

RIVERBED DYNAMICS OF SUCEAVA RIVER AT THE TRANSITION BETWEEN THE CARPATHIANS AND THE EASTERN LOWLANDS

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ABSTRACT

This study examines the morphological evolution of the mountain riverbed reach of Suceava river over a span of more than 150 years using historical maps, orthophotos, and satellite imagery. Key morphological parameters, including sinuosity and braiding indices, as well as variations in active river area and floodplain width, were analysed from 1869 to 2021. The findings reveal periods of increased river dynamics, marked by active meandering and braiding, alternating with phases of stabilization of the riverbed. Both natural processes and anthropogenic interventions have contributed to these adjustments, interfering with regional flood risks, sediment transport, and habitat development along the watercourse. This analysis underscores the need for adaptive management strategies to promote sustainable river management in the context of ongoing hydrological and environmental changes.

Keywords: *Braiding; Evolutionary trend; Morphology; Riverbed dynamics; Suceava river*

1. INTRODUCTION

Rivers are dynamic geomorphological systems which play a crucial role in shaping landscapes, ecosystems, and human settlements through processes like erosion, sediment transport, and deposition (Leopold et al., 1964; Schumm, 1977). Watercourse behaviour results from the interaction between climatic variability and human intervention, which underscores their importance for studies focused on water resource management, flood risk mitigation, and environmental conservation (Knighton, 1998; Foley et al., 2005; Langat et al., 2019; de Musso et al., 2020; Korjenić et al., 2021).

At the global scale, long-term trends in river discharge remain difficult to generalize, as regional signals often outweigh any overarching trend (Eyring et al., 2021). At the European level, however, analyses covering the second half of the twentieth century reveal pronounced spatial contrasts, including declining streamflow in southern regions, mixed responses in central areas, and increasing discharge in the north (Caretta et al., 2022). Against this background, the investigation of river channel dynamics over the last 150 years has become a central component of river management. Long-term reconstructions allow past adjustments to be placed in context and provide a framework for interpreting present-day channel behaviour and potential future trajectories (Mandarino et al., 2019; Mandarino, 2022).

Recent methodological approaches increasingly use historical cartographic sources and remote sensing data to trace channel adjustments across multiple temporal scales. The integration of old maps, aerial photographs, and satellite imagery supports both qualitative interpretations and quantitative assessments of planform and morphological change in river systems worldwide (Harmar & Clifford, 2006; Schwenk et al., 2017; Batalla et al., 2018; Langat et al., 2019; Verduyck & Grabowski, 2021).

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A growing body of research has examined the evolution of European rivers over the past two centuries, emphasizing the interplay between natural processes and human pressures. Studies from Italy indicate that many channels underwent a prolonged phase of narrowing and bed incision beginning in the late nineteenth century, followed more recently by partial widening and local bed stabilization. These trends are mainly associated with sediment extraction, engineering works and dam construction, which altered sediment supply more strongly than discharge regimes (Surian et al., 2009; Mandarinò et al., 2019; de Musso et al., 2020). Evidence from other Southern European catchments, including rivers in Spain, points to wider planform reorganization under the combined influence of hydrological variability and human disturbance (Baena-Escudero et al., 2019; Llana et al., 2020). Similar multi-decadal adjustments are reported in Albania, where satellite-based reconstructions document high planform variability and active channel reconfiguration in response to sustained anthropogenic pressure (Spada et al., 2018). In Slovenia, recorded channel changes are linked primarily to land-use shifts, especially agricultural abandonment and reforestation, which reduced sediment yield and flood peaks and were followed by incision and bar stabilization (Keesstra et al., 2005). For Croatia, Pavlek and Faivre (2020) highlight progressive channel contraction, reduction of bar surfaces, and island growth associated with dam building and hydropower development.

Western European examples from Scotland and France reveal how channelization, flood protection, and flow regulation have transformed previously mobile multi-thread reaches into more confined channels (Winterbottom, 2000; Bulteau et al., 2022; Jautzy et al., 2022). Central European case studies describe river systems under sustained human pressure, where narrowing, incision, and planform simplification are frequently reported. Evidence comes from Germany (Eschbach et al., 2018), Austria (Hohensinner et al., 2004), and Poland (Rinaldi et al., 2005; Zawiejska & Wyzga, 2010; Hajdukiewicz & Wyzga, 2023). Hungarian rivers display regulated meander adjustment (Amissah et al., 2018; Kiss & Blanka, 2012), while Slovak mountain channels preserve active braided-wandering sectors (Kidová et al., 2016); comparable transformations have also been observed in the Czech Republic (Škarpich et al., 2013). In Eastern Europe recent studies from Ukraine, combining historical topographic maps with satellite imagery and GIS analysis, reconstruct long-term channel deformation patterns, including lateral migration and width variability (Burshtynska et al., 2024). Research on major Russian rivers indicates that channel boundary changes and pattern adjustments reflect both large-scale human regulation (especially reservoir construction) and natural controls, depending on basin and reach characteristics (Alexeevsky et al., 2013).

Romanian rivers generally align with the broader European tendency of channel adjustment, although several studies point to a slower tempo of geomorphic change and a delayed response to sustained anthropogenic pressures (Bălteanu et al., 2012; Rădoane et al., 2017). Compared with rivers from Italy, France, or Germany, where incision, narrowing, and planform shifts often developed earlier under similar disturbances, many Romanian systems show more progressive, cumulative adjustments. Research carried out in Romania addresses both vertical and planform dynamics across multiple temporal scales. Early investigations examined the long-term evolution of longitudinal profiles in the Carpathians (Rădoane et al., 2003), while more recent work documents shorter-term changes such as bed incision, aggradation, and flood-related threshold responses (Rădoane et al., 2010; Rădoane et al., 2013; Ioana-Toroimac et al., 2020; Dumitriu, 2021). These results indicate that channel morphology reflects the combined effects of hydrological variability, engineering works, sediment extraction, and land-use change.

Channel geometry has been reconstructed mainly through the comparison of historical maps, aerial photographs, and satellite imagery, allowing the tracking of sinuosity changes, braiding structure, and lateral migration over roughly the last 150 years (Cristea, 2011; Perşoiu & Rădoane, 2011; Chiriloaei, 2012; Chiriloaei & Rădoane, 2015). The integration of older cartographic sources with modern remote sensing data improves the detection of long term channel shifts.

Case studies further show that structural modifications of river corridors (including dams, bank consolidation and embankments, and floodplain reclamation) alter sediment transfer and channel behaviour, as documented for Suceava river (Romanescu, 2013), the Prahova river (Ioana Toroimac

et al., 2010; Armaş et al., 2013), the Prut river (Rădoane et al., 2008), the Siret river (Salit et al., 2015), the Ialomiţa river (Radu & Comănescu, 2025), and the Danube corridor (Greco et al., 2017). At national scale, the dominant tendency points toward channel simplification and stabilization, with notable differences in timing and magnitude between basins.

Previous investigations (e.g., Ujvari, 1972; Romanescu, 2003; Horodnic, 2023) describe the Suceava River in north-eastern Romania as a representative example of a channel system that has undergone substantial morphological transformation. These changes are linked to the combined effects of hydrological processes and human pressures, including deforestation, agricultural expansion, and urban development. Within this context, analysing multi-decadal shifts in channel sinuosity, braiding, and width provides valuable insight into the mechanisms through which multiple drivers have interacted over time to reshape the river corridor.

The present study examines the Suceava river valley at the contact between the Obcinele Bucovinei mountain sector and the Moldavian Plateau lowlands. The objective is to identify the main geomorphic and hydrological changes recorded in this sector over time. Since the late nineteenth century, the morphology of the Suceava river valley has undergone notable transformations, as evidenced by historical maps, orthophotographs, and satellite imagery. These records reveal alternating phases of heightened fluvial activity (characterized by shifts in channel width, sinuosity, and braiding), followed by intervals of relative stability associated with both hydrological variability and human intervention. Gaining a better understanding of these dynamics is important for developing effective river management strategies, particularly as fluvial systems face increasing pressure from climate change and human activity (Diaconu, 1999). Accordingly, this study analyses key parameters of morphological evolution, including the width of the active river area (ARA), as well as sinuosity and braiding indices over more than a century, in order to clarify how the Suceava river has responded to natural controls and anthropogenic forcing.

2. MATERIALS AND METHODS

2.1. Selecting the study area

Covering approximately 391 km², the study area follows the course of the Suceava River within the Rădăuţi Depression. In this extra Carpathian sector, the river flows for about 113 km along its main channel, from Straja at the Carpathian margin to the area upstream of Dorneşti. The region marks the transition between the Eastern Carpathians (characterized by low mountains generally ranging from 500 to 1000 m a.s.l.) and the adjacent hilly landscape of the Moldavian Plateau (as detailed by Oprea, 2014), which includes piedmonts and depressions situated between 320 and 500 m a.s.l. (**Fig. 1**).

To delineate the investigated sector, we integrated historical cartographic materials with high resolution LiDAR data (**Fig. 2**). This dataset enabled the identification of fine geomorphological features, including paleo-meanders, channel displacements, and subtle morphological adjustments that are difficult to detect using conventional DEM products.

Similar methodological frameworks have been successfully applied in north-eastern Romania. Stoleriu et al. (2020) and Huţanu et al. (2020) demonstrated that integrating dense LiDAR point clouds with HEC-RAS modelling significantly enhances the accuracy of flood hazard assessments by allowing a more precise representation of channel morphology and flood prone areas.

2.2. Data collection and preparation

Channel planform dynamics were analysed using a diverse set of cartographic materials, aerial photographs and complementary historical sources, following established approaches in fluvial geomorphology (Kondolf & Piégay, 2003; Perşoiu, 2010) and based on the cartographic assemblage illustrated in **Fig. 3**. The dataset includes historical maps from multiple survey stages, beginning with Austro-Hungarian editions and continuing with later Romanian series, obtained from archives, libraries and specialized cartographic collections.

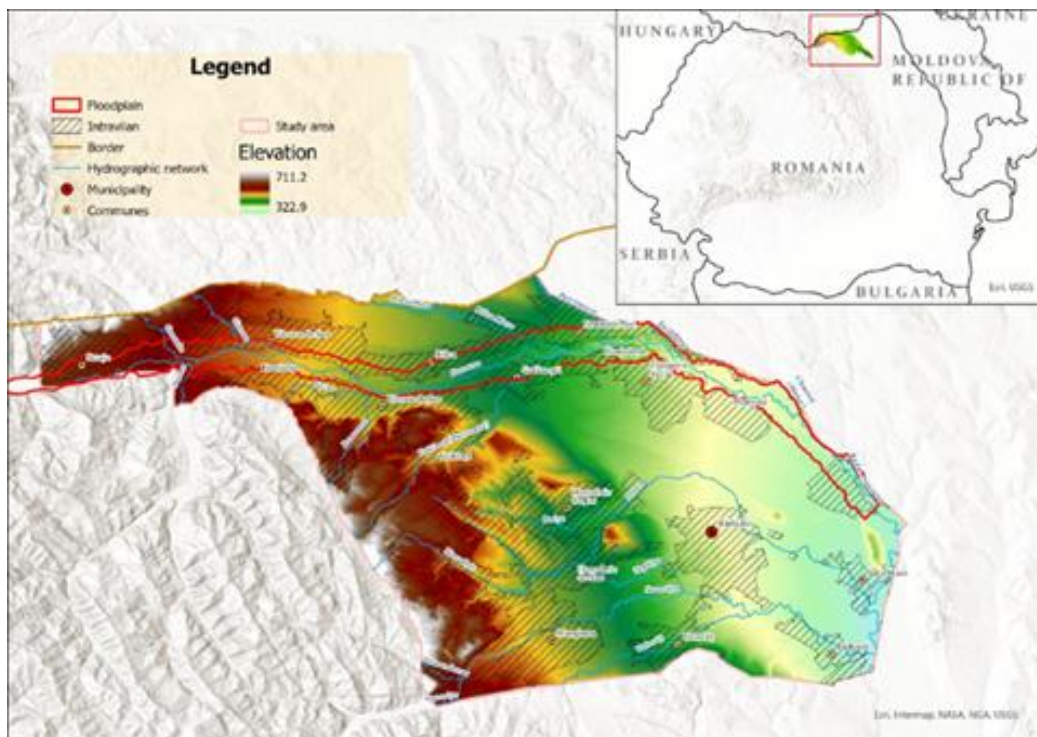


Fig. 1. Location of the study area in Romania and the regional setting.

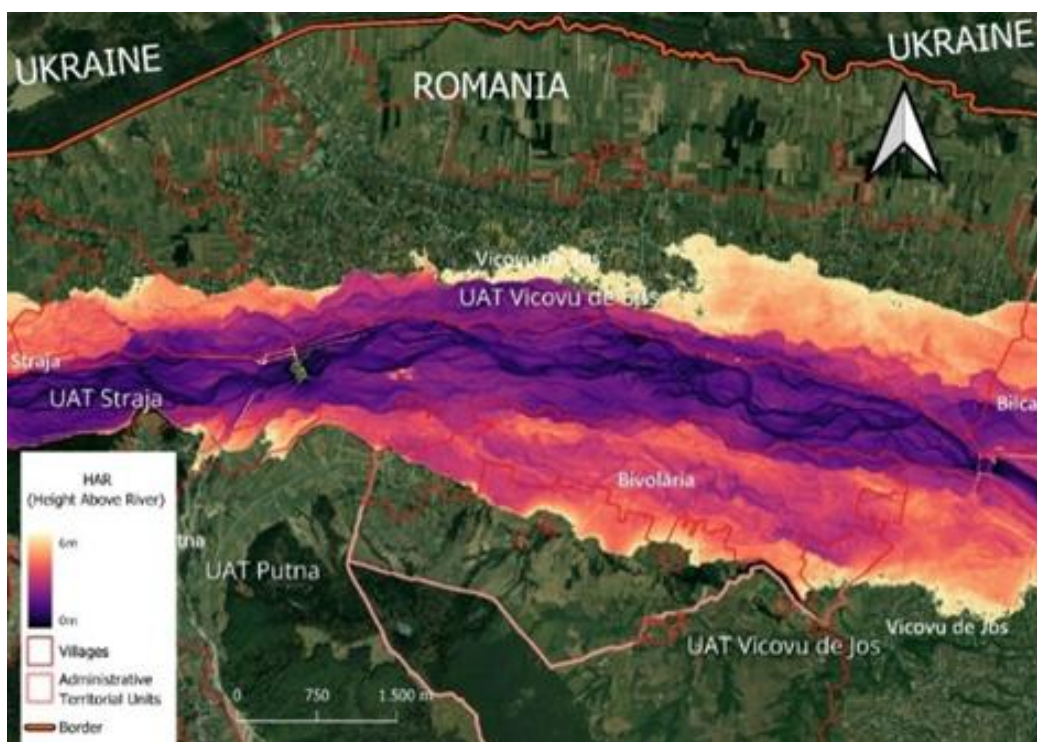


Fig. 2. Study area delimitation based on LiDAR-derived imagery.

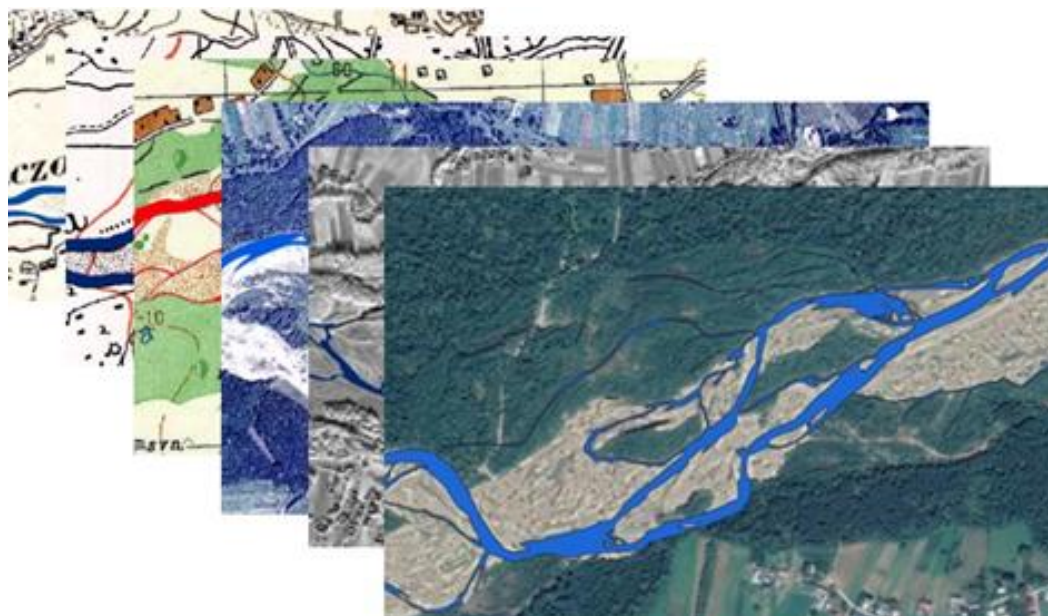


Fig. 3. Historical and modern cartographic sources supporting the analysis of channel planform changes.

High resolution orthophotos from 2006 and 2011 were acquired from national geospatial providers (ANCPI) and dedicated platforms such as www.geospatial.org, ensuring an accurate representation of the river corridor and adjacent landscape. Together, these sources supported the construction of a spatial database covering more than 150 years of channel evolution, from late nineteenth century surveys to recent satellite imagery, for the extra-Carpathian sector of the Suceava river.

2.3. Vectorization process

Historical maps, orthophotos and satellite imagery were digitized in ArcGIS Pro 3.2. River features identifiable in both historical and recent cartographic sources were manually traced and vectorized. To maintain consistency and reduce operator-related variability, the digitization was performed by a single analyst using a uniform workflow, as recommended in comparable multi temporal channel studies (see, for example, Mandarino et al., 2019).

2.4. Cross-section generation and reach subdivision

Cross-sections were generated along the river valley at regular 400 m intervals using GIS-based tools. These profiles, oriented perpendicular to the channel, captured the main features of valley morphology and planform variability. The study reach was divided into nine subsections, each comprising 11 measurement transects.

The digitized river morphology and cross sectional data were integrated into a comprehensive spatial database, which was used for the subsequent analysis, enabling an in-depth assessment of the morphological characteristics and shifts of the riverbed. Additionally, the results obtained using this approach provide a reliable data source for future studies on fluvial dynamics, water resource management, and environmental conservation strategies in Suceava drainage basin.

2.5. Extraction of the geomorphological database from cartographic documents (1869-1884, 1897-1902, 1977, 2006, 2011, 2021)

To characterize the morphology of Suceava river channel, a detailed morphometric database was created based on a collection of cartographic sources (**Tab. 1**), focusing on identifying the features of

the floodplain, which is relatively recent in origin, and is subject to rapid changes due to more intense fluvial processes compared to other areas.

Table 1.

Summary of cartographic materials used in the study.

Name of the map	Timeframe of completion	Year(s) of publication	Scale	Projection	Data
Third Austro-Hungarian Survey	1869 - 1884	1890 - 1910	1:25,000	Stereographic projection of Tg. Mureş on the Bessel 1841 ellipsoid	Institute of Military Geography, Vienna
“Plan Director de Tragere”	1897 - 1902	Different years of printing	1:20,000	Lambert Projection	Serviciul Geografic al Armatei Române
Topographic maps	1977	1978 - 1979	1:25,000	Gauss - Krüger Pulkovo, Cylindrical Projection 1942	IGFCOT
Orthophotos	2004 - 2006	-	1:5,000	Stereographic projection Stereo70 ellipsoid Krasovschi	ANCPI
Orthophotos	2011	-	1:5,000	Stereographic projection Stereo70 ellipsoid Krasovschi	ANCPI
Satellite Imagery	2021	-	1:20,000	WGS 84	Google Earth

The construction of the database was based on the careful definition and measurement of morphometric parameters, following the cross-sectional valley methodology (Fig. 4) as outlined by Rapp & Abbey (2003), and Rădoane et al. (2008).

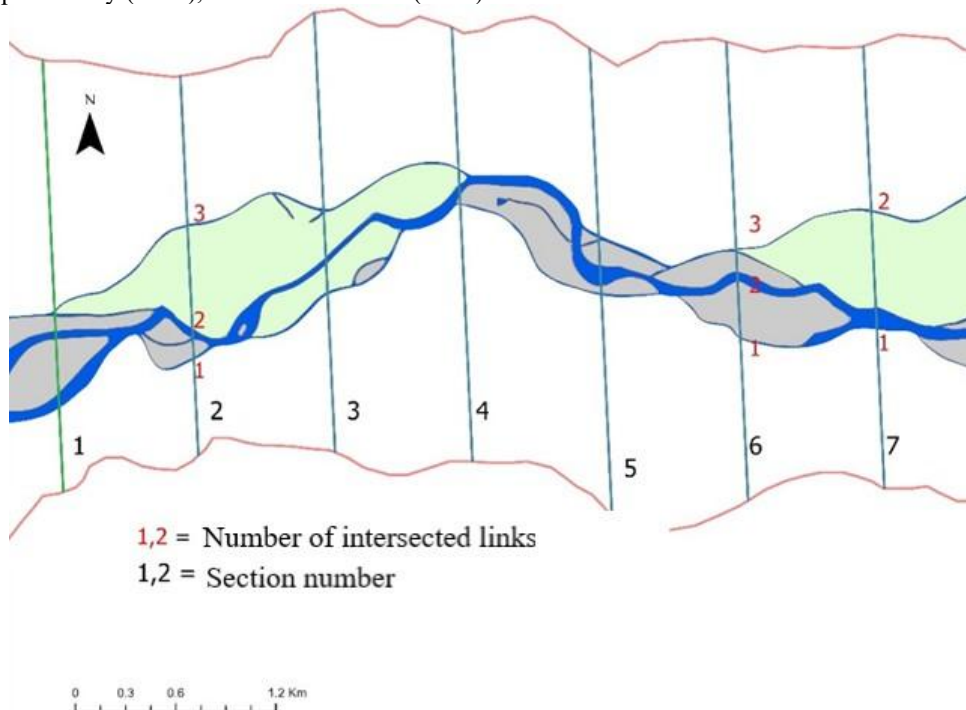


Fig. 4. River braiding index calculation according to Ashmore (1991) with cross-sections along Suceava river.

Morphometric measurements were conducted on the valley bed, which includes the floodplain - an area situated on either side of Suceava river channel, with relatively low elevations, of up to 5-7 meters in height above the channel. The floodplain consists of the active river area (ARA), representing the free migration zone of the river, and the terraces situated at 2 meters, 4 meters, and 5-7 meters above the channel level. On the surface of the floodplain, traces of the old river channels can be observed in the form of abandoned river branches. The integration of these data into a comprehensive spatial database allowed for a detailed assessment of the morphological characteristics of Suceava river, providing a consistent foundation for further studies on river dynamics in this region.

2.6. Definition and classification of riverbed morphology

In the investigation stage dedicated to defining and establishing the riverbed morphology (Fig. 5), the primary objective was to fully understand its current physical characteristics and behaviour. This analysis relies on gathering essential data, such as the natural (including climatic) attributes of the surrounding environment, the degree of constraint affecting the river channel (whether influenced by natural terrain morphology or man-made structures), and critical metrics such as the sinuosity index, which measures the extent of meandering along the river course. Additionally, parameters such as the braiding index, which indicates the complexity and number of channels in the riverbed, and the anastomosis index, quantifying the branching degree of the channels, are essential in this assessment.

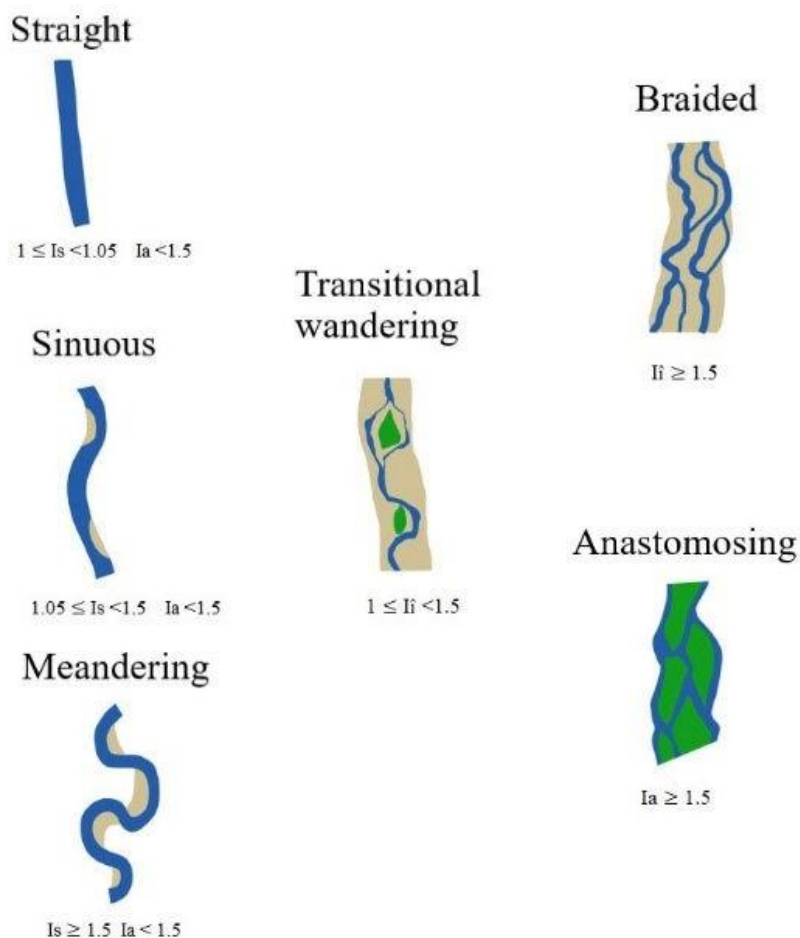


Fig. 5. Fluvial morphology scheme and variability ranges of the main planimetric indices: Si, sinuosity index; Bi, braiding index; Ai, anastomosis index (adapted from Brice, 1975).

- **Straight channels:** Are characterized by a single, relatively unaltered course, with a braiding index close to 1 and sinuosity index below 1.05. These are rare in natural environments, as emphasized by Brice (1975), Malavoi & Bravard (2010), and Rinaldi et al. (2011).

- **Sinuuous channels:** Are defined by a sinuosity index greater than 1.05. According to Brice (1984), channels with a sinuosity index of up to 1.25 are slightly sinuous, while those exceeding this value are highly sinuous or meandering. Leopold & Wolman (1957) suggest that the transition to meandering occurs at a sinuosity index of 1.5.

- **Meandering channels:** Occur when the sinuosity index exceeds 1.5 (Leopold & Wolman, 1957) or, according to alternative classifications, 1.3 (Chang, 1979).

- **Transitional channel types:** Exhibit intermediate characteristics between sinuous, meandering, braided, and anastomosing forms.

- **Wandering transitional channels:** Are defined by a diffuse braiding index greater than 1, but lower than 1.5. The term wandering has no precise equivalent in Romanian, where specialized literature uses *vagabond* or *divagant* (Brice, 1975; Rinaldi, 2003).

- **Sinuuous Transitional Channels with Alternating Arms:** Are characterized by a single, strongly sinuous channel with braiding index values close to 1 and a sinuosity between 1.05 and 1.45 (according to Rinaldi, 2003). A distinctive feature is the continuous and alternating presence of lateral bars, which has led some authors to refer to this type as "pseudo - meandering."

- **Braided:** These channels have multiple arms separated by islands, with a braiding index above 1.5 (Fig. 5).

- **Anastomosing:** Characterized by multiple channels separated by vegetated islands, and described by the anastomosing index.

2.7. Braiding index according to Brice (1964) and Ashmore (1991)

The braiding index is commonly used to quantify the degree of channel subdivision in multi thread rivers. A synthesis of the main calculation approaches was provided by Thorne (1997), who discussed, among the most widely applied formulations, those introduced by Brice (1964) and Ashmore (1991).

Brice (1964) defined the braiding index using a length-based formulation (Eq. (1)):

$$Bi = \frac{2 \times (\text{sum of the lengths of the branches or channels})}{\text{length of the sector measured across the channel}} \quad (1)$$

Ashmore (1991) later proposed an alternative approach based on the number of channel branches intersected by cross-sections (Eq. (2)):

$$Bi = \frac{\text{number of intersected branches (average values obtained)}}{\text{number of considered sections}} \quad (2)$$

For the present dataset, we assessed the suitability of both formulations and selected the Ashmore (1991) method as more appropriate for the cross-section based analysis used here. Its implementation is illustrated in Fig. 4.

2.8. Sinuosity index

Channel sinuosity was calculated for each defined river sector as the ratio between channel length and the corresponding distance measured along the valley axis (Eq. (3)).

$$Si = \frac{la}{lv_1 + lv_2 + lv_3 + lv_4} \quad (3)$$

Sinuosity may be measured along reaches of different lengths, but segments must be sufficiently long to yield meaningful values. A commonly accepted reference scale corresponds to distances of

about 10-14 channel widths, which provides a representative measure of channel curvature (Thorne, 1997). This procedure supports the evaluation of channel curvature and planform complexity, both relevant for interpreting fluvial dynamics and channel evolution.

2.9. Data analysis and interpretation

The resulting dataset was organized in Microsoft Excel, where all calculated indicators were recorded in a consistent format. We used graphical outputs to examine temporal and spatial variation in the indices and to identify patterns in channel behaviour. Reaches with higher sinuosity were generally more prone to bank erosion and sediment accumulation, whereas sectors with higher braiding values showed uneven flow distribution and more frequent bar development.

In order to ensure that the results we obtained were reliable, we applied strict quality checks at every stage. We compared our findings with field data to validate the digitized river features and cross-sectional profiles, and we ran sensitivity analyses to test the robustness of the calculated indices. These steps helped confirm both the accuracy and the consistency of our results.

3. RESULTS AND DISCUSSION

3.1. Active river area (ARA) width variation

For the morphological analysis of Suceava river valley, several relevant periods and years were identified in order to structure the temporal record and capture the distinct phases of channel dynamics. The multi-year periods (1869-1884, 1897-1902) were selected because they correspond to blocks of historical cartographic materials with comparable coverage and consistency (topographic/cadastral maps), allowing robust cross-sector comparisons. Furthermore, the individual years (1977, 2006, 2011, 2021) were chosen as methodological and data milestones which coincide with aerial photogrammetric campaigns, orthophotos, or the transition to high-resolution remote sensing and LiDAR. These timeframes reflect key hydrological or anthropogenic moments, such as flow regime changes, engineering works, land use modifications etc., which could explain abrupt shifts or thresholds in channel width (**Fig. 6**). This combined approach leverages the advantages of multi-annual windows (sensitive to long-term trends) and reference years (sensitive to episodic or geomorphic thresholds).

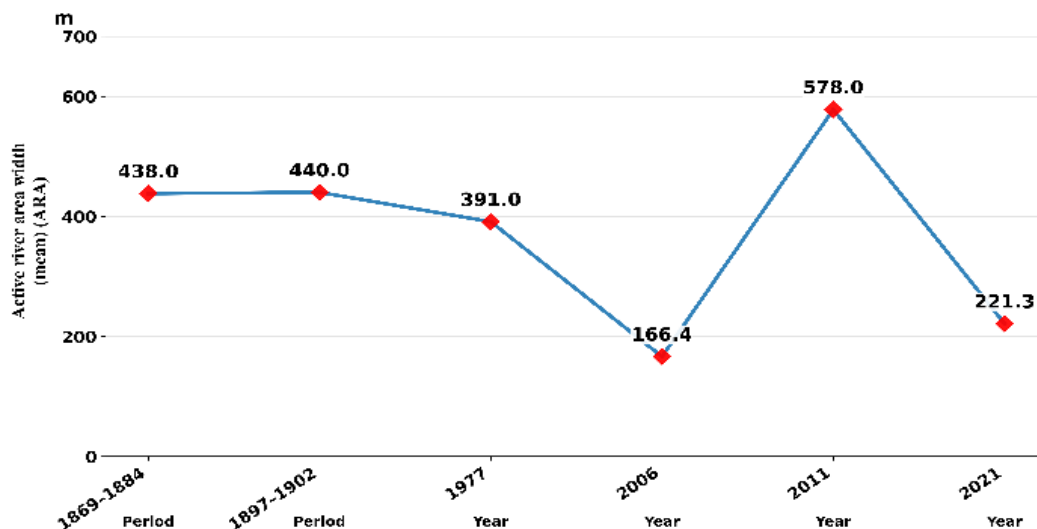


Fig. 6. Width of the mean active river area (ARA).

1869-1884: The active river area (ARA) width varied significantly across sectors, with Sector 1 ranging from 108.42 m to 78.48 m, Sector 2 from 542 m to 287 m, Sector 3 from 526.64 m to 105 m, and Sector 4 from 718 m to just 142.11 m. These variations reflect local factors and prevailing hydrological conditions.

1897-1902: ARA width continued to vary notably. Sector 1 ranged from 55.26 m to 203.66 m, Sector 2 from 396.15 m to 431 m, Sector 3 increased from 344.11 m to 600.96 m, and Sector 4 ranged from 518.85 m to 302.78 m, indicating responsiveness to changes in flow regime and major hydrological events.

The ample variations in ARA morphology during these intervals could be related to large-scale changes in the landscape occurring from 1790 to 1864, when a total area of ca. 1085 km² was affected by major land use/landcover shifts, accounting for 39.2% of the area of Suceava drainage basin (Horodnic, 2023). By 1964, just 48% of the drainage basin area was covered by forest, compared to approx. 65% in 1790, indicating a severe drop in the protective function of vegetation and increased erosion. Subsequently, between 1864 and 1985, significant land use/landcover changes affected ca. 35.84% of the drainage basin. Additionally, during the same period exceptional amounts of precipitation were recorded in the Suceava region in 1837, 1846, 1850, 1893-1897, 1900-1901. In 1897 the annual volume of precipitation at Slatina (in the plateau area) exceeded by approx. 185% the mean annual amount of 645 mm. Of the total 1844 mm of precipitation recorded in 1897, 1574 mm fell between April and June, surpassing by 570% the average amount of the rainy season. The abundant precipitation has likely contributed to ARA width adjustments in the upper and mid-course of Suceava river, particularly considering the large-scale deforestation of mountain and hill slopes occurring at a fast pace in the drainage basin.

1977: Significant variability was observed. Sector 1 varied from 40 m to 286.59 m, Sector 2 from 211 m to 288.38 m, Sector 3 from 344 m to 758 m, and Sector 4 from 292 m to 994 m in width, suggesting considerable changes due to river flow modifications and human interventions.

Prior to this year, considerable precipitation amounts were recorded in the upper basin of Suceava river in 1970 and 1975, possibly contributing to the dynamics of the river channel as reflected by ARA width changes. Moreover, additional human intervention occurred in the basin, in the form of small embankments (e.g. on Putna river at confluence in 1959, and on Suceava river at Dornești in 1970), while agricultural lands expanded to the detriment of forests, which accounted for just 39.2% of the total drainage basin in 1985 (Horodnic, 2023), distributed mainly in the montane sector.

2006: Width variability remained significant. Sector 1 ranged from 13.5 m to 199.9 m, Sector 2 from 27.25 m to 248.96 m, Sector 3 from 105.55 m to 508.93 m, and Sector 4 from 65.73 m to 464.85 m, likely influenced by local factors such as flow variations and anthropogenic activities.

2011: Notable variations persisted. Sector 1 ranged from 17.18 m to 175.25 m in width, Sector 2 from 16.13 m to 315.88 m, Sector 3 from 28 m to 472.8 m, and Sector 4 from 22.24 m to 445.25 m, reflecting changes in flow regimes following recent floods. The entire 2005-2010 period was exceptionally rainy, with high precipitation occurring in 2005, 2006, 2008 and 2010, typically ensued by historic levels of Suceava river and tributaries, particularly during the major 2008 and 2010 flood events. During this timeframe the annual precipitation and the peak streamflow discharge reached record values: at Țibeni gauging station (in Rădăuți Depression) the measured discharge was as high as 200 m³/s on 26 July 2008, compared to the mean discharge of 14,3 m³/s.

2021: Significant variability continued, with Sector 1 ranging from 65.67 m to 245.97 m, Sector 2 from 126.85 m to 431 m, Sector 3 from 73.27 m to 473 m, and Sector 4 from 56.95 m to 232.52 m, indicating active fluvial dynamics driven by both hydrological changes and human interventions.

From 2011 to 2021 changes in the land use/landcover were not as significant, with the exception of forest fragmentation which continued as large portions of forests were reclaimed by private owners and logging became a major source of income for the population inhabiting the mountainous part of Suceava drainage basin. This timeframe has also coincided with a period of marked climate changes in north-eastern Romania, including an increase in temperature (by 0,36°C per decade, according to Piticar, 2013) and extreme precipitation events, both in terms of amount per event, intensity and frequency.

As regards other man-made structures which interfere to a significant degree with the dynamics of the river channel, additional embankments were installed along Suceava watercourse at Straja, Vicovu de Sus, Bilca, Frătăuții Noi, Costișa, Frătăuții Vechi, Măneuți etc. (Fig. 7), as well as some of its main tributaries at: Putna and Gura Putnei (on Putna river), Voitinel (on Voitinel river), and Horodnic de Jos (on Pozen river). Donati et al. (2019) demonstrated that rivers where such structures exist are potentially exposed to degradation, as shown in the case of rivers in metropolitan France.

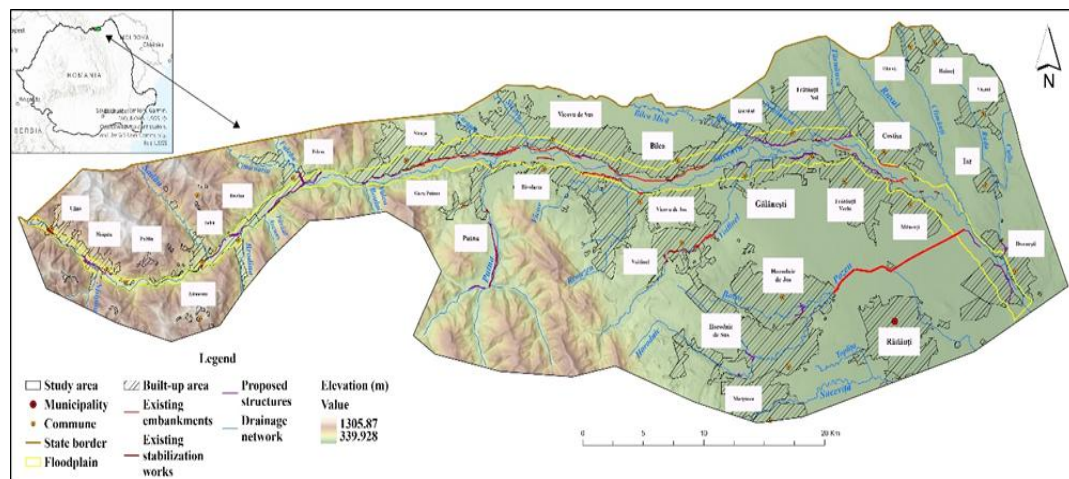


Fig. 7. Location of embankments (marked in red) and stabilization works (marked in purple) in Suceava drainage basin.

3.2. Variation in floodplain width

The data analysis focusing on the floodplain width (Fig. 8) reveals considerable variability along the river course, reflecting a dynamic fluvial landscape influenced by geomorphological, hydrological, and anthropogenic factors.

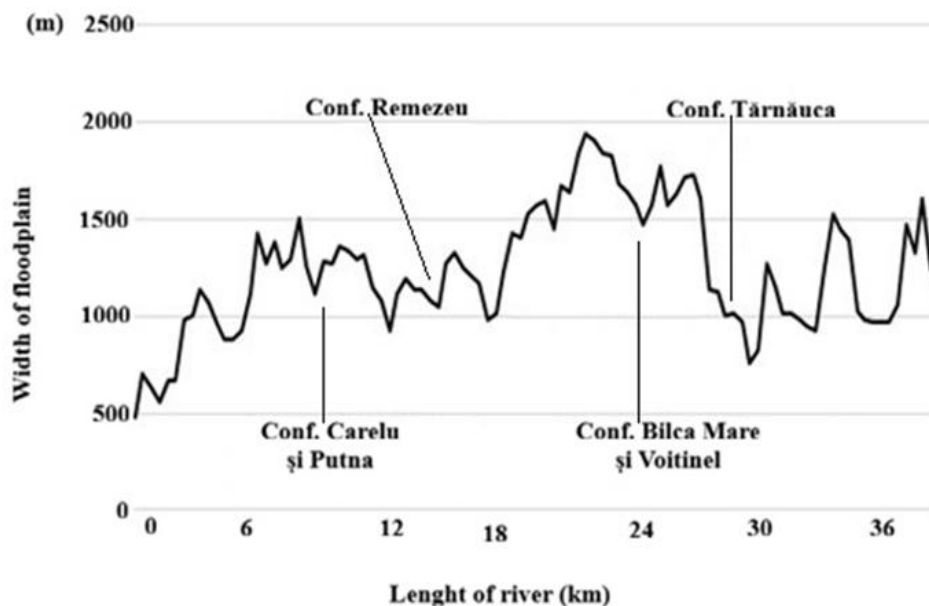


Fig. 8. Variation in floodplain width.

The floodplain width ranges from minimum values around 700 meters to maximum values exceeding 1900 meters. This variability indicates the presence of sections with intense lateral erosion and significant sediment deposition. For instance, the channel width increases significantly in the 8-12 km and 18-24 km reaches, suggesting areas with active sedimentation processes and extensive floodplain formation.

In certain sectors the floodplain narrows, potentially reflecting areas of intense lateral erosion or anthropogenic interventions (Fig. 8). For example, the width decreases to below 1000 meters at kilometres 2, 4, 8, 18, and 28. These narrower zones are influenced by topographical constraints, such as rocky slopes or anthropogenic infrastructure like embankments or bridges. Conversely, wider zones, such as the reaches between 22-24 km and 38-39 km, indicate regions with significant sediment deposition and the potential for formation of extensive floodplain (with widths between 1500 and 1900 m).

3.3. Braiding index (Bi)

The braiding index of Suceava river (Fig. 9) has been analysed throughout six timeframes: 1869-1884, 1897-1902, 1977, 2006, 2011, and 2021, across nine reaches. This index assesses the complexity of the braided river channel and is influenced by water levels and geomorphological changes.

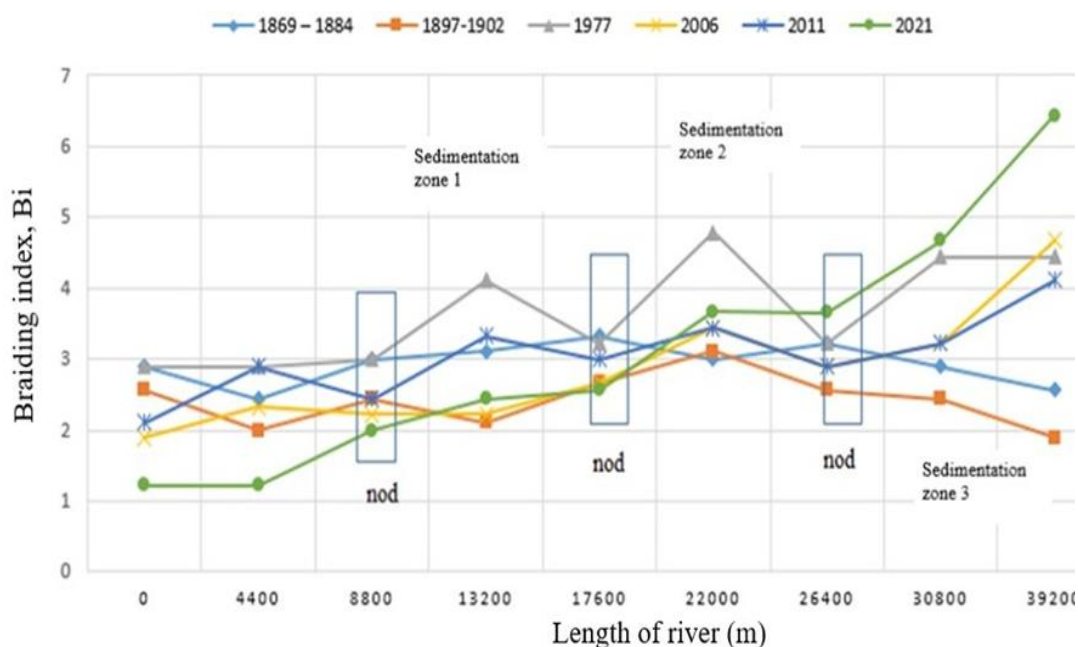


Fig. 9. Variation in braiding index (Bi) and sedimentation zones.

1869-1884: The braiding index values ranged from 2.44 to 3.33, indicating moderate to high channel complexity. Higher values (3.33) denote more dynamic and complex patterns, while lower values (2.44) suggest greater stability.

1897-1902: The index varied from 1.89 to 3.11. Lower values (1.89) in sectors 9 and 10 indicate increased stability, while the higher values reflect moderate fluvial activity.

1977: A notable increase was observed in this period, with values ranging from 2.89 to 4.78. Sectors 9 and 10 showed the highest values (up to 4.78), thus indicating intense fluvial activity and significant morphological changes.

2006: Index values ranged from 1.89 to 4.67, with sectors 8 and 9 showing the highest values (4.67), suggesting high geomorphic activity in these reaches, while lower values indicated more stable regions.

2011: The index fluctuated between 2.11 and 4.11. Again, the most dynamic sectors were 8 and 9, with values of up to 4.11, while partial stabilization occurred in other areas.

2021: Values ranged widely from 1.22 to 6.44. The highest values of the braiding index (6.44) pertained to sectors 8 and 9, indicating very active dynamics and instability, while reaches with lower values (1.22) appeared more stable.

Over time, coarse sediment accumulated in "sedimentation zones" separated by nodal points (Fig. 9). While the length of these zones has remained relatively constant, their width has significantly decreased.

3.4. Sinuosity index (Si)

The analysis of sinuosity indices for Suceava river across the specified periods revealed significant variations in river morphology (Fig. 10).

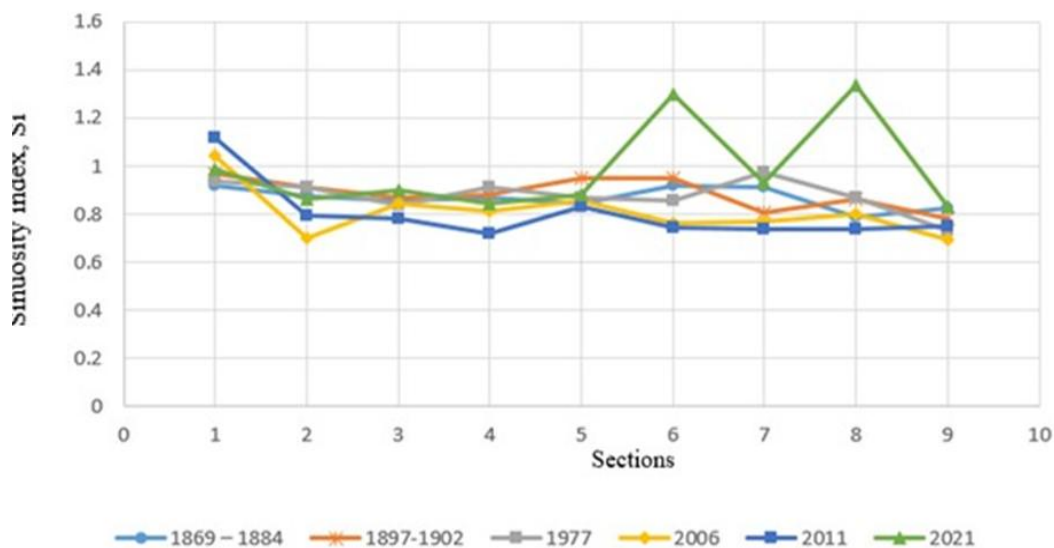


Fig. 10. Sinuosity index variations.

1869-1884: Sinuosity indices ranged from 0.78 to 0.92, indicating a relatively straight course, while sectors 1 (0.92), 6 (0.92), and 7 (0.91) are moderately sinuous.

1897-1902: Indices varied between 0.77 and 0.96, with sector 1 (0.96) showing the highest degree of sinuosity, followed by sectors 5 (0.949) and 6 (0.950).

1977: The index ranged from 0.73 to 0.97, with sector 6 (0.97) being the most sinuous.

2006: Values fluctuated between 0.692 and 1.041, with sector 1 (1.041) exhibiting clear sinuosity.

2011: Indices ranged from 0.72 to 1.11, with sector 1 (1.11) showing pronounced sinuosity.

Compared to earlier periods, in **2021** a general trend towards increased sinuosity became apparent in sectors 6 (1.29) and 8 (1.33).

Sectors with indices above 1 indicate a significant evolution towards more pronounced sinuosity. This trend may be influenced by natural factors such as erosion and sedimentation processes, as well as human interventions, including hydraulic works or changes in land use in the area adjacent to the river.

4. CONCLUSIONS

The analysis of morphological changes along the Suceava River over the 1869-2021 interval shows how channel form has evolved under the combined influence of natural processes and human interventions. Using historical maps, aerial imagery, and recent geospatial datasets, the study reconstructs more than a century and a half of channel adjustments and outlines the main directions of long-term change. The results point to a progressive reorganization of channel pattern and geometry, with a gradual increase in structural complexity compared to the earliest mapped conditions.

The quantified indicators confirm a clear intensification of channel complexity over time. In the earliest surveys (1869-1884), the braiding index generally ranged between 2 and 3, whereas the most recent measurements show values reaching about 4.5-5.5, indicating a higher degree of multi-thread development. A similar upward shift is visible for sinuosity, which increased from roughly 1.1-1.5 at the beginning of the record to about 1.6-2 in the latest stage (2021), reflecting stronger channel curvature and lateral development.

The active river area (ARA) exhibited substantial variability, expanding from 28-311 m (1869-1884) to a peak of 508 m in 2006, followed by a contraction to 65-245 m in 2021. This pattern reflects alternating phases of channel expansion, relative stability, and subsequent adjustment. Similarly, floodplain width increased from 86-594 m to over 1000 m by 1977, before narrowing to 65-245 m in recent decades, pointing to a dynamic interaction between the channel and its floodplain.

Hydrological records from 2014 to 2022 at Brodina in the mountain basin reveal pronounced seasonal contrasts. Mean streamflow discharge typically ranges between 0.2-0.9 m³/s in winter months (January - February, November - December) and 1.0-3.5 m³/s in spring-summer (April-June), with occasional peaks above 5 m³/s. Minimum discharge frequently falls below 0.2 m³/s, especially in late summer and winter, highlighting drought sensitivity. Inter-annual variability is evident: for instance, in 2015-2017 the seasonal regimes were relatively stable, with mean values between 0.3-1.0 m³/s, while in 2019-2020 higher oscillations were documented, with monthly averages reaching 3-5 m³/s, followed by a decline in 2021-2022, when values generally remained below 1.0 m³/s.

This variability corresponds with precipitation data from the same period, where monthly totals at Brodina ranged from less than 1 mm in dry months to more than 70-80 mm in wet months, outlining the role of short but intense rainfall events in driving flood events. Data from the Brodina hydrometric station (on Suceava river) show an increase in mean annual temperature from around 7.50°C (2015-2021) to 8.59°C in 2023, indicating a rise of more than 1°C over the course of less than one decade, accompanied by increasing inter-annual oscillations which could have an effect on the development of fluvial processes.

Along with climate variability, the drivers of changes in riverbed morphology are likely linked to anthropogenic impacts relating mainly to large-scale land use/landcover shifts in the river basin. Landscape changes relied on deforestation and massive expansion of arable land from 1790 to 2020: while forested areas decreased by more than 42% (660 km²) at an annual rate of ca. 3 km²/yr in the entire basin (6 km²/yr in the montane region) and natural pastures diminished by 33%, arable land and built-up areas increased by ca. 210% (450 km²) and 310% (300 km²), respectively (Horodnic, 2023).

The geomorphic effects of recent environmental changes and anthropogenic impacts have also been documented by the analysis of lake sediments in NE Romania, with findings from lacustrine sites demonstrating that sediment accumulation rates have predominantly increased over the last 150-year period (e.g. at lakes Știol and Buhăescu Mare in Rodna Mts and Sfânta Ana in Harghita Mts). Moreover, sediment yield and accumulation rates in lowland and mid-elevation lake basins were strongly influenced by the socialist land-use regime, which promoted intensive agriculture and large-scale deforestation

Therefore, the combination of human-induced land use/landcover changes and climate shifts has likely contributed to enhancing channel braiding and sinuosity, and increased hydrological variability, thus amplifying the vulnerability of Eastern Carpathian rivers.

The dynamics of Suceava river valley mirrors the trends observed in other Romanian rivers, with channels displaying delayed but cumulative responses to long-term anthropogenic pressures, including hydrotechnical works, land use changes, and floodplain reclamation. This evolution is in line with the shift toward more complex fluvial patterns under combined climatic and human drivers documented by several multi-decadal studies across Europe.

Sector-specific analysis showed that sectors 8 and 9 are particularly dynamic, aligning with findings indicating that localized reaches often concentrate migration and braiding activity (Brice, 1975; Rinaldi, 2003). The observed increase in sinuosity and braiding points to greater sediment mobility and a tendency toward instability, which directly influences erosion, flood risk and land use/landcover planning across the basin.

The dynamic of Suceava river valley throughout the last 150 years exemplifies the sensitivity of rivers in the NE region of Romania to both natural and anthropogenic drivers. The adjustments observed in the river evolution closely resemble those determined for the neighbouring Moldova river basin, where braided to meandering transitions and pronounced channel metamorphosis have been documented during the last century (Chiriloaei, 2012; Chiriloaei & Rădoane, 2015). Such parallels outline that although each river responds to local hydrological and geomorphic settings, the broader pattern of increased complexity and instability under human and climatic pressures is consistent across the region.

The results obtained through this detailed analysis of riverbed dynamics in the past 150 years along Suceava river at the transition between the mountainous area and the eastern lowlands can be utilized for establishing science-based river management strategies. Priority should be given to dynamic sectors such as 8 and 9, where intensified braiding and sinuosity raise concerns for bank erosion, flood risk, and infrastructure vulnerability.

Based on the data yielded by this study, further research in the area could link morphological adjustments with hydrological records and climate variability and projections, exploring sediment budgets in dynamic sectors. Future studies should expand monitoring efforts by incorporating high-resolution UAV surveys, repeated LiDAR scans, and automatic image analysis to capture short-term morphological adjustments that complement the long-term perspective derived from historical cartography. Such an approach would support the development of adaptive management strategies and contribute to enhancing resilience in Suceava basin, while also providing data for comparative studies of fluvial dynamics across Romania and Europe. Adaptive strategies could include buffer zones, controlled floodplain reconnection, and eco-geomorphological restoration measures, aligning with European directives on river basin management. Moreover, multi-river studies including NE Romanian rivers such as Moldova, Prut, and Siret, would provide a stronger empirical basis for anticipating future changes under projected climate scenarios and increasing human pressure.

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