, in addition to the software and the staff that manages this database. [5]

Besides generating floods, it is, generally, accepted that rainfall affects the stability of slopes and can cause landslides. The way that rainfall causes the reduction of the slope stability is by the infiltration of the rainfall water through the porous media of the soil. This problem was studied by V. Matziaris and M. Sakellariou [15] .

The application of the model is presented on a part of the Râşca basin. The basin is located in the North-Eastern part of the Apuseni mountains (**Fig. 1**) in Cluj county. Romania.

The hydrograph is presented for 5 sub-basins of the Râşca basin, with the area ranging from 0.5 to 1.2 km^2. The altitude in the area ranges from 869 to 1152 m. Most of the land in the area is occupied by agriculture, but there are zones with mixed forests or pastures. All soils in the area can be included in the B hydrological soil group according to the SCS (Soil Conservation Service) classification [18].

Runoff curve numbers determined from using the SCS method for antecedent moisture condition II range from 60 to 78. The precipitation data was obtained from the Vlădeasa meteorological station at approximately 20 km in the NW direction.
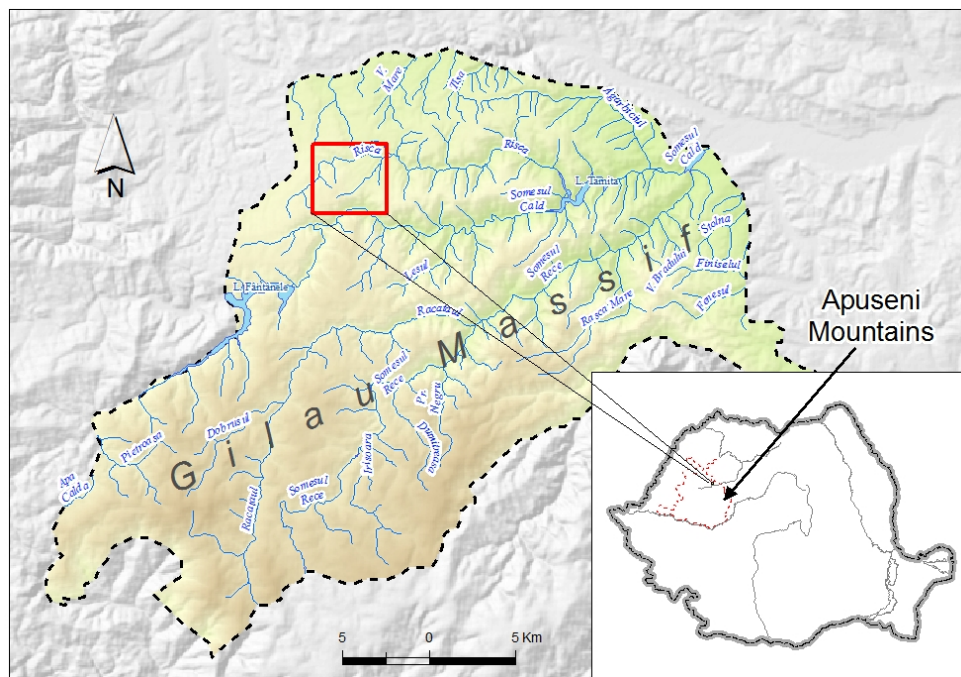

Fig. 1 The location of the studied watershed

2. METHODS AND DATA

The study is based on the application of an automated GIS workflow to estimate the hydrograph determined by surface runoff in a mountain basin.

GIS is an efficient tool to collect and process data required for modeling. GIS functions are characterized by relatively simple operations manipulating various data. "Contrarily, hydrological models are characterized by complex operations including iterations on a more reduced number of data. Thus, GIS permit to group all disposed watershed data into structured database system" [16].

The current model was built by implementing some well known hydrologic methods in GIS and consists of four components that address the following requirements: *the runoff depth* in mm, *the runoff coefficient*, *the travel/concentration time* and *the discharge*.

The model was built in the ArcGIS geographic information system using the ideas described by the authors in a recent study[8]. Like most geographic information systems, ArcGIS allows the user to create custom workflows through programming or by creating models using a graphical interface.

The model uses some raster layers as parameters, most of which represent the characteristics of the terrain and the rainfall event (**Fig. 2**). The final result of the application of the model in ArcGIS is the spatially distributed discharge generated by the rainfall, in the form of a table.
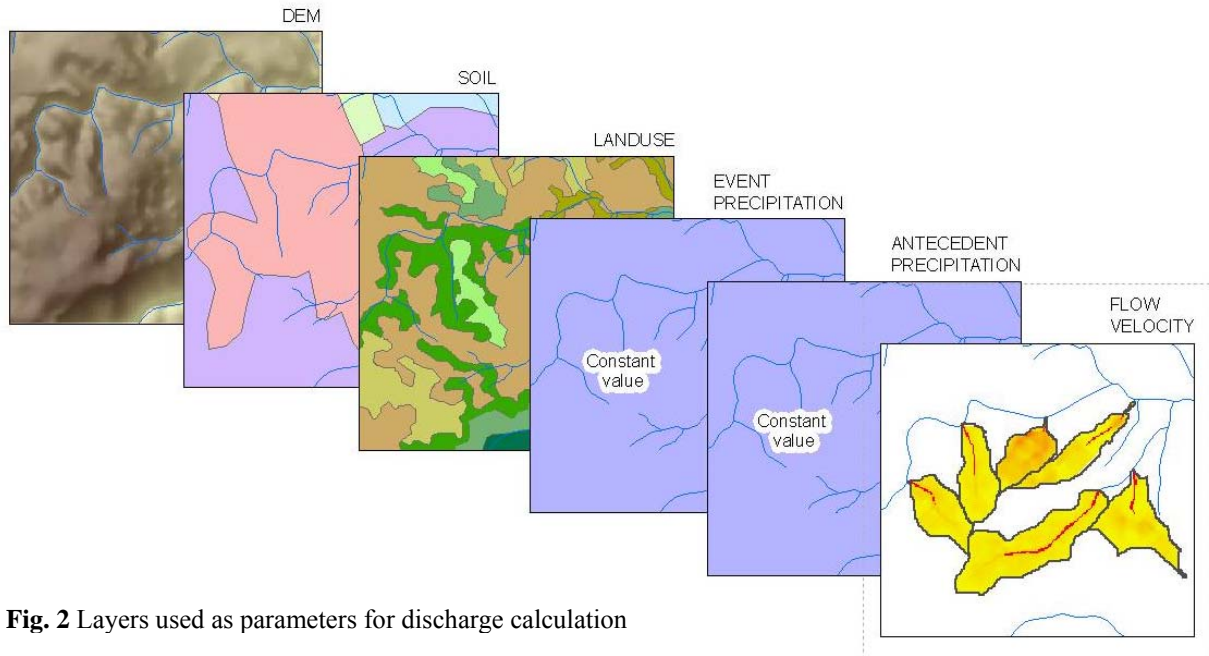

Fig. 2 Layers used as parameters for discharge calculation

After the spatially distributed flow is calculated for each raster cell, the MATLAB software is used to calculate the flow accumulation and route the flow to the watershed outlet.

The values for discharge at the watershed outlet are interpolated, then plotted over time to obtain the final graphic hydrograph. The workflow used for calculating the hydrograph is presented in **fig. 3**.
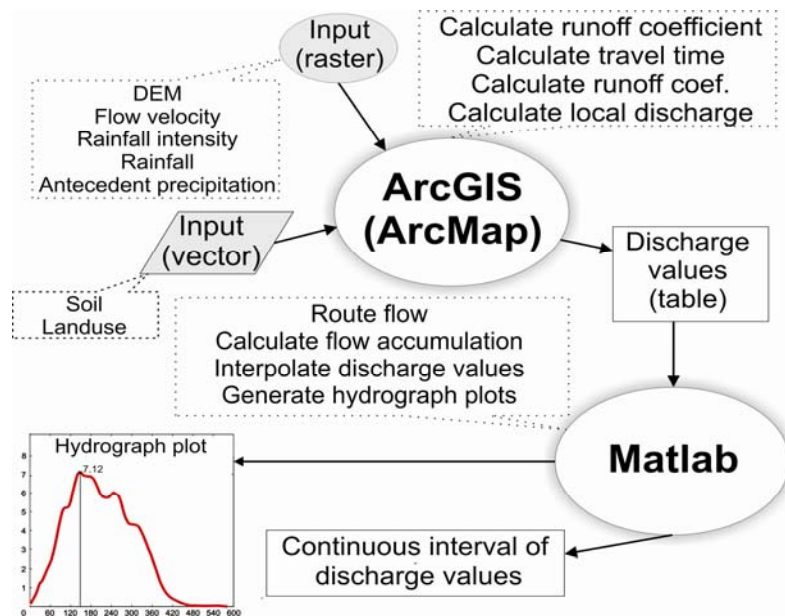

Fig. 3 Workflow used in calculating the discharge hydrograph

The model was built using a modular approach, and each module can be used independently if the result of the module is needed for another scope.

A schematic diagram [9] of the model can be seen in **Fig. 4** and the independent components of the model that are presented can be identified in this figure.

Each component of the model uses known and tested hydrologic methods, and these components are presented in the following chapter.
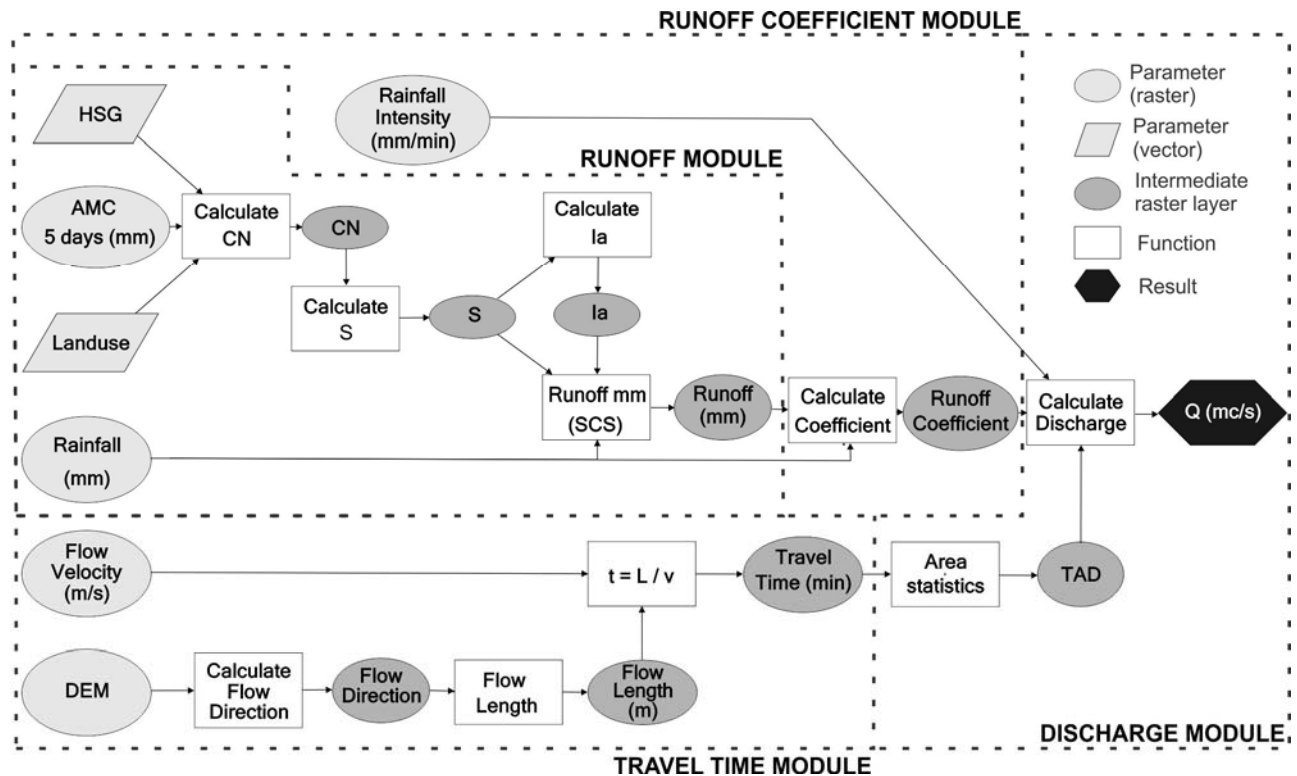

Fig. 4 Workflow diagram [9]

2.1 Runoff depth

The first component, used to calculate the runoff depth in mm (R) from basin rainfall (P, mm), is based on the SCS-CN (Curve Number) model.

The Curve number (CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration. This component uses both polygon (Landuse, Hydrologic Soil Group) and raster layers (Digital Elevation Model -DEM, Rainfall, Antecedent precipitation) as input parameters.

Using these data, the model offers intermediate results regarding the CN, Initial abstraction (I_a) and Potential maximum moisture retention. (S).

The SCS method is applied at cell level using the input rasters according to the equation:

$$R = \frac{(P-I_a)^2}{P-I_a+S} \tag{1}$$

where:
P - rainfall (mm)
I_a - Initial abstraction
S - potential maximum retention

The potential maximum retention is based on the CN and the CN is obtained from the sum of precipitation for the 5 previous days (Antecedent

Moisture Conditions - AMC), the hydrologic soil group (HSG) and the landuse.

The equations for the initial abstraction (I_a) and potential maximum retention (S) are the following [10, 16]:

$$S = \frac{25.400}{CN} - 254 \; ; \qquad I_a = 0,2 \cdot S \qquad (2)$$

The CN is calculated according to tables available in literature [1] and its calculation uses the hydrologic soil group and the antecedent soil moisture condition, given as parameters.

The landuse values are automatically extracted from the Corine Land Cover CLC2000 database. CORINE Land Cover program is currently the most important activity in Europe for Land cover and landuse mapping based on remote sensing. The nomenclature of CLC2000 distinguishes 44 land cover and land use categories in three hierarchical levels. The main categories are urban and artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies. [11]   . The third level of classification was used in the automatic calculation of the CN.

The water infiltration capacity was classified by USDA-SCS in four classes, called hydrologic soil groups [15, 16]. The HSG's, which are A, B, C, D are one element used in determining runoff curve numbers.

The four groups are defined as follows:

(**A**) - low runoff potential. This group is specific to deep, well to excessively drained sand or gravel, with an infiltration rate of more than 7,62 mm/hr.

(**B**) – moderately low runoff potential. This group is specific to loamy sand or sandy loam soil textures. These soils have a moderate rate of infiltration (3,81-7,62 mm /hr).

(**C**) – moderately high runoff potential. Group C soils typically have loam, silt loam, sandy clay loam, clay loam, or silty clay loam soil textures. These soils have a low rate of infiltration (1,27-3,81 mm /hr).

(**D**) – high runoff potential. Soils in this group have very low infiltration rates and are usually clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils

over nearly impervious material. These soils have a very low rate of infiltration (0-1,27 mm /hr).

The study area contains soils characterized by a loamy texture that can entirely be included in the B group.

If the model is used for short-term flow simulation or event-based flood prediction, the antecedent moisture condition becomes one of the most important factors in runoff production as well as its distribution. [3] . The AMC value (Table 1) is determined according to the sum of all precipitation for the last 5 days and the season (dormant or growing). [16].

Table 1. Antecedent Moisture Conditions

AMC	Five-day precipitation	
	Dormant season	*Growing season*
I	< 12,7 mm	< 35,6 mm
II	12,7 – 28 mm	35,6 – 53,4 mm
III	> 28 mm	> 53,4 mm

The CN values from tables are calculated for normal AMC (**Table 1**). The CN values for dry doil (AMC I) or saturated soil (AMC II) are calculated using the following formulas [14] :

$$CN_I = \frac{(-75 \cdot CN_{II})}{(-175 + CN_{II})}, \text{ for AMC I (dry soil)} \qquad (3)$$

$$CN_{III} = \frac{(175 \cdot CN_{II})}{(75 + CN_{II})}, \text{ for AMC III (saturated soil)} \qquad (4)$$

The perimeter where the model was applied has CN values ranging from 60 (for coniferous forests) to 78 (for agricultural lands) (**Table 2**).

Table 2.. Curve Number values for studied area

HSG = B	
Landuse	**CN**
Coniferous forest	60
Broad-leaved forest	66
Pastures	69
Land principally occupied by agriculture, with significant areas of natural vegetation	69
Complex cultivation patterns	78
Transitional woodland-shrub	60
Mixed forest	62

2.2 Runoff coefficient

The dimensionless *runoff coefficient α* is the proportion of rainfall that contributes to runoff from the surface. The coefficient accounts for the initial runoff losses (e.g., depression storage), continuing losses (e.g., surface infiltration) and implicitly accounts for the hydrodynamic effects encountered as the water flows over the catchment surface. [7]

In our case, the runoff coefficient (α) was calculated as the ratio of runoff depth to the total precipitation. The calculated runoff depth is used to determine the coefficient raster as the ratio between runoff and rainfall. The method used in this calculation is an adjustment of a previous algorithm for deriving the runoff coefficient according to soil moisture based on GIS functions [6].

2.3 Travel and concentration time

The travel time (t) from every cell in the watershed to the outlet was calculated according to the flow velocity. The flow velocity (V) for each cell and the DEM from which the flow length grid is obtained are used to calculate the travel time.

There are different methods and models that can determine runoff velocity, like the Manning formula or the Kinematic Wave Equation, and any of these can be used to generate the velocity raster needed as an input parameter.

Using the flow velocity raster, the cell travel time can be calculated as the ratio between the distance traveled through the cell (D, m) and the flow velocity through the same cell (V, m/s).

The travel time from each cell to the outlet is determined by adding the travel time for each cell on the flow path to the outlet. Depending on the direction of the flow through a certain cell the estimated distance traveled through the cell can vary. A GIS function called Weighted flow length that calculates the flow length according to the flow direction and depending on the travel speed through each cell was used to determine total travel time.

The calculated travel time raster is reclassified in 1 minute time intervals (isochrones). This reclassification is carried out for determining the best estimate of time variation for the calculated discharge. **Fig. 5** shows the travel time from each cell in two subwatersheds from the study area and the 30 minute isochrones associated. A time-area diagram for 30 minute time intervals is also presented in the figure.
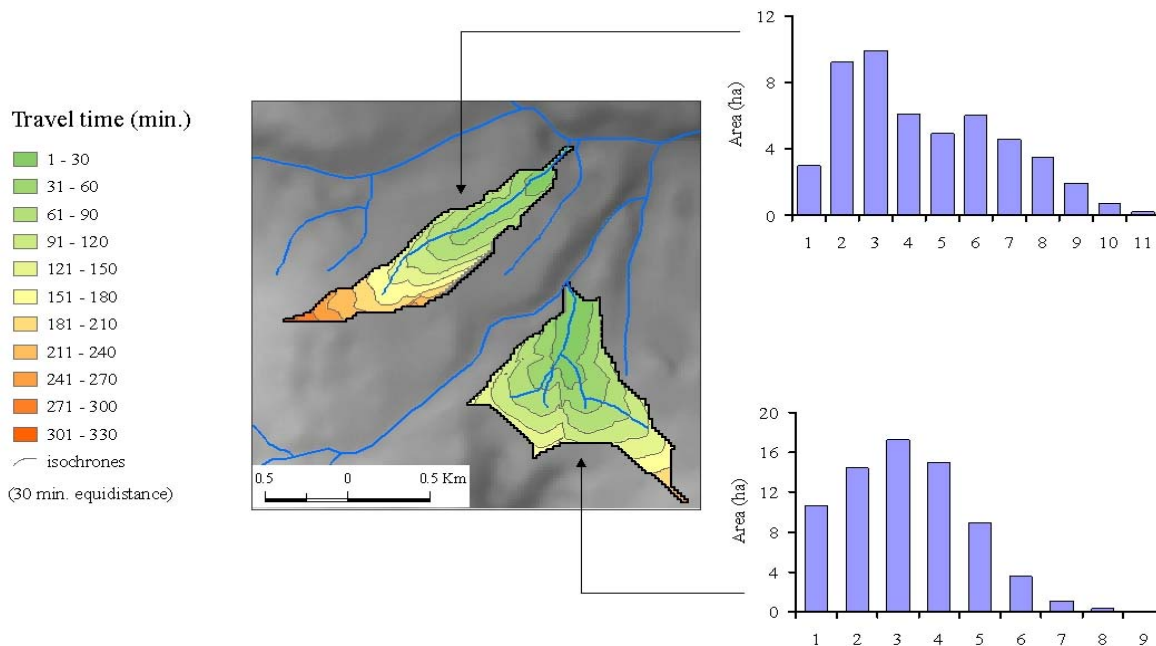

Fig. 5 The spatial distribution of runoff time and the time-area diagram (30 minutes)

2.4 Discharge calculation

The discharge component is used to calculate the discharge generated by rainfall in each point of the catchment. The time-area diagram was calculated for the basin and classified in isochrones according to the flow speed and the basin area characteristics.

After the determination of the contributing area for each isochrone the total discharge for each isochrone can be determined. The discharge values for each isochrone are stored in a table.

The results from the previous component are used as an input for the discharge calculation. The parameters needed to calculate the discharge are all the parameters needed for the calculation of the previous results and consist of vector parameters (Landuse and HSG) and raster parameters (DEM, Rainfall, AMC, Precipitation Intensity and Flow Velocity). The discharge calculation is carried out by applying the rational method in each cell of the watershed to determine the specific discharge for that cell [4, 7]:

The rational method was published by Thomas James Mulvaney (1822-1892) in 1851. The method is a simple equation that can determine the peak discharge generated by rainfall. [4]

The equation was the following:

$$Q = 0,167 * S * i * \alpha \qquad (5)$$

- where (the parameters are adapted for application at cell level):

Q – Peak discharge for each cell (m^3/s)
S – Cell area (ha)
i – Average rainfall intensity (mm/min)
α – Runoff coefficient

The result consists in the discharge for each time step (1 min) and is stored as a table with discrete values. The flow accumulation during the rainfall has to be calculated and the discharge values need to be interpolated because the hydrograph represents a continuous evolution of the discharge in time, not just the discrete values of the discharge.

2.5 Hydrograph generation

The final hydrograph is generated in the MATLAB software package.

The name MATLAB is derived from the term "matrix laboratory." It provides an interactive development tool for scientific and engineering problems and more generally for those areas where significant numeric computations have to be performed. The package can be used to evaluate single statements directly or a list of statements called a script can be prepared. Once named and saved, a script can be executed as an entity [13] .

The tabular data with the discharge is imported in MATLAB and used to calculate the flow accumulation and routing. A script was created for the import of the data and for the automated calculation of the discharge values at the basin outlet.

During the rainfall both the runoff accumulation and routing are calculated simultaneously. After the rainfall period has ended, the runoff routing is performed until the concentration time is reached.

The runoff routing is linear and based on the calculated travel time from the travel time component. The final result of this MATLAB script is a list of discrete numerical values representing the total discharge at the basin outlet for each time step.

The discrete discharge values are interpolated using a Spline interpolation to determine a continuous evolution of the discharge in time. The result is then plotted on a graph which represents the final hydrograph.

3. Results and discussions

3.1 Model usage

Our model can be used directly from the ArcMap GIS application. All the components are stored in an ArcToolbox file that can be imported in the application. A new toolbox containing the four modules of the model will be available to the user after importing. The series required to set the parameter values (the location of each needed layer) before running the model.

The raster layers used in the current application have a resolution of 20 m. If the cell dimensions are different between the layers used as parameters, the raster results will have the resolution of the parameter with the largest cell size. The model shows a simple user interface for setting these values (**Fig. 6**). After the user sets the parameter values, the model can be run, and the results will be stored in the folder given as a parameter value.
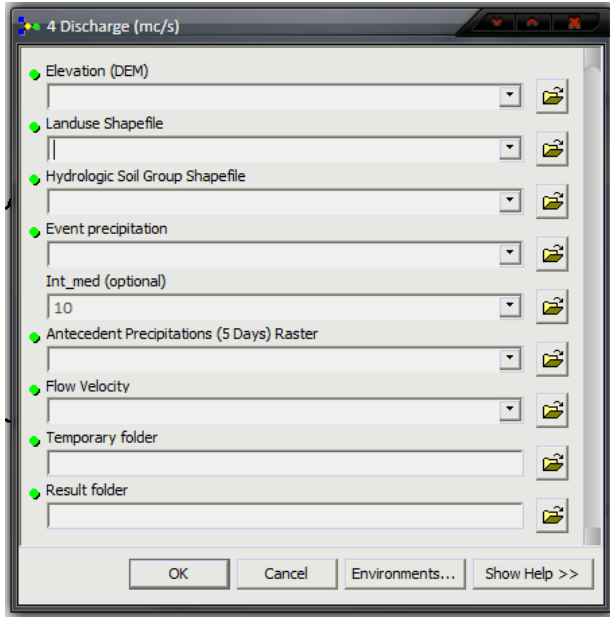
Fig. 6 Discharge model interface [9]

3.2 Application example

Six subwatersheds located in the Râşca village, close to housing and private properties were selected.

The rainfall data used in this example is derived from a storm that occurred in 27 June 2009 in the area. The precipitation recorded at the Vlădeasa meteorological station and considered constant over the study had the value of 54mm. The antecedent moisture condition are in the AMC II category, because the rainfall recorded in the 5 previous days sums 36.2 mm.

The model parameter representing the overland flow speed was determined by using an approach based on Manning's formula [2].

The calculated flow velocity varied from 0.05 m/s to 3.5 m/s. The time of concentration for six basins that were analyzed in the Râşca area vary between 157 and 330 minutes for the rainfall data used. The discharge was calculated for all six sections in studied area, and the results are presented in **Fig. 5**.
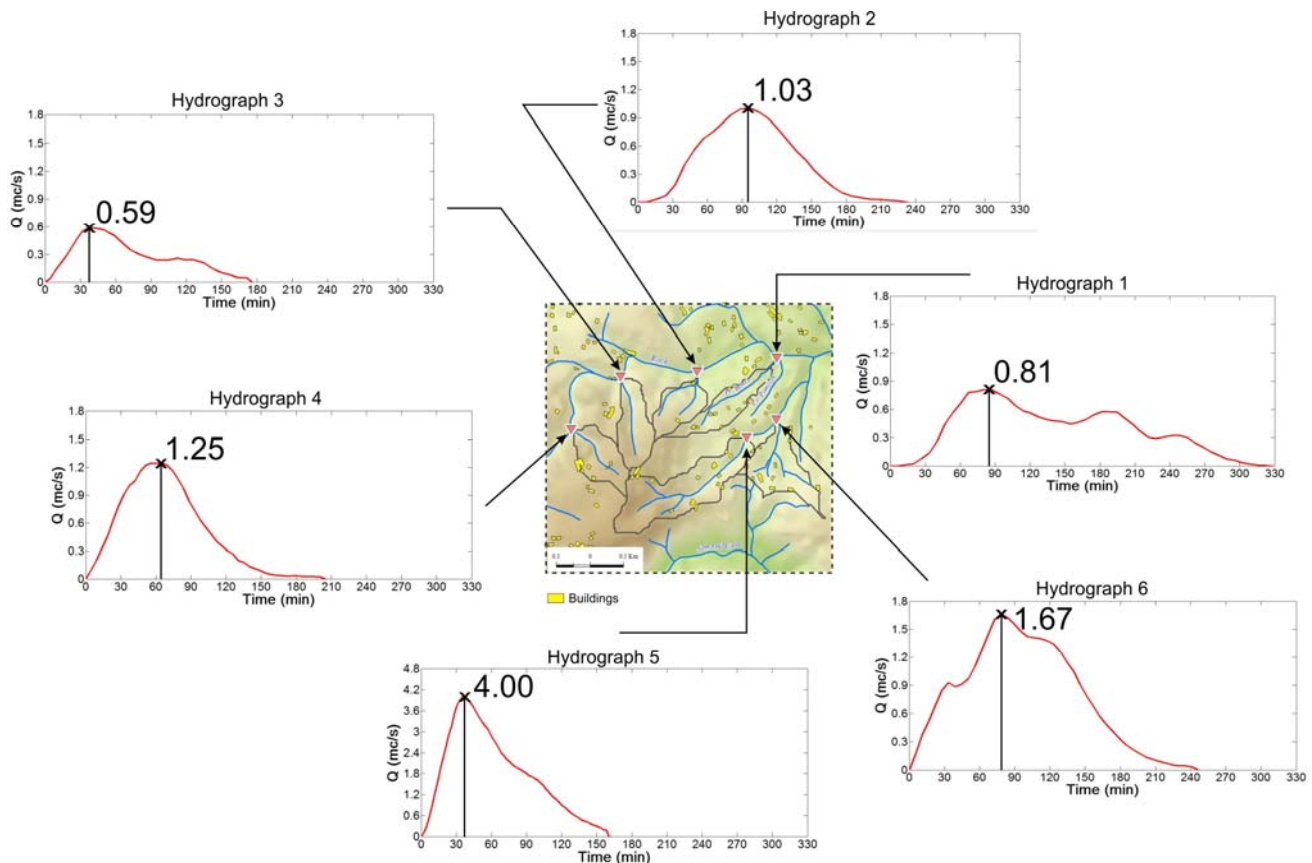

Fig. 5 Runoff hydrograph example calculated for six sections of the Râşca basin

The maximum discharge calculated in this case was about 4 m^3/s in the subwatershed corresponding to hydrograph 5.

The specific maximum discharge (q_{max}) was also calculated based on the maximum values of the estimated discharges and the subwatershed surface for each of the six basins in the area.(**Table 3**).

Table 3. Maximum discharge characteristics in the six subwatersheds from the study area

Watershed	F (km^2)	I (%)	Q$_{max}$ (m^3/s)	q$_{max}$ (l/s/km^2)
1	0.51	10.04	0.81	1577.63
2	0.44	18.2	1.03	2369.39
3	0.54	20.03	0.59	1082.23
4	0.52	17.1	1.25	2411.13
5	1.23	16.77	4	3254.23
6	0.72	9.38	1.67	2325.81

where:
F - watershed area
I - slope
Q$_{max}$ - maximum discharge
q$_{max}$ - specific maximum discharge

These results show that the watershed surface is not necessarily the main factor in determining the maximum discharge for a rainfall. The first four basins have a smaller maximum discharge.

The subwatershed corresponding to hydrograph 3 has the smallest maximum discharge because its area is mostly forested and the CN has a smaller value. The subwatershed corresponding to hydrograph 1 has a small maximum discharge because of the long shape and the small slope that causes a low flow speed and a long concentration time.

The highest hydrograph peak and the smallest concentration time can be seen in watershed 4. This is caused mainly by the long drainage length through the subwatershed and the fast flow speed through the drainage channel. Subwatershed 6 also has a significant discharge because of the quick concentration of runoff caused by its shape.

After this study we concluded that the settlements from basins corresponding to hydrograph 5 and 6 are the most vulnerable to flash floods in case of torrential rainfall.

5. Conclusions

This work presented the application of a methodology based on Geographical Information Systems for calculation the flash flood hydrograph in small catchments in mountainous areas. The model is automated, and only requires the input of some parameters related to the rainfall and the terrain.

The model can be used as a warning tool for flash flood if the predicted rainfall is used as an input. The model can also be used to determine the necessary information for building flood protection infrastructure or taking the necessary actions in preventing flood disasters.

Once the runoff hydrograph is estimated in the ungauged sections, another stage in the determination of the flash flood can be started, and that is the estimation of the water level caused by the flood and the areas that are affected by the flood.

The research can also be continued by evaluating the flood risk in the settlements from the basin area and estimation of the human and financial losses generated by a flood.

20 torrential rainfalls from year 2008 and 2009 were examined, and the inhabitants from the villages in the study areas confirmed an important discharge, but a quantitative result could not be determined.

A quantitative evaluation of the water level in streams will be created considering the profile morphometry and the cross section of interest which can be measured in the field.

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