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Posted Date: 24 November 2025

doi: 10.20944/preprints202511.1708.v1

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Article

Prolonged Dry Periods Are Exacerbating Riparian Vegetation Growth and Channel Simplification

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Abstract

Climate change is impacting rivers worldwide, with a reduction in normal flow conditions in temperate regions like Poland. Such changes have an influence on riparian vegetation, as depicted by this study, which focuses on a 250km-long reach of the Polish Vistula River and investigates variations of monthly maximum discharges and vegetation conditions over the period 1984–2023 by means of Landsat satellite images. These satellite data were handled via Google Earth Engine, looking at a common index such as the Normalized Difference Vegetation Index, considered as a proxy of vegetation coverage variations. Results suggest that a process of riparian vegetation growth and consequent oversimplification is affecting this river reach, particularly over the last couple of decades, during which water availability has decreased significantly. Using the Vistula River as an exemplary case study, this research suggests that prolonged dry periods, more common in recent decades due to climate change, might impact large rivers located in temperate climates, favouring the development of vegetation on exposed sandbars, eventually resulting in a less dynamic active channel.

Keywords: Google Earth Engine; Landsat; remote sensing; Riparian vegetation; Vistula River

1. Introduction

Alluvial river channels are inherently dynamic systems, continuously adjusting their morphology in response to fluctuations in water discharge and sediment supply from upstream sources [1–3]. This self-regulating behaviour highlights the need to study rivers through a holistic lens, which can capture the intricate feedback mechanisms and mutual adjustments linking landforms with both physical and biological processes [4]. Vegetation plays a central role in these interactions, as its presence along river margins, floodplains, and in-channel bars contributes to the shaping of distinct fluvial forms by altering hydraulic conditions, redistributing flow velocities, and influencing sediment transport rates. Vegetation also modifies the trajectory of channel evolution by stabilizing certain areas while enhancing deposition in others. Conversely, the establishment, growth, and spatial distribution of riparian plants are themselves strongly controlled by local environmental factors that include the frequency and magnitude of floods, sediment dynamics, and the morphodynamic disturbances generated during extreme hydrological events [5,6].

Apart from the impact of humans, recognizable in many rivers worldwide [7,8], climate change is emerging as a major driver of fluvial and riparian transformations. In particular, it is altering the synchrony and asynchrony of flooding regimes and associated ecological processes across Europe. Recent studies suggest a shift toward more synchronous flood events, a trend that may have profound implications for the long-term functioning of rivers and their adjoining floodplains [9]. One of the most visible consequences of such altered hydrological patterns is the expansion of vegetation on riverbanks and in-channel bars. The establishment of riparian vegetation is highly sensitive to both the timing of seed release and germination, and to hydrological variability, particularly the occurrence and magnitude of annual peak discharges [10–12]. When peak flows are reduced in frequency or intensity, conditions become favourable for seedlings to survive the vulnerable early

stages of growth, leading to increased vegetation encroachment in previously active fluvial zones. Over time, this process not only modifies channel morphology but also affects habitat availability, sediment transport, and the resilience of riparian ecosystems.

In temperate regions such as Central Europe, recent decades have been marked by a noticeable decline in precipitation and the occurrence of increasingly prolonged dry periods [13]. This trend is not unique to Poland but reflects a broader global phenomenon, as extended droughts are becoming more frequent in many parts of the world, with far-reaching negative impacts on diverse environmental systems [14,15]. Focusing on Europe, historical records indicate that since the 1950s the frequency of drought events has risen across southern and much of Central Europe, while conversely declining in several northern regions [16–18]. Situated in Central Europe, Poland has not been exempt from these climatic shifts, and multiple studies have documented an increase in both the frequency and duration of dry periods within the country, relying on a combination of in situ measurements and remote sensing analyses [19–22]. As these investigations consistently demonstrate, shifts in climatic conditions are strongly reflected in fluvial systems, influencing key compartments such as water availability, sediment dynamics, and riparian vegetation. Reduced water availability not only constrains ecological functions and biodiversity within riparian zones but also affects the long-term resilience of river corridors, emphasizing the need for integrated water management and adaptation strategies under a changing climate.

Remote sensing, and satellite imagery in particular, has become an indispensable tool for monitoring fluvial dynamics across a range of spatial and temporal scales [23,24]. By conceptualizing the river corridor as an integrated unit comprising river channels, fluvial deposits, riparian zones and adjacent floodplains [25], remotely sensed data provide a powerful means of capturing the complex interactions that shape river systems. These datasets support a variety of bio-geomorphological applications, from tracking channel migration and sediment deposition to assessing riparian vegetation cover and dynamics [26].

Among the many Earth observation initiatives, the Landsat programme stands out as a cornerstone of global surface monitoring. As the longest-running satellite programme dedicated to terrestrial ecosystem observation, Landsat has been delivering moderate-resolution imagery since the launch of its first satellite in 1972 [27]. Over the decades, successive missions have carried advanced multispectral sensors, culminating in the current operation of Landsat 9, started in 2021. These sensors capture detailed surface reflectance data, which have been extensively used for scientific and management purposes, including the analysis of river morphology [28,29] and the monitoring of vegetation coverage [30–32].

The growing reliance on satellite-based information has driven the development of innovative data infrastructures and processing tools capable of handling vast volumes of Earth observation data. One of the most transformative platforms in this respect is Google Earth Engine (GEE), a cloud-based system that provides access to petabytes of geospatial datasets while offering advanced computational capacity for planetary-scale analyses [33]. By enabling large-scale, high-frequency, and long-term assessments, GEE has proven particularly valuable for bio-geomorphological research [34]. Since its introduction, it has become the most widely adopted cloud-processing tool for remote sensing applications, playing a pivotal role in advancing spatial analyses across diverse disciplines [35,36].

Previous studies on European alluvial rivers have shown that fluctuations in water levels and flood regimes strongly influence riparian plant communities, often facilitating the establishment of vegetation on floodplains, banks and in-channel bars [34,37]. Alterations to the natural flow regime, whether driven by human interventions or by climate change, have been demonstrated to exert a direct impact on riparian ecosystems, reshaping community structure and distribution patterns [38,39].

In light of these findings, the present study investigates how the recently observed decline in water availability in Poland has affected riparian vegetation along the Middle and Lower Vistula River. To this end, hydrological records were integrated with satellite imagery to assess vegetation

dynamics over a 250 km-long section of the river, spanning the period 1984–2023. The analysis specifically considers monthly maximum discharges as a proxy for flow variability, since such events are capable of mobilizing both sediments and seeds, thereby creating favourable conditions for vegetation establishment [40–42]. The study area covers an upstream part that is relatively natural but increasingly threatened by vegetation encroachment and morphological simplification [24,43], and a more anthropized part that traverses the anthropized urban landscape of Warsaw, where human pressures intersect with climatic stressors to shape vegetation patterns. Vegetation dynamics across this corridor were inferred using the Normalized Difference Vegetation Index (NDVI), one of the most widely adopted spectral indices for monitoring vegetation condition and coverage [44,45].

As demonstrated with this case study, the proposed methodology can provide insights into the medium- to long-term evolution of alluvial watercourses. In addition, thanks to its relative simplicity and low costs, this approach can be transferred to relatively ungauged basins and used to evaluate the long-term evolution of large rivers, covering temporal horizons of several decades.

2. Materials and Methods

2.1. Study Area

The research focus is a 250 km-long reach of the Polish Vistula River between Dęblin and Płock (Figure 1). The Vistula River basin has a total drainage basin area of around 194,000 km², of which 87% (169,000 km²) lies within Poland, while the remaining part of the basin is located in Belarus, Ukraine, and Slovakia [46]. The Vistula rises in the south of Poland at around 1,200 m a.s.l. in the Carpathian Mountains, and then flows north through metropolises such as Kraków and Warsaw, emptying into the Vistula Lagoon or directly into the Gdansk Bay of the Baltic Sea [24]. The regional climate of Poland is generally temperate, characterized by cold winters, warm summers, and the absence of a pronounced dry season. In the southern mountainous areas, similar conditions prevail, with higher altitudes exhibiting tundra-like climatic characteristics in the highest peaks [47].

The study reach (Figure 1b) crosses the middle and lower part of the river, where the land use structure is dominated by arable land (66%), with forests and semi-natural ecosystems covering around 29% of the territory, and only 3% classified as urban areas [46].

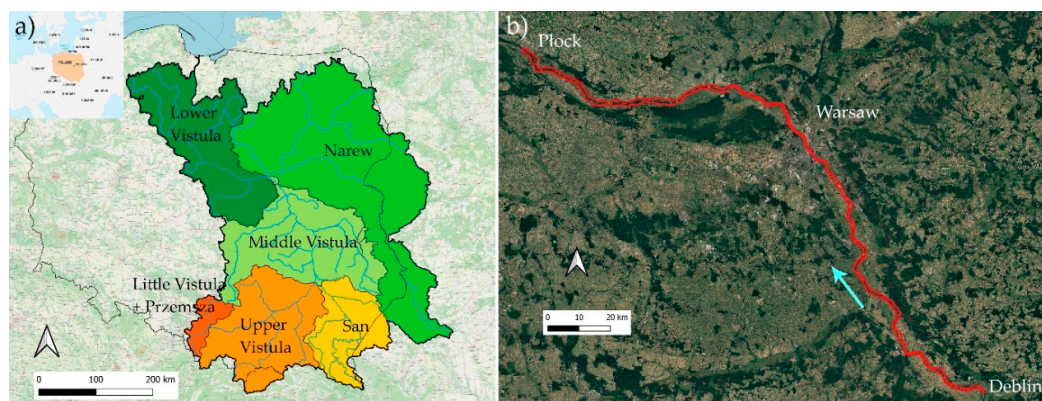


Figure 1. a) Vistula River basin and sub-basins. b) Study reach between Dęblin and Płock.

2.2. River Morphology

The Vistula River and its valley possess a geological history that spans more than two million years [48]. Although the current landscape has been predominantly shaped by processes active over the last 14,000 years, fluvial dynamics such as riverbank erosion and sediment deposition within the main channel continue to actively modify the system. Unlike many other European rivers, the Vistula exhibits a unique management history shaped by centuries of political fragmentation and varied human interventions [49]. In fact, from the late 18th century until 1918, the Vistula basin was divided

among Austria, Russia, and Prussia, with each authority implementing river management strategies tailored to its own administrative and economic priorities. In the lower course, Prussia initiated extensive river regulation projects during the nineteenth century, while repeated flooding in the Upper Vistula prompted Austrian authorities to undertake channelization works. Meanwhile, the central section of the river, the longest stretch under Russian administration, remained largely unmodified until Poland regained independence. Today, this middle reach still retains many natural characteristics, including braided channels, islands, and relatively unaltered floodplain features. Despite this persistence of natural elements, traces of past human interventions remain clearly visible, superimposed on the ongoing geomorphological and ecological processes that continue to shape the river corridor [50]. This interplay of historical management and active fluvial processes provides a distinctive context for understanding the Vistula's current morphology, hydrology, and riparian vegetation dynamics.

The study area (Figure 1b) encompasses a 250 km-long section of the Vistula River, extending from Dęblin to Płock, situated between the river's middle and lower courses. During the 18th and 19th centuries, this reach exhibited a predominantly braided channel pattern, characterized by numerous bars and islands, with only a few abandoned meanders appearing where the valley widened. This watercourse is rather natural with respect to other large rivers in Europe. In fact, even if the earliest flood protection and river regulation measures were introduced toward the end of the 19th century, downstream of Warsaw, significant channelization works were not implemented until the 1960s. As a result of these interventions, the average channel width has contracted substantially from its original 1,000–1,600 meters to approximately 300–500 meters. These changes have modified flow dynamics, increasing flow velocity and driving morphological adjustments, as evidenced by sandbar migration rates ranging from 0.4 to 2.4 m/day [51]. Further transformations followed the construction of the Włocławek Dam in 1968–1969, which fundamentally altered hydro-morpho-biodynamic processes [52]. The dam created a backwater zone that trapped incoming sediment and induced substantial downstream changes in sediment transport and channel morphology [53]. The combined effects of channelization and backwater influence have markedly reduced lateral erosion, while promoting rapid vertical aggradation and the formation of new terraces along the channel [50]. These modifications in river morphology have important ecological consequences: the contraction and stabilization of the channel, combined with altered sediment dynamics, have diminished the provision of ecosystem services and created potential challenges for protected and endangered species that depend on dynamic riverine habitats [54].

2.3. Hydrological Data

The study reach starts at the gauging station of Dęblin, and the minimum, mean, and maximum monthly discharges were retrieved from the Polish Institute of Meteorology and Water Management database, considering the period 1984–2023 (Figure 2).

The data acquired in this station were considered representative of the whole reach hydrology, on the basis of the observations reported in Nones (2021), who pointed out that the presence of a major tributary like the Narew does not significantly alter the trend of discharges [24]. It is worth reminding here that this research aims to evaluate how a different pattern in flood frequency impacted the riparian vegetation dynamics, rather than specifically analysing the quantitative variations.

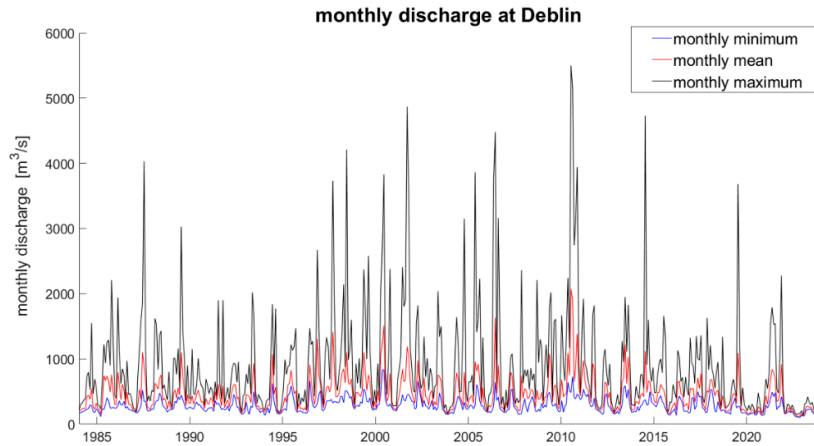


Figure 2. Monthly discharges measured at Deblin during the period 1984–2023.

2.4. Satellite Data

Google Earth Engine (GEE) was employed to extract information on vegetation dynamics from multi-temporal, multi-spectral satellite imagery. Specifically, Landsat surface reflectance products, including Landsat 5 TM, Landsat 7 ETM, Landsat 8 OLI, and Landsat 9 OLI/TIRS, covering the period 1984–2023 were selected as the primary data source. These products, available through the GEE data catalog (developers.google.com/earth-engine/datasets/catalog), have been atmospherically corrected, enabling more accurate and consistent comparisons of spectral reflectance measurements across different acquisition dates. The Landsat dataset is particularly well-suited for assessing long-term changes in riparian vegetation along large rivers such as the Vistula due to several factors: i) it offers near-continuous temporal coverage, with revisit intervals ranging between 9 and 17 days [55], ii) it provides a spatial resolution of 30 meters for most spectral bands. These characteristics allow for reliable detection of both gradual and abrupt changes in vegetation patterns, supporting the analysis of spatiotemporal dynamics across extensive river reaches over multiple decades.

The region of interest (ROI) was initially delineated using QGIS, by mapping the active river channels within the main levees with reference to Google Earth imagery. A temporal range corresponding to the study period, from 1 January 1984 to 31 December 2023, was established, and a time filter was applied to select all available Landsat surface reflectance imagery within this interval. To improve data quality, the CFMask algorithm was applied to each image in the collection to identify and mask cloud and cloud shadow pixels [56], ensuring that only cloud-free observations were retained for subsequent analysis. This approach is particularly advantageous because it provides a dynamic masking capability, which accounts for hydrodynamic variations in river stage between different acquisition dates, thereby capturing temporal changes in the extent of the active channel [57]. Using only the retained pixels, the Normalized Difference Vegetation Index - NDVI [44] was calculated as:

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

where NIR represents the near-infrared band and R is the red band. NDVI is a common index for vegetation monitoring [58], with higher values for more vegetated and healthier areas, and negative values indicating the absence of vegetation.

3. Results

3.1. Hydrological Variability

Vegetation dynamics is driven by high water levels [34,59], and therefore, in the current analysis, only maximum annual discharge were considered.

Looking at maximum monthly discharges measured at the gauging station of Dęblin (Figure 3, blue line), it is possible to observe an increase in discharge after around 1998, with relatively constant maximum values until 2015. After this, a general decrease in water levels, and consequently discharges, was recognizable, as also pointed out recent studies [43]. A 5-year moving average (Figure 3, black line) was utilized to highlight such a reduction in maximum monthly discharge, which is forecasted to continue due to climate change [60].

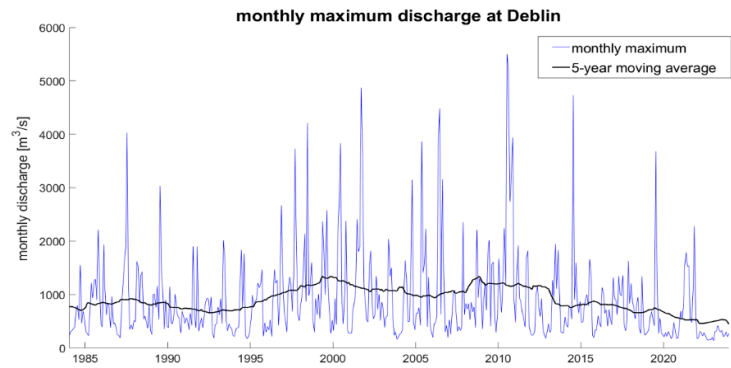


Figure 3. Monthly maximum discharges measured at Dęblin during the period 1984-2023, with 5-year moving average.

Vegetation needs time to develop, and therefore the monthly maximum discharges were clustered in 20-year periods, namely 1984-2003, 1994-2013, 2004-2023, to relate hydrological variability with vegetational dynamics. As visible in Figure 4, the period 1994-2013 was very humid, with high maximum discharges that flooding events [61], while the period 1984-2003 was characterized by lower maximum discharges. Looking at the cluster 2004-2023 a significant reduction of water flow is observable, which eventually implies variations for both river morphology and riparian vegetation, as already observed by other scholars [24,43].

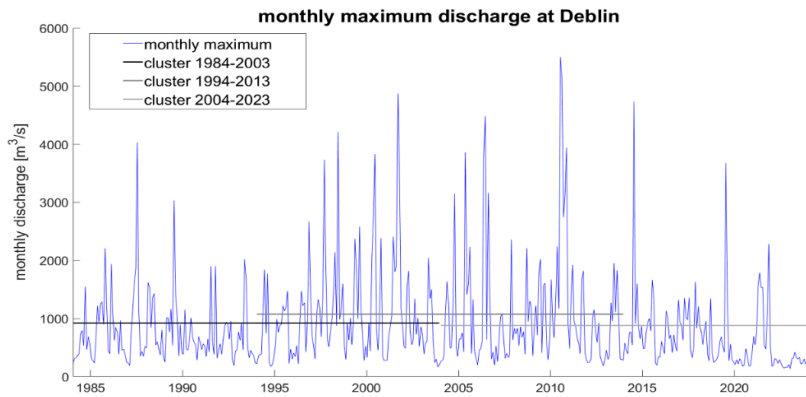


Figure 4. Monthly maximum discharges measured at Dęblin during the period 1984-2023, with 20-year average over the periods 1984-2003, 1994-2013, 2004-2023.

3.2. Vegetational Dynamics

NDVI values for each image were derived from GEE as a single value covering the whole study area. Mean NDVI values were computed using cloud-free, non-water acquisitions, along with the 25th and 75th percentiles that indicate the lower and upper quartiles of the NDVI response. A slightly increasing trend is observable (Figure 5), meaning that vegetation is nowadays more present and healthy in the area with respect to what it was at the beginning of the observational period. At the same time, it is worth noticing some outliers, which might be connected to the quality of the images.

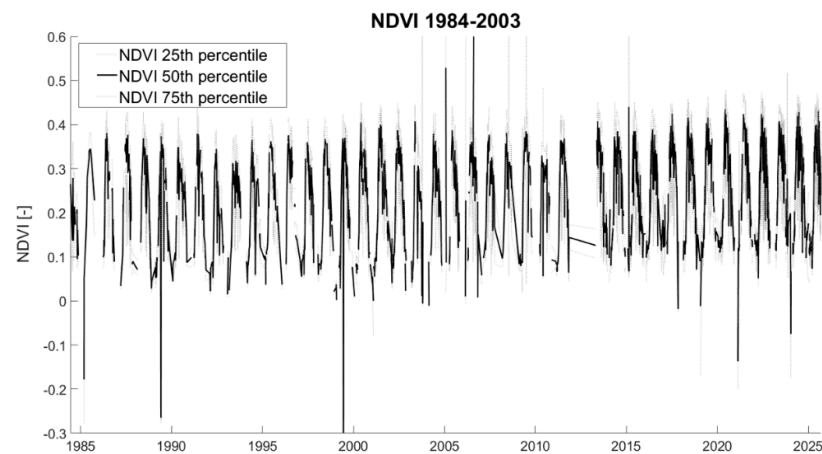


Figure 5. Variation of NDVI over the periods 1984-2003, considering median values and 25th and 75th percentiles.

As depicted by Figure 6, analysing long-term variations of NDVI, it is possible to observe an increase in both very negative (< -0.5) and very positive (> 0.8) values when comparing early acquisitions (period 1984-2003, blue bars) to the recent situation (period 2004-2023, orange bars). This trend confirms the results previously reported, and indicates an increase in vegetated areas over time, which consequently reduces the room for the river, given that the total area (i.e., the masked ROI) remains constant.

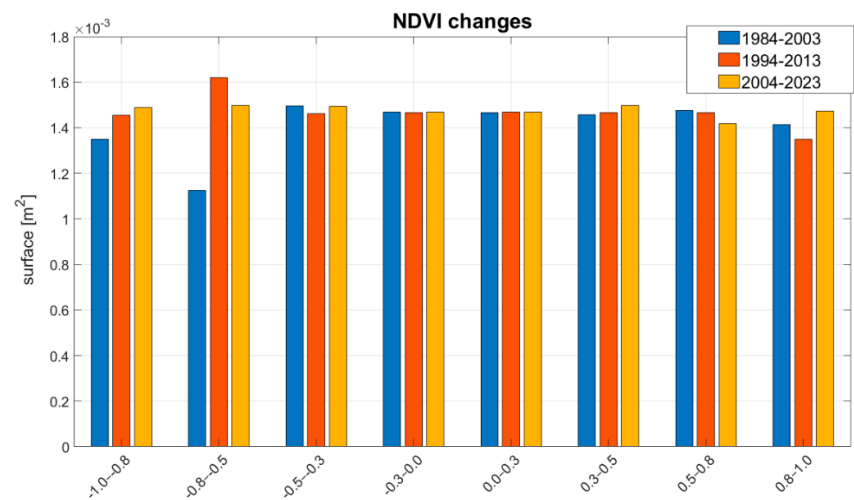


Figure 6. Changes in NDVI over the periods 1984-2003 (blue bars), 1994-2013 (red bars), 2004-2023 (orange bars).

Spatially, vegetation is changing dynamically, likely as a response of hydrological changes (Figure 7). During the 1994-2013 period, characterised by higher discharges, vegetation tend to distribute across the entire valley, with a reduction of in-channel vegetation in favour of its

establishment on bars and banks, eventually contributing in starting new islands (Figure 7b). Periods characterized by low monthly maximum, such as the recent years 2004-2023 (Figure 7c) helps vegetation in establishing along banks and on secondary channels, eventually causing their closure and redirecting the flow into the main channel, with consequent deepening.

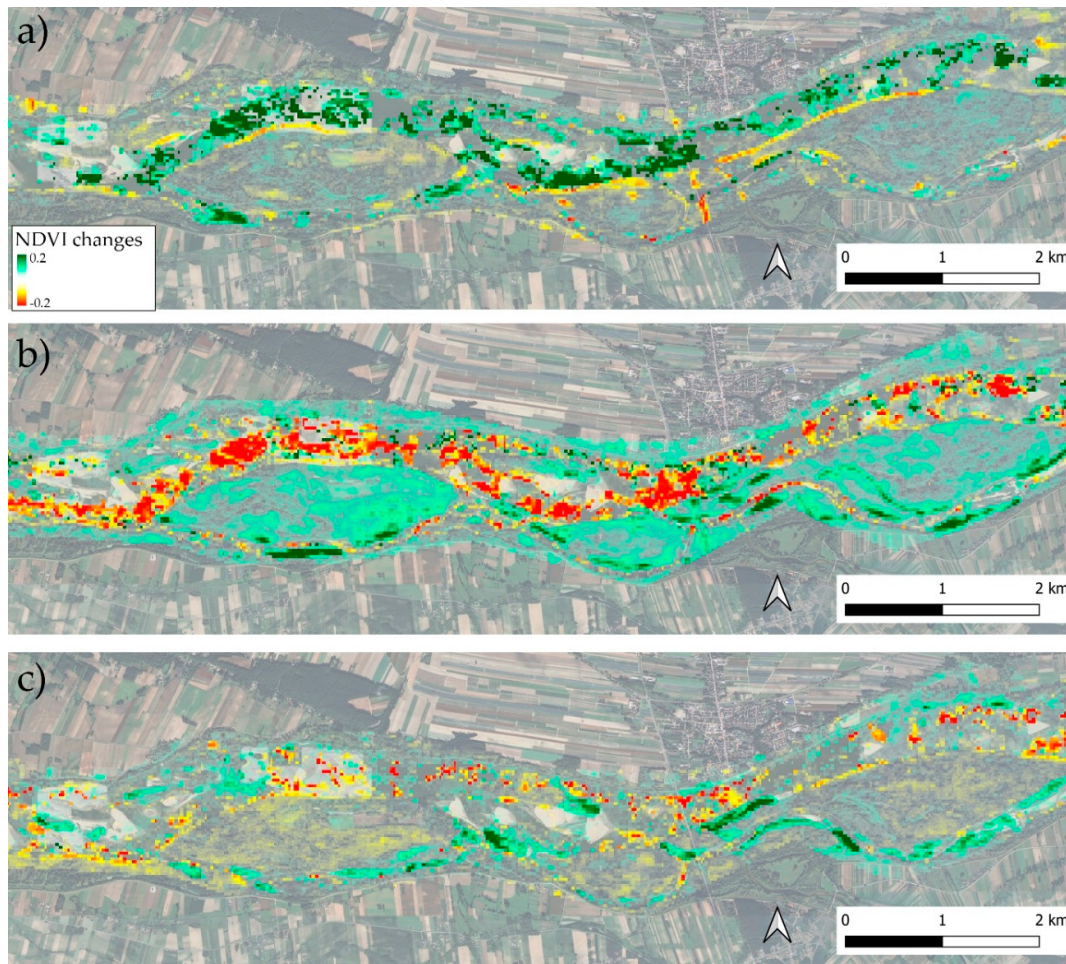


Figure 7. Changes in NDVI the periods a) 1984-2003, b) 1994-2013 and c) 2004-2023 in a selected reach close to Wyszogród, downstream of Warsaw. Red and yellow colours indicate a reduction in NDVI during the period, while cyan and green indicate an increase in NDVI values.

4. Discussion

Fluvial dynamics represent highly complex, multiscale processes that arise from the continuous interaction among water flow, sediment transport, and riparian vegetation [42,62]. Over the years, researchers have approached the study of these processes using a wide range of methodologies. Initial investigations were often conducted at the local scale with the aid of field instruments and in situ measurements [63]. More recently, advances in technology have made it possible to study riverine environments at broader spatial and temporal scales through the deployment of uncrewed aerial vehicles (UAVs) and Earth observation satellites [64].

In the present investigation, which focuses on the largest river in Poland and one of the major river systems in Europe, remote sensing techniques have proven particularly valuable for detecting the long-term development of riparian vegetation. Such an approach not only enables the identification of vegetation trends over extended time horizons, but also facilitates linking these patterns to possible driving factors, such as variability in river hydrology.

Despite past studies and also the current results demonstrated the advantages of using remote sensing approaches in riparian vegetation investigations, the application of satellite-derived vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), does not come without significant challenges. For example, NDVI values are known to be influenced by a variety of external factors, including atmospheric conditions, topography, and soil reflectance characteristics [65,66]. Furthermore, when NDVI is computed from medium-resolution imagery such as Landsat, each pixel often represents a combination of vegetation types and bare soil. These so-called “mixed pixels” [67] can obscure subtle differences in vegetation composition and reduce the accuracy of vegetation mapping, making it difficult to detect species-specific responses. Another limitation is related to sparse or patchy vegetation, which may not generate a sufficiently strong spectral signal to be reliably classified as vegetation, thereby leading to underrepresentation of these communities [68]. Despite these constraints, a growing body of literature has demonstrated that NDVI remains a useful tool for assessing vegetation dynamics in riparian corridors [45,57,69,70]. Its ability to capture general vegetation trends over space and time makes it particularly suitable for large-scale, long-term studies. To strengthen and validate the insights derived from satellite data, however, future research should complement remote sensing approaches with targeted field campaigns. Collecting species-level information through ground surveys would allow the creation of updated and high-resolution databases, thereby enabling more accurate assessments of how different plant communities respond to both natural disturbances and human-induced pressures.

The analysis of permanent water along the study reach confirms the reduction of extreme vents during the last decades. Such information derives from the JRC Yearly Water Classification History, which is a dataset containing maps of the location and temporal distribution of surface water from 1984 to 2021, generated from Landsat 5, 7, and 8 acquired between 16 March 1984 and 31 December 2021 by classifying each pixel into water/non-water [71]. Figure 8 shows that early periods (1984-2003, blue bars) were characterized by the majority of pixels not always covered by water, meaning that water was flowing along multiple channels over time. The increment of areas covered by permanent water (i.e., higher bars towards 80-100% of coverage) depicted during the more recent decades implies that water nowadays flow in a rather constrained active channel. This shift of vegetation is mostly attributable to the growing of vegetation due to the reduction of flooding events, as described in the previous section and pointed out by similar investigations worldwide [34,43,72].

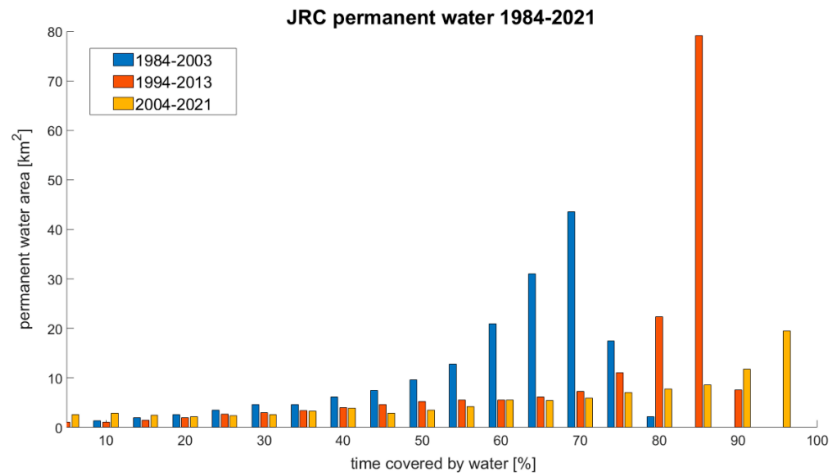


Figure 8. Areas covered by water, as derived from the JRC Yearly Water Classification History dataset.

The findings of this study highlight the influence of climate change on the riparian vegetation growing along the Middle and Lower Vistula River. A long-term decrease in monthly maximum discharges creates conditions that favour vegetation colonization bars and banks. Over time, this establishment of riparian vegetation contributes to an oversimplification of the main channel,

reinforcing a feedback loop between channel morphology and vegetation growth. Specifically, once vegetation becomes established, it promotes the trapping and accumulation of sediments as well as seeds that would otherwise be transported downstream, leading to recurring cycles of deposition and vegetation expansion in the same areas [43]. This type of vegetation–morphology interaction is not unique to the Vistula River. Similar processes have been documented in other major European river systems, where reduced hydrological variability and altered flood regimes facilitate the encroachment of vegetation into active channels [34,73]. Such transformations carry important implications for river management, as they may affect flood conveyance, water quality, biodiversity, and the overall resilience of riparian ecosystems.

Addressing these challenges requires innovative strategies that integrate ecological and geomorphological perspectives. In this regard, the approach proposed in the current study offers a preliminary but important step toward developing such strategies. By exploiting open-access data sources and freely available analytical tools, and by leveraging the broad spatial and temporal coverage provided by Landsat satellites, this investigation provides a cost-effective means of identifying long-term hydrological and vegetation dynamics. As such, it can serve as a valuable foundation for future management plans aimed at reconciling the ecological and societal needs of large river corridors under changing climatic conditions.

5. Conclusions

Leveraging satellite imagery and Google Earth Engine, the present study investigated the impact of changes in monthly maximum discharges on the riparian vegetation along a 250km reach of the Vistula River in Poland, considering the period 194–2023. The opportunity to utilize high-performance computational tools such as GEE allow for providing results at a large spatiotemporal scale, which is paramount to properly inform policymakers and water managers to develop adequate management strategies.

The analysis pointed out variations in the river hydrology during the observed period, with more humid years in the middle of such period, and a decrease of maximum monthly discharge during the last 20 years, likely connected with a more severe impact of climate change. Such reduction of water flow allow more time for vegetation to establish on river bars and banks, eventually creating new islands and causing an oversimplification of the active channel, a phenomena observable across many European piedmont rivers.

To corroborate the results presented here, as well as to depict plant-species dynamics, additional studies are needed, considering a combination of methods such as field investigations, numerical modelling and high-resolute imagery.

Author Contributions: Conceptualization, M.N.; methodology, M.N.; formal analysis, M.N. and Y.G.; resources, M.N.; data curation, M.N.; writing, M.N. and Y.G.; supervision, M.N.; project administration, M.N.; funding acquisition, M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the NCN National Science Centre Poland – call PRELUDIUM BIS-3, Grant Number 2021/43/O/ST10/00539. This work was partially supported by a subsidy from the Polish Ministry of Education and Science for the Institute of Geophysics Polish Academy of Sciences.

Data Availability Statement: Data are available within the article or could be asked to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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