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Monitoring of horizontal displacements and changes of the riverine area of the Dniester River

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Abstract

The article discusses the monitoring of horizontal displacements of the channel of Dniester, the second largest river in Ukraine, based on topographic maps, satellite images, as well as geological, soil and quaternary sediment maps. Data processing has been carried out using the geographic information system ArcGIS. The monitoring over a 140-year period (1874–2015) has been performed at the river's transition from a mountainous to plain terrain on the 67 km section of the river. During this period, maximum displacements in the study area were 590–620 m. The research examines water protection zones needed for channel displacements. The article describes the monitoring methodology and analyses changes over a period of 18 years (2000–2018). The analysis includes the anthropogenic influence on the channel in the monitoring area. Results of the research may be useful for construction and cadastral works related to the channel in the area concerned, as well as for water management.

Key words: *channel processes, Dniester River, monitoring, riverbed displacements, riverine areas, satellite images, supervised classification, topographic maps*

INTRODUCTION

Climate change, global warming, as well as the anthropogenic factors influence channel processes. Thus, natural floods, which led to devastating results, have become more frequent in Ukraine, especially in its western region. Floods are the main cause of changes in river channels. Anthropogenic factors associated with ineffective management are the most important factors determining the condition of river channels, floodplains, and river shore areas. These factors primarily include deforestation, large scale extraction of stone and gravel out of river channels, and building structures developed in floodplain areas. Changes in riverbed areas result from growing settlement areas and the economic activity of the local population.

Horizontal displacements are an essential part of channel processes. Since they determine channel stability, results of such studies should be taken into account when constructing anti-flood and hydraulic structures, choosing locations where power lines and pipelines cross the river, as well as performing the cadastre calculation of water protection zones.

The multinational cooperation of countries which use a common waterway requires special studies and agreements [OSCE/UNECE 2005]. In this regard, the monitoring of horizontal displacements of riverbeds and adjacent areas is an urgent task of hydrological research using remote sensing and GIS. Each river has its own characteristics which depend on its location, geological structures, tectonics of the region, lithology, as well as climatic changes. Therefore, each river should be investigated separately.

Several factors have determined the choice of the research topic: the location of the source and part of the Dniester River and its right-bank tributaries in the Carpathian region of Ukraine, the participation of one of the authors in a sport and tourist expedition of 1984 which helped to discover the magic of this unique river, as well as the fact that in the pre-war era some scientists of the Lviv Polytechnic

Institute worked on a large project of establishing the Dniester River as a part of the waterway from the Baltic to the Black Sea, a project which was highly appreciated and supported by the then entrepreneurs.

Since 2006, the scientists of the Department of Photogrammetry and Geoinformatics of the Lviv Polytechnic Institute have been researching various aspects of changes in the hydrological regime of rivers of the Dniester basin based on remote sensing and geoinformation technologies. We consider the development of methodology for determining horizontal displacements of riverbeds based on space images, topographic and special maps (geological, soil and quaternary sediment maps), and the processing of data using the ArcGIS geoinformation system, a significant achievement. The methodology is the basis for monitoring of river channel horizontal displacements. The proposed research continues this subject matter. In the course of research, we have considered various factors, including the anthropogenic ones, which influence changes in the channel regime of river systems.

Since the Dniester River is the main waterway of Western Ukraine, the interest of scientists from different research areas in water supply, flow, and ecological state is understandable.

The article describes the main results of our research with regard to various aspects of rivers in the Dniester basin. SHEVCHUK [2009] presents the principle of zoning depending on morphology and types of channel meandering, as well as peculiarities of the course of the Dniester River and its tributary in the mountainous area. It has been proposed to divide this section of the river into five parts for a more detailed research.

The analysis of displacements of the Stryi River in a 140-year period indicates that the largest horizontal displacements can be noted in its mouth, in the place of its confluence with the Dniester River. These have been compared with other tributaries, such as Bystrytsya, Limnitsa, and others [SHEVCHUK, BURSHTYNSKA 2011]. Horizontal displacements reach 1200 m and the trend is clearly visible on quaternary sediment maps. There is a clear influence of lithology and anthropogenic factors, such a random movement of stone, gravel and sand from the riverbed and floodplain.

The monitoring for the estuary of the Stryi River in 1896–2006 was based on a similar methodology using topographic maps and images from Google [HORISHNYY 2014]. An interesting attempt was made to examine the displacement of the river against the lithological structure of the Ciscarpathian foredeep.

The influence of upper geological structures on the character of the Dniester and its right-bank tributaries in the foothill part has been considered by the authors [RUD'KO, PETRYSHYN 2014]. The specific geological structure of the Ciscarpathian foredeep, with its powerful sand and gravel deposits, has resulted in the extraction of this valuable raw material, but also contributed to significant ecological disturbances and losses in the area concerned. The authors note that boulder-gravel-sandy rocks in Ukraine are distributed very unevenly. Their significant reserves are concentrated in the Ciscarpathian foredeep. They are formed by quaternary alluvial, delluvial, fluvioglacial, and aeolian deposits. They occur in the form of lenses and stratal deposits up to 20–25 m, powerful at a depth of 0–3.0 m.

The work by BURSHTYNSKA *et al.* [2017] describes monitoring of displacements of the Dniester River from its source to the city of Zalishchyky in different parts of the plain and canyon.

The research, which has become possible thanks to the new channel monitoring approach and technologies, has been described by other authors [BURSHTYNSKA *et al.* 2019]. It shows a significant difference between horizontal displacements of the right- and left-bank tributaries of the Dniester, which rest on different geological structures within the Ciscarpathian foredeep, on the right, and in the Volyn-Podilsk Upland, on the left. In the same work, mathematical expressions used to determine the stability of channels have been analysed. The largest differences between calculated stability and the stability criterion are established for the mountain and canyon parts of the ridge.

Based on the developed methodology, horizontal displacements in the plain area of the Dniester and Tisza Rivers have been determined and analysed. The authors obtained interesting results, indicating the influence of various factors, especially on the entire flood regime. The method and research results were presented at the ISPRS Congress in 2016 [BURSHTYNSKA *et al.* 2016].

Let us consider some works describing deforestation in the river basin as another factor that has a significant impact on the hydrological regime of the Dniester.

The monograph by KOVAL′CHUK and PETROVS′KA [2003] discusses natural factors of channel processes, in particular rivers flow in the Dniester basin and precipitation in the area in the second half of the 20th century. The monograph highlights an insufficient amount of afforestation of watersheds (40.2% in the Ukrainian Carpathian Mountains, and 25% in the Precarpathian). The research also notes the condition of forests, including excessive deforestation, changes in the age and species composition of forests, anthropogenic decline of its upper border by 200–300 m, as well as the fact that the percentage of afforestation in the Carpathians is steadily decreasing.

Environmentalists of the state agency of Ukraine have long been sounding the alarm around the unauthorized deforestation. The research by KABAL [2016] indicates a large role of forests in maintaining the water balance. The optimal forest coverage for elementary watersheds is 65–70%. Trees start to accumulate water after reaching the age of 40. PARPAN and OLIYNYK [2009] analyse factors contributing to floods, structure of forests and their water-regulating role in the Ukrainian Carpathians. They also put forward proposals for strengthening the protective properties of forests. Input included 50-year statistical afforestation data, as well as results of hydrological and experimental studies. In recent decades, scientists and practitioners have indicated that in the Carpathians forest reduces the slope water runoff about 4–5 times, and trunks and crowns of trees restrain water flow by 20–30%. Forest prevents landslides, while in dry weather it contributes to the soil feeding of rivers. The work of [BAYRAK 2011] describes deforestation in the basin of the Pidbuzh River, as well as changes in its hydrological regime.

BURSHTYNSKA *et al.* [2014] discusses problems of tree felling in the Carpathian Region. The research has used satellite images of high spatial resolution. It established that it is possible to determine not only areas, but also the time of felling based on these images.

Morphological features and meandering of rivers are widely discussed in the literature. FRIEND and SINHA [1993] proposes changes to standard definitions of tortuosity and meandering to highlight the quantitative morphology of each river's channel despite whether it has single or several branches.

There are cases when the plowing of floodplain lands led to soil erosion and the transformation of meadows into unproductive territories [MAKAREVICH 2016]. These problems arise not only in Ukraine, but also in many European countries, for example, the Netherlands, Italy and France. Some municipalities decided to plan their urban development without coordinating it with the activity of the riverbed. This created translated into significant costs for flood control measures and emphasized the need and importance of the long term stability of the channel. Further floodplain development may lead to higher flood levels. Therefore, the priority of the new land use policy is to establish maximum protective borders, while taking into account the future meandering of rivers.

In addition, in some European countries, the restoration of rural and mountainous areas contributes to the growth of forests, reduced supply of precipitation to rivers, and an increase in the speed of river flow.

Changes in the morphology of the mountain part of the Vistula River channel and their impact on land and infrastructure flood risks are discussed by ŻELAZIŃSKI [2014]. The author concluded that river regulation is accompanied by dangerous phenomena. A detailed description of the types of channels using data related to channel forms, accumulative elements, and characteristics of watercourses and development of the territory are presented by KRZEMIEŃ [2006]. The author suggests using ground-based observations, maps, and satellite images for channel analysis. It is noted that the regulation of Carpathian Rivers has caused erosion in deep layers of their channels, which, in turn, has contributed to negative changes in channels themselves and caused a change in land use. According to the author's research, the abstraction of alluvial material from channels causes great harm to these channels.

A broad-scale research on riverbed evolution have been conducted abroad. 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 *et al.* 2014]. The authors study the impact 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, have been laid out in the following papers (PIRMEZ *et al.* [1995], BEIGHLEY *et al.* [2009]).

Processes in the rivers of Western Australia are discussed in the report [JANICKE 2000] on the impact of anthropogenic factors onto the transportation of deposits and silting. Attention has been drawn to the solution to river degradation and riverbed processes. A survey on the impact of bank erosion and methods of its assessment is included in [WATSON, BASHER 2006].

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

GÜNERALP *et al.* [2011] analyse migration of the Brazos River stream in Texas in 1910–2010. The study 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. It has determined future migration zones of the riverbed, which is an analytical instrument for determining areas which can be at risk of catastrophes and floods.

Rivers of Western Washington have been an object of research, or more specifically, the migration of their riverbeds [LEGG, OLSON 2014]. It is pointed out that riverbeds migrate along floodplains due to riverbed broadening, alteration of bends and their frequency.

In order to assess the interrelation between the change of climate, relief formation, percentage of forest land and the modern dynamics of riverbeds, the study based on stratigraphic, geo-morphological and paleo-environmental data from high-altitude watersheds in the Great Basin of Central Nevada [MILLER *et al.* 2001]. The study indicates that the transition to drier, warmer climate conditions 1300–2500 years ago caused a complex set of geo-morphological reactions. It was followed by the stabilization of rock-origin fine-grain deposits, and specifically, the alteration of depositing and the flow. It was pointed out that modern dynamics of riverbeds and associated riverbank ecosystems have a significant impact on the shape of forestland.

As described in the literature (RUD'KO and PETRYSHYN [2014]), every river has its own properties depending on natural and anthropogenic factors. Factors affecting the deformation of riverbeds can be divided into two groups: natural and anthropogenic, which may have direct or indirect impacts.

The article by GRENFELL *et al.* [2014] considers processes of channel formation in four tropical sandy meandering rivers. The work expands the previous empirical analysis, which emphasizes the role of the elongation of a meander in the formation of the channel shape.

The study by HOOKE [2006] describes a number of meanders in the UK to address the issue of their morphological adaptation and changes. Peak runoffs in recent decades have been analyzed to identify patterns and trends.

The processes of meandering of riverbeds in Western Washington are described by LEGG and OLSON [2014]. This research also reveals patterns of meander development.

The analysis of the main channel-forming factors is presented by PERUMAL and BHASKARAN [2010]. A classification of images by remote sensing has been developed in order to obtain information about the riverbed.

PHIRI and MORGENROTH [2017] considers the development of methods for classifying the soil and vegetation cover on Landsat images from the 1970s to present, and describes the main ways to optimize them.

Based on the simulation, ZOLEZZI *et al.* [2012] investigate the morphodynamic feedbacks between the oscillations of spatial curvature and the width in the river meanders and related channel shapes. A particular attention has been paid to intra-river changes.

KOKHAN *et al.* [2020] describe stages of conceptual modeling for creating a system of crop monitoring. The monitoring is based on spatial data obtained from several sources. This approach can be proposed as a methodology for a wide range of monitoring systems.

MATERIALS AND METHODS

CHARACTERISTIC OF THE OBJECT OF RESEARCH

The object of analysis in this research is a part of the Dniester River and its horizontal deformations over the 141-year period (1874–2015). The length of the section examined is 67 km.

General characteristics of the Dniester River. The Dniester River is the second largest river of Ukraine. Its length is 1362 km; the area of the basin is 72 100 km^2. The Dniester Basin is located in three countries: Poland, Ukraine and Moldova, but most of it is located in Ukraine. A small part of the basin is in north-western outskirts of Poland. In Moldova, the Dniester basin occupies more than half of the territory of the country, covering its eastern and northeastern regions [OSCE/UNECE 2005]. The Dniester River and the right-bank tributaries of its basin originate from the Carpathian springs at the altitude of 800–1000 m. In fact, the mountainous nature of the river with access to a wide floodplain determines its hydrological characteristics. In its upper part, toward the town of Sambir, the Dniester is a typical mountain river, which flows in a narrow valley between steep rocky banks. Then, the Dniester reaches a plainland and flows through a wide, first swampy and then grassy, valley whose width reaches 13 km. There, its flow becomes much calmer. This is the area of the river's free meandering. Then, the Dniester cuts deep into the granite base of the Podilsk Upland. In the section between towns of Halych and Khotyn, it flows in the Dniester Canyon, which is one of the most picturesque natural wonders of Ukraine (Photo 1).

Photo 1. View of the Dniester River near the town of Zalishchyky (Ternopil region, Ukraine) (phot.: https://pro.te.ua/wp-content/uploads/2019/08/Zalishhyky.jpg)

It was formed more than 1000 years ago due to the movement of tectonic plates. The Dniester Canyon is included in the list of protected sites of the Emerald Network of Europe that must be protected under the Berne Convention. From time to time, rocky high banks resemble mountain ranges. Layers of limestone, shale and sandstone come to the surface. Numerous cliffs and outcrops are natural monuments. Further, in a deep narrow valley, dense limestones and sandstones come to the surface, and near the Kamianets-Podilskyi city, we can see crystalline rocks, including granites which form steep slopes near the village of Yampol. The Dniester flows into the Dniester estuary of the Black Sea. Its floodplain is divided by many tributaries. The width of its valley near the Dniester estuary is 16–22 km.

The river network of the Dniester. The channel of the Dniester is winding, there is an unevenly developed riverine network, which is the densest in the upper part of the basin, especially on its right bank where a large number of tributaries flow from the Carpathians. Tributaries that begin in the Podilsk Upland or in the Roztochcha are shallow. The Dniester in its middle course receives mainly left tributaries, whereas in its lower part, there are very few of them. Within Ukraine, it has 14,886 small tributary rivers (with total length of 32.3 thous. km) and 6 medium tributaries (1.0 thous. km). The Dniester has 386 tributaries. The main ones are: Stryi, Svicha, Limnytsia, and Bystrytsia (right), and Zolota Lypa, Strypa, Seret, Zbruch, and Smotrych (left) [DBPUVR undated]. The river network in the basin is unevenly developed. It is the densest (over 1.0–1.5 km·km^{-2}) in the Carpathian part of the basin, and less dense on the left bank (0.5–0.7 km·km^{-2}).

Morphometric characteristics of the river and its basin. The mountainous and foothill parts of the basin, where the main water runoff is formed, occupy 9% of its area. In the upper reaches of the Dniester River, it is a mountain V-shaped valley (80–100 m) and the river width is up to 40 m·km^{-1}. The average width of the channel is 23–25 m and the average depth is 0.5–0.8 m. In the middle part, the speed is 0.5 m·s^{-1}, slope up to 20 m·km^{-1}, depth 1.2–1.7 m, and the average width of the channel is 100–180 m. Morphometric and hydrological characteristics of the Dniester River are shown in Table 1.

Table 1. Morphometric and hydrological characteristics of the Dniester River

River characteristics	Upper Carpathian part	Middle Podilsk part	Lower Black Sea part
Morphometric characteristics			
Width (m)	10–100	100–120	100–200
Depth (m)	2.5–3.0	3.0–4.0	2.5–16
Flow rate (m·s^{-1})	1.0	0.2–0.7	0.2–0.7
River network density (km·km^{-2})	1.0–1.5	0.5–0.7	0.2
Meteorological and hydrological characteristics			
Precipitation (mm)	1000–1200	450–700	350–500
Average annual flow (m^3·s^{-1})		260	322
Annual flow module (dm^3·s^{-1}·km^{-2})	4.7–10.0	3.0–5.0	0.2–1.1

Source: own elaboration based on data of OSCE/UNECE [2005] and DBPUVR [undated].

Dniester feeds on rainwater and snowmelt and it has a characteristic flood regime. In terms of water volumes, the average runoff of the Dniester River per year is 8.4 km^2 all year round [OSCE/UNECE 2005]. The upper part of the basin accounts for about 2/3 of the annual runoff of the Dniester. The measuring of water consumption makes it possible to estimate the natural flow of the river at the Zalishchyky hydropost station at 226 $m^3 \cdot s^{-1}$ or 7.13 km^3 per year. In the upper reaches and in the canyon, the river has a characteristic incised meandering, whereas in its flat part, free meanders.

Water levels and floods. Floods are a characteristic phenomenon of the Dniester. During floods, 50–70% of the annual water runoff is formed. Average long-term river runoff coefficients range from 0.17–0.23 (Podilsk Upland) to 0.4–0.7 (Precarpathians and Carpathians). During extreme floods, the runoff coefficients of right-bank tributaries reach 0.74–0.92. Mountain tributaries are characterized by a pronounced seasonality in the distribution of runoff, high frequency of floods (5–12 per year), related to the maximum water output in the summer period, intensive rise of the water level (0.5–1.5 m per day and more) and its much slower decline. The average duration of floods in small and medium-sized rivers is 3–10 days, in large (Stryi, Limnytsia, etc.) from 7 to 20 days or more.

Water levels can rise by 3–4 m, and sometimes more. The relatively small channel capacity of the river contributes to the preservation of significant level of the rising of water in the rivers that are formed in the Carpathians [DBPUVR undated; OSCE/UNECE 2005]. The river network of the upper Dniester has a pronounced asymmetry: most of its tributaries flow from the Carpathians. During heavy rains or snowmelt, these tributaries can quickly change their levels, as well as the water level in the Dniester.

In the XX century, catastrophic regional floods in the northeastern macroslope of the Carpathians were observed in the warm season of 1911, 1927, 1941, 1955, 1969, 1980, 1984, 1989, 1997, and in the southwest – in the cold season of 1926, 1947, 1957, 1970, 1998. Particularly significant environmental damage and economic losses were caused by floods in 1998, 2001 and 2008, and the last flood, which occurred on June 23–28, 2020. The latter one is considered the largest in the last 60 years. The Dniester River rose to an incredible mark of 7 m at the water posts in the town of Halych. Damage caused this flood includes destroyed bridges, and other transportation infrastructure, shoreline protection structures, and residential buildings. Judging by the frequency of floods in the Carpathian region, the monitoring of water bodies is necessary. In Carpathian and Precarpathian regions, natural and anthropogenic phenomena cause great damage to the economy and nature. The annual damage to the areas affected by the flood is more than EUR 150 million, and in 2008, according to preliminary estimates, losses were estimated at EUR 250 million. Apart from natural disasters, damage is caused to a certain degree by anthropogenic factors, such as unauthorized deforestation, abstraction of stone, gravel and sand from riverbeds and floodplains, and construction at floodplain lands. According to the analysis of the damage caused by floods of 2008 and 2020, most of flooded buildings were built on floodplains.

Tourism, economic activity, and ecology. The Carpathian region is a recreational and tourist area of Ukraine. Sports and tourist complexes (Slavsk, Yaremche, Bukovel) and popular tourist routes, known not only in Ukraine, attract thousands of amateurs and athletes engaged in rafting. A popular past time is fishing in mountain rivers, and more romantic tourists go to explore unique Carpathian landscapes.

Until recently, most of the Dniester was navigable. It is also popular for swimming and rafting; the latter especially in the forest area along the river. According to historical data, steamships navigated along the river since 1862, a river port was built in Halych together with berths and a railway sidings. The founders of navigation on the Dniester River are the following: the Society of Steam Shipping on the Dniester (1863) and the union “Steam Shipping on the Dniester Bronislav Slonetsky and Kazimir Navarsky” (1882). Later, in 1938 the Professor of Lviv Polytechnic Matakiewicz proposed to build a waterway from the Baltic into the Black Sea through Vistula–San–Dniester–Prut–Danube, a project which was approved by industrialists. With the advent of the Soviet power in 1940, most Dniester vessels were exported to Russia, to operate on the Volga River. Later, after the end of the Second World War, the entire Dniester River became a part of the former USSR, and navigation began to develop again. However, in the 1980's and 1990's, the use of the Dniester waterways began to decline. The river became very shallow and muddy. Nowadays, the tourism business is developing rapidly, the center of which are in towns with unique nature and interesting and rich history. These include Zalishchyky, a well-known resort in Polish times, with a mild microclimate, together with Halych, Kamyanets-Podilsky, and Khotyn, which are cities of significant historical events and battles between the Christian and Muslim worlds. In general, from every town or village, this land speaks to everyone through ancient towers, castles, spires of churches, rock monasteries, etc. Therefore, more and more ferries, specially designed steamers, and various other boats can be seen in this section of the river. The same applies to Tiraspol, Moldova, where tourist pleasure boats sail along the Dniester.

People have settled on the banks of the Dniester River since ages. The Dniester Archaeological Expedition, which operated successfully in 1960–1970, found houses dating back to 6^{th}–7^{th} centuries. Now, ten million people live within the Dniester basin; it is a densely populated region. Agriculture is widespread and intensive, and there are a large number of large enterprises in the basin (42 in the Lviv region alone) dealing with oil refining, chemical production, and agro-refining industries. Additionally, there are fishing cooperatives. All the economic activity is often violates legal environmental requirements, i.e. absence or only partial use of wastewater treatment plants, pollution of waterways with industrial waste, deforestation, and plowing of slopes and grazing. The quality of river bank protection structures does not always meet standards. In addition, the environmental protection program is not sufficiently implemented.

Forest landscapes and mountainous rivers play an important role in the formation of floods in the Dniester. The forest provides water and soil protection functions. It regulates surface water runoff and hydrological regime, counterbalances soil erosion, stabilizes riverbeds, etc. However, the forest cover of the Carpathians is generally insufficient. Forest ecosystems, valleys and riverbeds have undergone significant changes primarily due to human activities: deforestation, extraction of stone and gravel from river channels, dumping waste in riverine territories, and the destruction of floodplains. Today, the protection and preservation of the Dniester basin requires a comprehensive approach to the use of its natural resources.

In 2015, the Government developed a project to build a cascade of six hydroelectric power plants on the Dniester, which would change the character of the river. Only effective protests of ecologists, public organizations, and the WWF in Ukraine prevented the implementation of the idea and the project was postponed.

MONITORING OF THE RIVERBED DISPLACEMENTS

The research focuses on channel processes in the plain part of the Dniester River and changes in the riverine territory due to economic activity of the local population. The length of the research area is 67 km from the town of Halych to the village of Dibrova, and the width 7–12 km from the shoreline on either side.

Purpose of the study. The purpose is to monitor:

- horizontal deformation in the channel of the plain part of the Dniester River over a 140-year period on the basis of the processed methodology, which includes the use of topographic maps, satellite images and special maps;
- adjacent territory in an 18-year period on the basis of a technique that involves the use of space images.

Objectives of the study:

- analysis of natural and anthropogenic factors, in particular after floods, which affect channel processes;
- an estimation of horizontal riverbed displacements in the plain part of the Dniester River; and
- examination of changes in the riverbed territory of the same part of the river caused by anthropogenic factors.

The conceptual model used to study the horizontal displacements of the Dniester River is based on topographic maps of various scales, satellite images, special maps developed in various periods. The model diagram is presented in Figure 1.

The figure shows input materials and processing methods that must be applied to achieve the appropriate accuracy in determining horizontal displacements of river channels. As for the proposed research, it relates to the first column of the conceptual scheme, i.e. the accuracy of determining horizontal displacements is 10–30 m.

The general block diagram reflecting the research of river displacements and its main stages is presented in Figure 2 [BURSHTYNSKA *et al.* 2017].

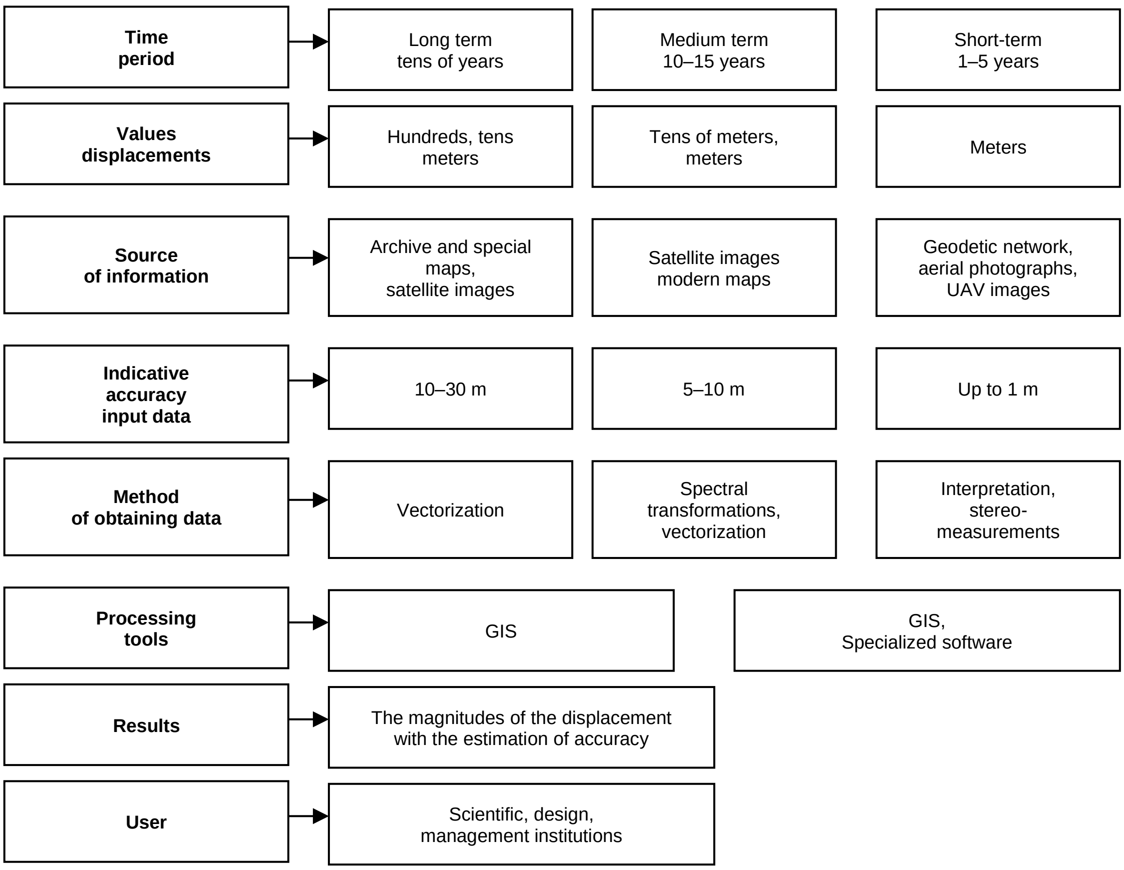

Fig. 1. The conceptual model to study horizontal displacements of rivers; source: own elaboration

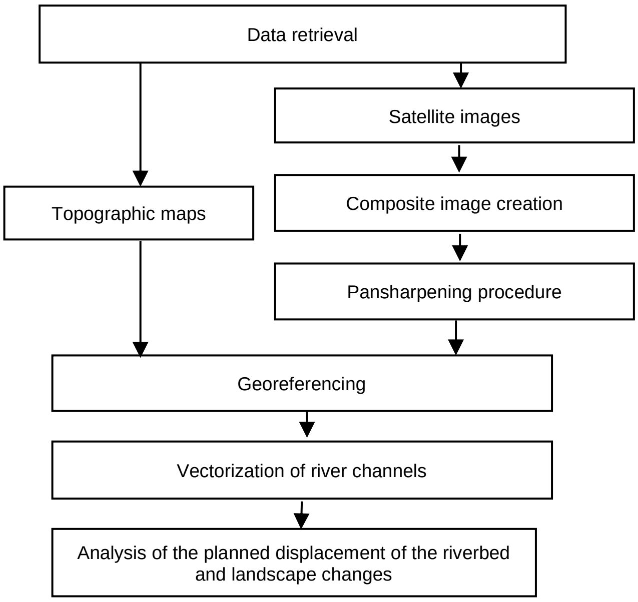

Fig. 2. The structural diagram for the analysis of horizontal displacements of the Dniester River; source: BURSHTYNSKA *et al.* [2017]

METHODS OF ANALYSIS OF RIVERINE AREA OF THE DNIESTER RIVER

Since the Dniester River basin is densely populated, it is advisable to analyse changes in the development of its banks in connection with its intensive exploitation. For this purpose, we use popular mathematical methods used to solve this type of a problem [KOKHAN 2015].

The research of changes in the riverine area of this section followed the structural diagram shown in Figure 3.

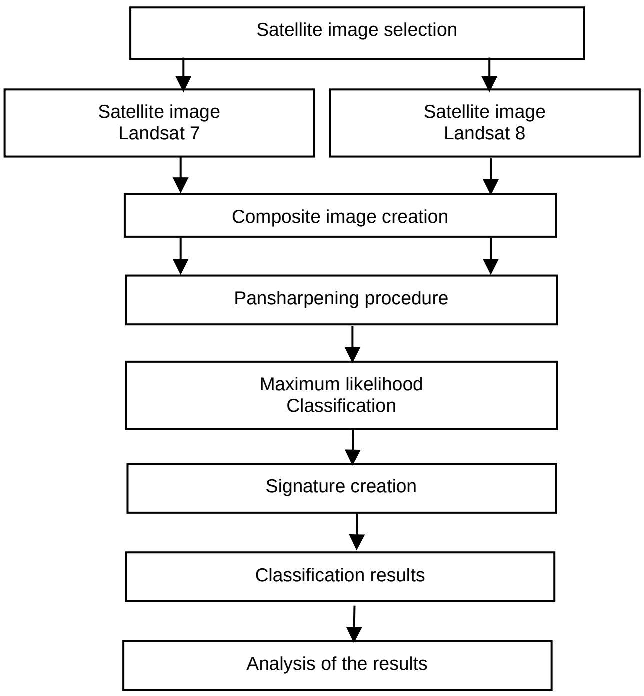

Fig. 3. The structural diagram of the research of changes in the riverine area of the Dniester River; source: own elaboration

The equation for the classification according to maximum probability [LYALKO 2006]:

$$D = \ln a_m - 0.5 \ln|K_m| - 0.5[X - M_m^T]K_m^{-1}[X - M_m] \quad (1)$$

where: D = weighted distance (probability); a_m = percentage of the probability that the classified pixel belongs to class m (equal to 1.0 or is entered on the basis of a priori data); $|K_m|$ = determinant of matrix K_m.

The choice of signatures is fundamental for the controlled classification.

MATERIALS

The purpose of this paper is to research horizontal displacements of the Dniester riverbed in 1874–2015 and detecting changes in the landscape of the riverine area in 2000–2018 in the transition area from the mountainous part of the river to the plain one using topographic maps, remote sensing data and GIS technologies.

The following materials have been used to identify and analyse changes in the position of the Dniester riverbed in the research area:
- maps of the Austrian period (1874), scale 1: 75,000;
- maps of the Polish period (1923), scale 1: 100,000;
- maps of the Soviet period (1988), scale 1: 100,000;
- maps of the geological, soil and quaternary sediments in 1969–1970, scale 1: 200 000;
- satellite image from UAV Landsat-7 (2000);
- satellite image from UAV Landsat-8 (2015 and 2018).

The materials, used in the research of the Dniester River are presented in Figure 4. Visualization of changes in the Dniester River was based on the ArcGIS 10.3 software.

For detecting changes in the landscape of the riverine area were used satellite images from Landsat 2000 and Landsat 2018, have been obtained from: USGS [undated].

RESULTS

The analysis has focused on the part of the Dniester River from the town of Halych to Dibrova village (Fig. 5) and determined riverbed horizontal deformations over a 141-year period (1874–2015). In addition, the purpose of this research is to study landscape changes in the riverine area of the Dniester River, which have affected channel processes.

This section is located at the transition from the hilly part of the river flowing area to the flat part, which is characterized by significant bends and interweaving of the channel. As seen in topographic maps and satellite images, a significant number of oxbow lakes and alluvial islands were created by water sediments at different time periods.

The monitoring is based on the use of topographic maps, satellite images and special maps (soil and geologic maps) from different periods.

The geological structures of the Ciscarpathian foredeep and the Volyn-Podilsk Upland influence the formation of the Dniester channel and its tributary.

Topographic maps were collated with the coordinate system of satellite images (WGS-84) to study changes of

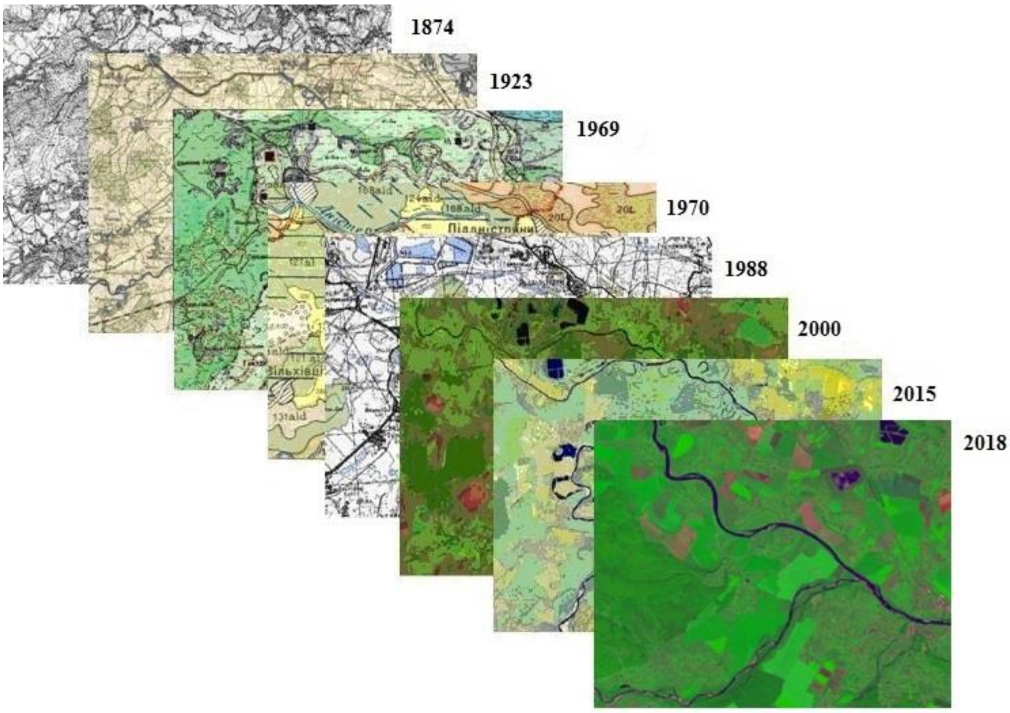

Fig. 4. Research materials; source: own elaboration based on maps of the Austrian period – Free map [undated a], of the Polish period – Free map [undated b], of the Soviet period – Free map [undated c], and special maps – Free map [undated d]

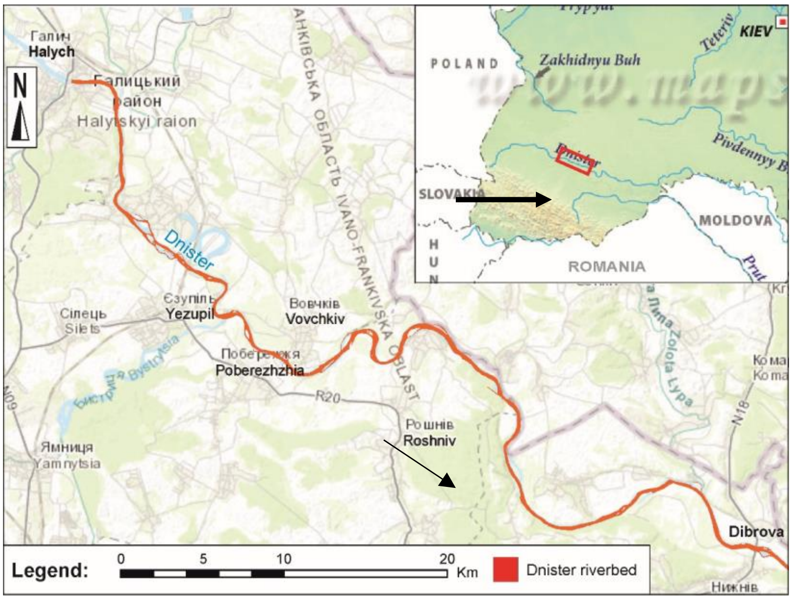

Fig. 5. Location of the research area on the Dniester River (Ukraine); source: own elaboration

the channel using cartographic materials. Maps have been bound to reference points, such as crossroads, bridges, mountain peaks, etc. Georeferencing of topographic raster maps was done with the use of 10 points selected on clear contours. Polynomial of second order was chosen to achieve better accuracy which did not exceed 15 meters on the intrinsic convergence. Then, all georeferenced raster maps were transformed to the WGS-84 coordinate system of satellite images.

The composite bands procedure is used for the processing of satellite images to create composite images. It combines three spectral RGB channels, the combination of which provides the best contrast of the object (river) against the background of the terrain [BODNYA 2013]. Channels 5, 4, 1 are used for a satellite image from UAV Landsat-7, and channels 7, 5, 2 for Landsat-8. The application of the Pansharpening procedure has improved the resolution of images from 30 to 15 m.

After digitizing and bringing all the materials into a single coordinate projection, it is possible to measure horizontal displacements of channels in different periods. Figure 6 shows riverbed of different periods, oxbow lakes, and points, according to which the measurement of riverbed displacements has been performed.

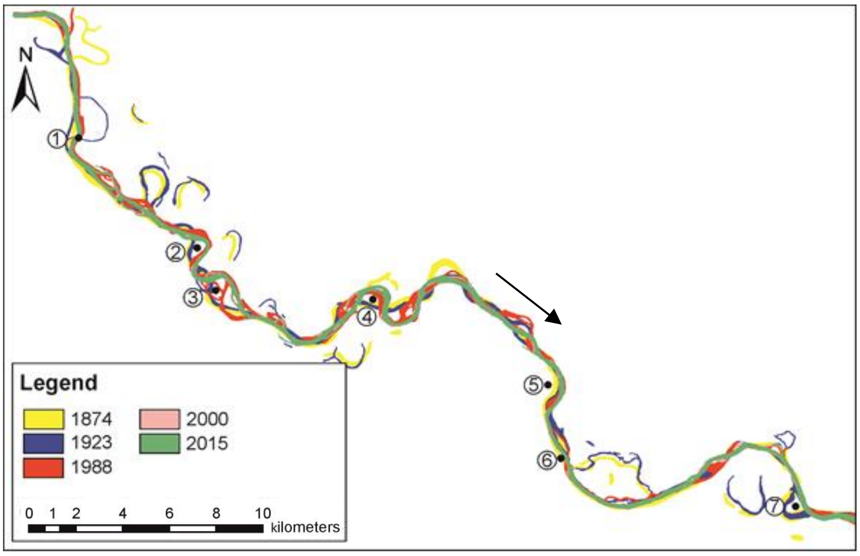

Fig. 6. The superimposed digitized layers of the river channel for a different time period for the study area with the designations of channel displacements; *1–7* = points with significant changes in the horizontal position; source: own study

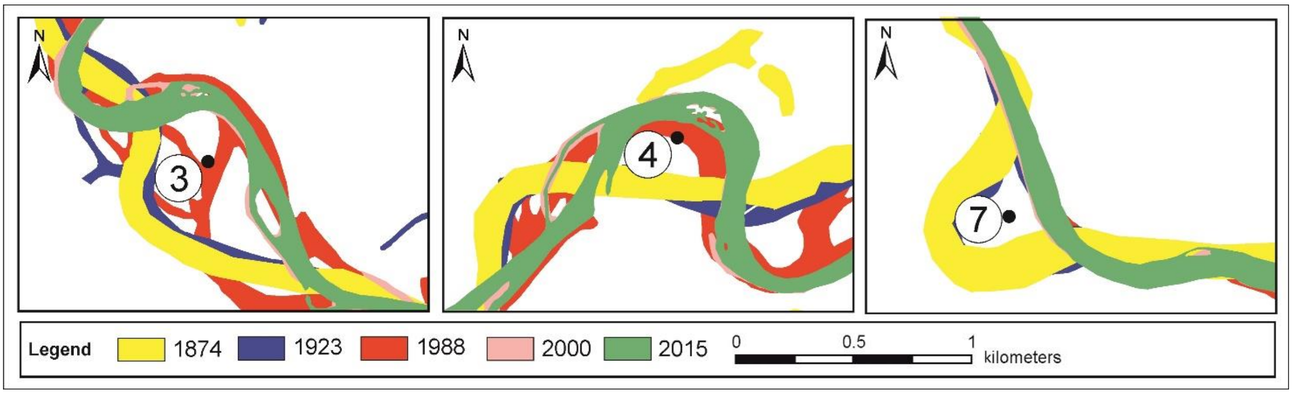

Fig. 7. Sections of channel displacements and enlarged fragments detailing maximal changes; source: own study

To determine the index of displacements of the Dniester River channel, seven points were selected in the indicated section, at which significant changes in the horizontal position were noted.

Figure 7 shows fragments of significant riverbed changes in an enlarged scale for the studied period (numbering of points corresponds with Fig. 6). In 1874, the river substantially meandered, forming significant bends. After the hydraulic works in 1930, the channel straightened significantly. In some areas, channels were artificially dug. This led to a change in the position of the river. Oxbow lakes remained in former places of old channels. Until 1988, the riverbed became calmer and less meandered. From 2000 to 2015, no special changes were observed in the channel.

Maximal displacements of the river channel for a different period (1874–2015) are presented in Table 2. The formula for determining the average displacements for one year is as follows:

$$l = L/\Delta t \qquad (2)$$

where: l = average annual displacement (m); L = displacement for the specified period (m); Δt – determination period displacements.

Table 2. The channel displacement in the plain part of the Dniester River

No. point	Displacement (m) in the period					
	1874–1923		1923–1988		1988–2015	
	total	average for the year	total	average for the year	total	average for the year
1	180	3.7	330	5.0	50	1.9
2	110	2.2	465	7.2	110	4.0
3	30	0.6	620	9.5	185	6.9
4	185	3.8	415	6.4	290	10.7
5	350	7.1	145	2.2	40	1.5
6	340	6.9	200	3.1	–	–
7	220	4.5	590	9.1	30	1.1

Explanation: red values are the maximum values (in meters) of channel displacement for the investigated period.
Source: own study.

Changes in the area of the oxbow lakes and alluvial islands within the studied area in 1874–2015:
- 1874 – 154 ha,
- 1923 –108 ha,
- 1988 – 103 ha,
- 2000 – 45 ha,
- 2015 – 10 ha.

As can be seen, the area of the oxbow lakes has decreased, which indicates a decrease in meandering. Most oxbow lakes were formed before 1923. Satellite images for years 2000 and 2015 show that the oxbow lakes are overgrown with grassy vegetation and have become almost invisible.

Changes in the alluvial islands in 1874–2015:

- 1874 – 96 ha,
- 1923 – 110 ha,
- 1988 – 211 ha,
- 2000 – 181 ha,
- 2015 – 169 ha.

As for the alluvial islands on the river, in 1988 their area increased 1.5–2.5 times compared with 1923, due to a decrease in the speed of water flow caused by summer floods of 1974 and 1975. The floods led to the increase in the sediment volume. The alluvial islands are formed by pebbles and sand drifts.

The largest displacements found in 1923–1988 reach 590–620 m. In some parts of the river, the channel was regulated, which led to insignificant displacements. In 1988–2015, the maximal displacements were up to 300 m.

In addition to river channel displacements, water protection zones have also been considered. In each country, regulatory documents have been developed taking into account economic and legal factors that regulate the width of water protection zones depending on the characteristics of rivers [MARTYN, POKYD′KO 2012]. In Ukraine, for rivers longer than 200 km, the water protection zone extends 100 meters from the shore. The designation of a water protection zone is legally regulated. However, it does not take into account horizontal riverbed displacements.

On an enlarged scale, Figure 8 shows three areas in which the Dniester channel has shifted most often over 27 years (1988–2015): the channel of 1988 is shown in red, whereas the channel of 2015 is shown in green.

Figure 8 focuses on the stability of rivers, in particular horizontal displacement of channels, which is the most important while establishing water protection zones. These zones are regulated by the state and clear boundaries are established for deviations from river shorelines. In these zones, dimensions of which depend on the characteristics of the river (length and width), it is prohibited to develop any economic activity. Revision of regulations should be correlated with the determination of the channel stability, in particular with the analysis of horizontal riverbed displacements.

Even when the regulation of the channel is provided after significant floods, the energy of water can destroy hydraulic structures, and the riverbed has the tendency to return to its natural position. Such phenomena were observed on the Dniester River near the town of Mykolayiv, Lviv Region, after floods in 2008 and 2014. Economic and legal issues extend beyond the scope of this article. However, in our opinion, the stability of riverbeds in some areas should be taken into account.

For better visualization, Figure 8 shows three channel displacement samples with water protection zones near points 1, 3, and 4. The horizontal riverbed displacements actually either reduce or block water protection zones within a new channel.

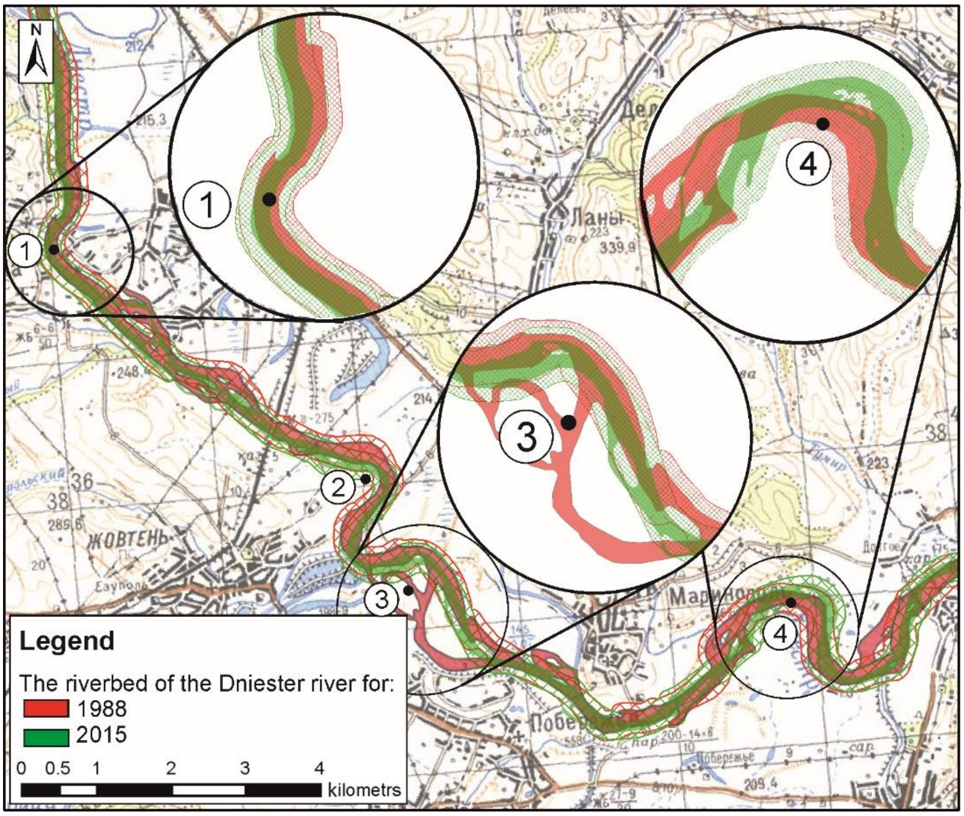

Fig. 8. Riverbed displacements within water protection zones; source: own study

In all these parts, water protection zones coincide only when the riverbeds overlay. Due to horizontal displacements, the 2015 riverbed (shown in green) would not have a water protection zone at all: 1 – from western side; 3 – from southern and eastern sides; 4 – from northeast and east sides.

Due to a significant reduction in the water protection zone, plowing leads to the sliding of soil into the river and then to its siltation. This primarily applies to small rivers which disappear in hundreds from the surface of the earth [YATSYK *et al.* 1991] remaining only in old topographic maps.

Thus, protection zones should be selected taking into account the stability of riverbeds in a specific period.

Therefore, the second part of our research has focused on the analysis of riverine areas using the controlled classification method. The technique is described by BURSHTYNSKA *et al.* [2014] and KOKHAN [2015] and allows you to determine changes in the course of human activity and, as a result, a change in the riverine area. Such changes were analyzed for a period from 2000 to 2018 based on satellite images obtained from Landsat 7 and Landsat 8.

The research covered the following classes of objects: hydrography, forests, grassy and artisanal vegetation, buildings, arable land and exposed soils. In the 2018 Landsat 8 image, a class of roads was added, as their coverage was improved and they were clearly identified. According to statistical research [PERUMAL, BHASKARAN 2010; PHIRI, MORGENROTH 2017], the optimal signature values for classes correspond to the number of channels multiplied by 100 pixels: for Landsat 7 – about 700 pixels and for Landsat 8 – about 1000 pixels.

The largest difficulty was to choose signatures of classes that were close in spectral characteristics: buildings and roads, arable land and exposed soil. As for the analysis of the classification results for the "arable land" class, several subclasses with different spectral characteristics depending on crops (green vegetation, dry vegetation, arable land) were selected. Signatures on exposed soils, near floodplains and in existing quarries were selected separately. To obtain results, all subclasses were combined into one class. For classes with uniform spectral brightness, signatures of 50–100 pixels in size were typed in several places.

To highlight settlements, it was necessary to select smaller signatures (20–40 pixels), mainly on the roofs of buildings or on building sites. Such signatures were selected in many locations throughout the image. In general, the number of signatures reached 40–50. A special filter was used to smooth the obtained classified image, making it possible to eliminate single pixels with mixed brightness.

The results of classification images are shown in Figure 9, and the area values are given in Table 3. The research area is 1099 km^2.

When classifying objects based on the 2000 image, roads were not allocated to a separate class, because they did not have a hard surface, i.e. they were unpaved, and thus roads were put into one class with arable land.

Thus, according to the results of the classification based on Landsat 7 and Landsat 8 images, surface areas of the main classes are (in ha):

– **Landsat 7:** hydrography – 2,100; building – 3,500; forest – 18,300; herbaceous and shrub vegetation – 30,300; arable land – 55,700.
– **Landsat 8:** hydrography – 2,200; building – 8,100; roads – 5,300; forest – 21,300; herbaceous and shrub vegetation – 43,100; arable land – 29,900.

It was established, that for the 18-year period (2000–2018) the area of forests and the territory occupied by herbaceous and shrub vegetation increased by 3,000 and 12,800 hectares, respectively; the area of arable land decreased by 25,800 hectares, but the area of urbanized territories increased by 4,600 hectares. The area occupied by hydrography for the indicated period practically did not change.

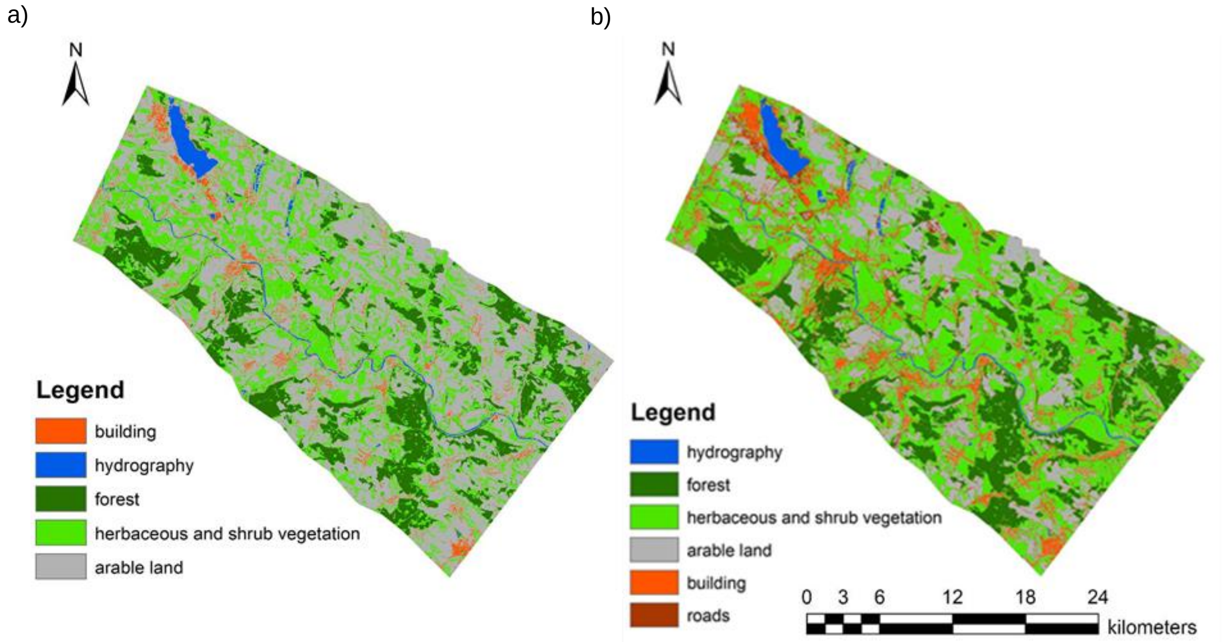

Fig. 9. The classification map for the image: a) 2000, b) 2018; source: own study

Table 3. The attribute table of classified maps 2000 and 2018

No	Rowid	Value	Count	Name	Area_ha	Percent
2000						
1	0	125	156 776	building	3 500	3.2
2	1	126	91 316	hydrography	2 100	1.9
3	2	184	815 064	forest	18 300	16.7
4	3	228	1 349 000	herbaceous and shrub vegetation	30 300	27.5
5	4	441	2 474 309	arable land	55 700	50.7
2018						
1	0	1	95 704	hydrography	2 200	2.0
2	1	2	947 508	forest	21 300	19.4
3	2	34	1 917 198	herbaceous and shrub vegetation	43 100	39.2
4	3	536	1 327 558	arable land	29 900	27.2
5	4	537	360 138	building	8 100	7.4
6	5	858	234 271	roads	5 300	4.8

Source: own study.

DISCUSSION

Below we compare the two rivers Tisza and Dniester to show how different factors influence the channel processes.

Each river requires a separate study because of the factors that shape the flow and hydrological regime. However, there is no mathematical model that would take into account the main factors of a complex channel process. Therefore, the study of channel deformations has been based on the comparison of various channel deformations. We compared horizontal displacements of the channels of two large rivers Dniester and Tisza [BAYRAK 2011] in a region where they leave the mountainous Carpathian area and flow to plains. The study sites have been 100 km long for each river. Methodology, materials and results were presented at the ISPRS Congress in Prague in 2016. The research period covered 130 years, with maximum displacements in the selected section of the Dniester River 620 m with the average annual flow of 300 $m^3 \cdot s^{-1}$. For the Tisza, with the water runoff of 900 $m^3 \cdot s^{-1}$, the maximum displacement was 930 m. The Tisza basin is twice the size of the Dniester basin, which explains the higher water runoff. In addition, the increasing hydrological regime is influenced by the geomorphological factor, in particular, the heights from which the tributaries of the Tisza flow (1000–2020 m a.s.l.). The Dniester and its tributaries flow from the heights of 900–1200 m a.s.l. There is also a bigger flood regime, because summer floods on Tisza tributaries are accompanied by winter and spring ones, which are especially significant on such tributaries as Teresva and Borzhava. Geological structures along these two rivers are nearly identical. In the case of the Dniester, these are the Skybovi Carpathian Mountains and the Ciscarpathian foredeep, while in the case of the Tisza, they include the Skybovi Carpathian Mountains and the Transcarpathian foredeep.

In the proposed research, the authors tried to examine changes in the natural channel process on the part of the Dniester River, as well as the impact of anthropogenic activity on riverine changes. The main attention focused on the horizontal riverbed displacements, monitoring of which has become possible due to the latest technologies and the use of different materials, such as topographic maps for different periods, Earth remote sensing materials, quaternary sediment and soil maps. All the materials were processed using GIS-technologies.

Results of these studies allow to suggest a new approach to the designation of water protection zones and emphasize the need of changes in the pertinent regulatory framework.

A more responsible attitude to the development and revision of the existing regulatory framework based on the analysis of channel processes, in particular horizontal channel displacement, will help to avoid many harmful phenomena associated with the river exploitation, as well as international conflicts, if the border passes along the fairway of the river, what has already happened in the recent history of European states.

As for the first part of the research, related to the determination of channel displacements over a multiple-year period under the influence of both natural and anthropogenic factors, the accuracy depends on the type of source materials and the accuracy of their transformation in a single projection. Since satellite images are presented in the UTM projection, all maps have been converted accordingly. Maps from the Austrian and Polish periods are created in the local coordinate system, and those from the Soviet period – in the Gauss-Krueger coordinate system.

The accuracy with which horizontal displacements are determined depends on the accuracy of materials selected for the study, i.e. the root mean square error of measurements on the map is 10–20 m (1: 100,000), and according to space images obtained from the Landsat satellite after processing by the pansharpening method, the root mean square error is 15 m. The previous studies of georeferencing maps to space images using a polynomial of the 2nd degree and measuring coordinates at ten common points on the map and image are: for maps of the Austrian period – 20–25 m, for the Polish and Soviet periods – 10–15 m. Taking into account the value of horizontal displacements of river channels, it can be argued that the materials for the research have been selected correctly. If a higher accuracy of displacement determination is required, it is necessary to use larger-scale maps and images of a high spatial resolution. In fact, this requirement applies to any geodetic or photogrammetric measurements.

The second part of the study is related to automated classification methods. First of all, it should be noted that the riverine territories of the Dniester River are complex objects, densely populated, with significant proportion of arable land and meadow vegetation. The method of controlled classification was selected, which is based on the way maximum probability. The choice was based on one of author's research on the classification of objects in different terrain types with specification of signature values and their locations [BURSHTYNSKA *et al.* 2016]. Pay attention to the specifics when choosing signatures.

For objects, such as populated areas and arable land, signatures were selected as follows: settlements – large quantity of small size signatures (20–50 pixels), vegetation – large size signatures (100–150); for arable land in clearly defined fields with different spectral brightness, it was necessary to distinguish signatures (e.g. with green vegetation, dry vegetation, plowed field, etc.). The signature size was about 100 pixels. However, they had to be combined into one class.

A more accurate result is possible when we use complex classification methods, for example, a two-stage classification [BURSHTYNSKA *et al.* 2014], in which one can mask out settlements, carry out classification and, at the second stage, classify settlements.

CONCLUSIONS

1. The analysis of the literature has established that the hydrological regime of rivers whose sources are located in the Carpathian upperlands depends on the deforestation in the river basin and extraction of construction materials from riverbed and floodplain. Significant floods in the Carpathians due to uncoordinated flood control measures cause rapid filling of channels, flooding of riverine areas, and the destruction of surrounding buildings. The largest damage is caused to constructions built on floodplains, which is proof of inefficient management decisions.

2. Long-term monitoring of riverbed displacements has to identify unstable and significant displacement areas of the river. Riverbed displacements should be taken into account while planning hydraulic engineering works, the designation of water protection zones, and transboundary activities.

3. It has been proposed to monitor displacements based on the methodology, which includes the use of topographic maps, satellite images and special maps, as well as geological, ground and quaternary sediment maps.

4. The accuracy of displacements determined depends on the accuracy of maps and the spatial resolution of satellite images. In this study, the accuracy is 15–20 m. If higher accuracy is necessary, large-scale maps and images of higher spatial resolution should be used.

5. The analysis performed on a part of the Dniester River across the transition from the mountainous to plain areas over a 140-year period indicates significant displacements of the channel, the maximum values of which are 590–620 m.

6. Failure to comply with the norms applicable to water protection zones leads to erosion and silting of the river, which causes additional channel displacements.

7. The analysis of changes in the river-bed area of the Dniester River based on an automated method over an 18-year period indicates an increase in the area of settlements and paved roads. It also shows an unexpected decrease in arable land, which requires additional socio-economic explanation.

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