Present Environment and Sustainable Development
Volume 17, number 2, 2023
DOI: https://doi.org/10.47743/pesd2023172003

Automation of the Rational Formula using GIS infrastructure – Case study Siret River Basin - Romania

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Keywords: Rational formula; maximum discharge; automation; runoff coefficient

Abstract: One of the main concerns and challenges of applied hydrology is estimating the peak flood discharge for an ungauged river. The method currently used in case of rivers with small catchment areas (less than 5 km²) is the Rational Formula as it had been proposed by Diaconu (1994) using the updated values of runoff coefficients presented by Miță (2019). Taking full advantage of the tools offered by the GIS software for digitizing the spatial information of the parameters related to a river and its catchment, this paper, for the first time in literature, approaches the Rational method as it is presented by Diaconu and Miță (1997), by means of an automated method based on GIS infrastructure, which greatly increases the accuracy of the results while significantly reducing the time needed to determine the end result. Therefore, using ArcMap software, one can create the necessary raster images based on DTM (30 m resolution), CLC 2018 shapefile and soil shapefile, an automated geoprocessing workflow with the help of Model Builder for extracting the necessary parameters for the Rational Formula, which will then be integrated in a custom Excel workbook that will generate the magnitude and frequency of peak discharge at the point of interest using a log-Pearson Type III probability distribution. This method has been applied on the Romanian catchment area of Siret river, but it can be used on almost all small river basins in Romania, because the given parameters and coefficients have been determined for the entire territory.

1. Introduction

The rational formula has been used throughout the world for more than 150 years (Mulvany, 1851; Dooge, 1974) and it is based on the same concept as the method that it is being used in Romania, however the value of rain intensity and runoff coefficient (C) are being determined differently.

The Rational method proposed by Diaconu in 1994 is an accomplishment after 30 years of research and analysis of the peak runoff in small river basins (Avram et al., 2022; Bejenaru and Dilan, 2022). Kestlin put this method forward in 1968 and up until 1985 it has been used in accordance with Frevert's runoff coefficients. In 1997, Diaconu and Miță published the methodology for determining rainfall intensity and, in 2019, Miță presents the refined runoff coefficients.

Previous research studies delivered by hydrology experts provided the foundation and the methodology to apply the Rational Formula to the rainfall – runoff particularities of Romania, but applying current instructions either leads to generalized values of some coefficients, or are time consuming, eventually resulting in possible errors in assessing the characteristics of the river basin facies (Apopei et al., 2023).

Taking full advantage of the tools offered by modern GIS software for digitizing the spatial information of the parameters related to a river and its catchment it is significantly easier to quantify these characteristics together with an increase in accuracy (Huțanu et al., 2018).

At present there are numerous papers and studies that deal with determining peak discharge with the use of GIS infrastructure, however these uses either Frevert's runoff coefficients (Bilașco, 2008), "C" runoff coefficient (Suheri et al., 2019) or the SCS – CN method (Domnița et al., 2009; Mahmoud et al., 2014; Haidu et al., 2017).

In comparison with the aforementioned approaches, this paper applies the methodology described by Diaconu and Miță (1997) alongside the updated Miță's runoff coefficients (2019) to an automated process based on the GIS – ArcMap infrastructure, which creates the raster images and extracts the elements of the formula for the given area of interest, parameters that are later imported in a predefined Excel workbook that will generate the magnitude and frequency of peak discharge at the point of interest using a log-Pearson Type III probability distribution (Iosub et al., 2014; Mihăilă et al., 2022).

2. Materials and Methods

2.1 Study area

The methodology presented in this paper has been applied on the Romanian basin of the Siret River, but it is suitable for almost all river basins throughout Romania because the parameters and coefficients of the Rational formula have been determined for the entire territory (Figure 1).

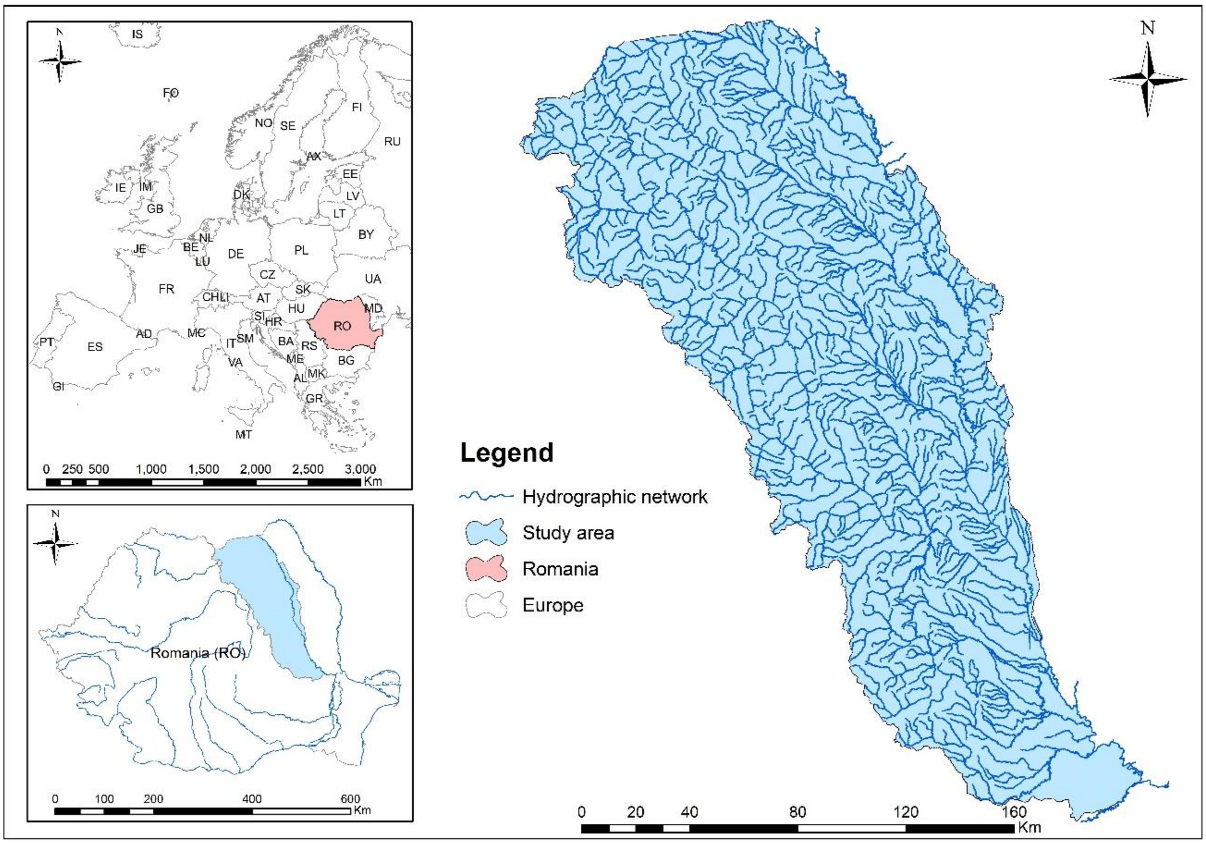


Figure 1. Position of the study area

2.2 Materials and Methods

The procedure for determining the required calculation coefficients of the Rational formula has been retrieved from "*Instructions for calculating maximum runoff in small basins*" developed by Diaconu and Miță at INMH (INHGA) and the values of the runoff coefficient α has been used in accordance to Table 1.3 presented in "Runoff coefficient in rivers" written by Miță (2019). The software used to process and deliver the necessary materials and the end result are ArcMap 10.7 and Excel 2016. The necessary GIS materials used in this methodology are DEM raster image (30 m resolution), CLC 2018 shapefile, Soils shapefile (Istrate et al., 2021; Romanescu et al., 2015; Secu et al., 2022; Simon et al., 2022).

With the help of the aforementioned instruments, it was possible to generate seven new raster images in accordance with the required coefficients of the Rational formula, to extract their values specifically for the study area, and transpose them in a predefined Excel workbook that will generate the magnitude and frequency of peak discharge at the point of interest using a log-Pearson Type III probability distribution.

The Rational formula as it is presented in "*Instructions for calculating maximum runoff in small basins*" (INMH, 1997), is:

$$Q_{1\%} = 16.67 \times \alpha \times i_{1\%} \times F$$

where:
16.67 – conversion coefficient from mm/min to m³/s/km²
α – runoff coefficient
i – rainfall intensity (mm/min)
F – drainage area (km²)

Extreme rainfall rate as the main factor responsible for the peak discharge is being determined as rainfall intensity (i) and it is strongly related to the time of concentration (t_c). To determine the i value, the following equation is applied:

$$i_{1\%} = \frac{S_{1\%}}{(t_c + 1)^n}$$

where:
S_1% - given parameter (map)
n – given reduction coefficient (map)
t_c – time of concentration

Following the current approach (1997), determining the S_1% and n parameters is done by approximating the area of interest and the appropriate value on a given coefficient map of the entire country. Moreover, in order to determine the average slope of the river and its basin, the instruction presents the use of planimeter and/or curvimeter, suitable for that period but extremely time consuming.

In order to automate the use of the Rational method with the aim of providing an increase in accuracy and a decrease in the necessary time to obtain the end result, this paper presents the following approach (Figure 2):

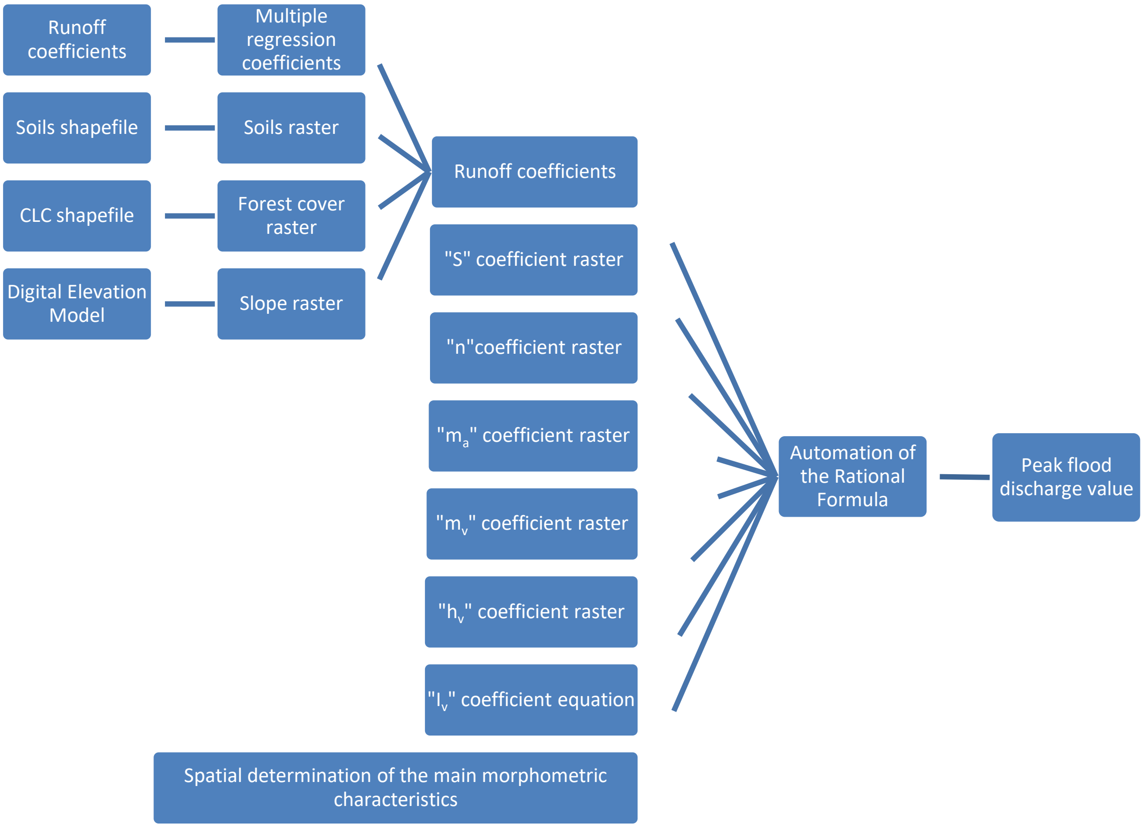


Figure 2. Flowchart describing the necessary steps.

2.2.1 Part I – Runoff coefficient

In order to create and apply these coefficients raster images to the automation process, a series of preliminary steps are required.

First and foremost, all the required and resulting files used in the GIS software must have the same coordinate system and the same extent (Project, Extract by Mask, Clip).

a) Determining the multiple regression coefficients

The runoff coefficient α is defined as a ratio between the runoff depth in a period of time h_s (mm) and the rainfall depth on the given basin area h_p (mm):

$$\alpha = h_s/h_p \ \alpha < 1$$

where:
h_s (mm) – the runoff volume Ws (m^3) on the area of the basin F (km^2) in a given time period;
h_p (mm) – rainfall depth on the basin area (Miță, 2019).

In his paper, Miță presents a series of tables which synthetize the values of the runoff coefficient as a variation of rainfall rate P (mm), 10 days previous rainfall rate API_{10}, forest cover percent C_p (%), average river basin slope I_b (%) and soil texture.

Given the fact that for the Siret river basin the 1% probability rainfall rate is 125 mm and the expected peak discharge is a result of an extreme situation, we used the values given for the P = 125, API_{10} = 40 scenario.

The scenario is divided into three sections, classified according to soil texture (heavy, medium, light) (Table 1).

Table 1. Runoff coefficients for the P = 125, API_{10} = 40 scenario (Miță, 2019)

HEAVY TEXTURE					
C_p(%)/ I_b(%)	0	25	50	75	100
1	0.370	0.340	0.313	0.282	0.262
3	0.525	0.500	0.472	0.440	0.417
5	0.590	0.560	0.533	0.500	0.470
10	0.640	0.612	0.577	0.550	0.520
15	0.680	0.652	0.612	0.585	0.550
25	0.725	0.695	0.660	0.625	0.590
35	0.760	0.730	0.696	0.662	0.620
45	0.790	0.760	0.726	0.690	0.650
60	0.830	0.795	0.765	0.730	0.685
MEDIUM TEXTURE					
C_p(%)/ I_b(%)	0	25	50	75	100
1	0.273	0.257	0.244	0.235	0.222
3	0.423	0.408	0.390	0.370	0.350
5	0.470	0.451	0.430	0.405	0.380
10	0.520	0.495	0.475	0.448	0.420
15	0.547	0.530	0.503	0.476	0.446
25	0.580	0.562	0.536	0.510	0.480
35	0.610	0.587	0.561	0.530	0.500
45	0.635	0.610	0.582	0.553	0.520
60	0.670	0.635	0.605	0.570	0.537
LIGHT TEXTURE					
C_p(%)/ I_b(%)	0	25	50	75	100
1	0.215	0.204	0.190	0.180	0.158
3	0.340	0.327	0.310	0.290	0.265
5	0.378	0.365	0.345	0.323	0.303
10	0.418	0.397	0.380	0.355	0.335
15	0.447	0.430	0.407	0.380	0.360
25	0.472	0.452	0.435	0.403	0.380
35	0.492	0.470	0.452	0.425	0.400
45	0.510	0.487	0.467	0.443	0.418
60	0.530	0.505	0.480	0.460	0.430

The values presented in this table have been transposed into an Excel worksheet into separate columns for each characteristic, mentioning that the zero values of C_p have been written as 0.00001 (because the natural logarithm function is defined only for x>0) and the textures have been reclassified as below:

- heavy texture = 3;
- medium texture = 2;
- light texture = 1.

The next step is to convert all the values to their natural logarithmic form using the Excel formula "=LN(cell)". Using the logarithmic form of the values and the Data – Data Analysis – Regression tool in Excel, where Input Y Range is the runoff coefficient column and the Input X Range are the texture, forest cover and slope values, a new Worksheet will be created which will provide the multiple regression coefficient for each input characteristic.

In order to analyze the residual errors, the predicted values need to be converted to their exponential form using the formula "=EXP(cell)". By comparison, the average error for the entire runoff coefficient range was 0.03, value that we considered acceptable.

The values of the regression coefficients will later be used to create the runoff coefficient raster.

b) Soils raster image

In the Table 2 from the paper "Runoff coefficient in rivers", Miță details the characteristics for each soil texture class as they are presented in the runoff coefficients` tables. The corresponding values are presented below:

Table 2. Soil characteristics for different textures and their effect on runoff coefficient (Miță, 2019)

Soil texture	Characteristics	Effect on permeability	Effect of permeability on infiltration	Effect of infiltration on runoff coefficient
Light	Sand Sand – silt Silt – sand	Very high permeability	High infiltration rate	Very low runoff coefficients
Medium	Silt Silt – Clay	Medium permeability	Medium infiltration rate	Medium values of runoff coefficients
Heavy	Clay – silt Clay	Very low permeability	Low infiltration rate	Very high runoff coefficients

The soils shapefile has to have a field in the Attribute Table that contains the descriptions of the texture for each type of soil. Therefore, it is necessary to reclassify this shapefile based on the characteristics presented in the Table 2. This task can be carried out right in the Attribute Table by adding a new integer Field and assigning the values 1 for light texture, 2 for medium texture or 3 for heavy texture to each corresponding characteristic, based on Table 2 and the Excel reclassification. To ease this process, it is recommended to Dissolve the soils shapefile, based on the texture field, before the reclassification step. Once the editing process is stopped and saved, by using the Polygon to Raster tool, it is possible to create the soils raster image, using the newly created field as Value field (Figure 3). Also, because the DEM raster image has a 30 meters pixel size, it is advised to maintain the same resolution throughout the entire future steps.

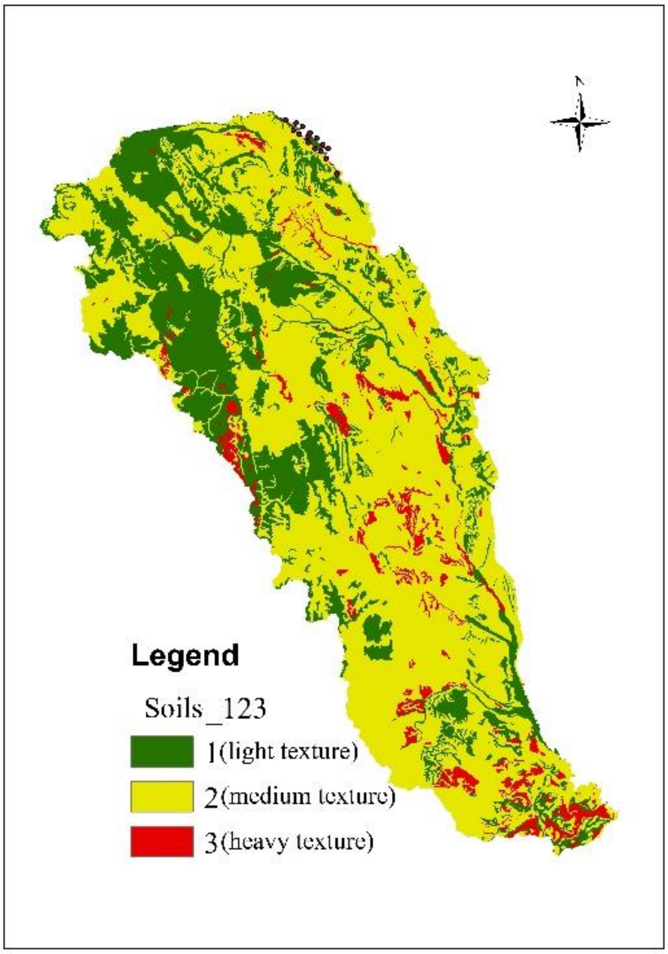
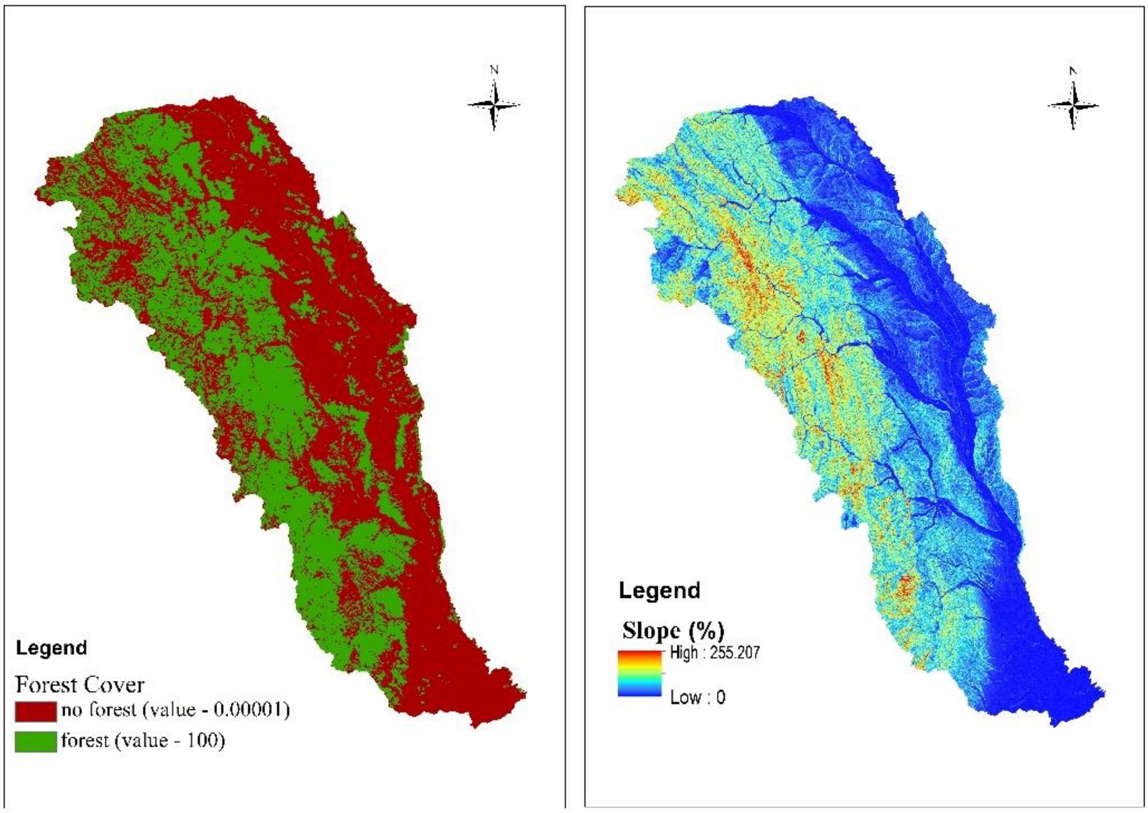


Figure 3. Soils raster image

c) Forest cover raster

In order to create the Forest cover raster, it is recommended to use the CLC 2018 official shapefile and, as aforementioned, it has to be clipped to the area of interest. Given the fact that Miță doesn`t differentiate between types of forests, the CLC shapefile can be reclassified just as two values. As stated before, features that do not relate to forest will be given the value 0.00001, while CLC codes 311, 312 and 313 will be reclassified as 100. Just like for the Soils raster, it is recommended to *Dissolve* the CLC shapefile by the CLC code and then add a new float type field that will serve for the reclassification process. The Polygon to Raster tool will have a 30 m pixel size, the reclassified Value field and a relevant name as inputs (Figure 4a).



a) b)

Figure 4. a) Forest cover raster image; b) Slope raster image

d) Slope raster image

The slope raster image is created using the *Slope* tool using the DEM as input raster and in the *Output measurement* box, select the *PERCENT_RISE* option because the runoff coefficient uses percent (%) as slope value not degrees (Figure 4b).

e) Runoff coefficient raster by means of regression coefficients

This step combines all three previously created rasters' using the Raster Calculator tool and applying the regression coefficients to each raster.

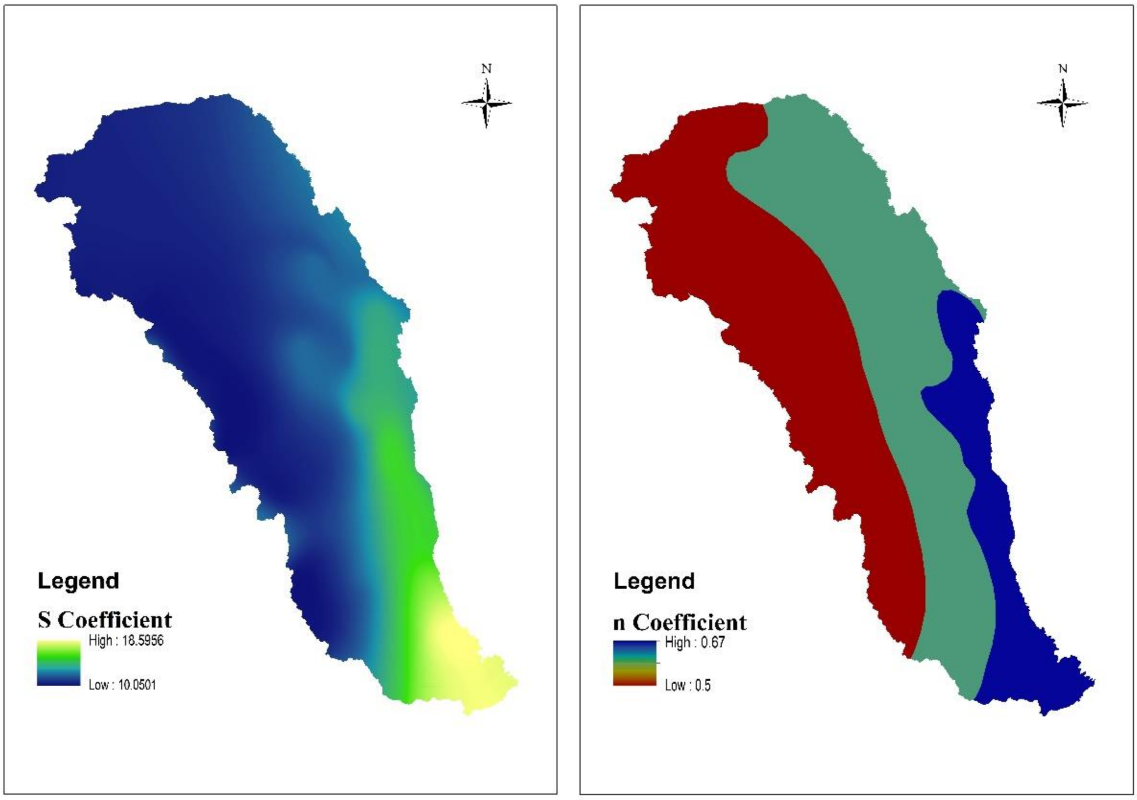
2.2.2 Part II – Rainfall intensity parameters

The first step in determining the rainfall intensity $i_{1\%}=S_{1\%}/(t_c+1)^n$ is creating two raster images spatially defining S and n parameters. For both of these coefficients, there are given maps in Deacon's instructions (1997). Each map has to be scanned as image and put through the Georeferencing process.

a) "S" and "n" coefficients rasters

S and *n* coefficients are given parameters presented by Diaconu (1997) as maps.

For the *S* parameter it is required a new *Polyline* shapefile, because this coefficient`s value is defined as a contour line and for the *n* parameter it is required a new *Polygon* shapefile because it`s value defines an area. For each shapefile, in the *Attribute table* one must add a new field that will be edited with the corresponding value of the digitized feature. After the two maps have been digitized, the *S* parameter raster will be created using the *Topo to Raster* tool in which the value field will be used as Contour and the *n* parameter raster will be created using the *Polygon to Raster* tool (Figure 5a,b).



a) b)

Figure 5. a) "S" coefficient raster; b) "n" coefficient raster

The time of concentration t_c is determined using the equation:

$$t_c = 1.2{t_a}^{1.1} + t_v$$

where:
t_a – channel time of concentration;
t_v – basin time of concentration.

The channel time of concentration t_a is a ratio of:

$$t_a = \frac{1000 \times L_a}{m_a \times {I_a}^{1/3} \times {Q_{max}}^{1/4}}$$

where:
L_a – length of the main river channel (km);
m_a – river bed roughness coefficient;
I_a – main channel average slope;
Q_{max} – an approximation of the peak discharge (m^3/s).

b) River bed roughness coefficient ("ma") raster

For this intermediary stage, it is necessary to create the *ma* raster image. In the paper "*Instructions for calculating maximum runoff in small basins*", Diaconu provides a table containing the characteristics of the main channel in which mountainous streams channels have the roughness value of 7, for sinuous channels with vegetation and high sediment transport rate the assigned value is 9 and 11 for linear and clean channels. Due to the geomorphology of the Siret river basin, for small tributaries, the value of 11 cannot be applied to any river. Therefore we assumed that the range of coefficients will vary from 7 to 9, thus correlating it to the $f(D_{50},H)$ relationship, where D_{50} is the medium sediment size and H is the altitude at which the D50 has been determined. Consequently, for altitudes higher than 560 m the value is 7 and for altitudes less than 560 m the value increases gradually due to a linear regression (Figure 6) until the altitude of 12 m, which is correspondent to Lungoci gauging station on Siret river.

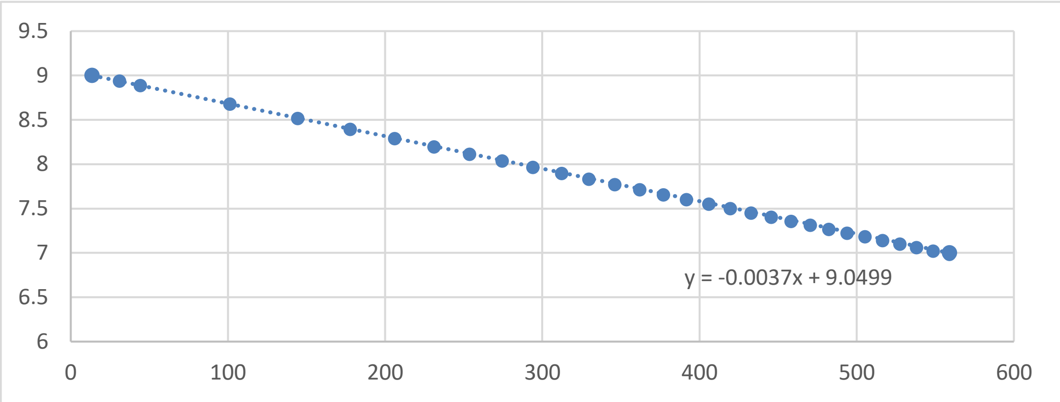


Figure 6. Linear regression for the relationship $f(m_a,H)$

Using the *Raster Calculator* tool, the equation of the $f(m_a,H)$ relation has been applied on the DEM raster image where x=DEM pixel value, thus creating an elevation distributed m_a raster image (Figure 7).

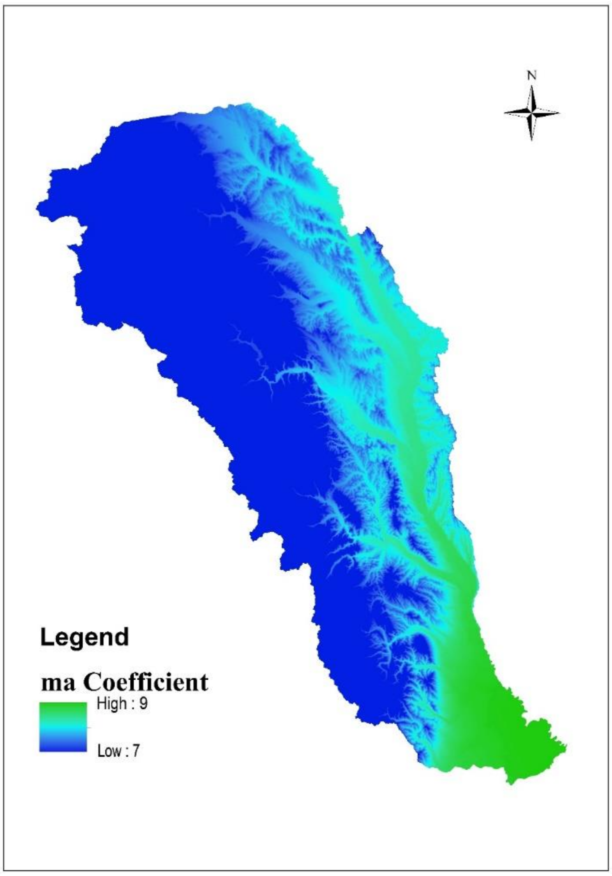


Figure 7. River bed roughness coefficient raster ("m_a")

The values for L_a, I_a and Q_{max} will be determined afterwards because there is no need for these to create new raster images.

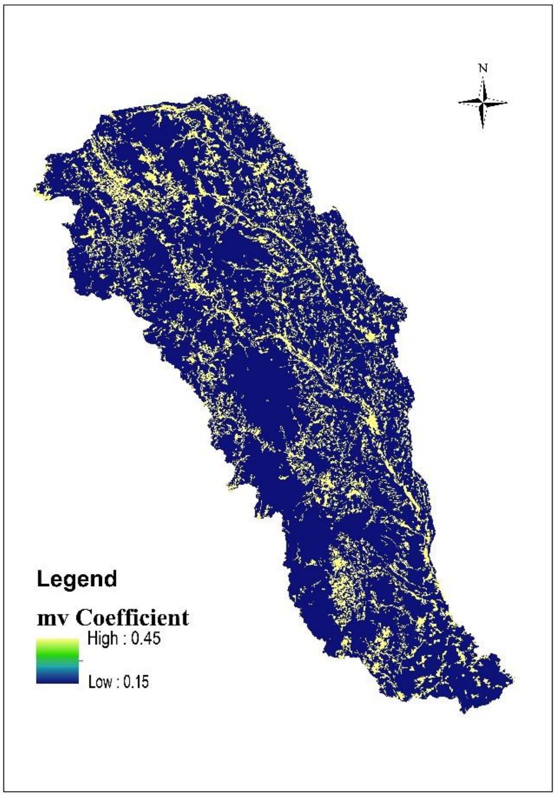
The basin time of concentration t_v is determined using the equation:

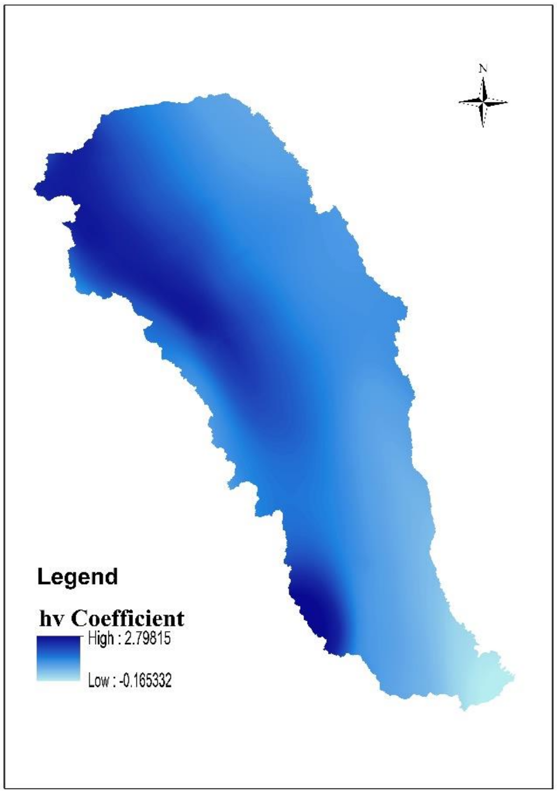
$$t_v = \frac{(1000 \times \bar{l}_{v)}^{1/2}}{m_v \times I_v^{1/4} \times h_v^{1/2}}$$

where:
l_v – average length of the hillslopes (km);
m_v – roughness coefficient of the slopes;
I_v – average basin slope (m/km);
h_v – average intensity of the peak discharge rate (mm/min)

c) Slope roughness coefficient ("mv") raster

Similar to the channel roughness coefficient, Diaconu provides a table related to the roughness coefficients of the slopes taking into account types of land use. These values range from 0.50 in case of tarmac or concrete (urban areas), 0.25 – 0.40 for pastures like terrain, 0.20 – 0.30 for agricultural and sparsely populated areas and 0.10 – 0.20 for forests, rural inhabited areas or with high rates of geomorphological processes. Therefore, after reclassifying the Corrine Land Cover shapefile in accordance with the given table, the *Polygon to Raster* tool creates the m_v raster image (Figure 8a).





a) b)

Figure 8. a) Slope roughness coefficient ("m_v") raster; b) Average intensity of the peak discharge rate coefficient ("h_v") raster

d) Average intensity of the peak discharge rate coefficient ("hv") raster

According to Diaconu (1997), the value of h_v is determined by the equation *0.06 * $B_{1\%}$ (m³/s/km²)*, where *0.06* is a conversion coefficient from m³/s/km² to mm/min and $B_{1\%}$ is the 1% discharge determined for one square kilometers. Here as well Diaconu provides a map of Romania that contains the isolines of this parameter's value. The map needs to be scanned, georeferenced and digitized. Afterwards one can either apply the coefficient`s formula in a new field using the *Field Calculator* tool (recommended) or can create a $B_{1\%}$ raster image which will then be adapted using the Raster Calculator tool. (Figure 8b)

e) Average length of the hillslopes parameter ("l_v") equation

To determine the value of l_v (average length of the hillslopes) we determined the equation:

$$\bar{l}_v = \frac{\sqrt{{\Delta_{med}}^2 + (\frac{\Delta_{med}}{I_v} \times 100)^2}}{1000}$$

where:
Δ_{med} – average basin elevation amplitude (m);
I_v – average basin slope (%).

The reasoning behind this equation is based on the fact that an average value is needed. Therefore, knowing the average slope of the basin expressed in percentage and the average amplitude of the basin as the difference between the average elevation and the minimum elevation of the basin, using the Pythagoras theorem in correlation with Thales` basic proportionality theorem it is logical and easy to determine the average length of the hillslopes.

2.2.3 Part III. Spatial determination of the main morphometric characteristics

Before presenting the automation methodology for determining the required coefficients in GIS, it is necessary to determine the main spatial characteristics of a river basin, and these are the position and area of the basin and the position and length of the river channel. Therefore, it is necessary, for each area of interest, to create two shapefiles, a polygon type for the basin that will spatially define the shape, position and area and a polyline type for the river that will spatially define its course, position and length. This is achieved first by digitizing the spatial characteristics of the basin and the river and then by adding a new field (float type) to the *Attribute table* use the *Calculate geometry* tool selecting *Square kilometers* for the basin area and *Kilometers* for the river length.

2.2.4 Part IV Automation of the Rational formula

The last part of this methodology is based on a GIS tool called *Model Builder*. ESRI describes it as a visual programming language for building geoprocessing workflows. It basically enables you to automatically run a series of predefined tools over and over again. The necessary structure in order to extract the necessary coefficients are presented in Figure 12.

As soon as the model process is completed, the program will automatically generate a message in the *Results* section that will contain all the calculated values. The structure of this message is identical every time the model is run. Therefore, in order to apply these calculated coefficients to the Rational formula, this message will be copied as is in a predefined Excel worksheet designed to read and transform to value only the number part for each coefficient.

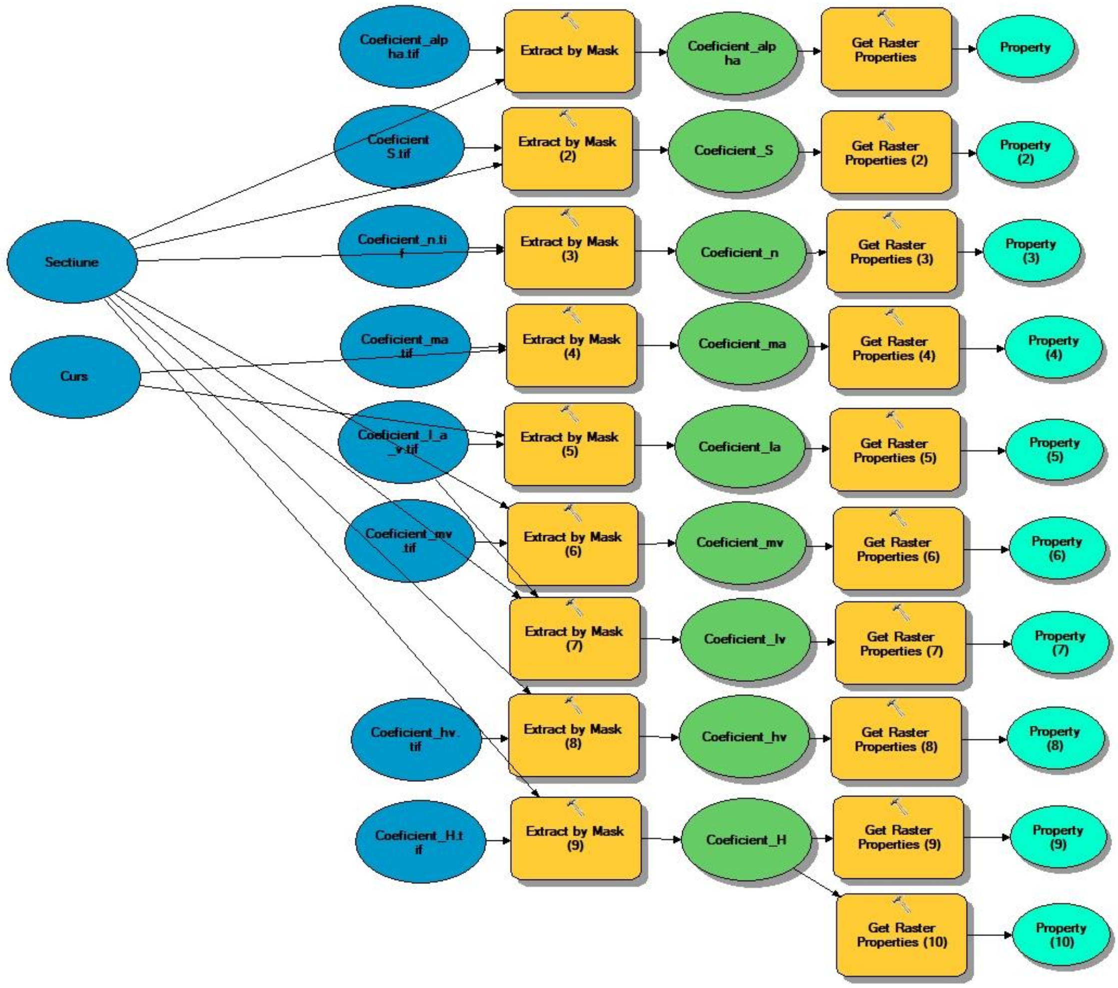


Figure 9. Model Builder structure

3.Results and Discussion

Although the creation of these coefficients` raster images may seem time-consuming, the following determination of the values for all the coefficients is done in 10 to 15 seconds. This methodology, just as every other approach in the study of hydrology is subject to improvement and the results that this methodology provides have to be put to question by expert judgement and field reality. Just as Diaconu states "the processes on the surface of a basin that can manifest in a short period of time (1 – 2 decades) can essentially influence the peak discharge" (Diaconu and Miță, 1997). This is why it is mandatory that information such as DEM, land use or forest cover (CLC) to be as recent as possible, because any major modification in the analyzed area can have a major impact on the peak discharge.

The Excel workbook that we created contains two sheets, one in which there are presented the equations and the necessary steps and one in which the *Model builder Results* message in GIS is pasted. Taking into consideration the fact that this method has never been presented in its automated state, it is important to highlight that in order to determine the peak runoff for small river basins throughout the Romanian territory, this methodology is the optimal approach when it comes to the accuracy of the results, because the particularities of this Rational Formula have been determined and confirmed by more than 50 years of measurements and records at the gauging stations administered by National Administration "Romanian Waters".

In this regard, the only limitation of this method is the area of the basin that can be analysed, which cannot exceed 5 km^2, because the particularities of the genetic factors that influence the runoff have an uneven distribution throughout larger areas, thus requiring a different approach.

4.Conclusions

Apart from the scientific perspective, estimation of the peak discharge is a necessity in order to prevent and manage flood effects. While for gauged rivers it is possible to apply statistic methods in order to estimate the characteristics of the maximum river discharge, small basins have to be approached by means of the genesis factors and the conditional factors that generate and influence the flow rate. These small basins can be so particular throughout a main river basin that they cannot be subject to a correlation matrix for the main river.

The Rational method is highly recommended and certified in probabilistic analysis of the maximum discharge for small basin areas because it takes into account all the main factors that contribute to the runoff process.

Recent climate changes, along with the expansion of human activities close to river areas, emphasize the need to accurately calculate the maximum discharge rates. Therefore, it is essential to precisely quantify the factors that contribute to the runoff. This paper not only provides the means to significantly speed up the process of determining the Rational formula coefficients but also presents a methodology to accurately determine the values for each parameter, using modern software.

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