Morphodynamic Transformations of the Tysa River Channel across the Volcanic Carpathians over the Period 1880–2025 (Ukraine)

Transformations morphodynamiques du lit de la rivière Tysa à travers les Carpates volcaniques au cours de la période 1880-2025 (Ukraine)

Galyna BAYRAK[1]*

[1]Geography faculty, Ivan Franko National University of Lviv, Ukraine

***Correspondence to:** Galyna BAYRAK. E-mail: halyna.bayrak@lnu.edu.ua.

Vol. 35.2 / 2025, 53-68

GEOREVIEW

Received:
6 May 2025

Accepted:
25 June 2025

Published online:
8 July 2025

ABSTRACT : This study investigates the morphodynamics of the Tysa River channel over a 145-year period along a valley segment that intersects the Vyhorlat-Hutyn Volcanic Ridge. This section is characterized by minimal anthropogenic alterations and exhibits natural variability in channel types, including single-thread, multi-thread, and braided configurations, as well as straight, slightly sinuous, and meandering forms. Our analysis revealed that in the late 19th and early 20th centuries, multi-thread sinuous channels predominated. Since the 1980s, they have largely transformed into single-thread meandering channels. By the early 21st century, only single-thread forms were present, with slightly sinuous types being the most common, followed by meandering and straight reaches. Since 2020, single-thread meandering channels have become dominant. The study identifies a cyclic pattern in the transformation of channel morphological types, with a recurrence to initial states observed on approximately 40–50 and 100-year intervals.

KEY WORDS: river channel morphodynamics, fluvial cycles, channel typology, river evolution, fluvial geomorphosystems, Tysa River, Transcarpathia.

RÉSUMÉ : Cette étude examine la morphodynamique du lit de la rivière Tysa sur une période de 145 ans, le long d'un tronçon de vallée traversant la chaîne volcanique de Vygorlat-Gutyn. Cette section se caractérise par des modifications anthropiques minimales et présente une variabilité naturelle des types de chenaux, incluant des configurations à lit unique, à plusieurs bras et en tresse, ainsi que des formes rectilignes, faiblement sinueuses et méandriformes. Notre analyse a révélé qu'à la fin du XIX^e^ et au début du XX^e^ siècle, les chenaux sinueux à plusieurs bras dominaient. Depuis les années 1980, ceux-ci se sont en grande partie transformés en chenaux méandriformes à lit unique. Au début du XXI^e^ siècle, seules des formes à lit unique étaient présentes, les chenaux faiblement sinueux étant les plus fréquents, suivis par les méandriformes et les rectilignes. Depuis 2020, les chenaux méandriformes à lit unique sont devenus dominants. L'étude met en évidence un schéma cyclique dans la transformation des types morphologiques de chenaux, avec un retour aux états initiaux observé à des intervalles d'environ 40–50 et 100 ans.

MOTS CLÉS : morphodynamique fluviale, cycles fluviaux, typologie des chenaux, évolution des rivières, géomorphosystèmes fluviaux, rivière Tysa, Transcarpatie.

How to cite this article:
Bayrak, G. (2025) Morphodynamic Transformations of the Tysa River Channel across the Volcanic Carpathians over the Period 1880–2025 (Ukraine). Georeview, 35, 2, https://doi.org/10.4316/GEOREVIEW.2025.02.04

1. Introduction

The dynamics of river channels represent one of the key geomorphological processes through which the erosional and accumulative activity of watercourses is realized, shaping the modern fluvial landscape. This process determines the rate and direction of river valley development and reflects the continuous changes in river morphometric characteristics in response to natural factors (such as tectonics, climate, and hydrology) and anthropogenic influences (such as land reclamation and hydraulic engineering). Particular attention is drawn to the dynamics of Transboundary Rivers, such as the Tysa, which plays a crucial role in the hydrological regime of the Carpathian region. In certain sections, under conditions of a natural flow and a wide floodplain, it exhibits complex morphodynamics, indicating active fluvial processes and the sensitivity of the river system to climatic, tectonic, and anthropogenic factors.

The classification of river channels began to be developed in the 1950s. R.J. Russel (1954) and L.B. Leopold and M.G. Wolman (1957) identified three types of channels based on *channel configuration*: straight, meandering, and braided. In 1978, B.R. Rust, while studying lowland rivers in Southeast Asia, added a fourth type – *anastomosed channels*. S.A. Schumm (1963) based his classification on the sinuosity of channels and distinguished the following types: straight, transitional, regular, irregular, and tortuous channels. K. Richards (1982), based on *channel pattern*, identified *single-thread* and *multi-thread* channels (Charlton, 2008).

M.Ye. Kondratyev, I.V. Popov, and B.F. Snyshchenko (1982) and R. Chalov (1985) developed a channel classification that is still used in Ukraine: *belt-and-ribbon type channel* (or *straight channel*); *Sinuous channel with point bars type*; *Confined meandering*; *Free meandering*; *Incipient meandering*; *Braided*; *Bifurcated / Anabranching channel* (Obodovskyi, 1998; Chalov, 2011).

M. Bukhin, O. Kaftan, and V. Bazylevych (1974) identified the following types of river channels in the Ukrainian Carpathians: *Confined non-erosional channels with poorly defined banks*; *Confined channels with steep banks*; *Confined alluvial channels with high sediment load*; *Confined meandering channels*; *Bifurcated channel systems*; *Transition-type meandering*; *Free meandering* & *Canalized (or anthropogenically altered) channels* (Obodovskyi, 1998).

In recent years, river channel morphodynamics has been intensively studied across various geographic regions, with a particular focus on identifying patterns of spatial and temporal variability. Special attention is given to the cyclic nature of morphogenetic changes, which is observed in both meandering (Hooke, 2022; Finotello et al., 2024) and braided river systems (Ghosh et al., 2023). Several studies (Jackson et al., 2022; Candel et al., 2018) interpret river rhythmicity as the result of interactions between autogenic processes (such as bar migration and meander shifting) and allogenic drivers—including hydrological impulses, climatic fluctuations, and anthropogenic impacts. For instance, the analysis of the Bollin River in the UK (Hooke, 2022) revealed that changes in the amplitude and rate of meander migration exhibit a clear multi-year rhythm associated with the frequency of peak discharges. In large river basins such as the Yangtze and the Ganges, multi-decadal cycles of bar erosion and deposition have been documented, driven primarily by flood events and monsoon-related discharge variability (Wang et al., 2018; Ghosh et al., 2023). The transition in channel type during the Late Holocene observed in the Vecht River (Candel et al., 2018) illustrates the long-term sensitivity of fluvial morphosystems to climatic trends and land use changes.

The morphodynamics of rivers in the Carpathian region is quite active. This is confirmed by numerous studies focused on changes in river channels, including: the Dnister River between Halych and Zalishchyky cities (Burshtynska et al., 2017), and Rozvadiv–Halych cities (Radzii, Zaiats & Tretiak, 2018), and in Sambir Transnistria (Horyshnyi, 2024); the Stryi River from Stryhantsi to its mouth (Horyshnyi, 2014); the Stryvihor River near village Pidbuzh (Bayrak, 2016, 2017); the Sukel River (Rybak & Dubis, 2021); the Yablunka and Oriava rivers (Pylypovych & Kovalchuk, 2017); the upper mountain section of the Tysa River (Obodovskyi et al., 2018); the Prut River near the Chernivtsi city (Yushchenko, 2005); the Bystrytsia River (Bayrak, 2024); previous studies of the Tysa River crossing the Volcanic Ridge (Bayrak, 2011).

Channel morphodynamics is most active in the foothill sections of rivers, where the role of limiting factors is minor and channels retain a natural character. In mountain regions, the morphodynamics are constrained by factors such as low water flow, prevalence of confined channel types, and the absence of wide floodplains. Rivers in lowland areas often have anthropogenically modified channels, and their lateral dynamics tend to be stable.

The main goals of the study is to identify the character and patterns of morphodynamic transformations of the Tysa River channel over a 145-year period within the section crossing the Vyhorlat-Hutyn Volcanic Ridge, with a focus on the typological evolution of channel forms and the cyclicity of fluvial morphogenesis.

2. Study area

The morphodynamics of the Tysa River were studied at the narrowest section of its lowland course — in the area where it crosses the Vyhorlat-Hutyn Volcanic Ridge of the Ukrainian Carpathians. As it traverses the ridge, the river changes its flow direction multiple times — from northwestern to western and then to southwestern. The valley near the city of Khust reaches a width of 1.0–1.2 km, with the floodplain spanning 250–600 m. This is the narrowest point along the river's entire lowland course, known as the "Khust Gate." Downstream, the valley widens to 1.8–2.0 km along the east-west stretch. After a sharp turn to the southwest, the valley gradually broadens, reaching 3 km near the village of Korolevo. In the Transcarpathian Lowland, its width expands to 10–12 km. The river channel itself is about 85 m wide near Khust with a depth of 2.5 m, and 160 m wide with a depth of 1.5 m further downstream. The flow velocity is approximately 0.8 m/s. Within the studied section, the river exhibits a lowland character.

The Tysa Valley at the crossing of the Vyhorlat-Hutyn Volcanic Ridge consists of a floodplain and a first above-floodplain terrace (Figure 1). The floodplain is mostly unilateral, as the river frequently erodes the first terrace or the bedrock banks. It is composed of gravel and pebble material with inclusions of boulders and sand and is considered to be of Holocene age. The first above-floodplain terrace is unevenly developed: it is bilateral in the section before the Khust Gate, right-sided along the east-west segment, and left-sided in the area near Korolevo. It reaches a width of 1–3 km and a height of 2–2.3 m. The terrace age is Upper Pleistocene (Kravchuk, 2021). Its base consists of a layer of pebbles with distinct cross-bedding, overlain by interlayers of sandy, loamy sand, and clayey materials.

The Tysa River's flow regime is predominantly alimented by snow and rainfall. Approximately 40% of the annual runoff occurs during the spring period. The average water discharge near the city of Rakhiv reaches 246 m^3/s (Obodovskyi et al., 2018). The river gradient varies significantly along its course: at the crossing of the Volcanic Ridge, the slope is 1.1 m/km, whereas in the upper reaches, it reaches as steep as 250 m/km.

The river channel and its floodplain serve as the primary zones for flood development. Historical data on the rivers of Transcarpathia indicate that 34 major floods occurred during the 20th century, 12 during the 19th century, and only 4 in the 18th century (Kovalchuk et al., 2013). Particularly catastrophic floods were observed in June 1969, November 1998, April 2000, and July 2008 (Romashchenko & Savchuk, 2002). In the 21st century, during the first quarter of the century, there have already been 11 major flood events: April 2000; March 2001 (Susidko et al., 2006); July 2004, 2008, 2010, 2014; November 2016; December 2017; June 2020; February 2021; and January 2022 (State Hydrometeorological…, 2025).

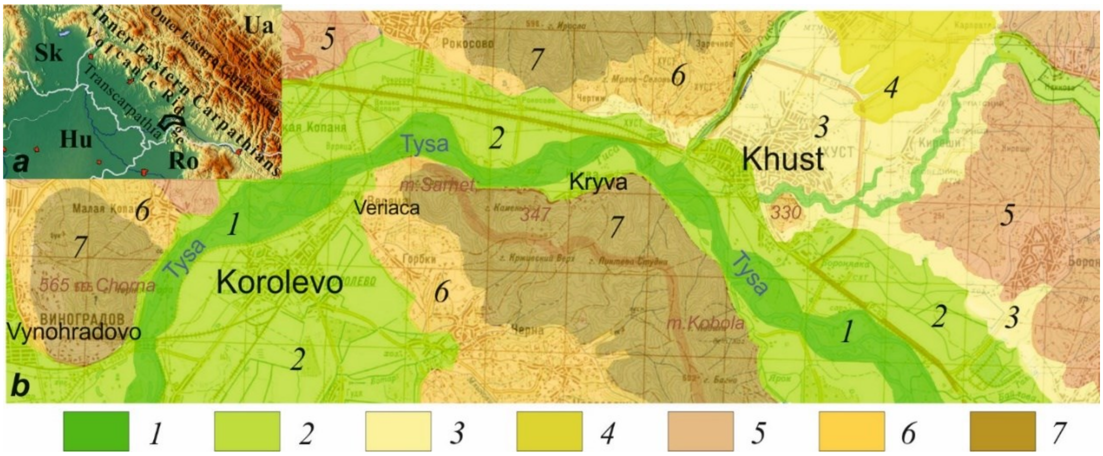


Figure 1. ***a***. Location of the research area within the Eastern Carpathians (*source: https://maps-for-free.com*); ***b***. Geomorphological map (*made by the author based on a topographic map in scale 1:50,000*). Legend. Fluvial relief: *1* – floodplain of the Tysa River and its tributaries; *2* – first floodplain terrace; *3* – second floodplain terrace; *4* – third floodplain terrace; *5* – complex of high terraces. *6* – Erosional-denudation relief. *7* – Structural-denudation (volcanic) relief.

The primary causes of these floods include long lasting summer rainfall—amounting up to 150–200 mm over 2–3 days, and up to 300 mm in some mountainous areas. Winter floods have generally been triggered by sudden thaws, accompanied with rainfall and rapid snowmelt. During such events, water levels in the Tysa River rose between 2.6 and 8.5 meters, with the observed maximal rise reaching 12.83 meters above pre-flood water levels.

3. Methods

To identify the channel dynamics of the Tysa River, six temporal snapshots were analysed:

1. the late 19th century, based on the Austrian-period map of 1880;
2. the early 20th century, based on the Czechoslovak-period map of 1938;
3. the late 20th century, based on the Soviet-period map of 1976 and satellite imagery from 1985 (Google Earth resource);
4. the early 21st century, using satellite imagery from 2000 (Landsat, EO Browser resource) and 2005 (Google Earth resource);
5. the period from 2011 to 2019 (Google Earth resource);
6. the present period, based on satellite data from 2020–2024 (EO Browser resource).

The scale of the source materials is approximately 1:100,000. All maps were georeferenced in QGIS (Projected Coordinate Systems WGS 84/UTM Zone 35N) for subsequent digitization of the river channel for each period. The total timespan over which changes were analysed is 145 years, making it the one of the longest study period for the river dynamics in the Carpathian region within the territory of Ukraine.

One of the key criteria used in the typology of river channel morphology is the degree of sinuosity, which is quantitatively expressed using the sinuosity index (k), calculated as the ratio of the channel length to the valley length. Based on the value of this index, channels are classified as straight ($k < 1.2$), slightly sinuous ($k \approx 1.2–1.5$), sinuous ($k \approx 1.5–1.75$), and meandering ($k > 1.75$). This approach allows for an objective classification of the spatial structure of the channel and enables researchers to trace its transformations over time. In our study, the slightly sinuous and sinuous types were combined into one type (slightly sinuous). A second important criterion is the number of flow threads, which distinguishes between single-thread and multi-thread channels. Multi-thread channels, in turn, may exhibit braided or anastomosing patterns, reflecting differences in hydraulic conditions and sediment transport regimes. In our conditions, exclusively braided channel types are common. To assign a morphological type to a given channel reach, a 70:30 ratio was used: if 70% or more of the reach length corresponded to a particular type, the entire reach was classified accordingly. In cases of a 50:50 or 60:40 distribution, both channel types were recorded as coexisting for that segment.

4. Results and discussion

4.1. Morphodynamics of the Tysa channel

In our studies, we took into account the following types: *straight*, *slightly sinuous* (sinuous channel with point bars type and incipient meandering) and *meandering* (free and confined meandering). By the number of channels, *single-thread*, *double-thread* and *multi-thread* (three or more thread) riverbeds are common (Figure 2). To characterize the channel morphodynamics, we have identified four sub-sections of the valley. For these sections, the genesis of changes in riverbed types over time was analyzed.

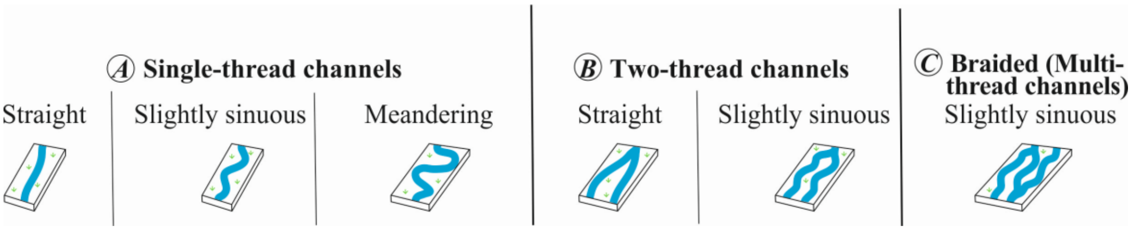


Figure 2 Morphological types of Carpathian channels.

4.1.1. Subsection One – Near the City of Khust

This segment of the Tysa River channel is located near the city of Khust, just upstream of a valley constriction known as the “Khust Gate” (Figure 3). The channel section trends submeridionally, oriented approximately southeast to northwest.

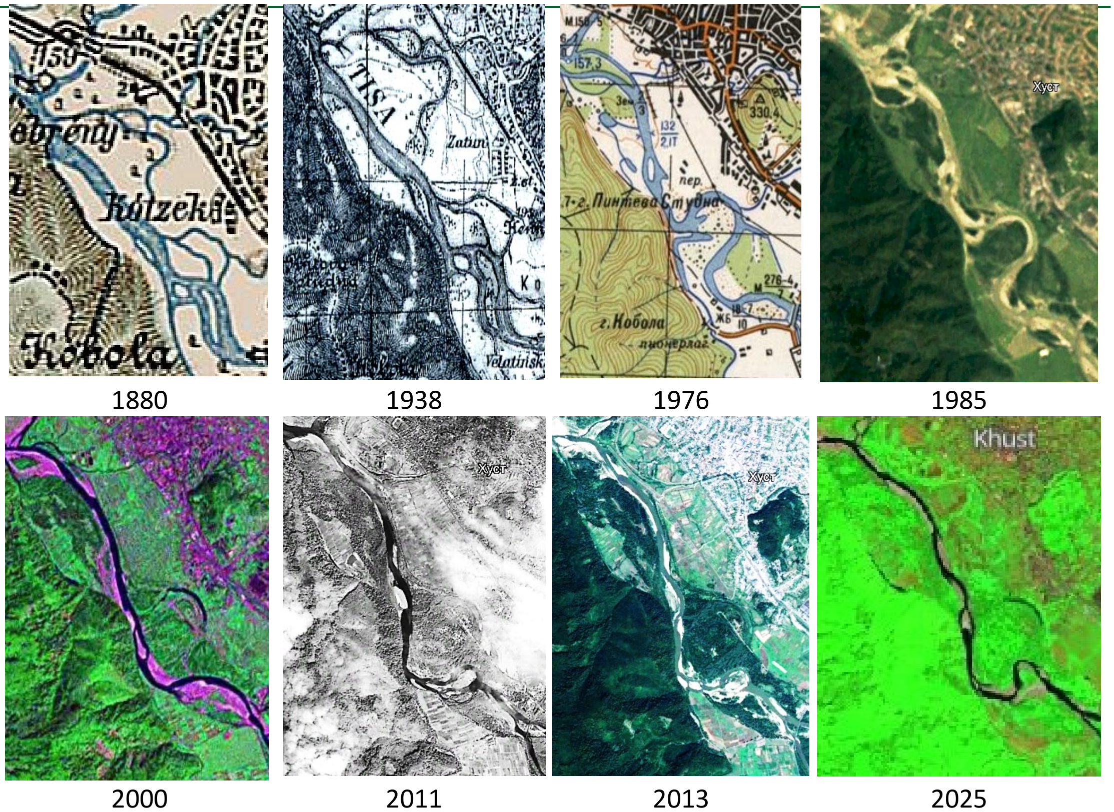


Figure 3 Channel changes of the Tysa River near Khust over time: the channel exhibits a transformation cycle from floodplain multi-thread (1880, 1938) to single-thread meandering (1976, 1985), followed by a straight configuration (2000, 2005). Between 2011 and 2019, sinuosity increased again. By 2025, the channel remains single-thread and predominantly straight.

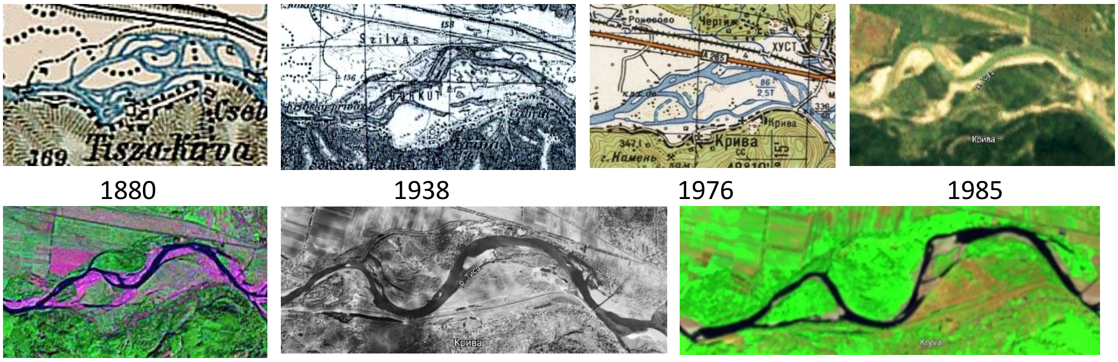
At the beginning of the study period in the late 19th to early 20th century, the channel was multi-thread. By 1976, a large meander developed with a radius of 570 m and an azimuth of 30°. In 1985, the meander apex had migrated to an azimuth of 50°. By 2000, the meander was breached, leaving an oxbow lake at the apex position—still present today—and the channel straightened. Between 1985 and 2000, the channel shifted laterally by 1.2 km. Currently, a smaller meander has formed with an apex azimuth of 350°.

Downstream, the channel was also multi-thread at the turn of the 20th century. Between 1976 and 1985, it became double-thread, and from 2000 onward, it evolved into a single-thread channel. Over the observation period, the Tysa migrated from the left to the right bank, with a total lateral shift of 725 m. While in the 19th century the river eroded the base of the left-bank terrace, since the second half of the 20th century it eroded the right-bank terrace.

Overall, increased channel sinuosity is evident during 1976–1985 and 2013–2019. The most significant changes occurred following major flood events in 1969 and 2008. During 1880, 1938, and 2000–2011, the channel remained mostly straight, while in 2020–2025, it became slightly tortuous. A multi-thread channel type is typical for 1880, 1938, and 2013–2019.

4.1.2. Subsection Two – Along the Village of Kryva

This latitudinal segment runs along the village of Kryva, constrained between a northern road embankment and the southern slope of an unnamed 371.3 m hill (Figure 4).



1880 1938 1976 1985

2000 2011 2025

Figure 4 Channel changes in the second subsection over time: the channel evolved from multi-thread (1880) to double-thread (1938, 1976), and subsequently to a single-thread meandering channel (1985–2025).

In 1880, the channel was multi-thread, with the main current eroding the left bank. Several interconnected watercourses crossed the valley bottom perpendicularly. By 1938, the channel has migrated northwest toward the right bank, likely as a result of major floods in 1882, 1887, 1902, 1912, and 1925. During these floods, sediment accumulation in the main channels likely led to flow redistribution through deeper secondary branches.

By 1976, the channel became double-threaded, with the right thread serving as the main channel. Instead of a single sharp bend, two gentle meanders developed. These changes were driven by significant flood events in 1941, 1947, 1955, and especially the catastrophic 1969 flood.

By 1985, following a period of increased water discharge in 1978 and 1980, the channel became distinctly meandering, forming two well-defined, confined meanders still partially preserved today. The main flow shifted toward the right bank, while former channels became oxbow lakes.

From 2000 to 2025, the channel has remained meandering, with one confined eastern meander and one free western meander. Despite 11 major floods (including 2008), the channel structure remained relatively stable. Morphological changes were limited—eastern meander transformed into a truncated meander with a broad base, and the western meander into a sinusoidal pattern. A new distributary formed in the western segment, giving rise to a double-threaded channel. Limited change is likely due to reduced sediment load from increased forest cover (Global forest change…, 2024) and shorter flood durations, preventing significant channel transformation.

4.1.3. Subsection Three – Along Mount Sarget

This downstream segment flows past Mount Sarget (Figure 5). Over the 145-year period, the channel underwent a sequence of morphodynamic transformations: slightly tortuous (1880) → meandering (1938) → double-thread (1976) → straight (1985) → slightly meandering (2000) → distinctly meandering (2007–2025).

A full cycle between the repeated transition from a straight channel in 1880 to a straight channel again in 1985 spans nearly 100 years, while the interval between repeated meander formation is approximately 70 years. The large meander evident in 1938 had a radius exceeding 500 meters. This meander began to regain such dimensions around 2007 and has persisted to the present day, although its bend angle has become more gradual. In 1976, this meander existed as a side branch, which gradually transformed into an oxbow lake. Satellite imagery from 1985 shows that the oxbow lake was already barely discernible at that time, with only isolated segments still containing water.

By 2000, channel curvature increased, and the meander radius reached approximately 1,000 meters, forming a segmented-type meander. From 2007 onward, the meander became more expansive and evolved into a block-shaped form.

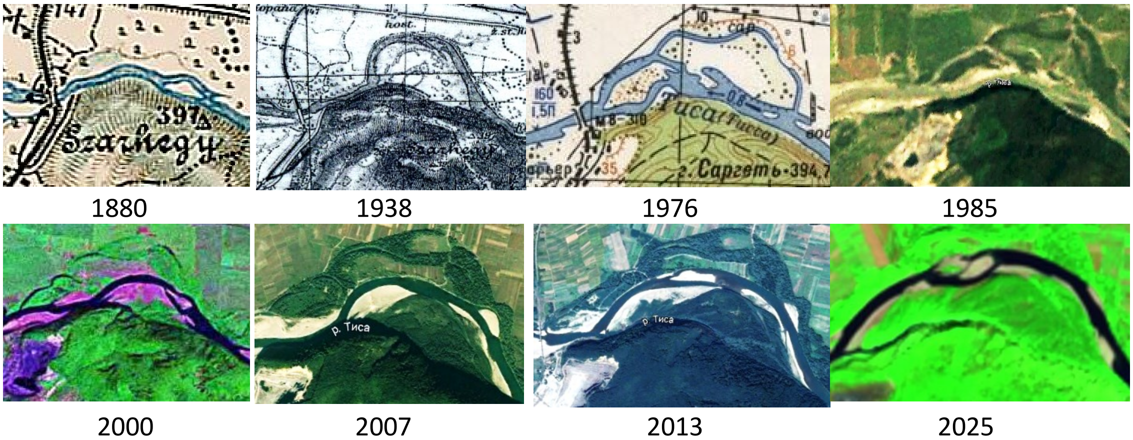


Figure 5 Channel changes of the Tysa River near Mount Sarget over time. The channel morphology changed from slightly tortuous (1880) to confined meandering (1938), from double-thread and mostly straight (1976) to single-thread and slightly tortuous (1985), then to meandering (2000), and again to confined meandering (2007–2025).

It should also be noted that the channel has not only changed in form but also in position within the valley bottom. In 1880, it eroded the left bank terrace at the base of Mount Sarget. By 1938, it had retreated to the central part of the floodplain. During 1976–1985, the Tysa again eroded the left terrace of Mount Sarget, and since 2000, it has once more shifted to the central part—mirroring the position it held in 1938. These observations underscore that the Tysa River is a highly dynamic watercourse, with substantial channel mobility and active erosion–deposition processes.

4.1.4. Subsection Four – Along Mount Chorna

This submeridional section flows from northeast to southwest, skirting the village of Korolevo on the left bank and Mount Chorna on the right (Figure 6). At the upper part of this section, the river crosses its floodplain laterally from left to right.

In 1880 and 1938, the channel was highly braided, with 3–5 active threads that coalesced near Mala Kopanya into a single-thread reach. Further downstream, two threads developed along Mount Chorna. By 1976, a single-thread straight channel dominated, though small remnants of side branches and oxbow lakes remained.

In 1985, minor channel bends developed, with radii reaching up to 150 meters and wavelengths ranging from 300 to 800 meters. Near the point of floodplain ingress, the channel bifurcated. Since 2000, meandering activity has intensified, resulting in the formation of two segmented meander loops, which gradually merged into a single, sinusoidal meander by 2013. Between 2019 and 2022, this meander reverted to a larger, segmented configuration. At the downstream end, a new reverse (or backward) meander with its apex oriented southward began forming after 2013. The river currently exhibits active lateral erosion at the foot of Mount Chorna near Mala Kopanya—an erosional trend not previously recorded. This indicates a transition toward a regime dominated by lateral channel migration.

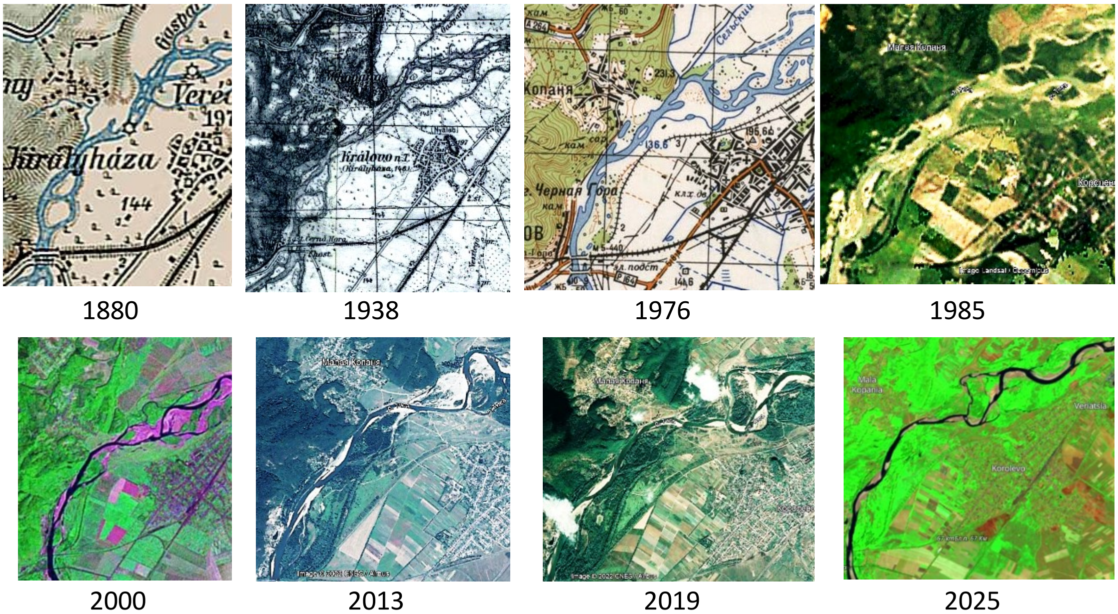


Figure 6 Channel changes near Korolevo over time. The river transitions from floodplain and channel multi-thread (1880, 1938) to a predominantly straight single-thread channel (1976), then to a meandering type (1985), and back again to meandering during 2013–2019. In 2000 and 2025, the channel straightens once more.

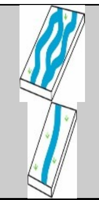
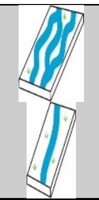
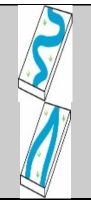
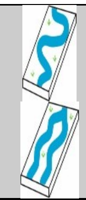
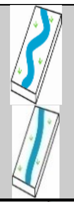
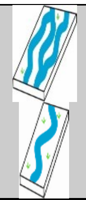
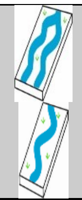
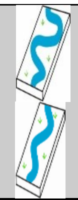
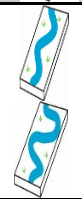
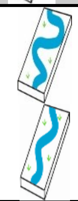
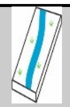
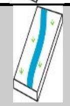
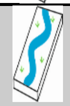
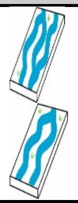
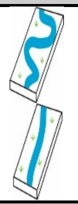
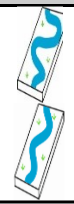
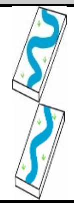
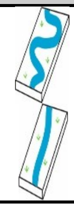
As a result, the fourth subsection reveals a dynamic trajectory from multi-thread to straight single-thread and slightly tortuous configurations, followed by a shift to meandering and once again straightened conditions in recent years.

4.2. Morphodynamic States of the Tysa River and Its Transformations Over Different Time Periods

Significant channel reconfigurations of the river occurred after extreme floods. Therefore, the channel states recorded on maps and aerial imagery for different time periods were grouped according to the dates of major extreme flood events, resulting in nine historical time slices and the current state. These include the channel states prior to the major floods of 1900, 1927, and 1941; the catastrophic flood of 1969; major floods in 1980 and 1989; the catastrophic flood of 2008; significant floods in 2014 and 2020; and the present state as of 2024 (Table 1).

Analyzing the changes in morphodynamic channel types of the Tysa, it is evident that in the 19th and early 20th centuries, multi-thread and meandering channel types predominated. A hundred years later, these types are only found in one reach following the 2008 flood. Single-thread types began to develope most actively from the 1980s and now dominate. Meandering channels were present throughout all time periods, but their development intensified from 2014 onward. Straight and slightly sinuous types were most common between 1980 and 2008. Today, meandering channel types prevail: the meander wavelengths are long and stretched along the floodplain, resulting in many straight segments of the river.

Table 1 Channel types of the Tysa River at different time slices before extreme flood events of the 19th–21st centuries.

	1900	1941	1980	1989	2008	2014	2020	2024
One subsection (near the Khust City)								
Two subsection (along the village of Kryva)								
Three subsection (along m. Sarget)								
Four subsection (along mount Chorna)								

The spread of multi-thread channel types in the 19th and early 20th centuries can be explained by increased sediment accumulation on the floodplain and high water discharge, which caused the river to split into multiple branches. In the 20th century, economical development of the Carpathian river basins intensified significantly (Pylypovych & Kovalchuk, 2017), along with an increase in extreme flood events, making channel dynamics more pronounced. Since 1989, most sections have developed single-thread channels. Multi-thread and two-thread types have disappeared across most segments. A short stretch of multi-thread channel briefly re-emerged between 2008 and 2014 in the first sub-reach, but then transitioned into two-thread and single-thread channels by 2024. In the fourth segment, a large portion of the riverbed occasionally becomes straight—particularly following the catastrophic floods of 1969 and 2008, and currently during the low-water period. The changes in the early 21st century toward more natural straightening of the channel are linked to reduced anthropogenic pressure, fewer major floods, the ongoing low-water period, and floodplain forest stabilization. In the first and second decades of the 21st century, the river's dynamics tended toward increased meandering, associated with a prolonged high-water period (Obodovskyi et al., 2018). Toward the end of this period, summer dry spells became longer (2017, 2018), while major floods shifted to late autumn (November 2016, December 2017). In the third decade of the 21st century, the Tysa River channel evolved toward slightly sinuous and meandering types, likely due to reconfigurations during almost annual major floods, which mostly occurred in winter or early summer (June 2020, February 2021, January 2022) (Figure 7).

Figure 7 The Tysa River after the flood in the summer of 2020 in the area of the second subsection along the village of Kryva (photo from open sources).

4.3. Cyclicity of Tysa River Channel Changes

An analysis of the Tysa's channel dynamics over 150 years shows that the changes are cyclical in most cases (5 out of 6). This cyclicity lies in the fact that a certain channel type recurs after a period of time. The channel undergoes horizontal deformations but eventually returns to its initial state. Several studies confirm that river systems can exhibit various rhythmic patterns influenced by both natural processes (e.g., water level and discharge variations, climate fluctuations) and anthropogenic impacts (e.g., dam construction) (Bassani et al., 2024; Hooke, 2023; Jackson et al., 2022; Tongal et al., 2016).

The most consistent cyclicity is observed in single-thread straight channel types. Four complete morphodynamic cycles and two incomplete ones were identified. The *first cycle* (Figure 8*a*) has one iteration consisting of three stages: single-thread straight → two-thread straight → single-thread slightly sinuous → two-thread slightly sinuous → single-thread straight. An *incomplete cycle* is as follows: initial stage (single-thread straight) → single-thread slightly sinuous → ?unknown future stage.

The *second cycle* also has one iteration with the following stages: single-thread straight → single-thread meandering → two-thread slightly sinuous → single-thread straight (Figure 8*b*). The *incomplete cycle* includes: single-thread straight → single-thread slightly sinuous → single-thread meandering → ?future stage.

The *third cycle* includes two iterations (Figure 8*c*). In the first: single-thread straight → single-thread meandering → single-thread straight. In the second: single-thread straight → single-thread slightly sinuous → back to single-thread straight.

Two-thread types are relatively short-lived, with one cycle consisting of one iteration: two-thread slightly sinuous → multi-thread meandering → single-thread slightly sinuous → single-thread meandering → two-thread slightly sinuous (Figure 8*d*).

Multi-thread channel types form one complete cycle with one iteration, and one incomplete cycle. The full cycle follows the sequence: multi-thread slightly sinuous → single-thread meandering → single-thread slightly sinuous → multi-thread (Figure 8*e*). The *incomplete cycle* comprises stages of multi-thread → two-thread → single-thread types, all of which are sinuous.

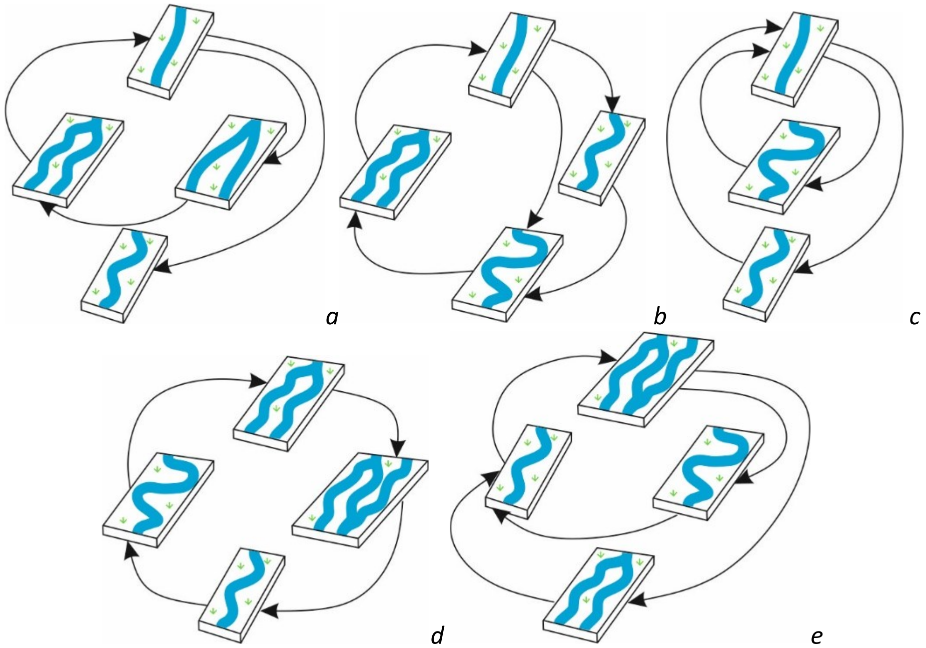


Figure 8 Cycles of morphodynamics of segments of the Tysa channel crossing of the Volcanic Ridge.

4.4. Results of Cyclicality Analysis

The cyclic nature of channel changes demonstrates that rivers, despite undergoing morphological transformations associated with lateral migration , tend to return to a form similar to their original configuration over time. However, there is no absolute identity between the initial and final states of the channel. While slightly sinuous or meandering channels may revert to the same general type after several intermediate stages, the resulting bends typically differ from the original in terms of radius, amplitude of deflection, and location of meander apices.

Morphodynamic cycles are characteristic of small piedmont rivers formed within wide floodplain geomorphological settings. In contrast, for large lowland rivers that meander within broad floodplains, morphodynamic changes are typically expressed through variations in sinuosity index, while the morphotype itself rarely changes. In incised or anthropogenically regulated lowland rivers, as well as in mountain rivers with single-thread straight channels, changes in channel morphotype are generally absent.

The primary triggers of morphodynamic transformations are major and catastrophic flood events. Other influencing factors can be categorized as local and regional. Local factors include increased sediment deposition due to localized erosion of the riverbed and slopes, the influence of tributary inflows and erosional forms, in-channel gravel pit, abrupt channel bends, and alternation between narrow and wide floodplain sections. Regional factors encompass climatic and meteorological conditions and their variability; the geological and geomorphological structure of the river valley; increase in hydrological parameters; changes in forest cover within the basin and the extent of floodplain forests; and more extensive anthropogenic land use practices across the watershed.

5. Discussion

The findings of this study reveal a clear pattern of cyclic morphodynamic transformations of the Tysa River over the past 145 years, marked by transitions between multi-thread and single-thread channel types, as well as shifts in sinuosity. While previous research has predominantly focused on temporal variations in meander geometry, migration rates, or bar morphology (e.g., Hooke, 2022; Ghosh et al., 2023), the recurrence of distinct channel morphotypes over decadal to centennial timescales has rarely been quantified. The cyclicity observed in this case supports the broader conceptual framework of fluvial rhythmicity and self-organization processes (Jackson et al., 2022), particularly in piedmont valley settings where channels interact with wide floodplains and respond dynamically to hydrometeorological impulses.

Compared to large lowland rivers, where morphodynamic change tends to manifest as gradual variation in sinuosity index without a shift in fundamental channel type (Finotello et al., 2024), the Tysa River exhibits more pronounced typological transformations. These are driven by a combination of major flood events, variable sediment supply, tributary junctions, and floodplain morphology. Similar observations have been made in paleo-hydrological reconstructions (Candel et al., 2018), where long-term shifts from laterally stable to meandering systems were identified over millennial timescales. In our case, morphotype recurrence is observed on shorter, more regular cycles, typically at 40–50 and approximately 100-year intervals.

The present analysis is based exclusively on planform evidence derived from historical maps and remote sensing imagery. Although this approach effectively captures lateral changes in channel configuration, it does not provide direct geomorphological or stratigraphic confirmation of former channel positions across the floodplain. To substantiate the proposed cyclicity more robustly, future studies should incorporate sedimentological or subsurface data (e.g., floodplain coring, soil profile analysis) to trace abandoned channels, overbank deposits, or buried bar structures. Such evidence would help validate whether the river had indeed occupied different sectors of the floodplain in earlier stages and whether planform changes correspond to shifts in sedimentary environments.

Therefore, the observed morphodynamic cyclicity—documented through repeated alternations of channel forms—contributes valuable insights to the understanding of medium-term fluvial evolution and the resilience of channel patterns under varying hydrological and sedimentary regimes.

6. Conclusion

The analysis of the Tysa River channel over a 145-year period has revealed a predominantly cyclic character of morphological changes, observed in five out of six documented cases. This cyclicity manifests as the periodic return of the river channel to a similar morphological type following phases of lateral deformation. Although the channel does not return to an absolutely identical initial configuration, the general structural form tends to be restored over time. Variations in channel curvature, meander amplitude, and apex positions indicate morphological flexibility within a broader framework of structural persistence. The results confirm the hypothesis of rhythmic evolution in river systems, suggesting an inherent capacity for self-organization under external forcing. The river channel thus functions as an open nonlinear system with internal regulatory mechanisms that maintain quasi-equilibrium conditions. From a scientific standpoint, the study deepens our understanding of structural stability and morphogenetic trajectories in fluvial systems. Knowledge of channel cyclicity forms a valuable basis for reconstructing past hydromorphological states and forecasting future dynamics. In practical terms, these findings are crucial for river management, particularly in planning channel regulation measures and assessing the risks associated with land use along river corridors. Understanding channel morphodynamics is vital for developing adaptive catchment management strategies, especially in the context of climate change and increasing anthropogenic pressure. The data obtained can be applied in the design of flood mitigation systems, restoration of natural river networks, and the establishment of green corridors. Overall, the study enhances our understanding of the spatiotemporal organization of fluvial systems and provides a scientific foundation for regional models of channel evolution.

References

Bassani, F., Bertagni, M.B., Ridolfi, L., Camporeale, C. (2024). Unexpected transient dynamics of meandering rivers with unsteady flows. Geophysical Research Letters, 51, 22, e2024GL110650, 10 pp. https://doi.org/10.1029/2024GL110650.

Bayrak, G. (2016). Changes in riverbeds in the context of changes in the forest cover of their basins (on the example of the Pidbuzh River in the Starosambir district). Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers, 1(6), 18–31. (In Ukrainian).

Bayrak, G. (2024). Bystrytsia River morphodynamics in the Precarpathian Upland since 147 years ago. Problems of geomorphology and paleography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers, 2(17), 112–129. https://doi.org/10.30970/gpc.2024.2.4561. (In Ukrainian).

Bayrak, G. R. (2011). Modern riverbed processes and dynamics of the Tysa riverbed at the intersection of the Vyhorlat-Hutyn volcanic range. Physical geography and geomorphology, 62, 45–54. (In Ukrainian).

Bayrak, G., Kovalchuk, U. (2017). Morphology and dynamics of the Stryvihora riverbed in the Carpathian Mountains. Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers, 1(07), 64–76. http://dx.doi.org/10.30970/gpc.2017.07.1962. (In Ukrainian).

Burshtynska, Kh., Tretyak, S., Shevchuk, V. (2017). Research on the meandering of the Dniester River using geoinformation technologies. Modern advances in geodetic science and production, I (33), 113–138. (In Ukrainian).

Candel J., Kleinhans M., Makaske B., Hoek W.Z., Quik C., Wallinga J. (2018). Late Holocene channel pattern change from laterally stable to meandering – a palaeohydrological reconstruction. Earth Surface Dynamics 6(3):723-741. https://doi.org/10.5194/esurf-6-723-2018

Chalov, R. S. (2011). Riverbed science: theory, geography, practice. Vol. 2: morphodynamics of river channels. Moscow: Krasand, 960 p. ISBN 978-5-396-00325-5. (In Russian).

Charlton, R. (2008). Fundamentals of Fluvial Geomorphology. London; New York : Routledge. 233 p. https://doi.org/10.1111/j.1475-4762.2009.883_5.x

Finotello A., Durkin P., Sylvester Z. (2024). Meandering streamflows across landscapes and scales: a review and discussion. Geological Society, London, Special Publications, 540, 1 – 41. https://doi.org/10.1144/SP540-2024-33

Ghosh S., Mandal P., & Bera B. (2023). Dynamics of channel bar morphology on multi-decadal timescales in a braided river within Himalayan foreland basin, India. Journal of Earth System Science, 4. https://doi.org/10.1007/s12040-023-02187-x

Global forest change. 2024. URL: https://glad.earthengine.app/view/global-forest-change#dl=0;old=1;bl=1;lon=23.33406904187936;lat=48.330572277487384;zoom=9

Hooke, J. (2023). Morphodynamics of active meandering rivers reviewed in a hierarchy of spatial and temporal scales. Geomorphology, 439. https://doi.org/10.1016/j.geomorph.2023.108825.

Hooke, J.M. (2022). Morphodynamics of a meandering channel over decadal timescales in response to hydrological variations. Earth Surface Processes and Landforms, 47, 8, 1902-1920. https://doi.org/10.1002/esp.5354

Horishnyi, P. (2014). Horizontal deformations of the lower reaches of the Stryi River bed in 1896-2006. Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers, 1(5), 68–74. (In Ukrainian).

Horishnyi, P. (2024). Horizontal deformations of the Dniester riverbed in Sambir Transnistria. Morphodynamics of processes in the western region of Ukraine: development and ecological consequences. Monograph / edited by R. Hnatyuk, L. Dubis. Lviv: Publishing House I. Franko National University of Lviv, 90–95. (In Ukrainian).

Jackson, S., Anderson, E.P., Piland, N.C., Carriere, S., Java, L., Jardine, T.D. (2022). River rhythmicity: A conceptual means of understanding and leveraging the relational values of rivers. People and Nature, 4, 4, 949–962. https://doi.org/10.1002/pan3.10335.

Kovalchuk, I., Mykhnovych, A., Pylypovych, O. Rud'ko, G. (2013). Extreme Exogenous Processes in Ukrainian Carpathians. Book chapter in : Geomorphological impact of extreme weather: Case studies from central and eastern Europe. Loczy Denes. Series: Springer Geography, Part 1, 53–67.

Kravchuk, Ya. S. (2021). Relief of the Ukrainian Carpathians: Monograph. Lviv : Publishing house of Ivan Franko National University of Lviv. 576 p. (In Ukrainian).

Obodovskyi, O. G. (1998). Riverbed processes: Textbook. Kyiv: RVC "Kyiv University", 134 p. (In Ukrainian).

Obodovskyi, Yu. O., Khilchevskyi, V. K., Obodovskyi, O. G. (2018). Hydromorphoecological assessment of channel processes of rivers of the upper part of the Tysa basin (within Ukraine): monograph / edited by O. G. Obodovskyi. Kyiv: Print Service, 193 p. (In Ukrainian).

Pylypovych, O. V., Kovalchuk, I. P. (2017). Geoecology of the river-basin system of the upper Dniester: monograph / edited by I. P. Kovalchuk. Lviv-Kyiv: Ivan Franko Lviv National University, 284 p. (In Ukrainian).

Radziy, I., Zayats, I., Tretyak, S. (2018). Research of the Dniester River bed displacements using GIS technologies. Modern advances in geodetic science and production, II (36), 106–113. (In Ukrainian).

Romashchenko, M., Savchuk, D. (2002). Water disasters. Carpathian floods. Kyiv: Agrarna nauka. 304 p. (In Ukrainian).

Rybak, N., Dubis, L. (2021). Horizontal deformations of the Sukil riverbed within the Pre-carpathian height in 1880–2019. Problems of geomorphology and paleography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers, 1 (12), 197–211. http://dx.doi.org/10.30970/gpc.2021.1.3464.

State Hydrometeorological Service of Ukraine. (n.d.). https://meteo.gov.ua. Retrived at 01.03.2025

Susidko, M. M., Polyakova, S. O., Shcherbak, A. V. (2006). Catalog of characteristics of rain and snow-rain floods on the rivers of the Carpathian region for 1989–2002. Scientific works of the UkrNDGMI, 255, 299–310. (In Ukrainian).

Tongal, H., Demirel, M. C., Moradkhani, H. (2016). Analysis of dam-induced cyclic patterns on river flow dynamics. Hydrological Sciences Journal, 62(4), 626–641. https://doi.org/10.1080/02626667.2016.1252841.

Wang Z., Li H., & Cai X. (2018). Remotely sensed analysis of channel bar morphodynamics in the Middle Yangtze River in response to a major monsoon flood in 2002. Remote Sensing, 8, 1165. https://doi.org/10.3390/rs10081165

Yushchenko, Y. S. (2005). Geohydromorphological patterns of riverbed development. Chernivtsi, 320 p. (In Ukrainian).