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GIS IN THE ANALYSIS OF HYDROMORPHOLOGY OF SELECTED MEANDERS OF THE CRNA REKA

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ABSTRACT
GIS in the analysis of hydromorphology of selected meanders of the Crna Reka
Hydromorphological changes in river systems, particularly in the context of meanders, are crucial for understanding the dynamics of fluvial environments. Meandering is a natural process in lowland areas where rivers form curved, sinusoidal flows driven by the complex interaction of hydraulic forces, sediment transport and bank erosion. These changes alter the physical morphology of rivers, influencing water quality and flood risks. The meandering process of the Crna Reka can be assessed through the processing and analysis of topographic maps and satellite imagery from the Landsat mission (1983–2013) and Sentinel-2 mission (2018–2023). Parameters analyzed include river channel width, the central flow line within a given sector, the sinuosity of the river channel, the radius of curvature of river bends, the length of meandering belts, the width of meandering channels, and riverbed migrations. Between 1964 and 2023, an increase in the sinuosity coefficient, a rise in the number of bends from 10 to 23, changes in the radius of curvature from 271 m to 577 m, and alterations in the length and width of meandering were observed. Significant lateral erosion on the right bank and dominant sedimentation on the left bank were also evident. Understanding these processes is crucial for predicting future river flow changes and mitigating potential environmental impacts.

KEY WORDS: GIS, meandering, Crna Reka, Sentinel

1. Introduction

Water is the most widespread substance on Earth. Most of the surface of the Planet Earth is covered by the so-called World Ocean. Within the land, water is represented in the form of streams and rivers, swamps, lakes, glaciers, etc. A total of 96.54% of the total amount of water (fresh + salt water) is in the World Ocean (Radevski, 2021). On the land territory, rivers are the most common form of surface water. The river constitutes a water mass that moves through a bed - a depression cut into the land (Vasileski, 2004). Since the river flow is permanent in the land, with the passage of time, there is a continuous change in the dynamics of the river flow, a change in the river bed, the river valley, etc. Because rivers are spatially connected systems, forming connections at a range of spatial and temporal scales (Fryirs and Brierley, 2013). The meandering is the most striking feature of the rivers in the plains, where under the influence of the inertia of the water mass and the erosion of on the sides of the river course, there is the formation of more pronounced bends – meanders (Vasileski, 2004).

Meandering, as a hydrological process, occurs in areas where the riverbed is cut into clay or sand. In the upper mountain parts, the river flows they usually have a small sinusoid, which mainly depends on the local geology. The river bed is filled with numerous coarser sediments such as gravel, coarse sand and stones, which are deposited in the lower streams as a consequence of the action of fluvial erosion (Crossato, 2008). The longitudinal the profile of the mountain stream is characterized by sharp and deep sections, at times followed by short shallower sections, and then again by sharp and deep sections. However, there are additional influencing factors on the meandering process of the river course, as of a natural character, but in the last few decades, and of anthropogenic character (Morais et al., 2016). Meandering rivers are essential to the study of floodplain dynamics and flood risk assessment (Raj et al., 2015). As they naturally change and evolve, they can influence and on infrastructure and human settlements. In addition, meandering rivers are very sensitive to changes in the environment, including human activities such as sewerage and land use changes, adding additional research complexity.

The last few decades, in more recent researches, more and more intensively new technologies begin to be applied in detailed and scientific studies and analysis. Much attention is paid to it the application of Geographical Information Systems and Remote Sensing in the evolution of meandering (Mithun et al., 2012; Yang et al., 1999; Yang et al., 2015), morphodynamics (Basnayaka et al., 2022), spatio-temporal variations in the change of the river bed during the meandering of the river (Morais et al., 2016). Also, the use of high-quality satellite images (Jana and Paul, 2014) and aerial photographs from drones in monitoring and mapping the course of the river channel (Flener et al., 2013), studying floodplain dynamics and flood risk assessment (Raj et al., 2015), as well as depth mapping of river courses based on freely commercially available aerial photographs (Legleiter, 2013; Langovic, 2020; Butnariu et al., 2016). In addition to newer ways and data to study, they are also inevitably still topographic maps are also used to monitor hydromorphological changes (Khairul et al., 2014). From the previously mentioned previous researches, it can be seen that the factors and processes of meandering are followed and studied with great interest the river bed, as well as the consequences of that natural hydrological process. Meanders migrate downstream, and river channels change in the direction of floodplains, creating a significant contribution to spatial change. Therefore, there is a need to understand the processes, rates and patterns of movement and, if possible, to develop methods to predict meandering movement. The rivers involved in the meandering process are very important because of the biodiversity they possess, offering a range of types of biological habitats.

2. Study area, data and methodology

The river Crna Reka is located in the central part of the country, in the area of the Tikvesh basin. Crna Reka is the largest right tributary of the Vardar River. It originates in the southeastern part of Ilinska Mountain, from the Crna Dupka source, above the village of Zheleznec at 760 m.a.s.l. The river passes through the area of Demir Hisar, Pelagonia, Mariovo and near the ancient site of Stobi, at an elevation of 129 m.a.s.l. flows into the river Vardar. The length of the river is 207 km (Gashevski, 1979).

The Tikvesh Valley occupies an area of 2518 km^2 and extends between 100 and 2166 m above sea level, has an elongated shape with a length of 50 km and a width of about 40 km. The basin was formed by intense tectonic processes that took place until the Neogene. The territory of the Tikvesh basin is characterized by Neogene sands due to the fluvial relief that is represented in the area.

The selected meandering study section is characterized by 4,470 m width and 6,135 m length, with a total area of 28.29 km^2. The main factor in choosing which area (sector) of the Crna Reka course is represented by the appearance, i.e. recorded meandering process of the river itself (Figure 1).

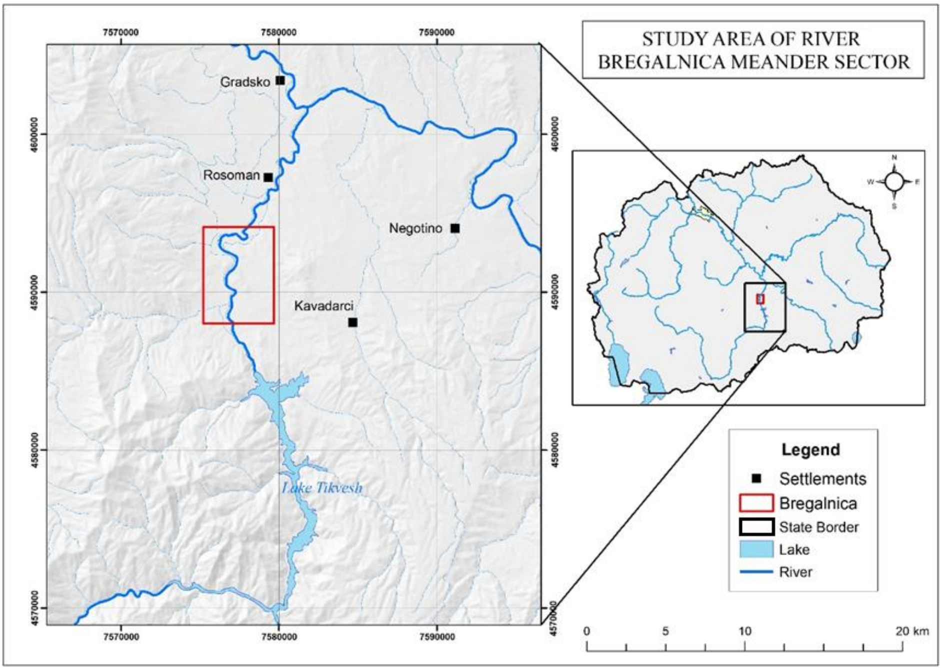

Figure 1: Map of Study Area of Crna Reka.

Data can come from different sources, be in analog (paper form) or digital (electronic form), statistical data, photos, video displays, etc. Data collection is an important process that involves considerable time in the work (Gorin, 2021). In the research of the selected area of meandering, the following data were used: Landsat series of satellite images for the period 1983-2013; Sentinel series of satellite images for the period 2018-2023; Data from other spatial data sources. Based on the available satellite images and topographic maps, a studied period from 1964 to 2023, which is 59 years, was selected. A total of 8 series of satellite images with different resolutions were required (Table 1 and Table 2).

Also, topographic map with a scale of 1:50,000 - Prilep Sheet 782-2, made by the Military Geographical Institute in Belgrade in 1986. In addition to topographic maps, geological maps with a scale of 1:100,000 were also used - Sheet Prilep K-34 -92 for the territory of Macedonia, prepared by the Federal Geological Survey in Skopje. Analog data sources (topographic and geological maps) were scanned with a resolution of 300 DPI, in order to preserve the quality of the contents in electronic raster form. In addition to the geological maps, an interpreter for General Geological Maps OGK – Sheet Prilep K34-92, (1:100 000) was used for their interpretation.

Table 1: Data for Landsat series of satellite images.

Year	Satelite	Sensor	Resolution (m)	Path	Row	Projection/Datum
1988	Landsat 5	TM	30	184	31	UTM / WGS-84
1993	Landsat 5	TM	30 (120)	184	31	UTM / WGS-84
1998	Landsat 5	TM	30 (120)	184	31	UTM / WGS-84
2003	Landsat 7	ETM+	30 (15)	184	31	UTM / WGS-84
2008	Landsat 7	ETM+	30 (15)	184	31	UTM / WGS-84
2013	Landsat 8	OLI/TIRS	30 (15)	184	31	UTM / WGS-84

Table 2: Data for Sentinel series of satellite images.

Year	Satelite	Level corection	Resolution	Orbit number	Orbir direct.	Projection/ Datum
2018	Sentinel-2B	L1C	10 (20, 60)	93	Descending	UTM / WGS-84
2018	Sentinel-2B	L1C	10 (20, 60)	93	Descending	UTM / WGS-84
2018	Sentinel-2A	L2A	10 (20, 60)	93	Descending	UTM / WGS-84
2023	Sentinel-2B	L2A	10 (20, 60)	93	Descending	UTM / WGS-84
2023	Sentinel-2B	L2A	10 (20, 60)	93	Descending	UTM / WGS-84
2023	Sentinel-2B	L2A	10 (20, 60)	136	Descending	UTM / WGS-84

Satellite images were taken from two online sources, namely the United States Geological Survey (USGS, 2024) website for the Landsat mission satellite image series, and for Sentinel mission, they are available on the Copernicus program website (Copenicus, 2024). Satellite images have been downloaded that are "cloud free", i.e. are not covered by cloud cover, or the cloud covers less than 10% of the entire satellite image. In relation to the time period when the satellite images were created, the months of August, September, October and November were selected, for better visibility of the space. The scanned maps are georeferenced in the Macedonian State Coordinate System zone 7 (Macedonia State Coordinate System zone 7) code EPSG_6316 (AKN, 2024).

The satellite images are imported into the software package ArcMap 10.8, they are rectified and the 30 m band resolution is connected to the 15 m panchromatic band, in order to obtain a new composite image with a higher spatial resolution of 15 m. The following procedure represents the process of separating the riverbank and the riverbed through manual digitization, where the accuracy and precision is greater than with the automatic method of vectorization. It is specified in a minimum digitization scale of 1:5000 in the zoom level of the 30-meter images, up to 1:2000 for the satellite images of the 10-meter Sentinel images.

The next step in the processing of the digital images is the radiometric and atmospheric correction of the satellite images. The is followed by selection of the most appropriate spectral bands (bands) that would allow the best reclassification of the satellite images and the best recording of the water surfaces. For the Landsat-4MSS/TM and Landsat 7 ETM+ series, a combination of 4-3-2 spectral bands was chosen, while for Landsat-8 OLI, a combination of 5-4-3 spectral bands was used. These combinations of spectral bands are also known as near-infrared composite images. For the Sentinel-2 series of satellite images, a combination of 8-4-3 spectral bands is used, which also represent near-infrared composite images. NDWI (Normal Difference Water Index) is also applied - normal difference in the water index. This index uses the green and near-infrared spectral bands, which are suitable for identifying water bodies from the surrounding space. Because in November 1979, December 1985 and February 1986, there were intense rains and floods, they contributed to drastic changes in the riverbed of the river Crna Reka, and they were taken (Hydrological yearbook 1979, 1985, 1986).

The software packages for digital cartographic processing that have been applied are ArcMap 10.8, Quantum GIS v.3.22.11. The digitized data are then followed by several calculations of the planimetric parameters of the meandering of the selected area.

3. Results

The selected area is characterized by a width of 4,470 m and a length of 6,135 m, and a total area of 28.29 km^2. Width of the Crna Reka river channel varied throughout the selected section, from 22 m at the beginning, up to about 30 m at the exit of the studied sector and with the greatest width of 50 m in the central part of the course in the sector with a slope of the river course of 1.21%.

The elevation of the elevation of the river course at the beginning of the studied sector is 156 m.a.s.l., while the elevation at the exit from the studied sector is 144 m.a.s.l. (Google Earth Pro), which brings us to the record that the river Crna Reka has a height drop of 12 m. In relation to the sinusoidity of the river channel, the value of sinusoidity and the number of bends in the selected sector in the period from 1964 to 2023, a trend of continuous increase in the sinusoidity of this part of Crna Reka, i.e. a value greater than 1.5, which can be clearly seen in the following Figure 2.

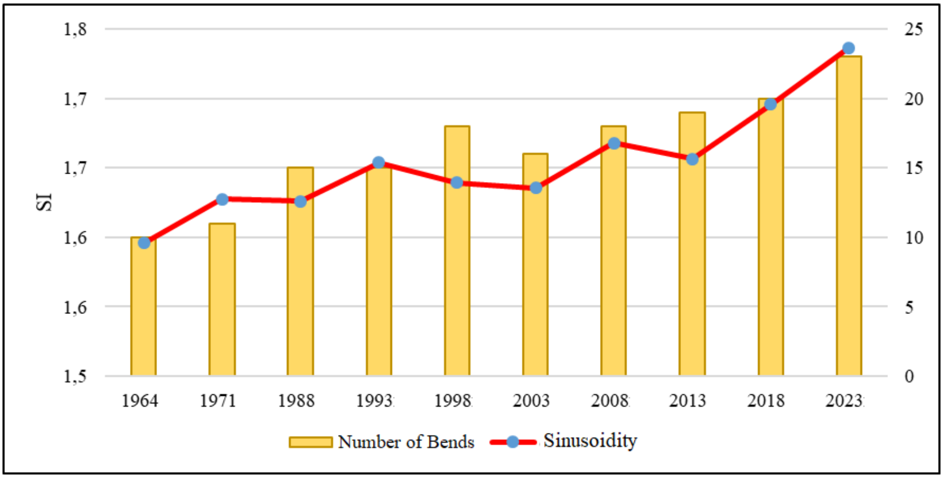

Figure 2: Sinusoidity and number of bends of selected meander on Crna Reka.

The significant increase in the coefficient of sinuosity and the number of distortions is primarily due to the large flood that covered the Pelagonian region at the beginning of 2015, as a consequence of several days of torrential rains and melting of snow due to increased average daily temperatures (FAO, 2018).

The radius of curvature is a measure of the "tightness" of a meander curve and is inversely proportional to sinusoidity (Bag et al., 2019; Morais et al., 2016). The smallest radius of curvature was measured in 2008, with a value of 271 m, while of the maximum values, the highest value was measured in 2003 with a value of 577 m. A trend of small changes in the radius of curvature is also noticeable (Figure 3).

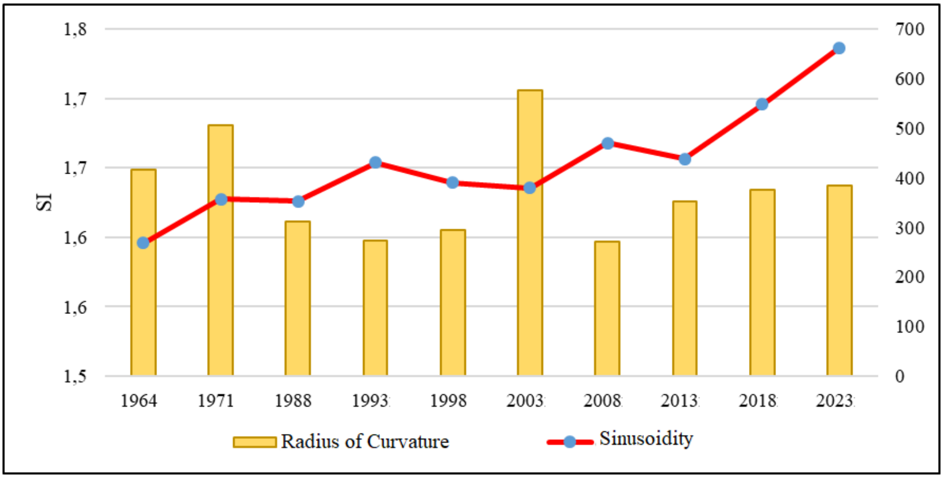

Figure 3: Radius of curvature and sinusoidity of Crna Reka.

The next significant planimetric aspect in the study of the meandering of Crna Reka is the minimum and maximum length of meandering of the bends and the amplitude, i.e. the maximum width of the meandering bend. The absolute lowest length was measured in 2023 and is 248 m, while the highest minimum length was measured in 1971 and is 471 m (Figure 4).

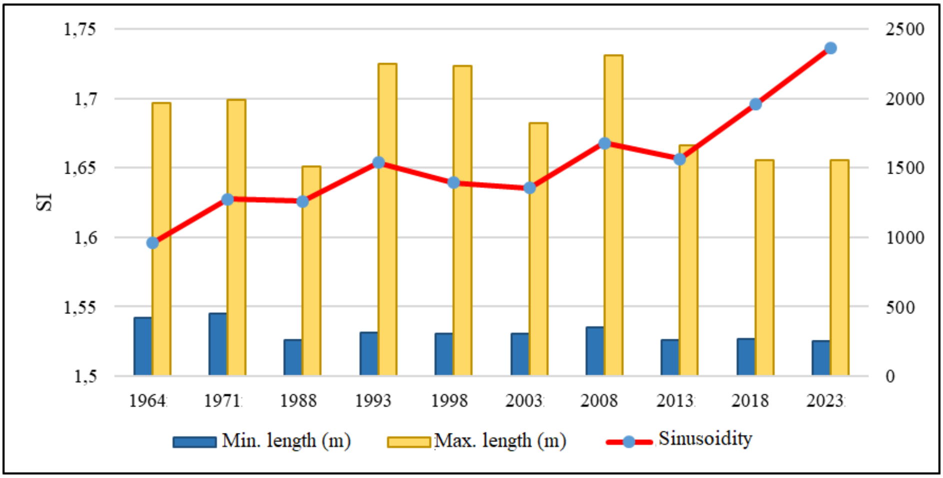

Figure 4: Minimum and maximum meandering length and sinusoidality of Crna Reka.

Among the maximum measured lengths, the smallest length was measured in 1988 and is 1508 m, while the absolute largest length was measured in 2008 and is 2306 m. The minimum and maximum length of the river are not mutually related to the sinuosity of Crna Reka in the examined selected part. During the period 1964-2023, there are significant changes in the width of the meander bend. In 1964, the maximum width was 1211 m, while the highest maximum measured width was in 1971, which was 1235 m. In the further period, there is a gradual decrease in width, so the lowest value was measured in 2003 and it is 1094 m. In the next five-year period, in 2008, there is an increase in value and it amounts to 1173 m. In the following three five-year periods (2013, 2018 and 2023), it can be recorded that there is a stabilization of the meandering width, despite the fact that the number of turns increases (18 turns - 2008, up to 23 turns - 2023), that is it has a rise of 5 meander bends (Figure 5).

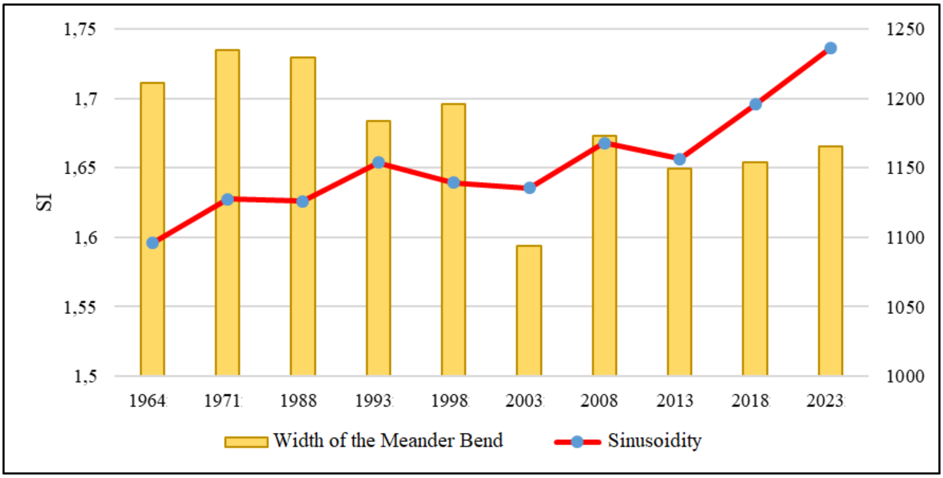

Figure 5: Maximum meandering width of Crna Reka.

The migration of the river bed i.e. the change of the river bank occurs on both river banks, covered in the process of meandering. The migration of the river bed is caused by the two processes of erosion and accumulation of the river sides, which leads to the retreat and advance of the banks of the river course. The state of the river in 1964, according to the digitized contents of the Prilep-2 topographic map, sheet 782-2, was taken as the initial reference year for measuring the changes in migration on the banks of the Crna Reka. It is recorded that the right bank has represented greater erosion, while the left bank has represented significant sedimentation of the river sediment (Figure 6, 7 and 8).

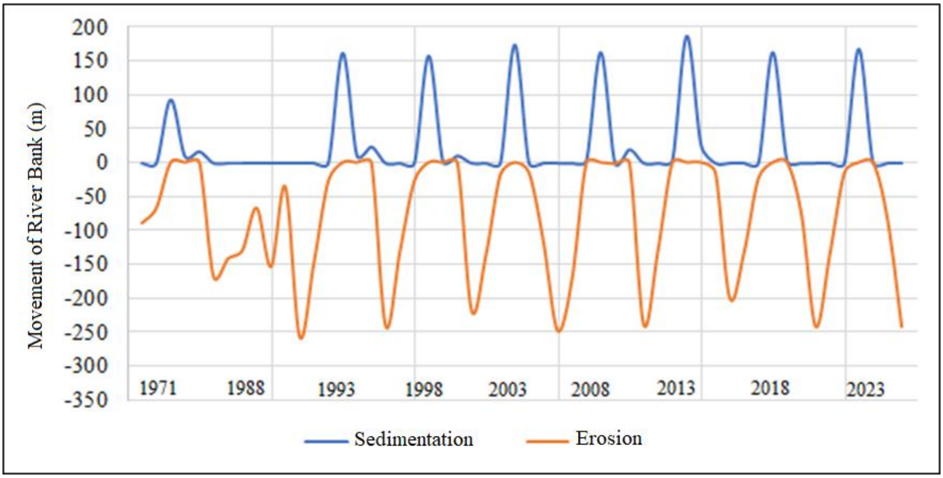

Figure 7: Movements on the right bank of Crna Reka.

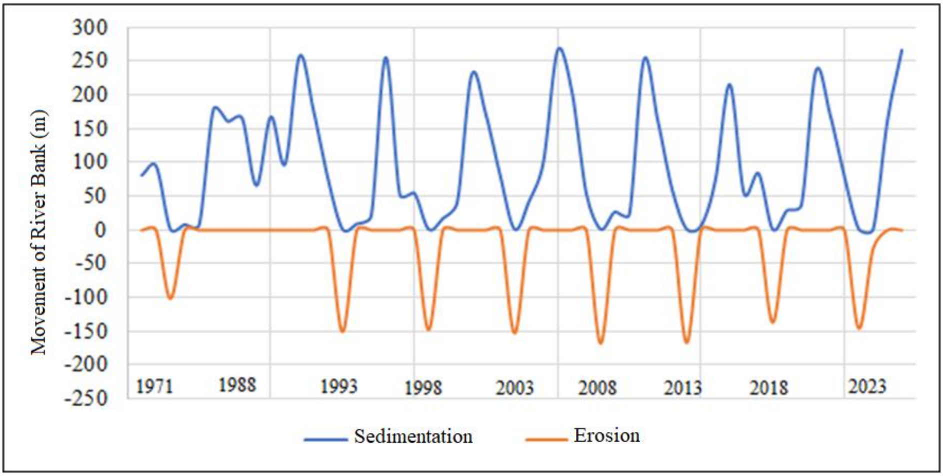

Figure 7: Movements on the left bank of Crna Reka.

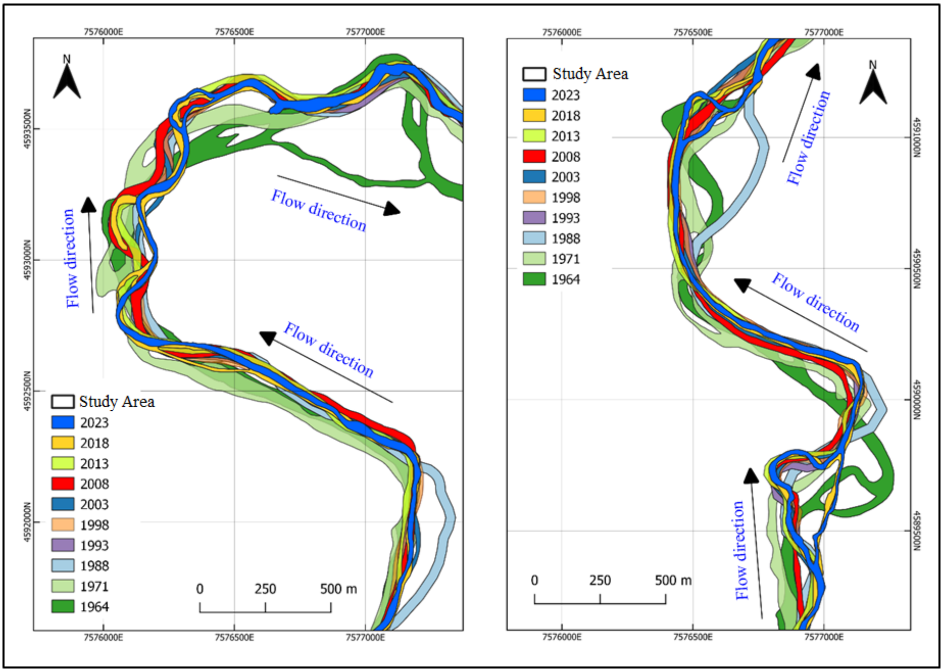

Figure 8: Two most prominent meandering bends of Crna Reka, period 1964-2023.

4. Discussion

The coefficient of sinusoidity on Crna Reka is also variable throughout the studied period, with a trend of continuous increase. Thus, in 1964, the sinusoidal coefficient was 1.596, and the number of turns was 10, while in 2023, the sinusoidal coefficient was 1.736, and the number of turns was 23. Then, the smallest radius of curvature of Bregalnica was measured in 2008 (271m), while the highest value was measured in 2003 (577 m). The smallest length of meandering was measured in 2023 (248 m), while the largest length was measured in 2008 (2306 m). The greatest meandering width was measured in 1971 (1235 m), while the smallest width was recorded in 2003 (1094 m). The biggest changes on the right bank for sedimentation were in 2008 and 1993, while for erosion, the biggest changes were in 1998 and 2003. On the left bank, sedimentation is highest in 1988 and 2003, while erosion reaches the highest value in 2008, 2013 and 2023. The facility for excavation and separation of river sand, gravel and stone, which is located on the very bank of the river, north of the village of Trstenik, Tikvesh valley, has a significant influence on the process of river bed migration and meandering. The situation is similar with the river Sava, along its river course in the territory of Slovenia, where there is degradation and change of the riverbed in the period from 1989-2006 and after 2009, because part of the water is taken for cooling the nuclear reactor of the Nuclear Power Plant. "Krško", where there are changes in the river course of about 200 m downstream (Mikoš et al., 2015) (Figure 9).

Figure 9: Satellite view of a facility for excavation and separation of river sand and gravel on Crna Reka, 2005-2023 (History Imagery on Google Earth Pro).

Three segments with significant meandering were examined in South Morava. The biggest changes were observed in the first meandering sector, - an increase of 32%. The second meandering sector has an increase of 28% and the third meandering sector has an increase of 32% and 37%. These data support the fact of a pronounced process of lateral channel migration. There are a variety of natural and anthropogenic factors that influence lateral channel migration rates, with particular emphasis on the occurrence of peak discharge values (Langovic, 2020).

The evolution of the riverbed of the river Prut in the Republic of Romania, a 26 km long area with a width of the river channel varying from 41 m to 102 m is taken. The changes that have occurred in the last 125 years were analyzed here. Topographic maps of different scales, as well as images from the Landsat and Sentinel mission series, as well as LIDAR data for 2012 and images from Google Earth, were used as sources. The Normalized Difference Water Index (NDWI) method was applied (Butnariu et al., 2016). The evolution of river channels is carried out through lateral migration, especially in the case of meander channels.

After 1890, the Prut River was characterized by high mobility in the river channel, in a created buffer zone of 400 m, but in the years after 1980, mobility in migration decreased, the river channel gradually stabilized with lateral (lateral) migration and with a slow tendency of vertical degradation.

5. Conclusion

Knowledge of the migration of riverbanks as a consequence of meandering, both past and present, is crucial for the subsequent management of river systems. The meandering takes place in the plain area of the Tikveshka valley. The selected sector is characterized by wide flood plains, extremely low land slope (< 4% slope) and dominant alluvial soils.

The time period of studying the hydromorphological analyzes in selected sectors of Crna Reka covers the period of 59 years, i.e. from 1964-2023, where topographic maps with a scale of 1:50000 and satellite images from the Landsat and Sentinel-2 series were used. With the exception of the first period from 1964-1988, where there is a time frame of 24 years, the rest of the time period of research and analysis covers the changes that occur in the space every 5 years, in order to more adequately display the spatio-temporal changes. For the selected meandering sector of Crna Reka, according to the conducted research, it was recorded that there is a continuous increase in the sinusoidal coefficient throughout the entire investigated period, an increase in the number of bends, significant changes in the minimum and maximum radius of curvature. Also, throughout the study time period of 59 years, the radius of curvature is in continuous change and there is no correlation between radius and sinusoidity. Regarding the width of meandering, it changes over the years, where the highest maximum measured width of meandering was measured in 1971, which is 1235 m, while the lowest value was measured in 2003 and it is 1094 m. Regarding the migration of the river bed of Crna Reka in Sector-2, it is evident that the right bank has represented greater erosion in contrast to the sedimentation, which is smaller, while on the left bank, significant sedimentation of the river sediment has been represented in relation to erosion.

The use of Geographic Information Systems (GIS) and modern technology is crucial for researching meander areas due to their ability to provide accurate, comprehensive, and timely data. Meanders, which are winding curves or bends in a river, are dynamic landscapes shaped by a range of natural processes, including erosion, sediment deposition, and vegetation growth. Understanding these processes requires precise monitoring and analysis, which GIS and modern technology can offer.

GIS allows researchers to analyze spatial data, map changes over time, and visualize patterns in meander evolution. It enables the combination of multiple data sources, such as hydrology, climate data, and soil composition, providing a holistic view of the factors influencing meander formation and change. This is essential for assessing risks such as flooding and erosion, and for developing strategies for sustainable land use and river management.

Modern technologies like satellite imagery and remote sensing provide up-to-date and high-resolution data on land cover, vegetation, and river morphology. These technologies make it possible to detect subtle changes in meander patterns, which are often invisible to the naked eye. The integration of these tools supports informed decision-making in environmental management, conservation, and infrastructure planning, ensuring that human activities align with the natural dynamics of riverine systems.

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