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MODELLING AND HYDRO-MORPHOMETRIC ANALYSIS OF SUB-WATERSHED. A CASE STUDY OF MESTA RIVER SOUTHWESTERN BULGARIA

Galina V. BEZINSKA
South-West University "Neofit Rilski, Department Geography, ecology and natural protection, Blagoevgrad, Bulgaria
galinabezinskaswu@gmail.com

Krasimir S. STOYANOV
South-West University "Neofit Rilski, Department Geography, ecology and natural protection, Blagoevgrad, Bulgaria
krasi_sto@swu.bg

Abstract

In the present article some morphometric characteristics of small catchments (a total of 28) in the Mesta River were calculated and mapped. Some of the maps are obtained by calculation based on a vector model. For the detailed study, we used digital elevation model (DEM) for the surveyed territory and the application of a cartographic algebra in the GIS environment. As a result, GRID models have been obtained for some of the parameters. Different thematic maps (i.e. Surface runoff direction, Classification of the river network, Orientation of the catchments, Topographic factor of the slope of catchments, Kernel drainage density, Standard deviation of elevation, Basin-scale Ruggedness etc.) have been prepared by using the ArcGIS software. Authors have computed more than 20 morphometric parameters of all aspects. This study is very useful to implement different analysis of hydro-morphometric characteristics of catchments and also to solve various hydrological problems for watershed management.

Keywords: *Hydro-morphometric analysis, Small catchments, DEM, GIS, Thematic mapping, Mesta River*

1.INTRODUCTION

According to Clarke (1966) and Pike (2008), the geomorphometry is a science of quantitative land-surface analysis. This is a modern, analytical-cartographic approach to representing bare-earth topography by computer manipulation of the terrain height. Furthermore, the morphometry analysis constitutes a method of mathematical evaluation of shape, size and dimension of land forms, and configuration of earth's surface.

The geomorphometric analysis was distinguished for the first time by Horton (1932, 1945); it was further reviewed by Evans (1972).

The calculation of the morphometric characteristics of the relief is the basis of complex modeling and exploration of the catchments, because it enables us to understand the relationship among different aspect of the drainage patterns within the basin (Strahler, 1964; Horton, 1945; Miller, 1953; O'Callaghan et David, 1984).

In Bulgaria, Simeonov and Totzev (1997) and recently Tcherkezova (2015), considered these issues in their papers.

With recent GIS and remote sensing technologies, it is possible to calculate and modelling new morphological and hydro-morphological characteristics of watersheds.

Most of contemporary's authors classify these features in terms of linear, areal and relief aspect (Bhatt at al, 2018; Bera et al, 2018; Kannan et al, 2018), while there is no uniform classification in Bulgarian literature.

The obtained morphometric hydrological models are an important source of information on water management and simulation of various hydrological processes (Singht et al, 2002; Hojati and Mokaram, 2016; Piloyan, 2016; Mandal, 2018). Maidment (1993); Chalam et al (1996) and others have established some of the relationships between hydrologic and geomorphologic variables using statistical methods. Until now, the small Mesta River catchments have not been studied in detail. Their flow pattern is characterized by great fluctuations and has a significant depend on the morphometric characteristics of the relief. To obtain information about these characteristics will be crucial for solving a number of practical issues related to river flows, water management, etc.

The aim of this article is to define 25 morphometric characteristics in the catchment area of the Mesta River, to analyse their values and to determine their geomorphological and hydrological significance. For this purpose, we opted for a DEM available on (https://land.copernicus.eu/imagery-in-situ/eu-dem). Using a spatial analysis in the GIS environment, we obtained the basic parameters characterizing the catchment of the Mesta River and we realized an interactive map available on http://gis.swu.bg/MappetizerMESTA. In addition, we created 25 thematic maps of the catchment area of the Mesta and 28 composite small catchments. Finally, we analysed the hydrological and geomorphological significance of the obtained maps.

2. MATERIALS AND METHODS

Traditional hydro-morphometric modelling and analysis in the GIS environment is based on the representation of the earth's surface as a GRID model. We used a freely available DEM for the study area with a pixel size of 30/30 m. The calculated characteristics of the basin of the Mesta River and its constituent (total of 28 catchments) were imported into GeoDatabase in ArcGIS environment. Some of these characteristics were obtained by calculation based on the vector model. For modelling and analysis of continuous data in a GIS environment, GRID is typically stored. The cell size of the resulting raster models is selected according to cell size of DEM (30/30 m).

Characteristics for each catchment are calculated, mainly as averages (for example, slope) or percentage values (for example, woodland of the total area) in space. Based on raster analyses, they are computed by complex algorithms and many other features that were not yet possible to do. It should be noted, however, that for the purposes of hydrology, it is imperative to correct the errors in the DEM. Two options are available in ArcGIS. The first one is with the Hydrology tools of the Spatial Analyst Tools application. The following function can be used to identify and remove errors to create a correct hydrological model: Arc Toolbox / 3D Analyst Tools / Raster Interpolation / Topo to Raster. Another better tool is the specially developed Arc Hydro Tools, application for ArcGIS.

The next steps present how to obtain a correct hydrological model based on DEM (Bera et al, 2018). They can be summarized as follows:

1. Introduction of the digital model of the relief and obtaining a correct hydrological relief (Sink and Fill operations);
2. Determination of the direction of the water flow (Flow Direction);
3. Flow accumulation;
4. Determination of Pour Point inflow points from a lower order;

5. Watershed outline.
6. Hydro-morphometric analysis.

Data modelling has been done using the hydrology tools proposed by ArcGIS 10.4.1.

All calculated characteristics are part of the resulting hydro-geomorphological database for the catchment of the Mesta River. Some of them refer to the basin of the Mesta River and are represented as a static surface by a GRID model. Their advantage is that data can be derived for each desired point in the catchment. Others are calculated for all 28 small catchments along the main river.

We propose the following hydro-morphometric characteristics of the catchment area to be summarized in three main categories: physico-geographical, morphometric (geometrical) and hydro-climatic characteristics. Their names and descriptions are presented in Table 1.

Table 1. Hydro-morphometric characteristics of watershed

Main physico-geographical characteristics		Description
1	Geographic location	
2	Geological and geomorphological structure	
3	Basin topography	A total of all surfaces (protrusions, concavities, and plains) that make up the physical earth's surface.
Basic morphometric (geometrical) characteristics		
4	Basin Area, km^2	This territory, which is located between the watershed lines that separate it from other ones.
5	Basin Perimeter, km	Basin perimeter is the outer boundary of the watershed that enclosed its area. It is measured along the divides between watersheds and may be used as an indicator of watershed size and shape. .
6	Maximum Height of the Basin (Z) m	
7	Total Basin Relief (H) m (Strahler, 1952) H = Z - z	It is calculated as the arithmetic mean of all pixel altitudes in the DEM.
8	Mean Basin Slope, degree	It is calculated as the arithmetic mean of all pixel in the Slope GRID.
9	Circularity ratio (Miller, 1953) $Rc = \frac{4*\pi*A}{P^2}$ A-area of the basin; P- perimeter of the basin	It is explained as the ratio of basin area to the area of a circle having the same perimeter as the basin. A coefficient ranging from 0 to 1. As the value is closer to 1, the more round is the shape of the catchment area
10	Elongation ratio (Schumm, 1956) $R=\frac{2}{\pi}*\sqrt{\frac{A}{L^2}}$ A – area of the basin; L – basin length	Elongation ratio is defined as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. Its value varies from 0 (highly elongated shape) to 1 (round shape)
11	Drainage density (Horton, 1932) $K = \frac{\sum L}{P}$ $\sum L$ – total length of all streams of the basin, km P – area of the basin, km^2	Drainage density is defined as the stream length per unit area in region of watershed.
12	Basin centroid	The geometric centre of the basin, whose coordinates are the average values of the

		coordinates of the boundary points of the contour.
13	Length of the main river, km	River length from the source to the mouth, km.
14	Channel sinuosity index (Leopold et al, 1964)	A coefficient representing the relationship between the length of a given current and the length of the line connecting the point of origin and the point of infusion. Approximately ranges between 1 and 4. Flows with an index greater than 1,5 are called meandering.
15	Concavity Index (Ca) (Snow and Slingerland, 1987) $Ca = A_1 / A_2$	The depth of the riverbed is the longitudinal change in the slope of the studied part of the river.
16	Configuration of catchment area: • Symmetry; • Length; • Average width;	Conformity in the location of the water catchments in relation to the main river; Defined by the most remote points of the catchment; Average between the narrowest and widest part of the catchment.
17	Local Relief Index (LAR) (Fonstad, 2003) $L_R=\sum_I (Z_{max}-Z_{min})/n$, where Z_{max} – maximum height extracted from DEM, Z_{min} – minimum height extracted from DEM, n – number of pixels in the watershed .	High LAR values may indicate that the catchment has been subject to a severe tectonic impact and / or incision.
18	Orientation of the catchments	Orientation in terms of geographical directions.
19	Basin Relief Ratio (Schumm, 1956) $R_r = \frac{Z_{max}-Z_{min}}{L}$, L – basin length as the longest dimension of the basin parallel to the principal drainage line, m	This simple morphometric index can be used to compare a set of catchments between one mountain range and another. Values may reflect differences in active tectonics, geology, geomorphological processes, climate impacts, etc.
20	Basin Form Factor (Horton, 1941) $F = \frac{A}{L^2}$, A – area of the watershed, m^2 L – the longest distance measured parallel to the main stream, m.	Basin shape factor. It varies from zero (strongly elongated forms) to one (round shape).
21	Basin Shape factor (Horton, 1932) $BSF = \frac{L}{W}$, L – the length of the watershed; W – width of watershed	Basin Shape factor
22	Elevation Relief Ratio (Schumm, 1956) $$ERR = \frac{Z_{avg} - Z_{min}}{Z_{max} - Z_{min}}$$	Difference in the elevation between the highest point of a watershed and the lowest point on the valley floor is known as the total relief of the river basin.
23	Relative Topographic Position Index $$RTPI = \frac{(\text{meanDEM} - \text{minDEM})}{(maxDEM - minDEM)}$$	Relative topographic coefficient for erosion disintegration. It is similar to the Elevation Relief Ratio, but a raster is obtained by using the so-called focal statistics.
24	Standard Deviation of Elevation (Ascione et al, 2008) $$SDE = \frac{(\text{mean DEM} - \text{DEM})}{(\max DEM - \min DEM)}$$	Standard deviation of elevation correctly identified breaks of slope and was good at detecting regional relief. Ratio, which measures topographic roughness. A raster is obtained by the so-called; focal statistics, with values ranging from -1 to 1. Positive values match the

		streams and the negative ones the watersheds lines.
25	Standard Deviation of Slope (Grohmann et al, 2011)	Standard deviation of slope (SD_{slope}) also correctly identified smooth sloping areas and breaks of slope, providing the best results for geomorphological analysis.
26	Slope variability (Ruszkiczay-Rudiger et al, 2009) $SV = \max slope - \min slope$	A raster is obtained by the so-called focal statistics. The slope should be in degrees.
27	Basin scale ruggedness $R_b = \frac{A}{D_d}$, A – area of the watershed, km^2, D_d – drainage density	The relief roughness coefficient used to compare the basin relief using the surface area and the drainage density.
28	Melton ruggedness number (Melton, 1965) $\frac{Z_{max} - Z_{min}}{Sqrt(A)}$	The relief roughness coefficient
29	Terrain Ruggedness Index (Riley et al,1999)	Terrain Ruggedness Index (TRI) is the difference between the value of a cell and the mean of an 8-cell neighborhood of surrounding cells.
Hydro-climatic characteristics		
30	Water surfaces in the catchment area $K_e = \frac{F_e}{F}$ – lakes index, F_e – total area of all lakes in the catchment F – area of catchment	Part of the catchment area occupied by lakes
31	Topographic Wetness Index (TWI) (Beven and Kirkby, 1979) $TWI = \ln\left(\frac{a}{tg\beta}\right)$, a – upstream contributing area, m^2; β – slope raster	Topographic Wetness Index. High values represent low portions of the earth's surface, and low values are also peaks.
32	Hillslope-erosion-potential index (Flint, 2003) $HEP = Mean\ Annual\ Precipitation * Slope$	Potential erosion coefficient. A GRID model is obtained.
33	$Q_{max\ av.}$, m^3/s	Average annual water quantity
34	$q_{max\ av.}$, m^3/s.km^2	Module of the average multi-year runoff
35	Surface runoff (R_{mm})	River waters that run off the surface of the river basin under the influence of geological geomorphological, climatic, hydrographic and soil-plant features of the basin

3. STUDY AREA

The catchment area of Mesta River is located in Southwestern Bulgaria and covers an area of 2785 km2 (Figure 1). The basin is mountainous, developed on the territory of the Rila-Rhodope massif, part of the extensive Macedonian-Thracian Massif and it has an average altitude of 1227,03 m. The Mesta River is formed by the confluence of the Bela and Cherna Mesta rivers is 941 m a. s. l., located 2,5 km north-east of the town of Yakoruda. The length of the main stream is 273 km of which 126 km are on the Bulgarian territory. The river basin encompasses the southern and southeast slopes of the Rila Mountains, the northeastern and eastern slopes of Pirin as well, and finally Slavyanka and the western and southwestern slopes of the Western Rhodopes. The catchment area has an elongated shape with an enlarged lower part. The approximate length of the Mesta River basin is 85 km north-south and 42 km east-west in its widest part. The highest point is the Vihren peak (2914 m, a peak of the Pirin Mountain) and the lowest is the level of the river at the exit from the Bulgarian territory - 393 m a. s. l.

Approximately 25 larger and higher stream flows of 1st and 2nd order feed the Mesta River. In the high mountain belt of Rila and Pirin (over 2100 m a. s. l.), glacier lakes are formed at the bottom of the cirques. Their sizes are quite small and insignificant. The largest lake is called the Popovo Lake (12,4 ha) and it is located in the Pirin Mountains.

The main basin of the Mesta River includes a total of 28 small catchments. Their areas range from 25 to 504 km2 and the average area is 99,5 km2.

The study area is geologically made up of heterogeneous metamorphic, magmatic and sedimentary rock formations of different ages. The mountain part of the basin is composed mainly of magma and metamorphic rocks, represented by various species of gneisses, gneiss-schist's, marbles, amphibolite's and others. The Magnum granite plutons of Paleozoic and Upper Cretaceous-Paleogene age occupy vast areas in the Mesta valley and build the heart of the highest mountains Rila and Pirin and the Western Rhodopes as well.

During the Paleogene, more specifically in the Oligocene era, an intensive volcanic activity takes place in this area; as a result, the famous volcanic area of the Mesta river valley was formed. Furthermore, during the Paleogene and Neogene periods, deep breaks and intense, differentiated tectonic movements on the local subdermal zone give rise to the Tertiary Razlog and the Gotse Delchev valleys. They are filled with Neogene and Quaternary sedimentary rocks such as clay, gravels, boulders, sands and conglomerates.

The study area is characterized by some transitional features, between the temperate and Mediterranean climates, which are heavily influenced by relief and altitude. The average annual temperatures fluctuate from 11,5° to minus 2°. The coldest month is January with temperatures ranging from 0 to minus 10°, and the warmest month is July with temperatures going from 22 to 6°. In the mountains, there is a tendency to shift the minimum temperature in February and the maximum in August. Temperature inversions are generally observed in the valleys.

The amount of precipitation depends on the altitude and the sun exposure. A shadow of rain is usually observed in the valleys. The annual rainfall varies from 600 mm in the Razlog valley to 1300 mm in the Pirin Mountains. The maximum precipitation is measured in November-December for the south part of the basin and in May-June for the north part. The minimum rainfall is recorded in August and September. A thick snow cover is formed in the mountains; in Rila and Pirin, it usually lasts for 7 - 8 months.

The river has a mixed nutrition. It is distinguished by a high-stream spring flow (in March-June) and by a low-stream summer-early-autumn flow (in August-October). The average annual runoff in the town of Hadzhidimovo is 41,5m3/s and the average runoff flow rate is about 15 l/s/km2.

Figure 1. Location map of Mesta basin

4. RESULTS AND DISCUSSION

In this research we obtained the following characteristics summarized in Table 2.

Table 2. Calculated characteristics for the Mesta River catchment

Characteristics of the main catchment area of Mesta River	Characteristics for 28 composite catchments
✓ Flow Direction	✓ Basin Area, km^2
✓ Stream Order	✓ Basin Perimeter, km
✓ Drainage density(*Kernel drainage density and Potential drainage density*)	✓ Maximum, minimum and mean Height of the Catchments, m
✓ Hillslope Erosion Potential	✓ Summary Channels length, km
✓ Standard deviation of elevation	✓ Maximum and mean Slope of the Catchments, degree
✓ Slope variability	✓ Orientation of the Catchments
✓ Terrain Ruggedness Index (Riley et al, 1999)	✓ Form Factor
✓ Standard deviation of slope	✓ Elevation Relief Ratio
✓ Topographic Wetness Index	✓ Drainage density
✓ Potential erosion coefficient	✓ Basin-scale ruggedness
✓ Surface runoff	✓ Melton ruggedness number (Melton, 1965)

As illustrated in the above table, we distinguished two types of features. One the one hand, using the method of cartographic algebra and focal statistics, we obtained the characteristics of the main catchment area of Mesta River. They are represented by a GRID model and are illustrated in figures 2, 3, 5, 6, 7 above. One the other hand, we used a spatial analysis of vector data to calculate the characteristics related to the 28 composite catchments of the Mesta River. They are available on an interactive map http://gis.swu.bg/MappetizerMESTA.

In the following section, we focus on the presentation of our main results.

First, we will discuss the Kernel density (Figure 2).The thematic map presented on Figure 2 is developed with the spatial tool available in ArcGIS for Kernel density that gives more detailed presentation of one of the main basin parameter - not only in the final values (from 0.50 to 2.9 km/km2) but also in its spatial distribution. This indicator can be used for detailed geomorphological studies of the intensity of erosion processes combined with a characteristic of topographical slope, lithological basis and rainfall, soil and vegetation cover.

Second, we will consider the Slope variability (Figure 3). The slope variability of the Mesta River indicates crucial differences in the values – from 0 to 68°. The highest values are in the high parts of the North Pirin and high in the deep-buried rivers Kanina, Satovchanska Bistritsa, Momina klisura Gorge of Mesta, and also at the base of the discontinuous slopes of Pirin, where this indicator changes sharply. The lowest values are in the Razlog and Gotse Delchev kettles, especially in the even Gotse Delchev field. In the other regions this indicator has average values – about 23-30°. These comparatively low values in the Rhodopes constitute a striking particularity of the basic territory.

Third, we talk about the Melton ruggedness number (Melton, 1965). This indicator determines the differences in elevation of the catchment area relative to its area (Figure 4). The obtained values have some peculiarities. Watersheds that have a significant difference in their topographic surface; have the same coefficient value - e.g. the Glazne River and the Dabnishka River - 0,20. This shows that the coefficient is too dependent on the area of the respective catchment area - those with a smaller area (which is in the denominator) (Glazne River - 118 km2, Dabnishka River - 28 km2) show higher values. On other morphometric indicators, the mentioned above two catchments have the following characteristics - mean slope - Glazne 18,4°, Dabnishka - 15,7°, maximum - 65,2° and 44,2° respectively. This coefficient can be used successfully for catchment areas having similar surfaces.

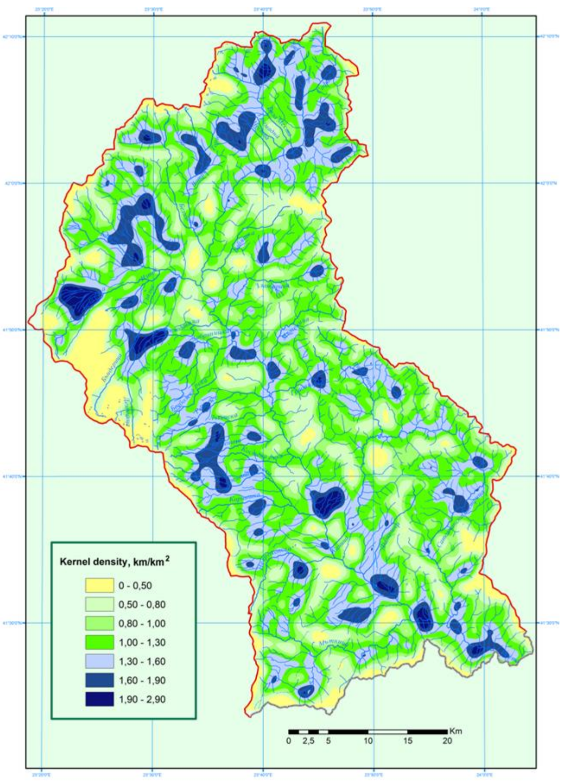

Figure 2. Kernel density

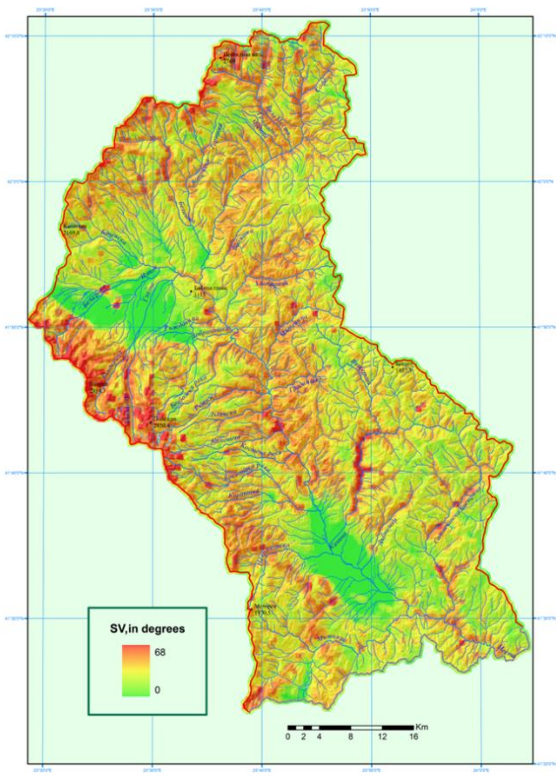

Figure 3. Slope variability

Fourth, we will deal with the Terrain Ruggedness Index (Riley et al, 1999). It provides a quick and easy way to calculate a topographic roughness ratio using DEM (Figure 5). For each cell of the GRID model, the difference in altitude between the central cell and the other eight surrounding it is calculated. The obtained coefficient is suitable for analysis and mapping of the spread of habitats in large areas where DEM errors do not affect the biologic interpretation of the data. This map better represents the strong differentiation of the basin roughness of Mesta River. Terrain Ruggedness Index highest values are given by the sharp ridges and the slopes of the steep and deeply incised cirques of the North Pirin. The smallest values are in Razlog and Gotse Delchev kettles. It is also well differentiated and the wide ridges typical for Rhodopes and Southeastern Rila, where the index has smaller values.

Fifth, we will discuss the Topographic Wetness Index (TWI) (Beven and Kirkby, 1979). Relief is an important factor in the formation of hydrological processes. It influences soil moisture, but indirectly also soil pH (Högberg et al, 1990; Giesler et al, 1998). Soil moisture and pH are important variables that affect the distribution and species diversity of higher plants. One of the ways to quantify the degree of soil moisture is the Topographic Wetness Index (TWI). This index was developed by Beven and Kirkby (1979) and it serves to model the spatial distribution of soil moisture and surface saturation. It is a hydrological index that depends of the area and slope of the catchment. Territories with high values in this index are zones that will be moistened most quickly in the rain. TWI expresses the effect of relief on surface runoff and serves as a physical-based index, equating the locations of areas with surface humidification and spatial distribution of water in the soil. (Beven and Kirkby, 1979; O'Loughlin, 1986; Barling et al, 1994). Areas that have similar TWI values are assumed to have similar hydrological characteristics in rainfall as well as other natural components such as vegetation, soils and rocks being the same or at least similar. TWT is a widely used index and finds practical application in agriculture. (Qin et al, 2011). The thematic map (Figure 6) reveals areas with differences of soil moisture. According to the accepted five-degree scale, the regions with insignificant humidity coincide with the watershed ridges and peaks, especially those from the North Pirin, which are clearly differentiated and outlined. Areas with strong humidity are the floodplains of the Mesta River and its larger tributaries. It is very humid in the low and plane parts of the Razlog and Gotse Delchev kettles. This especially applies to the latter, whose central field and the slope of the topographic surface is practically zero.

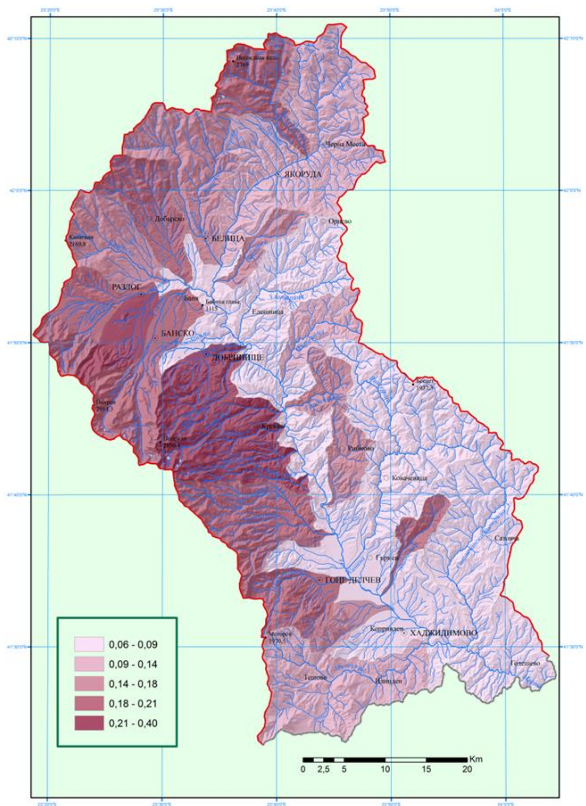

Figure 4. Melton ruggedness number (Melton, 1965)

Figure. 5. Terrain Ruggedness Index (Riley et al, 1999)

Sixth, we will mention the Hillslope erosion potential index (Flint 2003). This is the average annual rainfall (Climate Directory 1990) multiplied by the slope of each DEM cell. This is a coefficient that reveals the spatial differences in erosion, but the obtained values are relative and do not present the magnitude of the actual earth / rock erosion. A five-step scale is introduced that reflects the degree of potential erosion. The resulting model (Figure 7) reveals an expressive difference in the index, due to the change in slope and the amount of precipitation. The maximum values are in the high alpine part of the North Pirin and then they are clearly outlined, followed by its values on the steep circular walls of Rila. This index is also relatively high in the steep slopes of the Mesta River at Momina Klisura, the Belishka River in the Stenitsite locality, the Kanina River and the Satovchanska Bistritsa River. This approach for determining the potential erosion index allows the determination of actual erosion by including in the analysis of the soil cover, geological structure and nature of the vegetation. Potential erosion coefficient may be an indicator for the determination of landslides and collapsing processes, glacier, etc.

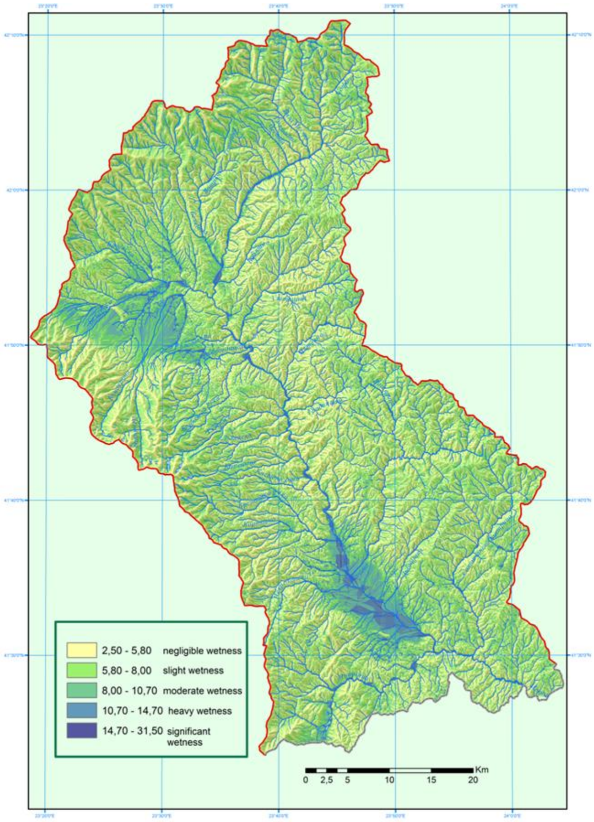

Figure 6. Topographic Wetness Index (TWI)

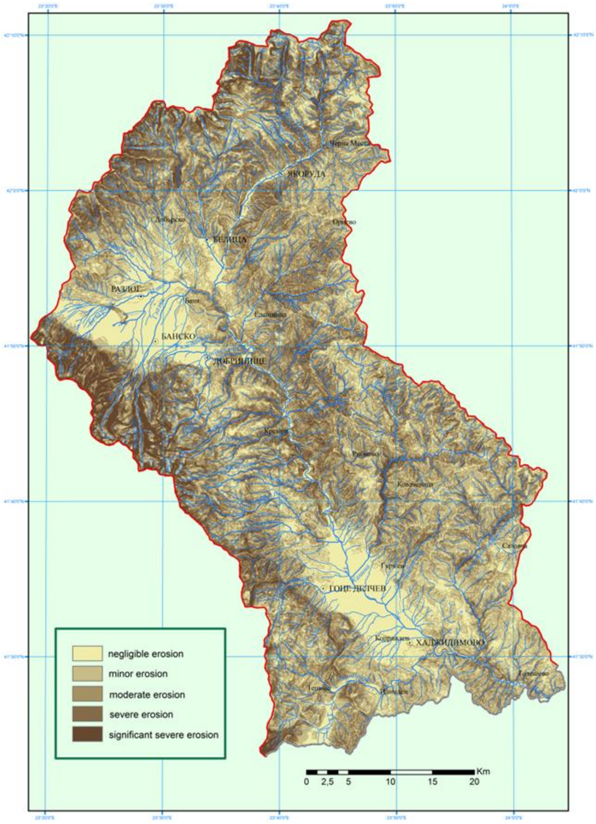

Figure 7. Hillslope erosion potential index (Flint, 2003)

5. CONCLUSION

This study focuses on the application of GIS technology to determine the characteristics of the Mesta River basin. An own database of more than 20 calculated features has been created. Recent research in this area, applicable to GIS analysis, has been used.

The approach we used to modeling hydro-morphometric characteristics can be successfully applied to mountain catchments, which are distinguished by the great differentiation of all natural components.

The complex mountain relief of the Mesta river basin determines the complex of factors that form the hydrological characteristics of the river and its tributaries. Therefore, even within a small catchment area, large differences in the number of geomorphological and hydrological indicators, such as slope gradient, degree of erosion, terrain wetness's, etc., can be identified.

From the presented maps, we can conclude that none of the traditional methods used in cartography to date can provide such a good visualization and detailed information as the GRID models. The application of focal statistics and cartographic algebra enables a detailed characterization of the geomorphological and hydrological features of the basin.

The advantage of this detailed modeling and mapping is that it can be applied to distinguish fault zones, areas of intense erosion, contemporary external relief formation processes like landslides and massive rock fall, potential flood areas, etc. The obtained results can support the basin management process.

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