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HORIZONTAL DEFORMATIONS OF THE SUKIL RIVERBED WITHIN THE PRE-CARPATHIAN HEIGHT IN 1880-2019

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Abstract. The article presents the results of the study of horizontal riverbed deformations of the Sukil river in the area from the town of Bolekhiv to its confluence with the Svicha river during 1880–2019. The studied section of the riverbed is located within the Precarpathian height and is marked by significant dynamics of the riverbed, which is mainly due to frequent floods, including catastrophic ones.

The analysis of long-term horizontal riverbed deformations of the Sukil river and identification of the main factors of their manifestation were carried out in three stages. The first stage involved an assessment of the riverbed displacement over a long-term period of tens of years and was performed based on topographic maps of 1880, 1929-1939, and 1990. The second stage focused on the analysis of the riverbed displacement during a short-term period of 5-7 years and was conducted on the basis of Google Earth satellite images of 2006, 2011, and 2017–2019. The third stage was dedicated to the verification of the obtained results by field research and to the identification of the main reasons for the development of horizontal riverbed deformations. The analysis of historical maps and satellite images was mainly conducted by cartographic methods using ArcGIS 10.1.

The riverbed of the Sukil river has significant differences in the development of horizontal deformations on the section of Bolekhiv – the village of Podorozhnie (the mouth of the river). According to the type of manifestation and scale of the riverbed deformations development, two sections (hereinafter dynamic sections) with significant horizontal deformations have been identified: the first one – from Bolekhiv to the village of Lysovychi; the second one – from the village of Lysovychi to the village of Podorozhnie (the Sukil mouth). On dynamic section 1, the horizontal deformations are differently manifested depending on the type of the riverbed. The maximum displacements which were found on the meandering sections are approximately 340 m. They were recorded during the period of 1880–1939. On the sections with a “transitional” type of riverbeds (in the late 19th-early 20th century they were braided, and now they are single channel), the deformations are small (up to 60 m) and are manifested mainly within the boundaries of the riverbed. On dynamic section 2, the Sukil riverbed is meandering and the deformations are much larger. The maximum riverbed displacements reach approximately 500 m (during the period of 1880–1939). For dynamic section 2 as well as for the whole section of the Sukil riverbed from Bolekhiv to the mouth, a certain tendency of the riverbed changes on the plan has been revealed. Thus, from 1889 to 1990 we observe a decrease in the meandering of the riverbed caused by anthropogenic influence, in particular, by the straightening of the riverbed in the 70-80s of the last century and by change in the position of the mouth; since 1990, a natural increase in the Sukil riverbed’s meandering has been observed.

***Key words*:** horizontal deformations; riverbed types; Sukil; meandering; historical maps; remote sensing.

ГОРИЗОНТАЛЬНІ ДЕФОРМАЦІЇ РУСЛА РІЧКИ СУКІЛЬ У МЕЖАХ ПЕРЕДКАРПАТСЬКОЇ ВИСОЧИНИ ЗА 1880-2019 РР.

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Анотація. У роботі представлені результати досліджень горизонтальних руслових деформації річки Сукіль на ділянці від м. Болехів до впадіння річки у Свічу протягом 1880–2019 рр. Досліджуваний ділянка русла знаходиться у межах Передкарпатської височини і відзначається значною динамікою русла, що зумовлено головно частим проходженням паводків, у тім числі й катастрофічних.

Аналіз багаторічних горизонтальних руслових деформацій річки Сукіль, встановлення головних факторів їх прояву проведено у три етапи. Перший етап – це оцінка зміщення русла за довгостроковий період – десятки років, виконаний на основі топографічних карт 1880, 1929–1939, 1990 рр. Другий етап – аналіз зміщення русла за короткочасовий період – 5–7 років, проведений на основі космічних знімків Google Earth 2006, 2011, 2017–2019 рр. Третій етап – верифікація отриманих результатів польовими дослідженнями та встановлення головних причин розвитку горизонтальних руслових деформацій. Аналіз історичних карт та космознімків здійснено головно картографічними методами зі застосуванням ArcGIS 10.1.

Русло річки Сукіль на відтинку м. Болехів – с. Подорожнє (гирло ріки) має значні відмінності розвитку горизонтальних руслових деформацій. За характером прояву та величиною розвитку руслових деформацій виокремлено дві ділянки (надалі динамічні ділянки), де горизонтальні руслові деформації є значними: перша – від м. Болехова до Лисович; друга – від с. Лисовичі до с. Подорожнє (гирла Сукелю). На динамічній ділянці 1 руслові горизонтальні деформації проявляються по-різному, залежно від типу русла. Максимальні зміщення виявлено на звивистих відтинках і вони становлять приблизно 340 м. Їх зафіксовано за період 1880–1939 рр. На відтінках з “перехідним” типом русел (наприкінці ХІХ – на початку ХХ сторіччя багаторукавних, а нині однорукавних) є невеликими (до 60 м) і проявляються головно у межах русла. На динамічній ділянці 2 русло Сукелю є меандруючим і руслові деформації є значно більшими. Максимальні зміщення русла сягають приблизно 500 м (за період 1880–1939 рр.). Для динамічної ділянки 2, як і для цілої ділянки русла Сукелю від м. Болехів до гирла, встановлено певну тенденцію зміни русла у плані. Так, з 1889 по 1990 р. спостерігаємо зменшення звивистості русла, що зумовлено антропогенним впливом, зокрема спрямленням русла у 70-80-х роках минулого сторіччя, та зміною положення гирла, а з 1990 року – природне збільшення меандрування русла Сукелю.

Ключові слова: горизонтальні деформації; тип русла; Сукіль; меандрування; історичні карти; ДЗЗ.

Inroduction. The study of horizontal riverbed deformations is important for understanding the functioning of the fluvial relief and trends in its development. This is especially true for mountain and foothill rivers of the Ukrainian Carpathians. They possess significant dynamics of water discharge in the riverbed, which is the main reason for its significant changes, in particular, for the development of horizontal and vertical deformations. To assess the development of horizontal riverbed deformations and, accordingly, the changes in riverbeds on the plan, archival materials are needed, including historical maps and other cartographic materials, as well as remote sensing data. According to a number of authors (Grafi et al. 2008; Bayrak, 2011; Burshtynska & Shevchuk, 2012; Horishniy, 2014; Burshtynska, Movchko & Shevchuk, 2015;

Bayrak & Kovalchuk, 2017 and others), historical maps are a valuable source of information on changes of riverbeds on the plan. However, their use is possible provided that the geographical location of the constant orientation elements, e.g., churches, bridges, etc., can be identified (Andreychuk & Yamelynets, 2015) and the peculiarities of cartographic approaches to creating maps and their generalization are taken into account. The comparative analysis of historical maps and satellite images allows us to understand certain trends in the development of riverbeds (Jaskulski et al., 2013; Noszczyk, Nawieśniak, Hernik, Strutyński & Taszakowski, 2015 and others), which is important for the economic use of river valleys and their spatial planning in order to protect settlements, roads and agricultural lands primarily from catastrophic water floods. Thus, the scientific novelty of the presented work consists in determining the scale of horizontal deformations of the Sukil riverbed within the Precarpathian height for the period of 1880-2019. For the first time, based on the analysis of historical maps, remote sensing materials, and field research, the size of long-term horizontal deformations has been identified with taking into account the type of the Sukil riverbed and its changes in time.

Research territory. It covers the lower part of the Sukil river basin in the area from the town of Bolekhiv to the confluence with the Svicha river (Fig. 1). The length of the studied riverbed is 29.9 km. The basin is located within the Precarpathian height and occupies part of the Kalush (Limnytsko-Bolekhivska) lowland (Kravchuk, 1999; 2021). Its north-western part is bounded by the Morshyn height, and the south-eastern part – by a common drainage divide with the Svicha river. According to the scheme of tectonic zoning of the Ukrainian Carpathians suggested by S.S. Kruglov (1986 ed.), the study area is located within the Precarpathian Depression, in particular, within Sambir and Boryslav-Pokut covers (Fig. 1) and is the most anthropogenically transformed territory.

The main purpose of the study is to identify the main tendencies and the scale of the development of horizontal deformations of the Sukil riverbed within the Precarpathian height for the period of 1880–2019. An important task of the research was to reveal the features of the development of horizontal deformations of the Sukil riverbed on the sections with a different type of the riverbed and its changes during this period.

Research methodology. The study of horizontal riverbed deformations was carried out mainly by cartographic methods using ArcGIS 10.1. The research was based on different time topographic maps covering a period of approximately 140 years. These were Austrian topographic maps of 1880 with a scale of 1:75 000; Polish maps of 1929–1939 with a scale of 1:25 000; maps of the Soviet period of the 1990s with a scale of 1:50 000. The study of the current dynamics of the riverbed was conducted based on Google Earth satellite images of 2006, 2011, and 2017–2019. Additionally, the data of the hydrological post in the village of Tysiv for the period of 1959–2020 were analyzed, a number of sources on the geological and geomorphological features of the territory have been studied, and the results obtained have been verified by field research. Cartographic materials were analyzed within the Pulkovo 1942 geographical coordinates.

The algorithm of the study, including the source cartographic materials and their analysis, is shown in Fig. 2.

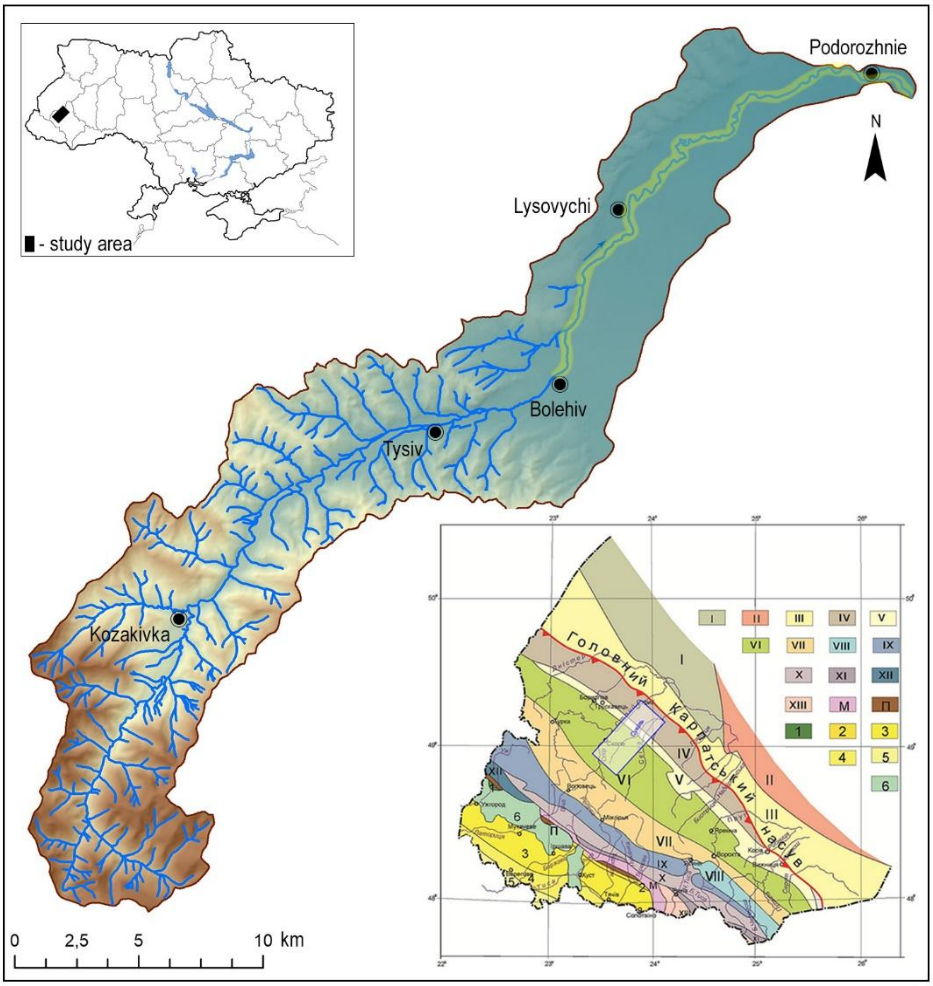

Fig. 1. Localization of the studied section of the Sukil riverbed. The square indicates the investigated river in the scheme of tectonic zoning of the Ukrainian Carpathians according to V. Glushko and S. Kruhlov (1986 red). Legend: I – Western European Platform, II – Eastern European Platform, III – Precarpathian Depression, IV – Sambir cover, V – Boryslav-Pokut cover, VI – Skyba cover, VII – Krosno cover, VIII – Chornohora cover, IX – Duklia cover, X – Porkulets cover, XI – Rakhiv cover, XII – Magurska cover, XIII – Marmaroskie massif, M – zone of Marmaroskie cliffs, П – zone of Peninski cliffs. Transcarpathian Depression (TD) and its zones: 1 – Pidhallia, 2 – Krayova, 3 – Central, 4 – Pripannonska, 5 – Pannonska Depression, 6 – Vyhorlat-Huta volcanic ridge.

Since the materials available for the study were developed within different time periods and in different cartographic projections, it is necessary to reduce all maps and satellite images to a single topographic projection of Gauss-Krueger and to a single Pulkovo 42 coordinate system (SK-42). The maps of the Soviet period with a scale of 1:50 000, developed in the above-mentioned coordinate system, served as a topographic reference basis.

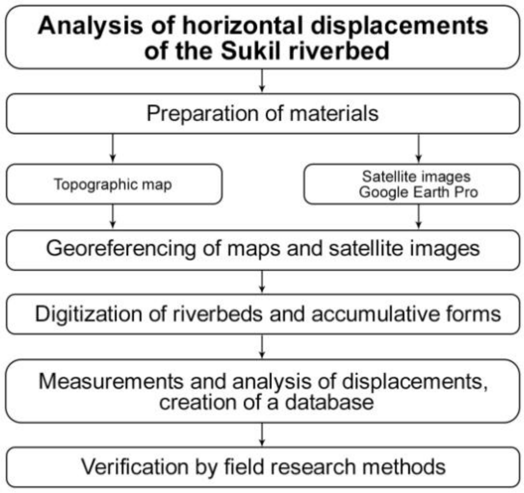

Fig. 2. Algorithm for the study of horizontal deformations of the Sukil riverbed.

Topographic maps with a scale of 1:25 000 (1929–1939) lack rectangular and geographical coordinates. Therefore, their georeferencing has been carried out according to the common points which are identified by typical, permanent objects over time: road intersections, railway crossings, bridges, geodesic marks, survey benchmarks, etc. Such a georeferensing is less accurate than the coordinate reference. Its root mean square error in a 3rd order polynomial is 25–30 m. The georeferencing error of Austrian maps is 20–25 m. This is due both to a larger scale of 1:75,000 maps and the transformation of the projection (Soldner-Cassini to Gauss-Krueger) and the coordinate system (Halychyna in SK-42) as well as to the imperfection of the transfer of objects identified on the ground, distortion of the sheets of maps, and deformation of paper during storage and digitization (Mularz, 2004; Noszczyk, 2015).

The Google Earth satellite images made in 2006, 2011 and 2017–2019 were used for a detailed study of the riverbed relief, its changes, and patterns. The 2006 satellite images are georeferensed to 1:50 000 scale maps with a mean square error of 5 m. The 2017–2019 images were georeferensed before the 2006 satellite survey, this having allowed us to obtain a residual error of 1.5–3 m (Table 1).

To assess the horizontal riverbed deformations, the places of the largest displacements were identified, and their measurements for the selected period were performed. The measurements were performed between two extreme points, perpendicular to the direction of the river. The shift of the riverbed towards the right bank was marked by the minus sign, and the shift towards the left bank – by the plus sign (Table 2).

Results. The comparative analysis of historical maps and satellite images of the studied section of the Sukil riverbed (Fig. 3) allowed us to reveal a general tendency of its changes on the plan for almost 140 years. It is connected with a decrease in the meandering of the Sukil riverbed during the period of 1880-1990, which is mainly determined by human impact. Thus, in 1880, the coefficient of meandering of the Sukil riverbed in the studied section was 1.56; in 1929–1939 –1.42; in 1990 – 1.26. The maximum changes in the meandering of the riverbed are observed on the 1990 map,

Table 1. Main cartographic materials and reference data for the study of horizontal riverbed deformations of the Sukil river

No	Source material	Year	Coordinate system	Georeferencing to:	Root mean square error
1	Topographic map (USSR) 1:50 000	1990	SK-42	Rectangular coordinates	8 m
2	Topographic map (Polish) 1:25 000	1929-1939	SK-42	USSR topographic map 1:50 000	25–30 m
3	Topographic map (Austro-Hungary) 1:75 000	1880	Coordinate system of Halychyna	USSR topographic map 1:50 000	20–25 m
5	Google Earth satellite images	2006	WGS-84	USSR topographic map 1:50 000	Up to 5 m
6	Google Earth satellite images	2011	WGS-84	Google Earth satellite images 2006	1,2 m
7	Google Earth satellite images	2017-2018	WGS-84	Google Earth satellite images 2006	2 m

after the melioration of the swampy part of the Sukil valley in the 80s of the last century. At that time, a number of artificial canals and a system of artificial reservoirs to the east-southeast of the village of Mezhyrichchia were constructed, the right tributary of the Sukil – Herynia stream was straightened, and flood embankments from the village of Zaderevach to the mouth of the Sukil were built. These changes are recorded on the 1990 map (Fig. 3). From 1990 to 2019, there was a natural increase in meandering (coefficient of meandering in 2018 was 1.34), especially on dynamic section 2, which will be discussed below. Changes in the development of horizontal deformations, and hence of the riverbed on the plan, are also connected with a change in the position of the river mouth, which is mainly due to the morphodynamics of the Svicha riverbed (Rybak, Dubis & Bubniak, 2021). During the study period, the maximum displacement of the riverbed has been more than 3 km, which is clearly recorded on the 1929 map and on the satellite image (Fig. 3) as well as confirmed by field research.

Within the study area, *two dynamic sections of the channel* have been singled out, which differ in the configuration of the riverbed on the plan and in the nature of riverbed processes. The first dynamic section is located between the settlements of Bolekhiv and Lysovychi, while the second one occupies part of the riverbed from the village of Lysovychi to the village of Podorozhnie (the Sukil mouth).

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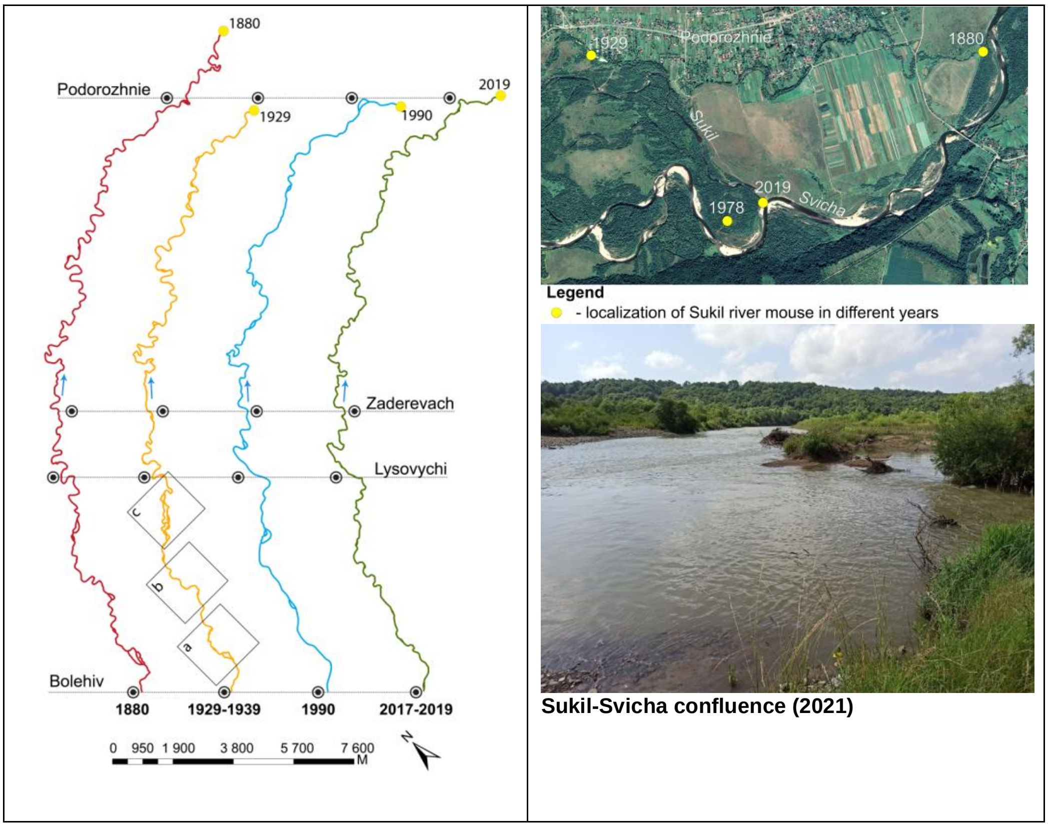

Fig. 3. Vectoral models of the Sukil riverbed and the localization of its mouth for the period of 1880–2019 (a, b, c squares indicate map areas in Fig. 4).

Dynamic section 1 is characterized by the alternation of single-channel (straight and meandering) and “transitional” (from braided to single-channel) sections of the riverbed. The latter are recorded on the historical maps of the Austrian and Polish periods as braided ones. On the maps of 1950 and 1990, there are also small single branches in these areas, although they are classified as single-channel ones. It should be noted that the traces of the multi-channel riverbed on the satellite images of different periods can be clearly seen only on the 2011 image, after the 2008 catastrophic flood.

According to the studies by a number of authors (Schumm 1977, 1981, 1985; Leopold, 1957), the braided type of a riverbed is formed in places of significant change (reduction) of the stream gradient, this reducing the transport capacity of the flow, and, as a consequence, leading to significant accumulation of alluvium (Chalov, 2007). On dynamic section 1, there are two sections of the braided channel, in the vicinity of Bolekhiv and the village of Lysovychi (Figs. 4a, 4c) shown on the 1880 and 1939 maps. The length of these sections is small, which will be discussed below. The first section (in the northern outskirts of Bolekhiv) is due to a decrease in the slope of the river. Upstream from the section to the village of Tysiv, the Sukil river is braided, and the stream gradient is about 5.8 m / km, while within the section it is 3.4 m/km. The second section is located south of the village of Lysovychi, where the river deviates to the east from the ledge of the Morshyn height. Thus, in the area of the Morshyn height (upstream of the braided second section), the stream gradient of the channel is 3.1 m / km, and within the section near the village Lysovychi – 2.5 m / km.

Comparing the described braided sections in 1880 and 1929–1939, we notice certain changes. On the first section, the bifurcation and size of accumulative forms decrease as well as the length of the section itself which decreases by almost 300 m, from 700 m to 420 m, respectively (Fig. 4a). On the second section near the village of Lysovychi, on the contrary, the bifurcation and length increase. Thus, in 1880 the length was 435 m, and in 1929-1939 – 1517m. Another change is observed in the period of 1990-2018. The bifurcation of the riverbeds almost disappears, and there are only small local sites. In the satellite images of 2006, 2013, 2015, 2016, 2017, and 2019, the riverbed on these sections is mainly meandering and single-channel.

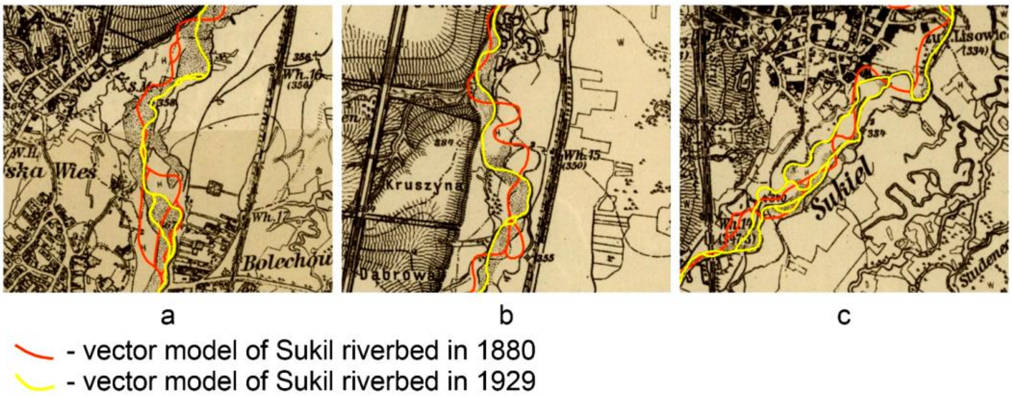

Fig. 4. Vector model of the branched Sukil riverbed in 1880 and 1929.

As mentioned above, the traces of the braided riverbed within the riverbed are well seen only in the satellite image of 2011 and are the result of catastrophic floods in 2008 and 2010 (Fig. 5). According to the features of manifestation of riverbed processes during the highest and lowest water, these areas can be classified as a transitional type of riverbeds developing from braided to a single-channel one (Chalov, 2007).

The meandering of the riverbed *in dynamic section 1* during 140 years has also significantly changed. Thus, the coefficient of meandering on this section in 1880 was 1.35, in 1929–1939. –1.27, 1990 –1.06, and in 2017 –1.15. According to this coefficient, the Sukil riverbed within the first dynamic section was meandering in 1880–1939, and in 1990–2017 it was winding. On the maps of 1990 and the satellite image of 2017, we clearly observe the straightening of the riverbed within the local areas (Fig. 6).

Anthropogenic impact seems to be the most probable reason for the decrease in meandering, in particular, for the straightening of the riverbed within Bolekhiv and changes in the functioning of riverbeds caused by melioration of the swampy part of the Sukil valley and for its straightening in the lower part (dynamic section 2). Actually, the largest horizontal riverbed deformations were recorded on the meandering sections (Fig. 3b). Thus, the maximum channel displacement for the period of 1880–1929 was 283 m, and in the period of 1929–1990 – 341 m.

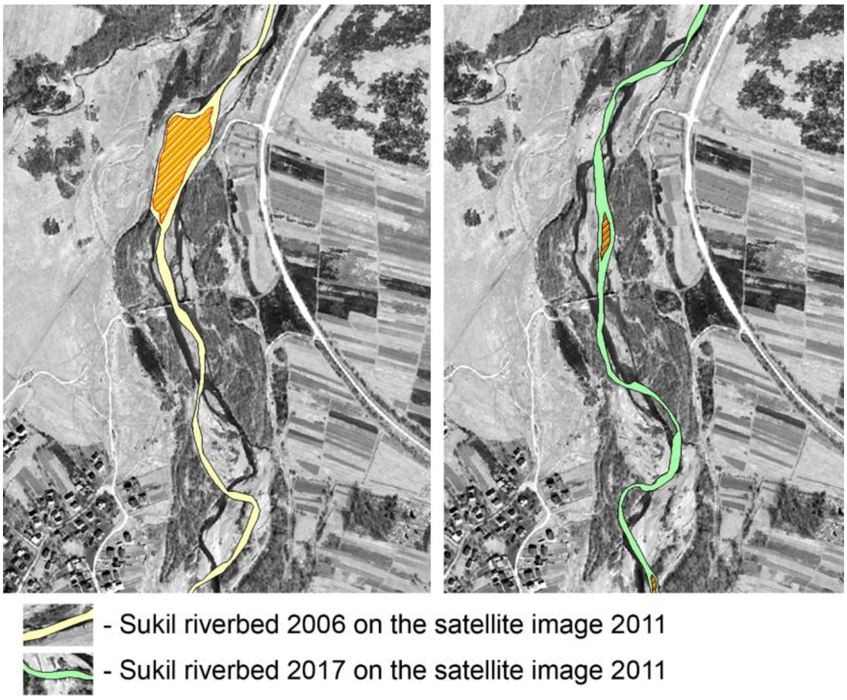

Fig. 5. Vector models of the Sukil riverbed in 2006 and 2007 in the northern suburbs of Bolekhiv on the 2011 satellite image.

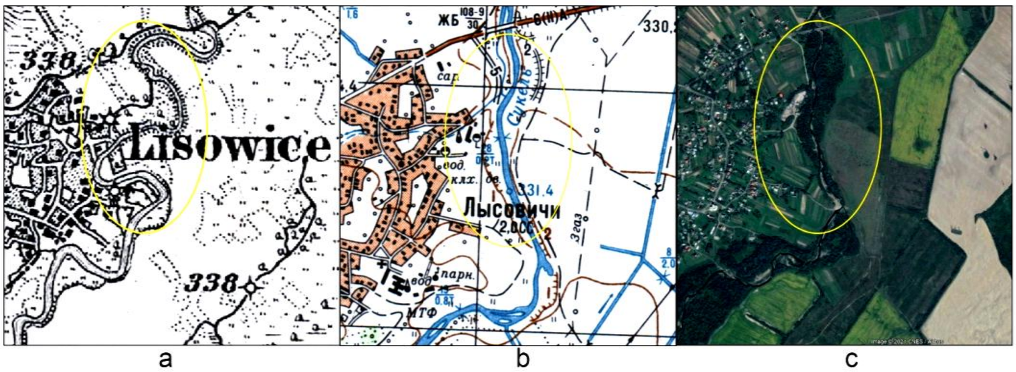

Fig. 6. Change of the Sukil riverbed in the vicinity of the village of Lysovychi (a – 1880 map; b – 1990; c – 2017 satellite image).

More accurate data on horizontal displacements within *dynamic section 1* were provided by the analysis of riverbed deformations conducted based on satellite images of 2006, 2011, and 2019. It has shown that the largest displacements took place in 2006-2011, when the catastrophic floods which had a significant impact on the reformatting of the riverbed and riverbed deformations (Leopold, 1957; Krzemień, 2012) occurred (2007, 2008, 2010). The maximum channel displacement during this period is 168 m (observation point 21, Fig. 7). Its formation is connected with the straightening of the meander, the development of a new riverbed within the high floodplain, and the drying of the old channel. The riverbed displacements over 50 m for the period of 2006–2011 are recorded in the places of observations 4, 5, 6, 11, 12, 13, 14, 15, 18, 21 (Table 2; Fig. 7).

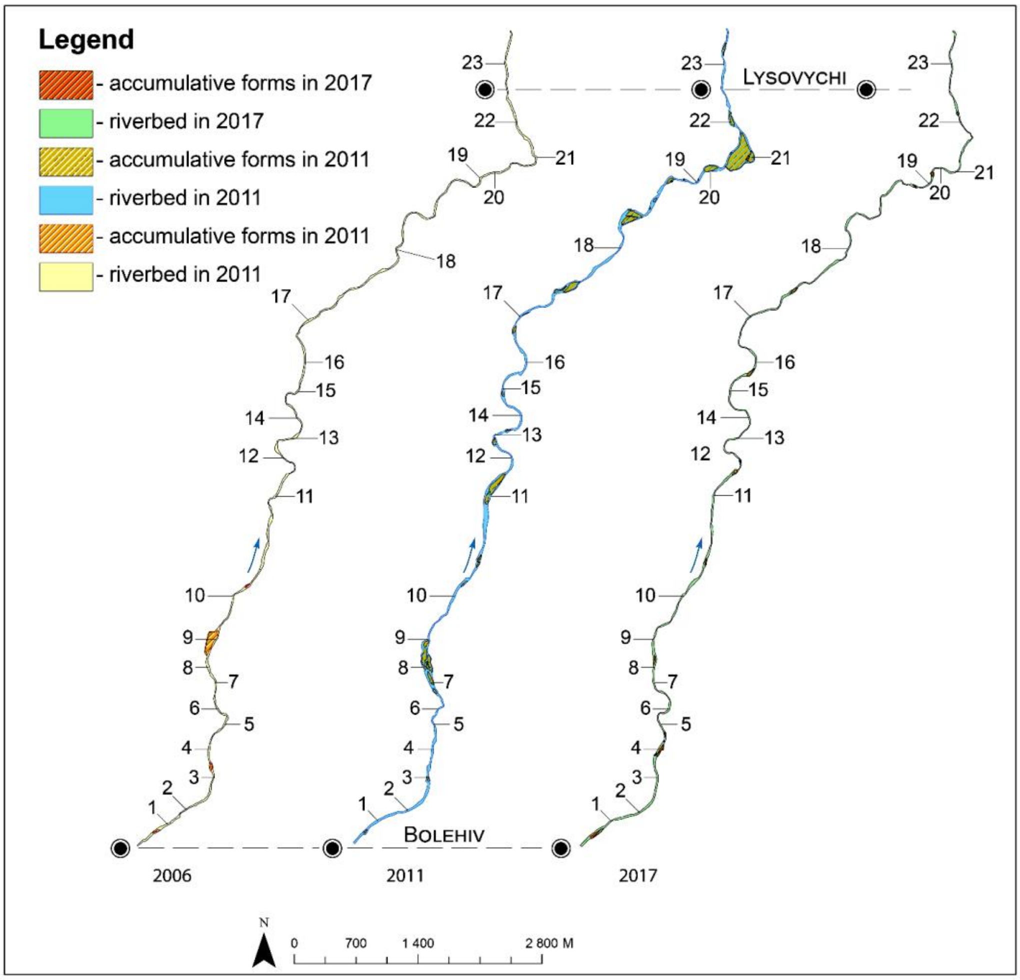

Fig. 7. Vector models of the Sukil riverbed within the first dynamic section (Bolekhiv–Lysovychi) based on Google Earth satellite images (the numbers indicate the places of identification of the size of horizontal deformations presented in Table 2).

In the period of 2011–2017, no severe floods were recorded, and thus the riverbed deformations are smaller. The maximum displacement is 58 m (observation point 21). It is caused by lateral erosion, retreat of the right bank at the top of the meander, and the growth of the left one. Horizontal deformations, the dimensions of which exceed 50 m, were also recorded in observation points 12, 13, 21. In observation points 8, 10, 11, 15, 17 no displacements were recorded (Table 2; Fig. 7). The reformatting of the riverbed can also be found at observation points 7–9. It is caused by clogging and drying of one of the two channels and the formation of a single-channel, relatively straight type of a riverbed. This mechanism of change is described by Leddy (1993) based on braided riverbeds.

Table 2. Parameters of horizontal riverbed deformations of the Sukil river on the Bolekhiv-Lysovychi section for the period of 2006–2011–2017

<table>
<tr><th colspan="7">Horizontal riverbed deformations of the Sukil river</th></tr>
<tr><th rowspan="2">№, Fig. 7</th><th rowspan="2">Meters</th><th colspan="2">Change of the riverbed type</th><th rowspan="2">Meters</th><th colspan="2">Change of the riverbed type</th></tr>
<tr><th>2006</th><th>2011</th><th>2011</th><th>2017</th></tr>
<tr><td>1</td><td>33</td><td rowspan="4">Relatively straight</td><td rowspan="4">Relatively straight</td><td>-23</td><td rowspan="4">Relatively straight</td><td rowspan="3">Relatively straight</td></tr>
<tr><td>2</td><td>-59</td><td>-11</td></tr>
<tr><td>3</td><td>23</td><td>-23</td></tr>
<tr><td>4</td><td>-63</td><td>37</td><td>Braided</td></tr>
<tr><td>5</td><td>79</td><td rowspan="3">Meandering</td><td rowspan="2">Meandering</td><td>48</td><td rowspan="2">Meandering</td><td rowspan="2">Meandering</td></tr>
<tr><td>6</td><td>-87</td><td>-23</td></tr>
<tr><td>7</td><td>32</td><td rowspan="5">Braided</td><td>24</td><td rowspan="5">Braided</td><td rowspan="7">Relatively straight</td></tr>
<tr><td>8,1</td><td>22</td><td rowspan="4">Braided</td><td rowspan="2">0</td></tr>
<tr><td>8,2</td><td>-33</td></tr>
<tr><td>9,1</td><td>42</td><td rowspan="2">18</td></tr>
<tr><td>9,2</td><td>-41</td></tr>
<tr><td>10</td><td>-49</td><td rowspan="2">Relatively straight</td><td rowspan="2">Relatively straight</td><td>0</td><td rowspan="2">Relatively straight</td></tr>
<tr><td>11</td><td>56</td><td>0</td></tr>
<tr><td>12</td><td>-52</td><td rowspan="5">Meandering</td><td rowspan="5">Meandering</td><td>-51</td><td rowspan="5">Meandering</td><td rowspan="5">Meandering</td></tr>
<tr><td>13</td><td>50</td><td>-51</td></tr>
<tr><td>14</td><td>-53</td><td>-28</td></tr>
<tr><td>15</td><td>103</td><td>0</td></tr>
<tr><td>16</td><td>-45</td><td>-37</td></tr>
<tr><td>17</td><td>38</td><td>Relatively straight</td><td>Relatively straight</td><td>0</td><td>Relatively straight</td><td>Relatively straight</td></tr>
<tr><td>18</td><td>-71</td><td rowspan="4">Meandering</td><td rowspan="3">Meandering</td><td>-22</td><td rowspan="3">Meandering</td><td rowspan="4">Meandering</td></tr>
<tr><td>19</td><td>-36</td><td>-36</td></tr>
<tr><td>20</td><td>37</td><td>5</td></tr>
<tr><td>21</td><td>168</td><td>Braided</td><td>-58</td><td>Braided</td></tr>
<tr><td>22</td><td>31</td><td rowspan="2">Relatively straight</td><td rowspan="2">Relatively straight</td><td>-34</td><td rowspan="2">Relatively straight</td><td rowspan="2">Relatively straight</td></tr>
<tr><td>23</td><td>-24</td><td>-10</td></tr>
</table>

*(horizontal displacements of the riverbed towards the right bank are indicated by the “-” sign, towards the left – by the “+” sign)

Dynamic section 2 covers part of the riverbed from the village of Lysovychi to the mouth near the village of Podorozhnie. It is characterized by a flat course of riverbed processes, a slow flow of 0.7 km/h, and by a stream gradient of 2.3 m/km. The predominant type of the riverbed is a meandering one, with the scale of meandering varying during 1880-1990. Thus, the coefficient of meandering was: in 1880 – 1.62; in 1929 – 1.53; in 1990 – 1.30. in 2017 – 1.36. Its change indicates a decrease in meandering during the period of 1880–1990, which is mainly due to anthropogenic influence and its natural growth during the period of 1990–2017. The remains of old depressions recorded as a riverbed on the map of 1880 can be seen in many parts of 1918 satellite images (Fig. 8).

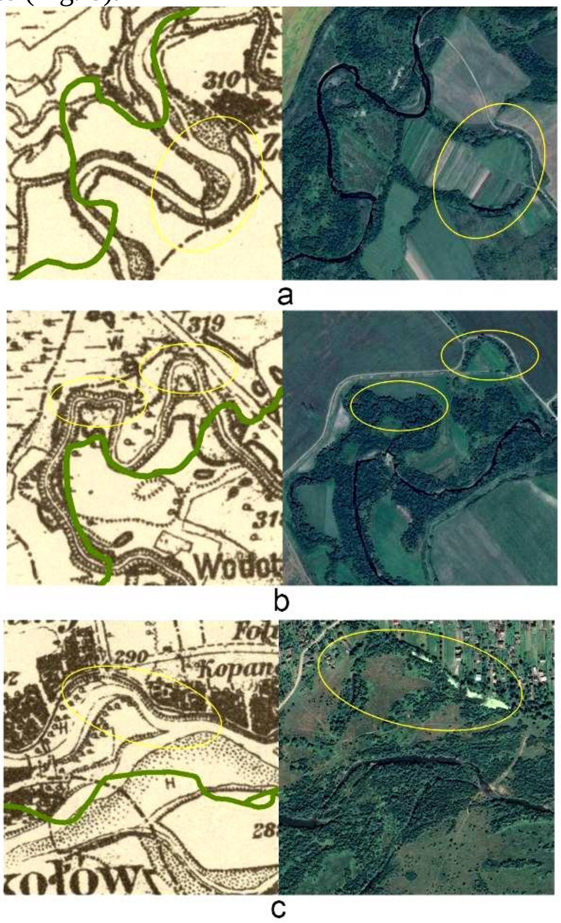

Fig. 8. Local changes in the Sukil riverbed recorded on the 2017 satellite image (the 1929 map is on the left)

In the period of 1880–1929, according to the measurements on maps (21 places), the maximum horizontal displacement was about 500 m, and in 10 places it exceeded 100 m. In the period of 1929–1990 (29 measurements in total), the maximum displacement was 496 m. In 8 places of measurements, the size of horizontal displacements was over 200 m, and in 14 places –100-200 m.

The general tendency towards decreasing the curvature of the riverbed in the period of 1929–1990 is caused by its straightening, construction of flood banks, and channels of the land reclamation network.

The horizontal deformations which occurred during the period of 2006–2011–2018 in dynamic section 2 are much smaller, their maximum value being 45 m for the period of 2006–2011 and 54 m for the period of 2011–2018. Mainly, they occurred at the mouth of the river due to lateral erosion. The average value of the maximum channel deformations for the whole period is 25 m. The analysis of satellite images and displacement measurements did not show the influence of the 2008 flood on the deformation of the lower course of the Sukil riverbed, although revealed changes in its mouth. Thus, since 2006, an accumulative form was formed at the mouth of the Sukil, which has later turned into a point bar indicating the formation of a filling delta at the Sukil-Svicha confluence (Rybak et al., 2021). The accumulative form in the Sukil delta has reduced the width of the channel from 25 m to 6-7 m.

Discussion and Conclusions. The bed of the Sukil river on the section of Bolekhiv–the village of Podorozhnie (river mouth) is located within the Precarpathian height and has significant differences in the development of horizontal deformations. According to the nature of manifestation and the size of the development of riverbed deformations, two dynamic sections have been identified – from the town of Bolekhiv to the village of Lysovychi and from Lysovychi to the village of Podorozhnie (the Sukil mouth). *Dynamic section 1* is now mainly a single-channel meandering riverbed, although during the period of 1880 and 1939 it was characterized by a combination of single-channel and braided sections. Single local branches within the previously braided sections were also recorded on the 1990 map and 2006, 2013, 2015, 2016, 2017–2019 satellite images, although in general the riverbed is single-cahnnel and meandering. Thus, there is a certain long-term tendency of the transition from braided riverbed (gravel-bed braided river; Schumm 1977, 1981, 1985) to the single-channel meandering one. Only during the catastrophic floods of 2008 and 2010, the riverbed in these sections functioned as a braided one, as recorded on the 2011 satellite image. Such riverbeds can be classified as transitional (Chalov, 2007). In these sections, the horizontal deformations are small and occur within the riverbed. The largest horizontal riverbed deformations (up to 340 m) are recorded in the meandering sections of *dynamic section 1* during the whole period (140 years). Overall, for dynamic section 1, there has been a natural increase in the meandering of the riverbed, and hence horizontal deformations, over the last decade.

The riverbed of the Sukil river in the dynamic section 2 (from the village of Lysovychi to the mouth) was meandering during 1889-2018. From 1889 to 1990 we observe a tendency towards reducing the meandering of the riverbed due to anthropogenic influence including the straightening of the riverbed, construction of flood banks, and reclamation of the Sukil valley as well as a significant natural change in the location of the river mouth. Since 1990, there has been a natural increase in meandering of the riverbed as evidenced by the value of the coefficient of meandering and by Sukil meanders cutting flood banks in three places, this being recorded in 2006 satellite images. The horizontal deformations of the riverbed in this dynamic section are large and reach a maximum of 497 m. They occurred during the period of 1880–1929. In 2006–2019, the maximum horizontal displacements were small and constituted 54 m, which is probably also due to the stabilization of the Sukil mouth localization.

The results of the study of horizontal deformations of the Sukil riverbed within the Precarpathian height are important for the reconstruction and restoration of the destroyed areas of flood banks in order to protect agricultural lands as well as the villages of Lany-Sokolivski and Podorozhnie from floods. They also serve as a basis for a more detailed study of riverbed processes including the patterns of development of riverbed accumulative forms and vertical and horizontal deformations of the Sukil riverbed.

REFERENCES

Andreychuk, Yu., Yamelynets, T. (2015). GIS v ekolohichnykh doslidzhenniakh ta pryrodookhoronnii spravi [GIS in environmental research and environmental protection] (Tutorial), 282. (In Ukrainian).

Bayrak, G. R. (2011). Suchasni ruslovi protsesy i dynamika rusla r. Tysy na diliantsi peretynu Vyhorlat-Hutynskoho vulkanichnoho pasma [Modern channel processes and dynamics of the Tisza riverbed at the intersection of the Vygorlat-Gutyn volcanic ridge]. In *Fizychna heohrafiia ta heomorfolohiia*, 62. Kyiv: VHL "Obrii", 45–54. (In Ukrainian).

Bayrak, G., Kovalchuk, U. (2017). Morfolohiia i dynamika rusla Stryvihora na Peredkarpatskii vysochyni [Morphology and dynamics of the Strivigor river at the Pre-Carpathian height] In *Problemy heomorfolohii i paleoheohrafii Ukrainskykh Karpat i prylehlykh terytorii*, 07, 64–76. (In Ukrainian). http://publications.lnu.edu.ua/collections/index.php/carpathians/article/view/1962

Burshtynska, K. V., Shevchuk, V. M. (2012). Metodyka doslidzhennia zmishchen rusla riky Dnister [Methods of research of displacements of the Dniester riverbed] In *Heodeziia, kartohrafiia i aerofotoznimannia:* Lviv Polytechnic National University, 76, 102–110. (In Ukrainian).

Burshtynska, K., Movchko, L., Shevchuk, V. (2015). Monitorynh ruslovykh protsesiv ta povenevykh yavyshch riky Dnister za kosmichnymy zobrazhenniamy [Monitoring of channel processes and flood phenomena of the Dniester River by satellite images] In *Suchasni dosiahnennia heodezychnoi nauky ta vyrobnytstva*, 1, 124–128. (In Ukrainian).

Chalov, R. S. (2007). *Ruslovedenye: teoriia, heohrafyia, praktyka, T.1: Ruslovye protsesu: faktoru, mekhanyzmu, formu proiavlenyia y uslovyiah formyrovanyia rechnukh rusel* [Channel Studies: Theory, Geography, Practice, Vol. 1: Channel Processes: Factors, Mechanisms, Forms of Manifestation and Conditions for Formation of River Channels]. Moscow: Izd-vo LKI. (In Russian).

Glushko, V. V., Kruhlov, S. S. (eds). (1986). Tektonycheskaia karta Ukraynskykh Karpat [Tectonic map of the Ukrainian Carpathians]. (In Russian).

Google Earth Pro 7.3. (2006). *Chastyna Stryiskoho i Dolynskoho raioniv Lvivskoi oblasti* [Part of Stryj and Dolyna districts of Lviv region] 49°11'20.81"N, 24°4'5.02"E, 49°1'55.44"N, 23°49'41.80"E.

Google Earth Pro 7.3. (2011). *Chastyna Stryiskoho i Dolynskoho raioniv Lvivskoi oblasti* [Part of Stryj and Dolyna districts of Lviv region] 49°11'20.81"N, 24°4'5.02"E, 49°1'55.44"N, 23°49'41.80"E.

Google Earth Pro 7.3. (2017–2018). *Chastyna Stryiskoho i Dolynskoho raioniv Lvivskoi oblasti* [Part of Stryj and Dolyna districts of Lviv region] 49°11'20.81"N, 24°4'5.02"E, 49°1'55.44"N, 23°49'41.80"E.

Graf, N. E. (2008). *50 years of channel change on a reach of the Big Blue River, northeast Kansas* (Doctoral dissertation). Kansas State University.

Heneralnyi Shtab. (1990) *Topographic map of Bolehiv* 1:50 000. M-34-108-Г.

Heneralnyi Shtab. (1990) *Topographic map of Dashava* 1:50 000. M-35-97-A.

Heneralnyi Shtab. (1990) *Topographic map of Stryj* 1:50 000. M-34-108-Г.

Heneralnyi Shtab. (1990) *Topographic map of Velyka Turia* 1:50 000. M-35-97-B.

Horishnyy, P. M. (2014) Horyzontalni deformatsii nyzhnoi techii rusla richky Stryi u 1896-2006 rr. [Horizontal deformations of the lower riverbed of the Stryy river in

1896-2006]. In *Problemy heomorfolohii i paleoheohrafii Ukrainskykh Karpat i prylehlykh terytorii*, 68–74. (In Ukrainian).

Jaskulski, M., Łukasiewicz, G., Nalej, M. (2013). Porównanie metod transformacji map historycznych [Comparison of transformation methods of historical maps]. In *Roczniki Geomatyki*, 11(4 (61)), 41–57. (In Polish).

Kravchuk, Ya. S. (1999). *Heomorfolohiia Peredkarpattia* [Geomorphology of Precarpathian]. Lviv: Merkator, 188. ISBN 966-7563-00-6. (In Ukrainian).

Kravchuk, Ya. (2021). *Relief Ukrainskykh Karpat:* Monohrafiia. [Geomorphology of Ukrainian Carpathians]. Lviv: LNU imeni Ivana Franka, 576. ISBN 978-617-10-0631-7. (In Ukrainian).

Krzemień, K. (eds). (2012) *Struktura koryt rzek i potoków (studium metodyczne)* [Structure of rivers and streams (methodological study)]. Kraków. Uniwersytet Jagielloński. (In Polish).

Leddy, J. O., Ashworth, P. J., Best, J. L. (1993). Mechanisms of anabranch avulsion within gravel-bed braided rivers: observations from a scaled physical model, Geological Society, London. In *Special Publications* 75, 119–127. http://dx.doi.org/10.1144/GSL.SP.1993.075.01.07

Leopold, L. B., Wolman, M. (1957). River Channel Patterns: Braided, Meandering and Straight. In *Geological Survey Professional Paper*, 282-B, United States Government Printing Office, Washington, 39–85.

Leopold, L. B., Wolman, M. (1957). River Channel Patterns: Braided, Meandering and Straight. In *Geological Survey Professional Paper*, 282-B, United States Government Printing Office, Washington, 39–85.

Mapa Szczegółowa Polski (1929-1939) Archiwum map. W.I.G. 1:25 000, P.52 S.38-B

Mapa Szczegółowa Polski (1929-1939) Archiwum map. W.I.G. 1:25 000, P.52 S.38-D

Mapa Szczegółowa Polski (1929-1939) Archiwum map. W.I.G. 1:25 000, P.52 S.38-G

Mularz, S. (2014). *Podstawy teledetekcji. Wprowadzenie do GIS*. [Basics of remote sensing. Introduction to GIS]. Politechnika Krakowska, Kraków, 67.

Noszczyk, T., Nawieśniak, M., Hernik, J., Strutyński, M., Taszakowski, J. (2015). Wykorzystanie map topograficznych do analizy zmian przebiegu koryta rzeki Krzyworzeka. In Episteme 26/2015, t. II, s. 109–116. (In Polish).

Rybak, N., Dubis, L., Bubniak, A., Bubniak, I. (Eds.) (2021). In International Conference of Young Professionals Geoterrace, Lviv, Ukraine: October 4–6.

Schumm, S.A. (1977). *The fluvial system*. New York; John Wiley; DA, 355. ISBN 0471019011.

Schumm, S. A. (1981). Evolution and response of the fluvial system, sedimentologic implications. In *SEPM Special Pub*., 31, 19–29.

Schumm, S. A. (1985). Patterns of alluvial rivers. In *Annual Review of Earth and Planetary Sciences*, 13(1), 5–27.

Spezialkarte der osterreichisch-ungarischen Monarchie (1880). 1:75 000, Zone 9 col.XXX. K.k. military georgafisches Jnstitut.