Monitoring Changes in Channel Morphology on the Orljava River Based on UAV and GNSS Surveys (Požega-Slavonia County, Croatia)

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Abstract: This study investigates morphological changes of distinct meander locations along the Orljava River, using multi-temporal imagery acquired by an unmanned aerial vehicle (UAV) and GNSS surveys since March 2022. The selected sites in the river's middle and lower course without bank protections show high channel dynamics. High-resolution digital surface models (DSMs) with a pixel size of 5 cm and orthomosaics with a pixel size of 1 cm were generated using Agisoft Metashape software. Ground control points and channel cross-section measurements were obtained using real-time kinematic (RTK)-GNSS. Various morphological features were analysed, including bank retreat, channel migration, fluvial sediment bars, and changes in bed level. Automated extraction of riverbank lines covered by low, sparse vegetation was performed using DSMs and convolution functions in ArcGIS Pro, while riverbanks covered by trees were assessed based on orthomosaics and digitised manually. The results showed that the most significant channel changes occurred following a flood event in December 2022. On certain meanders with riverbanks covered by sparse vegetation, the annual bank retreat rate amounted to 10–20 m. In addition, cross-sectional comparisons with data from 2012 revealed an increase in depth of approximately 1 m in the location upstream of the breached mill weir, indicating local bed incision. Although lateral channel migration presents a natural behaviour of actively meandering rivers, recently increased bank erosion is a pressing issue for local farmers due to the proximity of agricultural lands to the riverbanks.

Keywords: channel changes; river meandering; riverbank retreat; remote sensing.

1 Introduction

Rivers are dynamic natural systems that continuously shape the landscape through processes of erosion, sediment transport, and deposition. Actively meandering rivers are particularly dynamic, marked by lateral erosion and migration of meanders across the floodplain. Frequent changes in fluvial landforms contribute to the development of diverse riparian and aquatic habitats (Garófano-Gómez et al. 2017). However, bank erosion and channel migration can present challenges to human settlements and activities, especially in areas where they are closely situated to riverbanks (Bertalan et al. 2018).

Understanding the morphological changes of meandering rivers is essential for effective river management and mitigation of bank erosion and flood risks. Recent developments in remote sensing technologies have facilitated comprehensive and frequent monitoring of river channels and floodplains. Unmanned Aerial Vehicles (UAVs) equipped with high-resolution sensors are especially important for analysing geomorphic units and processes at smaller scales (Hemmelder et al. 2018, Rusnák et al. 2019).

This study investigates distinct meander bend sites on the Orljava River, which is characterised by significant channel dynamics in parts of its middle and lower course where bank protections are absent. By analysing multi-temporal UAV imagery and GNSS-derived topographic data, this research aims to quantify various morphological features and processes, including bank retreat, channel migration, fluvial sediment bars, and changes in bed level. Measured channel changes are compared with available hydrological records and hydromorphological characteristics of the river corridor, including riverbank vegetation, to examine potential controls on river processes. The results of this study are expected to offer valuable insights into the dynamic behaviour of the Orljava River, providing information for nature-based river management.

2 Materials and methods

2.1 Study area

The Orljava River, situated in Croatia's Požega-Slavonia County (Figure 1), is a 93.4 km long tributary of the Sava River (Čanjevac et al. 2022). Due to the round shape of its basin (1600 km^2), the river's hydrology is marked by frequent flash floods, threatening local communities and

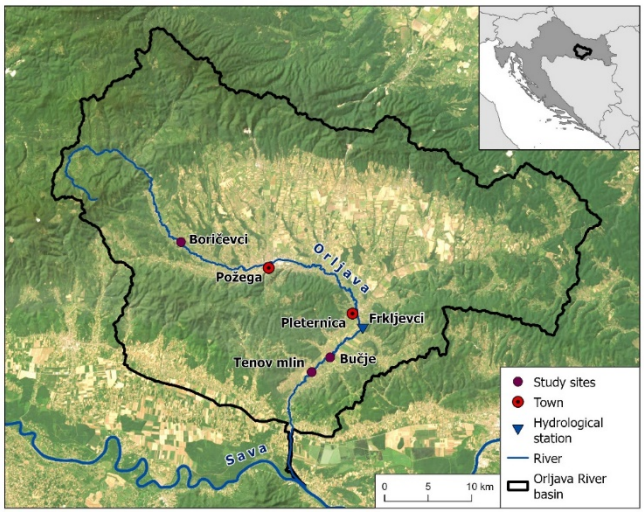

Figure 1. Location of the studied sites in the Orljava River basin.

agriculture in the river valley. The mean flows at the Frkljevci hydrological station are around 7 m^3/s, but peak flows can reach more than 200 m^3/s (DHMZ n.d.). In its middle and lower course, the Orljava is typified by gravel-bed conditions and active meandering. While the river is not extensively channelized (except in urban areas), various engineering works have been implemented to ensure river stabilization, including bank protections, weirs, artificial levees, and meander cut-offs. Additionally, riparian vegetation is occasionally removed to increase channel capacity.

The most upstream studied site is located near the settlement of Boričevci. Two consecutive meander bends were examined: the first with eroding bank adjacent to grasslands and the other with banks covered by woody vegetation. Channel morphology is characterized by large coarse gravel bars. Under mean flow conditions, the width of the wetted channel is around 10 m. At the downstream studied sites, Bučje and Tenov mlin, the channel bed predominantly consists of fine gravel. The width of the wetted channel during mean flows is approximately 15 m, with the active channel width (including sediment bars) amounting to 40 m. At the site Bučje, two meanders with grassland-covered banks were studied, both upstream and downstream the breached mill weir. At the Tenov mlin site, two consecutive meander bends with and without woody riverbanks were examined. All studied eroding banks are relatively equal in length (100 ± 10 m).

2.2 Field surveys and data processing

Aerial imagery was collected during four fieldwork campaigns conducted in March 2022, March 2023, October 2023, and May 2024. In the first campaign, imagery was captured using a DJI Phantom 4 Pro, while in subsequent campaigns, a DJI Phantom RTK was used. Ground control points and channel cross-section measurements were obtained using RTK-GNSS (Trimble Catalyst DA2). Cross-section measurements were specifically conducted during two campaigns, in October 2022 and October 2023. The surveys were carried out during periods of low-flow conditions to capture the morphological characteristics of the river channel, primarily occurring in early spring or autumn, both preceding and following the peak vegetation period. The UAV imagery was captured from an altitude of 50 m, with the collection of 10 control and 10 check points at each site. Cross-section measurements were conducted at the locations recorded in the 2012 topographic survey by the water management authority.

The UAV imagery was processed in Agisoft Metashape software to generate DSMs (digital surface models) with a pixel size of 5 cm and orthomosaics with a pixel size of 1 cm. Ground control points were used to refine the alignment and scale of the point cloud, enhancing the georeferencing accuracy of the final products.

2.3 Changes in river morphology

Changes in river morphology were analysed using ArcGIS Pro. Lines of eroding riverbanks, covered by sparse, low vegetation, were automatically extracted using an edge detection Laplacian filter applied to DSMs. The Laplacian filter calculates brightness changes to identify edges, enhancing their visibility and setting a threshold to finalize edge detection. A workflow, involving raster reclassification and thinning, was then established to automate the further process. However, analysing riverbanks covered by woody vegetation proved more challenging. The lines of these riverbanks were assessed using both orthomosaics and DSMs, and digitised manually.

The eroded floodplain area between two fieldwork campaigns was measured as the polygon area between two consecutive riverbank lines, while the maximum bank retreat distance was calculated using orthogonal transects from the starting riverbank line. Additional digitised morphological features include the wetted channel and unvegetated bars.

3 Results

According to ground check points, the horizontal error of produced models was estimated to 5 cm and vertical error to 10 cm. The most significant bank retreat, and consequently the largest area of erosion, occurred between the first two surveys (March 2022 – March 2023). Particularly considerable values were observed at the Boričevci left bank (LB), where the river eroded a total of 682 m^2 of adjacent grassland (Figure 2). The riverbank retreated by an average of 7.3 meters, with a maximum of 20.3 meters. The notable changes in channel morphology include meander rotation towards the east, channel widening and subsequent shifts in the distribution of fluvial bars. At the upstream part of the bend, a mid-

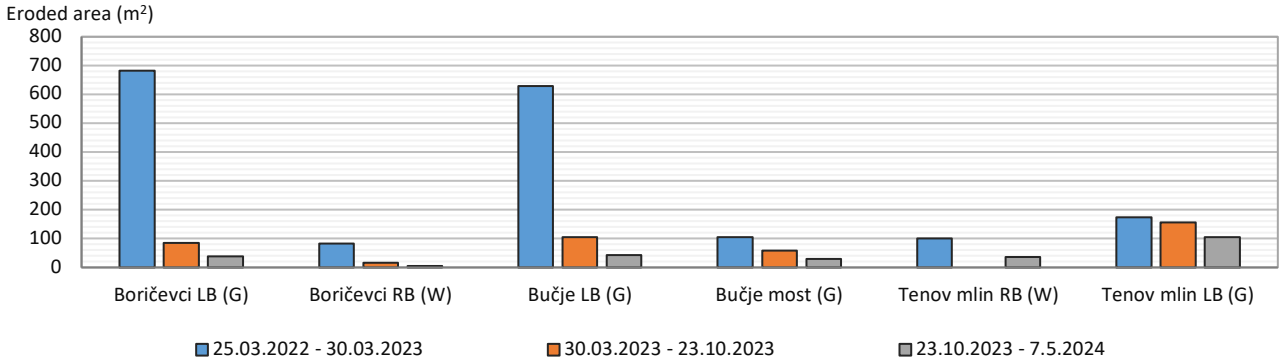

Figure 2. Total eroded floodplain area (m^2) between field surveys at the studied meander sites (G - grassland riverbanks, W - woody riverbanks).

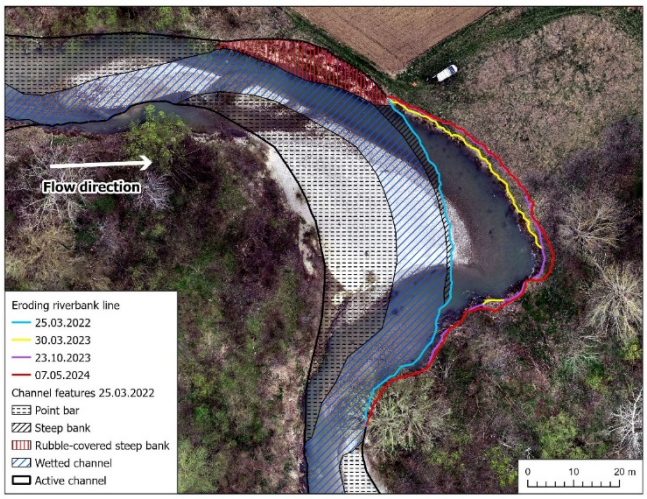

Figure 3. Study site Boričevci left bank, UAV imagery from 30 March 2023.

channel bar was formed in 2023 in the location of a previous side bar (Figure 3).

At the Bučje left bank (LB) site, located upstream of the breached weir, the total eroded area during the first period amounted to 630 m^2 of agricultural land, with the maximum bank retreat of 10.2 m. In the following two periods, the erosion rates at these two sites were significantly lower. At the site Bučje most (downstream of the breached weir) erosion affected the floodplain to a lesser extent, with erosion rates remaining relatively consistent between the first (8.7 m^2 per month) and second periods (8.4 m^2 per month), considering the duration of each period. Similarly, at the site Tenov mlin left bank (LB), total eroded floodplain areas varied less (ranging from 106 to 176 m^2) throughout the studied periods.

Generally, the lowest rates of floodplain erosion were measured at meander bends with riverbanks covered by woody vegetation. At the Boričevci site, over the entire study period (March 2022 – May 2024) the meander with woody banks eroded a total of 105.5 m^2, notably less than the upstream meander with grassland banks, which eroded 803.7 m^2. Similarly, at the Tenov mlin site, the eroding right bank, covered by woody vegetation, experienced less erosion (138 m^2) compared to the downstream meander adjacent to agricultural land, which eroded 435.1 m^2.

Cross-sectional measurements revealed a dynamic pattern in the changing riverbed level, closely linked to meander migration. However, in the laterally stable part of the channel at the Bučje site, located just upstream of the weir breached in 2016, an increase in depth of approximately 1 m was recorded compared to the 2012 survey data.

4 Discussion

The magnitude, duration, and frequency of high flows play crucial roles in shaping river channel morphology: during floods riverbanks erode widening the channel and fluvial bars are formed (Schumm 1977). In the studied meanders, the highest rates of floodplain erosion and bank retreat were recorded from March 2022 to March 2023, which includes the flood from December 2022, when the peak flow at the Frkljevci station reached 158 m^3/s (DHMZ n.d.). During 2023, no such flood was recorded, which is probably why bank retreat declined.

However, significant differences in eroded area and bank retreat were recorded in studied meanders during the same periods. Local differences in bank erosion rates can be influenced by the type of bank material, variations in channel morphology which affect flow velocity and turbulence, riverbank vegetation cover, and human activities like bank protection measures (Kiss et al. 2019). For the studied sites, precise data on bank material is not available, but it can be considered negligible since the meanders are consecutive and all riverbanks are mainly sandy.

On the other hand, the clear role of vegetation cover has been noted, since meanders with woody riverbanks experienced less erosion. Many studies have shown that vegetation, especially woody vegetation, increases bank strength through deep and strong root systems, reducing erosion (Gurnell 2014, Krzeminska et al. 2019).

At the Boričevci site, effects of channel morphology and human activities are notable. The site is downstream from a straight, narrow section, increasing flow velocity and stream power. The rubble placed by locals under the riverbank to protect adjacent agricultural land, combined with woody vegetation downstream, likely confined erosion to the grassland floodplain toward the east (Figure 3). On the other hand, at the Bučje site, a considerable bank retreat might be related to the breached weir downstream, which increased the local channel slope, therefore enhancing stream power and bank erosion.

5 Conclusions

This study examined morphological changes in three meander bend locations along the Orljava River, Croatia, using UAV imagery and RTK-GNSS channel bed-level measurements. The most significant rates of floodplain erosion occurred between March 2022 and March 2023, coinciding with a significant flood in December 2022. Vegetation cover showed to be an important factor of bank retreat, with meanders covered by woody vegetation experiencing less erosion compared to those adjacent to grasslands. Morphological variations among meanders, such as sinuosity and width, also apparently influenced local hydraulic conditions and bank retreat rates. Human impacts, particularly regarding bank protections and weirs, were also observed.

The removal of riparian vegetation by water managers as part of flood protection measures most certainly increases riverbank erosion, posing challenges for local farmers since agricultural areas are often adjacent to riverbanks. Future strategies should prioritize widening the riparian zone to allow more space for natural river processes in line with nature-based river management principles.

6 References

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