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TIME TRACKING OF THE PRUT RIVER BED EVOLUTION AT IASI COUNTY LIMITS

BY

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Abstract. The article presents the dynamics of the Prut riverbed in the sector Iasi, between 1890 and 2016, studied through the changes in the floodplain of the river as a result of the modification of the channel due to erosion/sedimentation phenomena, exposed by comparing the land surface changes of the 2nd UAT order of the IAŞI county over the analyzed period. The reference land area of UAT order 2 of Iasi County was considered the one defined by the territorial administrative limits established at the last cadastral delimitation and the Prut riverbed digitization based on the directive drawing plans 1:20 000 from the year 1940. The land areas of UAT order 2 of Iasi County used for the comparative study were determined on the basis of the territorial administrative limits and the Prut river channel digitization based on the LANDSAT TM and ETM + Satellite Records of 17 August 2000, SENTINEL 2A dated 1th of April 2016, as well as on the topographic maps 1st Edition and 2nd Edition at 1: 25,000 scale. The Surface Comparison Method allows the illustration, visualization, measurement, thematically mapping and the analysis of erosion and sedimentation phenomena for the entire studied area.

Keywords: erosion; change over time; Prut River; GIS; remote sensing.

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1. Introduction

The meandered rivers, such as the Prut River, can behave as a very dynamic geo-morphological system, as the change in the channel of these rivers in their natural environments show complex interactions in the floodplain and are often governed by a dynamic evolution of meandering.

The anthropogenic factor produces changes in the discharge regime of the river, influencing the flow of both the liquid and the solid, thus leading to the morphological adjustment of the riverbed. There are several man made interventions which are responsible for river modifying and resulting in river channel adjustments, such as forest clearing, dam construction, gravel exploitation, forestry, agriculture and urbanization (Gregory, 2006).

These interventions produce the modification of the width, depth, sinuosity or stability of the riverbed (Ziliani & Surian, 2012; Bollati *et al.*, 2014). On the other hand, in some cases, these are leading to a decrease in the flow dynamics of the river, where the process of meandering is active, leading to a high riverbed stability (Magdaleno & Fernandez-Yuste, 2011).

The presence of oxbow lakes in the Prut River floodplain suggests intense river processes during the last 200-300 years.

This study aims at: (i) assessing the cartographic and remote sensing sources used to extract the channel, (ii) assessing of survey technologies, (iii) identifying the spatial and temporal patterns of the Prut riverbed changes, (iv) analyzing the types and the mechanisms for morphological modifying of meanders and (v) investigating possible explanations for the channel position changes, in particular the influences of the anthropogenic factor and of the natural processes of evolution towards a stable riverbed.

Analysing the changes of the riverbed position in the studied area is also important because the Prut River represents the natural border between Romania and the Republic of Moldova.

Starting with 1948, Romanian state border with the former Soviet Union and later with Ukraine and the Republic of Moldova was established on the Prut River, from its entrance on the romanian land at Oroftiana village down to the confluence with the Danube. Therefore the Prut River is a water border, and so the people's access to it and the activities in this area are subject to a special legal regime. The strict regulations stipulated in the Treaty between the Government of the Romanian People 's Republic and the Government of the Union of the Soviet Socialist Republics concerning the Romanian - Soviet State Border Regime, Collaboration and Mutual Assistance in Border Issues (applicable today also in the absence of a Treaty on the Romanian - Moldovan cooperation, mutual assistance and assistance in border issues, between Romania and the Republic of Moldova) in terms of measuring the demarcation of the state border, this activity being carried out only within the Mixed Border Commissions (the last check of the state border route Between 1972 and 1974), but also the activities that neighbouring countries carry out on the banks of the Prut River, were the reasons why the study of the bank erosion rates of the riverbed and the evolution trends in the channel were not sufficiently studied in latest years.

The study was conducted for the 1890-2016 time frame, using topographic maps, remote sensing data (orthophotomaps and satellite images) and GNSS measurements.

2. Study Area

The Prut River, in the Iaşi County, marks the eastern border of Romania with the Republic of Moldova.

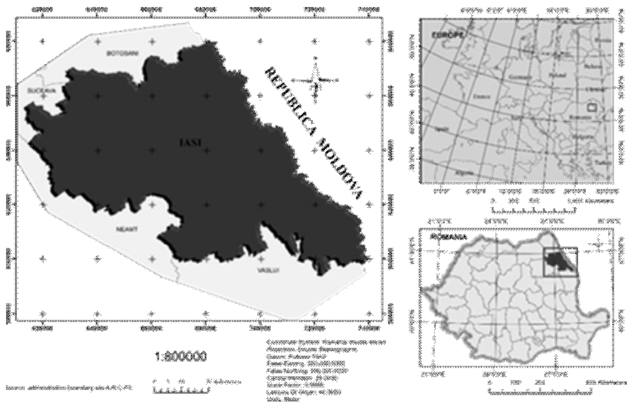


Fig. 1 – Study area.

The study area is located in the middle section of the Prut River, at about 48 km downstream of the Stanca-Costeşti Dam, in a zone characterized by a floodplain area with a width of 4,...,8 km, developed to a greater extent on Republic of Moldova's side.

The channel has a length of 220 km with a slope of less than 0.02%. The minor riverbed has a width of between 41 and 120 m (Fig. 2).

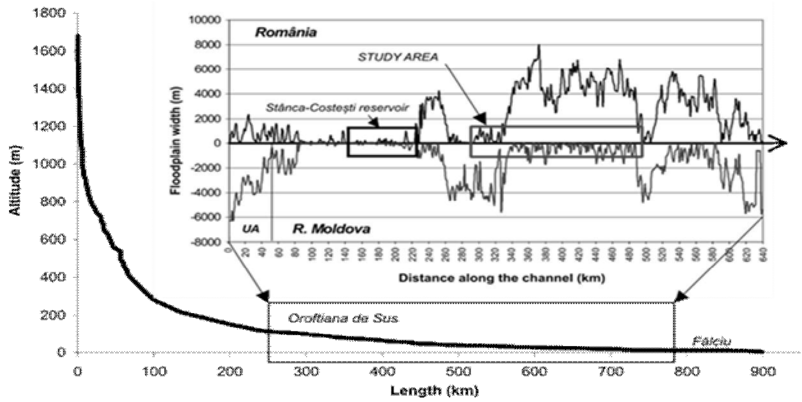


Fig. 2 – The Prut River's longitudinal profile in the study area.

The Prut is a meandered river characterized by side migration of the meanders. Its channel is sinuous and showing irregular meanders (Fig. 3 *a*). The meanders are in progress and in the last centuries there have been several cut-offs (Fig. 3 *d*), proof being the oxbow lakes (Fig. 3 *a*, *c*).

The meander type is dominated by the composed asymmetric ones and by some simple symmetric ones.

The morphology of the rifle-pulls characterizes the canal topography, with concave and inner banks (Fig. 3 *e*, *f*).

The geographic position of the hydrographic basin, namely the Plateau of Moldavia and the Lower Prut Plain, led to the installation of varied vegetation. The forest area is represented by deciduous forests belonging to the oak floor, being associated with species such as hornbeam, maple, birch, elm, poplar, crabapple, sometimes linden tree. The rarer forests allow for a high frequency of shrubs: horn, bloom, crust, rose, and a rich herbaceous flora composed of: lungwort, ferns, white nettle, but also the well-known spring ephemeris: wood violet, crested lark, alpine squill or lilly-of-the-valley.

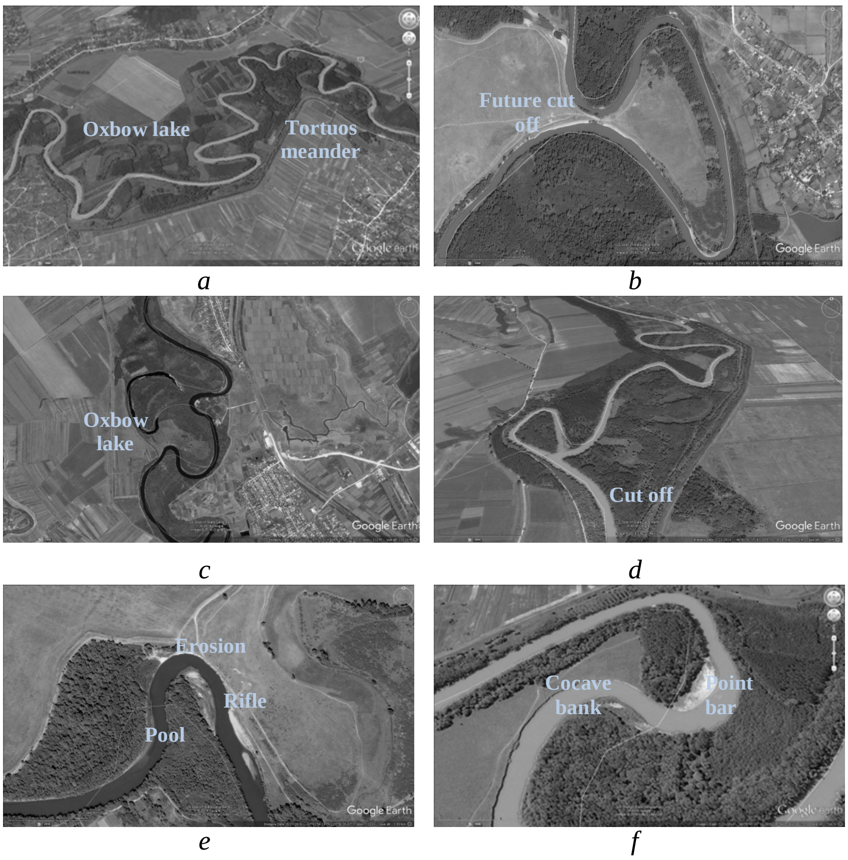


Fig. 3 – Meander types.

2.1. Climate and Hydrological Regime

The territory of Iasi County belongs to the temperate - continental climate zone under the influence of Atlantic and Euro-Asian anti-cyclones.

The global solar radiation, with 116 kcal/cm^2 mean values, is unevenly distributed during the year, with 40% in the summer (July = 17 kcal/cm^2), while winter has only 10% of the total (January = 2.2 kcal/cm^2).

The average annual air temperature rests between 8°C and 9°C in the south and between 9°C and 10°C in the north and northeast. The highest monthly average values are registered in July (20°C,…,21.5°C), and the lowest values are recorded in January (under – 4°).

The extreme temperatures have absolute maximums of + 40° and absolute minimums of - 35°. Temperatures above 5°C are recorded from 23rd of March and last until November 11th, and those above 10°C are recorded between the 11th of April and the 20th of October (180-185 days).
A thermal characteristic specific to the November-March interval is frost, which occurs on average in autumn, in October and spring in April, the average number of frost-days being 110. The earliest freezing occurred on September 10th, and at the latest on 21st of May. As a rule, the first frost occurs around October 14th and last on April 20th. In areas with altitudes under 350 m. the average number of days with frost is110.

During the warm season of the year, there are on average 85 summer days with maximum temperatures equal to or above 25°C and 23 tropical days of 30°C or more.

Rainfall in the county averages from 450,...,500 mm. over the northeast and south, to 550 mm. in the zone of contact between the high and the hilly plain. During the year the precipitation regime is also uneven, with large amounts in May and June, sometimes July (average 65,...,75 mm.) and small in December - March (on average 25,...,35 mm.). Around 70% falls as rain, with the exception of the interval from the last decade of November to the last decade of March, when there are 34 to 42 days with snowfall. Of all precipitation, 35-40% falls in summer, 23,...,35% in spring, 17,...,23% in autumn and 10,...,17% in winter.

A characteristic of the rainwater regime of the county is the abundance as well as the rainfall deficit, so to mention the torrential clouds, when in a short time there are recorded quantities exceeding 50,...,60% of the sum of the respective month, being the cause of floods and landslides, the activation of erosion, etc.

The characteristics of the hydrological regime of the Prut River in the study area are given by the measurements made at the Ungheni and Prisacani hydrometric station. Thus, for the geographic area under study, in the conditions of a more temperate continental climate, over a calendar year, in the regime of the rivers, the existence of four periods is constant:

1º *The Winter Period* (December to February) with a low drain, predominantly fueled by underground resources, characterized by the retention of precipitation on the ground as a snow cover and the presence of frost phenomena on the watercourses. During this period, the flows can drop below 10 m3/s as it was in 1964, when the minimum flow in Ungheni was 5.56 m^3/s; The average flow rate is 74.04 m^3/s.

2º *The spring period* (March - May), characterized by a great wealth of flow due to the melting of snow and precipitation. There are floods and high waters with longer durations. The average flow rate is 124.45 m^3/s.

3º *The summer period* (June - August). Percentages for annual flow volumes are lower than spring, but are still high due to high torrential floods. Maximum flows are recorded in June - July. The average flow rate is 134.12 m^3/s.

4º *The autumn period* (September to November). It is characterized by a lower flow, by increasing the role of underground resources. The average flow rate is 82.62 m^3/s.

At the Prisacani hydrometric station, based on the measurements, the multi-annual average flow was calculated to be 103.81m^3/s. The minimum flow rate recorded between 1981 and 2015 was 13.4 m^3/s recorded on January 30, 1988, and the maximum flow rate over the same time period was 900 m^3/s, recorded on 9 and 10 July 2010 The average monthly flow rate was 674 m^3/s in July 2010, the highest recorded monthly average flow, exceeding by almost 200 m^3/s the historical flow of 478 m^3/s in August 1955 (Butnariu, 2016).

3. Material and Method

In order to analyze the development of the Prut riverbed between 1890 and 2016, the river canal was obtained by digitizing the rivers Prut River (Oguchi et al., 2013) in ArcGIS using the following data:

a) *topographic maps* (Atlas of Moldova in 1890 at the scale of 1: 50,000 (Fig. 4 *a*)), the 1920 Army Plans at 1: 20,000 scale (Fig. 4 *b*), 1st Edition (1960) and 2nd Edition (Fig. 4 *d*) of the military topographic maps at 1:25,000 scale, the topographic maps from the album of the state border maps between the USSR and the Romanian RP elaborated in 1949 (Fig. 4 *c*);

b) *remote sensing data*: Landsat, Sentinel 1A and 2A satellite images (Fig. 4 *e*), orthophotomaps at 1:5000 scale in 2005 (Fig. 4 *f*), 2008-2010 (Fig. 4 *g*), 2010-2013 , 2013-2015.

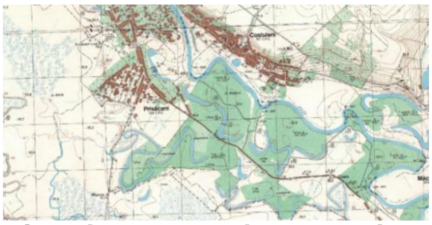
For the georeferenced of the 1:25,000 scale topographic maps the Gauss Krüger plane rectangular coordinates of the trapezoid corners and the crossing points of the kilometer grid in stereo rectangular coordinates Stereo – 70 with the Matlab software were transformed. Because the georeferencing of a raster image was used between 84 and 104 points to optimize local accuracy, the polynomial transformation method of the third order was used (Imbroane, 2012). For the 1:50,000 scale maps, 1893-1894 edition and 1:20,000 scale

Army Plans, 1940 edition, georeferenced was done using common points on these maps with those on the map at scale 1:25,000 1st edition of the Year 1960. The LANDSAT satellite imagery of August 17, 2000, as well as the Sentinel 2A from April 1 and August 9, 2016, delivered by the manufacturer are referenced in the UTM projection system with WGS84 datum. They were redesigned in the Stereo-70 projection system, the Pulkovo1942 datum, using the ArcGIS software (Imbroane, 2012).

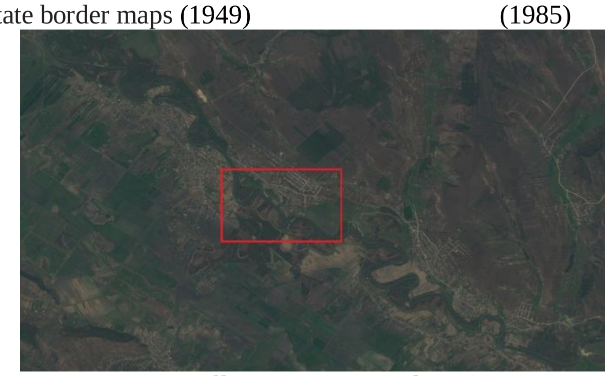
a – Moldavian Atlas (1890)

b – Army Plans (1920)

c – topographic maps from the album of the state border maps (1949)



d – Military topographic maps Ed. II (1985)



e –Satellite image Sentinel 2A (2016)

f – Orthophotomaps (2005)

g – Orthophotomaps 2008-2010

Fig. 4 – Data types.

The satellite imagery was used to make the Normalized Difference Water Index (NDWI) maps using the formulas:

$$NDWI = (Band_{NIR} – Band_{G})/(Band_{NIR} + Band_{G})$$

– for the LANDSAT TM image: NDWI = (B4 – B2)/(B4 + B2) (1)
– for the SENTINEL 2A image: NDWI = (B8 – B3)/(B8 + B3) (2)

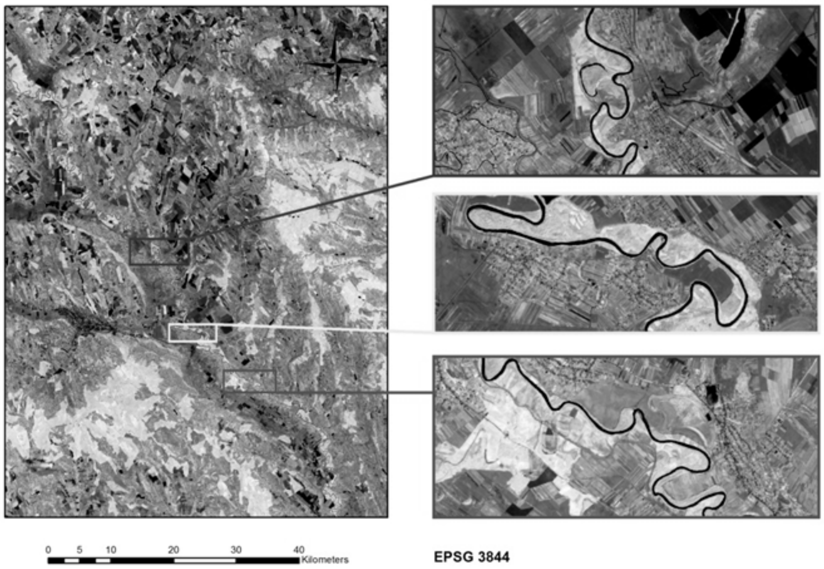


Fig. 5 – NDWI_2016 map for the study area.

These maps have highlighted the Prut River canal, and the index is also useful for mapping bodies of water, for visualisation of turbidity differences and vegetal content of water, alluvial soils or for differentiation of water content from vegetation. It also using green and near-infrared spectral bands. Dark gray levels (close to -1) expresses the water surface, bright gray levels (close to one), dry land and intermediate gray levels (close to 0), land containing intermediate moisture (Herbei, 2013) (Fig. 5).

In the DSAS application, transects lines of 1 km length were drawn at a distance of 100 meters between them in order to determine the lateral migration of the riverbed, the lateral migration analysis stages being shown in Fig. 6 (Butnariu, 2017).

3.1. Morphology

The mechanisms of the modification over time of the meanders were classified after Hooke and Harvey (1983), including the following types: growth, migration, limited migration, lobe, cut-off (breakthrough), retraction, new meander and complex changes (Fig.7).

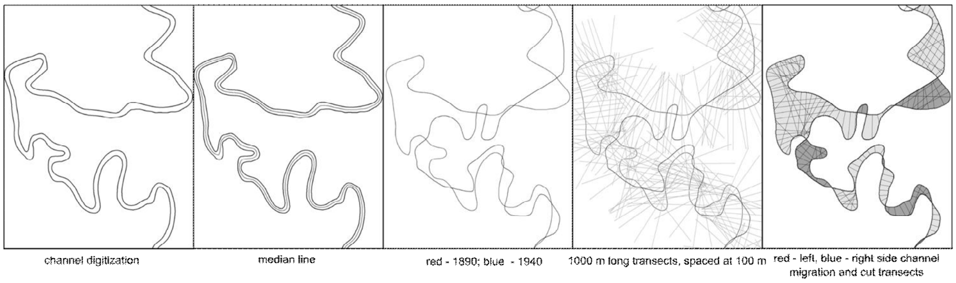


Fig. 6 – The workflow.

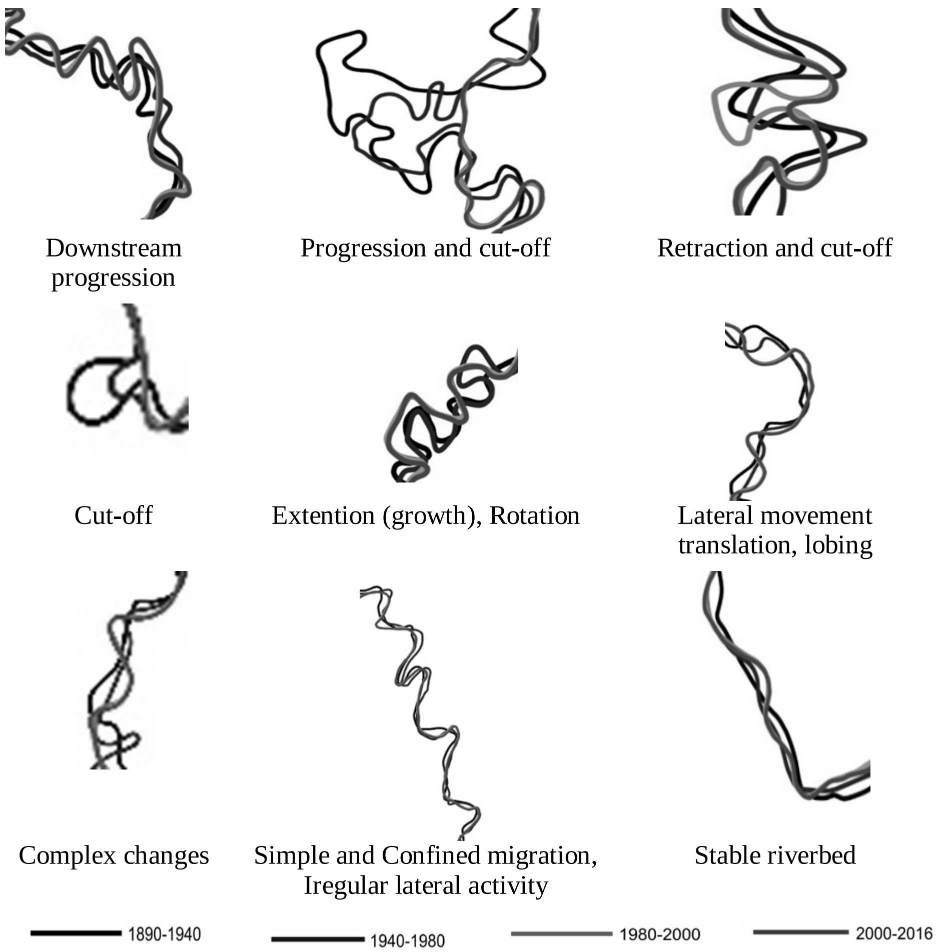


Fig. 7 – The riverbed modifying mechanism.

3.2. Morphometry

The changes were analyzed according to the variation of the sinuosity index for the studied river sector.

3.3. Morphodynamics

Morphodynamic analysis is carried out taking into account the changes to the floodplain area by altering the position of the river bed along the course of the analyzed period (Hooke *et al*., 2010). Land area affected by erosion (E), sediment deposition (D) were calculated using the ArcGIS *Symmetrical Difference* function and the newly created surface as a result of the two processes (T).

The reference land area of UAT Iasi was considered to be the one defined by the territorial administrative limit established at the last cadastral boundary and the middle of the Prut River digitized on the basis of the Army Plans at1:20, 000 scale from the year 1940.

The erosion/deposition rate (E/D) was also calculated. These parameters are used for the analysis of the change in the Prut River run during the analyzed period (Morais *et al*., 2016). The thematic maps were created for a better representation of erosion and sedimentation processes (Fig. 8).

For the years 2015 and 2016, GNSS measurements with the Leica 1200 system were carried out in Prisacani commune, Iasi County, for the validation of satellite images.

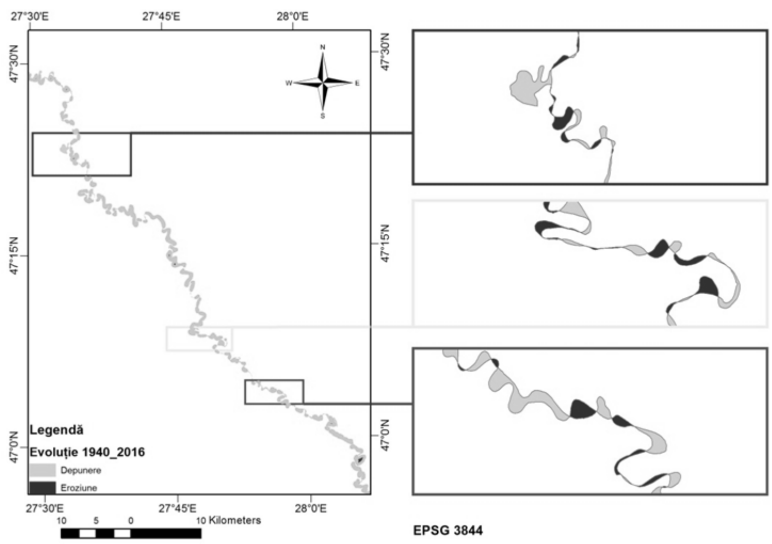


Fig. 8 – The thematic map with the erosion and sedimentation phenomena.

4. Results and Discussionss

As can be seen in Fig. 9, the meanders of the Prut river bed in the study area migrated downstream, increased, formed lobes, there were also cut offs, retractions, but also complex changes.

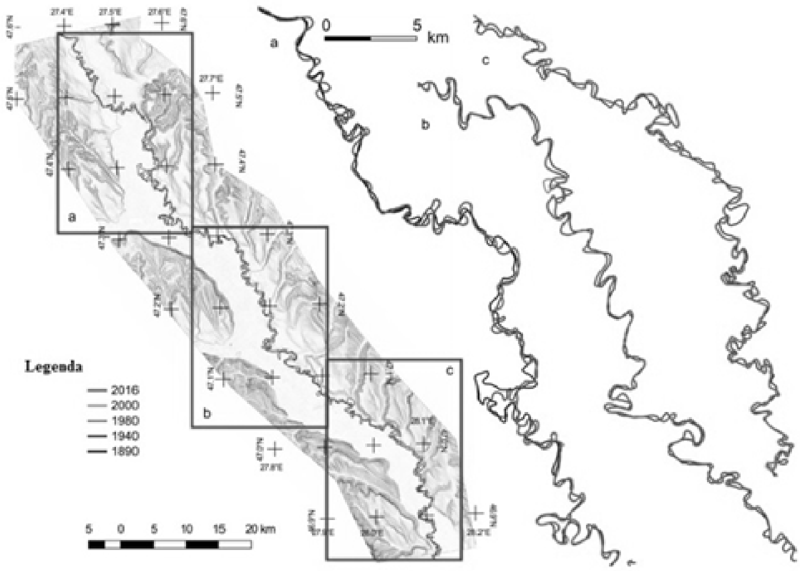


Fig. 9 – The thematic map with the erosion

The surface of the Territorial Administrative Unit of Iasi County has evolved due to the floods affected by the lateral migration of the Prut River, as shown in Table 1. The detailed statistics of the erosion phenomena, deposition of sediment for each analyzed period are presented in Table 2.

Also, the sinuosity index (KS) for the river sector of the study area was calculated, the results are presented in Table 3.

Downstream of the Stanca Costesti Dam, floodplains with low slope and sandy sediment, allowed the presence of a meandering channel. Prior to the river bed treatment, the meanders were free and highly mobile. After the flood control and protection floods works (1960–1970), the solid flow decreased and the levees constrained the development of the meanders.

Table 1
The terrain area over the analised time period

Year	Area of TAU IAŞI $m^2 \times 10^6$
1940	5,481.52
1980	5,478.42
2000	5,476.99
2016	5,477.39

Table 2

The Morphodynamic Values for Each Period.

Period	**E** $m^2 \times 10^6$	**D** $m^2 \times 10^6$	**AP** $m^2 \times 10^6$	**T** $m^2 \times 10^6$	**E/D** $m^2 \times 10^6$
1940 – 1980	14.93	11.83	-3.10	23.66	1.26
1980 – 2000	2.64	1.20	-1.43	2.41	2.19
2000 – 2016	1.43	1.84	0.40	3.67	0.78

E = **E**roded area, **D** = Deposited of sediments area, **AP** = the area formed by both process, **T** = Total Morphodynamic, **E/D** = **E**roded/**D**eposited rate

Table 3

Values of Sinuosity Coefficient

Year	River sector length **L**, **[**m]	Straight line distance **D**, **[**m]	Sinuosity coefficient $\mathbf{K_S}$
1940	211,532.288	99,905.062	2.12
1960	219,282.288	99,940.952	2.19
1985	224,639.938	99,968.797	2.25
2000	227,684.006	99,961.274	2.28
2005	228,394.804	99,963.446	2.28
2013	227,924.459	99,943.387	2.28
2016	230,714.901	99,944.147	2.31

Thus, after 1890, the Prut riverbed had a great mobility in a buffer zone of ±400 m, and after the bed restoration work, the mobility substantially decreased (Fig. 10).

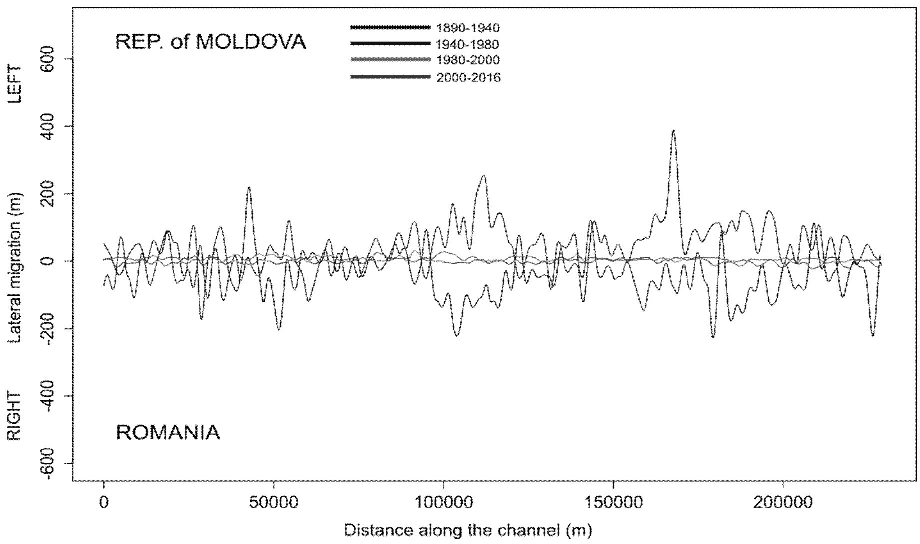


Fig. 10 – Lateral migration of the Prut River between 1890 and 2016.

The morphological changes of the riverbed were intense in the 1890-1940 and 1940-1980 periods, characterized by shore breaks and cut-offs, but also in the period 2000-2016 (the last cut-off took place in 2010, at the administrative limit with Vaslui County), period with rainy years (the historical maximum flow rate of 900 m^3/s in the Prisăcani station was recorded on 9^{th} and 10^{th} of July 2010), where, as can be seen in Table 2, the eroded area is approximately equal to the newly created by deposition of sediment, both of which have high values. This intense activity is also confirmed by the sinuous index, with significant increases over the same period (Table 3). The period between 1980 and 2000 is more balanced as seen in Fig. 10, which is also confirmed by the increase of Eroded area/Deposited area (E/D) in this period (Table 2).

5. Conclusions

The study identifies the specific characteristics of the typology of the Prut riverbed, which has evolved under different conditions in the past 130 years. Thus, until the construction of the dam from Stanca Costesti, the meanders had a free evolution, but with the construction of the dam, with the role of controlling the liquid and solid flows downstream and with the execution of the bed restoration works and the flood protection, lateral migration of the meanders is much decreased, after 1980 having values of up to 50 meters, and in some cases values up to 80 meters.

The river dynamics of the studied river sector is the result of cumulative anthropogenic factors. Fluid flow control has led to a diminution of wetlands, oxbow lakes.

Even though the meandering of the river has been considerably decreased lately, this process is one of progress, proof being the continuous increase of the sinuosity index from 2.12 in 1940 to 2.31 in 2016, but with a very small increase between 2000 and 2016 ($\mathbf{K}_S$ = 2.28 to 2.31).

In relation to the used satellite data, Landsat ETM + images allow only an approximate assessment of these changes. The relatively small resolution of 30 meters does not allow precise measurements. It is true that the use of very high resolution satellite imagery would reduce the uncertainty in current research but due to the fact that Landsat satellite imagery is provided by the USGS free of charge and covers time periods for which there is no other information as well as due to the fact that several articles in which the morphological changes of the riverbeds were analysed, articles published abroad in prestigious journals, the authors used Landsat satellite images, determined the inclusion of these satellite data in the present study (Chu *et al.*, 2006; Peixoto *et al.*, 2009; Ahmed & Fawzi, 2011; Thakur *et al.*, 2012; Henshaw *et al.*, 2013; Morais *et al.*, 2016: Yousefi *et al.*, 2016) thus being useful in detecting areas where the erosion or sediment deposition is present.

For the year 2016 Sentinel 2A satellite images with a resolution of 10 m were used. These were downloaded free of charge from Copernicus.eu, these images being available only from the end of 2015.

The validation of vector data resulting from digitization on these images was done by measuring the right bank of the Prut River in the years 2015 and 2016 with the Leica 1200 GPS system.

Taking into account the climatic changes and the fact that many human settlements are in the floodplain area, in the immediate vicinity of the minor riverbed of the Prut River, on the background of some rainy future seasons, there is a risk that the population in the area will suffer from major floods.

Also, the importance the riverbed path evolution over time is given by the fact that since 1949 the Prut River in the Iasi County forms the natural border with the Republic of Moldova.

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URMĂRIREA EVOLUȚIEI ÎN TIMP A ALBIEI RÂULUI PRUT ÎN SECTORUL IAŞI

(Rezumat)

Este prezintată dinamica albiei râului Prut în sectorul Iaşi, în perioada 1890-2016, ca urmare a fenomenelor de eroziune / depunere de sedimente, evidențiate prin compararea modificării suprafeței de teren a UAT Prisăcani în perioada de timp analizată. Suprafața de teren de referință a UAT Prisăcani a fost considerată cea definită de limita administrativ teritorială stabilită la ultima delimitare cadastrală şi malul drept al râului Prut digitizat pe baza hărților topografice scara 1:25 000 din anul 1985. Suprafețele de teren ale UAT Prisăcani utilizate pentru efectuarea studiului comparativ, au fost determinate pe baza limitelor administrativ teritoriale şi a malului drept al râului Prut, digitizate pe baza înregistrărilor satelitare LANDSAT TM şi ETM+ din data de 17 august 2000, 13 august 2010 şi 4 martie 2015. Metoda de comparare a suprafețelor permite evidențierea şi măsurarea distinctă a fenomenelor de eroziune şi depunere de sedimente, pentru întreg arealul studiat, vizualizarea, realizarea hărților tematice şi analizarea fenomenelor.