Effects of anthropogenic vegetation removal on channel dynamics: Insights from a meandering river in Croatia

Effets de l'élimination anthropique de la végétation sur la dynamique fluviale : analyse d'une rivière à méandres en Croatie

Katarina Pavlek[1], Ronald E. Poeppl[2], Mateo Gašparović[3]

[1]Department of Geography, University of Zagreb Faculty of Science, Zagreb, Croatia, katarina.pavlek95@gmail.com
[2]Department of Geography and Regional Research, University of Vienna, Vienna, Austria, ronald.poeppl@univie.ac.at
[3]Chair of Photogrammetry and Remote Sensing, University of Zagreb Faculty of Geodesy, Zagreb, Croatia, mgasparovic@geof.hr

RÉSUMÉ

Cette étude analyse les changements du lit à méandres de la rivière Orljava en Croatie au cours des 50 dernières années, en se concentrant sur la réponse de la rivière aux inondations avant et après l'élimination anthropique de la végétation riveraine en 2011. Les images aériennes, les orthophotos et les cartes topographiques ont été utilisées pour analyser les changements morphologiques du lit. Pour la période 2011-2021, une classification orientée-objet de l'occupation du sol a été appliquée aux images afin d'automatiser la vectorisation des formes fluviales. Pour déterminer les facteurs influençant les taux de migration latérale (le principal indicateur lié à la morphologie méandriforme), des données sur la taille et la durée des inondations, la végétation ligneuse riveraine et la géométrie du lit (largeur, sinuosité et pente) ont été analysées statistiquement. Les résultats indiquent que le taux de migration latérale a quadruplé, tandis que l'élargissement du chenal a atteint 40 % après l'élimination de la végétation en 2011. L'analyse statistique a révélé que les taux de migration latérale étaient négativement liés à la présence de végétation riveraine et positivement liés à la durée et à la magnitude des inondations ainsi qu'à la pente du lit. Ces résultats soulignent le rôle de la végétation dans la stabilisation des rives et la réduction de l'érosion, suggérant que sa restauration est essentielle pour réduire les risques d'inondation et améliorer la stabilité du lit. En outre, la préservation de la sinuosité naturelle favorise la diversité géomorphologique et renforce la stabilité du lit en réduisant la pente et la puissance du courant.

ABSTRACT

This study investigates channel changes in the meandering Orljava River in Croatia over the past 50 years, focusing on the river's response to flood events before and after the anthropogenic removal of riparian vegetation in 2011. Channel features were measured using aerial images, orthophoto and topographic maps. For the 2011–2021 period, object-based land cover classification was applied to the images to automate the vectorization of channel morphology. To determine the factors affecting lateral migration rates (as the primary metric chosen due to the meandering channel pattern), data on flood size and duration, riparian woody vegetation, and channel geometry (width, sinuosity, and slope) were statistically analysed. The results indicate that lateral migration rates increased fourfold while channel widening amounted to 40% following vegetation removal in 2011. Statistical analyses revealed that lateral migration rates were negatively related to the presence of riparian vegetation and positively related to flood duration, magnitude and channel slope. These findings highlight the role of vegetation in stabilizing riverbanks and mitigating lateral erosion, suggesting that its restoration is crucial for reducing flood risks and enhancing channel stability. Additionally, preserving natural sinuosity promotes geomorphological diversity and increases channel stability by reducing slope and stream power.

KEYWORDS

channel morphology, flood, human impacts, lateral migration, riparian vegetation

morphologie du lit, inondation, impacts humains, migration latérale, végétation riveraine

1 INTRODUCTION

Lateral channel migration is a defining characteristic of meandering rivers, but it is often disrupted by human interventions aimed at controlling flooding and riverbank erosion. Engineering works such as channelization, meander cutoffs, and the construction of weirs frequently involve the removal of riparian vegetation which is a crucial element for the stabilization of riverbanks (Gregory, 2006; Hohensinner et al., 2018). While designed to control river processes, these modifications degrade river habitats and can even increase flood risks or accelerate bank erosion, since the loss of riparian vegetation is linked to increased bank instability, channel migration, and channel widening (Gurnell, 2014; Micheli et al., 2004; Pollen-Bankhead et al., 2009). In this study, we investigated changes in channel morphology of the Orljava River in the Pannonian Basin, Croatia. The Orljava is one of the few remaining meandering lowland rivers in Croatia that has not been fully laterally confined by engineering works. However, significant human-induced changes have occurred over the past decade, including the deliberate removal of riparian vegetation in 2011. The objectives of this study were to investigate changes in river channel morphology from 1966 to 2021, with a particular focus on the last two decades (2001–2021), considering two flood events, i.e. one that occurred before the vegetation removal (2010) and one thereafter (2014). We hypothesized that the anthropogenic removal of vegetation along the Orljava River led to increased channel dynamics, particularly in terms of channel migration and widening. Additionally, we propose that higher channel gradient and sinuosity further contribute to increased lateral migration rates.

2 STUDY AREA

The Orljava River is a 93.4 km long tributary of the Sava River, located in the southwestern part of the Pannonian basin in eastern Croatia. Due to the round shape of its basin (1,600 km^2), the river's hydrology is marked by frequent flash floods, threatening local communities and 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.). This study examined channel changes in a 14 km segment in the Orljava's lower course, typified by gravel-bed conditions and active meandering. In two decades (2001-2021), two major floods occurred: one in June 2010 (Q_{max} = 203 m^3/s) and another in May 2014 (Q_{max} = 209.3 m^3/s), both close to the 20-year return period flood (213.8 m^3/s). During the 2010 flood, dense riparian vegetation slowed the high discharge, creating backwaters that threatened the upstream settlements. Due to the lack of natural flood retention upstream, water managers removed riparian vegetation in 2011 to increase channel capacity, accommodate higher discharges and mitigate flood risks. Some meanders were also cut off to prevent erosion of nearby levees. The studied segment was divided into two reaches based on the location of a mill weir, which affects flow and sediment connectivity and related water and sediment dynamics. The weir existed in the late 18th century (Arcanum, n.d.) but it was breached in 2016 due to lack of maintenance. The upstream reach 1, which is 7.3 km long with an average channel gradient of 0.83 m/km (0.083%, based on pre-breach data), was partially impounded until 2016. In contrast, the downstream reach 2 is 6.3 km long and has a steeper average gradient of 1.09 m/km (0.109%).

3 DATA AND METHODS

Channel changes on the Orljava River were analysed using aerial images, topographic, and orthophoto maps from the period 1966–2021 provided by the State Geodetic Administration of Croatia. Channel features from the earlier images and maps (1966, 1980, 2001, 2009) were vectorised manually in GIS. On RGB (Red, Green, Blue) and near-infrared aerial images from the period 2011–2021 the object-based classification of floodplain land cover was conducted (Pavlek et al., 2024). Five land cover classes within the river corridor were mapped: water, bare soil, sparse vegetation, dense vegetation, and shadows. A digital surface model, generated from the images, was used to differentiate between bare river channel units ("river sediments") and bare soil in the floodplain, as well as to identify high vegetation, while agricultural land was classified manually. Land cover classification automated the vectorization process of channel features and allowed for further investigation of the vegetation dynamics. The following morphometric parameters were analysed: Sinuosity (index), channel length, width, lateral migration rate, floodplain erosion and deposition areas, and the percentage of riparian woody vegetation. To determine the factors affecting lateral migration rates (chosen as the most representative metric due to the meandering channel pattern), data on flood size and frequency, riparian woody vegetation, and channel geometry (width, sinuosity, slope) were statistically analysed for the period 2001–2021. To enable a more detailed investigation of data variability, the river reaches were divided into six 1-km subreaches. Relationships between variables were tested using Spearman's rank correlation analysis and linear mixed models to account for potential pseudoreplication in the data.

4 RESULTS

Woody vegetation initially covered approximately 65% of the riverbanks in both reaches in 1966, increasing up to 75% in 2009. However, anthropogenic vegetation removal in 2011 caused a drastic decline, leaving only 5% of riparian woody vegetation in both reaches. In the following years, vegetation gradually recovered, reaching the initial value from 1966 (65-70%). Human interventions also altered the river's sinuosity. In 1966 and 1980, the sinuosity index in reach 2 was 1.68, indicative of a meandering channel pattern. After 1980, engineering works (meander cutoffs) reduced sinuosity by nearly 25%, reaching 1.28 in 2021. The sinuosity of reach 1 remained more stable (1.52–1.62) due to fewer meander cutoffs. Analyses of lateral migration and channel width showed distinct differences between the period before and after 2011. From 1966 to 2011, lateral migration rates were generally low, mostly under 1 m per year in both reaches. However, in 2011–2014, lateral migration rates in reach 2 (downstream the weir) increased to over 4 m per year (Figure 1), and the channel widened by more than 40%. This period also saw a substantial rise in floodplain erosion area, amounting to over 27,000 m² per year. In subsequent periods (2019–2021), lateral migration rates declined to less than 0,5 per year. In contrast, the upstream reach, regulated by a weir, showed less dynamic channel changes after 2011. The highest lateral migration rates (1.28 m per year) occurred during 2014–2017, following the breach of the mill weir in 2016. The weir breach also led to a 17.5% reduction in channel width due to removal of the impoundment. Statistical analyses revealed a significant negative relationship between the proportion of riparian woody vegetation and lateral migration rates. In contrast, a positive relationship was found between lateral migration rates and hydrological parameters (the duration of flows higher than 1.1-return period and maximum flows), as well as channel slope. However, no statistically significant relationship was observed between lateral migration rates and sinuosity, neither in correlation analyses nor in linear mixed models.

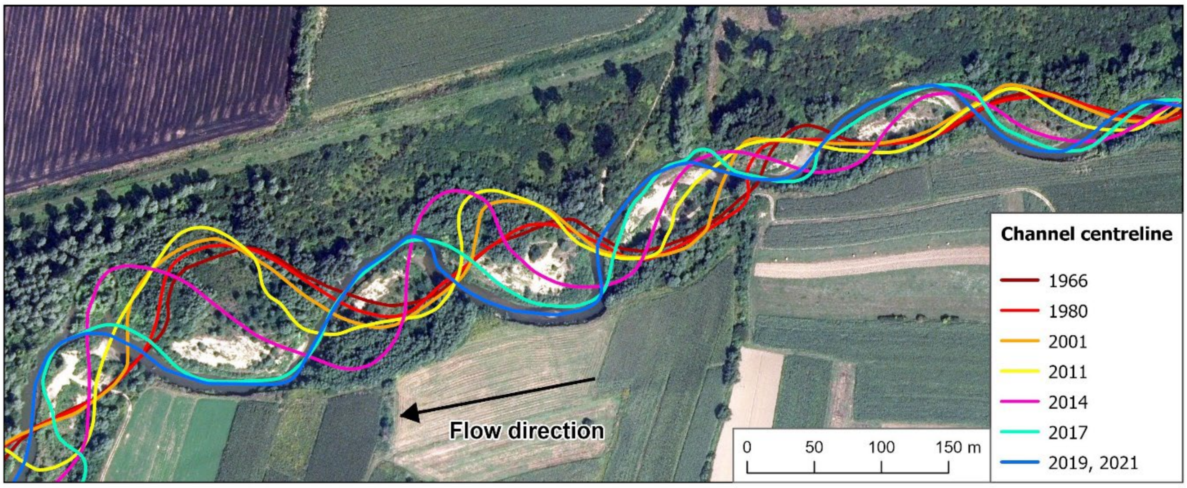

Figure 1. Downstream migration of the Orljava River channel centreline in reach 2 (1966–2021)

5 DICUSSION

Flood size and frequency are generally key drivers of natural channel morphodynamics (Bertoldi et al., 2009; Schumm, 1977). However, on the Orljava River, the flood of 2010 did not cause as intense morphological changes as the 2014 flood, despite being similar in magnitude (around 200 m³/s). The key difference in river conditions between the two events was the extent of riparian woody vegetation. In 2010, the riverbanks were largely vegetated, while by May 2014, the vegetation had not yet regenerated after its near-complete anthropogenic removal in 2011. Correlation analysis and linear mixed models confirmed negative relationships between lateral migration rates and woody vegetation cover. Generally, many studies have highlighted the importance of plants, particularly woody species, in strengthening and stabilizing riverbanks through root development, thus reducing erosion (Gurnell, 2014; Pollen-Bankhead et al., 2009). However, when woody vegetation is sparse, the primary factor influencing lateral migration rates becomes the magnitude and duration of high flows. This was also observed on the Orljava River, as evidenced by the increased correlation coefficient between these variables after vegetation removal. Flow magnitude also plays a crucial role in vegetation recovery: Reduced flows lower erosion rates and promote vegetation growth, which further stabilizes the banks and mitigates lateral erosion (Kiss and Blanka, 2012). Since vegetation removal and flooding occurred along the entire length of both reaches, the observed differences in morphological changes are primarily due to their varying hydromorphological characteristics and local human impacts. The downstream reach has not been impounded and has experienced more meander cutoffs, resulting in a steeper channel gradient and greater instability. The linear mixed model identified positive relationships between channel slope and lateral migration. A steeper channel generally increases stream power, leading to higher rates of lateral erosion (Alber and Piégay, 2017; Ondruch and Mačka, 2015). In contrast, a weir dam locally reduces channel slope, which lowers stream power and erosion rates (Poeppl et al., 2015).

6 CONCLUSION

Quantifying past and current channel changes and identifying cause-and-effect relationships provides valuable insights into the Orljava River's evolution and its response to vegetation removal, informing future river management strategies. To reduce further bank erosion in areas where vegetation has been removed, the key measure is to protect and restore riparian vegetation, which helps to stabilize the channel and to reduce lateral erosion. While hydrological factors like flood duration and magnitude dominantly drive morphological changes in rivers, this study demonstrates that riparian woody vegetation is an important controlling factor for reducing erosion during high flows. On the other hand, the absence of artificial bank stabilization and natural sinuosity allows for the development of diverse geomorphological forms and habitats, increasing the channel's capacity to absorb and store high flows, thus reducing flood risk. Additionally, increased sinuosity lowers channel slope and stream power, contributing to channel stability. To improve the hydromorphological condition of the Orljava River (as well as other rivers in similar environments), a holistic approach to river management is needed, which focuses on managing the river at the catchment level and prioritizes nature-based solutions over traditional “hard” engineering measures.

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