# RESEARCH OF THE MORPHOLOGY OF RIVER DNIESTER USING REMOTE SENSING AND CARTOGRAPHIC DATA

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## Abstract

The aim of the work is to research the method of studying horizontal displacements in the channel of the Dniester (the second largest river in Ukraine) from river source to canyon using data of different periods – topographic maps, space images and special maps. The main factors of displacements and meandering of the Dniester riverbed were considered. The boundaries of the Precarpathian bend and Volhynian-Podolian upland are shown as their structures influence the formation of the character of the Dniester riverbed. The monitoring was carried out on the site with a total length of about 400 km for over a 100-years period. Data for conducting research includes topographic maps (1890, 1928, 1986) and space images obtained from satellites Landsat 5 (1979), Landsat 7 (2000) and Sentinel (2017), as well as special ground maps and maps of Quaternary deposits. The general workflow of data processing is presented. Depending on the type and the displacement of the riverbed, the research site is divided into 5 sections. Visualization and studies of changes in the Dniester riverbed were carried out with ArcGIS 10.1 software. The sinuosity coefficients of the Dniester river channel were determined, and measurements of the maximum displacements of the river on its five selected fragments of the channel were performed. The maximum displacement during the 100-year period is 950 meters. For the analysis of the influence of relief, the digitized river channel was imposed on DEM. It was established that the main effective method for forecasting channel changes is a hydrological and morphological analysis based on different topographical data, and information obtained on the basis of remote sensing data, which involves the combination and analysis of modern and past configurations of the riverbed.

**Key words:** monitoring, channel processes, riverbed displacement, meandering, alluvial and deluvial sediments

## Introduction

It is commonly known that with time riverbeds change their plane position and elevation. Depending on the type of river, it can move by a measure, which significantly exceeds the width of the riverbed, new straits and distributaries can appear, or a riverbed can change its configuration in 50-100 years. Therefore, results of monitoring of riverbed deformation processes need to be taken into account while solving a series of tasks related to riverbed processes, and specifically:

- developing and building hydraulic engineering facilities;
- designing power transmission grid across rivers;
- laying natural gas transmission pipeline;
- determining flood hazard zones and the scale of destruction after flash floods or seasonal floods;
- establishing boundaries of land conservation areas;
- managing recreation activities;
- studying the condition of frontier lands and establishing the border along the midstream of rivers.

Expenses for examining the riverbed and geological environment make a few percent of expenses for construction of a facility, but these engineering and geological examinations often determine successful use of the planned facility. Ignoring foreseeable displacements of riverbeds often results in unpredictable consequences. Thus, for example, a shift in the riverbed of the river can cause emergencies at submerged crossings of pipelines. Bank caving causes breakage of pipeline, which in its turn causes a massive explosion and fire, breakage of the pipeline causes oil spill and environmental disruptions. Significant losses to the economy of the country can be caused by bridge scouring, power transmission supports scouring, etc. Protection of frontier land and prevention of interstate contradictions can be mentioned as one of special tasks related to riverbed processes.

Among major works on topics, related to riverbed processes, the following works can be mentioned (GRENFELL et al., 2014; HOOKE, 1984, 2006; BURSHTYNSKA et al., 2015; ZOLEZZI et al., 2012).

Broad-scale researches of different nature on riverbed evolution are being conducted abroad. Hence, the impact of topography, geology, climate, vegetation and land use onto the space and time of riverbed shifting processes in the North West Pacific is pointed out in (BUFFINGTON, 2014). The authors study the impact of types of riverbeds on physical models that can be used for forecasting changes in the riverbed morphology.

The connection between the topography of ground surface and hydraulic characteristics of the riverbed, and specifically the impact of pre-channel and subsurface water flows, as well as the study of morphology and riverbed structure of the Amazon river is laid out in the following works (BEIGHLEY et al., 2009; PIRMEZ et al., 1995).

A survey on the impact of bank erosion and methods of its assessment is given in (WATSON, BASHER, 2005-2006).

Scientists from Great Britain (FRIEND, SINHA, 1993) studied the interweaving and sinuosity of single-distributary and multi-distributary rivers with determining interweaving and sinuosity coefficients. It has been found that multi-distributary rivers are more sinuous than single-distributary ones.

The study of issues of riverbed processes in the rivers of Western Australia is given in report (JANICKE, 2000). It has revealed the impact of anthropogenic factors onto the transportation of deposits and silting. Attention has been drawn to the solution of the issue of river degradation and riverbed processes, which is the responsibility of a special Water and Rivers Commission.

Research (GUNERALP et al., 2011) analyses migration of the Brazos River stream in Texas in 1910-2010. It uses topographic maps and satellite images from different years. It analyses not only the riverbed migration, but also meanders, tilting and form of the riverbed of this river. It has determined migration zones of the riverbed in the future, which is an analytical instrument for determining areas, which can be at risk of catastrophes and floods.

In Article (LEGG, OLSON, 2014) rivers of the Western Washington serve as an object of research, or more specifically – migration of their riverbeds. It is pointed out that riverbeds migrate along floodplains due to processes of riverbed broadening, alteration of bends and their frequency.

In order to assess the interrelation between the change of climate, processes of relief formation, percentage of forest lands and the modern dynamics of riverbeds, stratigraphic, geo-morphological and paleo-environmental data from high-altitude watersheds in the Great Basin of Central Nevada have been collected (MILLER et al., 2001). They indicate that the transition to drier, warmer climate conditions 1300-2500 years ago caused a complex set of geo-morphological reactions. The initial reaction was a massive upland erosion with simultaneous gravitation of side valley alluvial deposits. It was followed by stabilization of deposits because fine-grain deposits were formed out of rocks, and specifically – alteration of deposit processes and the flow took place. It was pointed out that modern dynamics of riverbeds and the associated riverbank ecosystems have a significant impact on the shape of forestland.

From literature sources (BURSHTYNSKA et al., 2016, MORISAWA, 1985, RUD'KO, PETRYSHYN, 2014) it is known that every river has its own properties depending on natural and anthropogenic factors. Factors affecting deformation processes of riverbeds are divided into two groups: natural and anthropogenic, which in turn are divided into direct and indirect factors. Classification of the main factors influence on riverbed displacements are given in Table 1.

**Table1.** Classification of main factors influence on riverbed displacements.

| **Riverbed processes** | | | |
|---|---|---|---|
| **Natural** | | **Anthropogenic** | |
| Direct | Indirect | Direct | Indirect |
| Landslides and bank erosion | Rainfall regime | Hydro-technical construction | Watershed destruction |
| Soil drifting | Erosion intensity at the watershed | Overregulation of the water flow | Deforestation in the basin |
| Surge of the river | Water-blocking capacity of the soil | Streambed and floodplain quarries | Mining for mineral resources at the watershed |
| Freeze-up and frozen soil | Vegetation at the watershed | Communications across rivers | Hydro-technical and amelioration measures at the watershed and floodplains |
| Vegetation in the river and on the floodplain | Landscape structure of the watershed | Amelioration works in the riverbed | Gravel and stone extraction |
| Water flow | | Settlements along riverbanks | |
| Sediment run-off | | | |
| Geological and morphological structure | | | |

*Source: Own study based on the information from OBODOVSKY (2001).*

## Materials and methods

The object of research is the second biggest river in Ukraine – the Dniester river from the headwaters to the canyon part (the city of Zalishchyky) (Fig.1). It is no coincidence that this river was picked up for research, because its flowing along the borderline of two geological structures – the Precarpathian bend and the Volhynian-Podolian upland, the structures of which affect the formation of the character of the riverbed. The length of the section under research makes 440 km. The stream gradient is 4,5 m/km at the upper reaches and up to 0,3 m/km at the lower reaches. The width of the riverbed is up to 10 - 15 meters at the upper reaches and up to 300 meters at the lower reaches. The average depth is from 0,5 to 1,0 m, maximum depth of the riverbed is 2,5-2,8 meters (Transkordonne…). The river is rain–fed and snow-fed. The freeze-up period is from the end of November to the middle of March. Spring floods and spring-fall flash floods are common for the river. The Dniester river has a very sinuous riverbed in certain sections of it with the most interesting meanders around the village of Kruzhyky.

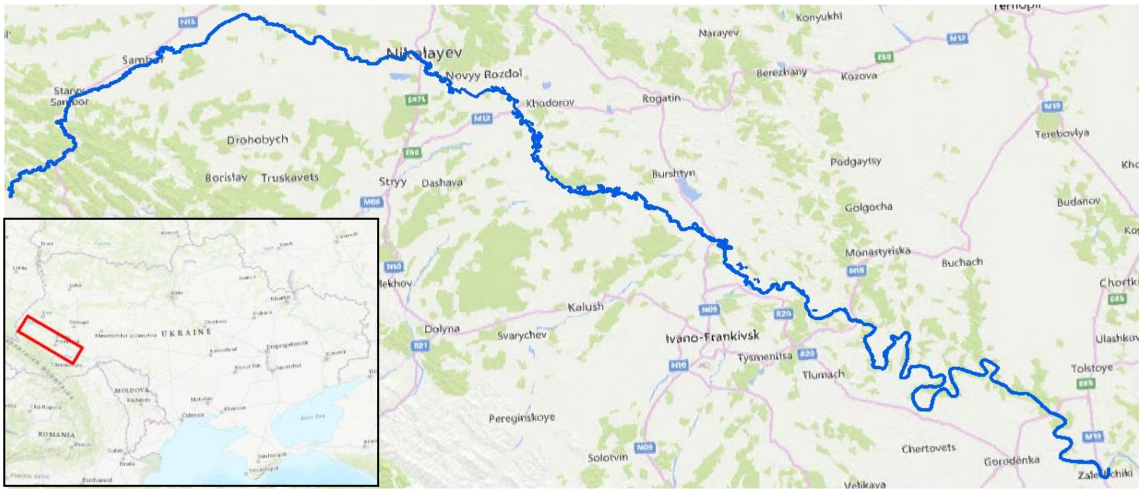
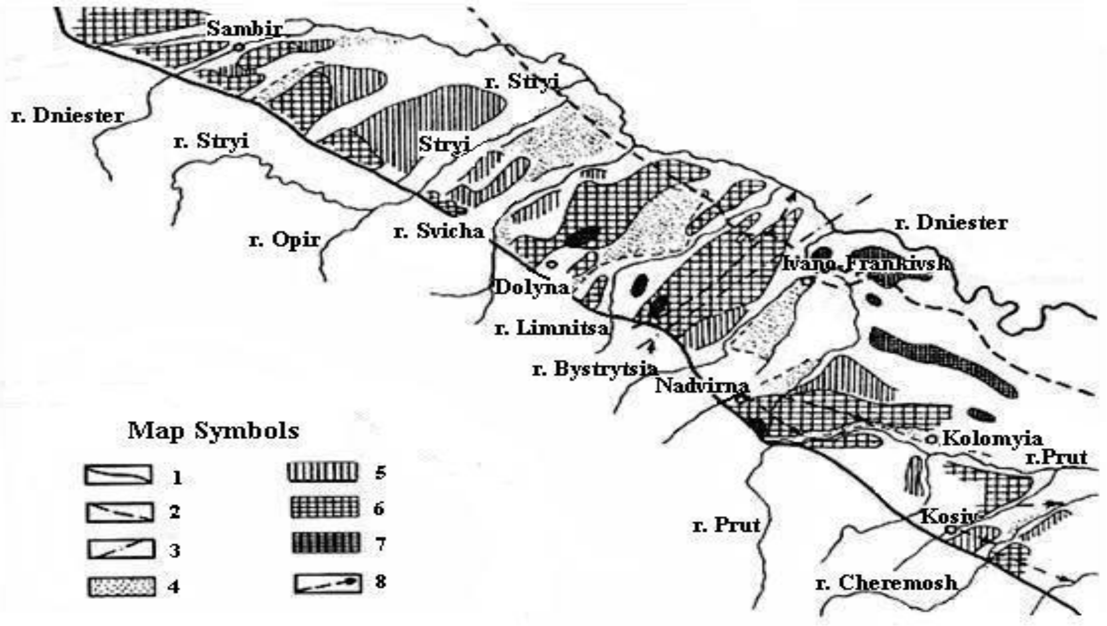


**Fig. 1.** General view of the field of research.
*Source: Own work and map from bing.com.*

The Precarpathian bend is a young alpine area of Earth's crust subsidence, which is located between the Carpathian Structure and the Volhynian-Podolian upland (KRAVCHUK, 1999). Figure 2 shows the boundaries of the Precarpathian bend and the Volhynian-Podolian upland, the structures of which affect the formation of the Dniester's riverbed, as well as of its right-bank tributaries.



**Legend:**
**1 - the edge of the Carpathians;**
**2 - the edge of Volhynian-Podolian upland;**
**3 – the Kovalivka-Smykovtsi line and its Carpathian continuation;**
**4 – accumulative terraces;**
**5 – low terrace level;**
**6 – high terracing level (Loyeva level);**
**7 – the highest level;**
**8 – some ancient directions of Precarpathian rivers.**

**Fig. 2.** Precarpathian bend.
*Source: (Kravchuk, 1999).*

Methodology of the research is based on the principles of hydrological and morphological analysis, which has been conducted using topographical maps and satellite images from various times.
For monitoring displacements and meandering of the Dniester's riverbed in the stretch between the headwaters area and the city of Zalishchyky with the length of 440 km the following has been used:

- topographic maps in scale 1:100000 (Austrian period – 1890y., Polish period –1928y., the Soviet period – 1986y.);
- satellite images Landsat 5 (1986y.), Landsat 7 (2000y.) and Sentinel 2 (2017y.);
- soil map in scale 1:200000.

The materials used in the studies are presented in Figure 3.

The technological scheme of investigations is presented on Fig.4. Visualization and analysis of planar Dniester's riverbed variations has been done using ArcGIS software. Horizontal displacements of the riverbed have been determined according to satellite images received from satellites Landsat5 (1986) Landsat7 (2000) та Sentinel2 (2017) and topographic maps. Spatial interval of images from the Landsat system makes 15 meters after the pansharpening; and 10 meters from the Sentinel2 systems channels. Georeferencing of topographic raster maps was done with use of 10 points coordinates of which determined from the kilometer grid. Austrian period map with absent kilometer grid was georeferenced using coordinates transformation of easily identifying points (bridges, road intersections, geodetic control points) on existing georeferenced maps. Polynomial of second order was chosen to achieve better accuracy which not exceeds 15 meters on the intrinsic convergence. Afterwards all georeferenced raster maps were transformed to WGS-84 coordinate system in which satellite images was given.

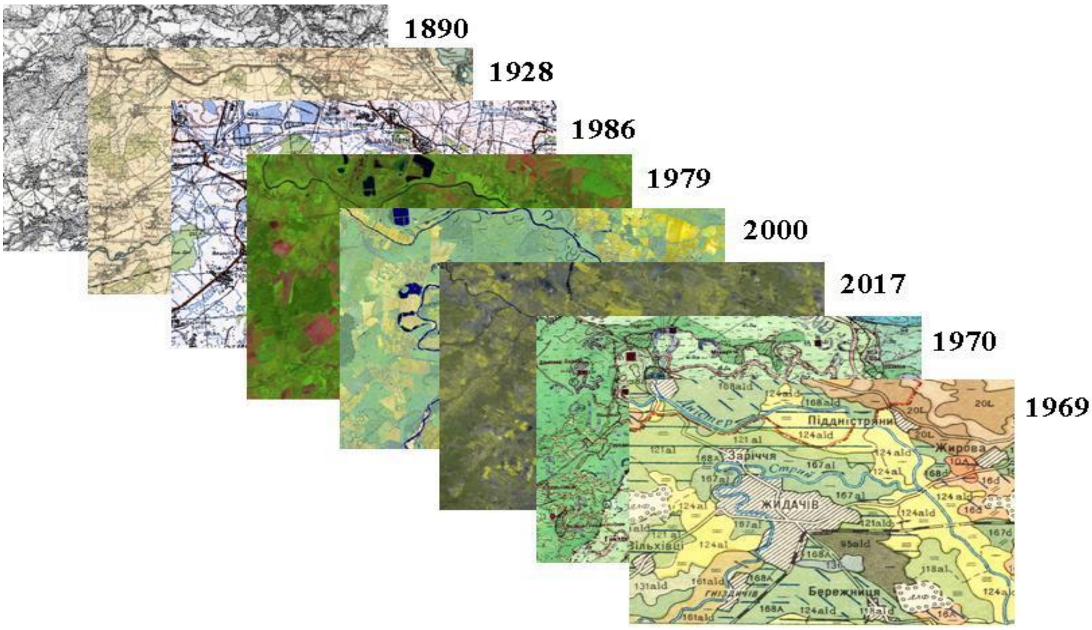


**Fig. 3.** Materials of research.
*Source: Own study.*

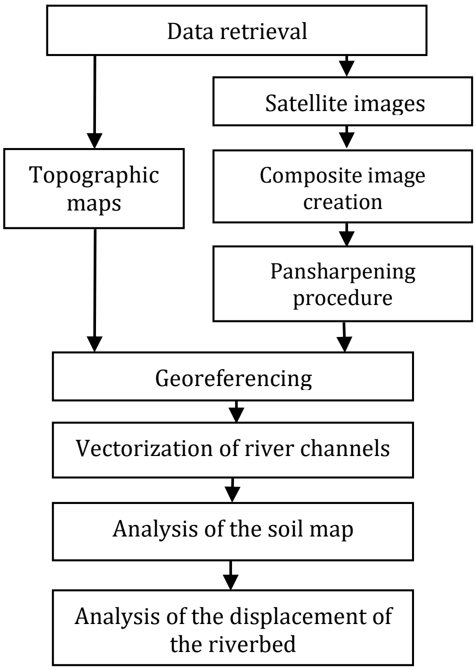


**Fig. 4.** Technological scheme of investigations.
*Source: Own study.*

## Results and discussion

As it has been defined in reference books and geographical descriptions of the river (Transkordonne…), the properties of the riverbed give reasons to mark out three major sections: mountain, valley and river mouth ones. The conducted research showed an approximate approach to this division, and specifically to the valley section, the description of which does not take into account geological structures and the types of soil having the determining influence on the character of the riverbed.

The task presumed the study of horizontal displacements of the Dniester River, determining sections of maximum displacements, analysis of various approaches to the assessment of the riverbed rigidity and calculation of rigidity coefficient considering displacements of the riverbed.

One of the principal characteristics of the rivers is sinuosity coefficient $K_l$, which is determined from the correlation (Table 2):

$$K_l = L'/L, \tag{1}$$

where: $L'$ is the length of the riverbed in the area;
$L$ is the length of the riverbed of between the extreme points measured in a straight line.

**Table 2.** Sinuosity coefficient of the research river and type of soil.

| | Sections of research | | | | |
|---|---|---|---|---|---|
| | I | II | III | IV | V |
| **Sinuosity coefficient** | 1,29 | 1,33 | 1,5 | 1,31 | 2,39 |
| **Type of soil and rock** | Outputs of country rock, small boulders, pebbles | Small pebbles, large gravel | Gravel, sand | Gravel, sand | Fine gravel |

*Source: Own study and information from OBODOVSKY (2001).*

According to the character of horizontal displacements and morphological features, the stretch of the Dniester River under study has been divided into 5 sections: 1) mountain; 2) hill and valley; 3) wetland and valley; 4) valley; 5) canyon.

The mountain section is predominantly straight with some sinuosity of 1,35 (Fig. 5a), and a V-shaped narrow valley; the steam gradient is – 4,45 m/km; displacements are minor, reaching 130 meters. In places where the tributaries flow into the river, the valley is broader, and displacements can reach 400 meters.

The increase of meandering and the $K_l$ coefficient to 1,33 is common for the transition from the mountain section to the valley one. An especially complex character of meandering is observed near the village of Kruzhyky, where opposite banks of the river differ in their height and the steepness (Fig. 5b). The analysis of the topographic map of this section testifies to major soil erosion, which is reflected in the formation of gullies, which with time and after consolidation of soil become covered with plants.

The most unexpected stretch at the transition from the mountain and hill section of the riverbed to the valley one is the stretch, located in a broad wetland valley (Fig. 5c). The riverbed sinuosity, shown in the topographic map of 1886 is significant and the sinuosity coefficient reaches 1,97. In this map we can see a lot of dead arms of the river, which testifies to major meandering of the riverbed as compared to previous epochs, the riverbed displacements reach 950 meters. Taking into consideration the valley type of the locality, the angles of slopes gradient are 0,5°. A great number of submerged and partially submerged lands is typical for this territory. Thus, since the 30s of the past century, riverbed straightening and bank protection works have been conducted here. In the 60s-70s amelioration works were conducted along the Dniester river. Some channels got silted up. River bank protection got broken in some places. It is worthy a note that certain stretches of the riverbed tend to shift to the riverbed of 1886.

In the fourth section the riverbed clearly depends on geomorphological properties of the locality: in places with a broad valley the meandering is significant and reaches 870 meters (Fig. 5d).

The fifth section is the transition from the valley to the canyon section, which is not dependent on the sinuosity or stream gradient, but first of all on the types of rocks, forming the canyon (Fig. 5e). The space of the floodplain is not big and makes up to 370 meters. Riverbed displacements are also insignificant – 200-350 meters.

As to the measure, which characterizes the riverbed stability, two approaches are described in special literature. According to the first approach, the riverbed stability index is determined at specific stretches of insignificant length, where the river has similar characteristics (ROSGEN, 2001, SIMON, KLIMETZ, 2008). It presumes taking into account major parameters, often detailed ones, determined through ground measurement (for instance - the depth of the river near two banks, or erosion, caused by bank caving, etc.) according to empirical criteria, which are then added to determine the riverbed rigidity (MAKKAVEEV, CHALOV, 1986). The second approach determines indices of stability according to the data of morphometric characteristics using mathematical relations.

The table 3 gives main morphometric characteristics of the above five sections of the riverbed, and table 4 shows calculated riverbed stability indices. The study demonstrates significant discrepancy between the stability indices, which refers to sections I and V in particular.

The sinuosity coefficient can be one of the stability indices only for sections with a significant width of the floodplain. For example, for the canyon section the sinuosity coefficient $K_l$=2,4, however the riverbed is stable because the stability factor are rocks forming the banks of the river.

It is proposed to show the riverbed stability index as a correlation of the width of the floodplain to the width of the riverbed:

$$K = B'/B, \qquad (2)$$

where

$B'$ is the width of the floodplain, determined based on the maps of quaternary deposits.

Measurement of the characteristics of the channel for each of the sections was carried out at selected points in 3-4 km (in total at 120 points). Stability criteria: stable – 1–3, moderately stable – 4–10; non-stable – > 10. The proposed criterion is congruent with horizontal displacements of the riverbed determined for the period of 100 years.

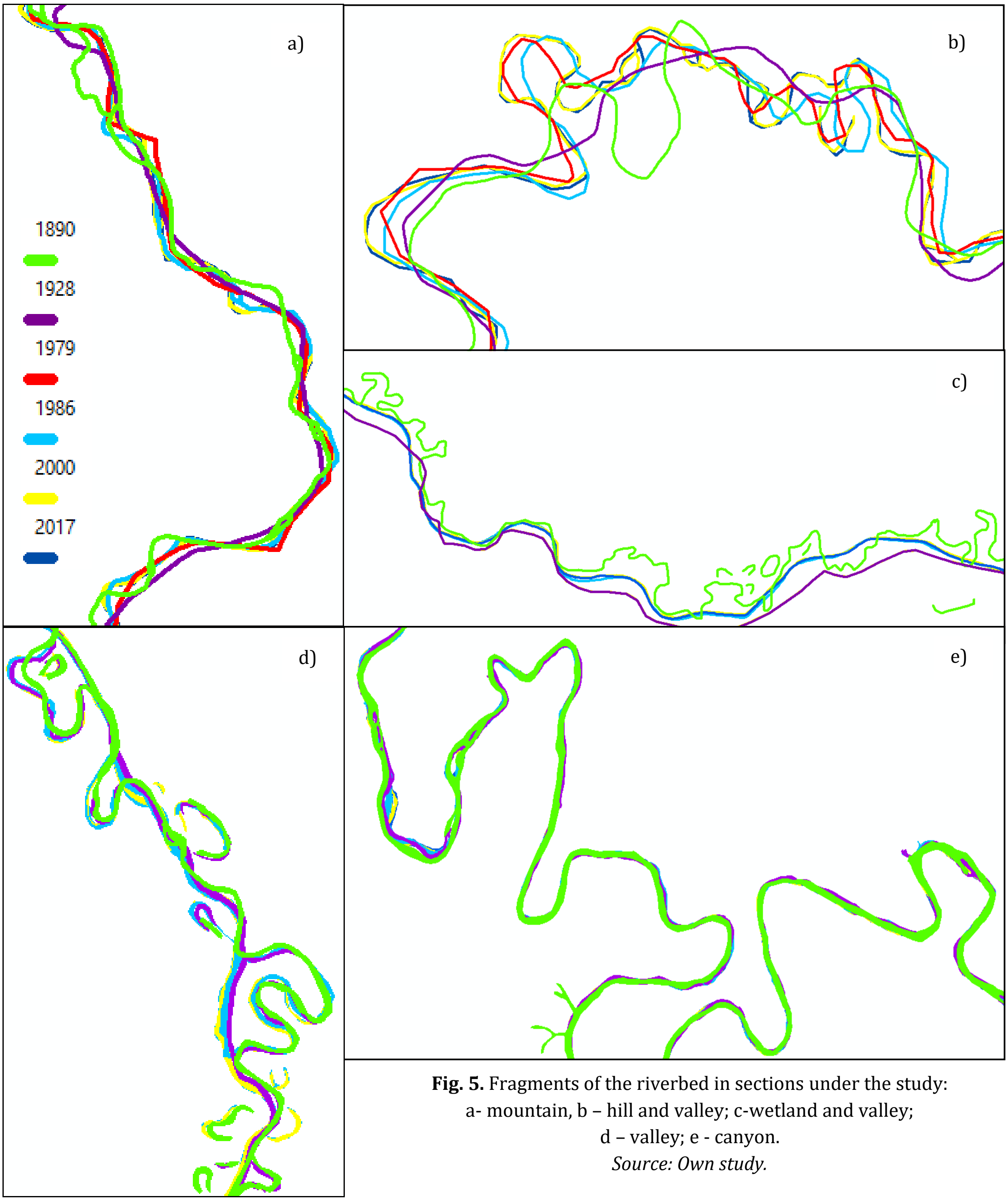


**Fig. 5.** Fragments of the riverbed in sections under the study:
a- mountain, b – hill and valley; c-wetland and valley;
d – valley; e - canyon.
*Source: Own study.*

**Table 3.** Main morphometric characteristics of the above five sections of the riverbed.

| Main morphometric characteristics | Sections of research<br>I | <br>II | <br>III | <br>IV | <br>V |
|---|---|---|---|---|---|
| Length *l*, km | 38,2 | 36,1 | 71,1 | 157,5 | 137,4 |
| Difference in altitude of river section *ΔH*, m/km | 170 | 78 | 19 | 54 | 50 |
| Stream gradient I, m/km | 4,45 | 2,16 | 0,27 | 0,34 | 0,36 |
| Average width of the river, *B*, m | 23 | 28 | 25 | 100 | 180 |
| Average depth of the river *h*, m | 0,5 | 0,8 | 1,0 | 1,2 | 1,7 |
| Average sediment diameter *d*, mm | 50 | 10 | 1 | 1 | 2 |
| Average width of the floodplain *B´*, m | 210 | 500 | 1180 | 2010 | 380 |

*Source: Own study and data from* O*BODOVSKY (2001).*

**Table 4.** Calculated riverbed stability indices.

| | Main relations for determining riverbed stability index | Stability criteria of the riverbed, from not stable to stable | Sections of research | | | | |
|---|---|---|---|---|---|---|---|
| | | | I | II | III | IV | V |
| 1 | $L = d/I$ | 2 – <50 | 11,2 | 4,6 | 3,7 | 2,9 | 5,6 |
| 2 | $L_o = (d/I) \cdot (B/h) \cdot A$, ($A$ – erosion coefficient (0,03)) | 2 – <50 | 10,1 | 5,2 | 5,6 | 10,9 | 11,9 |
| 3 | $K_s = 1000 * (d/B \cdot I)$ | 6 – >100 | 749 | 154 | 74 | 20 | 46 |
| 4 | $\Psi = d/h \cdot I$ | 1 – 15 | 22,5 | 5,8 | 3,7 | 2,5 | 3,3 |
| 5 | $G = (\sqrt{B})/h$ | 18 – 1 | 7,7 | 6,8 | 7,1 | 10,2 | 6,4 |
| 6 | $K_u = \sqrt{(B \cdot d/h)}$ | 5 – 40 | 38,7 | 19,4 | 7,1 | 11,2 | 11,9 |
| 7 | $K_r = (d \cdot B)/(h \cdot I)$ | 30 – 1500 | 337 | 174 | 185 | 368 | 392 |
| **8** | $K = B'/B$ | **100 – 1** | **9,1** | **18** | **47** | **20** | **2,1** |
| | Maximum displacements, m | | 370-400 | 540-610 | 900-950 | 610-870 | 230-370 |

*Source: Own study*

## Conclusions

The methodology of studying horizontal displacements of hydrographic objects based on the use of satellite images and topographic maps from various periods of time, as well as quaternary deposits and the soil, has been tested.

The analysis of major geological structures shows that the Precarpathian bend, full of alluvial deposits from various epochs, and the Volhynian-Podolian upland have a predominant impact on the character of the Dniester River and its right-bank tributaries.

Shift monitoring data for the period of 130 years have been used. Depending on the character of horizontal displacements and morphological properties, the stretch of the river under study has been divided into 5 sections: 1) mountain; 2) hill and valley; 3) wetland and valley; 4) valley; 5) canyon. It has been established that maximum displacements of the riverbed have been observed on the valley sections and reach from 600 to 950 meters. The mountain and canyon sections have insignificant displacements, which in certain areas reach 400 and 370 meters correspondingly.

Using the dependences taken from the specialized literature, riverbed stability indices have been calculated for the fragments of the river under study. Contradicting results have been received specifically for sections 4 and 5. It is therefore proposed to use the stability criterion based on the width of the floodplain and the width of the riverbed, which has proved to be efficient while determining displacements.

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