Fractal drainage model – a new approach to determinate the complexity of watershed

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This study uses fractal analysis to make a fractal drainage model, a new way to determinate the complexity of watershed. The drainage model is a graphical representation considering the logarithmic scale of the number, length and average length of the river segments of a different order. The drainage model of Jijila watershed was based on classifications elaborated by Strahler and Zăvoianu using fractal analysis.

This morphometric model allows the observation of qualitative and quantitative inter-determination of the watershed. The fractal analysis of river segments reflects the over-execution of the Jijila watershed due to the elongated development of the watershed, asymmetry, low average gradient. Hence, the Jijila watershed should have more of 2nd and 3rd order river segments.

The morphometric analysis was made in the watershed Jijila, a small river in the South-East Romania, Dobrogea, from Măcinului Mountains. The fractal analysis of the fractal drainage model was made using topographic maps of 1:50000 scale, geological map of 1:200000 scale and field trips. The Image J 1.51 software for image processing and Benoit software to determinate the fractal dimension box-counting of the river`s watershed were used. Our research confirms the hypothesis that the fractal drainage model confirms over-realization of the Jijila watershed, and it may be further successfully used.

This model has the big advantage that it does not require measurements of number, length and the average length of river segments, preventing errors that may be introduced by the determination of lengths and average lengths.

Keywords: *fractal analysis; drainage model; morphometric patterns; hydrographic network; box-counting; geometric progressions.*

Introduction

The drainage model is a graphical representation with logarithmic scales for the number, length and average length of the river segments of various orders. With this model, qualitative and quantitative descriptions of watersheds are possible (Zăvoianu, 1985). Hydrological analysis and geomorphological processes from watershed lead to morphometric characterizations to obtain new information about the apparition and development of hydrographic network and geomorphological processes (Singh, 1992, 1995).

Important morphometric research work was performed (Horton, 1945; Strahler, 1952, 1957, 1958, 1964; Schumm, 1956; Hack, 1957; Melton, 1958; Morisawa, 1962; Chorley and Haggett, 1967; Chorley and Kennedy 1971). Other surveys that solved hydrometrical issues used morphometric indices to solve limnology problems and investigate territorial hydrologic regionalization (Moraru and Savu, 1954; Diaconu and Șerban, 1994; Gavrilă et al., 2011; Andronache et al., 2015; Ciobotaru, 2015, Blistanova, 2015).

The fractal analysis was used in geographical studies related to deforestation and evolution of forests in Romania (Andronache et al., 2016a,b; Petrișor et al., 2016; Diaconu, 2016; Pintilii et al., 2016).

The assessment of drainage models and the management of water resources are represented by the use of the Geographic Information System (GIS) (Gavrilă et al., 2011; Valjarević et al., 2015; Kršák, 2016), and by the use of fractal analysis (Andronache et al., 2016; Ciobotaru, 2015).

A fractal is a rough or fragmented geometric shape that can be split into parts, each of which is (at least approximately) a copy of the whole reduced in size (Mandelbrot, 1982). The fractal dimension is a measure of complexity, of the extent to which the fractal "fills" space, quantifying the degree of irregularity and

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fragmentation of a geometrical structure or of a natural object. Usually, its actual value is higher than the topological dimension. Based on Gray equation (Gray, 1961), B. Mandelbrot indicated that rivers have a fractal dimension of 1.2 (Tarboton et al., 1988). Models subsequently designed by B. Mandelbrot highlighted the fractal nature of rivers (Tarboton et al., 1988). Based on B. Mandelbrot's contributions (Mandelbrot, 1982, 1977), many researchers applied fractal analysis in river surveys, such as (Andronache et al., 2015; Hjelmfelt, 1988; La Barbera and Rosso, 1989; Tarboton et al., 1990; Veltri et al,. 1996).

In this study, our purpose is to perform fractal analysis of the drainage system for the Jijila watershed based on classifications elaborated by Strahler and Zăvoianu.

Materials and Methods

Data analysis

Topographic maps of 1:50000 scale were used to collect data for watershed and altimetry elevations. Tulcea sheet L-35-XXIX, 1967, a topographic map of 1:200000 scale was used to collect the type and age of rocks. ASTER GDEM with 30 m spatial resolution of terrain data was used as the basis of the digital relief model (Ciobotaru, 2015).

Experimental design

Based on topographic, geological and landslide maps, a drainage model and fractal analysis could be elaborated for the Jijila watershed.

After extraction of topographic contours and generation of a binary image, the number, length, and average length were measured using ImageJ 1.51i software (Schneider et al., 2012). Fractal dimensions were computed using Benoit 1.31 software (TruSoft, 1999).

The watershed had been previously classified using the Strahler system (Fig. 1). This classification system allows a good evaluation of the order of a water course, and also allows the possibility for statistical processing of data achieved on value classes, as well as for elaboration of cross-referenced studies.

According to the Strahler classification system, springs are considered 1storder. The 2nd order occurs as a qualitative leap, as a consequence of confluence of two 1st order river segments. The 3rd order occurs following the confluence of two 2nd order river segments and so on. A higher order segment (4) receives a tributary of a lower order (1, 2 or 3), without a qualitative lap, it maintains its order (4).

In the Jijila watershed, 209 river segments were identified (with a distribution of 4.41 river segments /km^2), of which: 163 1st order river segments, 36 2nd order river segments, 9 3rd order river segments and 1 4th order river segment. We can see, especially for 1st and 2nd order segments, that most river segments are located on the right bank, where pediments are extended on a smaller surface.

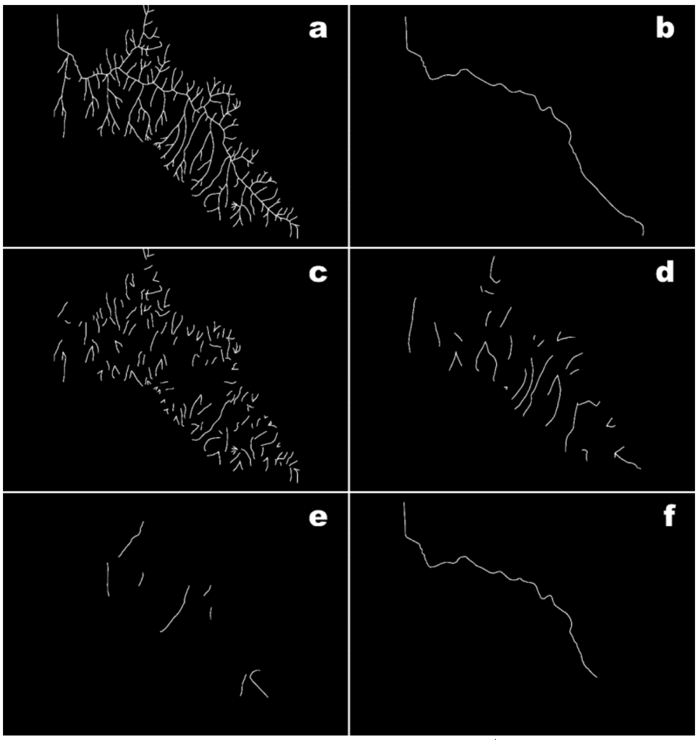


Fig. 1. Jijila watershed – Strahler classification: a. watershed; b. Jijila Valley; c. 1st order river segments; d. 2nd order river segments; e. 3rd order river segments; f. 4th order river segment.

Following equations were used for the drainage model:

$$R_c = \frac{\left[\left(\frac{N_{m1}}{N_{m2}}\right)+\left(\frac{N_{m2}}{N_{m3}}\right)+\left(\frac{N_{m3}}{N_{m4}}\right)\right]\times[(N_{m1}+N_{m2})+(N_{m2}+N_{m3})(N_{m3}+N_{m4})]}{(N_{m1}+N_{m2})+(N_{m2}+N_{m3})(N_{m3}+N_{m4})} \quad (1)$$

$$N_{ci} = \frac{N_{m3}}{R_c^{i-3}},\ i = 1,2,3,4 \quad (2)$$

$$R_L = \frac{\left[\left(\frac{L_{m1}}{L_{m2}}\right)+\left(\frac{L_{m2}}{L_{m3}}\right)+\left(\frac{L_{m3}}{L_{m4}}\right)\right]\times[(L_{m1}+L_{m2})+(L_{m2}+L_{m3})(L_{m3}+L_{m4})]}{(L_{m1}+L_{m2})+(L_{m2}+L_{m3})(L_{m3}+L_{m4})} \quad (3)$$

$$L_{ci} = \frac{L_{m3}}{R_L^{i-3}},\ i = 1,2,3,4 \quad (4)$$

$$R_l = \frac{\left[\left(\frac{l_{m1}}{l_{m2}}\right)+\left(\frac{l_{m2}}{l_{m3}}\right)+\left(\frac{l_{m3}}{l_{m4}}\right)\right]\times[(l_{m1}+l_{m2})+(l_{m2}+l_{m3})(l_{m3}+l_{m4})]}{(l_{m1}+l_{m2})+(l_{m2}+l_{m3})(l_{m3}+l_{m4})} \quad (5)$$

$$l_{ci} = \frac{l_{m3}}{R_l^{i-3}},\ i = 1,2,3,4 \quad (6)$$

where *m* are measured (real) values, *c* is calculated (using ratio obtained through weighted arithmetic mean), $\mathbf{R_c}$ is the river segment ratio; $\mathbf{R_L}$ is the river segment length ratio; $\mathbf{R_l}$ is the river segment average length ratio; $\mathbf{N_1}$is the number of 1st order river segments I; $\mathbf{N_2}$ is the number of 2nd order river segments; $\mathbf{N_3}$ is the number of 3rd order segments; $\mathbf{N_4}$ is the number of 4th order river segments; $\mathbf{L_1}$ is the sum of length of 1st order river segments; $\mathbf{L_2}$ is the sum of length of 2nd order river segments; $\mathbf{L_3}$ is the sum of length of 3rd order river segments; $\mathbf{L_4}$ is the length of 4th order river segments; $\mathbf{l_1}$ is the sum of average length of 1st order river segments; $\mathbf{l_2}$ is the sum of average length of 2nd order river segments; $\mathbf{l_3}$ is the sum of average length of 3rd order river segments; $\mathbf{l_4}$ is the sum of average length of 4th order river segments.

As a new approach, we propose a fractal analysis model for river segments of different orders. Box-counting was selected as the method to determine the fractal dimension. The box-counting dimension consists of counting the number of cells N(ε) required to cover the structure, depending on the size ε of these cells. Then these values are represented by logarithmic coordinates logN = f(log ε). The slope of a linear regression is an estimate of the fractal dimension. The mathematic equation is:

$$DB = lim_{\varepsilon\to 0}\left(\frac{log\ N(\varepsilon)}{log\frac{1}{\varepsilon}}\right) \quad (7)$$

Where DB is the box-counting fractal dimension, ε is the size of the box, and N(ε) is the number of adjacent boxes that do not overlap on the ε edge and are required to cover the area of the fractal object (Russel et al., 1980; Di Leva et al., 2007).

As the zero limit cannot be applied to digital images, DB is estimated by the formula:

$$DB = d, \quad (8)$$

where *d* is the log[$N(\varepsilon)$] gradient to $log\frac{1}{\varepsilon}$ [41].

For river segments, the box-counting dimension may have values between 1 and 2 (approximately 1 when the river segments are perfectly linear and approximately 2 when they are extremely sinuous, approaching the shape of a Hilbert curve).

The box-counting method is also adequate in the case of bi-dimensional, heterogeneous and irregular structures, where other methods usually face great difficulties to determine the fractal dimension.

The box-counting method is not only capable of determining the fractal dimension, but it also allows discrimination of possible scaling methods, gradient changes, corresponding to different scaling properties, for different scale ranges.

Based on fractal dimensions, we propose a new morphometric model: the fractal drainage model.

$$R_{FD} = \frac{\left[\left(\frac{DB_{m1}}{DB_{m2}}\right)+\left(\frac{DB_{m2}}{DB_{m3}}\right)+\left(\frac{DB_{m3}}{DB_{m4}}\right)\right]\times[(DB_{m1}+DB_{m2})+(DB_{m2}+DB_{m3})(DB_{m3}+DB_{m4})]}{(DB_{m1}+DB_{m2})+(DB_{m2}+DB_{m3})(DB_{m3}+DB_{m4})} \quad (9)$$

$$FD_{ci} = \frac{DB_{m3}}{R_{FD}^{i-3}},\ i = 1,2,3,4 \quad (10)$$

m are measured (real) values, *c* is calculated (using ratio obtained through weighted arithmetic mean), $\mathbf{R_{FD}}$ is the ratio of fractal dimensions of river segments and $\mathbf{FD_i}$ are the fractal dimensions of the ith order river segments.

Study area

Jijila River is part of the small Northern Dobrogea waters and streams from Măcin Mountains (from 300 m elevation), north-west from Greci Peak. It separates Măcin Mountains – Chițău Hill - Ciclăiași Hill – Văcăreni Hill from Pricopanu Crest – Sărăriei Hill – Orliga Hill. Jijila Lake located in Danube's flood plain (Romanescu and Cojocaru, 2010; Romanescu et al., 2013; Romanescu et al., 2014) (Fig. 2).

The Jijila watershed expands on a surface of 47.426 km^2, showing a moderate left side asymmetry. The asymmetry coefficient is 0.38, being higher in upper and middle courses. The surface of the left bank watershed is 28.238 km^{2,} and the surface of the right bank is 19.188 km^2.

This river usually has low flow rates with multi-annual average values reaching approximately 0.5 m^3/s, but with occasional fast flash floods with high erosional potential.

The watershed shows a high sinuosity coefficient (1.62), dictated by the elongated configuration and an average height of 176.3 m (indicating an intensely eroded landscape, pediment inselberg type). There is a small differentiation between the two components. The highest elevation on the left bank (208.12 m) is determined mainly by the presence of sharp inselbergs, generated on hard rocks, while the right bank (144.5 m) is dominated by rounded or domed inselbergs.

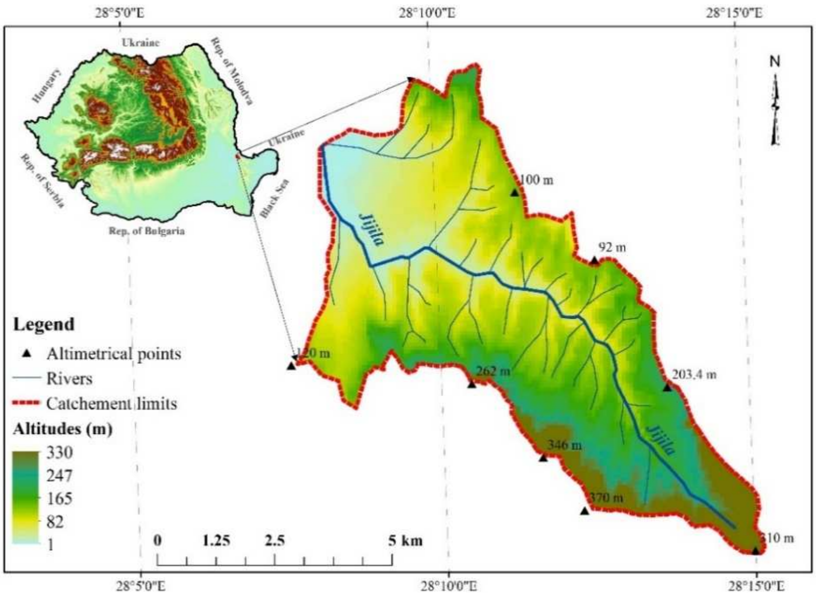


Fig. 2. Geographical position of the Jijila catchment area.

The Jijila catchment area overlaps with the North-Dobrogea Orogen (Pricopanu Crest – Măcin Mountains) and with the Danube's flood plain area. Lithologically, it overlaps with the Măcin nappe (made of gneiss, granite, granodiorite, amphibolite, quartzite, phyllite and quarzitic slate), partially drowned in loessoid deposits and quaternary loess (Ionesi, 1992). Apart from loess, there are also other quaternary deposits such as eluvia (on erosion stacks), diluvia, colluviums, proluviums (on slopes) and alluviums (in Danube flood plain) (Fig. 3).

The landscape generated by hercynian orogen was eroded starting in the Mesozoic, and thus it was gradually transformed into a plain that cut through its basal section, where the system of (very tight and faulted) folds and magmatic bodies appeared under the shape of almost parallel strips with NW-SE orientation. Pliocene neotectonic impulses slightly elevated this region, which was subject to a novel reformation exercised differently depending on rock strength. The most erosion-sensitive rock alignments were sedimentary strips and fracture lines, and valleys and depressions were formed along them. Interfluves remained between them, on hard rock's (granite, quartzite, crystalline slates) (Jacko et al., 2016). Modelling in a semi-arid climate favored sedimentation, leading to the formation of a specific Appalachian landscape, characterized by distinct litho-structural shapes.

The largest part of valleys fragmenting of Măcin Mountains is displayed longitudinally to the structure (Jijila, Luncavița), with the exception of Greci valley (SW from the homonymous locality) and Cerna valley which intersects transversally hercynian structures and tectonic dislocations.

The average density of fragmentation of the Jijila watershed is 2,089 km/km^2, the minimum value being 0 km/km^2 (Jijila pediment), and the maximum value 4,8 km/km^2 (Văcăreni Hill).

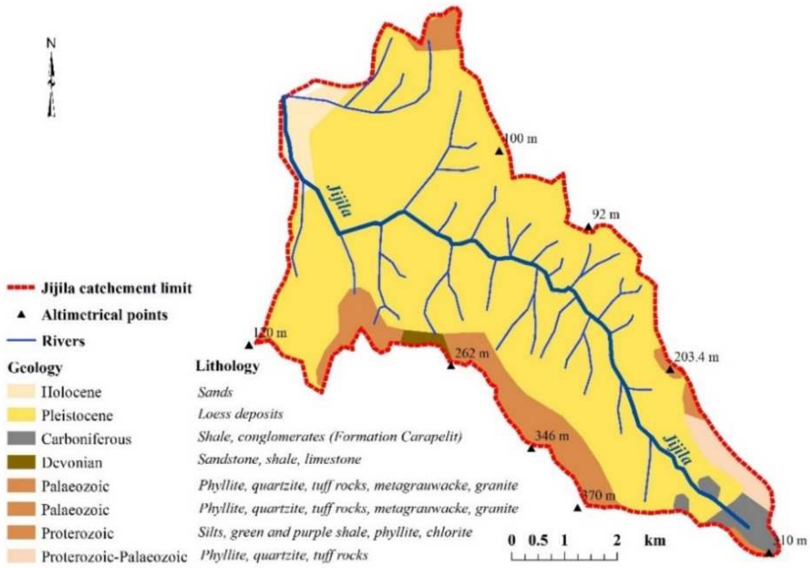
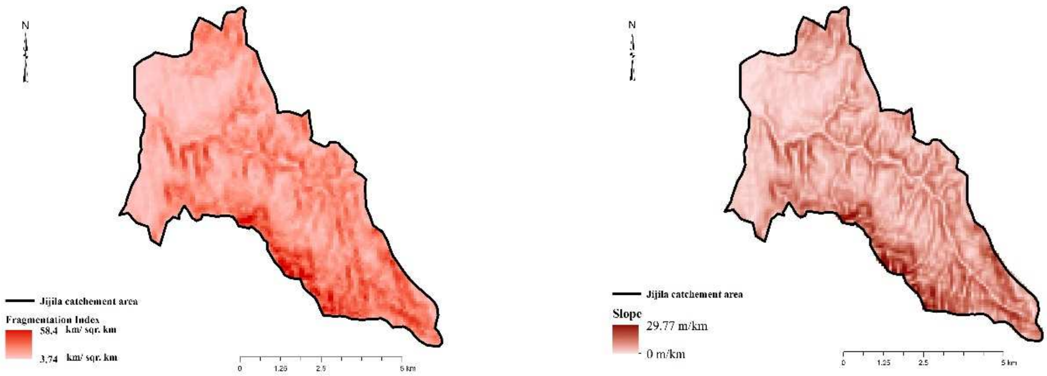


Fig. 3. Geology and lithology of the Jijila catchment area.

Groundwater in this area may be found at the bottom of a quaternary deposits layer, displayed on loessoid deposits with scree, formed at the bottom of slopes or on valleys due to disaggregation of base rock. Water courses running on valley bottoms are supplied from this groundwater. The phreatic surface is located at 0.5-2.5 m in Danube's flood plain and more than 7-10 m in a hilly area.

The highest elevation on the Jijila watershed is 370.3 m, and it is located in the southern area, on Pricopanu Hill, which is made of granites. From a hypsometric standpoint, more than 2/3 of the watershed surface are represented by the altimetry range of 0-100 m (of which approximately half is the altimetry range of 0-50 m), made of pediments and deluvial stripes. The altimetry range of 100-200 m corresponds to a higher erosion level, where erosion stacks were maintained, such as Văcăreni Hill (167.5 m) and Cornetu Hill (114.9 m). Elevations higher than 200 m are found in the S and SE regions of the watershed, being related to the granites and crystalline rocks located at the surface of Cheia Mountains (259.7 m), Pricopanu Hill (370.3 m) and Ciclăiași Hill (203.4 m).

The relief energy of Jijila Valley is 309.2 m, the elevation of the spring is 309.6 m and the elevation of the discharge point (Jijila Lake – Danube floodplain) is 0.4 m. The average relief energy is 63.068 m, the minimum value is 1.5 m in Jijila Pediment, and the maximum elevation is 188.5 m on Cheia Mountains. 55 % of the watershed surface shows low values of the relief energy, between 0-50 m, 40 % average values, ranging between 50-150 m, while only 5 % are high values above 150 m.



a) *b)*

Fig. 4. a) Fragmentation Index map and b) Slope map of the Jijila watershed.

Correlative analysis between landscape fragmentation density and relief energy density shows a moderate connection. 18 % of the paired values analyzed showed a strong connection, a strict dependency, the others representing whether indirect determinations or inexistent correlations. (Fig. 4a and 4b).

The Jijila watershed, located in an intensely, subaerially modeled region, shows low inclination slopes, in average 5 to 6^0. The lowest gradients are found in the flood plain, elluvial surfaces and pediments ($0\text{-}5^0$), followed by torrential watersheds and suffusion basins and by the deluvial stripe ($5\text{-}15^0$), and steeper gradients are found in sharp inselbergs ($15\text{-}25^0$). The average gradient of the Jijila Valley thalweg is reduced ($1^0 13^{'}$), being developed mainly in the pediment sector. Correlation between the average thalweg gradient with slope gradients reveals a thalweg erosion trend, imposed by the general layout of the watershed (Bobal et al., 2010).

In this survey, we propose a new model of analysis of the degree of execution of a watershed: the fractal drainage model, which shall add to the traditional morphometric models used until now.

Results and Comments

Using binary images (Fig. 1), measurements of number, length, average length and fractal dimension of river segments were carried out based on Strahler classification. Subsequently, using the weighted average (Eq. 1-6 and 9-10), the calculated values of these parameters were achieved. Results are shown in Table 1.

Tab. 1. Parameters of river segments.

Parameter		Order				Ratio
		i=1	i=2	i=3	i=4	
Number of river segments N_i	**Measured**	163	36	9	1	R_C **4.61**
	Calculated	191.3	41.5	9	1.95	
Summed length of river segments L_i	**Measured**	68.131	29.38	8.79	12.493	R_L **2.35**
	Calculated	48.494	20.646	8.79	3.742	
Average summed length of river segments $I_,$	**Measured**	0.418	0.816	0.977	12.493	R_l **0.19**
	Calculated	0.036	0.188	0.977	5.062	
Fractal dimension FD_i	**Measured**	1.25	1.16	1.10	1.12	R_{FD} **1.04**
	Calculated	1.19	1.14	1.10	1.06	

Drainage model

Distribution of river segments (N) of various orders is achieved based on a descending geometric progression (163 1^{st} order river segments, 36 2^{nd} order river segments, 9 3^{rd} order river segments and 1 4^{th} order river segment), with a ratio of 4.61. The determination of this ratio allowed the calculation of the normal value of a standard geometric progression. In conditions of a standard geometric progression, the 4^{th}order river segment should be improper, at 1.95. This reflects the over-realization of the Jijila watershed, which in normal conditions (without constraints imposed by existing physical-geographical conditions) should be of 5^{th}order.

The length of river segments (L) of different orders is 118.79 km. The drainage density (D = L/S; where D is the drainage density, L is the length of hydrographic network and S is the surface) is 2.5 km/km^2. The general average length of river segments is 0.73 km/segment. With regard to the distribution of summed lengths of river segments of different orders, we can note the existence of a descending geometric progression, excepting the sum of 3^{rd}order segments, with a ratio of 2.35. In conditions of a standard geometric progression, the length of 4^{th}order river segment should have been only 3.74 km, 8.75 km less than the actual length. Thus we may note a very high value of the measured 4^{th}order river segment of 49 km, which was formed in the middle course and which accounts for 74.19 % of the total length of Jijila Valley. This was possible due to dominant development in loessoid structures and pediments of the watershed.

The average length of river segments (l) of different orders is 14.71 km, and it represents the ratio between the sum of summed lengths (L) and the number (N) of river segments of different orders. Distribution of summed average lengths is based on an increasing geometric progression, with a ratio of 0.19. In conditions of a standard geometric progression, the average length of 4^{th}order river segment should be 5.06 km, 7.43 km less than the actual length.

The determination of the ratio allowed calculation of the normal value of a standard geometric progression for each parameter.

Based on these three parameters, the morphometric drainage model was elaborated using Microsoft Excel 2007 (Fig. 5).

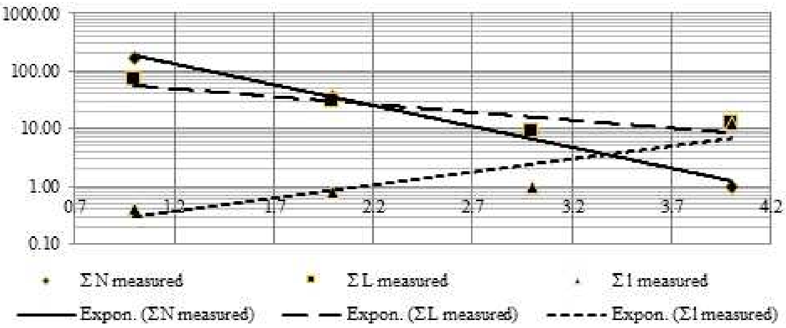


Fig. 5. Drainage model of Jijila watershed.

Analysis of this model reveals the following:

- The degree of realization of the watershed is displayed graphically at the intersection of the line of summed lengths with the line of summed average lengths, and it is 110 % (the point of intersection of these lines corresponds to an abscissa value of 4.1), showing over-realization.
- The calculated value of the river segment of the highest value (IV) is improper, amounting to 1.95, showing over-realization of the watershed. At a confluence ratio R_c = 4.61, this proves the presence of a relative balance within the entire watershed.
- Except for the 4th order segment, the other segments follow - somehow strictly - a geometric progression, thus supporting a relatively uniform evolution of the landscape.
- The measured value of summed lengths of 3rd order river segments is less than the 4th order segment length, due to poor development determined mainly by the landscape configuration (predominant pediments) and lithology (predominant loessoid deposits, that favor infiltration of waters to the detriment of surface runoff, determining very rarely formation of 3rd order river segments). With regard to the 4th order river segment, we may see that the calculated length and the average length are lower than the measured values, showcasing the over-sizing which supports an over-realization of the Jijila watershed. If the watershed had been executed, the length of a 4th order river segment would have been 3.74 km and not 12.49 km, which is the actual value.

Fractal drainage model

Fractal analysis of the 1st, 2nd, 3rd and 4th order river segments reflects, similar to the drainage model, over-realization of the Jijila watershed.

The fractal dimension of the 1st, 2nd and 3rd order river segments show the natural descending trend of fractal dimension with the increase in the order of river segments (the higher the order, the lower the number of segments and implicitly the summed length of these segments).

Exception from this rule is the case of Jijila watershed, the 4th order river segment, which has a fractal dimension higher than the summed fractal dimensions of the 3rd order river segments, thus reflecting over-realization of the watershed. The lower fractal dimension of the 3rd order river segments (1.10) compared to the 4th order river segments (1.12) are due both to a lower summed length and also to a lower sinuosity of 3rd order river segments. In the case of an executed watershed, which follows the geometric progression, the fractal dimension of 3rd order segments would be higher than the 4th order segments (1.10 vs. 1.06) (Fig. 6).

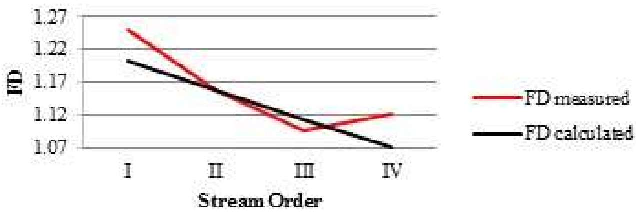


Fig. 6. Fractal drainage model of Jijila watershed.

The fractal dimension of Jijila Valley (Fig. 1f) is 1.22, and the fractal dimension of Jijila watershed (Fig. 1a) is 1.42 (including here all river segments, disregarding their order). Both situations reflect relative uniform physical-geographical conditions where Jijila watershed was formed and developed.

Our research confirms the hypothesis that the fractal drainage model confirms over-realization of the Jijila watershed, and it may be urfurther successfully used. This model has the big advantage that it does not require measurements of number, length and average length of river segments, preventing errors that may be introduced by the determination of lengths and average lengths.

Further research is needed both for other watersheds and for the Jijila watershed, but in progressive stages, in order to determine whether this model may be used for the determination of the evolution of the realization degree.

Conclusions

In order to be executed, the Jijila watershed should have more of 2nd and 3rd order river segments and at least two 4th order river segments and one 5th order segment. However, the specific physical-geographical segments where Jijila watershed was formed and developed did not allow such evolution.

Analysis of drainage model and fractal dimension reveals that the Jijila watershed is over-executed. This is mainly due to:

- Elongated development of the watershed, favoring development of lower order river segments (1 and 2);
- Watershed asymmetry (asymmetry coefficient of 0.38);
- Low average gradient ($5\text{-}6^0$);
- Predominance of pediments to the detriment of inselbergs;
- Lithology (predominance of loessoid deposits), that favor water infiltration, obstructing the formation of 3rd order river segments (3rd order river segments spring from inselbergs area, where diurnal rock surfaces, favoring surface runoff and implicitly a higher drainage density).

For a thorough analysis of the degree of realization of Jijila watershed, another morphometric models are required as follows: the surface model, the perimeter model, the elevation difference model, the average gradient model and the average elevation model.

In conclusion, the fractal analysis may be a viable, quickly and versatile model for assessment of the degree of realization of a watershed, and results achieved may be correlated with results generated by analysis of morphometric models for an accurate evaluation.

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