Historical changes in the extent of the flooded area of a mountain river induced by human impacts

Évolutions historiques de l'étendue des zones inondées des rivières de montagne induites par l'impact humain

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RÉSUMÉ

Au 20e siècle, de nombreuses rivières de montagne en Europe ont subi des impacts humains importants, modifiant significativement leur morphologie. Cependant, l'influence de ces changements sur les réponses des rivières aux inondations et sur l'hydrodynamique des chenaux reste incertaine. Cette étude utilise des données de photographies aériennes d'archives pour évaluer comment les changements induits par l'homme dans les paramètres hydrauliques des inondations et l'incision du chenal entre 1964 et 2012 ont influencé l'étendue des zones inondées de la rivière Czarny Dunajec (Carpates polonaises). Les données sur la position verticale du chenal ont été extraites (sous forme de Modèles Numériques d'Élévation) à partir de photos aériennes d'archives de 1964 et 1983, ainsi que d'un MNE dérivé du balayage laser aéroporté de 2012. Les valeurs de profondeur de l'eau, de vitesse d'écoulement et de contrainte de cisaillement du fond, ainsi que le diamètre critique des sédiments du chenal, ont augmenté entre 1964 et 1983. Toutefois, la vitesse d'écoulement dans la plaine inondable n'a pas augmenté pour les deux plus grands scénarios d'inondation en raison de l'expansion des forêts riveraines. L'augmentation du débit a été accompagnée d'une réduction de l'étendue des zones inondées, particulièrement entre 1964 et 1983 (de 44% pour 34 m^3/s). Entre 1983 et 2012, les changements dans les paramètres hydrauliques ont été moins marqués et la réduction de l'étendue inondée moins significative.

ABSTRACT

During the 20th century, many mountain rivers in Europe were subjected to intensive human impacts, which significantly altered their channel morphology. However, the influence of these changes on past river responses to floods and channel hydrodynamics remains unclear. In this study, we performed hydraulic modeling using data from archival aerial photographs to assess how human-induced changes affected hydraulic parameters of floods and channel incision between 1964 and 2012, influencing the extent of the flooded area of the Czarny Dunajec River (Polish Carpathians). Data on the vertical position of the channel were extracted (as Digital Elevation Models) from archival aerial photos from 1964 and 1983 and Airborne Laser Scanning-derived DEM from 2012. The values for water depth, flow velocity, and bed shear stress for four flood scenarios of different magnitudes, along with the critical diameter of channel sediment, increased significantly between 1964 and 1983. The flow velocity within the floodplain zone did not increase for the two largest flood scenarios, due to the expansion of riparian forests during the second half of the 20th century. The increase in flow rate was accompanied by a progressive reduction (by 44% for 34 m^3/s) in the extent of flooded areas, particularly between 1964 and 1983. Between 1983 and 2012, changes in hydraulic parameters were less pronounced and the reduction in the extent of the flooded area was less significant.

KEYWORDS

extent of flooded area, flood risk, historical DEM, human impact, hydraulic modelling

étendue de la zone inondée, impact humain, MNT historique, modélisation hydraulique, risque d'inondation

1. INTRODUCTION

Human-induced modifications in river ecosystems, such as channel narrowing, dam construction, gravel extraction, and land use changes, have significantly disrupted river equilibrium leading to geomorphic and ecological degradation. These activities often result in channel incision, which reduces flood frequency while intensifying flood hazards downstream (Wyżga et al. 2016). Additionally, they impair water quality and degrade river habitats, negatively affecting the ecological status of rivers, as outlined in the European Water Framework Directive.

In Europe, extensive channel narrowing and straightening during the 20th century accelerated hydromorphological degradation, particularly in mountain rivers, where sediment mining further exacerbated these impacts. This study focuses on the Czarny Dunajec River in the Polish Carpathians, which has experienced substantial channel modifications, including channel narrowing and large-scale, illegal gravel extraction. This study aimed to: (i) explore how the hydrodynamics, in terms of the flow velocity and unit stream power for a given flood discharge changed with progressing channel incision along a 2.5 km river reach of the Czarny Dunajec, and (ii) verify how these changes were reflected in the modification of the extent of the flooded area during two study periods: 1964–1983 and 1983–2012. This study is key to assess how past human impacts have influenced the ecological conditions on floodplains, as well as the risk of flooding in the lower river sections.

2. PHOTOGRAMMETRIC PROCESSING AND HYDRAULIC MODELLING

This study utilizes archival aerial photos to reconstruct historical Digital Elevation Models (DEMs) to analyze changes in the Czarny Dunajec River channel. Panchromatic and RGB aerial images from 1964, 1977, 1983, and 1994 were processed using photogrammetric methods with ground control points (GCPs) for exterior orientation and DEM accuracy assessment. The accuracy of DEMs varied between 0.25 and 0.45 m, meeting national geodetic standards for flood hazard analyses. Modern orthophotos and DEMs from 2009 and 2012 served as references. The photogrammetric process ensured high-accuracy terrain models suitable for assessing the study area's hydrodynamic changes and flood risks. The DEMs generated from archival aerial photos were evaluated using control points, with mean errors ranging from 0.3 to 0.4 m, meeting accuracy standards for hydrodynamic modeling. Local errors exceeding 1 m were linked to photo quality and forested areas. Errors were corrected using radiometric and geometric adjustments, ensuring the 1964 and 1983 DEMs were most suitable for modeling river hydrodynamics.

Hydrodynamic changes and the flood extent in the Czarny Dunajec River were examined using the 2D Iber hydraulic model for three years (1964, 1983, and 2012) and various flood scenarios, ranging from frequent to extreme events. DEMs were used to generate a computational mesh of approximately 183,000 elements. Flood scenarios were developed using hydrological data from the Koniówka gauging station, and model calibration focused on Manning's n roughness coefficients, adjusted based on sediment grain sizes and field observations. The model effectively captured hydrodynamic behavior under steady-state conditions, providing insights into historical flood dynamics and roughness parameter evolution across different periods.

3. RESULTS

The results of this study showed that the changes of all hydraulic parameters in the Czarny Dunajec river reach were more significant between 1964-1983 than between 1983-2012 and more relevant for the extraordinary and extreme flood scenarios (20-year, and 50-year floods) than for more frequent flood magnitudes (2-year, 5-year floods). From 1964 to 1983, water depth, flow velocity, bed shear stress and critical diameter increased significantly both, in the channel and floodplain, with the largest changes occurring during extreme floods. However, the modelled flow velocity for extraordinary and extreme flood magnitudes did not change practically in both study periods, indicating the influence of vegetation development in parts of the floodplain on the increase in surface roughness. Less pronounced changes between 1983 and 2012 suggest a reduced rate of channel incision, which must have been generated by larger flood events that could mobilise coarser and well-packed channel sediment that began to dominate in the channel after the 1980s.

Changes in hydraulic parameters led to an increase in unit stream power, causing the flushing out of finer sediments and accelerating channel incision, which was documented before (Hajdukiewicz et al., 2019). It was reflected in a significant reduction in the extent of flooded areas for all flood scenarios between 1964 and 2012 (Fig. 1). The most substantial decrease occurred between 1964 and 1983, with reductions ranging from 35% to 44%, depending on flood magnitude. Between 1983 and 2012, the reduction slowed, with decreases of 12% to 19%. For frequent floods (34 m^3/s), the floodplain extent was largest in 1964 and reduced considerably in

subsequent years, while for extreme floods (173 m^3/s), overflow from the channel occurred only in 1964 and 1983, which indicates a progressive increase in the channel capacity in the second half of the 20t^h century. These changes reflect evolving hydrodynamic and geomorphological conditions of Czarny Dunajec river reach, more pronounced during the first study period. However, continuous changes in the hydrodynamics during the whole study period, reflected a further tendency toward substantial geomorphological and hydrodynamic river evolution, induced by channel narrowing and gravel extraction.

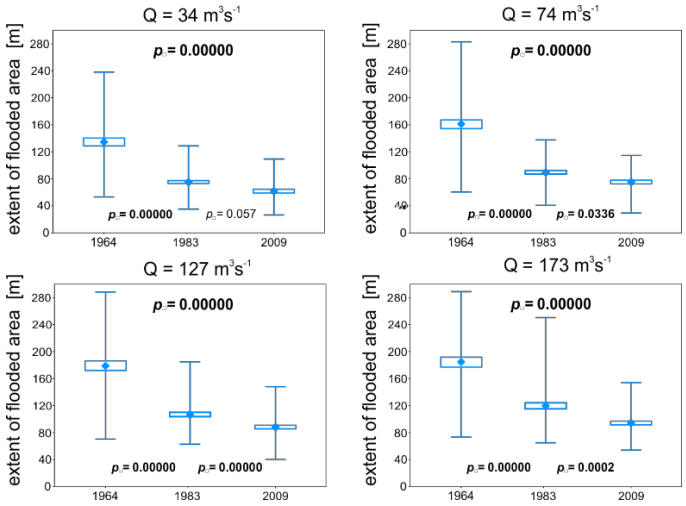

Figure 1. Changes in maximum, mean and minimum extent of the flooded area in the study reaches of the Czarny Dunajec between 1964, 1983 and 2012 modelled for frequent (Q = 34 $m^3 \cdot s^{-1}$), ordinary (Q = 74 $m^3 \cdot s^{-1}$), extraordinary (Q = 127 $m^3 \cdot s^{-1}$), and extreme (Q = 173 $m^3 \cdot s^{-1}$) flood scenario.

4. FINAL REMARKS

Our results demonstrate the effectiveness of combining photogrammetry with hydrodynamic modeling, a rare but powerful approach for studying long-term human impacts on rivers. This method provides high spatial and temporal resolution compared to traditional field data and water gauge stations, offering insights into past river conditions.

The study demonstrated that the incised study section of Czarny Dunajec acts as a sediment conveyor, transmitting disturbances downstream despite the presence of weirs located below the section, which cannot fully prevent sediment movement during high-flow events. The reduced flood extent and flooding frequency, as a result of the increase of channel capacity, has led to changes in floodplain vegetation, decreasing flood water retention potential. It is reflected in the currently existing area covered with mature forest and rare shrub vegetation. In turn, the increase in the channel capacity contributed to a systematic long-term increase in flood magnitudes and to the transfer of the flood water and channel sediment downstream. These findings highlight the need for river management to address channel deepening and restore sediment accumulation to mitigate flood risks and infrastructure threats in downstream river reaches. River restoration, such as using block ramps, can help restore sediment accumulation while mitigating the effects of ongoing channel incision. We propose that past hydrodynamic modeling is essential for assessing flood frequency and retention potential, particularly for restoring biodiversity and improving water management.

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