Carpathian Journal of Earth and Environmental Sciences, February 2015, Vol. 10, No. 1, p. 133 - 146

BANKFULL DISCHARGE AND STREAM POWER INFLUENCE ON THE NIRAJ RIVER MORPHOLOGY

Sanda ROŞCA[1], Ştefan BILAŞCO[1,2], Dănuţ PETREA[1], Ioan FODOREAN[1] & Iuliu VESCAN[1]

[1]*"Babeş-Bolyai" University, Faculty of Geography, 400006 Cluj-Napoca, Romania, rosca_sanda@yahoo.com, dpetrea@geografie.ubbcluj.ro, fioan@geografie.ubbcuj.ro, vescan@geografie.ubbcluj.ro*

[2]*Romanian Academy, Cluj-Napoca Subsidiary Geography Section, 9, Republicii Street, 400015, Cluj-Napoca, Romania, e-mail: sbilasco@geografie.ubbcluj.ro*

Abstract: The concept of dominant discharge is used in geomorphologic studies concerned with stability of riverbeds and riverbed management. The results of our study involves the specific energetic conditions on the Niraj River during maximum river flow (by analysing the bankfull discharge and the stream power during peak flow) and during normal flow (by analysing the stream power at average flow). The bankfull discharge value is considered fundamental for the present riverbed formation, for Niraj river beeing situated between 20.8 m^3/s and 928 m^3/s, depending on local morphometrical riverbed condition. Therefore using the Manning-Strickler formula, the bankfull discharge was calculated due to the fact that it is considered to be the main estimative parameter of the riverbed hydraulic geometry. The values of stream power varied between 3.51 (W/m^2) and 289 (W/m^2) and It was determined by means of data gathered on seven cross sections, taking into consideration the upstream riverbed typology. In two sectors, considered to be representative for the riverbed typology, the return periods were calculated, probability of exceedance (66%) and non-exceedance as well (1.5 year) as the influence of bankfull discharge on the Niraj riverbed dynamics in the 1970-2012 interval. The case study was performed on two different sectors taking into account the evolution of the sinuosity index, which is dependent on the influence of natural and anthropic factors. The analysis enabled the comparison of meandering rates for 100 year interval, both in the sectors with a natural evolution of the riverbed and in the sectors with high anthropic impact as a resuls of constraints of the dams. The high lateral dynamics is mainly caused by the decrease of slope gradient and the decrease of bank resistance due to extreme events with high energetic values (varying between 30.2 and 105.3 W/m^2 in the upper and middle sectors of the Niraj river). The obteined bankfull discharge values with 1.5 year probability (41.6 m^3/s for Cinta and 28.9 m^3/s for Bereni) were validated by comparing the calculated data within the cross sections located near the Gălești and Cinta hydrometric stations and the data obtained by hidrometrical measurements in the two stations mentioned above. The results are included in the confidence interval of 5%.

Keywords: Bankfull discharge, stream power, return period, meandering, Niraj River

1. INTRODUCTION

The concept of *dominant discharge* (riverbed-forming discharge) refers to the river discharge which determines in time the shape of natural riverbeds and shows the ability of rivers to transport the highest amount of sediments, higher than the annual average discharge (Wolman & Miller, 1960).

Starting from the change over time of riverbed depth, width and slope under the influence of solid and liquid discharge variations, the objective of this study is to identify the bankfull discharge values which determine changes in the minor riverbed morphology and typology, as a consequence of meandering tendencies. From a morphologic perspective, the bankfull discharge makes possible the identification of the boundary between the active channel and the floodplain, which is used in channel design (William, 2010).

By considering the discharge as an independent variable which influences the elements describing the riverbed morphometry (riverbed depth and width) and the flow velocity, Leopold &

Maddock (1953) identified a series of relationships: $B = aQ^b$, b = 0.5 (0.26 at the hydrometric station), $h = cQ^f$, f = 0.4, $V_m = kQ^m$, m = 0.1 (0.34 at the hydrometric station), where: B – riverbed width, Q – discharge, h – riverbed depth, V_m – average velocity; b, c, f, m represent the coefficients depending on the discharge variability and the position in which the measurement is taken in relationship to the closest hydrometric station. At the local level, the situation becomes more complex, as the evaluation of the role of lithology in the conditioning of meander patterns becomes necessary (Harvey, 1969; Roşca et al., 2012; Ahilan et al., 2013).

After 1966, when Bagnold used the bankfull discharge for evaluating the bedload transport, this concept has been used in many studies to determine behavioural characteristics, in particular channel patterns and meander dynamics (Brush, 1961, Ferguson, 1981; Rosgen, 1994; Fryirs & Brierley, 2013; Rădoane et al., 2013).

2. STUDY AREA, DATA AND METHODS

The Niraj River is one of the main left tributaries of the Mureş River (Fig. 1), its catchment area being extended on 658 km^2.

The source of the river is located on the western slopes of Gurghiu Mountains, at 1249 m elevation and the whole river is 82 km long. The Niraj crosses a succession of topography levels, from the mountain, in the upper catchment area, to the high hills (400.1-550 m), in the middle catchment area and the lower hills (284-400), towards the river mouth.

The Niraj hydrographic basin is characterised by a general orientation of the topography from north-east to south-west which channels the energetic fluxes in the same directions. The high slope angle of the catchment area determines the flash flood regime by influencing the concentration time of flash floods and the flow velocity in the collector channel (Roşca, 2011), leading to a reduced intervention time in the case of risk situations associated to flash floods. The energy flow which enables the processes of topography transformation is concentrated on the same direction, the Niraj receiving a significant amount of water from the tributaries flowing from the mountain area and having a pluvial and nival regime.

The analysis of the morphometric characteristics enabled the division of the active river channel into 7 sectors, their typology being mainly differentiated according to the slope and the sinuosity index (Table 1).

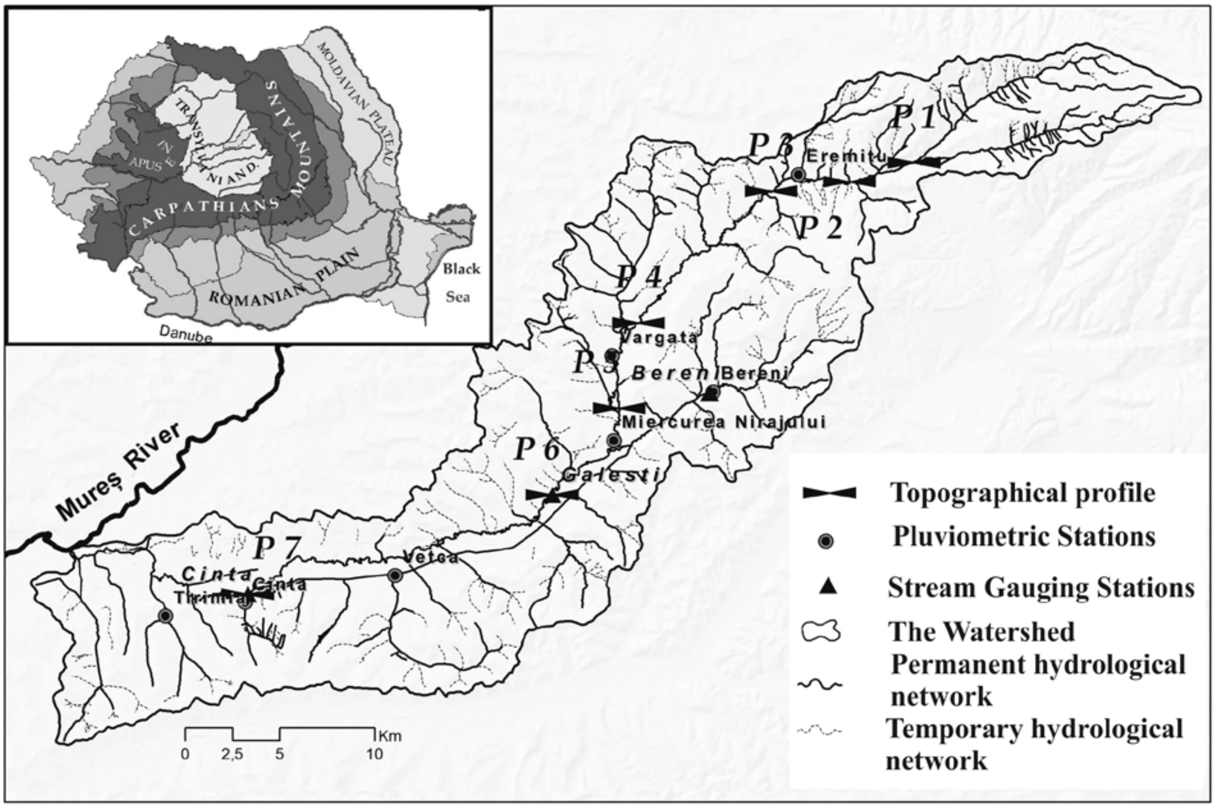


Figure 1. Geographic location of the Niraj catchment area and the 7 cross-sections (P1-P7).

2. 1. Determination of bankfull discharge

In this study the bankfull discharge is represented by the discharge responsible for the present riverbed formation. It is defined as the flow at which water fills the channel without overtopping the banks and without flowing on the floodplain (Dury, 1961, Copeland et al., 2000; Ahilan et al., 2013). In order to determine the bankfull discharge, a series of cross-sections were created in the field to identify the elements of the active channel cross-section for seven river sectors with different riverbed typology (Fig. 2).

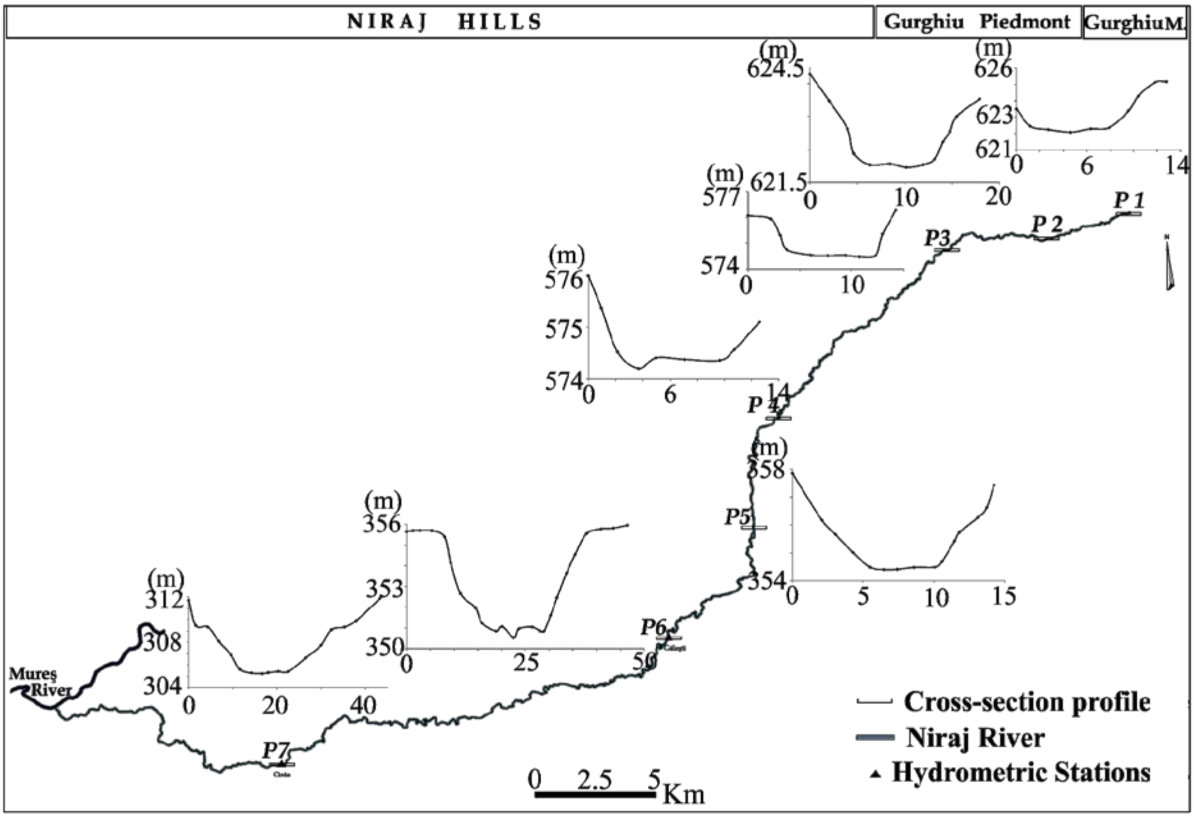


Figure 2. Position of cross-sections.

Table 1: Morphometric and geologic characteristics of the river sectors

Caract.	Sect. 1	Sect. 2	Sect. 3	Sect. 4	Sect. 5	Sect. 6	Sect. 7	Niraj
Geology	Ng+vs	pn	qh2	qh2	qh2	qh2	qh2	-
Lenght (km)	14	24	9	7	13	6	9	82
Slope (m/m)	0.00677	0.00966	0.00725	0.00516	0.00201	0.00114	0.00112	0.00364
Sinuousity max	1.62	2.27	1.95	1.58	1.75	1.27	1.12	2.27
Sinuousity medium	1.26	1.43	1.43	1.22	1.25	1.20	1.06	1.27

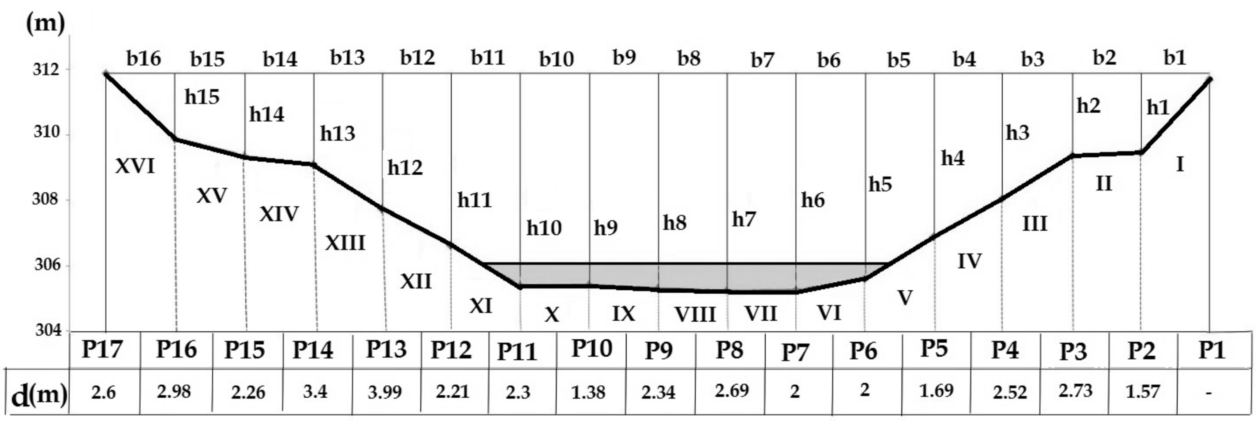


Figure 3. Profile of cross-section 7 downstream from the Cinta hydrometric station (represents the water level)

Using the data collected in the field, a series of specific parameters were identified (Fig. 3):

Active channel cross-section area (ω) as a sum of the subsections (I…XVI) limited by the vertical measurement lines ($h_1…h_n$), using known formulas to calculate triangular and trapezoid areas;

$$\omega = \frac{[(h_1 b_1)]}{2} + \frac{[(h_1 + b_2)b_2]}{2} + ... + \frac{[(h_{n-1} + b_{n-1})b_{n-1}]}{2} + \frac{[(h_n b_n)]}{2} \quad (m), \quad (1)$$

- Wetted perimeter *(P)* using the formula (Zăvoianu, 2007):

$$P = \sqrt{b_1^2 + h_1^2} + \sqrt{b_2^2 + (h_2 - h_1)^2} + ... + \sqrt{b_n^2 + h_n^2}, \quad (2)$$

where, b_1, b_n represent the distances between the vertical measurements

h_1, h_n represent the depth of the vertical measurements

The maximum depth (h_{max}), the average depth (h_{med}) and the hydraulic radius *(R)* have also been determined. The hydraulic radius was calculated as a ratio between the cross-section area (ω) and the wetted perimeter (P) (Table 1).

The bankfull discharge, named by Ichim et al., (1989), the discharge of a full riverbed, represents the fundamental estimative and dimensional parameter of the riverbed hydraulic geometry. A first stage in its calculation is represented by the identification of the bankfull water stage, both in the field and at the riverbed cross-sections.

Further on, the bankfull discharge was calculated using the Manning – Strickler formula Leopold, (1954):

$$Q_b = A \cdot k \cdot (R^{2/3} \cdot S^{1/2}) / n, \quad (3)$$

where: Q_b – bankfull discharge [m^3/s],
A –active channel cross-section area [m^2],
k –conversion constant [k=1],
R – hydraulic radius [m],
S – hydraulic slope (slope of the free water surface in uniform movement, equal to the slope of the thalweg slope)[‰],
n – roughness coefficient, calculated using the Strickler formula, $n = d_{50}^{1/6} / 21.1$ [m].

2.2. Determination of riverbed roughness

The riverbed roughness represents one of the main factors which influence the action of water on riverbeds and river banks, therefore, its determination is an important and indispensable stage in such a study as the present one.

In order to determine the riverbed roughness, the grain size of the channel deposits was analysed for each river sector. In the minor bed, this analysis was performed globally (without differentiating between pavement and subpavement), the results being classified into 14 granulometric classes according to the Wenthworth scale, at a 1 phi interval: blocks (> -8 phi), boulders (between -6 and -8 phi), gravel (between -1 and -6 phi), sand (between 4 and -1 phi) and silt (< 4 phi).

In the present study, the riverbed roughness was determined using the Stickler formula:

$$n = D_{50}^{1/6} / 21.1, \quad (4)$$

where:

n = roughness, A = area of cross-section, R = hydraulic radius, S = slope of the channel, Q = discharge, D50 = median diameter.

2.3. Stream power determination

The stream power is an indicator which is considered in the literature as the main factor in the assessment of minor bed erosion and dynamics (Hicking & Nanson, 1984), in the analysis of sediment transport (Bagnold, 1966) and sediment unloading (Simons & Richardson 1966), which is also dependent on the concept of bank resistance. The stream power expresses the capacity of a river to load and transport sediments during its flow, at a punctual level. Thus, the estimation of this parameter is essential in the identification of the riverbed dynamic trends.

In 1966, Bagnold defines the power of a water stream as a product between the specific water density, the discharge and the slope of the water surface:

$$\Omega = \gamma \cdot Q \cdot S, \quad (5)$$

where, Ω = stream power, ɤ = water density [kg/m3], Q = discharge [m3/s], S = slope of the channel [m/m]

By dividing the stream power per unit area, Bull (1979) uses the following expression in order to determine the available power for erosion and transport at each cross-section:

$$\omega = \Omega / W, \quad (6)$$

where: ω = Specific stream power [W/m],
Ω = stream power [W/m],
W = width of the active channel [m].

This indicator is calculated in the present study, per unit of the cross-section wetted perimeter.

Other studies determining the stream power have highlighted specific longitudinal trends (Magilligan, 1992; Lawler, 1995; Lecce, 1997; Knighton, 1999). The new GIS technologies and

LIDAR elevation models enabled the calculation of the stream power at continental scale (Finlayson et al., 2002; Finlayson & Montgemetry, 2003) as well as at the level of large and medium catchment areas (McCandless & Everett 2002; McCandless 2003; Jain et al., 2006; Worthy, 2005; Stacey, 2007), the authors stating the necessity of using a DEM with a minimum resolution of 1 m^2 in order to produce any useful results. However, the majority of studies related to bankfull discharge and its corresponding stream power (both for applications and innovative studies) use the relationships between the cross-section area and the width of the channel top (Williams, 1978), as well as the relationship between the magnitude and frequency of the bankfull discharge and its influence for each river reach (Woodyer, 1968; Castro & Jakson, 2001; Navratil et al., 2006; Shields et al., 2003, Xia et al., 2009).

3. RESULTS AND DISCUSSIONS

According to the previously described methodology, a series of indispensable work stages can be anticipated in the identification of the relationship between river flow and meander pattern, their results being described in the following section.

A first stage is represented by the identification of the granulometric spectrum of bed material in relationship to the variables which define the catchment area (surface, geology, elevation and slope) as well as the granulometric distribution on the longitudinal profile, determined through the granulometric statistical analysis (Fig. 4).

The ideal distribution of the riverbed deposits along the river follows the principle of the decreasing percentage of granulometric classes in the flow direction (Rădoane et al., 2002). In this case study, however, certain variations can be noticed which are explained through the material input brought by the main tributaries, as well as by the effect of dyke building and channel adjustment works.

In 1875, by analysing the variation of riverbed sediment dimension along rivers, Sternberg identified a decrease of the grain size according to an exponential relationship. The same situation can also be identified for the Niraj River (Fig. 5): blocks are dominant in the upper catchment area followed by the

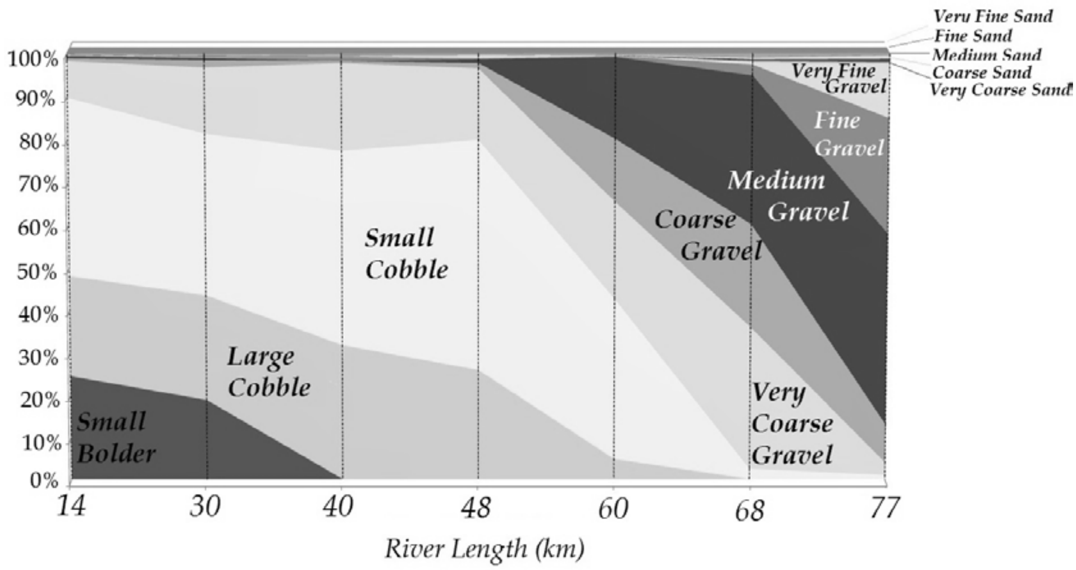


Figure 4. Granulometric spectrum of channel deposits.

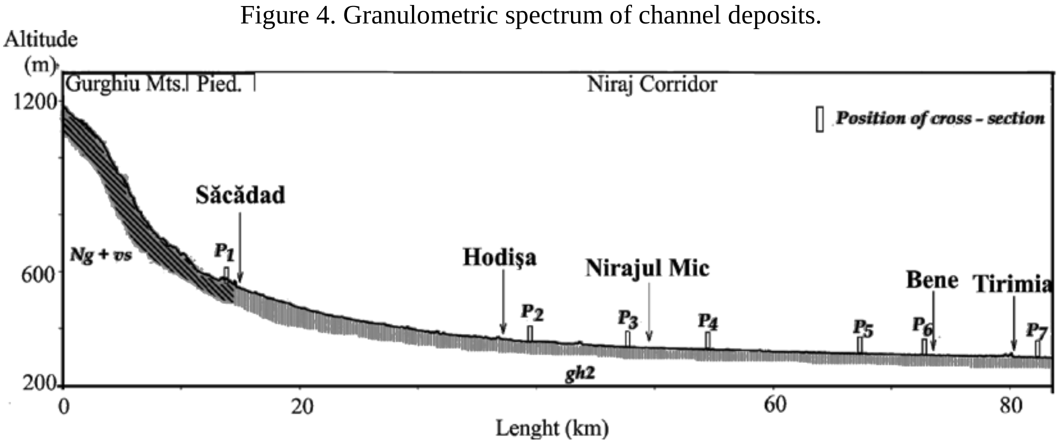


Figure 5. Longitudinal profile of Niraj river.

boulder and gravel classes, their percentage increasing in the medium and lower catchment area. This sorting process of riverbed material, progressing over a long period of time, took place according to the riverbed resistance to the effects of liquid and solid flow characterised by a specific stream power.

The histograms of the upper and medium sectors are characterised by unimodality (Fig. 6.A), while the histogram of the lower sector is characterised by the bimodality of riverbed sediments (fig. 6.B). The same characteristics can be identified for the rivers in north-eastern Romania, due to the competition between the processes of sorting and attrition (Rădoane et al., 2002). In order to determine the cause of the decrease of sediment dimension along the river, worldwide studies concentrated on the ratio between hydraulic sorting (Knighton, 1982) and mechanical attrition (Ibbeken, 1983), at the segregation level of riverbed deposits.

In the laboratory stage, the sampled data were statistically analysed and, as a result, the value of the median diameter was identified (D50), a necessary parameter in the quantification of minor riverbed roughness (Fig. 7).

A decreasing trend of the D50 value can be noticed along the river, from a value of 0.915, characterising the sample number 1 at the kilometre 16 of the river, to the value 0.356, for the sample number 7, on the lower part of the stream, at the kilometre 74 of the river (Fig. 5).

The average correlation (R^2=0.566) between the median diameter (D50) and the river slope also reflects a decrease in the dimensions of the riverbed material on the longitudinal profile.

By using the data of the cross-section profiles and applying the previously presented methodology and the Manning – Strickler formula in reference points, the values of the bankfull discharge were determined (Table 2).

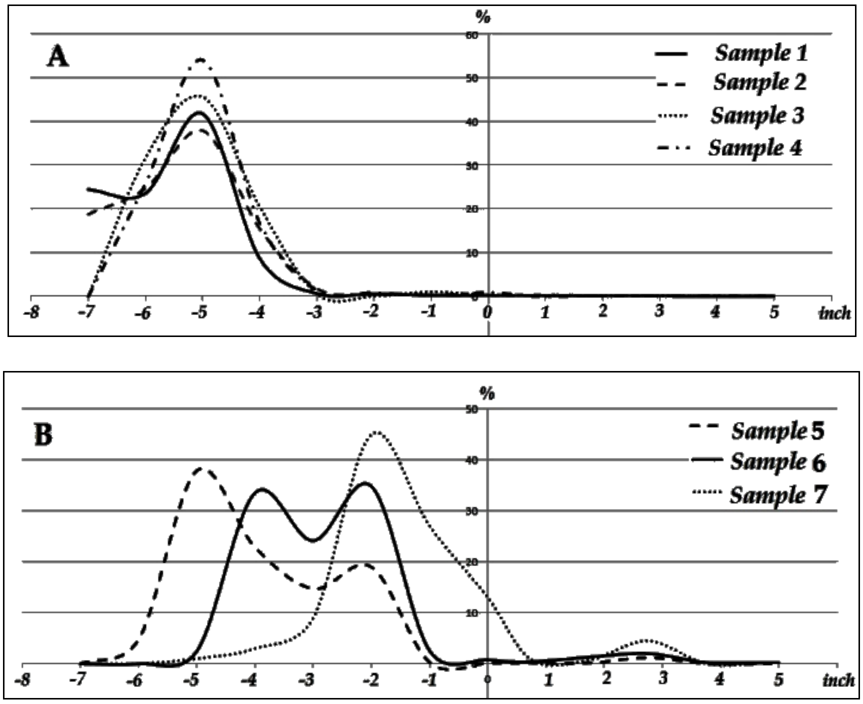
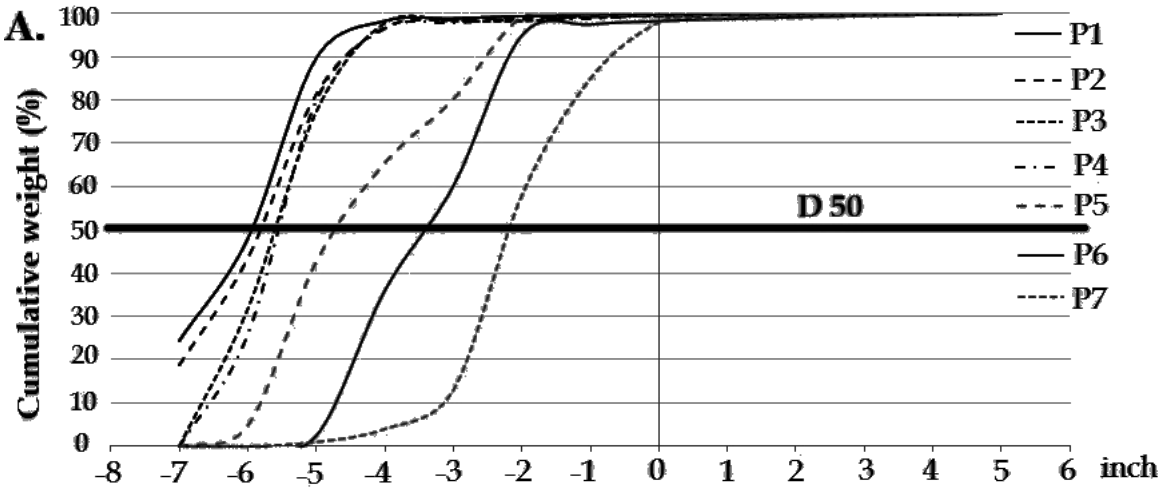


Figure 6. Distribution histograms of channel deposits

Table 2. Calculated values of bankfull discharge

Nr. of Cross-section	P (m)	A (m)	R (m)	S (‰)	n	Vm (m/s)	Q_b (m^3/s)	Q_m (m^3/s)
1	20.3	10.9	0.538	1.745	0.046	1.9	*20.8*	-
2	33.6	19.6	0.584	1.745	0.046	2.0	*39.3*	-
3	29.8	17.7	0.595	2.756	0.047	2.5	*44.7*	-
4	23.0	22.6	0.982	2.756	0.047	3.5	*79.6*	-
5	29.5	29.4	0.995	0.465	0.040	1.7	*50.1*	-
6	96.2	111.5	1.159	0.465	0.043	1.7	***195.3***	1.310
7	89.8	174.7	1.945	1.957	0.041	5.3	***928.2***	3.574

where P – wetted perimeter, A – area of active channel cross-section, R – hydraulic radius, S – slope of the channel, n – roughness, V_m – average velocity, Q_b – bankfull discharge, Q_m – average discharge (1950-2013).



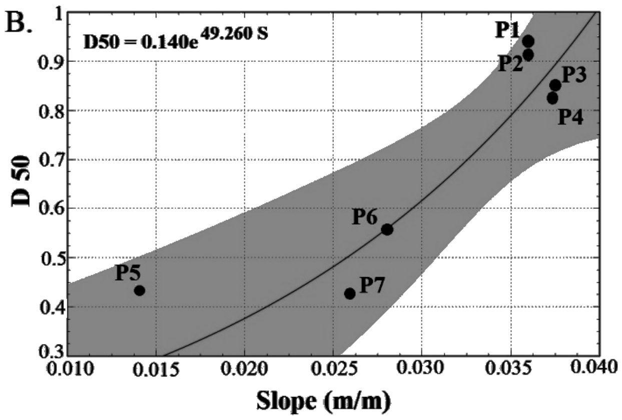


Figure 7. Value of median diameter D50 (7.A) and the correlation D50 – river slope (m/m) (7.B.).

In the case of two cross-sections the validation of the results is possible due to the proximity of hydrometric stations: Gălești (profile 6) and Cinta (profile 7).

One can notice an increase of the bankfull discharge values along the river due to the changes of the morphometric parameters characterising the minor bed (the wetted perimeter and the area of active channel cross-section), the highest calculated value is reached at profile 7 (in the close vicinity of the hydrometric station Cinta).

4. IDENTIFICATION OF RETURN PERIODS FOR MAXIMUM DISCHARGE

The literature treats channel migration in relationship with magnitude/intensity and the frequency of extreme flood events (Stover, 2001; Wellemeyer et al., 2005; Wallick, 2007; Crosado, 2008; Pandi & Horvath, 2012, Zaharia et al., 2012). Using the data available at the hydrometric stations Bereni and Cinta (located in the close vicinity of the cross-sections 6 and 7) the occurrence probability of the maximum discharge necessary in the estimation of future trends was determined.

In the present study, the maximum discharge, with a return period of 1.5 years, has the value of 41.6 m^3 (Table 3) at the Cinta hydrometric station and 28.9 m^3 at Bereni hydrometric station.

Table 3: Exceedance probability and return periods of the maximum and dominant discharges calculated at the Cinta and Bereni hydrometric stations.

Return period (T)	**Exceedance probability**	**Qmax**	
	(%)	**Cinta**	**Bereni**
1000	0.1	493	237
200	0.5	383	186
100	1	335	164
50	2	287	142
20	5	223	113
10	10	175	90.6
5	20	127	68.6
3	33	92.3	52.4
2	50	62.2	39.5
1.5	**66**	**41.6**	**28.9**
1	90	28.3	20.9

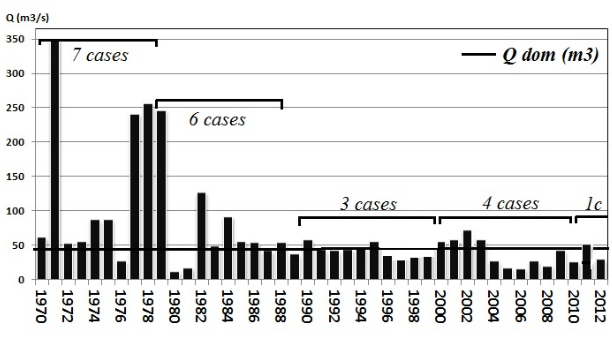


Figure 8. Absolute frequency of years in which the maximum discharge was higher than Q_{max} with 1,5 year probability.

Analysing the graphical variation of the annual maximum discharge (Fig. 8) one can notice the high number of years from the 1970-1979 decade in which the discharge being considered as dominant was over passed, a condition with a return period of 1.5 years in 7 cases. For the next decades, the determined number of such situations was: 6 (1980-1989), 3 (1990-1999), 4 (2000-2009) and a singular event in the interval 2010-2012.

5. STREAM POWER CALCULATION

Another important stage of the present study was represented by the assessment of *the energetic conditions which are specific to the maximum flow* (by analysing the discharge and the stream power during peak flow using the bankfull discharge) and *the normal flow* (by analysing the stream power at a multiannual average discharge).

Related to the adjustment of riverbed geometry from the perspective of the concept of optimum energy dissipation (stream power, Shield et al., 2003), the stream power at the level of the active channel cross-section was calculated for a normal flow regime ω_m (Table 4).

These energetic values offer information on the relationship between the transport capacity and the resistance to erosion of the river banks. Generally, the riverbed of Niraj River evolves in the context of medium and low energy. Thus, the sectors with low values of stream power, around the value of 10 W/m^2 (profiles 6 and 7 which are specific to the lower sector of the Niraj), correspond to the C class of low energy riverbeds (according to the energetic classification of riverbeds made by Nanson & Croke, 1992).

These are characterised by a high resistance of the river banks to water erosion which limits the lateral migration of the channel. The sectors with values of 30-300 W/m^2 correspond to the class B riverbed, with medium energy. These are considered as riverbeds in a dynamic equilibrium, rarely affected by extreme events as the river dissipates its energy along the major riverbed and its erodability being decreased by the protective role of the vegetation.

The river sectors with a stream power of 30.2 and 105.3 W/m^2 developed on gravel bed and characterise the upper and middle parts of the Niraj, which are included in the B2 class where major beds are highly stable to bank overflowing. The B3 class of major beds with lateral migration through meandering processes is characterised by a stream power of 10.4 and 62 W/m^2 in the active channel cross-section which determines the dominance of lateral over vertical erosion.

In what concerns the relationship between the bankfull discharge and the morphometric characteristics of the riverbeds, by using the same types of mathematical expressions describing correlations, one notices a high correspondence between these two set of variables (Table 5), both in national and international researches.

For the Niraj catchment area an increase of the active channel cross-section area can be noticed at the same time with the increase of the upstream catchment area (Fig. 9.A), as well as a direct relationship between the stream power and the bankfull discharge (Fig. 9B).

These correlations make possible the identification of the specific stream power corresponding to the discharge forming the riverbed on all river sectors.

6. EFFECTS ON THE RIVERBED

As a result of different researches concerning rivers from various geographical areas, a general tendency of rivers changing their morphometric characteristics according to hydraulic elements was identified (Wolman & Leopold, 1957; Pickup & Warner, 1976, Schmitt et al., 2004; 2007; 2011; Rustomji, P., 2009, Pandi et al., 2013).

In order to determine the temporal dynamics of the Niraj riverbed, its evolution was analysed both on the seven sectors and at a more detailed scale, using a unit distance of one kilometre.

Table 4. The maximum and average specific stream power and stream power values

Nr. Sect.	Q_b (m^3/s)	Ω_{max} (W/m)	Ω_m (W/m)	ω_{max} (W/m^2)	ω_m (W/m^2)
1	20.8	127477	-	289	-
2	39.3	53542	-	141	-
3	44.7	13763	-	14.51	-
4	79.6	28113	-	37.28	-
5	50.1	15788	-	14.95	-
6	195.3	14255	85.15	8.77	0.22
7	928	7559	534	3.51	1.21

Table 5. The relationship between the bankfull discharge, the morphometric characteristics of the riverbed (riverbed width, average depth) and the catchment total area (where: $A= aQ_{bkf}^{b}$, $l = cQ_{bkf}^{d}$, $d = eQbkf^{f}$)

Catchment Area (A)		River Width (l)		Average Depth (d)		Source / River	
a	b	c	d	e	f		
-	0.90^{+}	-	0.50	-	0.40	Leopold & Maddock, 1953	
-	0.87^{+}	-	0.42	-	0.45	Wolman (1955)	
0.90	0.83	1.65	0.50	0.55	0.33	Nixon (1959)	
-	0.91^{+}	2.17-3.98	0.52	0.16-0.20	0.39	Hey & Thorne, 1986	
0.28	0.94	1.46	0.52	0.19	0.42	McCandless (2002)	
0.79	0.8	2.65	0.47	0.3	0.33	McCandless (2003)	
0.764	0.70	-	-	-	-	Ahilan et al., 2013	
ROMÂNIA							
-	-	12.67	0.24	-	-	Ialomiţa	Minea, et al., 2011
-	-	6.03	0.43	-	-	Buzău	
-	-	3.75	0.42	-	-	Bâsca	
0.69	1.34	1.03	0.69	-	-	Prahova	Toroimac (2009), Toroimac et al., 2013
6.45	*0.78*	*6.13*	*0.26*	*0.73*	*0.43*	***NIRAJ***	

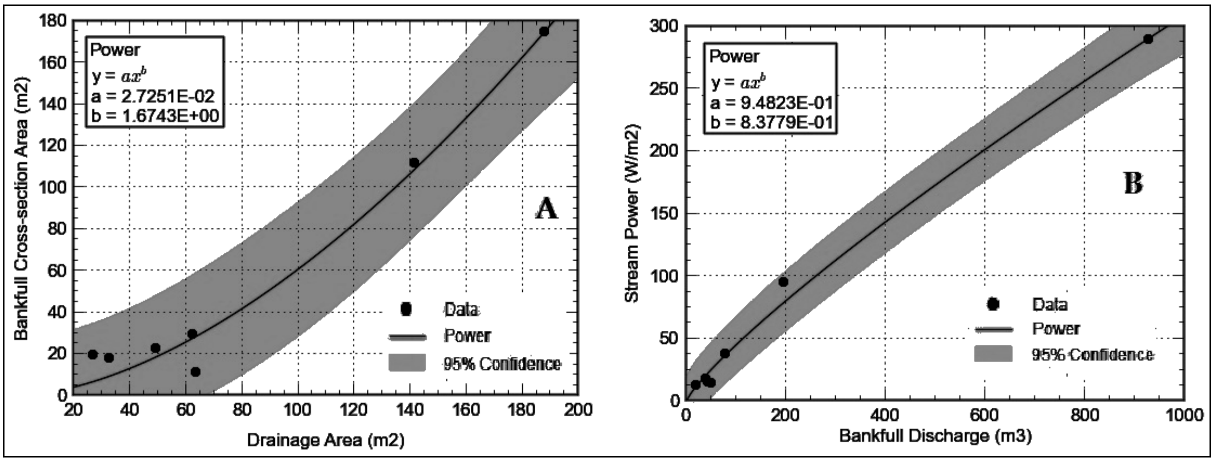


Figure 9. Correlation between the active channel cross-section and the upstream area (A), correlation between the bankfull discharge and the stream power (B).

A typological classification was eventually performed, the channel pattern being differentiated into straight channels, sinuous channels and meandering channels, using the sinuosity index (Brice, 1964). The Water Framework Directive 2000/60/EC recommends all E.U. member states a typological differentiation of all water streams using geoecological criteria (European Union, 2000).

The high lateral dynamics is mainly caused by the decrease of slope gradient and the decrease of bank resistance due to extreme events with high energetic values (flash floods and flooding).

The cartographic analysis of the Niraj riverbed dynamics using Austrian Maps, The Second Campaign (1860), The Third Campaign (1910), Topographic maps 1:25000 (1970) and SPOT satellite images (2012) enabled the identification of highly dynamic sectors.

By analysing the evolution of the Niraj sinuosity index (Fig. 10) for the seven river sectors, a high dynamics of the sectors 4 and 5 can be noticed, which also have the highest value of stream power at bankfull discharge (Fig. 10, Table 4).

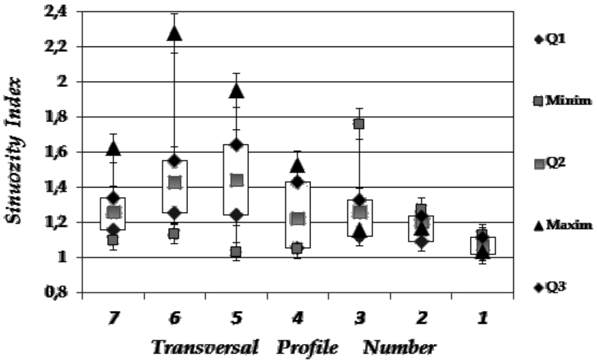


Figure 10. The variation of the sinuosity index on all river sectors

The most stable sectors are those from the mountain and piedmontal areas which have a high resistance to erosion, despite the high stream power (Roşca et al., 2013).

Extreme discharge values lead to meander undercutting (Fig. 11) determining a decrease of the river length and, thus, a decrease of the flow concentration time, having obvious effects on the minor bed morphology.

The slope of the channel determines higher stream power in cross-sections, especially during extreme events. The results indicate that the sinuosity of the main stream declined from 1.59 (specific to meander rivers) to 1.17 (specific to sinuous rivers), with variations at local levels. Consequently, the number of meanders has also decreased from 251 to 218 (Roşca et al., 2013).

Unstable sectors were identified through field observations in the built-up areas of Acăţari, Păsăreni (Fig. 12), Murgeşti and Leordeni settlements where 22 bridges, 1362 m of road and extended agricultural terrains were affected (Roşca et al., 2013). To illustrate this situation, two representative sectors were selected. The first sector is located between Vărgata-Mitreşti settlements (Fig. 14), it is 3.67 km long and has a sinuosity index of 1.27 (sinuous sector).

In the absence of natural and anthropic constraints (terraces, dykes), the river evolved in this sector by passing through lateral migration from a sinuous to a meandering sinuous sector (Fig. 13).

This sector is evolving in the context of an average stream power of 37.28 W/m^2 at maximum flow, which corresponds to a bankfull discharge with a shorter return period, namely 2.6 years.

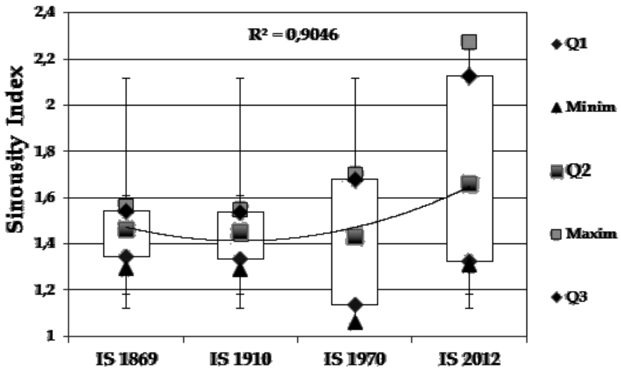


Figure 13. Sinuosity index variation in the interval 1869-2012, Vărgata-Mitreşti sector.

As a consequence, the river will disseminate its energy creating erosional processes depending on the erosional resistance determined by geology and vegetal protection. In the presented case study one can notice a complete change of meandering processes (according to Hooke classification, 1977) in the vicinity of Mitreşti settlement. The main cause of this change highlighted by the analysis of the existing data was lithology. The meander is located in the area where the lithology changes from marly clays to gravel and sand.

On the other hand, in the second sector (Fig. 16), located in the proximity of Acăţari settlement (with a total length of 3528 m and a sinuosity index of 1.65, which includes it in the category of meandering river sectors), a high river dynamics can be noticed in the interval 1869-2012, the variation from the average becoming more obvious especially in the last years (Fig. 15).

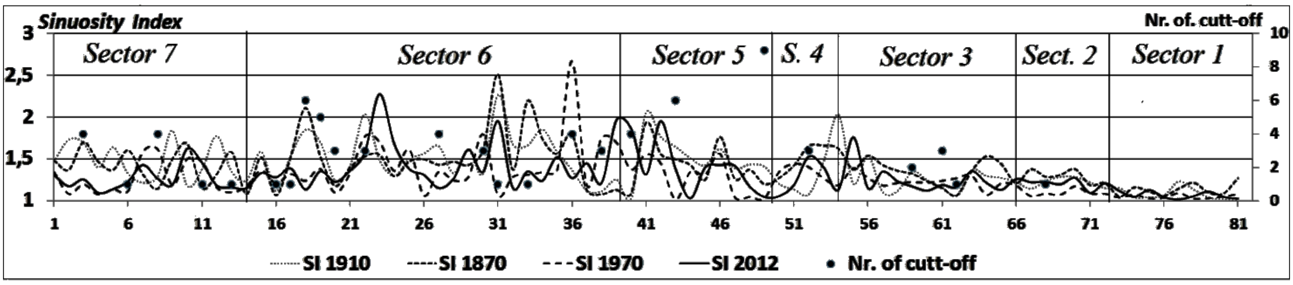


Figure 11. Variation of the Niraj sinuosity index in the interval 1910-2008.

Figure 12. Undercut banks through meandering processes near Păsăreni settlement (foto 4 June 2012).

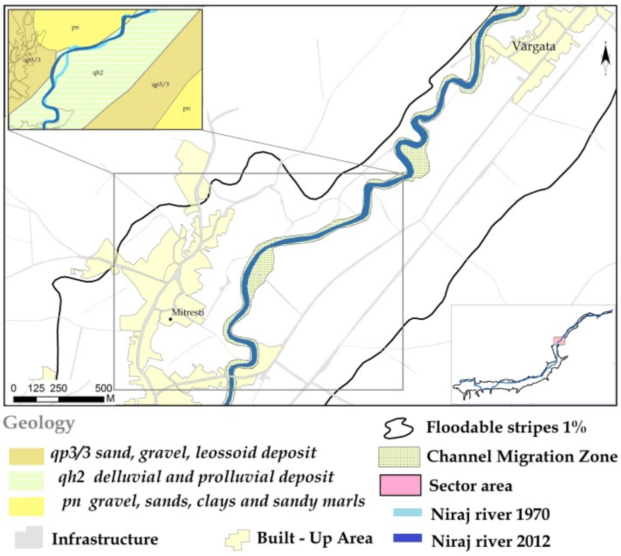


Figure 14. Channel migration zone on Vărgata-Mitreşti sector

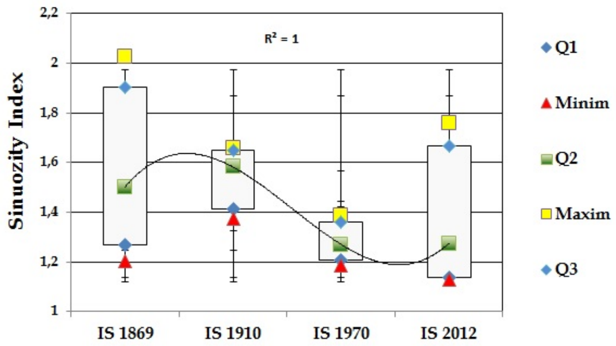


Figure 15.: Sinuosity index variation in the interval 1869-2012, in the proximity of Acăţari settlement

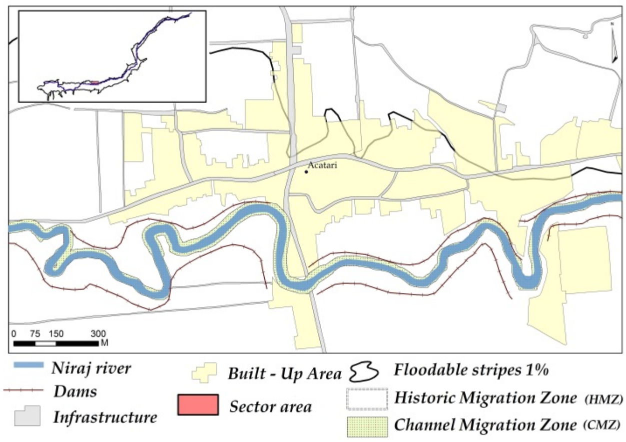


Figure 16. Channel migration zone in Acăţari sector

In this sector, the river evolves in a low energy context of 0.22W/m for the average flow and 8.77 W/m for the maximum flow, the return period of the bankfull discharge being 14.9 years.

This river sector offers an image on the effects created by dykes aimed to protect built-up areas against floods, but limiting the space required by river evolution. The same constraint determines the decrease of the Niraj minimum freedom of movement (Fig. 16).

7. CONCLUSIONS

The assessment of bankfull discharge and the stream power values enables the classification of river sectors according to their response power.

The values determined through the presented methodology punctually illustrate the stream power and the bankfull discharge, but the present study further aims at improving qualitative estimations through the quantification of hydraulic parameters and providing a more realistic image of the morphogenetic environments.

These are characterised by high, medium and low energy, correlated to the zones of the catchment area (according to Schumm, 1977).

River sectors evolving over the stream power of 35 W/m^2 were identified, having a short response time to the upstream changes (<10 years). An important result is represented by the identification of the energy which drives the river evolution, the assessment of bankfull discharge, as the parameter having the highest influence on riverbed stability, and the assessment of its return period. Nevertheless, the studies aiming at identifying the stability of the riverbed and its temporal dynamics will include additional information related to the resistance to erosion, the factor of protective vegetation and the anthropic intervention degree. However, the input determining the irremediable changes inside the system is represented by the maximum flow (during high waters and flash-floods) due to its maximum energetic capacity to produce quantitative and qualitative microscale changes.

Acknowledgments

This paper is made and published under the aegis of the Research Institute for Quality of Life, Romanian Academy as a part of programme co-funded by the European Union within the Operational Sectorial Programme for Human Resources Development through the project for Pluri and interdisciplinary in doctoral and post-doctoral programmes Project Code: POSDRU/159/1.5/S/141086.

REFERENCES

Ahilan, S., O'Sullivan, J., J., Bruen, M., Brauders, N. & Healy, D., 2013, *Bankfull discharge and recurrence intervals in Irish rivers. Proceedings of the Institution of Civil Engineers*, Water Management, 381-393.

Bagnold, R. A., 1966, *An approach to the sediment* *transport problem from General Physics, Physiographic and Hydraulic Studies of River*, United States Gouvernment Printing Office, Washington, 37 pp.

Brice, J.C., 1964, *Channel patterns and terraces of the Loup River in Nebraska*, United States Geological Society, 422 D, 47 pp.

Brush, Jr LM., 1961, *Drainage Basins, Channels, and Flow Characteristics of Selected Streams in Central Pennsylvania*. US Geological Survey, Washington, DC, USA, Professional Paper 282 (F), 145–181.

Bull, W, B., 1979, *Threshold of critical power in streams*, Geological Society of America Bulletin, 90, 453-464.

Castro, JM & Jackson, PL., 2001, *Bankfull discharge recurrence intervals and regional hydraulic geometry relationships patterns in the Pacific Northwest, USA*. Journal of the American Water Resources Association 37(5), 1249–1262.

Copeland, RR, Biedenharn, DS. & Fischenich, JC, 2000, *Channel Forming Discharge. US Army Corps of Engineers*, EDRC/CHL CHETN-VIII-5, 1–10.

Crosado, Alessandra, 2008, *Analysis and modeling of river meandering*, IOS Press, Amsterdam, 251 pp.

Dury, GH., 1961, *Bankfull discharge: an example of its statistical relationship*. Bulletin of the International Association of Scientific Hydrology 6 (3), 48–55.

Ferguson, R.I., 1981, *Channel forms and channel changes*. In: LEWIN J. ed. British Rivers. G. Allen & Unwin, London, 90–125.

Finlayson, D.P., Montgomery, D.R. & Hallet, B., 2002, *Spatial coincidence of rapid inferred erosion with young metamorphic massifs in the Himalayas*. *Geology* 30, 219-222.

Finlayson, D.P. & Montgomery, D.R., 2003, *Modelling large-scale fluvial erosion in geographic information systems.*Geomorphology 53, 147-164.

Fryirs, K.A. & Brierley, G.J., 2013, *Geomorphic Analysis of River Systems: An Approach to Reading the Landscape*. John Wiley and Sons, Ltd, Chichester, UK, 360 pp.

Harvey, AM, 1969, *Channel capacity and the adjustment of streams to hydrologic regime*. Journal of Hydrology 8 (1), 82–98.

Hey, R.D. & Thorne, **C.R.,** 1986, *Stable channels with mobile gravel beds*. *Journal of Hydraulic Engineering*, 112, 671-689.

Hicking, E. J. & Nanson, G., C., 1984, *Lateral migration rates of river bends*, Journal Hydraulic Engineering, Preceedings of the American Society of Civil Engineers, no 110, 1557-67.

Hooke, J.M., 1977, *The distribution and nature of changes in river channel patterns. The example of Devon*. In River Channel changes, Eiley and Sons, Chichester, 265-280.

Ibbeken, H., 1983, *Jointed source rock and fluvial gravels controlled by Rosin's law: a grain size study in Calabria, South Italy*, în Journal of Sedimentary Petrology, nr. 53, 1213-1231.

Ichim, I., Batuca, D., Radoane Maria & Duma, D., 1989, *Morphology and dynamics of riverbeds (in Romanian)*, Technical Publisher, Bucharest 300 pp.

Jain, V., Preston, N., Fryirs, K. & Brierley, G., 2006, *Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment*, New South Wales, Australia. *Geomorphology*. 74, 297-317.

Knighton, A.D., 1982, *Longitudinal changes in the size and shape of stream bed material evidence of variable transport condition*, în Catena, nr. 9, 25-34.

Knighton, A.D., 1999. *Downstream variation in stream power*. Geomorphology 29, 293-306.

Lawler, D.M., 1995, *The impact of scale on the processes of channel-side sediment supply: a conceptual model*. In: Effects of Scale on Interpretation and Management of Sediment and Water Quality. Proceedings of a Boulder Symposium, July 1995. International Association of Hydrological Sciences Publication 226, 175–184.

Lecce, S.A., 1997, *Nonlinear downstream changes in stream power on Wisconsin's Blue River*. Annals of the Association of American Geographers 87, 471–486.

Leopold, L.B. & T. Maddock, Jr., 1953. *The hydraulic geometry of stream channels and some physiographic implications*. U.S. Geological Survey Professional Paper No. 252, 64 pp.

Leopold, L.B., 1954, *Determination of hydraulic elements of rivers by indirect methods*. – Geological Survey Professional, United States Gouvernment Printing Office 32 pp.

Magilligan, F.J., 1992. *Thresholds and the spatial variability of flood power during extreme floods*.Geomorphology 5, 373–390.

McCandless, T.L. & Everett, R.A., 2002, *Maryland stream survey: Bankfull discharge and channel characteristics in the Piedmont hydrologic region. U.S.* Fish and Wildlife Service, Annapolis, MD. CBFO-S02-02, 40 pp.

McCandless, T.L., 2003, *Bankfull Discharge and Channel Characteristics of Streams in the Allegheny Plateau and the Valley and Ridge Hydrologic Region, U.S.* Fish and Wildlife Service, Annapolis, MD. CBFO-S03-01, 33 pp.

Minea, G., Toroimac, Ioana, G., Zaharia, L., Zanea, R. & Borcan, M., 2011, *Spatial Variation of Stream Power in the Buzău and Ialomiţa River Catchment (Romania)*, în Air and Water Components of the Environment, University Press, 283-291.

Nanson, G., C. & Croke, J. C., 1992, *A genetic classification of floodplains*, Geomorfology, 4, 459-486.

Navratil, O., Albert, MB., Herouin, E. & Gresillon, JM., 2006, *Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel bed river reaches*. Earth Surface Processes and Landforms 31 (11), 1345–1363.

Nixon, M.A., 1959, *A study of the bankfull discharges of rivers in England and Wales*. Institute of Civil Engineers Proceedings Paper No. 6322, 157-174.

Pandi, G. & Horvath, Cs., 2012, *Mures river middle course riverbed dynamics between the Aries and Strei confluence*, in Air and Water Components of the Environment, University Press, Cluj Napoca, 49-56.

Pandi, G., Horváth, CS. & Irimuş, I.A., 2013, *Mureş River Hydromorphological Clustering*, in în Air and Water components of the Enviroment, Cluj Napoca, 95-102.

Pickup, G. & Warner, RF., 1976. *Effects of hydrologic regime on magnitude and frequency of dominant discharge*. Journal of Hydrology 29(1–2), 51–75.

Rădoane, M., Obreja, F., Cristea, I. & Mihăilă, D., 2013, *Changes in the channel-bed level of the eastern Carpathian rivers: Climatic vs. human control over the last 50 years*, in Geomorphology, 193, 91-101.

Rădoane, Maria, Rădoane, N. & Ioniță I., 2002, *Size analysis and petrographic facies of the Suceava river bed (in Romanian)*, in Analele Universitatii „Stefan cel Mare" Suceava, X,37-48.

Roşca, Sanda, Petrea D. & Iacob I., *2013, Niraj River's channel migration: a response to hydro-climatic variability, in* Air and Water components of the Enviroment, Cluj Napoca, 391-398

Roşca, Sanda, Petrea D. & Iacob I., *2012, Vulnerability to channel migration on the Niraj river, în Geographia Napocensis, Cluj Napoca, 2, 40-46.*

Rosgen, D.L., 1994, *A classification of natural rivers*, Catena 22, 169-199.

Rustomji, P., 2009, *A Statistical Analysis of Flood Hydrology and Bankfull Discharge for The Daly River Catchment, Northern Territory, Australia*. National Research technical report, CSIRO Land and Water, Clayton South, Australia, 61 pp.

Roşca, Sanda, 2011, *The flash floods analysis, representative for Niraj river between 1970-2008,*în Air and Water components of the Enviroment, Cluj Napoca, 560-567.

Roşca, Sanda, Petrea D. & Iacob I., 2012, *Vulnerability to channel migration on the Niraj river, în* Geographia Napocensis, ClujNapoca, nr. 2, 40-46.

Schmitt, L., Valette, L., Valine, K., Piégay, H. & Hallot, E., 2004, *Preposition d'une method de typologie hydro-géomorphologique des coursd'eau et test sur un sous-bassin du Rhône (Bassin de l'Yzeron),* in Mosella, XXIX 3-4, 323-341.

Schmitt, L., Trémolières, M., Nobelis, P. & Maire, G., 2007, *Complémentarité entre typologie hydro-géomorphologique et biologique de rivières dans l'hydrosystemes fluvial ello-rhénan français.* In Trémolières , M., Schnitzler, A., Silan, P., editors: Protéger, restaurer et gérer les zones alluviales. Pourquoi et comment? Lavoisier, Editions TEC & DOC, Paris, 123-136.

Schmitt, L., Lafont, M.,Trémolières, M., Jezequel, C., Vivier, A., Breil, P., Namour, P., Valin, K. & Valette, L., 2011, *Using hydro-geomorphological typologies in functional ecology: preliminary results in contrasted ecosystems*. Physics and Chemistry of the Earth, Parts A/B/C, 36 (12), 539-548**.**

Simons, D.B. & Richardson, E.V., 1966, *Resistance to flow in alluvial channels*, United States Geological Survey Professional Paper, 422-J, 61 pp.

Shields, F. D., Copeland, R. R., Klingeman, P. C., Doyle, M. W. & Simon, A. 2003. *Design for stream restoration. J. Hydraul. Eng.*, 129, 8, 575–584.

Schumm, S., A., *1977, The fluvial system,* Wiley and Soons, New York, 338 pp.

Stacey, M., *2007, Testing specific stream power threshold of channel stability with GIS,* in Wilson, A.L., Dehaan, R.L., Watts, R.J., Page, K.J., Bowmer, K.H., & Curtis, A. (2007). Proceedings of the 5th Australian Stream Management Conference. Australian rivers: making a difference. Charles Sturt University, Thurgoona, New South Wales, 1, 384-389.

Stover, S., C., 2001, *Channel change and flooding,* Skokomish River, Washington, in Journal of Hydrology, 243, 272-286.

Toroimac, Gabriela, 2009, *La dynamique hydrogéomorphologique de la rivière Prahova (Roumanie): fonctionnement actuel, évolution récente et conséquences géographiques*. Thèse de doctorat, Université Lille 1 Sciences et Technologies, 341 pp.

Toroimac Gabriela, Minea, G., Zaharia, Liliana, Zarea, R. & Borcan, Mihaela, 2013, *Hydrogeomorphological river typology in the Ialomiţa and Buzău catchments (Romania),* in European Continental Hydrosystems, Pheil, München, 261-272.

Wallick, Jennifer R. Grant, G. E. Lancaster, St. T., Bolte, J.P. & Denlinger, R.P., 2007, *Pattern and Controls on Historical Channel Change in the Willamentte River, Oregon, USA,* in Large River, Geomorphology and Management, 491- 516.

Wellemeyer, J., Stattery, M. & Philips, J., 2005, *Quantifiying downstream impacts of impoundment on floow regime and channel platform, lower Trinity River, Texas,* in Geomorphology, nr. 69, 1-13.

William, A., H., 2010, *Finding Bankfull Stage in North Carolina Streams*, N.C. Cooperative Extension Service, 4 pp.

Williams, GP., 1978, Bankfull discharge of rivers. Water Resource Research 14 (6), 1141–1154.

Wolman, M.G., 1955, *The natural channel of Brandywine Creek, Pennsylvania*. U.S. Geological Survey Professional Paper 271. U.S. Government Printing Office. Washington, D.C, 59 pp.

Wolman, M., G. & Miller, J.P., 1960, *Magnitude and frequency of forces in geomorphic processes,* J. Geol., 68, 54-74.

Wolman, MG. & Leopold, LB., 1957, *River Flood Plains: Some Observations on Their Formation.* US Geological Survey, Washington, DC, USA, Geological Survey professional paper, 282-C, 87–107.

Worthy, M., 2005, *High-Resolution Total Stream Power estimates for the Cotter River, Namadgi National*

Park, Australian Capital territory, in Roach I.C., ed. Regolith 2005 – Ten Years of CRC LEME. CRC LEME, 338-343.

Woodyer, KD., 1968, *Bankfull frequency in rivers*. Journal of Hydrology 6 (2), 114–142.

Zaharia, L. Toroimac, G.I., Catană, S., Minea, G.,& Delporte, C., 2012, *River lateral dynamics and floods in relation to human communities. Case study: Moara Domneasca village (on lower Teleajen river)*, in Air and Water Components of the Environment, University Press, Cluj Napoca, 119-126.

Zăvoianu, I., 2007, *Hydrology (in Romanian)*, Publishing of Tomorrow Foundation Romania, Bucureşti, 256 pp.

Xia, J, Wu, B., Wang, G. & Wang, Y., 2009, *Estimation of bankfull discharge in the Lower Yellow River using different approaches*. Geomorphology 117 (1–2), 66–77.

***, *2000, Directive 2000/60/EC of the European Parliament and the Council establishing a framework for the Community action in the field of water policy*. Official Journal of the European Communities, L 327, 72 pp.

Received at: 30. 04. 2014
Revised at: 22. 09. 2014
Accepted for publication at: 07. 01. 2015
Published online at: 15. 01. 2015