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THE LAW OF THE ORDER OF WATERSHEDS

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ABSTRACT. – The Law of the Order of Watersheds. In fluvial geomorphology studies that aim at deciphering the evolution of landforms, apart from the identification of the order of streams, it is also very useful to know the order of the watersheds. The main purpose of this paper is to formulate the law of the order of watersheds. It also checks if the stream order and the nearby watershed order have the same value. In order to highlight this, a methodology has been established in order to formulate the above-mentioned law. As a starting point, we used the order of the streams law, in Horton-Strahler system, in the form used by Zăvoianu in 1978. An analogy between them was established, in the sense that the node rate or the watereshed intersection rate was used instead of the confluence rate, because watersheds do not form a confluence, but gather into orographic nodes. In order to verify this law, 12 watershed models have been selected from the autochtonous drainage systems, representative for the Transylvanian Basin. The acquired results demonstrate on one hand that the law is valid, and on the other hand that it is not necessary that streams and bordering watersheds have the same order. This fact is possible because the difference between the order of a major watershed and of the bordering main streams also presents variations. In most of the cases, the order of the watershed is higher than the one of the neighbouring streams. The difference recorded in these cases increases as the number of lower order streams do not form confluences, in order to increase the drainage system order, but they flow directly into an upper order mainstem, whose order cannot be increased.

Keywords: *watershed, node rate, order, drainage network.*

1. OBJECTIVES

As a result of the fluvial evolution of different territories, a complementarity between drainage network and watersheds may occur. In the case of the drainage network, a series of laws regarding their order have been conceived and demonstrated. The bifurcation ratio was also described, and was later redefined and named as the confluence ratio (Horton, 1945, Zăvoianu, 1978). In these circumstances, one may consider the formulation and validation of the law of the order of watersheds, based on the node ratio or watershed intersection ratio (because they do not form confluences, but gather in orographic nodes). The analysis of the order of watersheds and streams, which is based on a similar methodology, allows the opportunity to verify the existence (or not) of the same order for the neighbouring streams and watersheds.

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2. METHODOLOGY

In formulating the methodology regarding the order of the watersheds, we started from the order of the streams law in Horton-Strahler system, initially created by Horton (1945), and later modified by Zăvoianu (1978).

The data series value representation, refering to the order of the stream segments, in semilogarithmic coordinates, allowed Horton (1945, p. 291) to formulate the law, which stipulates that: *„the number of different order rivers in a given basin converges towards an inverted geometric progression, in which the first term is the unit, and the ratio is the bifurcation ratio".*

$$R_b = \frac{N_u}{N_u + 1}$$

where: R_b – the bifurcation ratio; u – the order of the segment; N_u – the number of segments belonging to a certain order.

As a result of the analyses made on the drainage network of different basins, but mostly in Ialomiţa basin, and in order to use the confluence ratio instead of the bifurcation ratio (a stream of a certain order is formed after the confluence of two streams and not after their bifurcation), I. Zăvoianu (1978, p. 40) proposed the removal of the idiom "*the first term is the unit*" from Horton's law, which led to the reformulation of the law of the number of streams as following: "*the number of river segments belonging to consecutive orders in a given basin converges towards an inverted geometric progression, in which the first term (N_1) is given by the number of first order streams, while the ratio is the confluence ratio (R_c)*".

The confluence ratio is computed as follows:

$$R_c = \frac{N_x}{N_x + 1}$$

where: R_c – the confluence ratio; N_x – the number of segments of x order.

The difference between the two laws is that „the first term" is not the unit, as in Horton's law, but the number of the first order streams (Ichim, Bătucă, Rădoane, Duma, 1989).

The watersheds number law. As a result of the representation of data series values, refering to the order of the stream segments, in semilogarithmic coordinates, infers the law stating that: "*the number of watersheds segments belonging to consecutive orders, between two streams, converges towards an inverted geometric progression, in which the first term (N_1) is given by the number of first order watersheds, while the ratio is the node ratio or watershed junction ratio (R_j)*". In the case of this law, there is a similitude with the first above-mentioned law, where it is stipulated that the confluence of two first order streams form a second order stream.

Certain similarities can be noticed between the law, which stipulates that the confluence of two first order streams form a second order stream, and the proposed law. In this case, if two first order watersheds junction or unite, they form a second order watershed, if two second order watersheds junction, they form a third order watersheds, and so on and so forth; when two different order watersheds meet, the superior order of the watershed is kept.

The node ratio is computed as follows:

$$R_j = \frac{N_x}{N_x + 1}$$

where: R_n – the node ratio; N_x – the number of segments of x order.

One may determine the node ratio for every pair of segments:

$$R_{j_1} = \frac{N_1}{N_2}; \qquad R_{j_2} = \frac{N_2}{N_3}; \qquad R_{j_n} = \frac{N_n}{N_{n+1}}$$

where: R_{j_1} - the node ratio between the first and second order segments; N_1 – the number of first order segments; N_2 – the number of the second order segments.

In this case, the node ratio represents the arithmetic mean of individual ratios:

$$R_j = \frac{R_{j_1} + R_{j_2} + R_{j_n}}{n}$$, n – the order of the watershed.

The knowledge of the number of first and second order segments and of the node ratio provides the opportunity to compute the number of watersheds belonging to any *x* order, which represents nothing else than the ratio between the number of watersheds belonging to an immediately lower order and the node ratio (R_j).

$$N_x = \frac{N_x - 1}{R_j}$$

where: N_x – the number of segments belonging to x order; N_{x-1} – the number of watersheds belonging to an immediately lower order.

The total number of watershed segments (N) belonging to any (x) order is computed with the ratio:

$$N = \frac{N_\Omega \left(1 - R_j^\Omega\right)}{1 - R_j}$$

where: N – the total number of segments; N_Ω - the order of the main watershed.

3. RESULTS

In order to check the proposed method, twelve watershed models were chosen, located in autocthonuos drainage basins, in the Transylvanian Depression. The drainage basins to which we refer to, are drained by rivers with the second, third, fourth and fifth order in the Horton-Strahler's system. According to their order, the chosen watersheds can be classified in: two of the fifth order, eight of the fourth order and two of the third order.

As a result of the establishment of the number of segments, belonging to the twelve watersheds, and of their representation in semilogarithmic coordinates, the corresponding regression lines were obtained (Fig. 1 and 2). Their analysis indicates that the number of segments belonging to consecutive orders form a geometric progression, in which the first term (N_1) is given by the number of first order watersheds, while the ratio is the node ratio(R_j).

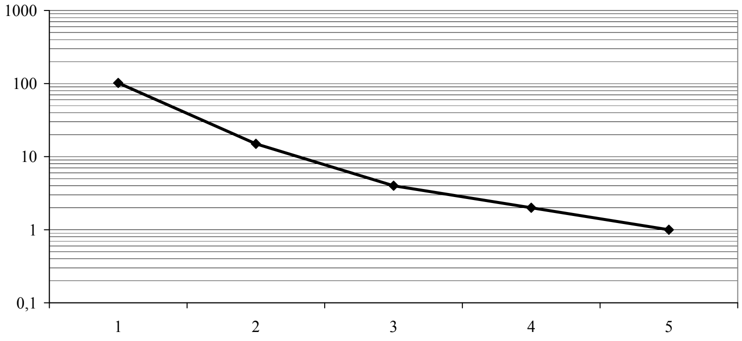

Fig. 1. The law of the order of the watersheds for Popeşti – Valea Mare watershed.

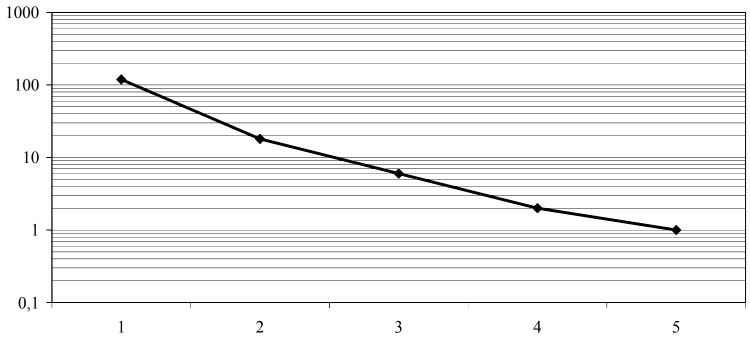

Fig. 2. The law of the order of the watersheds for Calva – Slâmnic watershed.

Because of the territorial differences, another suitable indicator that can be analysed is the **node ratio** (fig. 3). In this case there is a higher frequency of the values between 3.5 and 4.99 (table 1) recorded for the watersheds of the basins of Nadăş (3.63), Visa (3.65), Comlod (4.08), Cincu (4.33), Valea Lungă (4.49 in the basin of Târnava Mare), Almaş (4.83) and Coveş (4.96 in Hârtibaciu basin), followed by the values between 5.00 and 8.00 specific for Zăvoi (5.20 in Hârtibaciu basin), Luduş (5.25) and Fizeş (5.56).

Values over 8.00 are specific to the watersheds of Secaşul Mic (8.15) and Poiana (8.3 in Someş basin). The higher values in that basins show an intensive dynamics of the geomorphological processes, based on the fragmentation of the relief, as compared to the present situation in the basins with the values of R_j under 5 (table 2). The variation of R_j between 3.63 and 8.30 reveals the presence of orographic disparities among different units of the Transylvanian Depression.

The interpretation of the values for the twelve watersheds models, allows to underline the main final results according to the existing differences between the order of watersheds and the bordering streams.

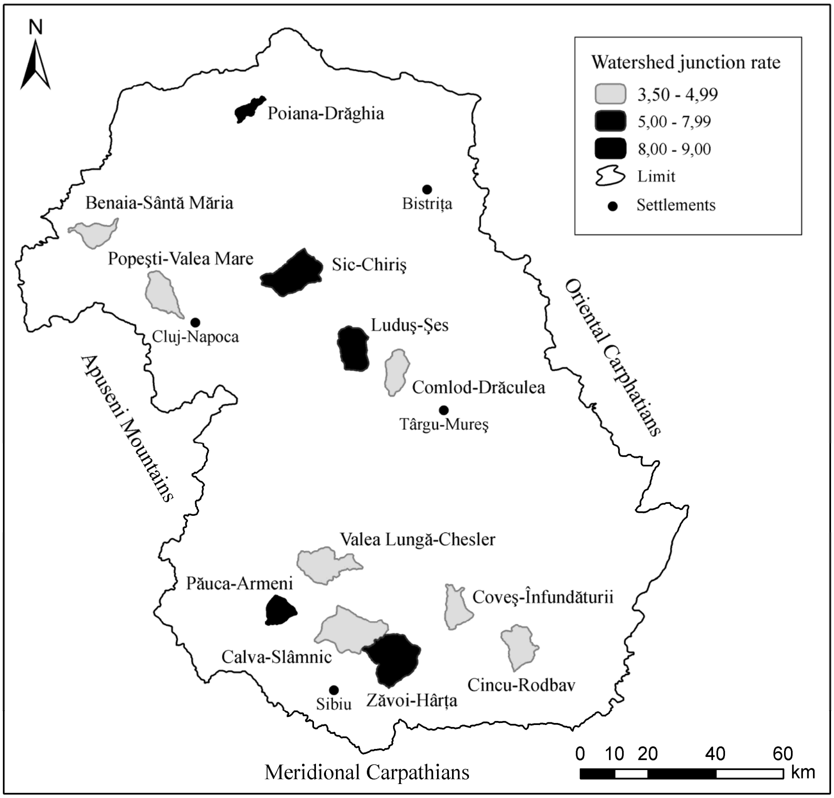

Fig. 3. Territorial differences of the node ratio in the Transylvanian Depression.

The basis of this analysis is given by the knowledge of the order of watersheds located between two streams whose order is also known. After a short synthesis of each case, one can establish the degree of similarity between the order of the streams and watersheds.

The watershed between Poiana and Drăghia (Someş basin) of the third order is located between a fifth order stream (Poiana) and a fourth order stream (Drăghia).

The watershed between Benaia and Sântă Măria (Almaş basin) is of the fourth order and is bordered by two third order streams.

The watershed between Popeşti and Valea Mare (Nadăş basin) is of the fifth order and is situated between two fourth order streams.

The watershed between Sic and Chiriş (Fizeş basin), of the fourth order, is bordered by a fifth order river (Sic) and a fourth order river (Chiriş).

The watershed between Luduş and Şes (Luduş basin) is of the fourth order and is located between a fifth order stream (Luduş) and a fourth order stream (Şes).

The watershed between Comlod and Drăculea (Comlod basin) is of the fourth order and is borderd by a fifth order stream (Comlod) and a fourth order stream (Drăculea).

The order and the number of segments of the watershed

Table 1

Watershed	**Order**	**Area** Km²	**The number of segments**					
			Measured / Calculated	N1	N2	N3	N4	N5
Calva–Slâmnic	5	131.85	m	119	18	6	2	1
			c	65.3	17.9	4.9	1.6	0.5
Popeşti–V. Mare	5	84.58	m	102	15	4	2	1
			c	54.0	14.8	4.1	1.1	0.5
Zăvoi–Hârţa	4	166.45	m	122	16	4	1	
			c	81.1	15.6	3.0	0.7	
Sic–Chiriş	4	137.55	m	136	16	5	1	
			c	86.5	15.5	2.8	0.8	
Luduş–Şes	4	96.28	m	115	19	7	1	
			c	99.2	18.9	3.6	1.3	
V. Lungă–Chesler	4	71.52	m	80	13	3	1	
			c	56.4	12.5	2.8	0.6	
Comlod–Drăculea	4	66.84	m	63	12	3	1	
			c	48.2	11.8	2.9	0.7	
Coveş–Înfundăturii	4	66.69	m	95	12	3	1	
			c	59.0	11.9	2.4	0.6	
Benaia-Sântă Măria	4	60.04	m	57	6	2	1	
			c	27.9	5.7	1.2	0.4	
Cincu–Rodbav	4	43.39	m	36	4	2	1	
			c	16.8	3.8	0.9	0.4	
Păuca–Armeni	3	51.96	m	40	3	1		
			c	20.4	2.9	0.3		
Poiana–Drăghia	3	25.70	m	41	3	1		
			c	24.8	2.9	0.3		

The watershed between Valea Lungă and Chesler (Târnava Mare basin) is of the fourth order and is located between a fourth order stream (Chesler) and a third order stream (Valea Lungă).

The watershed between Păuca and Armeni (Secaş basin) is of the third order and is located between a third order stream (Păuca) and a second order stream (Armeni).

The watershed between Calva and Slâmnic (Visa basin) is of the fifth order, but is situated between two fourth order streams.

The watershed between Zăvoi and Hârţa (Hârtibaciu basin) is of the fourth order, and is located between a fourth order stream (Zăvoi) and a third order stream (Hârţa).

The watershed between Înfundăturii and Coveș (Hârtibaciu basin), of the fourth order, is positioned between two third order streams.

The watershed between Cincu and Rodbav (Olt basin), of the fourth order, is located between two fourth order streams.

The node ratio

Table 2

Watershed	Order	Area Km^2	The node ratio (R_j)				
			N_1/N_2	N_2/N_3	N_3/N_4	N_4/N_5	Average R_j
Calva–Slâmnic	5	131.85	6.61	3.00	3.00	2	3.65
Popeşti–V. Mare	5	84.58	6.8	3.75	2	2	3.63
Zăvoi–Hârţa	4	166.45	7.62	4	4		5.20
Sic – Chiriş	4	137.55	8.5	3.2	5		5.56
Luduş – Şes	4	96.28	6.05	2.7	7		5.25
V. Lungă–Chesler	4	71.52	6.15	4.33	3		4.49
Comlod–Drăculea	4	66.84	5.25	4	3		4.08
Coveş–Înfundăturii	4	66.69	7.9	4	3		4.96
Benaia-Sântă Măria	4	60.04	9.5	3	2		4.83
Cincu–Rodbav	4	43.39	9	2	2		4.33
Păuca–Armeni	3	51.96	13.3	3			8.15
Poiana–Drăghia	3	25.70	13.6	3			8.30

The presence of all these differences shows that giving the same order to the watersheds, as to the bordering streams, is only uninspired and unrealistic. Of the 12 examples, there is one case (*Cincu - Rodbav watershed*) where the order of the watershed and that of the streams bordering it are the same. As for the others, the following situations are given: in one case (*Poiana – Drăghia watershed)* the order of the watershed is lower than the order of the bordering streams; in four cases (*Benaia - Sântă Măria, Popeşti – Valea Mare, Calva – Slâmnic, Coveş – Înfundăturii* watersheds*)* the order of the watershed is higher than the order of the bordering streams; in the other six cases, the value of the order of watershed is identical with the value of one of the bordering streams.

The high percentage (50%) of the cases, when the value of the order of the watershed is the same with the value for one of the bordering streams, sustains and confirms the argument which stated that it is not too good to ascribe the watershed the value of the order of one of the streams bordering it, not to mention that sometimes, none of the rivers are of the same order as the watershed.

The watersheds located between two streams of the same order, which receive the same value of the order, like the two streams, is finally a normal situation, as in the case of the watershed between Cincu and Rodbav (fig. 4). The same circumstances are specific for the watersheds located between two different order streams, but which are given the same order as one of the streams (fig. 5).

Differencies may appear when the order of the watershed is not identical with any of the main streams bordering it, and in this sense, two such situations have been distinguished.

The first of them is characteristic for the watersheds that have a lower value of the order than the streams bordering them. Among the examples provided, there is only one such situation, in the case of the third order watershed between Poiana and Drăghia, located between a fifth order stream (Poiana) and a fourth order stream (Drăghia) (fig. 6).

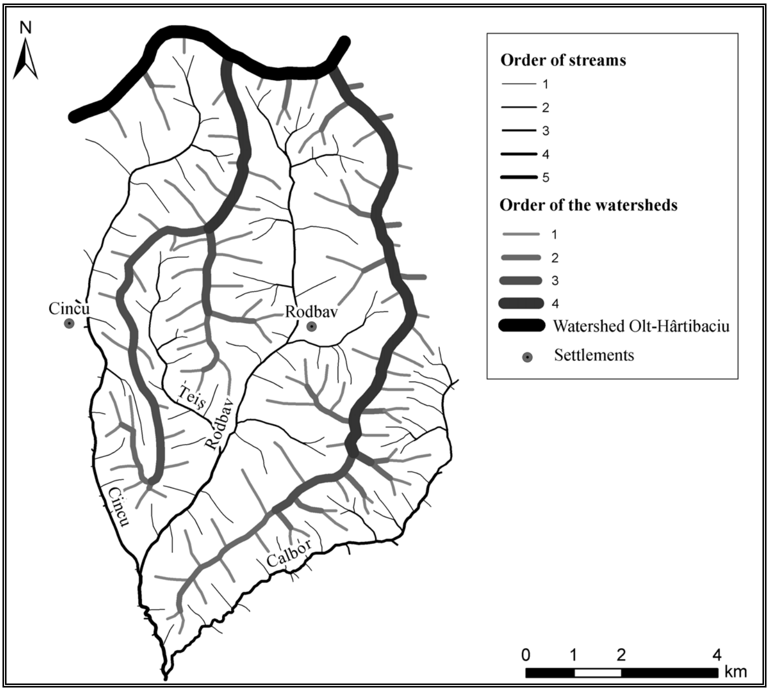

Fig. 4. The order of the watersheds between Cincu and Rodbav valleys.

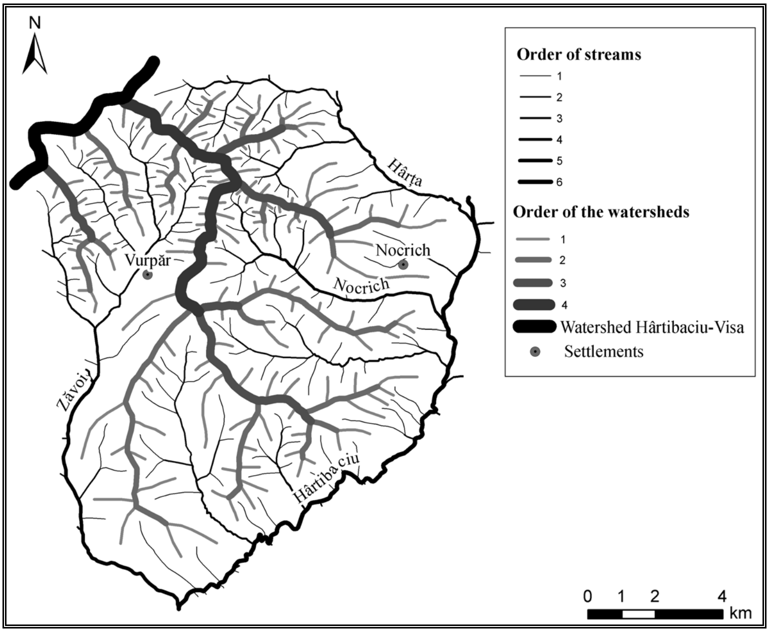

Fig. 5. The order of the watersheds between Zăvoi and Hârţa.

The existance of a lower value of the order of the watershed as compared to the bordering streams is explained by the independence between the drainage network and that watershed. In these conditions, the drainage network increased its order because of the river segments coming from the ”surface” of the watershed, on one side of the watershed, but especially, due to segments, to the tributaries coming from the other side of the watershed.

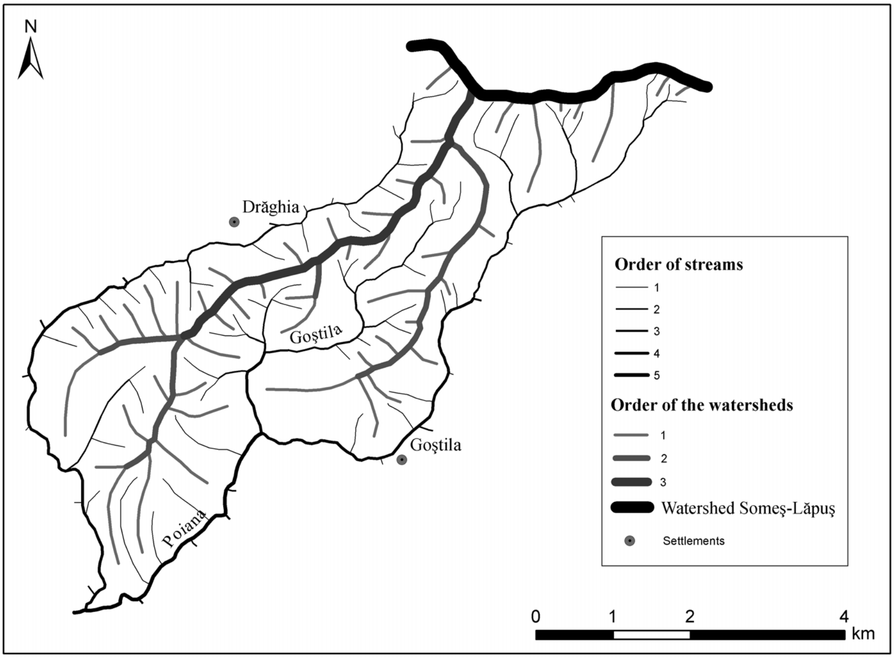

Fig. 6. The order of the watersheds between Poiana and Drăghia valleys.

The second situation is specific for watersheds that have a higher value of the order, than that of the streams bordering them. In the examples provided, four of them have these characteristics: Benaia and Sântă Măria watershed, Popeşti and Valea Mare watershed, Calva and Slâmnic watershed and Înfundăturii and Coveş watershed. The presence of the watersheds that have a higher value of the order than the main streams bordering them, is this time explained by the independent evolution of the slopes, and in connection, of the watersheds, as compared to the rivers below. The difference is made by the first order stream segments which, dividing the watershed, instead of being collected by the two rivers bordering it and thus increasing their order, are directly collected by the main stream, without increasing its order. For example, in the case of Înfundăturii-Coveş watershed (of the fourth order) , one may notice that a series of first, second and third order tributaries flow into Hârtibaciu between the confluence of Înfundăturii river and that of Coveş river with Hârtibaciu (fig.7). However, their upper streams do not reach the major watershed between

Târnava Mare and Hârtibaciu. Because they flow directly in Hârtibaciu, the mentioned tributaries determine the increase in order of the watershed, but not an increase in order of Înfundăturii (of the third order) and Coveş (of the third order) rivers, for them to have the same order as the watershed between them. Only in these conditions one may speak of an independent evolution between the watershed and slopes, on one hand, and the streams that bordered it initially, on the oher hand. An important role in the increase of the gap between the order of the watersheds and that of the streams bordering them initially is also played by the evolution of slopes by refragmentation, due to the lower order drainage systems.

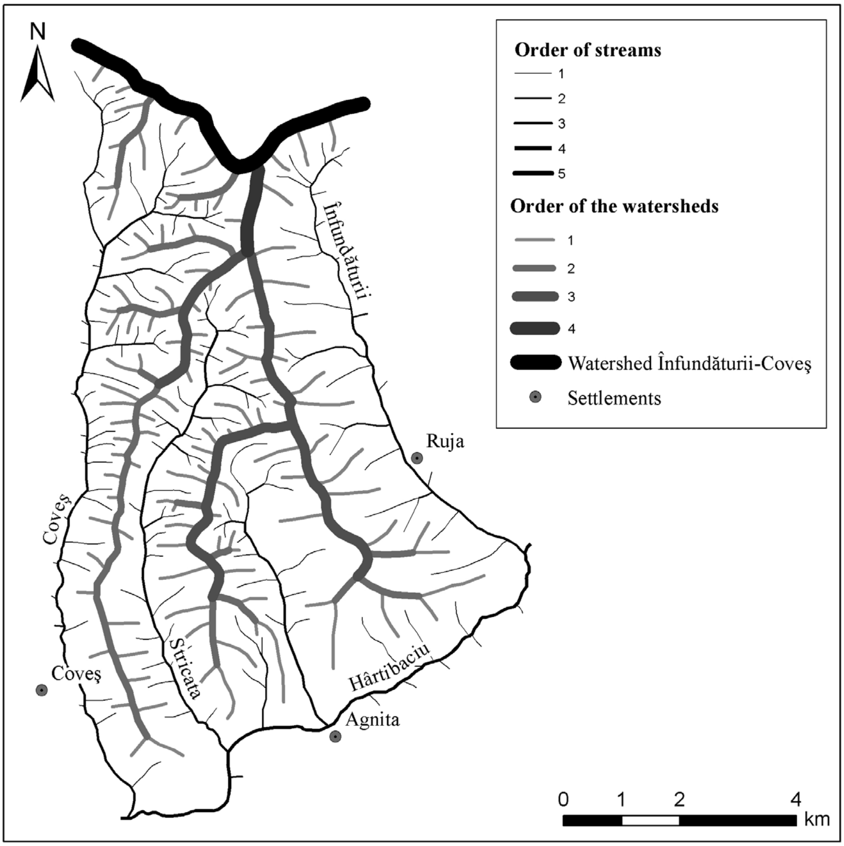

Fig. 7. The order of the watersheds between Înfundăturii and Coveş valleys.

Considering the differencies recorded in the examples above, a law may be stated, that *the difference between the order of a major watershed and that of the main rivers bordering it increases together with the number of lower order segments that divide it, without meeting any of the mentioned main rivers, thus increasing the order of the drainage network, but flowing directly into their main stream, without increasing its order.*

Other methodological aspects should also be considered, like those stressing that the number of watersheds is in direct relation with the number of the river segments, but the manner in which the qualitative leap is made from one order to the other depends on the manner in which (stream or watershed) segments comply with the geometrical progression.

Also, in this context, one may check the classification of the watersheds according to their genesis, which states the existence of generations of watersheds. For example, in the Transylvanian Depression, watersheds have been classified according to their genetic features (Mac, 1972; Josan, 1979; Irimuş, 1998, 2006 etc.), on which ocassion, two or three generations of watersheds have been established. As a conclusion, it is important to make a correlation between the results of the mentioned authors, and those obtained by establishing the order of the watersheds, applying the law of the number of watersheds, in order to seek a correspondence between them. Of course, there is a correlation, except for the watersheds with a higher order rank than the fifth or the sixth order of the watersheds, which have a probability of appearance only when the measured area becomes larger. This is because, in the case of the law of the order of watersheds, a qualitative leap is performed as the number of lower order segments grows, and they are more numerous as the surface becomes larger.

In the other cases (for the first to the fourth orders), if a map with the genetic classification of watersheds is overlapped with a map where watersheds are presented according to the mentioned method, the result is not a „perfect" correlation betweeen them, because of the different principles on which each of the two methods are based on (Roşian, 2008). It is sufficient to note just one of the differencies, meaning that when two third generation of watersheds "meet", the resulted order of the watershed belongs to the third generation of watersheds, while if the same watersheds are analysed according to the law of the order of watersheds, the result is an increase in order simply due to their junction.

4. CONCLUSIONS

Several conclusions have been drawn as a result of the presented methodology establishing the law of the order of watersheds and its application on the 12 models.

The law of the order of watersheds, as it was named, by analogy, after the Law of the order of streams, is valid for all the case studies taken into consideration. This is a result of the manner in which the values of the number of segments of the watersheds, of different orders, are shown in the tables, as well as in semilogarithmic coordinates representations.

Knowing the order of the watersheds in this way, one may compare the resulted values with those specific to the order of the bordering streams. Even if the watershed network was created by the evolution of the drainage network, it has been demonstrated that the order of the bordering streams and of the watersheds is not always the same. This is mainly because a major watershed of the fourth or the fifth order, borders two drainage basins, which are also drained by two rivers, whose orders are not always the same as a result of their evolution. The recorded difference, that the order of the watershed is higher than that of the bordering streams, is in most cases due to the way in which the confluence takes place between the main collector and the first or second order streams, which divide the watershed area. This difference is higher as the number of the segments of lower order streams, which fragment the watershed and increase its order, do not make any confluences between them, in order to increase the order of the drainage network, but flow directly into a higher order collector.

The assessment of the relation between the order of the streams and the order of the watersheds led to certain results, on the basis of which one may conclude that in the Transylvanian Depression the problem of the correlation and similitude between the drainage network and the watersheds remains open.

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